Effort Reduction and Collision Avoidance for Powered Wheelchairs; SCAD Assistive Mobility System

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PhD

2012

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This Thesis is submitted in partial fulfilment of the requirement for the award of the degree of Doctor of Philosophy of the University of Portsmouth.

December 2012

“Whilst registered as a candidate for this degree, I have not been registered for any other research award. The results and conclusions embodied in this Thesis are the work of the named candidate and have not been submitted for any other award”

ABSTRACT

The new research described in this dissertation created systems and methods to assist wheelchair users and provide them with new realistic and interesting driving opportunities. The work also created and applied novel effort reduction and collision avoidance systems and some new electronic interactive devices.

A Scanning Collision Avoidance Device (SCAD) was created that attached to standard powered wheelchairs to help prevent children from driving into things. Initially, mechanical bumpers were used but they made many wheelchairs unwieldy, so a novel system that rotated a single ultra-sonic transducer was created. The SCAD provided wheelchair guidance and assisted with steering. Optical side object detectors were included to cover blind spots and also assist with doorway navigation. A steering lockout mode was also included for training, which stopped the wheelchair from driving towards a detected object.

Some drivers did not have sufficient manual dexterity to operate a reverse control. A reverse turn manoeuvring mode was added that applied a sequential reverse and turn function, enabling a driver to escape from a confined situation by operating a single turn control.

A new generation of Proportional SCAD was created that operated with proportional control inputs rather than switches and new systems were created to reduce veer, including effort reduction systems. New variable switches were created that provided variable speed control in place of standard digital switches and all that research reduced the number of control actions required by a driver.

Finally, some new systems were created to motivate individuals to try new activities. These included a track-guided train and an adventure playground that including new interactive systems.

The research was initially inspired by the needs of young people at Chailey Heritage, the novel systems provided new and more autonomous driving opportunities for many powered wheelchair users in less structured environments

Keywords: Scanning Collision Avoidance generator, doorway navigation, effort reduction systems.

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DECLARATION OF CONFORMITY

I hereby declare that the research documented in this Thesis has been undertaken by the author and that any work included that was not undertaken by the author has been appropriately attributed.

Martin

Martin Langner

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ABBREVIATIONS

ABS	acrynol butile styrene
ADD	advanced detection distance
AGC	automatic gain control
AGV	automated guided vehicle
AIWC	advanced integrated wheelchair control
AM	amplitude modulation
CAN	control area network
CCD	charge coupled device
CCW	counter clockwise
CHS	Chailey Heritage School
CMOS	complimentary metal oxide silicone
CTFM	constant transmission frequency modulation
CW	clockwise
DC	direct current
DSP	digital signal programming
ECU	European Currency
EFCS	electronic flight control system
EM	electro magnetic
EMC	electro magnetic compatibility
EMF	electro motive force
EMP	electro magnetic pulse
EPIC	electric powered indoor chair
EPIOC	electric powered indoor outdoor chair
ESD	electro static discharge
FBW	fly-by-wire
FM	frequency modulation
GIDS	generic intelligent driver support
GND	ground – earth / signal path return
GPS	global positioning system
HCI	human computer interaction
Hz	frequency cycles per second
IC	integrated circuit
INCH	intelligent wheelchair prototype
IR	infrared
IVHS	intelligent vehicle highway system
KHZ	frequency cycles per second
LED	light emitting diode
LRF	laser range finder
M3S	input-device output-device safety-device protocol
MIC	mobile interactive control
mm	milli-meter
MOD	modulation
MOS	metal oxide silicone
ms	milli-second
Naidex	innovation and inspiration for the care industry
NERO	nuclear electric robot.
Op-Amp	operational amplifier
Opto	optical sensor
OSC	oscillator
PCB	printed circuit board

PIC	peripheral interface controller
PLL	phase locked loop
PPM	pulse position modulation
PSU	power supply unit
PWM	pulse width modulation
RFI	radio frequency interference
RFID	radio frequency identification device
RPM	revolutions per minuet
RX	receiver
SCAD	scanning collision avoidance device
SENARIO	sensor aided intelligent wheelchair navigation
SPRINT	strategic program for innovation and technology
TIDE	European unions collaborative funding initiative
TX	transmitter
VAHM	vehicle autonome pour handicapés moteurs
VCO	voltage controlled oscillator
VR	variable resistor
4WD	four wheel drive

Acknowledgements

The author wishes to express his gratitude to the following:
Specifically:
To Dr David Sanders TD for agreeing to direct the research and for his help, guidance and encouragement throughout. Many thanks to him for the speed with which he assisted with the last steps of the writing-up.
To Dr Giles Tewkesbury MBE for the management of academic matters related to the research and expertise in electronics and software engineering.
T0 Dr Simon Chester and Dr David Robinson for their help with chapter corrections and advice.

My sincere thanks go to:
Sylvia Lamb (Principal) and Simon Yates (Head of School) and the governors at Chailey Heritage for sponsoring the research and for enabling me to assimilate my engineering skills and test my research in the school environment.
Donna Cowan (Technical Director of Rehabilitation Engineering Services) for her help, support and encouragement. To Robert Taylor (Premises Manager) for giving me the time to finish my Dissertation and Vicky Smith (Roberts PA) for proof reading.

To Roger Greenland as my mentor and sounding board and the late Andrew Brown for his encouragement and understanding.
My friends, the children at Chailey Heritage School for their determination to succeed in their driving tasks and putting up with all my add-hock experimental trials.

But especially to
My family, Mum and Dad for having the faith in me to do the work.

In particular Sue (my wife), my children for their support and understanding, Alice (my daughter) for testing some of the systems and Alex (my son) for putting me straight on a few technical issues and generally for putting up with me, for being patient and for helping me by being guinea-pigs for some of the new systems and research.

DISSEMINATION

LANGNER M (2010) Using a scanning collision avoidance device to assist with steering. Journal of Intelligent Mobility, Volume 13, Number 2, ISSN:1472-7633, pp 213- 238.

LANGNER M,SANDERS D A & TEWKESBURY G E (2010) Improving wheelchair driving using a sensor system to control wheelchair-veer and variable-switches as an alternative to digital switches or joysticks, Industrial robot international journal Vol. 37 No.2, pp 157-167.

M LANGNER (2009) A new scanning collision avoidance device. Journal of Intelligent Mobility ISSN 1472-7633. Volume 12 (2), pp 182-199.

LANGNER M & SANDERS D A (2008) Controlling wheelchair direction on slopes, Journal of assistive technologies, Vol.2 No.2, pp 32-42.

Chapter 1

Introduction

Previous research undertaken by the Author of this dissertation had created a network of tracks at Chailey Heritage School. Track guidance provided limited driving opportunities for young people who were not considered suitable for powered mobility. This formed the background for the new research described in this dissertation. Many young people wanted to drive their wheelchairs away from the tracks but they could not do so safely.

Ethical considerations are included in appendix A

1.1 Summary of the research

This research resulted in the creation of the Scanning Collision Avoidance Device (SCAD), which was attached to standard powered wheelchairs. The new hardware and time line that was created during this research is listed below:

- Bumper detectors [Year 1-2]
- Audible object warning system [Year 1.5 - 2]
- The creation of SCAD [Year 2-4]
- Auto steering SCAD [Year 2-3]
- Side object detectors [Year 3-4]
- Direction lockout training interface [Year 3-4]
- Reverse turn manoeuvring systems [Year 3-4]
- SCAD proportional control [Year 5-6]
- Proportional switches [Year 6-7]
- Interactive playground and track guided train [Year 3 -6]
- Veer reduction system [Year 6-7]

To help prevent children from driving into things, initial work started by making mechanical bumpers (Page 88) to cut the drive power when a wheelchair was in collision with an object. To provide feedback about bumper operation an audible object warning was provided as an indicator that assistance was required for the diver. The addition of mechanical bumpers made many wheelchairs unwieldy to drive, so new research started with the creation of a novel system that rotated a single ultra-sonic transducer that sent sound pulses at stepped periods of rotation . This led to the development the SCAD (Page 112) which detected objects without making contact. For this new work, ultrasonic sensors were selected for non-contact proximity and ranging. This SCAD system provided object detection for the front of the wheelchair and gave a warning sound to a blind driver that objects were nearby. The SCAD was that it used a single rotating transducer in place of a multiple transducer array.

Non-contact object sensing provided new opportunities to extend this research. The SCAD was developed further to provide wheelchair guidance from detected objects in the path of travel. This became the auto-steering SCAD (page 150) capable of steering along a corridor when a single drive switch was activated.

The front castors caused a blind spot at the side of the wheelchair. Optical side object detectors (Page 153) were developed to cover this blind spot and also assisted with doorway navigation.

The SCAD provided wheelchair steering assistance, however NHS therapists that worked within the school were concerned that automated assistance may hider a child learning to drive for themselves. A steering lockout mode (page 270) was included for training purposes, which blocked driving toward a detected object. This provided a need for a diver to problem solve in order to seek an appropriate drive direction that was clear of obstacles.

The auto-steering SCAD enabled new or novice drivers to get into an area of confinement that required them to reverses out of the situation. Some drivers did not have sufficient manual dexterity to operate a reverse control. A reverse turn manoeuvring mode (page 275) was added to the SCAD control options. This applied a sequential reverse and turn function. The wheelchair then automatically manoeuvred away from detected objects when a turn control was operated, enabling the driver to escape from a confined situation by operating a single turn control.

The main applications for the SCAD were for drivers using switch controls that provided an On – Off control function. Switches did not control the wheelchair speed. Whilst this was suitable for those who did not have refined hand control movement, many people with finer control of their limbs used a proportional joystick and did not want to use switches.

A new version of Proportional SCAD (Page 212) was created that operated with a proportional control inputs. This blocked driving directions towards detected object that was logically the same as the auto-steering SCAD.

New systems to reduce veer including effort reduction systems (Page 64) were created towards the end of this research. New variable switches were created that provided variable speed control in place of the standard digital switches. That research generally reduced the number of control actions required by a driver (page 71). .

Finally, some new systems were created to motivate individuals to try new activities. These included a track-guided train (Page 363) and an adventure playground including new interactive systems (page 367).

Chailey Heritage staff, (NHS) Clinical Services Therapy staff, children, young adults (and their close associates) were involved at all stages.

Although the research was initially inspired by the needs of young people at Chailey Heritage, the novel systems provided new and more autonomous driving opportunities for many powered wheelchair users in less structured environments.

1.2 The earlier research

This new work builds the earlier research that had created a new track guided electromagnetic wheelchair guidance system that was published by the author in [Langner (2004)]. At the beginning of that earlier research it was observed that some children could not drive their wheelchairs because their hand function was not good enough to operate joysticks, which were the main type of control system. Joysticks required good hand grasping skills and movement coordination within a small area

(16 sqcm). Many children could not drive because of the demands of the joystick. Work continued to make switch controls that were easier for some children to operate. Switches could be put in positions that were more suitable for a child to reach and separated to spread out the control directions beyond the limited movement span provided by the joystick.

Children started to drive more because of the application of switch controls. Some children had limited hand function and could not operate the switches; other children had athotoid movements and problems with spasticity. Many children with poor hand function did have good head control and could turn their heads enough to operate suitably positioned switches. New controls were created that could be operated by children using their chin and some children started to drive competently by using these. Those children were mentally agile and did not require any type of additional guidance support. Work continued to create a variety of controls that could translate the young person's functional and repeatable personal hand or head movements into switched outputs. The creation of these new controls meant that many children started to drive and become independent in their powered wheelchairs.

Despite the creation of new switching controls, some children were still not able to drive their wheelchairs independently, even though many of their friends and classmates were. Many of these children had sufficient physical co-ordination movement and were not necessarily anymore physically disabled than children who were using the new switch controls to drive independently. They may not have had sufficient cognitive ability to be able to work out the sequence of controls necessary to steer their wheelchair. Helpers encouraged children to be mobile because they thought that these children were not doing everything that their classmates were doing. These children wanted to drive but could not, so some helpers pushed those children around in their wheelchairs or intervened to operate their controls for them, just to give them a sense of mobility. These children could not be given switch controls in case they might charge into a wall or be a danger to others and to themselves because they could not start, stop and steer.

It was necessary to determine if they simply needed more practice with driving or if there was something more fundamental in their development that meant they would not be able to use switch controls. It was obvious that these children wanted to drive but when they tried driving, they needed assistance from helpers to enable them to become mobile (or at least to have some experience of wheelchair driving). A turning point in the development of assistive technology centred on a girl who was almost totally blind. She had sensitive hearing and was intelligent but was severely physically impaired and could not use her hands to control a switch. She could use her chin and she did have good head movement.

Helpers encouraged her to drive because she wanted to. She could not be provided with a powered wheelchair because she did not meet criteria for competency to drive. A powered wheelchair was loaned to her with a joystick mounted on the side. She rested her arm on the joystick and drove in circles because that was the only thing she could do safely, although she was able to feel the experience of starting and stopping. Occasionally she lost control and would spiral out and crash into things so she was reliant on helpers to guide her. One of those helpers suggested that some kind of track, similar to a railway line, could be used to guide her wheelchair. A track system was created that enabled young people to get from one point to another without going astray. Children then became frustrated because the tracks did not always lead to the places where they wanted to be. For example, a blind track driver wanted to go to places other than her classroom and toilet areas, which were connected by track. There were also other problems; even on a track she would crash or bump into things. She had good hearing and could almost sense if someone was there but she could not sense inanimate objects.

1.3 Mechanical bumpers

The initial work described in this dissertation used mechanical bumpers to stop children from driving into things. This was challenging for a number of reasons. A strip bumper could be mounted around a wheelchair. When the wheelchair hit something, it could impact quite heavily and could be like a crash even though the motor power was cut after a collision had occurred. Trials with strip bumpers demonstrated that energy absorption was over a small distance of just a few millimetres. So children could drive into things and hurt themselves or damage equipment. A latched system was used in earlier experiments. That system cut power to the motor when the bumper was touched. The power would stay cut until a helper reset the system, after ensuring that the child was safe to proceed. Sometimes children did not understand why the wheelchair had suddenly stopped due to bumper operation. Prior to the application of bumpers, children just crashed into things and carried on driving. So an audible warning device was added to give an indication of when an object was struck. This modified system stopped the power or gave a sound warning or both, as described by these scenarios:

> Scenario A: A child drives along and strikes an object. The child hears a sound warning and takes his hand off the switch.
> Scenario B: A child drives along and hits something. Power to the motor is cut and he cannot drive any further until a helper resets the system.
> Scenario C: A child drives along and hits something. Power to the motor is cut and the child hears a beep at the same time.

These scenarios were tested with young people and new bumper systems were created to improve energy absorption. Bumpers operated over a 10 cm displacement, providing 10 cm for deceleration after contact with an object. These new bumper systems had to accommodate objects being hit at different angles of impact. Collisions with objects could be either ‘head on’ or side impacts. These bumpers were curved and semi circular to provide energy absorption from side impacts. On occasions these bumpers jammed as a result of a hard strike and could remain in the object struck condition resulting in the wheelchair driver being rendered temporarily immobile because the wheelchair drive power would be cut. Sometimes the bumpers needed repairing.

These new bumpers limited damage to children, wheelchairs and obstructing objects, but were subject to physical damage themselves. They also increased the length of the wheelchairs. To be effective, bumpers needed to protrude the normal dimensions of a wheelchair. Children were provided with trays on their wheelchairs and these could protrude beyond the bumper. This reduced the effectiveness of bumpers on collisions with walls because the tray would make contact before the bumper.

Extending bumpers caused wheelchairs to become un-drivable because the chair became too long and bumpers could be accidentally triggered, causing movement to be hindered. Results from tests with mechanical bumpers established that it was helpful to give children warning of impending collisions. Mechanical bumpers increased confidence of both children and helpers. The new bumper systems proved useful but were not practical or sustainable in the longer term.

Some children who had a mechanical bumper, became frustrated by it because it was vulnerable to damage and was an obstruction when helpers were transferring children in and out of their wheelchairs, although object detection was a helpful feature.

One child had a bumper at the back of her wheelchair because she had behavioural problems that caused her to reverse into people deliberately. A control system was created to cut the power for a timed period after contact with an object. Driving was reinstated after the timed period had elapsed, providing an object was no longer being detected by the bumper.

1.4 Non-contact object sensing

It was necessary to develop a better way of detecting objects that overcame the limitations of mechanical bumpers. The main methods used for non contact detection were ultrasonic, and infrared. Laser range finding systems were also commercially available but these were too expensive at the time of this research.

Infrared optical sensors were used for non contact detection. Objects could be sensed by triangulation where objects within a specified distance reflected an infrared beam back to a sensor. The colour of objects had affected how much reflective energy was returned. For example, white objects reflected well and were detected at a greater distance than dark objects, which were poor reflectors. There were problems with objects being detected at a specified range due to the target colour and area, particularly as lighter target objects reflected more light energy than darker objects. Infrared beams were narrow and had a small cross sectional area. This was necessary for background suppression, so objects could be detected within a specified distance. Multiple infrared beams could be used to cover sufficient area for efficient object detection at the front of a wheelchair. There could be problems with multi path reflections causing false detection. Auto-focusing systems used by video cameras were considered. Those systems were capable of focusing on a specific target. The active sensing areas were small compared to the area of objects that needed to be detected. Also, auto focus systems were too slow due to their processing times. Ultrasonic sensors were selected because objects could be detected and ranged quickly by the time of flight principle, where measuring the time taken for a sound pulse to travel between the sensor and the object can determine the object distance.

1.5 Creation of a Scanning Collision Avoidance Device (SCAD)

New research started creating a non-contact proximity object detection system that used ultrasonic ranging. A system was created that rotated a single ultrasonic transducer that sent ultrasonic pulses at stepped periods of rotation and was the first prototype SCAD object detector. This was a wide angle object detector and audible warning device for people using a track following powered wheelchair. The essential aspect of the SCAD system was the generation of multiple zones without increasing the physical size of the detector head. A natural progression beyond the imposed access limitations of the track routes was the creation of a system that guided itself by sensing the local environment. The SCAD provided a protected environment but required a higher driver skill level than was required for track driving. For the development of a guiding SCAD system, a method of determining the position of detected objects was required. This potentially offered more opportunities for learner drivers with visual impairments and spatial perception problems to drive with more freedom

1.6 Cost effectiveness

To provide effective object detection for a wheelchair, a significant number of separate transducers were required. The Nav chair described on (page 35) used twelve separate transducers, each individually protected in their separate enclosures. Associated with this was the signal processing electronics necessary each transducer.

The SCAD consisted of a single transducer and stepper motor that covered the same area as a 12 transducer array. This proved to be particularly cost effective, even when taking into account the cost of the stepper motor (similar in cost to a single transducer). Additionally many multi element transducer array systems needed their transducers to be performance matched, and this was not necessary with a single transducer.

At the time of writing there was not any directly comparable systems that were commercially available other than the SMART wheelchair system produced by Smile Rehab. The cost for this was approximately £11,000 including the wheelchair. This provided optical line following and had two ultrasonic detectors for object detection. It should be noted that this SMART system did not provide navigation or guidance support via the object detectors. Their purpose was to provide a stop function when an object had been detected directly at the front of the wheelchair.

The main cost a multi-element system was the transducers and their respective enclosures. The SCAD required only one transducer, enclosure and a motor. This represented a considerable cost saving. A SCAD system including the wheelchair could be made for half the cost of the SMART system approximately at £5000.

1.7 Structure of the Dissertation

This dissertation begins by investigating the literature and Chapter 2 is a survey and background to the research. Chapter 2 considers independent mobility and loss of mobility, ability to drive, safety aspects, the Smart wheelchair, AGVs (Automated Guided Vehicles), guidance systems, guidance, line detection, off-wire guidance, communications, the Swedish Slingan Project, sensors, control, joysticks, fly-by-wire, special needs and navigation and computer based vision systems.

Chapter 3 describes research to create new systems to assist users to steer their powered wheelchairs, including systems to reduce veer and the change from a set of digital switches to a set of new variable switches for some powered-wheelchair users. The term ‘effort reduction’ was applied to this new area of work

With the on-going implementation and use of the track guidance systems and as powered wheelchair users left the track systems, object detection needed to be considered. This is described in Chapter 4. Even on the track systems, drivers sometimes collided with people or stationary wheelchairs and there was no warning of an impending collision until it had occurred. These considerations formed the basis for experimenting with bumper systems for the detection of objects.

Bumpers made wheelchairs bigger, so later work went on to create a new contact-less proximity object sensing system. That system was called a Scanning Collision Avoidance Device (SCAD) and is described in Chapter 5. The new system offered a greater opportunity for learners to drive with more freedom, as the SCAD provided a protected environment but it required a higher driver skill level; in particular, navigation and recognition skills. Mechanical bumpers and energy absorption with audible warning devices were investigated along with infrared background suppressed sensors.

Events in which drivers collided or misjudged distance became the focus of further work and that is described in Chapter 6. The principle of rotating the ultrasonic transducer & sending ultrasonic pulses through stepped periods of rotation had been used and evaluated in Chapter 5, but with the development of the automatic assisted steering SCAD system, a better idea of the position of detected objects was required.

Chapter 6 describes the use of the SCAD to assist with steering because some children were being encouraged to drive more independently and often crashed. A new guidance system was created to help children gain a greater sense of personal independence by reducing the frequent need to be rescued.

More accurate positioning was considered so the width of scans was increased and segmented. Work then began to improve wheelchair control, particularly for those with in-built motor speed compensation. Side detectors that used infrared were introduced and the guidance system was further developed for use in unstructured environments.

Chapter 7 describes the initial testing of the SCAD and transition of the collision avoidance system from the laboratory to the real world; to be used with children in their familiar environment. The collision control system was developed by successive trial applications including collision avoidance testing. Real life driving issues are discussed and an understanding of the human versus automatic system help is formed. The difficulties experienced with motor speed compensation are discussed and range contraction is considered for doorway navigation. A new scanning method was created that halved the scan time but did not double the echo sampling frequency.

Chapter 8 describes the technical testing of SCAD. The first SCAD system described in Chapter 5 was used as a test bed to establish the principles. Further testing was undertaken to gain a better understanding. Specular reflection and transducer polar response are considered along with the separation between the detection of wanted and unwanted objects. Auto steering collision avoidance was tested and the position for the SCAD head mounting was investigated.

Chapter 9 describes trials with children at Chailey Heritage School, beginning with the mechanical bumper systems and moving on to the new contact-less SCAD system that included crashing, the addition of a reverse and turn function and an understanding of what wheelchairs were doing and why.

The research described in this dissertation attempted to reduce the number of control actions required by a driver. There were human issues that influenced system development and the direction of the research and these are discussed in Chapter 10. Interviews with helpers are included to validate the research. In general, the interviewees stated that the new assistive systems created in this research helped increase independence and provided new driving opportunities for children.

Chapter 11 is a discussion of the research and a consideration of the conclusions.

Chapter 12 proposes future work.

Appendix C describes the track systems that existed at Chailey Heritage at the beginning of the research and that were described in [Langner (2004)]. Those systems provided a form of mobility and an assessment tool for use with a range of postural support systems. Although the systems had track junctions, the children using the systems were restricted to driving on the tracks. The main work in this dissertation aimed to get the children away from the tracks to allow them to drive their wheelchairs wherever they wanted to go.

Appendix D describes different ways of using the new systems created during the research, specifically a track guided train, an adventure playground and interactive systems. These were created to motivate individuals to try new activities. They allowed children to exercise personal control and the train provided an early driving experience and introduced powered mobility as a fun activity.

1.8 Research work completed

During the research the following new systems were created to provide opportunities and driving experience for young people with complex needs:

New novel research work.

- Used scanning ultrasonic sensor to assist with steering
- Segmented scans from a single sensor to:
    - reduced scan time
    - identified where objects were
    - then automatically help to avoid obstacles
- Created a method to reduce ghosting from a scanning sensor
- Created a method to reduce ranges for doorway navigation
- Created methods to provide variable levels of assistance to a user
- Automatic reverse turn manoeuvring influenced by a user
- Created a method of veer correction
- Used proportional switches to provide bespoke fine motor control

The following new methods were created:

- Using a SCAD to assist with steering
- Object detection with detected object positioning
- Segmenting a scan
- Decreasing scan time
- Automatic steering obstacle avoidance
- SCAD trajectory collision control
- Range contraction for doorway navigation
- Automatic reverse turn manoeuvring
- Audio and visual Prompting systems

1.9 Published work

The following papers were published during the research

LANGNER M (2010) Using a scanning collision avoidance device to assist with steering. Journal of Intelligent Mobility, Volume 13, Number 2, ISSN:1472-7633, pp 213- 238.

LANGNER M,SANDERS D A & TEWKESBURY G E (2010) Improving wheelchair driving using a sensor system to control wheelchair-veer and variable-switches as an alternative to digital switches or joysticks, Industrial robot international journal Vol. 37 No.2, pp 157-167.

M LANGNER (2009) A new scanning collision avoidance device. Journal of Intelligent Mobility ISSN 1472-7633. Volume 12 (2), pp 182-199.

LANGNER M & SANDERS D A (2008) Controlling wheelchair direction on slopes, Journal of assistive technologies, Vol.2 No.2, pp 32-42.

Other relevant papers published before this research

LANGNER M (2004) A wheelchair guidance system for people with special needs, MPhil thesis, University of Portsmouth.

LANGNER M (2002) Single track system for powered wheelchairs to provide an opportunity for children to safely venture away from helpers with greater autonomy, Journal of Intelligent Mobility, Volume 5, Number 1, ISSN:1472-7633, pp 65-77.

LANGNER M (2000) Mobile and interactive equipment at Chailey Heritage School. Journal of intelligent Mobility, Volume 3, ISSN: 1472-7633, pp 35-37.

Chapter 2.

Literature survey and background to the research

2.1 Introduction

Studies of the behaviour of children with motor disabilities showed them to be poorly motivated and dependent on their carers [Butler(1986)]. They did not possess a curiosity about their environment, which a child would normally exhibit. This was the case even when their disability would not have interfered with their potential performance. [Butler (1984)] used specially constructed miniature powered vehicles for her work with young disabled children. Some improvements in behaviour and motivation were noticed during her work. Powered wheelchairs that were easy to use and safe could improve the chances of a severely disabled child achieving improved independence. The research described in this Dissertation created new systems to help achieve this.

Independence for young people may not be experienced for two important reasons: personal motor disability and low expectations of parents and carers [Langner (2000)]. Deprivation of an experience may lead to 'learned helplessness', a condition in which a child has given up trying to control his world [Verburg *et al* (1984)].

Failure to encounter an opportunity could significantly increase the time required to acquire the skill necessary to drive a powered wheelchair. Some of the problems experienced when teaching a new user to drive a powered wheelchair are described in [Chase (1990)]. [Douglas (1987)] described teaching a pre-school child to steer a powered wheelchair via a mouth-operated joystick. Some problems were encountered during learning, but positive effects on emotional, intellectual and behavioural development were noted.

Teaching a person to drive a powered wheelchair can be a long and difficult process for teachers and learners. The length of time required for some potential users to learn even basic skills can cause the cost to be large. A project at the CALL centre in Edinburgh used a SMART wheelchair [Nesbit (2000)] to teach potential users some basic skills of wheelchair driving [Craig *et al.,* (1995a) & (1995b)]. The response of a wheelchair to stimuli from a user was pre-programmed to suit the learning level of the user. As the user became more skilled, the responses of the SMART wheelchair system could be changed to encourage development. [Langner (1995)] and [Langner (2000)] used a track system at a Chailey Heritage special school to encourage self-initiated mobility. Some children found that system was beneficial as it allowed them the freedom to move unaided between classrooms, toilets and dining areas. That system has been in use since 1992 and has been extended to include the majority of the school and living areas.

A discussion of the need for and the effect of Smart wheelchair technology was presented in [Nelson (1990)]. Nelson advocated sympathetic application of technology to wheelchairs. He suggested that a wheelchair that does all the work for a disabled user will not force them to improve and adapt. Nelson also discussed safety aspects of the technology.

[Devito (1996)] proposed a wheelchair system that could be integrated into a nursing home. Devito's system was designed for elderly users and he suggested that many of them were probably motor car users. A smart wheelchair system would probably cost no more than a second hand car and could provide them with a higher standard of living. The proposed system used Intelligent Vehicle Highway System (IVHS) technology to navigate through a few known routes within the nursing home.

There have been many investigations into the application of technology for wheelchairs [Beattie (1993)], [Bell (1993) & (1994)], [Bourhis (1993) and [Nisbet (1988)]. Some investigations have applied AGV technology directly to a wheelchair application [Rao (1989)]; other investigations have used adapted AGV technology or attempted to create new algorithms and systems to assist a wheelchair user [Pruski (1992)].

Independent mobility such as crawling, walking and running are usually acquired in the first two years of life [Verburg (1984)]. Being able to transport oneself also had a positive effect on the general development of a person. [Hanson (2008)] suggested the provision of powered mobility as an effective accommodation for young children with motor impairments. Mobility also confers the benefit of learning through: fun, exploration, hide and seek, football (via foot rest) and follow my leader type activities Douglas [1987].

Perhaps more than any other physical deficit, loss of mobility is a constant reminder of an individuals dependence [Nelson (1990)]. [Chase (1990)] reported in a case study that an adult having severe disabilities demonstrated improvements in self-confidence, ability to socialize and general functional ability as a result of a 5 year powered mobility training program.

The CALL Centre in Scotland developed the SMART Wheelchair with 'Loop Steering' that defined mobility as giving benefits of increased motivation and other positive effects on the general development of a person resulting from the use of smart wheelchairs [Odor and Watson (1994)]. [Y Demiris (2009)] suggested knowing when to assist children and adults with sensori-motor disabilities significantly increased their autonomy through the use of assistive robots.

[Langner (2004)] created a system to give some children the opportunity to drive along predetermined pathways. [Goodwin (1992)] demonstrated the possibility of technologically aided systems that could enhance the prospect of improved independent mobility for some with a disability. [Kang W (2008)] developed an omni-directional robot that helped disabled people in a factory environment. [Hiroki Murakami (2009)] stated that driving performance needed be improved because of the number of driving accidents caused by elderly operator's narrow sight and poor joystick operation.

All of these studies suggested that a new powered wheelchair system could provide benefits. The research began by considering the technologies used in industry.

2.2 Automated guided vehicles (AGVs)

The technology to drive automated platforms around in structured environments such as warehouses or factories has been available for many years. Automated Guided Vehicles (AGVs) transport goods and raw materials from place to place within predetermined and controlled areas. Some AGVs depend on hidden tracks [Wakaumi *et al* (1989)]. Visible tracks painted or built into the floor of a factory have been practical alternatives to sinking cables into the floor [Hartley (1987)] & [Goodwin (1992)]. Marking the floor has been suitable for 'clean' environments where the floor does not become too obscured. [Bostel (1996)] described how AGVs could use static beacons or "bar codes".

Sonar sensors using the time of flight principle to measure range have been widely used on autonomous vehicles. [Jörg (1996)] discussed such systems. [Hinkel (1988)] described how some vision based systems used a stereoscopic view to detect obstacles but those systems could require time consuming data processing. As an alternative, a laser range finder could provide accurate and fast range information but those systems can be expensive [Sanders (1993)].

The new research work described in this dissertation used ultrasonic time of flight sensors.

Self powered mobility systems had been available for many years. Items could be transported to and from specific destinations by predetermined routes [Langner Mphil Thesis (2004)] AGVs could be track guided which was analogous to a railway system and AGVs could go into areas that would have been hazardous for people. The two most common forms of guidance technology were inductive and optical line guidance and systems using a mix of inductive line guidance and optical position markers. Measuring the distance and speed the vehicle had moved using odometry provided control flexibility for re-routing, for example, around temporary obstructions.

A method of automating the man-aboard tow truck that had been used in factories for years was devised in 1953 by Siemans Dematic Company. An example is shown in Figure 2.1. A track was created by embedding a wire in the factory floor. A guidance system was created with sensors on the bottom of the tow truck that looked for a magnetic field.

Figure 2.1.(1950's) Style Siemans Dematic AGV. GOX 'Guide-O-Matic'

The field was created by a current running through a wire or series of wires in the floor that a vehicle would read for steering and stopping at a station Figure 2.1 shows the AGVs that were made by 'Siemans Dematic' company over a forty year period.

AGVs incorporated systems that would travel under line guidance and positional information was retrieved from barcodes on the floor [Bostel and Sagarm (1996)], walls or overhead markers.

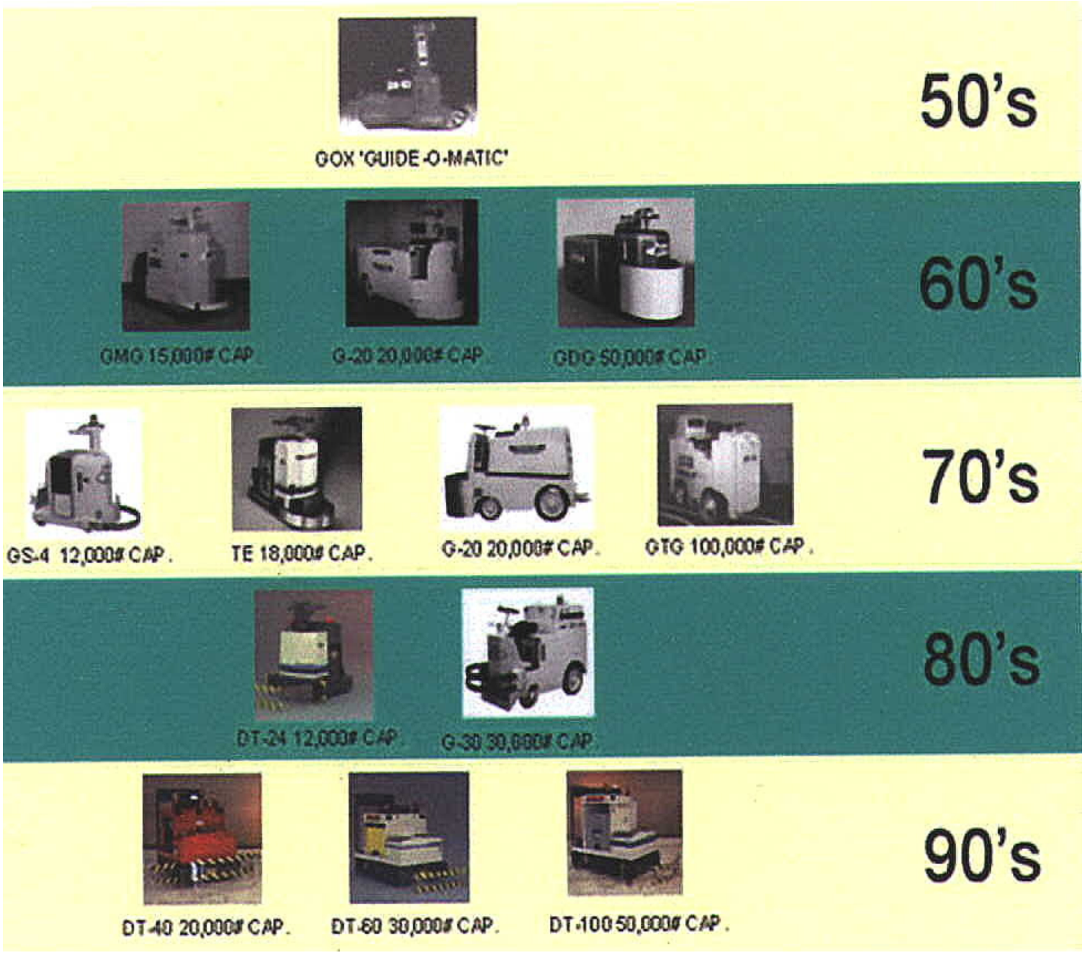


Figure 2.2 AGVs that were made by 'Siemans Dematic' through the decades

Other forms of positional sensing technology were developed that used radio frequency identification tags (RFID) that could be placed on pallets for delivery or collection from AGV pick-up and drop-off points.

A Landmark based navigation system was developed for robotic wheelchairs [DeLaCruz.C (2010)]. The proposed navigation was robust in the localization procedure which is a major problem in robotic navigation systems. Every landmark was composed of a segment of metallic path and a RFID tag. Odometry information was used for localization which was corrected on-line every time the robotic wheelchair was over a landmark.

2.2.1 Types of automated guided vehicles

Typically, Autonomous Guided Vehicles (AGVs) were designed to transport goods or raw materials. Many are described in [Stott (1997)]. Some more sophisticated vehicles, were able to leave a pre-set path and navigate a different route around an obstruction, for example the system described by [Hartley (1987)].

In 1998, a robot named Nomad was deployed into the Patriot Hills region of Antarctica. The robot was designed as an independent, isolated autonomous vehicle with little chance of operator intervention. The ability of a stereo vision system and laser scanner to perceive polar terrain and the autonomous navigation system were described in [Moorhead *et al* (1999)]. Navigation was assisted using landmark-based navigation and millimetre wave radar.

The NASA mission to Mars involved the Mars Pathfinder Rover or Microrover spacecraft. [Stone (1996)]. The Microrover was deployed from the mission vehicle onto the surface of Mars and was then employed on experiments and tasks that involved moving across the surface of Mars. The Microrover was a six wheeled, all wheel drive mobile robot [Matijevic (1996)]. It was equipped with many sensors to assist the vehicle to safely negotiate the Martian landscape.

Due to the communication delay caused by the distance from Earth to Mars, the autonomous system was required to deal with any unexpected hazards independently of the operator [Stone (1996)] & [Morrison, Nguyen (1996)]. Many mobile robots are wheeled vehicles. Walking robots have also been investigated.

A walking robot can have advantages over a wheeled robot especially in unstructured and rugged terrain. Several articulated legged vehicles have been built and the potential of these mechanisms for negotiating rough terrain have been described by [Kumar, Waldron (1989)].

A variety of automated AGVs have been built to provide manufacturing support and labor saving operations:

- Towing vehicles (designed to pull load carrying carts)

- Assembly vehicles (designed to transport products through an assembly process)
- Storage and retrieval vehicles (designed to lift and lower loads)
- Sorting transfer vehicles (designed to automatically load and un-load at pickup and deposit points located around conveyor systems)
- Wheeled tele-operated robots
- Walking and climbing tele-operated robots

2.3 Walking and climbing tele-operated robots

Climbing vehicles have been developed for the nuclear industry, notably these included the NERO and MAVIS vehicles as described by [Burrows *et al* (1991)] and [Luk *et al* (1993)], but these vehicles were non-articulated and were designed to operate in a particular mode. They were not suitable for unstructured environments.

At the University of Portsmouth a team led by Professor Collie developed several remotely operated articulated-legged climbing vehicles principally for nuclear environments [Beer (1994)]. A unique control technique provided a complaint force / position servo control at the limb level and a task orientated control system at the operator level [Luk *et al* (1991)]. With an articulated thorax [Collie *et al* (1993)] & [Collie, Luk (1993)]. RobugIIs was capable of performing autonomous floor-wall transfers [Bevan *et al* (1993)] and climbing semi-structured vertical surfaces, for example the side of a ships hull.

Previous work at the University of Portsmouth has investigated systems that would provide reflex control for pneumatically actuated articulated legged tele-robotic vehicles that would operate in a hostile nuclear environment [Hewer (1995)], [Beer (1994)], [Luk *et al* (1993)] and [Collie *et al* (1993)].

The environment in which a robot is required to work necessitates the need for intelligent control [Meystrel (1988)]. Systems that are subject to multiple purposes and abstract goals cannot be handled by current methodologies [Franklin, Selfridge (1990)].

[Yamaguchi (2007)] developed a robotic chair for mobility over steep and narrow stairways for elderly and disabled people living in a house with steep and narrow stairways. The robot chair was vertically moved by actuation of electric cylinders and horizontally moved by push-pull operation given by an attendant. Up and down motions of the robot chair on the stairway were executed through combinations of motor and cylinder actuations.

2.4 Wheeled tele-operated robots

[Galt (1999)] reported that ethical questions had arisen concerning the future development of robotic machines, in particular the relationship between robots and humans. Many people are simply scared by the thought of the inevitable loss of control that is a consequence of automation. [Fernandez-Carmona (2009)] considered wheelchair assisted navigation designed for disabled people who were able to drive a robotic wheelchair on their own. The main novelty was that the wheelchair provided the amount of help needed at each moment, to avoid loss of residual abilities.

A majority of 20th century robots were stationary or, had at most, limited motion along fixed guide ways in one or two directions [Galt (1999)]. Commercially used robots had little or no intelligence. One of the most common types of robot was the fixed-base manipulator arm used in industrial production lines. These robot "arms" were generally only mobile in the extension of the joints and as such had tightly controlled, well-defined work-spaces. A mobile robot does not necessarily entertain this luxury. The task of developing a mobile robot becomes more difficult when it is considered that :

- Environments in which the vehicle may be required to operate will often be geometrically unstructured, cluttered with obstacles and difficult to model or predict
- The complex nature of the operating environments may provide uncontrollable factors that cause the vehicle to malfunction or become damaged
- The facilities that a mobile robot has for sensing the environment are often incapable of achieving high accuracy and can give only approximate indications of the environmental structure. Also, without the facility for absolute calibration, these sensing errors will accumulate over prolonged periods

The past research concerning AGVs and robotics formed a starting point for the new research described in this dissertation.

2.5 Guidance

A guide path [Bohlander (2003)] is an artifact built into the factory or plant environment and generally into the floor. Different methods of guidance and navigation have been implemented [Langner (2004)]. Early automated guided vehicles inductively tracked a guide wire or an optical visible line, painted or made with tape on the floor. [Elgun (2003)] reported that some heavy engineering plants have Automated Electrified Monorails. Inductive line following relied on a wire laid in a slot cut in the floor. This wire was energized with an oscillating current (characteristically of a few KHz), the magnetic field emitted was detected by antennas carried by the vehicle. Figure 2.3 shows a guide wire placed in a channel and it's corresponding relationship to the sensor coils. The vehicle measured how much to the left or right it was from the centre of the field and corrected accordingly.

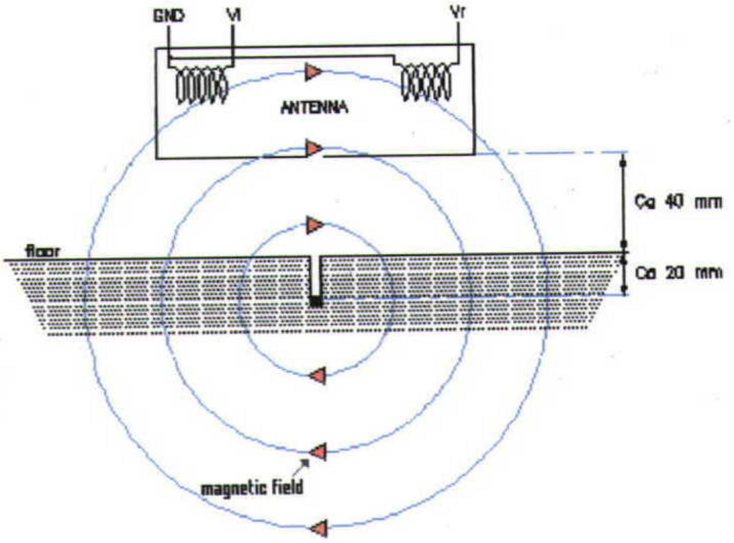


Figure 2.3 Reproduced from [Langner Mphil Thesis (2004)]

Optical line following used a tape or stripe on the floor for the vehicle to follow optically (CALL Centre SMART Wheelchair). Another example was when the stripe was made fluorescent, and the vehicle illuminated it with ultraviolet light [Bohlander (2003)]. The AGV carried a sensor attuned to the characteristics of the fluorescent light and sensed whether it was tending to the right or left relative to this bright marker line. Variations on this theme included the use of white stripes on a dark floor, retro-flective stripes that could respond to infra red light (Smart Wheelchair Systems) and metal film stripes [Goodwin (1992)]. In the latter case, the sensing of the guide path could be through metal detection rather than optical means. Ferrite stripes and magnetic sensing systems had also been developed [Wakaumi (1989)].

There was considerable interest in the development of systems that could operate without a guide wire or stripe. Many companies and people had tried to invent a replacement for the inductive guide wire. In later years agricultural AGVs used Global Positional System GPS navigation and systems with laser scanners, microwave transponders, inertia gyros, ultrasonic sensors, embedded magnets and camera vision systems.

Knowledge gained about the different tried-and-tested methods of line detection provided a baseline for consideration of guided systems described in this dissertation.

2.5.1 First generation off-wire guidance

It was common for vehicles to be able to leave a guide path when instructed and go for a short distance to a work station or pick-up / delivery spot, perform an operation, (for example load transfer) and then return to the guide path. In other cases, vehicles were programmed to make turns at intersections without using wires or to make ‘U-turns’ off wire. While it was away from the guide path a vehicle might count the number of wheel revolutions and may measure the angle of wheels used for steering, thereby constantly computing an estimated position. This form of navigation had commonly been referred to as dead reckoning by odometry [Borenstien (1997)]. After a distance of 3-10 metres, the position estimate accumulated error (from bumpiness in the floor, wheel slips and other noise) and the vehicle needed to return to the guide path to avoid getting lost.

Sometimes AGVs needed to cross a region where it was not practically possible to lay a guide path. This necessitated an independent form of navigation. It was possible for a vehicle to ‘home’ onto a beacon using a technique called ‘beam riding’. A light source (for example, a bright red LED or laser indicated the intended path the vehicle was required to go) was aimed at the vehicle. The AGV could be equipped with a sensor to detect this beam and guide itself by keeping the light at the centre of its field of view. Some problems included obscuration of the guiding beam. A related but more advanced method was the use of a vision system that looked ahead for landmarks.

2.5.2 Second generation off-wire guidance

Many users resisted changing paths or asking for new installations simply to avoid cutting channels in the floor. With software-determined guidance, it was possible to make frequent changes. This needed to be sufficiently accurate and reliable so that it did not represent a hazard. The accuracy obtained from a wire guided system could be used as a standard. ‘Off – wire’ guidance systems could be expected to position the vehicle to within 1 cm in areas of close proximity to other objects. Nearly all second generation machines made use of odometry and dead reckoning as an important source of information. Beam riding or similar optical schemes had also been used in some systems, particularly for alignment near a workstation.

Systems could navigate between workstations in a clean room by a combination of dead reckoning and inertial guidance. Conceptually, inertial guidance did not rely on external artifacts for its frame of reference. If inertial guidance was used as a primary source of positional data, a two or three axis accelerometer and a two or three axis rotation sensor were required. Measurements obtained from these devices could be integrated in order to derive the position and attitude of the vehicle. Any such inertial device would generate small spurious signals that caused the state of the information to drift with time and result in cumulative errors in positional data. It was necessary to reset the inertial navigator periodically before the drift moved the output out of tolerance.

Optical systems have been used in factory environments using ‘lighthouse navigation’ [Bohlander (2003)]. In these systems a vehicle repeatedly scanned a light beam through an arc around it and looked for reflections back from reflectors. The system could compute its location provided it was able to detect at least two or preferably three reflectors. When reflectors could not be seen then odometry and dead reckoning methods were used.

2.5.3 Third generation off-wire guidance

The development of machines that could mimic the navigation skills of human beings has formed the basis for on-going research. Candidates for this type of technology included: computer vision systems [Appleton, Williams (1987)], [McKerrow (1991)], [Sanders (1993)], [Sanders; Lambert; Graham-Jones, et al. (2009c)], [Sanders; Lambert,; Graham-Jones, et al. (2010c)] and laser range finding [Parnichkun and Samadi (1999)]. Sonic imaging techniques have also been developed using several different principles: modulated waves [Teshigawara *et al* (1989)], frequency sweeps [Lindstedt (1996)]. Echo location methods have also been described by [Stott,Sanders (1996)], [Stott (1997] and [Stott (2002)].

Vision systems involve a camera, lighting and a computer. There are at least two different ways to implement an attentive vision system, using either a bottom up approach or a top down approach [Garibotto (1999)]. For the bottom up approach the low-level features extracted from the camera image have been used to orient the system to a particular area of interest. With the top-down approach, the visual recognition task was driven by a specific goal and was constrained within a set of processing algorithms. Vision systems were suitable candidates for use on a mobile vehicle but their respective cost, complexity and environmental modifications could be less attractive. Further appropriate references can be found in [Appleton, Williams (1997)], [McKerrow (1991)] and [Sanders (1993)]. These systems were complicated and expensive. [Jia P,. Hu,H (2009)] created some novel human-machine interfaces for disabled and elderly people to control intelligent wheelchairs using facial and head gestures.

The various technologies were considered when selecting the sensors and systems for the powered wheelchairs used in the new research described in this dissertation.

2.6 Guidance technology for use with powered wheelchairs

Inductive systems tended to rely on hidden wires, ferrite markers and inductive loops set into the floor surface of the working environment [Wakaumi et al (1989)]. An active system required a signal current to generate a traceable magnetic field. Magnetic pickups would be able to sense the wire position. The inductive guidance frequency could be specific to certain routes [Wakaumi FMS Magazine (1989)]. Radio instructions could be transmitted to some vehicles to cause them to change their travel path [Hartly (1987)].

Other forms of passive guidance tracks included optically detected tracks such as painted lines on a floor surface. The principal of retro-reflection had been used by the Smart wheelchair [CALL centre publication (1993a)]. Retro-reflective optical tape could be stuck to the floor, when infrared light was targeted at a specific angle, generally the reflected light could be detected at the same angle back from the transmitted source. Navigation through a structured route using walls to provide a reference for guidance had been attempted [Goodwin (2000)]. In that research, ultrasonic sensors mounted on the side on an electrically powered mobility aide were used to detect the side wall. A time of flight principle was used to determine the distance from a wall and control software provided the feedback control to maintain the system at a controlled distance parallel to the wall. [Goodwin (2000)] demonstrated that computer control algorithms could allow a system to recognize typical signatures, for-example doorway apertures, and then set a course to compensate so that no significant course deviation occurred whilst passing an open doorway.

Work on the development of a guidance system for a powered wheelchair was undertaken by [Yoder, Baumgartner, Skaar (1996)]. The navigation and control of the wheelchair was based on accurate estimations of the location of the wheelchair within its operating workspace. Estimates of the wheelchair position and orientation were produced by combining drive-wheel rotation information with the visual observations of small passive 'cues' that were within the wheelchairs operating region, typically on the walls and on other stationary objects. The system could follow routes throughout the environment. Of particular interest was the task level (or supervisory) control strategies adopted. Task level control of the wheelchair allowed the user to specify the desired route to be performed by the wheelchair system, for example 'go to the kitchen table'. The desired task was chosen by the user by selecting the destination toward which the user wished to proceed. Once the task was specified, the wheelchair system controlled the chair in order to carry out the desired task. The user of the system retained supervisory control of the wheelchair at all times. Other forms of passive inductive line guidance included [Goodwin (1992)] who described the operation of an AGV that used four inductive sensors that detected adhesive aluminised tape fixed to the floor.

2.7 Advanced wheelchair systems

[Stott (1997)] discussed advanced and intelligent wheelchair systems. Of particular relevance to the work described in this dissertation was the SMART Wheelchair [Craig *et al* (1995a) & (1995b)] and [Nesbit (2000)]. The SMART wheelchair was described as a set of tools for assisting the development of disabled children and is described in section 2.7.2.

The NavChair project aimed to create a wheelchair system that co-operated with the user in a shared decision making process [Bell *et* al (1994)]. The modified wheelchair was equipped with a ring of ultrasonic sensors that could detect the environment and calculated new trajectories for the wheelchair which approximated to the nearest practical trajectory to that directed by the user.

A more robotic approach was the Senario project [Beattie (1993)]. The wheelchair was equipped with many sensors including scanners to read wall mounted bar-code beacons, laser range finders and radio beacon detectors to provide an automated navigational system. At an estimated cost of 20,000 ECU per wheelchair the system was expensive. Another development was a voice activated wheelchair [Murai (2009)]. The system had two major functions, firstly a collision avoidance function by using sensor information. This function had three autonomous movements of stop, avoidance and deceleration. The second function was the elevator entry/exit function which worked smoothly in a variety of situations.

Another wheelchair drawing heavily on robotic and autonomous technology was described by [Gomi, Ide (1996)]. An autonomous wheelchair system was built into an unmodified Fortress wheelchair. This system was interesting as behavior based artificial intelligence was used to control the wheelchair which reduced the dependence of the control algorithms on the hardware (by having a more flexible approach). The sensors were for collision detection, infrared rangers and a stereo vision system faced forward of the wheelchair. The vision system used landmark navigation to move autonomously. The joystick could be used at any time to override the control hardware. A behavior-based approach was used to establish on-board autonomy at minimal cost, maximum safety and transparency in appearance. Two power wheelchairs had been built and tried with the new system. Some autonomous navigation outside was demonstrated. The system was able to navigate the wheelchair in an automatic mode where the user did not need to make any decisions about the route that was being driven. The system was complex which would tend to make it expensive. A system of this type runs the risk of taking control from the user and becoming an automated platform. High cost systems would also be outside the scope of many powered wheelchair users. The systems described in this dissertation aimed to provide some of the functions of the system described by [Gomi, Ide (1996)] useful, in order to provide assistance to a powered wheelchair user without becoming too expensive to be practical.

[Bourhis, Pino (1996)] presented some results from the VAHM (Vehicule Autonome pour Handicapés Moteurs) project which aimed to improve the control of powered wheelchairs by adding autonomous mobility systems. Three operating modes were used to adapt the system to a diversity of situations. In the autonomous mode a global trajectory was planned, and the user intervened to point the goal and stop if need be. The assisted manual mode allowed access to wall following. Finally, in the manual mode, the powered wheelchair became the unmodified system again. [Yoder *et al* (1996)] discussed the development of an automatically guided wheelchair for individuals who were severely disabled. A combined vision and acoustic sensor system was used on the wheelchair. The techniques used were mainly concerned with autonomous navigation which differs from the approach adopted at Portsmouth, described by [Stott (1997)], where the user retained overall responsibility for navigating the wheelchair.

There were interesting developments in a four wheel drive omni-directional wheelchair described by [Masayoshi (2008)]. This was intended to enhance the mobility of conventional wheelchairs. The mobile mechanism equipped four wheels, two omni-wheels in front side and two normal tires in rear side.

The normal wheel and the omni-wheel, mounted on the same side of the base were interconnected by belt transmissions to rotate in unison with a drive motor, i.e. a synchro-drive transmission. To rotate a chair at the center of the mobile base about vertical axis, the third motor was installed on the platform.

The prototype wheelchair with the proposed 4WD system was capable of climbing over a high single step and translating a chair in any direction with/without rotation. The system enabled wheelchairs to move with greater freedom and led to the development of a novel control format in which the driver body postion controlled the wheelchair. [Kenichi (2008)] proposed an Omnidirectional Electric Wheelchair that had four omniwheels for the omnidirectional movement. Two of the omniwheels were arranged to be the X-axis direction and the other two were arranged to be the Y-axis direction. By controlling the movement of the omniwheels, the wheelchair could instantaneously rotate and move in all directions. The operator's posture was used as a signal to control the wheelchair.

2.7.1 INCH: An intelligent wheelchair prototype

Work by [Rao, Kuc (1989)] was an early look at the problems faced by visually impaired wheelchair users but could also be applied to wheelchair users with sensory-motor impairment. The "INCH" prototype wheelchair platform was powered by two stepper motors and a microprocessor based control system. Six Polaroid ultrasonic transducers were fitted to this platform in the following locations: directly in front of the front wheels for forward motion, directly behind the rear wheels for reverse operation and one each side of the front of the wheelchair for turning motions. The sensors were directed towards the floor to constantly check the chair to the floor distance.

Input from the user was simulated and the controller was able to modify the trajectory of the wheelchair when a drop off was detected. This early work demonstrated the positive assistance that could be afforded to a wheelchair user by a computer system. The prototype was successful in avoiding drop-offs when programmed to move in random directions on a tabletop.

2.7.2 The CALL center ‘Smart Wheelchair’

Work at the CALL center in Edinburgh resulted in the Smart Wheelchair described in the [CALL center publications (1993a), (1993b) and Nisbet (2000)]. Clinical trials were conducted at three schools and the Bioengineering Unit at Princess Margaret Rose Hospital. The Smart Wheelchair was a modular design and integrated with commercially available wheelchair systems [Nisbet (1995)] shown in Figure 2.4. The software and hardware architectures were presented in [Craig *et al* (1995a)].

Figure 2.4 The CALL center Smart Wheelchair.
Reproduced from [Nisbet (2000)]

The Smart Wheelchair used a distributed microprocessor based sensor and control system. This system enabled severely impaired children and adolescents to learn how to control a powered wheelchair. The "bump" sensors detected collisions and the wheelchair could be programmed to stop, reverse or reverse and turn. Their research work reported the benefit of mobility to it’s users as “increased motivation and other positive effects on the general development of the person as being the most important effects resulting from the use of the SMART wheelchairs” [Odor and Watson (1994)].

The system components of the smart wheelchair were categorized as tools. One such tool was the line following tool, this enabled the smart wheelchair to travel along a predetermined route that was set by floor based navigation markers. In particular retro-reflective optical tape was stuck on the floor. The line follower was based on an optical line operating with infrared transmitter / receiver sensors to detect the edges of the tape. The switch operated as a dead mans handle in which the system stopped when he or she had stopped pressing the switch.

Modification of the environment was required when floor based navigation markers were used which made them more suitable for use in schools where the markers were permanent. An additional tool used an array of six ultrasonic transceivers that could be attached to the front framework of the smart system, appropriately named the slow down tool. The sensors could detect an object in the forward path of travel and their outputs were used to reduce the speed of the wheelchair. This was part of a damage limitation philosophy [CALL centre publication (1993a)] and not intended to stop the pilot getting to where he or she wishes to be, only to stop them hitting it quite as hard. The Smart Wheelchair program was notable for its clinical based approach. [Craig *et al* (1995b)] discussed evaluation methodologies that were used during the Smart program. The [CALL centre publication (1993a)] indicated observed improvements in the motivation and quality of life of the users involved in the SMART wheelchair training system. This reasoning took account of conditions involved with detecting objects that could also stop the driver from reaching their intended destination.

An advanced vision based smart wheelchair system was described by [Satoh (2007)] to support safe self-movement for disabled people. This system had functions of detecting both the potential hazards in a moving environment and the control gestures of a user.

2.7.3 SENARIO

A large "smart" wheelchair project was the European TIDE project "SENARIO" described by [Beattie (1993)]. This project aimed to produce an autonomous wheelchair for a hospital environment. The project included fitting a laser range finder, tilt detectors, wall barcode readers, radio beacon detectors and an intelligent navigational capability to a powered wheelchair. The wheelchair system was designed to have an autonomous capability to enable a patient to be transported around a building without the need for a carer to be present. The cost of the SCENARIO wheelchair was in the region of 20,000 ECU per unit. This is expensive for even large institutions.

The new work described in this dissertation was aimed at low-cost solutions to some of the problems associated with mobility. An approach was taken during this new work described in this dissertation to maximise the impact of the new systems whist remaining affordable and transparent to the system user.

2.7.4 M3S

The M3S project ran under the IMMeDIAte program which was part of the European Union's Strategic Program for Innovation and Technology, (SPRINT). The project was concerned with providing a standard protocol for the connection of input and output devices to systems for use by the disabled [Dillon (1995)].

A standard wheelchair was limited to one input and one output device. The input device was normally a joystick and the output device or end effector was the wheelchair itself. As rehabilitation technology equipment increases in complexity and flexibility the need for standard plug-in connections may become more important. The M3S project allowed flexibility for the user of systems through the use of a standard bus system. All devices were able to connect to this bus and communicate automatically. This opened the possibility of a user having access to more than one input device, possibly a joystick for normal use and a set of head switches for use while carrying things. Other output devices could be operated from the same input device. For example, it may be more convenient to the user to have access to a keypad as well as a joystick to allow the seamless transition from driving the wheelchair to operating a manipulator. The system was also able to allow the addition of "smart" devices such as collision avoidance modules or navigational hardware. With an advanced system such as M3S the addition of high technology devices to a wheelchair could become more practical and allow wheelchair systems to be developed in line with an individual's changing requirements.

2.7.5 VAHM Assisted navigation for powered wheelchairs

[Pruski, Bourhis (1992)] and [Bourhis *et al* (1993)] described how a powered wheelchair was automated in order to assist a disabled user. Their work at The University Of Metz in France demonstrated how automating some of the low-level tasks involved in driving a powered wheelchair could assist a severely disabled user.

The VHAM wheelchair is shown in Figure 2.5. The user would indicate a goal to be achieved on a computer model of a bounded global environment. The automated wheelchair would then move to that location without any further input from the user. The wheelchair could be stopped or its trajectory modified at any time.

The powered wheelchair received information about its environment from ultrasonic sensors, infra red detectors, odometers and contact bumpers. Navigation through the environment was achieved using the world model that had previously been mapped. The wheelchair always started from a known coordinate. The turning points and the goal were derived from data supplied by the odometric devices attached to the wheels of the wheelchair. The ultrasonic and infra red sensors were used to avoid obstacles.

Figure 2.5 The prototype VAHM

(At the time of printing, this image could be viewed at the University of Metz website at**:** http://www.fernuni-hagen.de/www2bonsai/FTB/aaate99/paper/99_12/99_12.htm)

The wheelchair successfully navigated through a known environment and moved from room to room. Navigational errors occurred due to inaccurate odometric data and non-geographical features of the environment model caused problems. For example, a door could be closed when the model indicated an opening. [Horn (2008)] describes the perception of smart wheelchairs and shows how odemetric, ultrasound and vision sensors are used in a complimentary way in order to locate the wheelchair in its known environment.

2.7.6 NavChair

Work at the University of Michigan and The University of Michigan Hospital, USA developed a prototype system called the NavChair shown in Figure 2.6. The work intended to meet the needs of disabled people who were unable to operate available wheelchair systems. The NASCAR system aimed to share control with the user of the wheelchair to prevent unsafe manoeuvres. Adaptive shared control techniques were used on the NavChair in later work [Levine *et al* (1994)] & [Bell *et al*(1994)].

A wheelchair was fitted with ultrasonic sensors to detect the environment.

Figure 2.6 The NavChair

At the time of printing, this image could be viewed on the University of Michigan website at:http://www-personal.engin.umich.edu/~johannb/navchair.htm

The sensors could detect the environment and could indicate the existence of obstacles in the path of the wheelchair. A problem occurred when trying to provide assistance to a user because only that person themself knew their real intention. The sensor system sometimes detected several possible safe paths. For the wheelchair to act in an assistive manner it needed to detect the intentions of the user and take the user more easily to that goal. An identification technique was used in an attempt to interpret the wishes of the user and polar histograms were used to identify safe paths for the wheelchair. This information was combined and a modified path executed by the wheelchair. Conflicts occurred which interfered with the path selected by the wheelchair. When approaching a doorway for example, the wheelchair could not distinguish between the user's wish to perform a "door passage" routine or an "obstacle avoidance" routine, which would take it past the door, and alongside the wall. The system required more information about the intention of the user in order to automatically perform mode selection.

A technique called "Stimulus Response Modeling" (SRM) was developed that automatically determined the most appropriate mode of operation for the wheelchair. This improved the Navchair's ability to interpret the wishes of the user. The SRM technique learnt the user responses to stimuli by initiating a disturbance to the wheelchair movements and measuring the user's response to the disturbance. Also the Vector Field Histogram technique was developed into the Minimum Vector Field Histogram technique. The performance of the NavChair improved to the point where the chair would follow walls, avoid obstacles and navigate through doorways.

An aspect of this work was the requirement to successfully interpret the wishes of the user and the incorporation of this information in the execution of a collision free path. Sonar sensors were used to detect the environment and a local map was built in the computer. Tests showed that the NavChair could be driven through a corridor by a blindfolded operator at about half the speed of an experienced sighted user without collisions.

2.7.7 The Swedish slingan project

Work aimed at improving independent mobility for people with disabilities was undertaken in Sweden and described by [Langner (2004)]. This project offered persons with severe motor disabilities and additional developmental problems the opportunity to transport themselves using a wheelchair. The project was carried out in the form of a driving school. The participants visited once a week for driving training using a wheelchair. These systems used optical sensors with reflecting tape on the floor.

2.8 Sensors

The wheelchair used in this research needed to be capable of detecting the environment. A sensor system for a powered wheelchair needed to be accurate, rugged, reliable, suitable for attaching to a wheelchair and cheap. A human operator was the most accurate source of data but the accuracy of a human could be impaired by disability. In these cases a complementary sensor system was required to assist the operator. One of the key factors for obstacle avoidance was the implementation of sensors. Analyzing the characteristics of various sensors was undertaken by [Tian Zhihong (2009)] looking at a method of detecting obstacles and avoiding obstacles used by electric wheelchairs.

Sonar sensors using the time of flight principal to measure range have been widely used on AGVs [Hinkel *et al*, (1988)]. Some vision-based systems have used a stereoscopic view to detect obstacles but these systems can require timeconsuming data processing. As an alternative, a laser range finder could provide accurate and fast range information [Gutmann, Schlegel, (1996)]. Sensor systems could be considered to be within the following categories:

- Contact sensors
- Non-contact sensors
- Human operator

Contact sensors could be the simplest form of sensing for a system. Contact bumpers were fitted to the SMART wheelchair [Nisbet (1998)] and [Nisbet (2000)] and the chair described by [Langner (2000)]. Contact bumpers could also be used to initiate automatic sequences for the wheelchair such as reverse and turn. Other contact sensing methods were used by [Luk *et al* (1988)] and [Sanders *et al* (1987)] who used the change in motor currents of a robot manipulator arm to detect contact with the environment.

[Korzeniowski (1996)] optimised the tracking of a surface by an end effector. As the environmental conditions changed, the reliability of sensors could also change. The amount by which the systems reliance on sensor data must also change, was discussed. Tracking a surface is an integral task for many autonomous systems. It could be used for navigation, surface preparation or object recognition. There are two types of control for surface following, continuous and discontinuous. A robot may maintain contact and continuously track the surface or touch the surface at discontinuous points. In order that the whole process can be optimised in terms of time to complete a task and the amount of data collected. A balance was sought between the continuous and non-continuous methods. The tracking method was computed by a tracking algorithm using the partial data sets provided by sensors. It was common practice to outfit automated systems with the ability to gather data from many sensors. As the environmental conditions changed, the system's reliance on sensor data also changed. This work focused on the addition of the supervisory learning module for choosing the method of surface tracking.

Non-contact sensors use a variety of techniques and mediums to sense the environment. Typically the non-contact sensors may be passive or active. Passive sensors are dependent upon the target providing an output that can be detected by a sensor; such as heat, light or sound. Passive sensors would not normally be useful to mobile vehicle applications as the sensor system could not initiate a sensor sweep. Active sensor systems can initiate sensor sweeps of the environment on command of the control system. Data could therefore be provided to the control system when it was required, regardless of the target to be detected. Typically, a sensor system could use sound as in an ultrasonic sensor system or electromagnetic energy. Visible light was often used by sensor systems that used vision-based systems. Infrared could be used as a form of proximity sensing. Radio frequency (radar) could also be used along with scanning and rotating lasers. Some examples of suitable non-contact sensors are examined in this section. An unusual example of a multi-element sensors system is based on a radar sensor and is described by [Bouraima (2008)] who described a six port 77GHz collision avoidance radar sensor configuration. This system provided velocity and range information.

2.8.1 Ultrasonic sensing

Ultrasonic range-finding and object-detection systems have used several principles, including: modulated waves [Teshigawara *et al*, (1989)], frequency sweeps [Lindstedt, (1996)] or echo location [Stott, Sanders (1996)] & [Stott *et al,* (1997)]. Kay used a novel sensor array and constant transmission frequency modulation (CTFM) sweeps to assist blind people to detect their environment [Kay (1999a & b)]. A CTFM system examines the response of the environment to a frequency swept sine wave. The shape of the envelope returned to the receiver is determined by the properties of the environment. It is possible to recognise objects by the frequency spectrum of the receiver signal. [McKerrow, Harper (1999)] successfully differentiated between types of leafy plants with their system. More information on ultrasonic sensor systems can be found in [McCloy, Harris (1986)] and [Fu *et al* (1987)].

Single frequency pulse-echo systems can encode information on pulses in order to reduce interference between different systems. [Kleeman (1999)] used a known separation between two pulses to identify different systems. The receiver signal was rapidly sampled and the separation was read as each pulse train was received. Pulses from other sensors were rejected. Accurate angular resolution was also possible by using two receivers mounted close to the transmitter and measuring slight time delays between pulses.

Previous low cost systems for navigational assistance for disabled wheelchair users have provided little more than simple obstacle and collision avoidance, or have followed a pre-defined fixed route defined by a white line or a buried wire [Langner (2000)]. [Calder (2009)] described assistive technology devices that are portable electronic hand held devices that are either hand held or worn by the visually impaired user, to warn of obstacles ahead. Many assistive technology devices used ultrasonic pulse-echo techniques to gauge subject to object distance. Some used infrared light transceivers or laser technology to locate and warn of obstacles. These devices exhibit a number of problems, the most significant of which are related to the interface display that conveys navigation/obstacle warning information to the user. Other sensory channels should not be compromised by the device. This is exactly what can happen when, for example, audio signals are used in obstacle warning on/off displays or more significantly in orientation solutions, where continuous streams of synthetically generated stereo sound mask the natural ambient sound cues used by the blind.

Other research has used complex high cost multi-sensor mode systems closely resembling industrial, military or space exploration applications. These systems used natural features or artificial beacons to produce accurate maps of the operating environments. The progress of the vehicle is monitored and corrected using multi-sensor techniques such as vision cameras, odometry and triangulation from beacons located in the environment. Such systems have required modification of the operating environment and have resulted in a fully autonomous vehicle providing little or no overall control by the user. Whilst proving technical feasibility, their cost and complexity has not resulted in practical and affordable solutions for the wheelchair user.

The purpose of the present study was to bridge the gap between these two previous areas of research and to provide navigational assistance at an affordable cost, in the area described by [Goodwin (2000)] as maximum functionality at minimum cost. Low cost ultrasonic sensors enabled a wheelchair to operate in an unknown (previously unmapped) environment whilst leaving the user in overall control.
Hardware modifications to a commercial powered wheelchair enabled data from ultrasonic arrays and the user's joystick to be interrogated and mixed by a computer to provide appropriate signals for the wheelchair drive motors.

A simulation program was created to interpret the sensor signals that would be generated from the various conditions likely to be encountered by a wheelchair and to develop the various control strategies. The simulation was able to differentiate between the various environmental conditions and select the appropriate action using the control algorithms.

The sensor data interpretation modules together with the control algorithms, from the simulation, were incorporated into a practical system for controlling the wheelchair. In tests, data from the sensors were used to detect and evaluate localised changes in the environment and used to determine appropriate signals for the drive wheel motors. It was found that the wheelchair controller and the geometry of the wheelchair resulted in a degradation of the expected wheelchair response. This was overcome in two ways: firstly by modifying the control algorithm and secondly by changing the wheelchair geometry.

Ultrasonic sensors were selected for the new work described in this dissertation.

2.8.2 Vision Systems

Vision systems usually involve a camera, a lighting system and a computer. The camera must be capable of providing images of sufficient quality for the system algorithms to decode and recognise objects or features. There are at least two different ways to implement an attentive vision system, using either a bottom-up or a top-down approach [Garibotto (1999)]. In the case of a bottom up approach the low-level features extracted from the camera image are used to orient the system to a particular area of interest. In a top-down approach the visual recognition task is driven by a specific goal and is constrained within a set of processing algorithms. Garibotto referred to mail sorting systems, car number plate location, reading traffic control signals, signs and landmark identification in autonomous navigation systems. Garibotto suggests that a top-down scheme is more effective as a more accurate control of the system is possible.

[Volodymyr (2008)] described a system for guiding blind and visually impaired wheelchair users along a clear path that used computer vision to sense the presence of obstacles or other terrain features and warn the user accordingly.

[Elarbi-Boudihir (2008)] described a visual guidance system for autonomous navigation. The visual navigation of mobile robots rely mostly on road edge detection from images taken form an onboard camera. The algorythms used to detect road edges give globally satisfactory results. The control system involved a fuzzy approach to function in the presence of several image artefacts, such as shadows in spaces and lighting changes.

Anther interesting area of research was Playbot. This was a long-term, large-scale research project, whose goal was to provide a vision-based computer controlled wheelchair that enables children and adults with mobility impairments to become more independent. [Andreopoulos (2008)] showed how Playbot can actively search an indoor environment to localize a door, approach the door, use a mounted robotic arm to open the door and go through the door, using exclusively vision-based sensors without using a map of the environment. Vision systems are a suitable consideration when selecting a sensor system for a mobile vehicle system. Considering the cost and complexity of the system and the need to control the environment can make them a less desirable choice. Other information on vision systems can be found in Appleton and [Williams (1987)] & [McKerrow (1991)].

2.8.3 Laser range finders

Laser range finders can be effective and a fast method for measuring a distance to an object. Due to their fast response, they can be useful in real-time systems [Parnichkun (1999)]. In their paper, a long-range laser range finder (LRF) was developed. Not all LRF systems were designed for range finding. [Jiminez *et al* (1999)] described a laser-based computer vision system used on an automatic fruit recognition system. It was based on an infrared laser range-finder sensor that provided range and reflectance images and was designed to detect spherical objects in non-structured environments. Similar techniques could possibly be applied to navigational systems for the recognition of waypoints or landmarks. Further work concerning a direct application for disabled people was collision prevention of a compact powered wheelchair using an optical SOKUIKI sensor and applying fuzzy theory. This was described by [Yasuda (2009)]. Some wheelchair users could not operate a powered wheelchair sufficiently by using a joystick. A prototype control system was constructed consisting of buttons or levers. The obstacle detection was mainly provided by SOKUIKI optical sensors, which observed the front of the wheelchair. Additional auxiliary optical sensors observed the side of the wheelchair. Fuzzy logic was applied in order to improve system function for wheelchair user.

A novel automated mine detection system was described in [Das *et al* (1999)]. A human operator was capable of sweeping a mine detector across rough ground without hitting it. The operator can follow the ground profile with the detector head close to the ground without hitting the ground or any objects on it.

Other information on laser range finders can be found in [Schilling(1990)] and [Dodd, Rossol (1979)].

2.9 A Human operator within the control loop

Automated systems tend to carry out a set of tasks or procedures in response to stimuli such as sensor input or a pre-set collection of rules. A tele-operated system receives commands from an operator remote from the system via a communication link. The operator remains in control. In a system where the operator and a separate control system are working together, conflicts can occur. The problem of placing an operator within the control loop has been investigated widely. Notably with the introduction of intelligent and assistive systems to motor vehicles. A system was described by [Carlson (2008)] about collaborative control in human wheelchair interaction. It reduced the need for dexterity in precise manoeuvres. Distributing control appropriately between man and machine is particularly pertinent to assistive technology. Shared control techniques were used. Precise manoeuvres, such as driving through doorways, was achieved with a reduced level of dexterity, requiring fewer corrective joystick movements.

Work at the University of Portsmouth has investigated tele-operation [Sanders (2009a)]. That work discovered that the efficiency of tele-operation partly depended on the way a human interacted with a mobile-robot. The work investigated how to make tasks easier for a human tele-operator using an expert system to interpret joystick and sensor data [Sanders (2010a)]. Simple expert systems improved that interaction using ultrasonic sensors. Results were presented from a series of timed tasks completed by tele-operators using a joystick to control a mobile-robot [Sanders (2009b)].

Tele-operators completed tests both with and without sensors and using the recently published systems to compare results [Sanders (2010b)]. The research suggested that the amount of sensor support should be varied depending on circumstances [Sanders (2011)]. [Galer (1995)] described new ‘in-vehicle systems’ that provided the driver with information about the driving task, routes to take on a journey, the availability of parking facilities, congestion ahead and so on. Some systems went further than simply providing the driver with information, they also took appropriate action in place of the driver. Examples included autonomous intelligent cruise control and lane keeping devices. These technological advances have the potential to improve the comfort, convenience and safety and reduce accidents. When vehicular problems

become demanding, system designers have often proposed replacing the driver with computer automation (and non-human sensors) [McIlvaine Parsons (1996)]. [Little (1997)] presents more information on proposed systems for “smart vehicles”.
[Lee (1994)] and [Lee, Morey (1992)] investigated the increasing use of automation to supplement human intervention in controlling complex systems. The use of automation could change the operators’ role from active controllers (directly involved with the system) to supervisory controllers (managing the use of different degrees of automatic and manual control). The relationship between trust in automatic controllers, self-confidence in manual control abilities, and the use of automatic controllers are discussed. Trust, combined with self-confidence were examined and showed how trust and self-confidence relate to the use of automation.

In general, automation was used when trust exceeded self-confidence, and manual control when the opposite was true. Since trust and self-confidence were two factors that guided operators interactions with automation. The design of supervisory control systems should include provisions to ensure that operators trust reflects the capabilities of the automation and operators self-confidence reflects their abilities to control the system manually. There is an interesting connection with the two Airbus disasters discussed in [Learmount (1991)] and the work by Lee. [Carroll (1997)] discussed the use of computers in improving the usability of computer systems and applications in a history of Human-Computer Interaction over the last 20 years. Human-Computer Interaction (HCI) is described as the area of intersection between psychology and the social sciences, on the one hand, and computer science and technology, on the other. HCI researchers analyse and design specific user-interface technologies (e.g. three-dimensional pointing devices, interactive video). They study and improve the processes of technology development (e.g., usability evaluation, design rationale). Through the past two decades, HCI has progressively integrated its scientific concerns with the engineering goal of improving the usability, and establishing a body of technical knowledge and methodology.

[Parsons (1996)] presented a system that could advise an operator with the Generic Intelligent Driver Support (GIDS) project. The method proposed in the GIDS project was to create four simultaneous computer simulations (experts) of a car driver’s response to a common road situation. One simulation represented what a driver would be doing, another was a reference or what an ideal driver would be doing and the third detected the difference between them. The fourth model advised the driver what he should be doing. The system was said to be adaptive and would adapt to the driver’s intentions, capabilities and abilities.

Tele-operation was described by [Kwitowski *et al* (1995)] as a technology that could provide significant health and safety improvements in mining operations by locating machine operators hundreds of metres away from the face area. The US Bureau of Mines developed a tele-operation system for continuous mining and haulage equipment. This system featured near real-time closed-loop control.

A tele-operation system for a powered wheelchair was described by [Gunderson *et al* (1996)]. A remote camera system was fitted to a powered wheelchair and a video link was established with an operator at a control station. If the user of the wheelchair became ill or tired whilst outside the care centre, they could call the operator via a radio link, then the control station operator would guide the wheelchair back to safety using a tele-operation system and wheelchair mounted video cameras.

[Wiker (1993)] discussed Tele-robotics in general. Studies had shown that the effect of tele-robotics work on tele-operators could be having the reverse effect to that desired. It could take an operator longer to complete a task using tele-operation. Some operators become fatigued and frustrated and suffered from motion sickness during tasks. Whilst it was still desirable to use manually operated or automatic systems, there was still a place for tele-robotics in inaccessible or dangerous areas [Hewer (1997)].

Many wheelchair users had problems in orienting themselves and manoeuvring their wheelchair in congested environments. The ‘Collaborative Wheelchair Project developed a system for motion guidance [Boy E, Teo CL, E Burdet (2002)]. Motion guidance was provided by software defined paths corresponding to the users ability. Walk-through programming was used to define a path. The user physically traced out a path with the wheelchair in free mode. This path was recorded by odometer sensors and check points detected by on-board CCD cameras. The recorded path could then be used in subsequent operator movements. The collaborative learning process enabled the user to define a guide path by physical example and an 'elastic mode' of operation let the user deviate from the guide path. The two together gave collaborative learning. The Collaborative Wheelchair with Path Guidance Assistance was considered by [Zeng (2006)].

The concept at the heart of the Collaborative Wheelchair was to rely on the user's motion planning skills and to assist the maneuvering with path guidance. The user decided where to go and controlled the speed (including start and stop), while the system guided the wheelchair along software-defined paths. More information on tele-operation is in [Sheridan (1992)] and [Sheridan (1996)].

2.10 Control

The environment in which a robot is required to work necessitates the need for intelligent control [Meystrel (1988)]. Many of the assumptions made by control theory need to be reconsidered if robots are to handle future tasks. Systems that are subject to multiple purposes and abstract goals cannot be handled by current methodologies [Franklin, Selfridge (1990)]. A localization function was considered [Touati (2010)] as the main process for improving performances in terms of autonomy and mobility. Making a wheelchair intelligent and autonomous allowed the development of new methodologies to help people with disabilities.

Robustness is especially important if vehicles are to function effectively in complex environments. Robustness has two aspects. Firstly, it implies that a tele-operated vehicle can cope effectively with unexpected changes in its environment such as rough or uneven terrain. Secondly, it implies that a robot can also cope with damage to itself. Many authors have acknowledged that a hierarchal structure is essential for effective control of articulated limbed tele-robotic vehicles, [Vlacic, Harashima (2001)}, [Luk, Collie, Billingsley *et al* (1991)], [Meystel (1988)]. The higher levels define tasks or sub-goals for the lower levels and monitor their status [Kumar, Waldron (1989)].

Wheelchair controllers are produced by a number of manufacturers and are essentially servo controllers that allow the wheelchair operator to control the large currents of the drive motors using a joystick or other input device. Other features are built into the controllers that provide safety for the user. Acceleration, deceleration, speed and turning are affected by safety systems in the controller [Crane (1995)]. The safety systems can be adjusted by carers to suit the individual requirements of the user. Modular systems are available that have simplified the connection of controllers and their sub-systems using a bus system [Taylor (1995)]. The majority of wheelchair systems rely on a joystick as the only input to the system. In most cases this is sufficient. The work described in this dissertation was aimed at those situations when the user required a more intelligent controller system to drive a powered wheelchair safely.

In the past, the control system has been regarded as the most crucial aspect of a mobile robot [Galt (1999)] and [Song, Waldron (1989)]. The development of an effective control system is difficult. [Gray (1996)] stated that the development of system architectures for mobile robots and the integration of the required enabling techniques of control, actuators, sensors and artificial intelligence provide some of the most interesting intellectual challenges in current engineering development. [Fezari (2007)] describes the design of an embedded system used to facilitate the control of a wheelchair.

Wheelchair users are able to operate a joystick to control the chair but many more severely handicapped users need some other means of controlling this type of robot. The designed system is based on grouping a microcontroller with a set of ultrasonic modules and a voice recognition processor for isolated word and speaker control. The resulting design is used to control a wheelchair for disabled individuals based on a vocal command.

The control system is ultimately responsible for stable operation. Any foreseeable, and often unforeseeable events must be dealt with if the vehicle is to be used in serious applications where robustness, reliability and efficiency are essential. The control system must be planned and constructed so that the derived control behaviour, conforms to safety and efficiency specifications. Also, the control system should allow for future expansion and provide a means to reconfigure the system. The problem is considerable when the device to be controlled has many input and output parameters.

The most important considerations are the safety and reliability of both the human operator and the wheelchair (and others). Such issues generally vary depending on the application. In application areas such as healthcare, transportation, construction, surveillance, agriculture and the service industries, advanced robotic devices will come into close proximity to humans without the usual safety barriers normally associated with manufacturing robots. An advanced mobile robot should have the ability to operate in unstructured environments where hazards may be encountered.

Safety issues become paramount for both operational and legal requirements. This raises a paradox within the systems, complex, intelligent behaviour can be unpredictable yet it must be made possible to predict that the control system will ensure safety at all times. In essence, the control behaviour should be inherently robust and enable the device to cope with a span of difficult scenarios so that performance will degrade in a predictable and safe manner.

The architecture of the control system should be designed for minimum representation and complexity. This suggestion aims at creating an architecture which will be simple to follow and understand, and thus easy for new operators to use and modify. Also, reducing complexity will inevitably reduce development time by simplifying debugging operations. The potential for map-ability of the control system to new machines would greatly benefit from a minimalist design. The system must have provisions for reconfiguration and extension. It is clear that it would be difficult to devise an ideal control structure within the first iteration. It is therefore important to provide a generic framework that can be updated and improved with new principles and characteristics, without the requirement for major reconfiguration. Thus, over a period of time the system can evolve into one that is satisfactory for our needs. This approach also allows for the latest technologies to be integrated into the existing system.

Development time could be reduced if control systems were transferable. Often research and development of control systems have been specific to the vehicle in question, with map-ability to other systems difficult, if not impossible.

Many adaptive control strategies have been around for a long time but it is AI-based adaptive methods such as those using artificial neural networks and genetic algorithms, that are achieving results [Galt (1999)]. This is due to their ability to learn in a way that many believe is akin to human behaviour that can be found in nature. Adaptive control is being used more and more for the development of mobile vehicles [Galt (1999)]. A suitably applied control system that was self-optimising could make a wheelchair faster, safer and more efficient.

Two main drive wheel and caster configurations are widely available on powered wheelchairs. These being rear drive motors with front casters using differential steering, and or, front wheel drive with rear trailing castors. Generally powered wheelchairs were classified by wheelchair services and dealers into two types:

- (EPIC) (Electric Powered Indoor Chair)
- (EPIOC) (Electric Powered Indoor Outdoor Chair)

These could be difficult to steer on anything but smooth flat floor surfaces and hence driving performance was significantly affected by the type of terrain. [Collins, Kauzlarich (1998)] commented that a disadvantage of front wheel drive rear caster powered chairs was that they were known to be directionally unstable and required more manipulation by the joystick user. This was also typical of rear wheel drive types but the veer characteristic differed.

Caster drift and camber related veering was a problem for differentially steered front or rear wheel drive wheelchairs. The effect of the weight and the positioning of the wheelchair occupant affected the severity of the camber associated veer. To compensate for this, some wheelchairs, for example the NavChair, had rotation sensors built into the motor drive units. [Langner (2008)] developed a system that controlled and reduced wheelchair veer on slopes. This system used a rotation sensor on the caster to provide steering control feedback. Later work included implementing wheelchair deviation detection using solid state gyroscopes.

The NavChair shown in Figure 2.7, was developed at the University of Michigan Hospital [Levine (1999)]. This provided independent closed loop velocity feedback [Jaros (1993)]. By monitoring the velocity feedback, electronic speed compensation could be applied to keep the wheelchair on the piloted course.

In a closed-loop control the response of the system to previous inputs was monitored and part of the output was fed back in order to modify the value of subsequent input signals and hence provide automatic control of the variable [McKerrow (1993)].

Figure 2.7 The NavChair Assistive Wheelchair Navigation System [Levine (1999)]

Of particular interest concerning the control of a differential steered vehicle with closed loop guidance is [Hongo (1987)], who considered that the weighting of the control signal increased by the inverse of the velocity squared. Although at high speeds only small turns were necessary to change a vehicles course, large turns were required at lower speeds. Significantly, instability could result when the vehicles speed approached zero. Commercially available controllers had been developed from 1990 onwards with the enhancement of programmable control parameters. This enabled the fine tuning of the system to match the drivers abilities and requirements for control performance. Companies that introduced programmable controllers included Penny & Giles, Dynamic Controls. These systems provided alterable (programmable) options of, forward, reverse, turning and acceleration, deceleration speed and time values.

For developmental research, the preferred driver profiles did not offer the closed loop system performance required for alternative system guided control. [Jaro, Levine, Bell (1994)] found it necessary to redesign the joystick interface during their development of the NavChair wheelchair navigation system. Signal conditioning within the joystick module, that limited velocity and acceleration of the wheelchair when under normal user control, produced an unacceptable delay in the response of the wheelchair. The joystick was modified to bypass this conditioning feature and to enable the raw signal data to be input directly to the controller. For some systems there can be a fundamental limit on the processing signal speed. A good example is with the Dynamic DX system which was based on the CAN serial data transmission standard. Each transmitted frame took 20 ms and additional incremental program control operations increased this time further. During the creation of the Chailey track guidance system, modification was required to the commercial wheelchair controller in order to speed-up response time.

2.11 Fly – By –Wire (FBW)

Fly-By-Wire (FBW) is a term which loosely describes a system where control data is passed around a system using electronic signals by wire [Sanders, Baldwin (2001)]. [Machine Design (1992)] gives a brief general introduction to FBW technology. The technology has been applied to aircraft. [Hamond et al (1989)] described the Electronic Flight Control System destined for use on Boeing aircraft and notably, the Airbus aircraft. [Learmount (1991)] examined two Airbus crashes that cast doubt over the reliability of the FBW systems in aircraft. The reports are interesting because they may indicate the over reliance of the pilots on the technology.

[Hammond *et al* (1989)] describes the Electronic Flight Control System (EFCS) destined for use on Boeing aircraft. The use of multi-channel independent control systems are presented and the safety applications discussed. The entirely electronic FBW system replaced the mechanical cable/quadrant/pushrod system used on earlier aeroplanes. The FBW system, must meet high standards of integrity and reliability.

The heart of the FBW concept is the use of redundant, dissimilar computing and communication channels.

Modern wheelchair control systems, for example Dynamic Controls and Penny & Giles (Omni'+' ™ controls), used a control technology that fell within the definition of fly-by-wire. Control data is passed around the system by a serial data stream. The interlinked system components on a wheelchair could include: joystick, drive motors, actuators (elevating leg rest) and environmental control transmitters

An important aspect about FBW was its reliability and immunity from data transport errors that could have an adverse effect on personal safety. Factors concerning the transmission medium that could increase immunity to electromagnetic susceptibility to data corruption included the use of optical fiber signal lines. It is particularly notable that reliability is a key issue that must extend beyond the transport of data around a control system. An example of the design of a highly safe model vehicle for rear-end collision avoidance was described by [Kasuga (2009)] who presented the design of a highly safe driving control system using different kinds of sensors and its evaluation in order to avoid the rear-end collision of the model vehicle. An appropriate combination of different kinds of sensors is introduced to reduce the occurrence of multiple faults, it is also shown in the experiment that the rear-end collision avoidance can be achieved even if a fault occurs at any sensor.

2.12 Projects for people with special needs

Due to the rich diversity of user requirements, a project called the M3S interface was established to provide an adaptable interface for a wide range of needs. Performance factors for wheelchairs could be tailored to match individual requirements. The main purpose of the project was to allow different user control devices to be used. This entailed the development of joysticks, ultrasonic head movement detectors, speech recognition systems, eye movement detection and sip – puff tubes. A wide range of output devices such as environmental controls for domestic lighting and telephone communications had been developed and these were frequently used as add-on modules with a wheelchair.

Designing special switches and control systems for multiple disabled people was described by [Thronett (1990)] in a 'problem led approach'. Special user defined control systems were developed in a way sympathetic to the user. The apparent void of suitably available user controls on the market stimulated the development and creation of controls that could be instinctively operated. Such is the case when used with someone of so called 'low cognitive ability'. A body worn set of individually adjustable chin switches could be able to translate head turning into functional control. Many different control types were built to suit users that had varying ability levels both cognitively and physically. People having limited physical movement and hence little control dexterity could prefer the use of a scanning type of control mode. The directional choices could be displayed sequentially and the operator could select the desired direction via a single switch. This provided a complete set of drive selectable directions. This could be labor intensive and frustratingly slow. Here, the marriage of a sequential control was suitable to a multi-junction track guidance system which offered relief from constant mid-course corrections en route.

Figure 2.8 A young chin switch driver. [Thornett (1990)]

Further research work was carried out at Chailey Heritage to enable persons with disabilities access to information technology [Thornett *et al* (1990)].

Wheelchair drivers were provided with the means to select a driving mode or the control of an environmental control transmitter via a multi-purpose access device.
It was possible for an individual to combine powered wheelchair driving, operation of a wheelchair mounted communication device and remote control of a television and sound system from their chin operated controls. Figure 2.8 shows a young driver using a chin switch. The change of function switch can be seen on his extreme left.

Along-side the technological support for people with disabilities is also the supporting role of the care giver. The caring society has influenced the development of welfare devices suggesting there is a need to support care givers to alleviate the burden of nursing care. [Tashiro (2007)] describes one method to provide a caregiver with a power-assist control for an electric wheelchair. This method enables power-assisted wheelchairs to adapt not only to flat roads, but also to roads with steps. A reaction torque estimation detector was constructed to detect the human force input to the wheelchair. An inclination sensor is used to detect the step, and to determine the control while passing over the step.

2.13 Discussion

Research into robotic wheelchairs is becoming an ever more applied science. [Carlson (2010)] considered that there are many prototype robotic wheelchairs, but he asked “*what level of performance must they achieve before being accepted into mainstream society and how do we verify the reliability of such performance?, how can researchers evaluate their systems effectively”?* It was concluded that to design and execute successful experiments with robotic wheelchairs, researchers must draw not only on the experience of the intended end users, but also on the expertise of the medical practitioners who assess and support the people in the day–to–day use of their wheelchairs.

Many previous low cost navigational assistance systems have been aimed at providing simple obstacle and collision avoidance functions. Other systems, based on industrial automated guided vehicle technology, have enabled a wheelchair to follow a line or a buried wire along a pre-defined fixed route within a school or institutional environment. The routes were defined by the positioning of lines or buried wires, which have involved modification of the environment. Whilst reducing the wheelchair users dependence on helpers, these systems have provided limited personal choice in the selection of routes and increased a users level of independence to an extent where some have progressed to “normal” unguided powered wheelchairs.

Other research has been conducted using complex multi-sensor mode systems closely resembling industrial, military or space exploration applications. Natural features, artificial beacons and accurate maps of the operating environment have been created from which a trajectory has been determined. The movement of the vehicle has sometimes been monitored and corrected using multi-sensor techniques such as vision cameras, odometry and self-location from natural landmarks or artificial beacons located in the environment. Such systems have enabled a vehicle to operate in a previously known and modified environment.

More complex systems, that did not require modification of the environment, have enabled a vehicle to operate in a previously unknown environment. Both systems have resulted in fully autonomous vehicles that could provide little or no personal control to be exercised by the user. Although proving the technical feasibility of such systems within the laboratory, their cost and complexity have not provided the wheelchair user with a practical and affordable solution. Powered wheelchairs and many other aids for disabled people tend to be personally adapted for the individual person. Some requirements result in a unique piece of equipment being manufactured in a rehabilitation workshop. Even successfully deployed powered wheelchair systems such as the SMART wheelchair are not considered suitable for all powered wheelchair users. A generic solution, although theoretically and financially desirable, is probably not feasible.

The provision of navigational assistance, rather than fully autonomous transportation, to a powered wheelchair user which assisted that user to operate in a previously unknown and unmodified environment was a promising area for research.

Fully autonomous vehicles have tended to require accurate and fast sensing systems. Slow or inaccurate sensor systems tend to limit the speed of the vehicle and the accuracy that the vehicle could navigate. Any form of mapping an unknown environment by a free ranging vehicle can be a long process and demand a specific pattern for the vehicle to follow. It is possible that a free ranging wheelchair could gather enough sensory data to map an environment. It is likely that the map would contain gaps. It may be possible to use simple low cost sensors to provide navigational assistance for a free-ranging powered wheelchair. The extent to which the assistance could be intelligent, given the low quality of information that a low-cost system could produce, was investigated during the new work described in this dissertation.

Variations in the operating conditions, such as floor surfaces, gradients and tyres make the maintenance of a straight line course difficult even for an expert powered wheelchair user. The interface between the wheelchair system and the user could sometimes be confused. An obstacle avoidance system can prevent a user from driving a wheelchair to an exact position. An intelligent wheelchair system should aim to allow the user access to any safe area without injury to the user, damaging the environment or damaging the wheelchair system. The new intelligent wheelchair system created during this work would allow a severely disabled person to use a powered wheelchair more safely than with an unmodified powered wheelchair system.

There were problems involved with the application of assisted mobility systems for people with disabilities. Some of these were:

- The type of difficulties the person had with driving a powered wheelchair
- The application of the assisstive system
- What the system provided

At Chailey Heritage (pre-1990) powered wheelchairs were provided to children and young adults who could demonstrate suitable dexterity and fine control of joysticks as generally powered wheelchairs were fitted with joysticks. Before the start of the work described in this dissertation, joysticks were the main form of control. There was provision of bespoke switch controls that were developed and made by the Lady Hoare Rehabilitation Engineering Unit at Chailey Heritage.

The control systems that were provided were usually the preserve of those who had or were able to develop accurate switch control. A project that was research funded by the Spastics Society created special switch controls [Thornett (1990)]. This provided an increase in the variety of control options and these were made available to the school pupils. Two important aspects involved with driving were: the pupil's mental cognitive understanding and physical control dexterity. There could also be additional sensory impairments to consider, for example, visual impairment could exclude those who could be physically and mentally able to drive.

At Chailey Heritage high value was placed on personal mobility and many children were not driving. Some areas of this work were described by [Langner (2010)] to improve wheelchair driving using a sensor system to control wheelchair-veer and variable-switches as an alternative to digital switches or joysticks. The work done at centres elsewhere (The CALL Centre) offered mobility to those who could not drive conventionally. There were also Automated Guided Vehicle systems in use in industry that used techniques which could transfer into applications for assisstive mobility for disabled drivers.

The projects and systems described in this Chapter did not all relate to applications which assisted wheelchair users. The automated guided systems used in industry, demonstrated practical examples of how it could be possible to apply guidance control systems to motorized platforms. Systems that relied on white optically detectable lines or guiding signal wires along a pre-defined route or strategically located beacons, involved modification of the particular environment.

Research has been conducted using high-cost multi-sensor mode systems closely resembling industrial applications. Using environmental features or artificial beacons, maps of the operating environment have been created, enabling a trajectory route to be implemented. The subsequent travel of the vehicle can be monitored and/or corrected from the processed data obtained from using multi-sensor systems including vision cameras, odometry, triangulation and inertial guidance.

Such systems based on artificial beacons have enabled a vehicle to operate in a previously known and modified environment. More complex systems that did not require modification of the environment enabled a vehicle to operate in a previously unknown environment. Some systems have evolved into fully autonomous vehicles that provide little or no personal control by the user. Although proving the technical feasibility of such systems in the laboratory or industrial environment, their cost and complexity have not provided wheelchair users with a practical and affordable device. The development of the Chailey Heritage Multi-Junction Wheelchair Guidance System was specifically for users to drive in their living and school environment. Additionally, the system needed to operate within the constraints imposed by cost, environment, type of wheelchair and user control. These parameters could not be practically changed.

At the early stage of the research described in this dissertation, young drivers demonstrated an ability to initiate driving by the operation of a driving control switch. Often the nature of the operator's disabilities meant that stopping their wheelchair before contact or collision with an object was not reliable. Indeed some children could not understand the concept of stopping before impact, or could not stop because of sensory deprivation. Objects could be detected by:

- Contact sensor (bumper)
- Non-contact (proximity) sensors
- Personal operator sensory function and ability

Direct contact bumper detectors could provide a warning and cut power to the wheelchair drive motors when in a collision. These were basic forms of control intervention and were used on the SMART wheelchair [Nesbit (1996)] and [Nesbit (2000)] and the track following wheelchair described by [Langner (2000)]. The SMART system could be programmed to respond to physical contact with an object. Such sequences could include automatic reverse and turn manoeuvers.

Factory oriented AGVs could also be equipped with a contact sensor. They may also have additional non-contact proximity sensors mounted onboard. A mix of sensors and multiple sensor types on the same vehicle provided a safeguard in case of a failure of one of the sensors. If, for example, a sonic sensor 'mis-read' the mechanical bumper could be a backup. Other contact sensing methods were used by [Luk et al (1988)] and [Sanders et al (1987)] who used the change in motor current of a manipulator to detect contact with the environment.

Contact-less sensing had the advantage of detecting objects without physically touching and sometimes the ability to determine the range of an object. This could be through time of flight delay. Ultrasonic techniques have been widely used in this application due to their low cost and generally acceptable accuracy. [Stott (1997)] and [Stott (2002)] and [Goodwin (2000)] used ultrasonic time of flight ranging as the primary source of guidance for autonomous vehicle research. Other forms of object detection could be achieved optically using infrared transmitters and receivers, laser range finders, triangulation or phase correlation.

Laser Range Finding (LRF) could be an effective and fast method for measuring distance. Due to fast response LRF could be useful in real-time systems [Parnichkun, Samadi (1999)]. They described LRF as ‘a single point optical triangulation instrument, which detected distance information quickly without touching the object being measured’.

Sonar systems using time of flight principles were widely used in many vehicle systems as a means of obstacle detection and avoidance and this was generally cheaper than LRF technology. [Stott (1997)] used ultrasonic detectors in the development of a system that could detect doorway signatures for the purpose of doorway navigation.

Some extra notes on intelligence in robots, communication, force feedback, sensor fusion and navigation are included in Appendix B for wider reading.

Chapter 3
Effort reduction systems

This Chapter describes research to create new systems to assist users to steer their powered wheelchairs.

3.1 Veer reduction

A veer reduction system was designed to help wheelchair users drive across sloping ground without veering off course. The research involved the creation of simple and affordable systems that could be attached to many standard powered wheelchairs.

Engaging in an active lifestyle is beneficial for maintaining quality of life [Pate RR (1995), U.S. Department of Health and Human Services (2000)] and a powered wheelchair can help towards providing that lifestyle for some people. Independent mobility such as crawling, walking, and running are usually acquired in the first two years of life [Verburg (1984)]. These abilities and their development are often taken for granted but some disabled people do not experience them. Instead a powered wheelchair may provide a partially equivalent process [Langner (2004)].

[Trefler (2004)] completed a study to measure the effects of individually prescribed wheelchair systems. Wheelchair users rely on their wheelchairs for mobility for extended periods of time every day [Wolf E (2007)], [Cooper RA (2002)] and several studies have investigated the mobility characteristics and activity levels of wheelchair users, for example [Tolerico ML (2007)], although these have tended to concentrate on manual wheelchairs. It is generally accepted that wheelchairs have provided an opportunity for increased continuity in the lives of some people, for example stroke survivors [Barker DJ (2004)] and a wheelchair has often made activity and participation in wider society possible [Brandt A (2004)]. [Buning (2001)] stated that the transition to a powered wheelchair enhances occupational performance, competence, adaptability, and self-esteem for persons with severe mobility impairments.

As wheelchair technology becomes increasingly sophisticated and complex, so do decisions regarding who gets what wheelchair [Hubbard SL (2007)] and evaluating the use of powered wheelchairs is important because of the increasing number of people with disabilities who are being provided with one [Pettersson (2007)]. These decisions are even more significant because large amounts of money are being spent on wheelchairs. For example, manual and power wheelchairs and scooters were the second, third, and fifth highest Prosthetics and Sensory Aids Service spending totals respectively during the year 2000 (that translated to a cost of more than $50 million in that year alone for the US Veterans Health Administration).

[Woods B (2003)] wrote a short history of powered wheelchairs, a survey of wheelchair providers was completed by [Guerette P (2005)] and a survey of wheelchair-use by residents of nursing homes was completed by [Fuchs RH (2003)] and these are included as references for further reading.

Powered wheelchairs are normally supplied with a proportional joystick. This enables a user to control speed and direction. A small amount of joystick movement in the selected direction and the wheelchair will start a gentle turn in that direction. If the driver applies more joystick movement then the wheelchair will turn more sharply. Similarly for speed, when the joystick is progressively moved forward, the wheelchair will progressively increase speed.

Wheelchairs generally steer by having two swiveling caster wheels. This simple system provides maneuverability. The drive wheels rotate at speeds determined by joystick operation. To go forwards in a straight line both drive wheels rotate at the same speed. To turn, one drive wheel rotates faster than the other.

Problems with this configuration occur when the wheelchair is driven along sloping ground because the casters can swivel in the direction of the slope [Brubaker CE (1986)]. Gravity causes the wheelchair to start an unwanted turn or ‘veer’. The driver usually senses this and applies correction to counter this veer. This causes extra work for the driver as the chair goes in an unintended direction. This situation is exacerbated for switch users, as switches cannot provide fine control to trim and compensate for veer. A switch user will frequently need to hop between directions and forward control switches to keep control of the intended direction. Wheelchairs can also veer when driven over a flat surface. This can occur as a result of imbalances in the drive motors, tyre wear and mechanical friction of the moving parts and caster / wheel bearings. Some modern wheelchair controls can electronically trim and compensate so that a chair can hold a straight direction on level ground. They will not automatically correct for changes in wheelchair loading and sloping ground effects.

To address these problems, some systems were considered to model the environment around the wheelchair [Sanders (1995a)], predict terrain ahead of the wheelchair [Urwin-wright (2002)], [Urwin-wright (2003)] and [Stott (2000)], consider forces on the wheelchair [Sanders(2007)] or to plan paths for the wheelchair [Goodwin (1997)] and [Sanders (1995b)]. These were rejected as too complex and / or to expensive. Other researchers had investigated the use of safety restraints to assist in wheelchair use [Van Roosmalen L (2005)] but it was considered better to investigate ways of assisting users in steering their wheelchairs.

[Gaal RP (1997)] stated that aspects of wheelchair stability, particularly the effects of wheelchair configuration are important engineering issues affecting wheelchair safety. Some studies have investigated changing the rear-wheel camber angle to reduce veer but they have had differing results [Perdios (2007)]. Increased rear-wheel camber has some minor disadvantages, such as increased wheelbase and decreased wheelchair height although some studies report some advantages [Brubaker CE (1986)]. More recent studies suggest little or no advantage with cambered wheels to improve veer [Buckley SM (1998)] although [Trudel G (1997)] suggested that camber improved maneuverability and stability on a side slope and recent results of user preference surveys conducted by [Perdios A (2007)] appear to support this finding (although no difference in comfort was detected). Increased chair width can improve turning stability and reduce downward turning tendency on side slopes but any advantage in that change of design may be cancelled out by problems when a user is negotiating obstacles [Denison I (1994)] and [Trudel G (1995)]. In addition, many camber studies have been conducted using non-disabled subjects with little or no experience in using powered wheelchairs, with the results then extrapolated [Van der Woude LH (2001)], [Ruggles DL(1994)], [Brubaker (1986)]; [Reid M (1990)] and [Rudins A (1997)] and sometimes to powered wheelchairs. This method was often used to form larger or more convenient sample sizes, and the results may not all be directly applicable. The mode of wheelchair testing may also have affected the outcome of some of these tests as an individual user has particular skills and abilities, such as the ability to maneuver a wheelchair around various obstacles [Webster J(1988)]. To avoid subjectivity in the results presented in this dissertation, the powered wheelchairs and veer systems were tested with standard inputs to the wheelchair joysticks or switches and tests included standard ramps inside laboratories and set outside courses for comparison.

3.1.1 Adjusting for veer subjectively - corridor assessment

Early experiments showed that carefully setting up wheelchair control for straight line balance and optimizing motor compensation was not good enough. Young people expend considerable energy, get frustrated and can end up in crash situations as a result of un-controlled wheelchair veer and for this reason it can be considered dangerous. Most wheelchair drivers reported veer problems with their wheelchairs and Figure 3.1 shows a young person trying to control his veering wheelchair. Normally this would have been corrected by control programming and this would be carried out on a level and flat floor surface. The general procedure required the driver to drive along the corridor in both directions to demonstrate the tendency of the veer. Adjustments would be made to the drive program that changed the power drive balance to counteract the veer. Repeated attempts would be made along the corridor to assess any improvement. This process was time consuming and only applied to a flat level ground surface.

Figure 3.1 A young person trying to control his veering wheelchair

Veer problems were reported even when the wheelchair had a well balanced motor drive. This indicated that wheelchairs were susceptible to the subtleties of ground slopes and changes in surface texture. These variances made it difficult to anticipate every ground effect. In many cases a wheelchair can become un-drivable due to problems with veer. It was necessary to develop a method to assess how the wheelchair and control system performance was affected by sloping ground that could be reproducible. Other factors also contributed, for example weight distribution. In many cases where a young person had a special seating system, a high percentage of the weight could be shifted toward the casters and this correspondingly decreased the percentage of the weight over the drive wheels, resulting in traction problems and an increasing the amount of caster-drag. Wheel slip could also be a problem on even mild slopes (up to 5º) and could contribute to loss of control.

3.1.2 Objective methods of veer detection

Normally a veer would be detected by a wheelchair driver using visual sensory input (eyes), processing control (human brain), bio mechanical interface (muscle action), control (joystick) and wheelchair control medium (proportional joystick) or (digital switch control). This all results in added complexity and work for wheelchair drivers; particularly those with complex needs.

Sensing the drive motor EMF (Electro Motive Force) relating to motor speed was the most common form of speed compensation and tends to be used in commercially available systems. Some simple veer detection methods were considered, these were:

a) Odometer
b) Optical
c) Inertial
d) Caster swivel detection

A) Odometer: When commanded to go in a straight line, each drive wheel rotation was measured. If any difference was detected then control applied to keep them the same. Jockey-wheels friction-coupled to a drive wheel could provide accurate ground speed (even when considering slight differences in wheel diameter).

b) Optical: Ground movement sensing was similar to an optical (ball-less) mouse. Surface texture variations and reflectivity of ground surface could cause problems (particularly in wet and dry conditions). The ground detection range could be extended by using an optical magnifier.

c) Inertial: Gyro / rate of rotation sensor measuring the precession of a gyro to the rotation of the wheelchair when veer causes turning downhill. Consideration must be given to the effects of other variables, for example slopes, shock, vibration, drift and time to establish a reference heading.

At the time of writing the relative complexity and cost of these systems remains high compared to using caster-swivel-detection.

d) Caster swivel detection: The selected method for veer detection was by caster-angle-measurement. Providing direct measurement of steering error and providing feedback to the wheelchair drive control system. A single caster could lose contact with the ground and therefore averaging two caster-swivel-detector-outputs could provide and generate better feedback but to simplify the systems and reduce costs, experimental trials were based on a single caster-swivel-detector. To reduce the tendency for misreads if the caster lost contact with the ground, the system incorporated a short-term-memory and any sudden swivel changes were ignored by the correction system. Locking the casters manually required substantial further development of the caster mechanics and so caster locking was effectively achieved electronically by using swivel-feedback-information to feedback to the wheelchair drive controller.

3.1.3 Correction feedback

At the point when the veer was first detected, the chair had already begun to alter course. The job of the correction system was to minimize this drift from the required course. The amount of compensation feedback determined how accurately the wheelchair held its course against gravity pulling against the chair. The amount of applied feedback was critical to avoiding problems of instability.

3.1.4 The rolling road test bed

A rolling-road was developed as an assessment tool to study the affects of wheelchair loading in a controlled environment. For a wheelchair to travel in a straight line, both drive wheels needed to rotate at the same speed (assuming they were exactly equal in diameter). An accurate assessment can be obtained by using tacho measurement wheels coupled to the main wheelchair drive wheels. Tacho sensing of the motor drive shaft speed does not take into account variances of wheel diameters and wheel slip. Remote taco sensing provided sufficient accuracy for the straight line test but could not control the drive loading. The rolling-road test-bed shown in Figure 3.2, was developed to assess drive motor and control performance. This test-bed incorporated tacho-rotation speed-sensing and variable-dynamic-loading. The test-bed provided individual distance counters for left and right drive wheels respectively, differential drive balance indicator (veer) and drive speed Kph indicators. It was necessary to provide separate speed and distance information to determine the motor/drive speed characteristics separately.

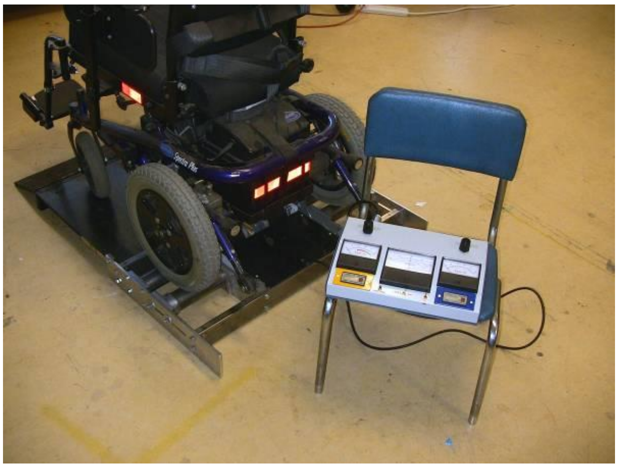


Figure 3.2 Rolling road test bed

Trials with the test bed were conducted on sample wheelchairs to evaluate the effectiveness of the rolling road system. These trials demonstrated the importance of measurable parameters that affected veer that were not apparent during corridor tests with wheelchair drivers. The rolling road system was also more convenient for younger wheelchair drivers who did not have to endure the frustrations of the corridor test (which could often be indecisive).

Most modern wheelchair control systems incorporate programmable load compensation. This helps keep the wheelchair speed constant when driving up or down slopes. For example, if increased load is applied to the drive motor, the control system applies more power to keep the speed constant. Motor compensation is applied in equal amounts to both motors. Interestingly, when testing the load compensation with the rolling test bed, the veer characteristic was affected by changes in load. This indicated that in practice powered wheelchairs may not veer on level ground, but the affect of motor compensation could introduce a veer when driving up or down a small gradient.

The acceleration or deceleration characteristics of each drive motor were not always matched. The distance (pulse count) for each drive wheel was measured from rest to the set drive speed and then to rest. There could be a mis-match in the count value of each drive wheel and this error could skew the heading of the wheelchair when starting or stopping, even when the drive wheel speeds were balanced and the wheelchair was on level ground.

Trials with the rolling road demonstrated that many variables affected veer and optimizing parameters for example, in a corridor was only valid in that one environment. A problem with conventional wheelchair control systems was with the way the wheelchair responded to a control action. To implement a solution it was necessary to provide global feedback to the control system. To provide meaningful feedback, careful consideration was given to factors that could degrade accuracy. For example, when considering the odometer methods, there could be issues with changes in wheel diameter and wheel slip. The caster's provide steering maneuverability, but they also caused a susceptibility to veer. With car steering, the turning angle is locked to driver control via the steering wheel.

If the wheelchair casters were locked in the straight forwards position then veer becomes less of an issue but manoeuvrability was lost. The intention of an effective control system described in this work was to develop an electronic solution to lock the caster steering position to the drivers control. Measurement of caster-swivel provided an error signal that was fed back to a control system. A small swivel detector was developed that could be attached to the caster swivel bearing (this is shown in Figure 3.3). This provided left, right and center swivel direction outputs.

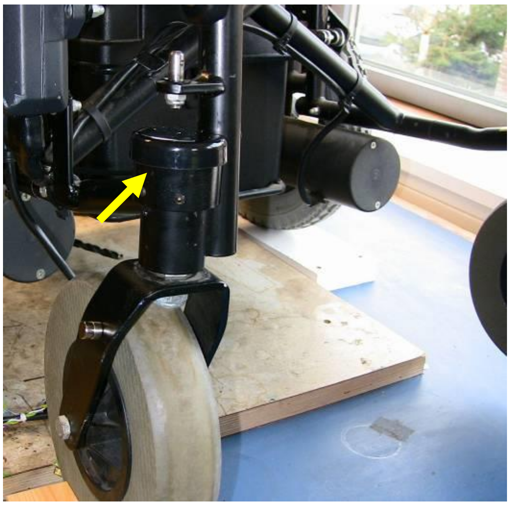


Figure 3.3 Swivel detector marked by the yellow arrow

Correction feedback was applied when the caster swivelled from the center position. The experimental tests indicated that the amount of veer was not always related to the slope camber but could change with the gradient due to control system and motor compensation imbalance. Furthermore, ground surface affects i.e., carpet fibers could induce a veer even on level ground.

3.1.5 Testing

The new veer correction system was tested in the laboratory and on sloping ground that was used regularly by children and young adults at Chailey Heritage School. Many young drivers had problems with their wheelchair veering off. Tests were conducted using switch controls as these were considered to be more difficult to use in correcting for veer (although the methods are easily transferable to potential joysticks etc).

The number of steering corrections needed to complete a test run were counted. A small video camera was mounted behind the driver to provide a dynamic record of events (Figure 3.4). With the uncorrected run there was a dominant veer downhill caused by path camber.

In a typical set of test runs, an average of eight left-switch corrections were needed to maintain direction along a path with a slope of 3°. The test was repeated with the veer-control-system engaged and the number of corrections was notably reduced, requiring an average of a single right correction and a single left correction to complete the test run.

Figure 3.4 The author testing the veer compensating system

A typical set of test results is shown in result group one and result group two. Result group one shows a set of results from an outside test on a path of length 28 Meters and an average camber / slope of 3° without the new veer system and sensors engaged.

Result group one

Run test with No Applied veer correction

Time to complete run = 2mins : 7 secs

Total number of steering corrections required = 8 left

Correction distance derived from time / distance approximations

Average speed = 0.22 meters per second

All left corrections after start of run distance in meters (M)

1st = 3.7
2nd = 6.4
3rd = 12.3
4th = 15.6
5th = 18.5
6th = 22
7th = 25
8th = 27.4

Result group two shows the improved results from the same slope with the systems engaged.

<ins>Result group two</ins>

Test with veer correction applied

Time to complete run 1 min : 29 secs

Average speed 0.315 meters per second

Total number of steering corrections required = 1 right and 1 left total

Approximate correction distance in meters (M)

1st Right correction distance = 9.4

1st Left correction distance = 22.4

Figures 3.5 and Figures 3.6 show video stills from an indoor veer test in the laboratory on a 4 meter ramp (with a left slope of 3º). The run had only the forward switch control activated. The wheelchair was weighted with 30 Kg. The difference between the trajectory with the system engaged and without the system is significant.

3.1.6 Ride quality

It was noted that when forward drive was selected after a turn manoeuvre then the wheelchair could be quickly ‘snapped’ back into straight-forward drive. This was due to the resulting caster angle after the turn being ‘off-center’. When forward drive was selected the fast acting correction system tried to restore the wheelchair to a straight-line direction. This post-turn harsh correction was not desirable for drivers who were used to a softer control characteristic.

To reduce this effect a short ‘post-turn veer-correction-delay’ was introduced after a turn manoeuvre. This provided time for the wheelchair to softly restore the straight line direction before the veer correction system cut-in.

Veer not compensated

Figure 3.5 No veer compensation

Veer compensated

Figure 3.6 Compensation applied

Figure 3.5 shows video still photographs from a test in the laboratory without veer compensated. Figure 3.6 shows video still photographs from a test in the laboratory with veer compensated.

3.2 Variable discrete controls

This Section describes how changing from a set of digital switches to a set of new variable switches could dramatically improve performance for some powered-wheelchair users. This was particularly so for some people with movement disorders that preclude independent mobility in a powered-wheelchair, for example people who did not have sufficient hand-grasp and release ability or sufficient targeting skill. These people had problems using joysticks. A simple input device is presented that isolates gross motor function and was tolerant to involuntary movements. At the time of writing the device had been tested for more than a year and was shown to assist powered-wheelchair users with poor targeting skills; a case study is described as an example. The new switches have been shown to reduce veer on slopes and to provide more control over turn-speed. They have provided a means to successfully control forward speed and turn speed and radius while reducing frustration and effort and improving energy conservation; for example, by avoiding switch-hopping. Users became more independent and said they did not want to return to digital switches.

The control interface was one of the most critical components of a powered wheelchair [Cooper (2000a)] and evidence suggested the existence of a patient population for whom mobility was severely limited if not impossible given currently available power wheelchair control interfaces [Fehr (2000)]. The control interface must accommodate the user's limitations and maximize their abilities. Excessive intention tremor, limited range of motion, athetoid motions, and spastic rigidity could reduce or prohibit control of a powered wheelchair [Cooper (2000b)].

[Pellegrini N (2004)] described how changing interfaces could dramatically improve performance and the paper describes research to create a driver-friendly proportional control for switch-users. Wheelchairs can be difficult to control with a proportional joystick (normally the preserve of people with fine hand function) but they can be especially difficult to drive with a switch. Clinicians indicated that 9 to 10 percent of patients who receive powered-wheelchair training found it difficult or impossible to use their wheelchair for daily living [Fehr L(2000)].

[Dicianno (2006)] reported that an estimated 125,000 Americans with movement disorders that preclude independent mobility in a powered-wheelchair could benefit from improved control devices. Surveys concerning powered wheelchairs in general have been completed by [Woods (2003)], [Guerette (2005)] and [Fuchs (2003)] and these are included as references for further reading. Other useful general information can be found in [Cooper (2002)], [Tolerico (2007)], [Trefler (2004)] and [Wolf (2007)].

If a person had fine control of hand (or head or foot) then a joystick could work well. A joystick can provide an intuitive control medium, accurately translating fine control movements. It can quickly respond to a progressive change speed and direction and was usually the device of choice. High intellectual function could be associated with fine control. Poor physical control was not always an indicator of low intellectual reasoning.

A typical joystick had a movement span change range from 1 to 16 square centimetres. For those with less fine control then a joystick could be extended. One of the fundamental requirements for a joystick to work was that the person had good hand grasp and release ability and good targeting skill; if there were any problems with these then operation could become frustrating.

[Krishnamurthy (2006)] suggested that some people who cannot achieve fine enough movements to control a joystick with their hand may be able to use their tongue, [Gosain (2007)] suggested foot control and [Taylor (2003)] suggested head movement. [Langner (2004)] suggested using a track system, [Goodwin (1997)] and [Stott (2000)] suggested navigation systems to assist and [Sanders (2007)] listed some force sensing systems that might help but generally simple switch input devices were used ; usually digital (on-off). A switch could provide:

- A simple input device in the first instance that was easy to operate
- Isolation of gross motor function
- Assistance to a user with poor targeting skills
- Tolerance to involuntary movements
- Selectivity (where control directions are separated)
- Immediate control output to a responding device

Research work described in this paper aimed to explore methods and ideas to create a more Proportional World (rather than digital) for a switch user and to help the users to derive a sense of proportionality within a digital switch medium.

Some initial questions were considered:

- Were switch candidates practicing and learning within their proportional control band of movement?
- Did people have sufficiency of fine movement device control?
- Should variable control format devices be given to young people as a first stage (their first introduction to control)?
- Did people who have switches need more graded control in their lives?
- Could people benefit if there was a way to provide them with fully graded-control?

3.2.1 Range of proportionality

Potential users were provided with some proportional control. If they did not use the proportional range but operated instead at the extremes (flat-out or ‘off’) then they did not have sufficient graded control.

The control band was adjusted to be within a range that matched their individual movement skill. For example, the first 50% of joystick movement could be translated to wheelchair linear speed. The next 50% of movement might be adjusted to only increase wheelchair speed by a further 25%.

Joystick control operation could also be fed back depending on system performance (how the wheelchair moved).

In everyday life, proportional control is applied to almost everything, for example when driving a car, the speed is controlled through pressing the accelerator, breaking is controlled by how hard the foot peddle is pressed, turn rate is controlled by the position of the steering wheel etc; in the home, taps are progressively turned on or off and objects are moved carefully using an appropriate amount of speed for the task or action.

For people using digital switches, timing becomes more crucial so consideration was given to methods that might be used to introduce some proportionalty (especially to give people a better sense of control). It was necessary to do this in such a way that did not worry them or make their task even more difficult. Many people find it hard enough to address a switch reliably, so the idea of introducing graded control could be thought of as an added burden.

To provide a sense of variable control when using switches it was necessary for wheelchair users to develop their timing skills. Drivers would briefly (momentarily tap) their switches in order to drive or turn more slowly because people did not always want to go at one fixed speed. Speed selection by a wheelchair driver using switches was considered, but it needed to be set in advance. A switch control interface was therefore developed (multimode interface) by the author of this Dissertation and this provided two selectable speed settings. Drivers were able to select slow or faster driving by operating a mode switch.

There were situations where time constraints did not allow for the selection of slower speeds without halting the wheelchair, for example when travelling relatively fast outdoors and stopping to reselect a slower appropriate speed for entering indoors and negotiating obstacles. Conversely a proportional control driver could seamlessly change their wheelchair speed without stopping.

3.2.2 Training to use proportional systems

Many people may not have a good mix of timing and perception skills to execute turns (some might under or over steer) and they may not be able to respond appropriately to driving dynamics. Some (with Cerebral Palsy for example) may have some degree of proportionality within their movements and this area of work could help to train them to exercise graded control and develop a sense of proportionality.

Devices were available that responded in a variable way (such as an electric light with a potentiometer) so that tests could be conducted to discover if potential system users could change the brightness (in other tests the colour could change in response to movement). A more practical example could be controlling the flow of water to fill jugs to a particular level (perhaps as a developing skill in preparation for driving). In this work a variable display unit was built to provide practice at variable control. This consisted of a light projection box with a ground glass screen that displayed an image from a disc rotated by a motor. The variable control output electronically determined the position of the disc. Figure 3.7 to show how the image changed in relation to varying control (as the control was progressively pressed down). The image disc could be changed to provide, for example, a colour spectrum. There were controls on the market and a number of technologies that could have been applied to detect proportionality of movement. For example with head controls (non-contact) an operator can move their head within a detection zone and the system provided a graded response. A modified joystick could increase or decrease the amount of control movement to widen out the band of proportionality. Technically ‘high-end’ contact-less systems could be too vague and undefined for some people. Work described here aimed to create a new control that looks like a switch that people were familiar with (or perhaps had already been introduced to).

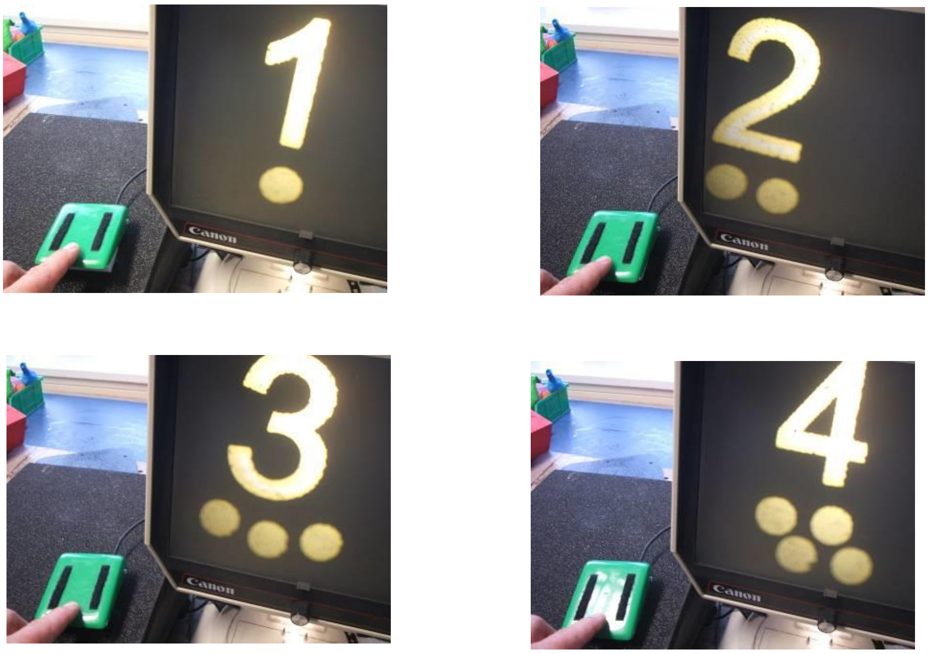


Figure 3.7 Progressive response to an applied control action

3.2.3 Variable switches

When an individual may have only one reliable output channel, then scanner based selection control systems were often used. Proportional control might also be introduced with that medium. A possibility was to create a proportional channel of control enabling the direction selected to be a proportional element, so that when a driver selected ‘forward’, grading control of that selected direction was possible (and similarly with other directions). A device of this type was being created by the author at the time of writing to offer added control flexibility to wheelchair driving.

Variable switch controls (vari-switch) were a new development created by the author. They provided an opportunity for switch-control operators to try-out controls that were tailored to match the ability of a person’s physical control movements. Figure 3.7 show the progressive response to the applied control action. Generally the only medium through which proportional (graded) control was given was by a standard joystick. This had a set movement span and often the control area was confined to within 9 Sq-cm.

For those with physical impairments this could be difficult to manage, where in particular, holding the joystick control knob was difficult, challenging and unreliable. The vari-switch could be placed in similar operating positions to those used by standard switches. Through the introduction of variable control it was hoped that people would be able to learn, distinguish and exercise progressive control. Vari-switches retained the virtue of switch operation, enabling combined functions (for example driving and computer or environmental control). Figure 3.8 shows a simple paddle switch developed by the author and used by students at Chailey Heritage School. This is shown in the Off position.

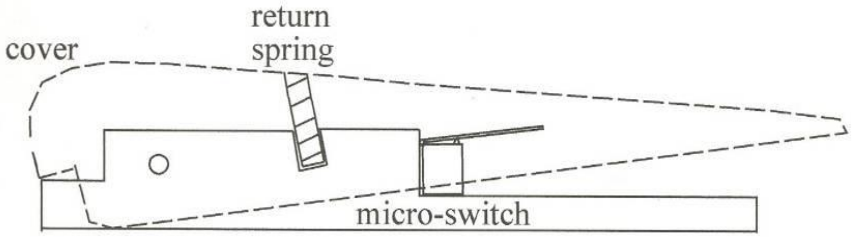


Figure 3.8 Paddle switch (un-operated)

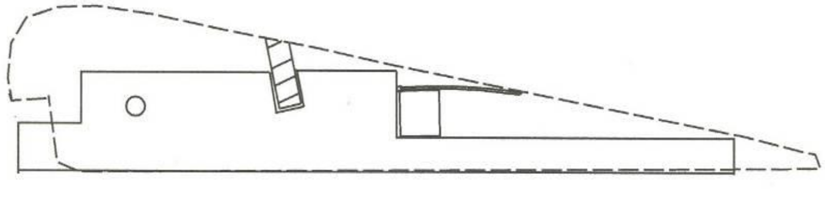


Figure 3.9 Paddle switch (operated)

The main armature consisted of a high impact polystyrene vacuum formed cover and the switch base plate was made of Delrin. When the switch was operated the cover acted against the micro switch lever arm as shown in Figure 3.9. The return spring provided sufficient return force to ensure the switch deactivated when not pressed.

In the new variable switches, the basic construction of the device remained the same. The micro switch was replaced by a Hall Effect integrated circuit. The cover had a small magnate attached to its underside as shown in Figure 3.10. The angle of cover movement was increased to provide the required movement span for graded control. Figures 3.10 and 3.11 show the extreme operating positions. The output from the Hall effect device changed in proportion to a magnetic field when the cover was pressed down.

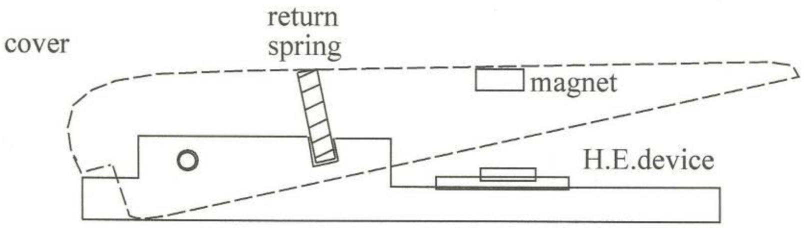


Figure 3.10 Paddle control (un-operated)

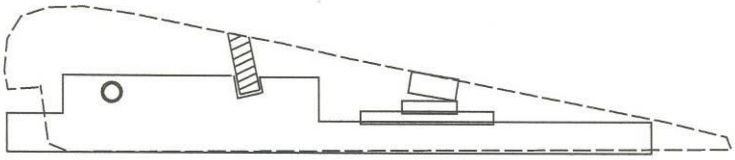


Figure 3.11 Paddle control operated

It was important that development was undertaken in parallel with the introduction of the concept to young people. That engendered a co-operative and collaborative result.

To enable the variable control to operate a powered wheelchair it was necessary to provide an appropriate signal to the wheelchair power controller. A variable control interface was developed that electronically combined control directions of forward, left, right and reverse into a joystick-control format. Directions could be mixed, for example if forward and left were both operated, this translated into graded control of a turn left direction.

3.2.4 Case study

As a case study, one of the 16+ pupils at Chailey Heritage School volunteered to take part in testing a vari-switch system.

He had been using a set of lever pad switches to control his wheelchair. These were placed in an Evosote foam switch surround known locally as a 'horseshoe'. This successful arrangement is shown in Figure 3.12. It provided control directions that were similar to a joystick and the sizes of the objects to be touched were large so as to improve the time taken to complete a prehensile movement [Bootsma (1994)]. His hand movements of forward, left or right directions were translated into the corresponding wheelchair-drive control. Reverse control was placed behind the main switch surround. He had learnt to reach and pull back on his reverse switch to implement reverse (similar to pulling back on a joystick).

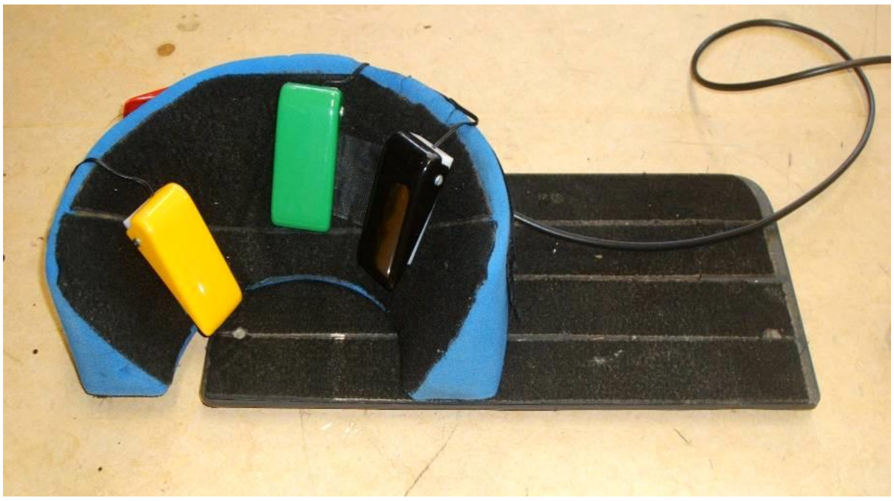


Figure 3.12 Hand switch controls

Switch controls were held in place by Velcro. This provided a convenient means to anchor the switches. Their positions could move when in use and therefore could be a source of frustration. To help accommodate his arm and hand movement-span, the controls were initially positioned outside the area of the wheelchair tray on the left side. It had been noted that he sometimes had trouble with the operation of all of his switches with the same ease. To accommodate his range of movement, the switch mounting was off-set but this position increased vulnerability when passing objects on his left side. The controls were then gradually moved to be within the confines of the tray structure as shown in Figure 3.13.his continued use of the switches enabled him to develop the finer elements of his control movements.

He was:

- A proficient driver and could understand complicated tasks
- Motivated to drive (and drove regularly)
- Unable to drive without his chair oscillating from side to side when driving
- Prone to easily veer on slopes and not follow the desired route
- Unable to keep wheelchair turn speed constant on different surfaces
- Sometimes frustrated by the system (especially if his controls moved out of position)
- Unable to change speed or turn his drive controls on or off while moving

Figure 3.13 Horseshoe surround switches

Once students had become proficient switch control users, they were given an opportunity to try a proportional joystick. This provided a gateway for the operator to practice more finely graded wheelchair control. This also had the advantage of improving energy conservation and allowing the driver to exercise graded control of the wheelchair on slopes and turns. Switches only provided an on-off function and the driver needed to control the wheelchair by repeatedly pressing switches (switch-hopping) and that could be labour intensive when compared to a proportional joystick.

3.2.5 Hampered by the wheelchair

Wheelchairs did not respond properly when driven over some surfaces, for example on rough or sloping areas the chair moved slowly or stopped while on smooth floors, or may turn too quickly. Figure 3.14 shows a young person battling with his wheelchair. Switch controls can provide only one level of speed and this cannot suit all driving situations. The application of variable controls could enable a driver to select a more suitable speed and power and improve effectiveness and safety.

Another problem encountered by wheelchair drivers was veer [Langner (2008)]. Switch users had to work hard to keep correcting their wheelchair in these situations. Variable controls allowed drivers to trim and counteract unwanted veer by shifting the position of their hand. This was only possible with variable or proportional controls and made them a valuable asset in improving energy conservation. Although he was not ready to use a standard proportional joystick, his switch controls were replaced by variable control devices. This allowed him to grade his speed in all directions. Proportional Vari-switch controls were selected for him for the following reasons.

To:

- Provide a means for him to control forward speed and turn speed/radius
- Reduce effort (for example, avoiding switch-hopping) and improve energy conservation
- Develop his finer hand and arm control functions
- Enable him to improve control of wheelchair veer and turn
- Help provide him with a smooth transition to a standard joystick if and when he feels comfortable to do so

Figure 3.14 The young person trying to control his veering wheelchair

This young person tested the prototype control system with the variable switches and demonstrated that he could control speed using them. The original arrangement of digital-switches (a horse-shoe arrangement) required control movements that were similar to a joystick (except for reverse). The horseshoe provided an expansion of movement which was a better match for his range of movement skills (although reverse control was more of a problem). Initially, a reverse switch was placed to the side of the horseshoe ring. Sometimes this would be a nuisance for him and he solved the problem by suggesting that the reverse switch should be placed behind the forward switch. This required a pull-back movement that was similar to using a joystick.

Most of the problems he had with driving control were due to the dynamics of the wheelchair and the way the wheelchair was affected by the type of ground he was driving on.

If he was driving along a path with a modest camber (for example from left to right), then the wheelchair had a tendency to drift to the right. He needed to work hard to counteract this drift by applying his left control more than his right in order to continue along the path.

An initial problem was that the switch function responded asymmetrically by turning faster to the right and slower to the left. His reactions to control to the right were not always fast enough. A second problem was that the wheelchair would stall when commanded to turn up the slope. Often the wheelchair’s speed compensation was not sufficient to provide a constant speed for different rolling resistances. Wheelchair veer was often controlled by drivers quickly alternating left and right control directions (switch-hopping).

The first introduction was to a variable control format that looked and behaved like a switch. This raised the question of whether long-term switch users could unlearn some of the coping strategies they had learnt with switch control.

3.2.6 Testing

He was equipped with a wheelchair mounted communication system. To access this he used two switches (scan and select). A member of staff was needed to remove his drive switches and replace them with the communicator switches and vice-versa.

The next phase of the development work was to provide him with a means to select what he wanted to operate for himself. This required an additional mode selector button on his drive controls. With the provision of a multi-functional interface he was able to sequentially select through the operational functions.

These are shown in table 3.1.

Mode select button	Selected operation	Confirmation sound
1st Press	Driving	Momentary buzz
2nd Press	Communication	Momentary beep
3rd Press	Systems turned off	No sound

Table 3.1 Operational functions that can be selected

When systems were off then the next press of the mode-select-button repeated the cycle and activated the driving mode. Sound prompts were used to convey the selected operation as this removed the requirement to mount a status-display-panel in the driver's field of view.

When the communication mode was selected then the left and right turn controls acted as switch inputs to the communicator. This suggested placing the mode select button adjacent to the reverse control and behind the main forward-drive-controls but at the time of writing, tests are taking place to confirm this. Reverse and mode select were used less often and this mounting position may help to reduce accidental operation shown in Figure 3.15.

Figure 3.15 Trialling his new vari-controls

The controls were mounted on an open structure with adjustable brackets. These were secured in place by screw fixings so their relative positions remained the same. The potential speed range of the controls was determined by the wheelchair DX control program. Speed values were set at a rate that he felt comfortable with.

This young person was able to mix his control directions and this was a significant benefit for controlling a wheelchair on sloping ground where there was a tendency for the chair to veer. Figures 3.16 show a sequence of video still pictures of him driving along a slopping path.

Many drivers had problems driving along this path because of the 3 degree slope (in particular those using switch controls). The picture sequence shows that he was able to maintain control against the slope without stopping to correct directions as was the case when he used switch controls   He significantly reduced the amount of switch-hopping between directions and this reduced energy expenditure and frustration.

a

b

c

Figure 3.16 Driving and maintaining his course across the path

At the time of writing, the young person described had been using his variable control for a year and has achieved a high level of driving independence. He has learnt to mix his control directions which helps in situations controlling wheelchair veer and he can grade his speed in critical situations. He says he does not want to go back to on-off switches as he can exploit the subtleties of proportional control for different drive conditions.

Outcomes included a reduced initial reaction time and movement time but a greatly improved driving accuracy.

3.3 Discussion

Tests with and without the new veer correction system demonstrated that a simple feedback system could reduce the amount of effort needed by a driver to counteract any tendency for a wheelchair to veer. It was important to develop a system that was robust and not affected by changeable parameters through normal wear and tear. The experimental system was primarily intended for switch users. Control feedback could be adapted and incorporated into proportional control systems as these provide a continuous feedback signal rather than on-off signals.

The limit of veer correction seemed dependant on the traction capabilities of the wheelchair, power of the motors coupled with the wheel grip characteristics and weight distribution over the ground surface which could be rough or smooth. The system still tried to correct the veer even if the drive wheel skidded. This could be a problem if the feedback was too aggressive, as a sharp response could cause skid (loss of traction). If the response was as shown in the experiments presented, then the veer was not completely removed.

The second section described how changing from a set of digital switches to a set of new variable switches could dramatically improve performance for some powered-wheelchair users. This was especially for some people with movement disorders that preclude independent mobility in a powered-wheelchair.

A simple input device was presented that isolates gross motor function and was tolerant to involuntary movements. The device has been tested for more than a year and has been shown to assist powered-wheelchair users with poor targeting skills (a more proportional world rather than digital is created for a switch user). A case study was described as an example. The new switches have been shown to reduce veer on slopes and to provide more control over turn-speed. They have provided a means to successfully control forward speed and turn speed and radius while reducing frustration and effort and improving energy conservation. Users have become more independent and say they do not want to return to digital switches.

More research work is required to test how many digital-switch users may be able to use the new switches and to test whether users are practicing and learning within their proportional control band of movement. Through the introduction of variable control it is hoped that people will be able to learn, distinguish and exercise progressive control. Vari-switches still retain the virtue of switch operation in that they can enable other combined functions. Research is also required to test whether some less motivated or proficient drivers could benefit (especially some with reduced understanding of complicated tasks) and whether these new systems might help provide a transition to standard joysticks for some people in the future.

Chapter 4

Object detection devices for powered wheelchairs

The wheelchair service only issued powered wheelchairs to individuals who could drive unaided and independently but excluded those who were not able to drive conventionally. The creation and use of the track guidance systems described in Appendix C provided more young people with opportunity to drive powered wheelchairs.

The purpose of assistive systems was to help increase the level of independence for users. Children demonstrated improved confidence and autonomy when given the appropriate tools. Providing a system to help with steering guidance solved some problems but there were other considerations.

Some users became more proficient since the provision of the track system. This assessment was subjective; although children may be driving greater distances to chosen destinations, there were other places of interest that drivers wanted to explore but could not do so because of limited track access.

Wheelchair users and helpers were concerned with reducing the likelihood of collisions with objects or people. Common types of collisions reported and observed were drivers not stopping and colliding with people, furniture, stationary wheelchairs and children lying or sitting on the floor. Users and people nearby had no warning of an impending collision until it had occurred. Collisions had a detrimental effect on the self confidence of drivers.

The independence of track users was being undermined by collisions with objects. Helpers would stay near to wheelchair users to prevent collisions or assist after a collision had occurred. This reduced the level of independence afforded to drivers. Some therapists believed that crashing was a learning experience and they had concerns that systems developed to stop children automatically would reduce their need to learn. These considerations formed the basis for experimentation with bumper systems, which could alleviate the urgent need for close monitoring and supervision of children.

4.1 Selection of switching method

Several types of switches that would be used to detect objects were considered. Conventional strip type switches were an option. Some experiments with pneumatic tubes, pressure switches and ‘stick on’ tape switches were conducted. Obtaining good energy absorption and a ‘bouncy’ characteristic with sufficient sensitivity proved difficult to achieve.

Problems were encountered, particularly with a specifically shaped profile. Large tube diameters were desirable but keeping control of the internal air pressure was difficult and air leaks were a problem. Notable problems with strip switches were dead spots and variable sensitivity along their length. Sensitivity could be affected by bending strip switches.

It was possible to cause an internal short within strip switches if their radius was small or a hard sharp object had been struck.

These early experiments are not described any further, particularly as tests with young wheelchair drivers were not attempted. The impact absorbing characteristic of bumpers was of concern. It was therefore decided that a purpose made design was necessary.

4.2 Prototype mechanical bumper

The first type of object detector tried was a contact type bumper and a prototype is shown in Figure 4.1. The prototype bumper was mounted in place of wheelchair footrests and was constructed out of curved plywood. It was important to allow movement of this bumper to reduce the impact jolt.

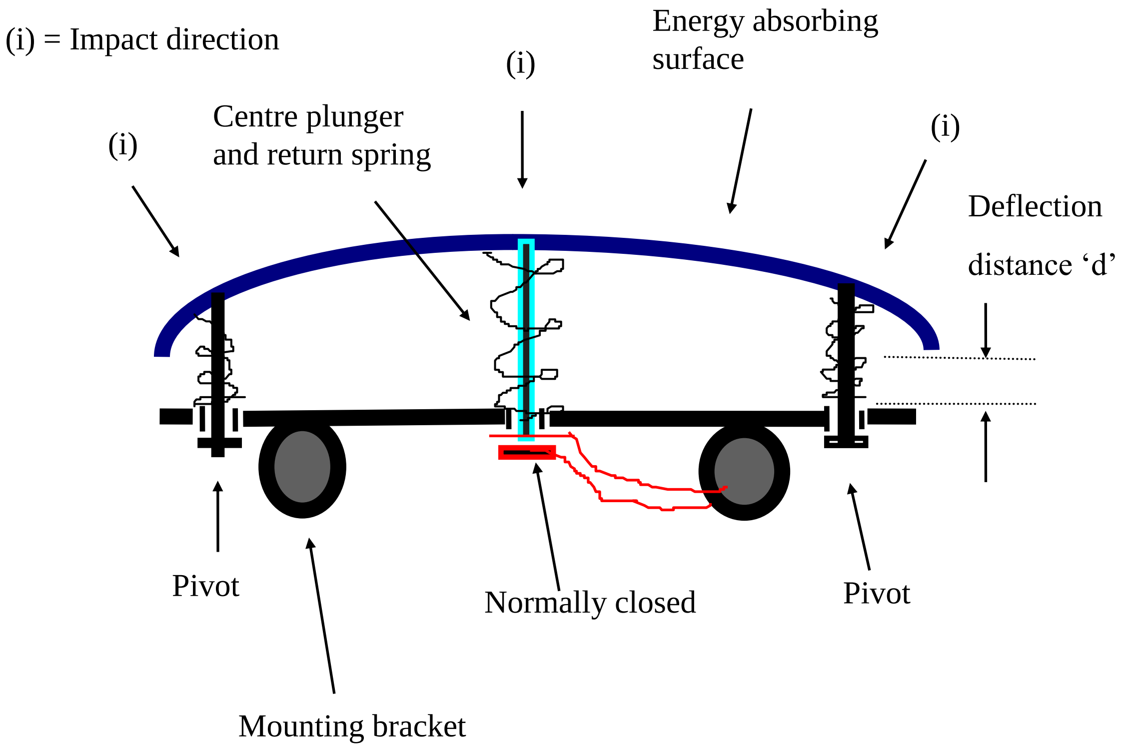


Figure 4.1 Prototype mechanical bumper

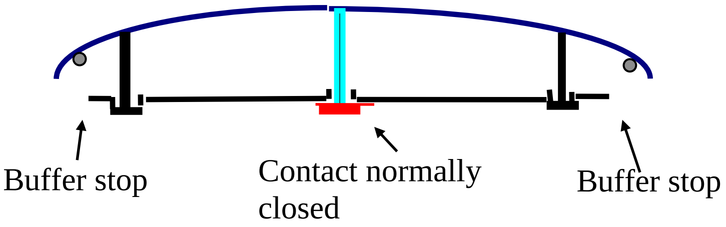
Important qualities of the prototype mechanical bumper are summarised as follows:

- An impact could occur at any point or angle (i) on the bumper surface. It was necessary to ensure that the device would respond reliably to different impact angles
- Impact absorption. The amount of bumper deflection had an effect on the retardation (deceleration time) and the amount of shock applied to wheelchairs and their occupants
- The bumper movement (d) against applied force affected how 'bouncy' the system was when it struck objects
- Vulnerability. Acceptable resilience and ruggedness, freedom from sticking and false triggering
- Overall compactness and mounting position
- Power cut-off or warning electrical interface functionality
- Appropriate sensitivity and uniformity over the total bumper area

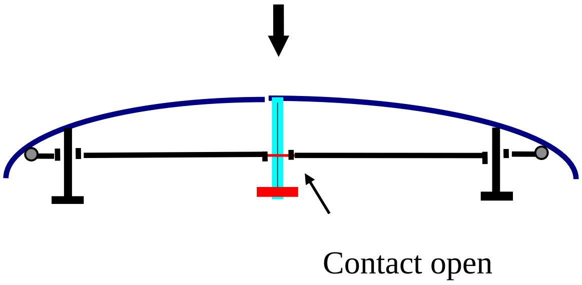
These considerations set the parameters for the development and testing of a practical bumper system.

4.2.1 Bumper collision response states

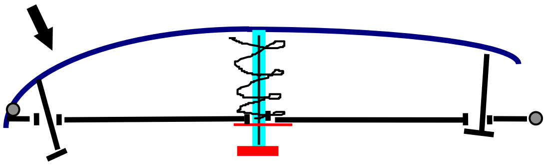
Bumper pre-collision



Frontal impact.



Impact on the left side



Impact on the right side

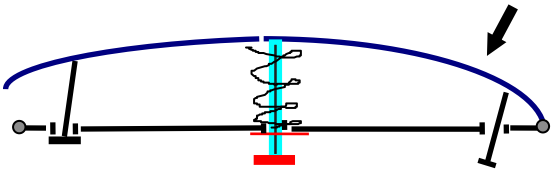


Figure 4.2 Bumper collision states

Figure 4.2 shows the expected movement of the bumper. The switch contact was a copper washer and strip that was normally shorted when the bumper was not in contact with an object. When a collision occurred, the initial movement of the bumper cover opened the contact. Any further movement was absorbed by return springs until hitting the buffer stop at the end of travel (in the case of a severe impact). The contact opened at the moment the bumper was hit, to provide the necessary electrical warning as soon as possible.

4.2.2 Drive motor interface

When the bumper collided with an object and the contact was opened, the drive control system needed to respond appropriately. The following options were considered:

- Direct intervention requiring power drive cut-off (controlled deceleration)
- Audible collision warning
- Power drive cut-off and audible warning
- Dynamic braking

A drive motor interface was created to act as an intermediary between the wheelchair drive controller and the motor. This consisted of a suitably current rated double pole change-over relay, shown in Figure 4.3.

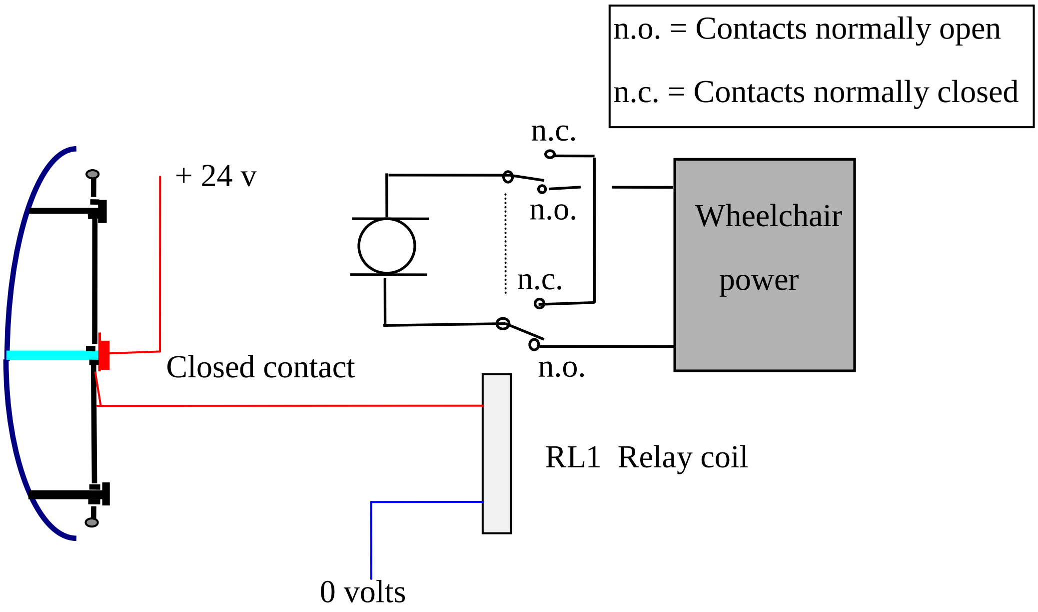


Figure 4.3 Bumper Electrical wiring diagram

Figure 4.3 shows a normal drive condition (a non-collision state) in which the bumper contact was closed. In this state an electrical current passed through the relay coil RL1, which operated the contacts and connected the power controller to the motor. The left drive motor circuit only is shown in Figure 4.3.

The circuit configuration for the right drive motor was identical.

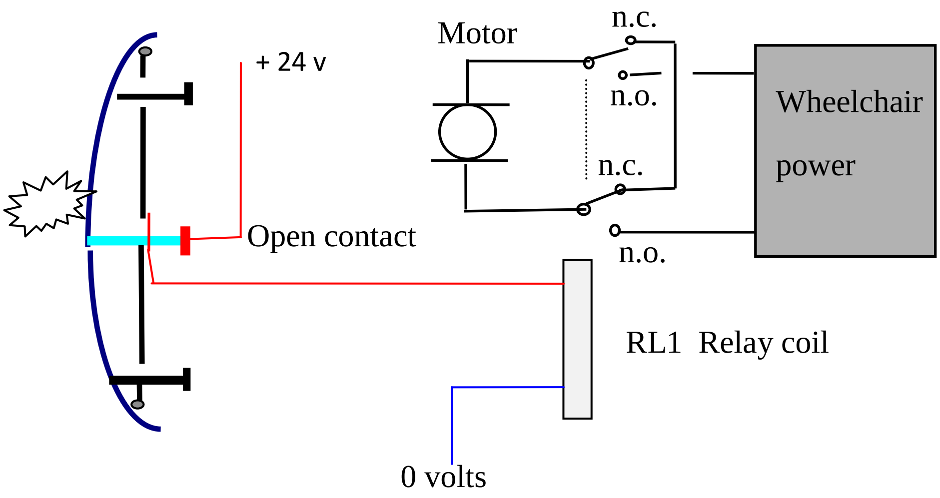


Figure 4.4 Bumper in collision

Figure 4.4 shows the bumper when it hit an object and the contact was open. The relay coil was de-energised and the relay contact's changed to their normally closed state (n.c.). The motor was shorted. This created a path for the short term generated motor current, and acted as a dynamic motor brake. If the drive controller was still active the open circuit relay contacts would not pass power to the drive motors. Wheelchair drive control restarted when the bumper contact returned back to the normally closed (non collision) state.

Dynamic braking produced a skid free and controlled stop. Without dynamic braking, there was insufficient deceleration resulting in wheelchairs impacting more heavily with objects. The relays used had a current switching capability of at least 20 amps. Some low rated types had problems with their contacts welding, particularly when shorting the generated motor currents. Replacing the shorting link with a wire wound resistor reduced the instantaneous current when the motor was shorted.

It was desirable not to alter wheelchairs, especially when they were the property of the wheelchair service. The dynamic brake circuit was designed to plug in between the drive motors and the wheelchair controller using standard in-line bullet connectors. This enabled easy removal of the drive motor interface and restoration of wheelchairs to their state when issued. The bumpers were a 'bolt on' accessory that could similarly be removed.

Power to operate the drive motor interface was obtained from a wheelchair charging socket.

4.3 Audible warning system

Drivers and bystanders were not always aware that a collision had occurred and that was the reason that a wheelchair could not be driven further. Sometimes those people incorrectly thought the wheelchair was not moving because its driver was not pressing their switch hard enough or not concentrating. An audible warning system was created to inform drivers and bystanders that an object collision had occurred.

Three possible options were considered for how the system should react when an object was struck:

Option 1:

- Power was cut to the drive motors
- Sound beep was activated until the object had been removed or the wheelchair
- Controller master switch had been turned off

Option 2:

- Power was cut to the drive motors
- Sound beep was activated when the user pressed their drive switch. The sound stopped when the switch was released. This provided the necessary sound warning when the driver wanted to move but was prevented by the detected object

Option 3:

- Power was cut to the drive motors
- Pressing the drive switch activated the bleep

These different options provided extra help when training young drivers to respond to warnings of collisions. It was interesting to note the effect of warning signals on drivers.

The loudness and sound quality of audible warnings were significant. Some warnings could be startling and disconcerting to drivers. Experimenting with the sound type and mode showed that option 2 was generally preferable with a soft pure tone.

Figure 4.5 A single switch operated track chair with mechanical bumper

Figures 4.5 and 4.6 show captured video pictures of a bumper fitted to a track chair. Figure 4.5 shows a young girl who used a single switch to control her track driving. She had poor vision and used the audible warning as feedback in addition to direct object detection intervention stopping.

Figure 4.6 Bumper in collision

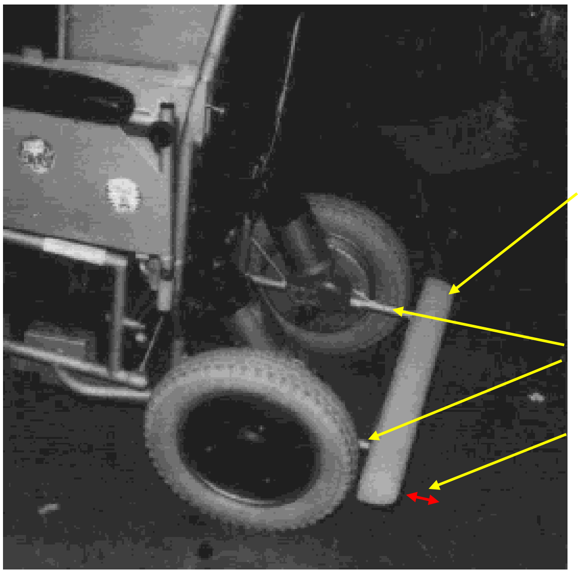
In Figure 4.6 the bumper had struck an object on the left side. This resulted in cutting power to the drive motors and sounding the audible warning. When she removed her hand from the drive switch the sound stopped. If she pressed the switch again the sound would be activated until the obstruction had been removed.

4.4 Reversing bumpers

The majority of the mechanical bumper systems were applied to track drivers. The normal mounting place was at the front, usually on foot rest mountings. The track systems did not have a reverse option and forward object sensing sufficed. Students who had previously used track guidance were referred to as ‘free’ or ‘unguided’ drivers. Another term which had been applied to this group of drivers, were those that had been ‘weaned-off’ the track system. This could be a critical time, particularly as free driving was more demanding. Children learning to drive unguided were expected to steer unaided and therefore needed to practice controlling their wheelchairs. One driver in particular had problems with reversing and would often crash into objects behind. A reversing bumper was created for this driver and this is shown in Figure 4.7. The new reversing bumper was not curved but spanned across the rear drive wheels. It was compact and built with foam padding to provide energy absorption.

Having struck an object, power was removed and the wheelchair was immobilised to reduce any further damage that could have resulted. Object collision warnings informed drivers and helpers that a collision had occurred. The electrical interface consisted of a reverse direction power cut-off. The driver often reversed into objects, so a timer was put in the system to prevent further reverse collisions for a timed period.

When the driver reversed into an object and triggered the bumper system, the reverse drive function was disabled for a period adjustable between 30 - 90 seconds. The time period that was initially set was gradually reduced because those delays were frustrating for situations that required multiple reversing manoeuvres to get out of confined spaces.



Energy absorbing linear bumper. This was mounted as close as possible to the rear drive wheels

The mounting support tube extensions

Bumper movement approx. (30mm)

Figure 4.7 Rear bumper fitted to a standard ‘Apollo powered wheelchair’

Considerable effort and time from therapists and teachers was spent in trying to train and help students understand driving controls. The responsiveness of the control system and any imposed delays could affect the sometimes, fragile nature, of the learning process.

Experience gained from tests of the new reverse bumpers suggested that it was better to dispense with any functional lockout delays as soon as it was ‘judged’ possible.

4.5 Chapter summary

Creation of a guiding system for children in powered wheelchairs provided them with opportunities for independent exploration. This was beyond the boundaries and restrictions imposed by the young person’s physical disability and reduced dependence on personal helpers. With normal un-guided systems, helpers steered young peoples chairs’ as a means to help. The tracked guidance system reduced this need. There was still a need for helpers to stop drivers from colliding into objects in the path of their travel. Helpers acted to protect children, others nearby, and reduce potential damage to their environment.

Independence gained by young people using the track was compromised by their inability to bring their wheelchair to a controlled stop when necessary. Helpers tried to train children to recognise situations leading up to a crash. Inevitably, this was hampered by children’s disabilities, particularly in cases of visual impairment. Some therapists believed that crashing was a learning experience and they had concerns that systems developed to stop children automatically would reduce their need to learn. Teachers however, liked to see children driving with increased independence, even with the addition of a bumper system.

It was important to note how the trainers, teachers, carers and child drivers responded during collision situations. There could be tensions and differences of opinion between the therapist and teachers so different system response modes of operation were incorporated into the development of a crash prevention system. The following statements describe what occurred when an object was struck by a wheelchair:

a) Wheelchair jolted when striking an object
b) Audible alarm was triggered
c) Drive power was cut
d) Events after the bumper had struck an object
e) Drive power reset

a) Physical contact with the object was fundamentally necessary for the bumper to operate. Control action was applied in a short space of time and distance after contact with the object. Physical transference of energy was unavoidable. The design of the bumper softened the rate of deceleration. For some drivers, knowing they had struck an object by the perception of a movement (jolt) was enough for them to take action for themselves and stop activating their control switch.

b) If a driver's perception or control awareness was not sufficient for them to perceive physical contact with an object, the addition of a bumper activated sound alarm provided reinforcement. The alarm also provided a warning to bystanders that a collision incident had occurred and this may need their attention. A certain level of trust was placed on the driver to stop when they heard the alarm and this emphasised learning and taking personal control responsibility.

c) Cutting the drive power was a significant control intervention. This was a statement that the child could not be trusted to take appropriate control action, particularly stopping in a critical situation. The effect of the bumper intervention was primarily damage limitation.

d) Power was restored when the object had been removed and the bumper deactivated. Observations indicated that typical circumstances were, firstly, objects moved away from the bumper. For example: a person or another wheelchair who reacted instinctively. Secondly, helper intervention acted to clear the object away from the wheelchair bumper. Drive power was subsequently restored when the bumper was no longer in contact with the object. Consequently this was a momentary mode of operation.

e) Child behavioural issues required higher levels of applied control intervention beyond just momentarily cutting the drive power after an object was struck. There were occasions when some children would repeatedly or deliberately crash.

Additional control interventions were applied where there were repeated attempts by a young person to collide with objects. Some helpers and therapists considered this to be attention seeking behaviour and additionally the noise caused and the physical jolting through crashing provided sensory feedback to the driver. Cutting the drive power once an object had been struck immobilised the driver from further collisions until an attendant reset the drive power. This bought the incident to the attention of people who could then specifically help the child. The most drastic form of intervention was a timed lockout. When the bumper had been activated the wheelchair drive power was cut for periods up to 90 seconds. This was an attempt to break the repeated cycle of children deliberately reversing and crashing into objects. There was no practical method for discriminating against accidental collision triggering. The lockout timer could be manually reset.

Detecting objects by physical contact was disadvantageous for the progression of children learning to drive with an assistive system. Positive control action needed to occur before object contact. The physical contact power cut-off system was a ‘last resort’ intervention. Mechanical bumpers often sustained damage mainly due to variations of object strike angles. Carers would sometimes be hampered by the bumper structure when placing a child in or out of their driving seat.

The appearance of bumper systems accentuated the aspect of a young person’s disability. Bumpers caused other difficulties because the necessary physical dimensions required by bumpers to absorb impact energy and this added to the footprint of the wheelchair. Unfortunately, bumpers increased the difficulty for wheelchair manoeuvring and reduced drivability, although this was less significant when using the track guided system.

Later work described in this Dissertation created a contact-less (proximity) object sensing system that provided the same function by applying contact-less collision avoidance.

Chapter 5

A new Scanning Collision Avoidance Device (SCAD)

5.1 Introduction

This Chapter describes the creation of a first prototype Scanning Collision Avoidance Device (SCAD). This became a successor to the mechanical bumper system used for track and limited driver training described in Chapter 4. A major limitation of the mechanical type bumper was its footprint size. This became untenably large when trying to increase the detection range to help improve the stop control performance of wheelchairs. Drivers collided with objects and misjudged object distance. This became the focus of further obstacle avoidance development work. New research started creating a non-contact proximity object detection system that used ultra-sonic ranging. This reduced the need for obtrusive physical bumper detectors. Pupils that had been using the track (described in Appendix C) had not been required to exercise their own steering control. It became possible for many track drivers to start practicing their wheelchair steering.

A natural progression beyond the imposed access limitations of the track routes was the creation of a system that guided itself by sensing the local environment. This potentially offered more opportunities for learner drivers with visual impairments and spatial perception problems to drive with more freedom. The SCAD provided a protected environment but required a higher driver skill level than was required for track driving. In particular the requirements for navigation and recognition skills within the drivers environment were greater than when track driving. A system was developed by the author of this dissertation that rotated an ultra-sonic transducer. This sent ultrasonic pulses at stepped periods of rotation and was the first prototype SCAD object detector. This was intended to be a wide angle object detector and audible warning device for people using a track following powered wheelchair. There were notable anomalies with the detector, mostly arising out of the repetitive pulse echo sampling. Old returning echoes would sometimes conflict with nearby 'in-range' target echoes. The sample update time was also slower than desired. The system worked well enough to be of value in detecting nearby objects. For the development of a guiding SCAD system, a method of determining the position of detected objects was required. The essential aspect of the SCAD system was the generation of multiple zones without increasing the physical size of the detector head.

5.2 Background

Some disabled children at Chailey Heritage were not able to drive wheelchairs. For example, their hand function was not proficient enough to operate a joystick, the most used form of control associated with wheelchairs. Joysticks required hand grasping and release skills and controlled movement coordination within a small area (16 Sq cm). Many children could not drive because of the demands of the joystick. New work started to make switch controls, which were easier for some children to operate than the joysticks. The switches could be placed in positions that were more suitable for a child to reach and separated in such a way that spread out the control directions so that children could discriminate between different control directions.

Some children began to drive more using switch controls. Some children did not have enough refined hand function though (even for switches), particularly children with athatoid movements and problems with spasticity. Many children with poor hand function could turn their heads to look at people and the author was involved in research to create new controls that could be operated by the chin. Some children started to drive competently with chin controls. Some of these children were mentally agile and did not require any type of additional guidance support. The research work continued to create a variety of controls that could translate whatever repeatable movement the young person had into a useable switched output. Children started to drive and become independent in their powered wheelchairs. Over a period of time it became clear that there were groups of children who were not driving and they could see that a lot of their friends and classmates were now driving (and they were not). What was interesting about this group was that they might have been co-ordinated and they were not necessarily any more physically disabled than any other group that were driving. They did not have the cognitive ability to work out the sequence of controls necessary to steer their wheelchair. Helpers tried to encourage children to be mobile and the children wanted to drive but could not.

Some helpers tried to help too much. They would push children in wheelchairs around when they did not need to. Staff would intervene and operate the drivers controls just to try to keep them safe while trying to give them a sense of mobility. For example, if a group of children were provided with switches, then at first they might drive straight into a wall or be a danger to others (and to themselves) because it took time to master starting, stopping and steering. This inspired new research to assist wheelchair drivers further. A question was, did children just need more practice at driving or was there something more fundamental in their development? (which could allow them to progress in such a way that they could become independent drivers). What was known was that children wanted to drive (and wanted to try to drive) but they needed specific (and a lot of) human help to enable them to become mobile or at least to have some experience of wheelchair driving.

The creation of the new assistive technology centred around a girl who was almost totally blind. Her hearing was good and she was intelligent but she was severely physically impaired. She could not use her hands to control a switch but she could use her chin. She could turn her head in the direction people were talking to her. She wanted to drive and staff were encouraging her but the wheelchair service would not provide her with a powered wheelchair because she could not drive unaided. A powered wheelchair was loaned to her. She would rest her arm on the joystick and go around in circles because that was the only thing she could safely do. Staff would hold her hands and she would go around in circles and at least feel the experience of starting and stopping. Occasionally she would spiral out and crash into things. She wanted to try to drive to specific places but she was reliant on helpers to guide her. A member of staff had said “it would be good if you could put her on some kind of railway line”. So that is what was done [Langner, (2002)] and that was the situation at the beginning of the research described in this dissertation.

The railway line concept allowed children to drive from one point to another without going astray. Children then became frustrated because the tracks did not go to all of the places where they wanted to go. The young girl driver wanted to go to other places besides just her classroom, toilet areas and the corridors where the track went. There we also other problems; even on a track she would crash or bump into things. This did not happen often because she had good hearing and could hear if someone was there, but she could not do that with inanimate objects.

5.3 Mechanical bumpers

Mechanical bumpers were investigated. This was more challenging than expected for a number of reasons. For example, if a strip bumper was placed around a wheelchair and it hit something, then it could impact heavily and crash. The motor power would be cut after the collision had occurred. When initial trials started with prototype strips, the energy was absorbed over a relatively small distance (a few millimetres) and children could drive into things, and although power was cut, the crash had already occurred. Part of the control system used for those earlier experiments included a latched system, in which if the bumper was touched, then it would cut the power. The power would stay cut until a member of staff reset the system and made sure that the object and the child were safe to proceed. A warning was needed to indicate to the child why the wheelchair had suddenly stopped so an audible warning device was added to give an indication of when an object had been struck.

The mechanical bumpers were subject to physical damage and they increased the physical length of the wheelchair because the bumper needed to protrude beyond the normal dimensions of a wheelchair in order to be effective. In addition, children were provided with trays on their wheelchairs and these could protrude beyond the bumper, which reduced the effectiveness of the bumper during collisions with walls (as the tray would make contact before the bumper). Extending the bumper increased driving difficulty because of the increased base size and there were problems with accidental operation of a bumper. The use of the mechanical bumpers established that it was necessary to give children warning of impending collisions. Bumpers were vulnerable to damage and were a hindrance when staff were transferring children in and out of their wheelchairs. Nonetheless, the bumpers proved that object detection provided help to wheelchair users.

Older and larger children had bigger seating systems, longer footrests, larger trays etc. The protection provided by the bumpers was compromised by overhanging equipment on the wheelchair. If a wall was struck ‘head-on’ then the tray or foot rest would make contact before the bumper. Extending the bumpers to overcome this caused problems with driving and functionality. The swing of the chair and the extended bumper was too large and door frames would often catch the bumper and un-necessary triggering would occur. It became clear that detection was required over a longer range to provide a warning for stopping the chair in a more controlled way.

An example of a more useful detection zone is shown in Figure 5.1. An advanced detection distance (ADD) would also provide greater scope for control of a wheelchair prior to any collision and so a proximity object detection system was considered.

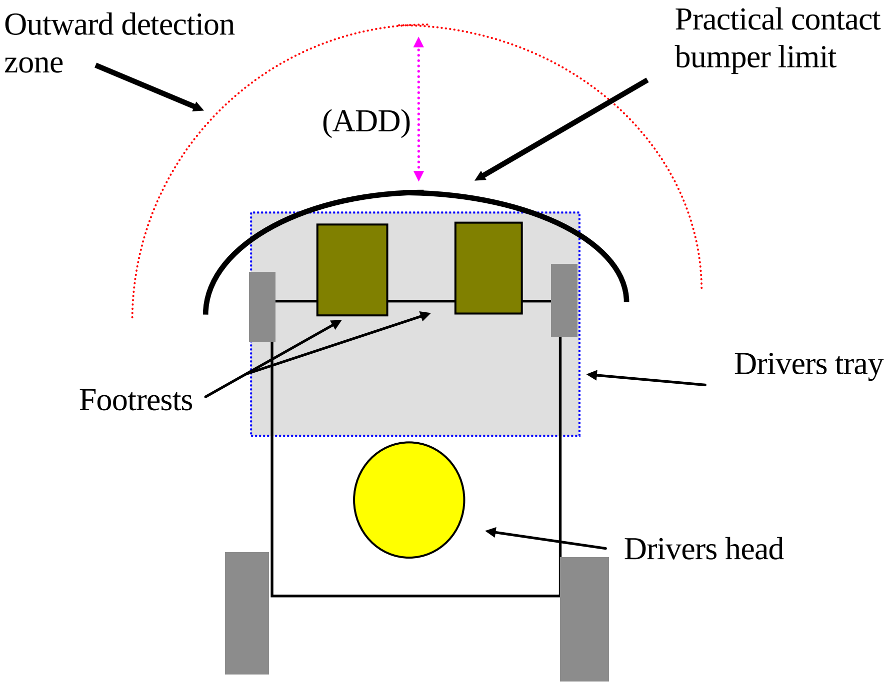


Figure 5.1 Simplified overhead view of a powered wheelchair and drivers head, showing a detection zone

5.4 Selection of the transducer

It was necessary to develop a better way of detecting objects. The advantages of proximity detection were:

- More useful object detection range
- Speed of detection
- Resolution (range information)
- Detection area / volume
- Cost
- Size and mounting of sensors

Cost and practical implementation were considered for different detectors and technologies. The main industrial methods for non contact detection were: ultrasonic, optical, laser range finding, infra red and vision systems.

Infra-red sensors were considered. They could use triangulation (where an object reflected the beam back to a sensor at a specified distance) but testing demonstrated that the colour of the reflecting object had an effect on how much reflective energy was returned. For example, a white object provided good reflection and could be detected at a greater distance than a dark object (a poor reflecting object). Infra-red beams were also narrow (they had a small cross sectional area) and background suppression was required. Testing suggested that several infrared beams would be needed to cover sufficient area at the front of the wheelchair.

There were also problems with multi path reflections from shiny objects (causing false detections). Most commercially available systems had background suppression but the retro reflective sensors were short-range and not suitable for object detection for a powered wheelchair. Vision systems were also considered, for example the auto focusing systems used by video cameras. They were capable of focusing on a specific target, but the active areas were small when compared to what was required for effective object detection and ranging in front of a powered wheelchair. Operation of the auto focus systems was slow and had unsuitable reaction times. To provide effective advanced warning of an object, a detection range of one to two metres was desirable.

Some systems were expensive (for example laser range finding) and others were potentially more complex (for example vision systems). Optical and ultra-sonic sensors were considered to be the most useful and their characteristics are presented in Table 5.1. Laser range finders and complex vision systems were not considered further due to cost restrictions. Experiments with optical and ultrasonic devices indicated that each had specific advantages and drawbacks and both could be affected by the nature of the object target. Optical target reflectivity and colour affected the optical sensing characteristics.

This could be further affected by the cross sectional area of the target object. Ultra-sonic detection was affected by target angle as most of the sound energy could be reflected away from the source (specula reflection).

Optical	**Ultrasonic**
Retro reflective	Pulse –echo sampling
Beam triangulation	Single transducer (transceiver)
Laser range finding	Two separate transducers (Tx / Rx)
Time of flight	Time of flight

Table 5.1 Characteristics of optical and ultra-sonic sensors

Object sound reflectivity also had an effect. Hard objects generally reflected well but softer objects tended to absorb some (or all) sound and hence provided a weak reflection. It was possible to purchase ready made systems for object detection. For example:

- Ultrasonic movement burglar alarms
- Car bumper reversing alarms
- General robotics sensors with multiple units
- Break beam intruder alarms
- Retro reflective optical detectors
- Laser scanners
- Camera automatic focusing systems

Many of the available optical systems tended to have a narrow field of view (thin beam). Many of the industrial retro-reflective systems were not true background suppressed systems (background suppression implies a focused triangulation method where a target at a specific set range can be detected). Many of the optical sensors using triangulation were operated within a range in tens of millimetres, their primary application being positional feedback control within servo controlled systems. Automatic optical focusing systems on cameras were slow to operate and tended to have a narrow field of view. The ultrasonic focusing systems used on Polaroid instant cameras ranged an object at the speed of sound + processing, but they still had a comparatively narrow field of view (approx.15 degrees). The effective object sensing range was suitable though; between 0.2 - 10 metres. Polaroid ultra sonic sensors were selected for further experimentation. They were affordable and generally could detect most objects in the environment.

Multi-element ultrasonic sensing systems were used for the (University of Edinburgh SMART Wheelchair). These consisted of six separate sensors mounted around the front of the wheelchair. These could demonstrably detect objects, but the system was structurally complex and had notable gaps in the detection area.

5.5 A prototype ultrasonic detection system

Ultrasonic sensors were cheap and during testing they provided adequate performance using time of flight measurements. Ultrasonic tape measures and focusing systems for cameras were accurate for the task. Ultrasonic methods were less complex than optical methods but when detecting some objects then problems occurred with specula reflection. The angle of the detected object affected detection. Polaroid produced transducers and the associated electronic driver electronics as a package. A prototype system was created that interfaced to the Polaroid system. It fired sound pulses and listened for target echoes. It was found that the system was capable of detecting pencil size objects at ranges of 1-2 metres and this was sufficient for the SCAD application. A problem was that the transducer dispersion angle (beam width) was approximately 15° and this was not enough to cover the area required for the wheelchair.

An object detection assessment was conducted within the intended environment, (Chailey Heritage School) specifically to determine the number and type of objects that could be detected at either wheelchair tray or footrest height. A single transducer was placed on a wheelchair. The wheelchair was then pushed around the school including the same areas in which the children would drive. Objects that could be detected were walls, objects protruding from walls, doorframes, other wheelchairs, bags, people and objects on the ground for example shoes and toys. Some objects did not always show an edge, sometimes causing unreliable detection including clothing. Some soft fabrics did not reflect sufficient sound to be detected reliably. The assessment indicated that approximately that 70% of these objects were detected at wheelchair tray height compared to 90% at footrest height. This increase was due to detecting a majority of objects at ground level.

Consideration was given to how children drove their wheelchairs. There were requirements for special seating systems that needed to be placed in and out of wheelchairs, perhaps many times daily, particularly when a child needed to use the toilet or to have therapy sessions. It was important that the transducer system did not get in the way or get damaged at those times. When mounted onto the tray structure, the system needed be removable and releasable cables and connectors were necessary. As a result the systems became vulnerable to misalignment.

The transducer was placed under the footrests so that objects at low level could be detected, for example curbs, shoes or low lying objects (small children and animals). The detector was securely fixed to the wheelchair frame (including connections). In this position, curb edges and wooden borders could also be detected. Roadways were created where necessary using simple detectable objects (for example, plastic cups). There were issues about not being able to detect objects due to the narrow vertical width of the scan when compared to width of the lateral scan. Overhangs from shelves, table tops and voids under tables could not be reliably detected. An experiment was conducted with a transducer looking upward. Specula reflection problems (due to the angle of the sound beam) prevented reliable detection and a vertical scanning system was not developed further. In later work there were problems with a child driving under tables and an experiment was conducted using an optical background suppressed sensor mounted between the footrest looking up at an angle of approx 45º in front of the wheelchair.

This provided useful single point detection for flat overhanging objects as the infrared beam was less affected by specula reflection because more detectable energy was reflected back to the sensor. There was a problem with the commercial optical object sensor device as this used a modulated infrared beam to provide immunity from environmental light interference. This operated on a similar frequency to the high frequency fluorescent lighting used in the building and because the sensor was looking upwards, then the wheelchair would often stop when under a fluorescent light.

The general detection of objects with the ultrasonic system was affected by specula reflection. The transducer could detect objects with a small cross-sectional area (for example a pencil when in a vertical position). An object placed at an angle may not be detected. Walking the wheelchair test system around the school provided valuable information about the type of objects that were detected and the nature of those that were not. There were notable problems with sloping objects (for example chair legs, especially when they sloped away from the detector). Most vertical (or near vertical) structures could be reliably detected. In fact, there were occasions when specula reflection was an advantage, particularly when the gradient changed when driving up a ramp. In those cases the ground was not detected at the point of transition between flat to sloping ground.

The horizontal width detection was too narrow to be of practical use with a single transducer. Multiple transducer arrays were considered to extend the area covered but there could still be gaps in the detection field. Several transducer elements would be required to reduce gaps and accordingly the whole transducer would become large. It was a concern that a system with many separate sensing elements would be vulnerable to damage and misalignment. Therefore was desirable to develop a cheaper, simpler and more compact system that would not significantly add to the wheelchair structure.

Placing the transducer onto a motor solved two problems. Firstly, only one sensor was needed so that it was not necessary to try to match the characteristics of separate transducers and secondly a single transducer and motor was compact and could therefore be mounted more discreetly onto a wheelchair. Firing sound pulses at intervals of rotation provided a potentially flexible way of creating detection zones. The choice of motor was significant though.

Two methods were considered for pulse echo sampling, firstly, the motor continuously rotated and pulses were sampled on the fly and, secondly, the motor starting and stopping at each sample zone. The first option required a rotary connection between the transducer and stationary electronics. Testing showed that taking a pulse echo sample when the transducer was moving smudged the transducer polar response and meant that it was not facing the same point when receiving an object echo. The second option (making the motor stop at each pulse echo sample zone) required a stepper motor for starting and stopping because it rotated in precise steps. A DC type motor required additional positional (and possibly velocity) feedback and continuous start-stops would need high starting and stopping currents to provide sufficient acceleration and deceleration between the sample zones and scan end points. This would have reduced the life of the motor brushes. Conversely, stepper motors required drive electronics and provided phase sequence switching to stimulate rotation.

The use of reciprocation motion or continuous rotation were considered. Coupling the transducer to the electronics for continuous rotation proved difficult with the prototypes. Two methods were considered: using a slip ring and an inductive connection. A slip ring was subject to wear and noise whilst inductive coupling required additional drive electronics (which altered the matching characteristics between the Polaroid ranging electronic interface and the transducer). In view of these considerations it was decided to use a reciprocating transducer scanning motion. The transducer could then be simply connected by a pair of thin wires. There were problems with wire fatigue (and the wires would break). This became the subject of some later work to develop an improved method of transducer wire connection.

A 15º per step motor was selected to obtain the closest match between the step angle and the transducer dispersion angle. An optical method was used to define the end points of the scan. A small disc was made from ABS plastic and fitted to the motor shaft. The underside of the disc was painted matt black. The top of the disc formed a mounting platform and the transducer was bonded to this with adhesive. The scan end points were identified with white marks painted on the black disc surface. Two small retro-reflective optical sensors were mounted on a purpose designed and built PCB that fitted between the top of the stepper motor and the underside of the disc. Control electronics were created to drive the stepper motor so that when the disc rotated the end point marker was detected and that triggered the motor to change direction. The step pulses were counted and the change of rotation was determined by a pre-set count value at the scan end point. The second optical position sensor acted as a guard, the position of the transducer was not initially at the start 'reset' point. This ensured that the transducer would not fully rotate when switched on, as a full rotation could damage the transducer connecting wires.

Using a stepper motor to rotate the transducer proved that scanning was a compact viable alternative to a multiple-transducer array. That next issue was to decide the rate of pulse echo sampling. Initially there were problems with false echoes from previously sent pulses being detected (causing ghost detection) from by multi-path echoes. The Polaroid ranging electronics was primarily designed for single shot ranging up to 10 metres. This was in excess of what was necessary for the wheelchair object sensing application (particularly when sending repeated pulse streams). The transmit power was reduced by placing a resistor between the pulse transformer and drive transistor. The energy of multi-path returning pulses was reduced and made the system usable within internal environments. Ghosting problems were reduced but not eliminated. In addition it was noted that increasing the frequency of the pulse echo sampling also increased the ghost problems.

The first scanning experiments were at low speed (approximately 20 Hz) and a complete scan cycle was completed in one second. It was desirable to increase the sample rate as the wheelchair moved less distance between samples and provided earlier detection of an object. This became the subject of some later work.

5.6 A first ultrasonic scanning collision avoidance device (SCAD)

The collision avoidance device needed to meet the following considerations:

- Compact physical size
- Wide angle (field) of view
- Gap-less detection zone
- Fast update (sample) time
- Simplified engineering construction
- Discretely mountable (not affecting general wheelchair engineering)

Polaroid ultrasonic sensors were selected. These were supplied with a single transceiver (transducer) and front-end electronic interface circuit board. A single transducer had a typical angle of dispersion of 12° or 15° depending on type.

In order to detect the presence of an object, the transducer operated as a transmitter and receiver (transceiver). A sound pulse was transmitted, a reflecting object in the path of the sound returned a sound echo. The time of flight between the transmit pulse and the received echo provided a measure of distance. Atmospheric conditions also affected the propagation of sound in air but this had little notable practical effect over the detection range of the SCAD system.

The following are considered:
a) Transmitting
b) Receiving
c) Receiving sensitivity (gain)

a) Transmitting. The transducer transmitted a burst of short sound pulses having a frequency of 50Khz, (this was the typical resonant frequency of a transducer). The resulting wave front dispersed at an angle of (12° or 15°) depending on the transducer type. An object in the path of the signal reflected a small portion back to the transducer. The amount of reflected energy was governed by the nature of the object's reflecting surface and the angle of incidence that the object was with respect to the transmitted sound (specula reflection). The time taken for sound to travel one metre in air at normal seasonal temperatures was generally 3.3 ms. The duration of the sound burst (pulse) was required to be as short as possible because the transducer needed to listen after transmission in order to detect objects at close range.

b) Receiving. The returning reflected pulses were detected by the same transducer that transmitted them. The return signals were of considerably smaller amplitude at the transducer diaphragm when compared with the transmitted pulse. For this reason the post transmission diaphragm pulse needed to be damped quickly so it was ready to receive the echo return pulses. After transmitting a pulse, a damping period of 1 ms was applied to mute the residual ringing tones in the transducer diaphragm. After this period the system switched to listening mode.

c) Receiving sensitivity (gain). The Polaroid circuit signal amplification interface compensated for the natural signal decay (proportional to the distance the sound travelled) by increasing the receiver gain in steps at specific time intervals after the transmit pulse. The system sensitivity was set with a gain pre-set. The signal detector consisted of a signal comparator with inputs from the amplified transducer received pulse and reference level. This reference level determined the detection threshold for a valid receive-pulse. Usually this was set above the noise floor provided by a quiet environment with no discernable echoes.

How the reference level was set affected the system operation. A low reference setting caused the system to be ‘trigger happy’ and responded to the general environmental noise and spurious side lobe effects of the transducer. Latent return echoes caused problems, especially when the system was repeatedly sending out pulses when scanning the environment. A high reference setting desensitised the system which may not respond reliably to the object echoes. It was possible to compensate for this by increasing the transmit power. Other problems, (for example, increased signal scatter) and the effect on similar sensing systems operating nearby needed to be taken into account. Generally a mid-way point provided good performance and effectiveness for object detection. The ability to make these adjustments could be useful when fine tuning and optimising system operation. For the Polaroid ranging system to work, the circuit board had the following interface requirements:

- Transmit gating pulse (Init). This initiated a transmit sound pulse. This was repeated for the SCAD operation at 30Hz
- A blanking pulse (Blink). This was required for post transmitted ringing pulse damping, having a duration or (1m/s). This needed to be short in order for the system to start listening after the transmit event
- Receive output (Echo). This provided a logic level output and could be logically ‘&’ gated with a timing pulse having a value that equated to the wanted signal range

Due to the transmission of a continuous stream of pulses it was necessary to lower the transmit power of the system during experimentation. This reduced problems with the generation of spurious signals and ‘ghost object image’ problems. The Polaroid system was normally capable of ranging objects within a distance of 10 Metres. The range requirement for the SCAD was one Meter. This was relatively short range (considering the maximum range capability of ten meters for a typical transducer) and the transmitted power was reduced by placing a resistor in series with the pulse transformer on the Polaroid ranging circuit. This also lowered the general power levels in the transmit pulse transformer & associated electronics.

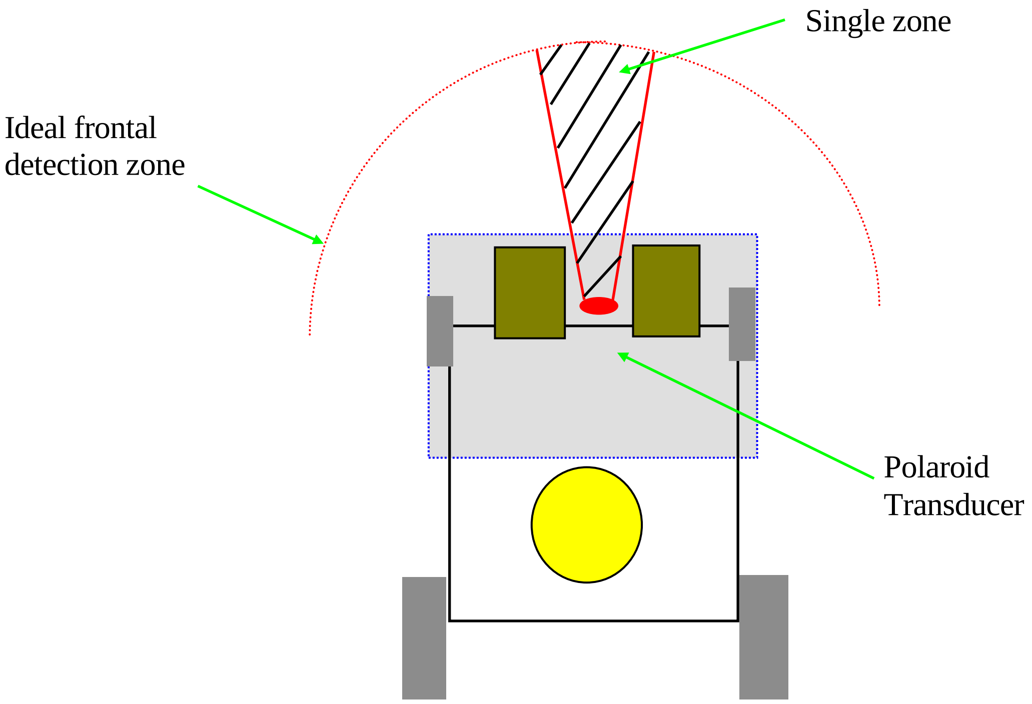


Figure 5.2 Single Polaroid transducer fitted to a powered wheelchair

Figure 5.2 shows a single sensor and its respective detection area in the line of travel of the wheelchair. The range could be set from 0.2 -10 metres. For general experiments the range was set typically to 0.4 - 1.0 Metres. The physical mounting place for the sensor was under the footrests.

An added benefit of the low mounting position was that it did not affect any of the special seating systems higher up on the wheelchair. The detection zone was only a small part of the overall coverage needed. Experimenting with the ultrasonic detection of objects determined a number of important conditions that needed to be respected in order to obtain an understanding of operational effectiveness.

Although factors such as object surface (sound absorption) and area affected the received echo, other conditions (for example object-shape) were also significant. A hard reflecting surface provided a strong reflection if this was perpendicular to the source direction.

It was found that a change of target angle could significantly affect the return signal.

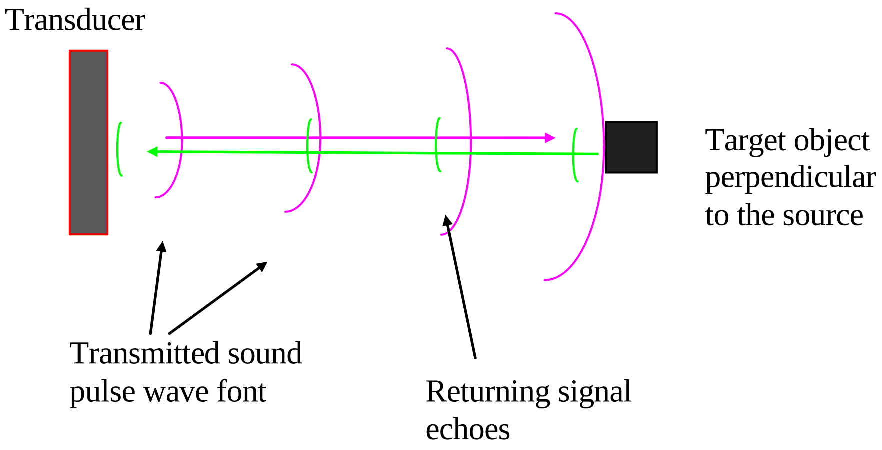


Figure 5.3 Strong target echo

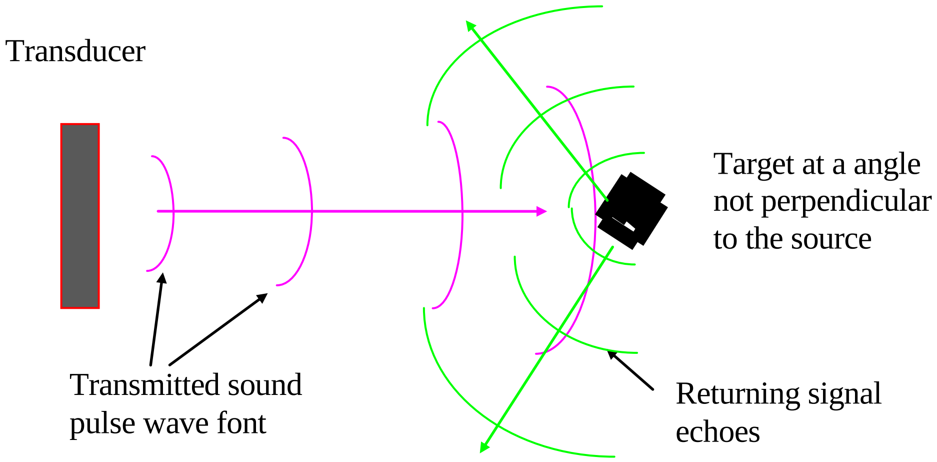


Figure 5.4 No detectable target echo

Figures 5.3 and 5.4 show that the respective angle of the object affected the received echo strength. Large reflecting targets such as walls or doors would not be detected if at an unfavourable angle. This was sometimes regarded as strange when small objects could be detected, for example pencils.

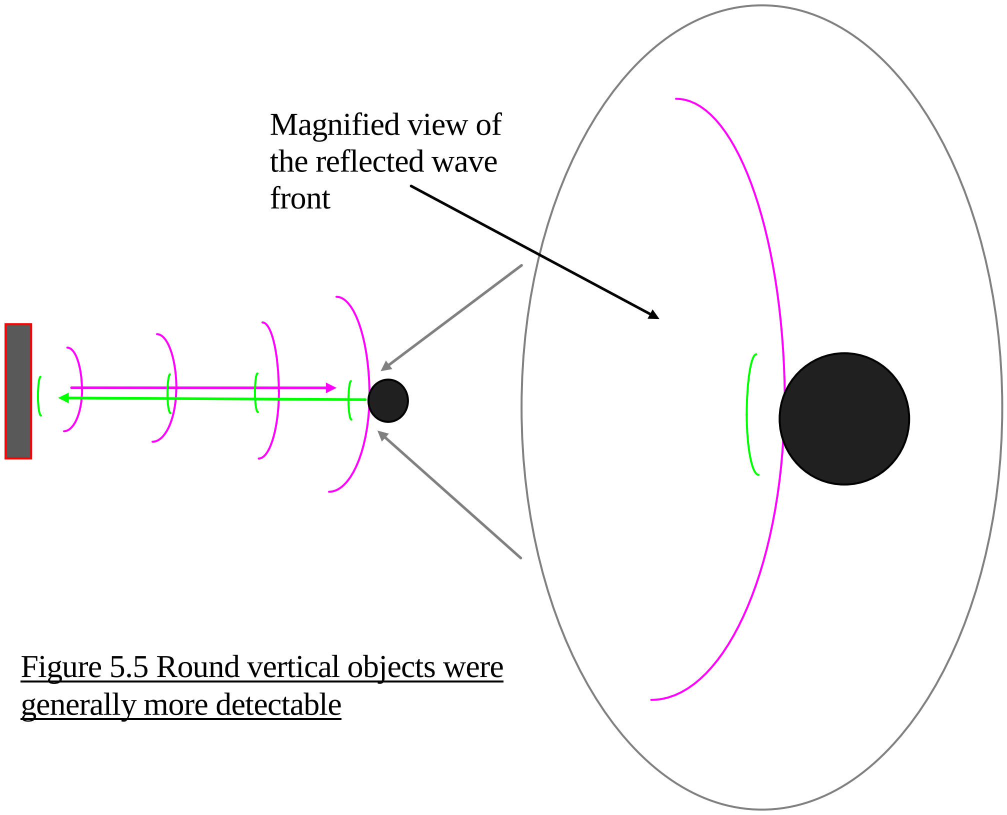


Figure 5.5 Round vertical objects were generally more detectable

The magnified view in Figure 5.5 shows that only a percentage of the transmitted pulse returned to the receiver. Objects with rounded corners could normally be detected. The radius had an effect on the return echo strength and that usually reduced with decreasing radius. A pencil (when stood vertically) could be easily detected, but when set at a slight angle towards or away from the transducer, then it became undetectable. So the early experiments indicated that an ultrasonic system would not be able to detect all of the objects in the environment because of their orientation and shape.

Using different transducer types working at higher frequencies was considered. Some other types were tested with disappointing results. On balance it was considered that the Polaroid transducer system provided convenient and acceptable levels of performance for the further development of SCAD. Some alternatives were more costly or awkward to use (due to transducer design and bulk). Some attempts were made to re-model the Polaroid transducer by reducing its size with smaller diaphragm diameters. This did not prove advantageous and the transducers were used as they were originally manufactured.

5.7 Further developments of SCAD

A wheelchair was tested with an ultrasonic detector on the front and that provided valuable information about the best mounting position and performance (how well it detected objects in real environments). Much time was spent in pushing wheelchair set-ups around laboratory and school to assess the ability to detect objects in the environment.

The next phase was to increase the horizontal detection area of the sensing system. A motor was used to rotate the sensor transducer to multiply the number of transducer response areas (referred to as 'Zones') from as single point. In principle each zone was a function of the motor rotation angle between pulse / echo samples. For gap-less object detection, the rotation angle was equal to, or less than, the dispersion angle of the transducer. This relationship determined the quality and quantity of possible dead spots in the large overall zone. The horizontal zone only was expanded. The vertical axis remained at (12° or 15°). Polaroid manufactured two basic types of ultrasonic transducer with different dispersion angles, as shown in Figure 5.6.

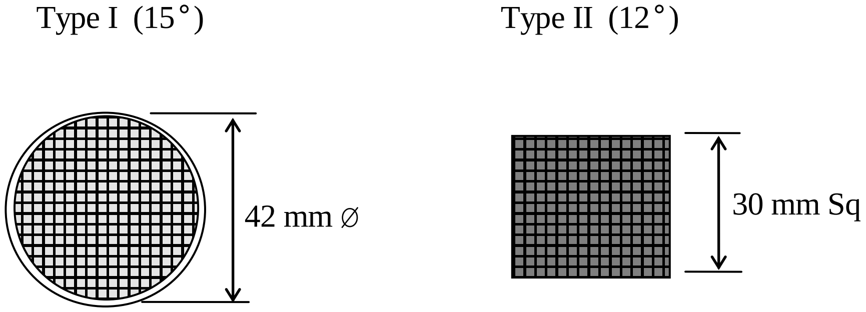


Figure 5.6 Transducer types

The specification for each type of transducer was similar, except for physical size. Experiments started with type II because it was smaller. As work progressed, type I was used in place of type II due to a greater sensitivity and improved polar performance. Although the horizontal axis was expanded, the type I transducer had a wider vertical acceptance than was the case with type II, and this was advantageous.

The angle of dispersion had a close relationship with the transducer movement angle between samples. Figure 5.7 and Figure 5.8 show the effect of this. In Figures 5.7

and 5.8 the dispersion angle of the transducer remained constant.

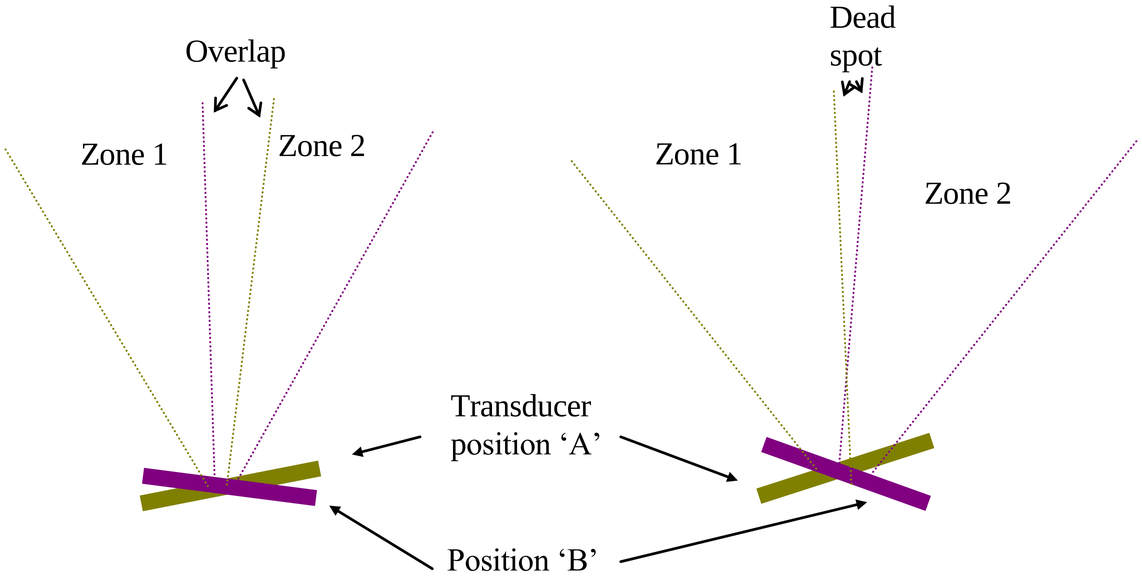


Figure 5.7 Transducer rotation (small)

Figure 5.8 Transducer rotation (large)

In Figure 5.7, the transducer was rotated less than the dispersion angle. It can be seen that an overlap occurred between the two zones. This overlap could be reduced or removed by rotating the motor more than the dispersion angle (as shown in Figure 6.8) but that could result in a dead spot between the two zones.

The rotation angle of the motor between samples was critical to the effectiveness and continuity of the object scan field. It was found that the sensitivity across the transducers resonance area cone was not uniform. The manufacture’s polar diagram response graph was of interest and is shown in Figure 5.9. The sensitivity reduced near the edges of the wanted transducer cone boundary (15°). A generous zone overlap was advantageous for improved uniformity of sensitivity within the object scan area.

Large overlaps resulted in an increased number of pulse / echo samplings (above what was necessary) for each sweep but that could slow down the effective scan rate of the system.

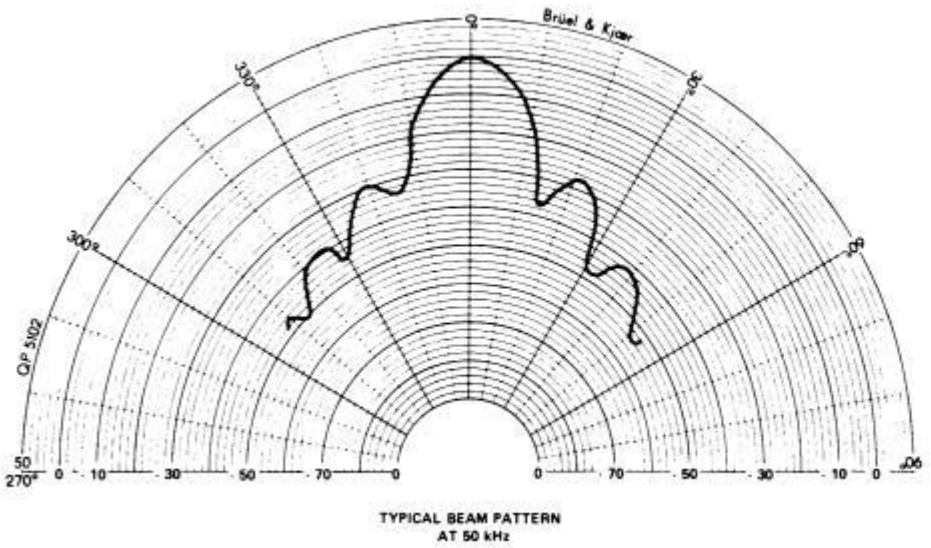


Figure 5.9 Polaroid 600 transducer polar response

The motor would rotate the transducer by the required amount for each pulse / echo sample. Using a type II (12°) transducer the rotation between pulses / echoes sampling should not be more 12°. Similarly, the type I (15°) transducer was not greater than 15°.

5.8 Considering continuous rotation

Considering a 12° transducer, the use of a direct current motor and incremental scanning was considered. The motor was required to start and stop at each 12° sector at which a pulse echo sample would occur. To control the rotation angle, an optical disc with 12° segments was needed on the motor spindle. The motor needed to accelerate and decelerate quickly and have a low inertia core to stop and start quickly for pulse echo sampling. Considering the angular movement of the transducer between the transmission of the sound pulse and the detection of an echo, this affected the boundaries (over / under-lap) between the object detection sectors. The motion of the scan needed to be decided for further development of the system and initially this was based on a sweep detection angle of approximately 90°.

The motor continually rotated the transducer whilst the sonic pulse / echo samples were being taken. The angular movement position was achieved using optical markers on the motor shaft. The markers related to the dispersion characteristics of the transducer to provide gap free detection. With a single transducer sweeping the detection angle of 90°, there was a wrap around delay resulting from the time to rotate the transducer the remaining 270° to the scan start position. The use of two transducers back to back was considered in order to reduce this time but that required electrical coupling and switching (either in the form of slip rings or inductive coupling to the moving transducer).

The transducer operated in two ways, as a (Tx) transmitter and (Rx) receiver. In order to transmit a sound pulse the transducers were excited with a short burst of pulses. The ultrasonic sound chirp was generated from 16 needle pulses that resonated the transducer diaphragm. This developed an electrostatic potential of 200-400 volts within the transducer. To receive a return echo the transducer became a sensitive electrostatic microphone. This generated a low level signal which was subsequently amplified. The dynamic range of the coupling medium had to be large enough to work in both modes. The following were considered:

a) Slip rings
b) Inductive coupling
c) Reciprocal scanning

a) Slip rings. Anticipated problems associated with slip rings included electrical noise and mechanical wear. Each transducer needed to be switched in and out at the appropriate part of rotation at the scan start and stop points.

b) Inductive coupling. This would involve specific development which detracted from the physical development of the scanner in its own right, particularly in view of the demanding electrical requirements of the transducer. It should be noted that the associated Polaroid ranging circuit board was designed to be connected directly to a transducer. The two components, transducer and ranging circuit, were designed to match their respective electrical characteristics. The interposition of any different coupling mediums may have caused problems (mis-matching) resulting in poor detection performance.

c) Reciprocal scanning. The problem with transducer coupling could be avoided by using a pair of flexible wires to connect the transducer directly to the ranging board. The scan motion would not rotate by more than approx. 90°. The transducer swept the wanted detection area by a repeating (left to right) then (right to left) motion. The corresponding scan angle was therefore (0° - 90°) and vice - versa.

5.9 Using a stepper motor

A stepper motor was selected to incrementally move the transducer between pulse / echo samples. The stepper motor had specific rotational step angles, depending on type. The control requirements for a stepper were different from those of a d.c. motor. The type of stepper motor used for the SCAD was a four phase type. The phase sequence was controlled by a stepper driver control integrated circuit (i/c). A specific phase sequence was generated by this i/c which had internal power driver transistors to apply current to the motor coils.

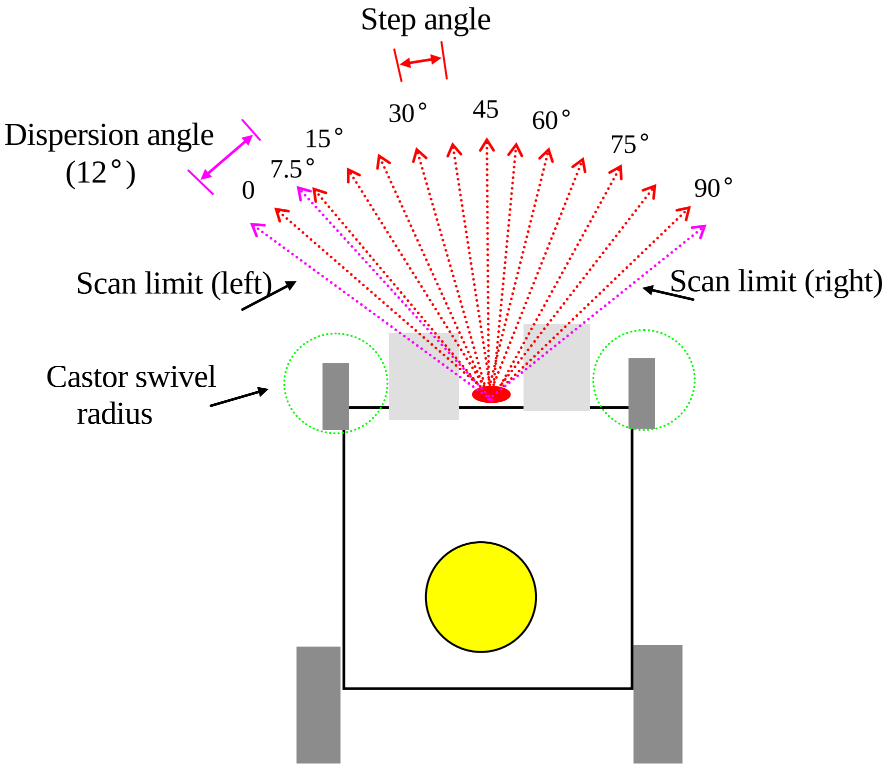


Figure 5.10 SCAD head position. Using 7.5° step angle motor. 12° dispersion angle transducer

To control the stepper motor, the driver chip required a step pulse that caused the motor to move by its step angle. The rotational direction was determined by a direction input on the driver i/c. For SCAD, the use of a stepper motor was particularly suitable. It was stepped, and a pulse / echo sample taken. It was then stepped again for the next sample. The step angle of the motor was fixed (depending on type). The first experimental SCAD system used a 12° transducer coupled to a 7.5° stepper motor. The best position for mounting the sensor appeared to be between the front castors of a wheelchair. The obscuring effect of the castors was taken into account.

Figure 5.10 shows a typical mounting position of the SCAD sensor with the scan limits imposed by the wheelchair. Initial experiments proved that it was possible to detect objects uniformly within the scan field without notable gaps. There was considerable overlap between each sector as shown in Figure 5.10. This proved to be detrimental to the object detect update time which needed to be improved. The scan update time was slow and the overlap needed to be reduced between sectors. A stepper motor with a step angle 15° was obtained and used in place of the previous 7.5°/step motor. There was a close match between the (15°) step angle and the 'type I' (15°) dispersion angle transducer.

The sweep time and number of steps per sweep was half of the previous value. Furthermore, if the number of steps per sweep was reduced, as shown in Figure 6.11, then a total area of 90° could be swept with a transducer rotation angle of 75°.

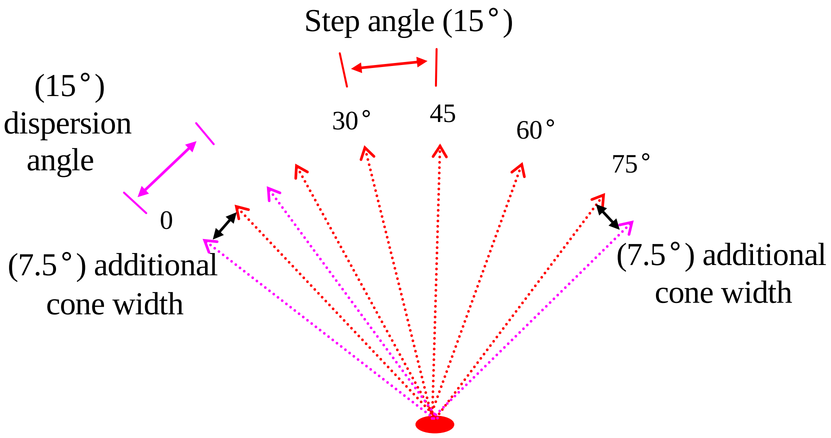


Figure 5.11 Scan sweep diagram

It was beneficial to scan the detection area quickly so that objects could be detected in the shortest possible time. There were two apparent delays: time of flight delay and scan target delay. Sound propagation in air is generally 0.3 Meters / ms. The distance of a detectable object from the transducer was determined by measuring the time between the transmission of the sound pulse and the time taken for the reception of the echo. The time allowed was for the round trip (there and back) from the object. For example the time taken for sound to travel one metre is 3.33 ms. This was doubled due to the return journey, therefore the total time required for ranging the object was 6.66 ms. The scanning motion required a finite amount of time to move between pulse echo samples. This took account of the time of flight delay and the mechanical movement constraints of the system.

The time taken for the detection of an object within the scan field was dependent on its position relative to the scan motion. The detection time for an object appearing within the wanted detection distance varied depending on which part of the scan cycle the object first appeared. The worst case (longest detect time) between updates was for the complete sweep cycle time. The shortest time was between adjacent sample sectors 15°. The sweep cycle time was therefore:

pulse sample time frequency (50ms) x number of sectors (12) = 600ms per sweep

Figure 5.12 shows a complete reciprocal scan cycle (sweep). The blue & red direction arrows indicate the cycle movement direction (one way and then the other).

The overall worst case detection delay was derived from:
Maximum detection delay = sweep cycle time + time of flight delay for a set object range.

Knowing this delay was a factor in determining the effective detection range for a moving wheelchair. If the detection response was slow compared to the vehicle speed then the object detection warning was too late. This could be compensated by increasing the range of detection (to look further ahead), but that caused problems with the unwanted detection of objects at the side of the wheelchair.

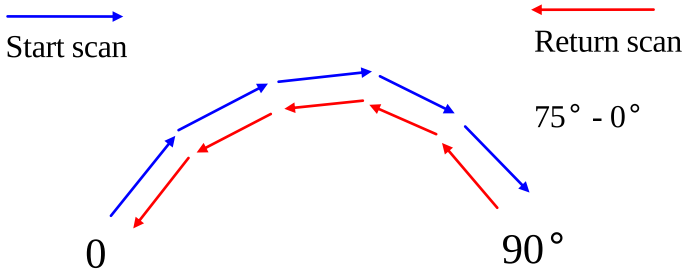


Figure 5.12 Scan motion (reciprocal scan)

For test purposes a prototype SCAD system was created in which the scan range / characteristics could be profiled. The usual scan shape was symmetrical and semi-circular. To provide increased advance warning in the forward direction of travel, the scan profile was made ‘bullet shaped’. This extended the forward range without affecting or increasing the sides of the scan profile.

Experiments started with pulse (sampling) frequencies of 25Hz. The motor was stepped and a pulse was sent as shown in Figure 5.13. The transducer was used as a receiver when it was switched to listening mode soon after transmission had occurred. The cycle in Figure 12 was repeated for the complete horizontal sweep cycle.

(1st) Transmit ultra-sonic sound pulse (chirp < 0.1 ms) frequency 25 Hz (50 ms)
(2nd) Receive return pulses from object (@ Range 0.5M Approx) 3.3 ms (Apprx)
(3rd) Rotate transducer into new sector (approx 20 ms)
(4th) Halt transducer rotation for stable position (approx time to next Tx 24-26 ms)

Each of the sample events was repeated at multiples governed by the number of sectors involved for a complete sweep. In this case it was 10 stepped sectors for a complete reciprocal sweep. The worst case update time for 10 sectors / 50ms (sample time) was 0.20 seconds. The detection time for an object within the sweep area could be 33 ms up to 500 ms. The detection time would be (on average) in the order of, (500 + 33) / 2 = 270 ms (0.27 seconds).

During this phase of the SCAD development, certain effects (anomalies) were observed.

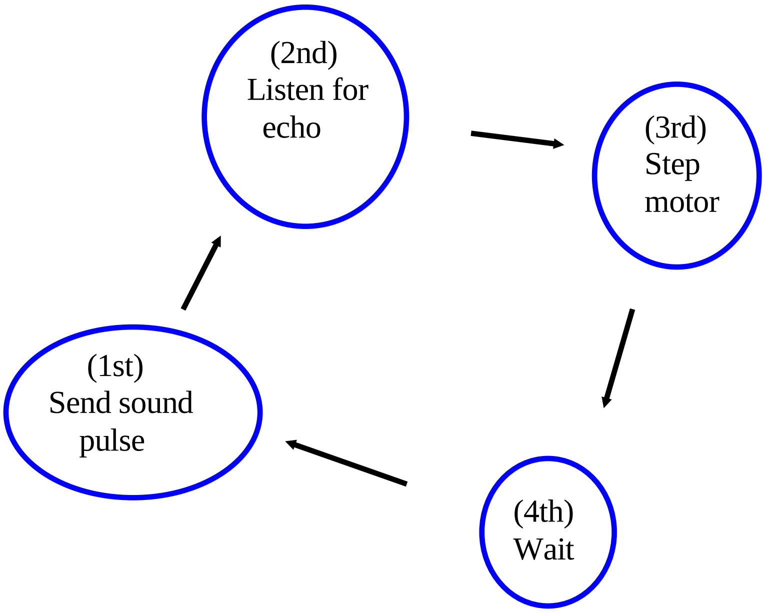


Figure 5.13 Ultra-sonic pulse / echo sample event sequence within one sector (object sampling)

An example was ‘ghost echoes’ where objects at certain multiples of the target range detection distance caused false detections. This worsened when the frequency of sampling increased. A balance was struck between the sampling frequency and the occurrence of ghost problems. This was a factor in the determination of the 25Hz sampling period. This was mid way between acceptable update performance and false detection problems.

Scan acquisition time was slow and improvements in the speed of object detection were necessary. The width of lateral detection also became the subject of improvement. Starting with 90°, then being widened to 150°, and eventually to 180° at the time of writing. The development of a wider angle (180°) and faster scanning SCAD was necessary to reduce the detection time. SCAD research continued to reduce the “ghost” problems and other experiments consisted of scan profiling and automatic range conditioning. Further experimental work involved the development of stereo sound object staging. Sound tones were generated and modulated to convey a sense of object distance and position across the SCAD detection zones. Assessment modes of operation were incorporated to increase the flexibility of the system for use with a variety of users. Following the assessment of the systems, more children began driving with SCAD support in preference to using track guidance.

The intended application for the first SCAD system was a warning system to take the place of a mechanical bumper; the drivers at the time of writing had particular visual (and other complex sensory) problems. Mechanical bumpers had been used and the drivers had become frustrated with hitting objects and then receiving a warning after the event. Young drivers much preferred to have an advanced warning so that they could exercise their own control. One particular driver could stop driving when told to do so, and therefore was an excellent candidate for trials with a SCAD. She had good hearing and a sensory feel for her environment. It was decided that the SCAD should not cut the drive power when objects were detected, but instead produce a quiet chirp sound indicating an object had been detected. This put her more in control of the system. It was noted that if a lockout power drive cut-off system was used then there could be problems with track guidance through doorways.

The detection of door frames would stop the chair, particularly when exiting the bend in a track. The use of sound warnings only indicated a door frame, but there would be no unwanted system intervention. It was hoped that drivers would learn to interpret the small differences in the sound warnings, particularly through doorways. The nature of the scan pattern provided a subtle clue as to where an object was within the sweep cycle. The ranging circuit provided a short pulse when a single object was detected. This pulse was stretched and used to operate a sound beeper. This produced a 'chirp' type of sound, particularly when gated at the 25Hz sampling rate. The 'chirp' varied depending on the position and number of sectors the object occupied.

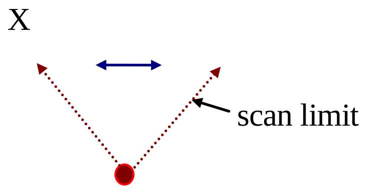


Figure 5.14 Single detected object 'X' off centre

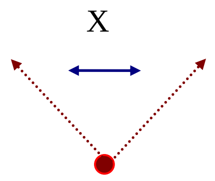


Figure 5.15 Single detected object 'X' at centre

In Figures 5.14 and 5.15, the position of the object affected the mark-space ratio of the beep tones. Figure 5.14.shows a single repeating beep at a frequency related to the complete sweep cycle period. Figure 5.15 represents a double beep. The object was detected on each half completed sweep twice. There was no distinction between left or right object position or object distance. It was possible to judge a doorway by the sound signature. Larger objects occupying more than one sector produced ‘chirp’ sounds as successive beeps repeating at 25Hz. in bursts. No particular emphasis was placed on the young driver in terms of training and understanding the differences of the sound beeps. This was an effect that was noted as a by-product of the scanning technique. Some blind users were intuitive and would often stop inches before a track junction even without hearing the chirping SCAD. They appeared to be able to sense when people were around and to extract information from the sounds in the environment, for example familiar sounds and voices.

So the SCAD was really supplementary for some blind powered wheelchair users, but it would give warning if something appeared unexpectedly. A power cut-off system was not developed for some of those users because they responded well to the warning sound and the SCAD would have problems with spurious detection (which could have stopped them unnecessarily).

There were still a lot of children with mechanical bumpers on their wheelchairs whilst some children were moved onto the prototype SCAD systems. To some extent the mechanical bumpers were becoming a liability because of their vulnerability and a lack of effectiveness (especially in not providing advanced warning). In order to be used by everybody, the prototype SCAD systems needed to change from being an audible warning system to a power cut-off system; mainly because the children with mechanical bumpers could not be relied upon to stop when they heard a sound warning. The focus of new research became contact-less object sensing, especially as it became “un-cool” to have a mechanical bumper on your wheelchair. The SCAD system needed modifications to operate in a power cut-off mode, but there were a number of issues to be addressed concerning false ‘ghost’ object detection and slow response time.

The essential requirements of the SCAD detector head were to be compact and simple. Figure 6.16 was captured from a video sequence showing the prototype SCAD sensor head mounted on a track following wheelchair. The mounting position was clear of detecting the foot-rests, so the sensor had a clear sweep in the front (line of travel of the chair). Figure 5.17.is a diagram of the prototype SCAD assembly.

This used a 15° stepper motor and 15° dispersion angle Polaroid Transducer. This transducer although slightly larger than the 12° version offered improved performance, particularly in sensitivity and uniformity of response over its sensing area.

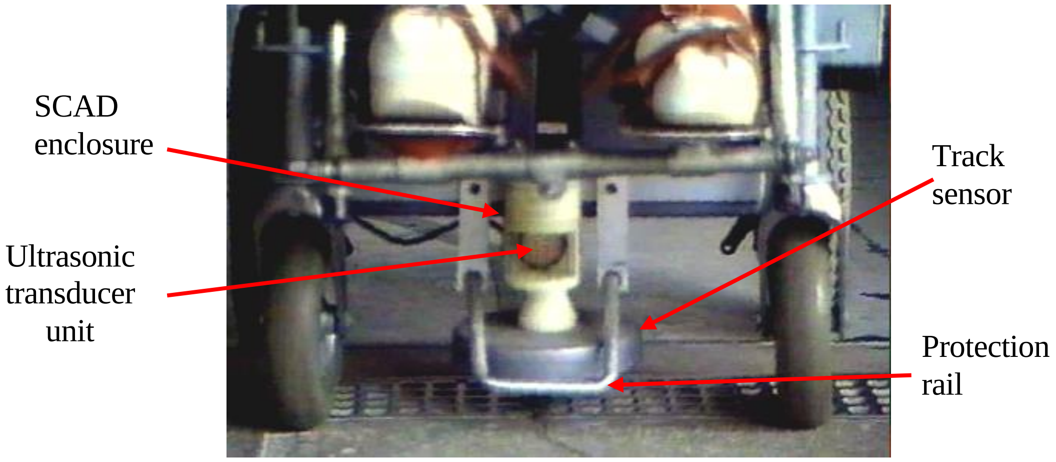


Figure 5.16 SCAD sensor head mounted on an 'Apollo' Wheelchair

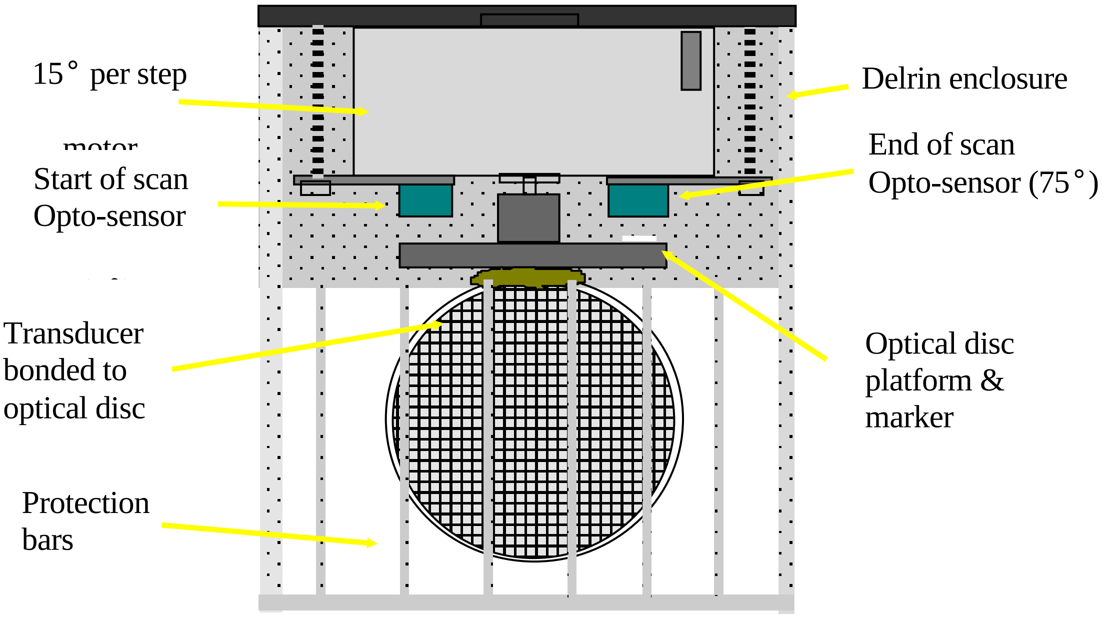
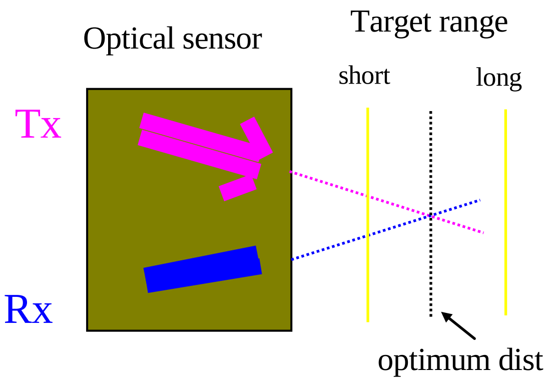


Figure 5.17 Prototype SCAD assembly and enclosure

The main elements within the enclosure are shown in Figure 5.17, including the stepper motor and transducer units. The scan start and stop positions were identified by an optical sensor and associated disc. The optical disc formed part of the transducer mounting former. This was made from ABS plastic by machining it to the required shape and dimensions by using a lathe. A small retro-reflective optical sensor was mounted on the motor body to detect a white marker placed on the disc. To provide sufficient contrast for reliable detection the disc was painted matt black and white Tippex whitener was used for marking. Two optical sensors were used to sense the starting (0°) position and a second sensor for the (75°) end of scan point. The relative positions of the optical sensors could be changed to help in the setting of the scan parameters. The optical disc provided two functions. Firstly, it was a mounting platform onto which the transducer was bonded and, secondly, providing positional markers for the scan rotation limits. To sense the position of the disc, two retro-reflective sensors were used. These were standard compact units that embodied an infra-red Tx (LED) and infra-red photo transistor Rx.



The general operating range varied between 1-4 mm.
White or silver coated makers on matt black backgrounds were be used

Figure 5.18 Retro-reflective sensor

In Figure 5.18, the optimum working point is shown at the convergence of the IR light beams. The contrast between the marker and the black disc background needed to be high for reliable pickup. The photo diode current increased when exposed to the reflected infra-red light from the white marker on the disc.

With reference to the circuit shown in Figure 5.19, the current flowing in R3 increased with a corresponding increase of light falling upon it. This occurred when the white maker reflected the light from the Tx LED. The switching threshold was determined by the CMOS ('&' gate) which had two resistors setting the amount of positive feedback for the system. The positive feedback provided a clean switching action at the transition point (light / dark boundary). The ratio between R1 & R2 set the margin between light and dark switching levels. This was important due to the contrast ratio between the white marker and black background of the optical disc.

Photo detector & output signal switching

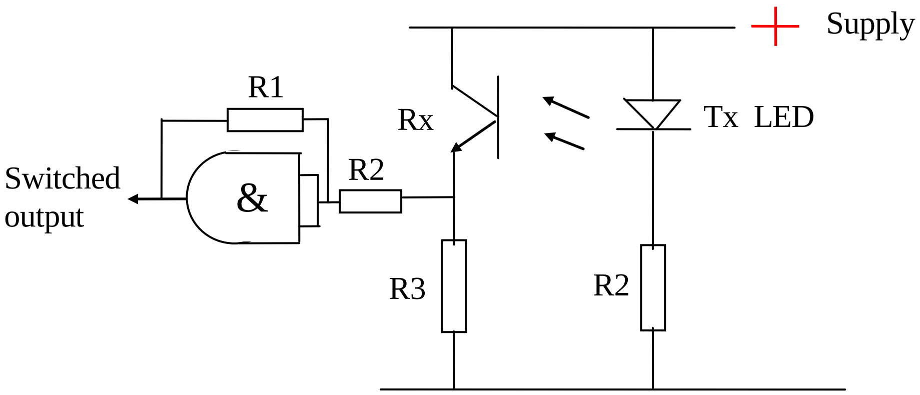


Figure 5.19 The test circuit used with an optical (photo transistor) sensor

To protect the delicate transducer connection cable, mechanical limit stops were placed at slightly beyond the normal rotational movement. These are shown in Figure 5.20. To control the rotation direction of the stepper motor, the stepper driver integrated circuit direction control line needed to be toggled. The (SA1027) IC stepped the motor clockwise (CW) with the control line low and counter clockwise (CCW) when high.

To facilitate the reciprocating motion between the 0° - 75° positions a set / re-set latch circuit was used. Table 5.2 shows the conditions possible for start up and normal running.

Disc marker position	**Motor rotation direction**	**Latch state**
Sensor ‘A’ (white)	CW	Re-set
Sensor ‘B (white)	CCW	Set
Between ‘A’ or ‘B’ (dark)	CCW	Set

Table 5.2 Possible conditions for start up and normal running

A latching circuit controlled the bi-directional action of the stepper motor. The values of the resistors were derived through a process of optimisation and were selected to provide stable working conditions. When the system was first switched on, the position of the disc could be anywhere between the two optical sensors.

The latch controlled the direction of the motor initially (CCW) towards the reset 0° position. At this point the direction changed to (CW), until when at sensor B, when the direction changed to (CCW) on a repeating basis.

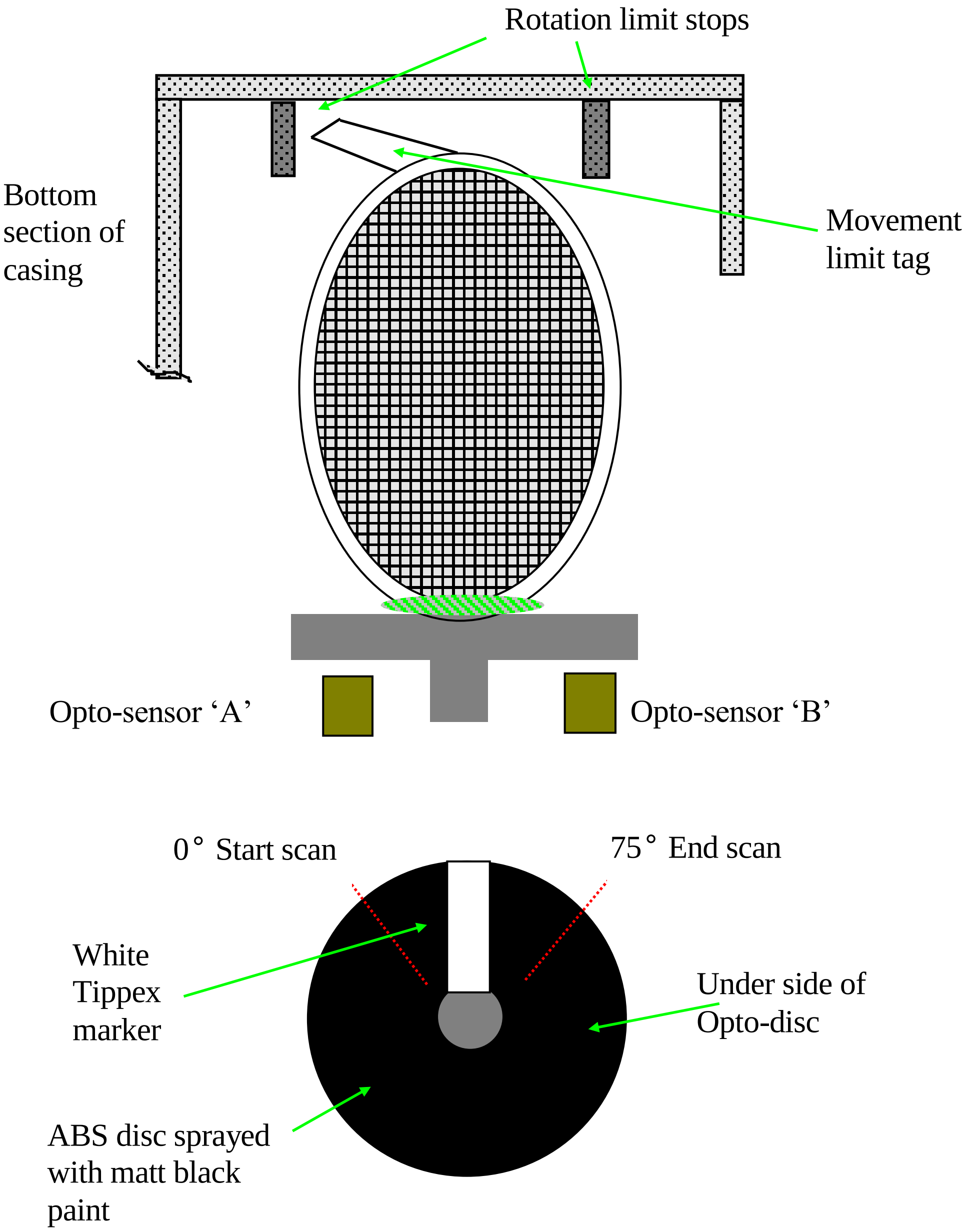


Figure 5.20 Optical disc and sensor assembly

With reference to Figure 5.21, when the white marker was between the optical sensors then ‘1’ was low and point ‘2’ was high. The corresponding output of the ‘&’ gate ‘3’ was low = (CCW) direction. When the white marker reached optical sensor ‘A’ point ‘1’ became high due to the increased current flowing in the photo transistor.

Component values.

R1 = 6K8 Rf = 6K8 R2 = 22K R3 = 82R (LED current limiting)

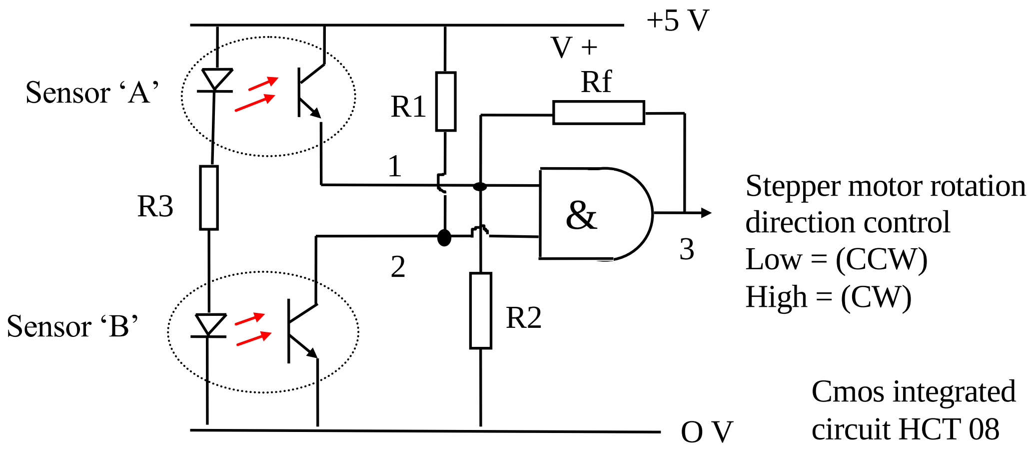
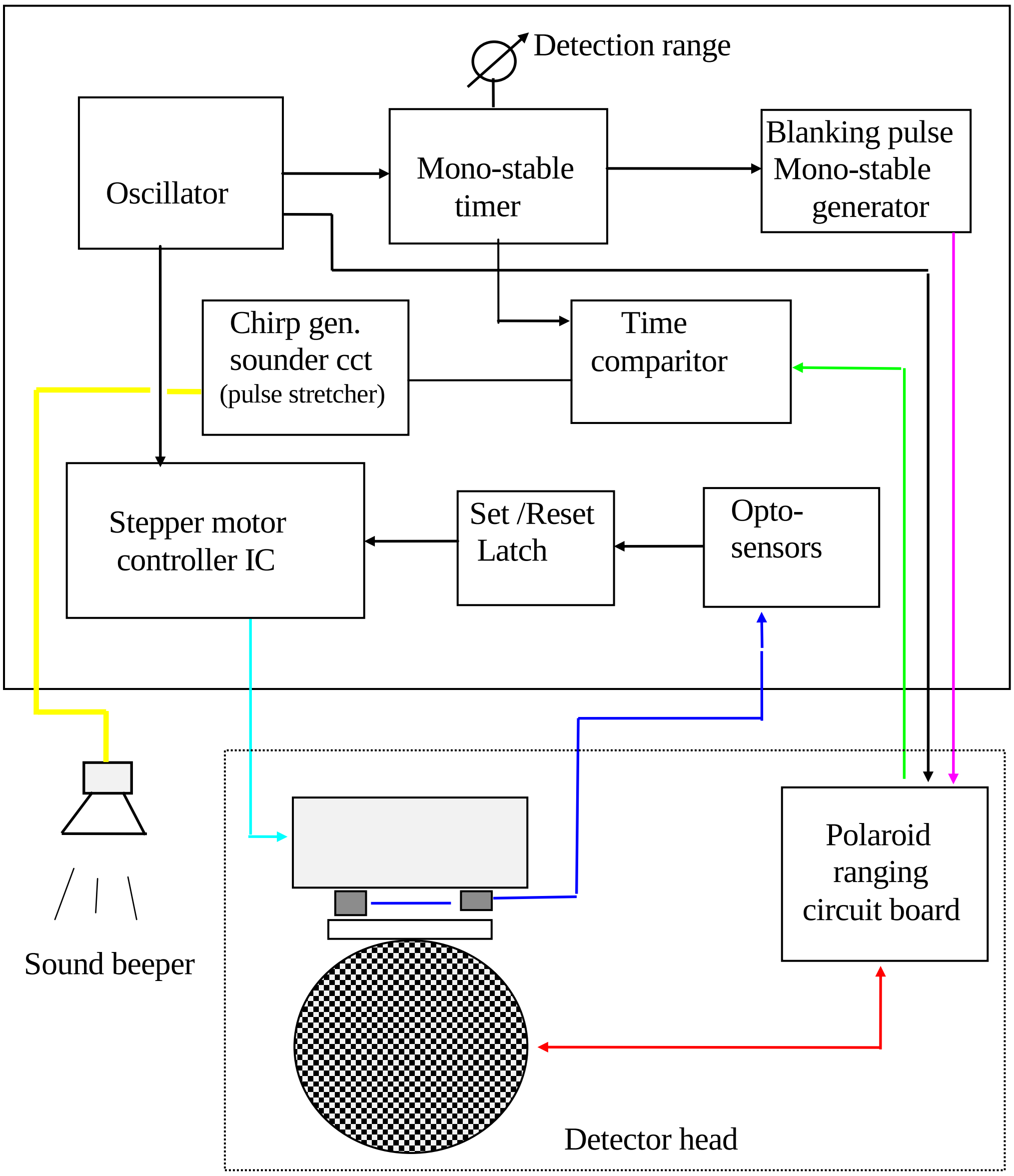


Figure 5.21 Latching rotation direction control circuit

Both inputs to the ‘& gate’ would now be high, therefore output point ‘3’ would go high. This changed the motor direction to (CW). The resistor Rf applied the necessary positive feedback to hold the output high until the white marker reached optical sensor ‘B’. The photo sensor (B) conducted and the voltage at point ‘2’ went low. This caused the gate output ‘3’ to go low. The motor now rotated in a CCW direction back to optical sensor ‘A’. The process continued, providing the scanning motion.

5.10 Object warning system

The first SCAD system provided a sound warning to indicate the presence of an object that could affect the driver. A block diagram of the system components is shown in Figure 5.22.



Control lines (colour Key)

— Transmit ultra-sonic sound pulse
— Blanking (post transmit damping)
— Received object echo signal
— Opto-sensor outputs
— Stepper motor control lines (4 phase)
— Ultra-sonic transducer coupling to ranging circuit
— Audible sound beeper

Figure 5.22 Schematic layout of the SCAD object warning system

The oscillator was a basic CMOS resistor capacitor (RC) oscillator with an adjustable frequency output. This ranged from 5Hz to 50Hz. The output waveform was a square wave with a 50:50 % duty cycle as shown in Figure 5.23. The positive edge of this square wave stepped the motor, the negative (falling) edge transmitted an ultra-sonic pulse and this was the clock signal for the system.

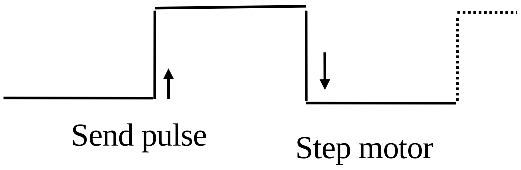


Figure 5.23 Oscillator waveform (main clock)

A monostable timer provided a time window in which the system listened for an echo. The value of this time period determined the maximum object detection range. To detect an object at a distance of 1 meter, the sound took 3.33 ms on the outward journey + 3.33 ms on the return journey. The complete time was therefore : 6.66 ms.

Distance / time : (1 / 6.66) = 0.15 meters per ms.

The period of adjustment used in the mono stable circuit ranged between 1.5 - 8.0 ms. Therefore:

(0.15 x 1.5) = 0.225 (0.15 x 8.0) = 1.2 (approx. 0.225 - 1.2 Meters)

The functional timing diagram shown in Figure 6.24 represents the interrelated events for the complete sweep cycle. Within this are the control signal events required for object ranging. Each event was edge triggered with the exception of the period allowed for listing. The ‘listen high control line’ time value directly determined the object detect range distance.

Blanking pulse generator.

Associated timing functions requiring a monostable included the generation of the blanking pulse. This muted the output of the receiver circuitry immediately after the transmission of the ultrasonic pulse. This was set to a period of 1ms. During the muting period, the residual ringing within the transducer decayed to a point where the system could begin to listen. The blanking pulse was short enough to enable the detection of an object at close range.

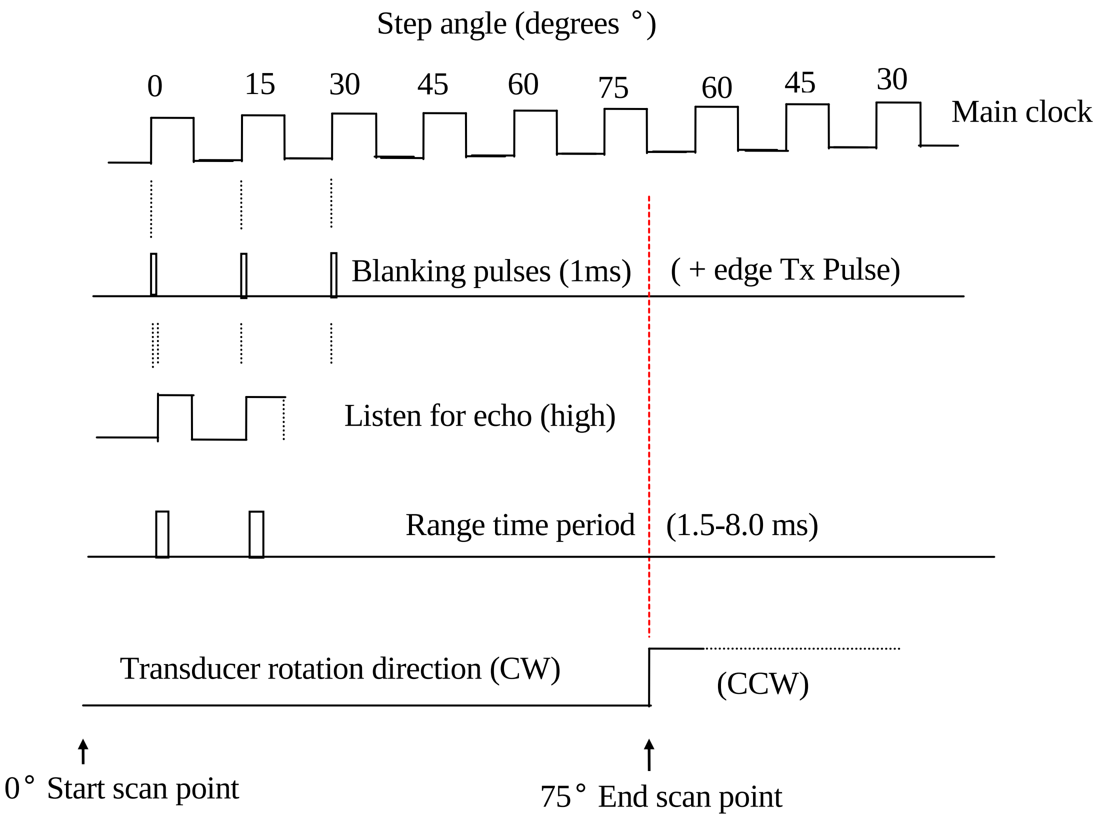


Figure 5.24 Functional timing diagram

The Polaroid ranging circuit was controlled by the square wave clock generator. Associated with this was the blanking period. This needed to occur at the correct time as shown in Figure 5.25. As shown in Figure 5.24, the 'listen for echo' period was valid for the period in which the 'listen' control line was high. The red time line (1.5 to 8 ms) markers indicate the possible listen 'for' echo periods relating the required object ranging distance. The negative (falling) edge of the square wave incremented the stepper to the next zone.

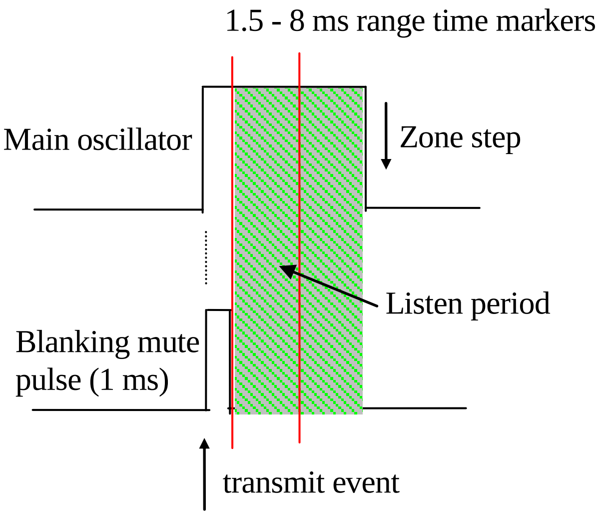


Figure 5.25 Blanking pulse timing

The output of the monostable timer was electronically (&ed) with the detected echo output of the Polaroid ranging circuit. This formed a time comparator function which delivered a pulse representing a valid object detection within the required range. The length of this pulse was the difference between the mono-stable range time value and the time taken for the echo to be received after the transmit pulse. This change in pulse length was an indicator of the object distance. The pulse width increased when the object to sensor distance decreased.

The change in pulse width was useful for conveying a sense of object distance to the driver. The time comparator pulse was too short for any useful output when directly coupled to a crystal type sound beeper. A simple diode pump circuit as shown in Figure 5.26, was used to increase the length of the pulse to generate a useful sound beep.

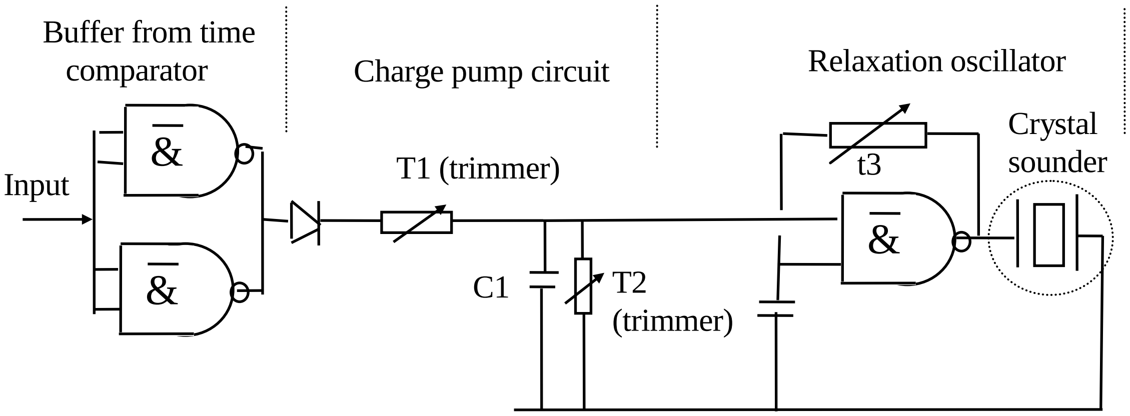


Figure 5.26 Pulse stretching and beep sound generator circuit

Figure 5.26 is the circuit used for pulse stretching and providing an audible output from a crystal sounder. Small crystal sounders could be driven directly from a single CMOS gate, providing a useful sound output. Trimmer (t3) was used to adjust the beeper frequency. Two (nand) gates were used in parallel (as a buffer) to provide enough charging current for the diode pump capacitor to charge quickly from the short pulse widths produced from the time comparator output. C1 is the charge storage capacitor. The discharge time was set by T1 and the charge time by T2. These determined the time constants for the pulse stretching requirement. Sound tones for each pulse echo sample, or multiple echoes from object's placed around the scan field could be adjusted to overlap and give a continuous tone.

A short piece of video and sound recording was taken in which this sound can be heard and that is available form the author on request.

5.11 Enclosure protection

It was noted that the construction of the SCAD scanner enclosure, particularly the protection bars could have an effect on the performance of the system. Due to the delicate nature of the transducer and motor assembly, damage could result if hit, poked or kicked etc. Experiments were tried using protective metal meshes and gauzes to wrap around the sensor system. Problems occurred with internal sound reflection problems. The ultra-sonic pulses bounced back and forth within the sensor enclosure. Better results were obtained by using metal bars of (3mm) diameter. Generally the amount of protection was balanced with system performance. For example, thin bars might be transparent to system operation but offered less structural protection than obtainable from thicker bars which, may cause unwanted false detection problems. Angling the bars slightly reduced the possibility of internal signal scatter by reflecting some of the sound energy away from the face of the transducer.

5.12 Discussion

The SCAD system described so far was created as a successor to the mechanical bumper system used for track driver training. The major disadvantage with the mechanical type bumper was its footprint size. This became untenably large when increasing the amount of advance object warning and stop control requirements for the wheelchair. Non-contact proximity object detection provided by ultra-sonic ranging reduced the need for large overhanging physical bumper detectors. Pupils that had been using the track had not had a real opportunity to exercise their own steering control. Many young and older track drivers began to start practicing with their wheelchair steering. One option was for them to try a normal switch or joystick to control a powered wheelchair. This did not have a protective mechanism except for a mechanical power cut-off bumper. This was normally implemented to reduce the amount of damage caused by a driver impacting with objects or people. Drivers colliding and misjudging object distance became the focus of further obstacle avoidance development work.

One of the main reasons for the creation of the track guidance system was to help train and provide experience for students driving within a safer environment. This enabled them to reach destinations of their choice with greater independence and freedom from staff and helpers. A natural progression beyond the limitation of access provided from the track routes was a system that could guide itself by sensing the local environment. This offered a greater opportunity for learner drivers and those with visual impairments and spatial perception problems to drive with more freedom. The SCAD provided a protected environment but required a higher driver skill level than for track driving. In particular the requirements for navigation and recognition skills of the environment were greater than those initially starting driving on the track.

The principal of rotating the ultra-sonic transducer and sending ultrasonic pulses through stepped periods of rotation had been used and evaluated with the first prototype SCAD single field detector. This had been intended as a wide angle audible warning device for people (such as a blind girl) using a track following powered wheelchair. There were anomalies with the detector, mostly arising out of the repetitive pulse echo sampling. Old returning echoes could sometimes conflict with nearby in-range targets, the sample time was also slower than desired etc. In spite of some of these drawbacks the system worked sufficiently to detect nearby objects. The phase of the development of the automatic assisted steering SCAD system required object position placement and this is described in Chapter 6

Chapter 6

Using the SCAD to assist with steering

Children were often given training sessions by therapists who encouraged them to drive more independently by walking with them and only providing help with controls when necessary. Some children often crashed into things and required help to negotiate an exit from a situation. This was by necessity a ‘hands on’ exercise. Often therapists and helpers prompted a child to help them problem-solve, but physical intervention was frequently required. Some therapists favoured a view that crashing was an important learning experience that provided valuable feedback to the driver. The objective behind creation of a guidance system was to help children gain a greater sense of personal independence by reducing the number of times help was needed. The SCAD provided children with an opportunity to negotiate a way forward in their driving situation without needing a helper to intervene (except perhaps verbally to offer advice or information).

The effect of system intervention had to some extent been tested by the use of the track guidance system, as children had become more independent from helpers when driving between track destinations. Children themselves demonstrated that they could safely venture away from helpers (and many enjoyed this).

6.1 Object detection positioning

The starting point for the creation of a new system was to partition the SCAD detection areas into three zones. Each zone consisted of two separate 15° sectors producing separate zones of left, forward and right (each being 30° wide). A new prototype SCAD was constructed using a 15° per step motor and a standard instrument grade ‘Polaroid’ ultra-sonic transducer. The construction method used was similar to the first SCAD (single field) unit. The transducer was bonded to an optical disc having a marker indicating the scan start point.

Figure 6.1 shows the SCAD zones relative to start scan point. The ultra-sonic transducer motion control system was operationally similar to the SCAD bumper prototype scanner.

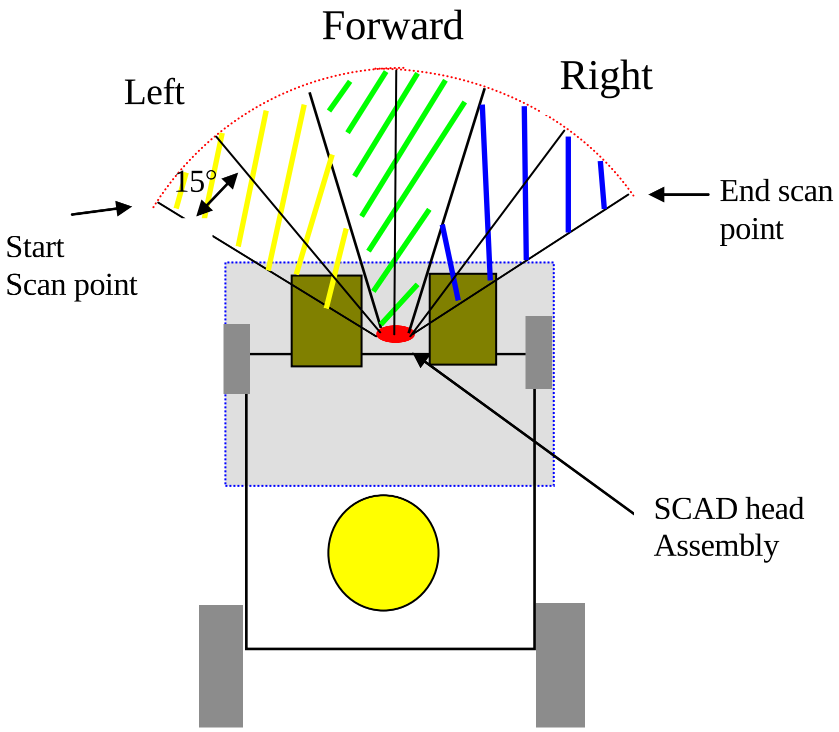


Figure 6.1 Multi-zone scan pattern

Additional electronics were incorporated to derive the separate zone areas. Figure 6.2 shows the SCAD control block diagram including the additional zone partitioning electronics indicated by the grey dotted lines. In Figure 6.2, the orange line from the time comparator carried a short pulse indicating an object detected within the set range. Each of the three '&' gates only passed a valid output when an object echo pulse occurred within the sector. This was determined by using a binary (4 to 16 decoder / demultiplexer).

Each of the sectors had its own decoder output (this represented a 15° scan wedge). In the first prototype, two of each of these sector outputs were paralleled to provide a 30° sector. This was connected to its respective '&' gate to provide a partitioned output.

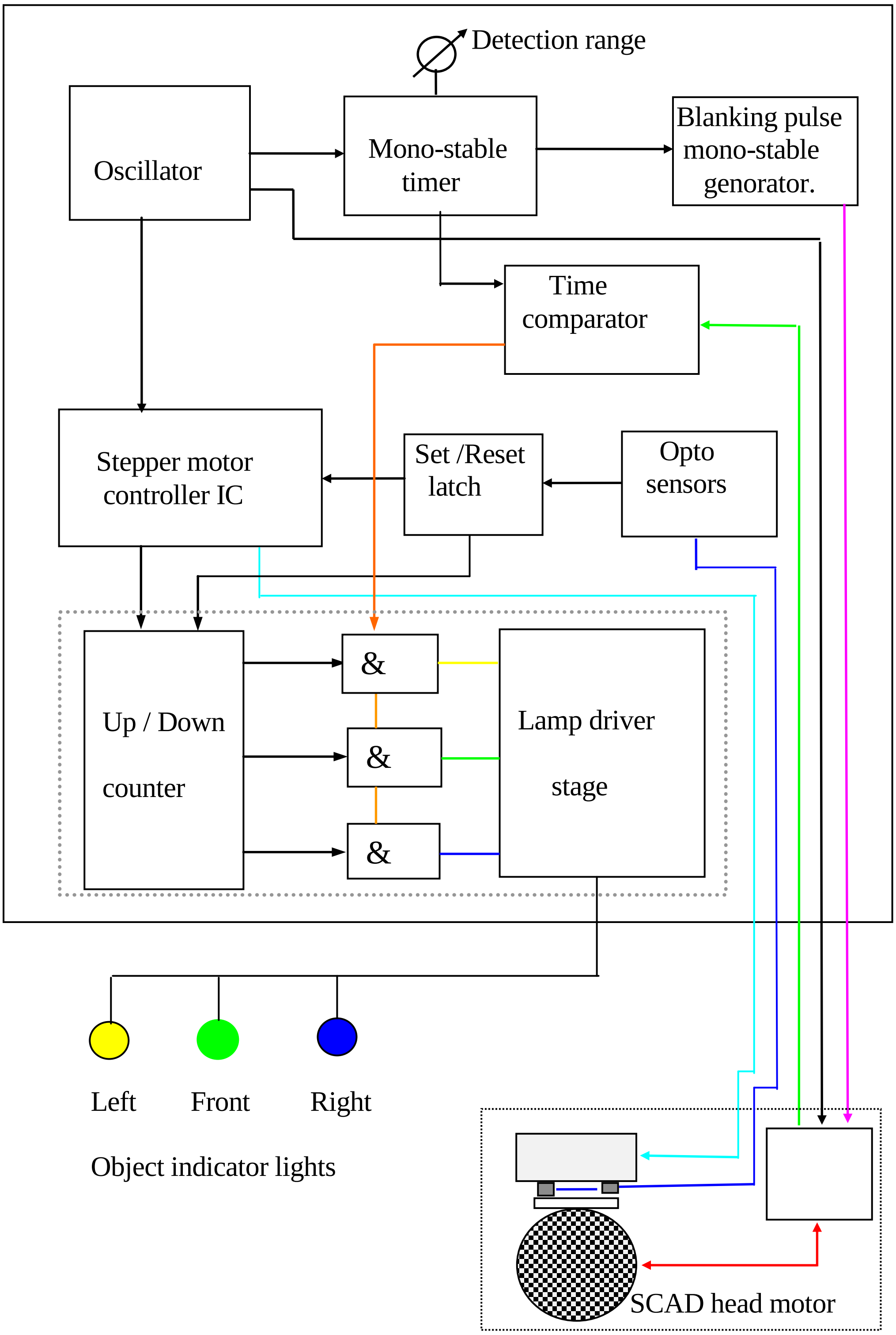


Figure 6.2 Block diagram of the SCAD control system and zone partition object indicators

A separate drive stage enabled the operation of indicator lights. This provided a basis for performance assessment and can be seen in Figure 6.3. The SCAD motor and transducer setup was placed on a white paper sheet so the scan sectors could be mapped and evaluated. Some dead spots were noted at points within the scan field.

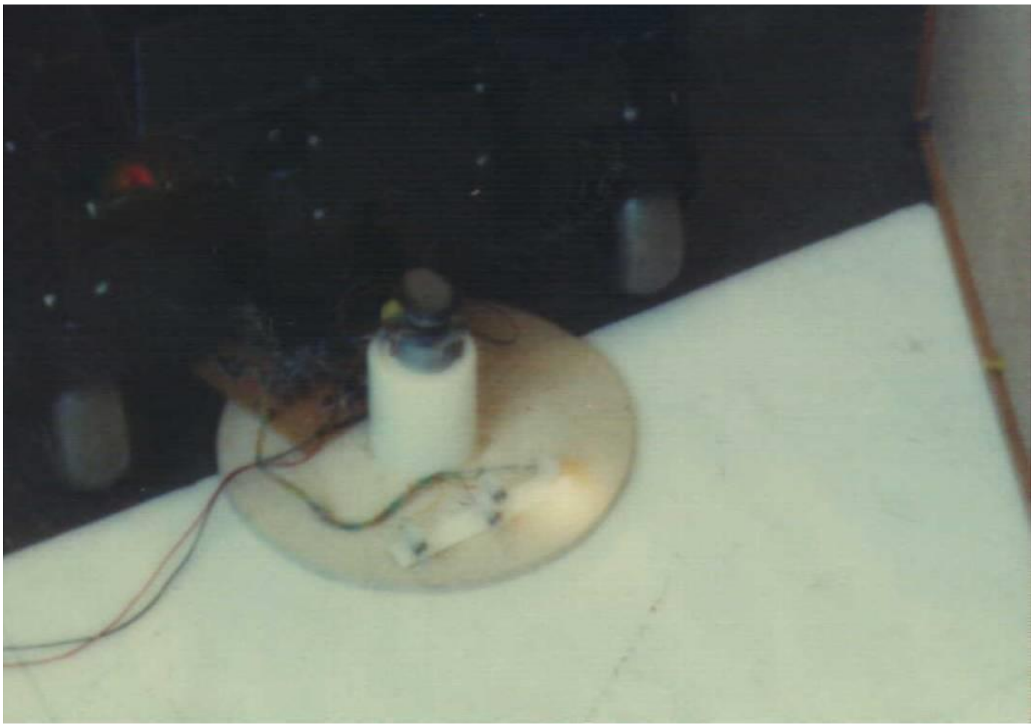


Figure 6.3 Close up picture of the prototype test SCAD and directional indicator lights

The system was attached to a push-along wheelchair and walked around a laboratory environment. Figure 6.4 shows this first prototype with the indicator lights seen on the tray. An object on the right side of the system had been detected and indicated by the right hand light. This helped establish how the system responded to the position of objects within the defined zones.

There were no trials with children at this stage. The rational was to test the idea of a single transducer working in a mode similar to a six transducer (fixed array) system. These initial tests established useable scan speeds and object miss-detection due to ghosting and specula reflection problems.

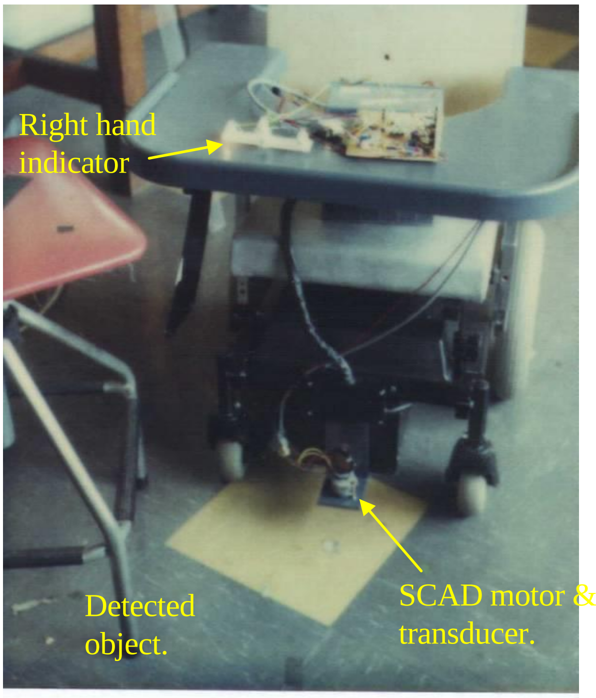


Figure 6.4 Prototype SCAD and bread board electronics placed on a wheelbase

A control interface was built to test the SCAD detector in a power cut-off mode. The extended range provided benefits for advanced warning but caused problems on track bends leading into doorway apertures, where the doorframe was detected. This also occurred at track bends near walls. Figure 6.5 shows the detection of a doorframe with extended detection range beyond that of a conventional mechanical bumper. In a power cut-off mode the wheelchair stopped at the doorway entrance.

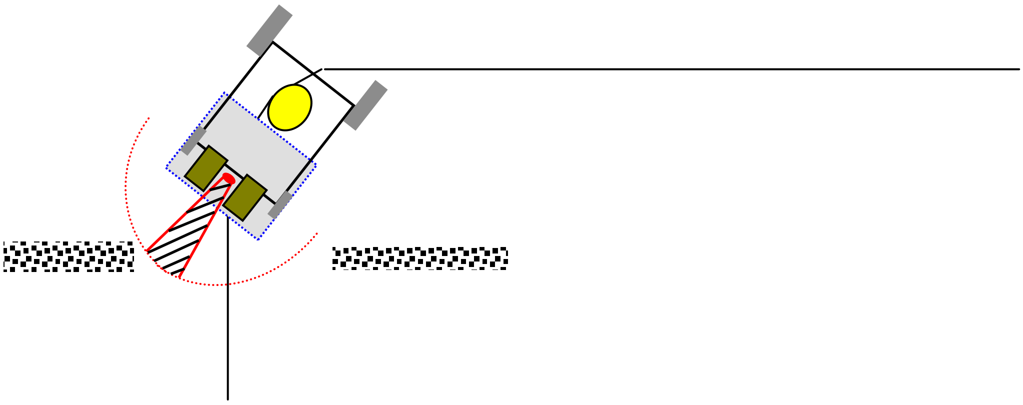


Figure 6.5 Detection of a doorframe with extended detection range stopped the wheelchair

Reducing the detection range reduced the stopping problem but decreased the effectiveness of having the advanced bumper function. Unlike the mechanical bumper, the SCAD detection zone did not have any physical presence and consideration was given to adapting the detection range to avoid the unwanted stopping problems. The dynamic profile adjustment was not implemented in this research but described as a consideration. Two methods were considered:

A) Dynamic profile adjustment

B) Fixed modified profile

A) Dynamic profile. Considering the track a left track bend, the zone range on the right hand part on the scan field could be reduced to prevent detection of the right side of the doorframe entrance. This profiled range control be achieved by; turning indication or track bend information being derived from the differential motor drive control voltages, or via caster swivel detection. This could provide an indication or control signal for either tracking in a straight line or around a track bend, possibly when leading into a doorframe type aperture. In the research described in Chapter 4, caster swivel detection was developed and applied to correct wheelchair veer. These developments were considered for muting the affected part of the object scan whilst preserving the extended detection (for normal object detection) whilst driving on a track. A track bend in open space would result in unnecessary reduction of the bumper function. Other methods were considered for identifying specific areas (for example door apertures), by using markers on the floor. This area of work was not taken further because of the additional installation requirements required within the wheelchairs operating environment.

B) Fixed zone profiling. A bullet shaped detection zone was generated where the centre part of the scan was at an extended range whilst the sides were more restricted. This reduced the possibility of detecting the sides of doorframes at the entrance point. This development was continued further to reduce speed for a non track driver when in an environment of objects close-by. Many children used track guidance for mobility, but the track was restrictive because of the limited number of destinations, particularly with more and more children using the systems. Some young people did not need (or like) the security of the track. They wanted to drive, but they needed helper support. One young girl in particular had lapses in her concentration and often crashed, although she had a reasonable level of driving ability. The track was inappropriate for her but she could not be left to drive unaided. A problem was that the SCAD was not good enough because the swept angle of 90º was not effective for guidance. The yellow arrow in Figure 7.6 shows the SCAD sensor mounting position on the wheelchair. The SCAD was set back on the wheelchair structure and scanned an area of 90º horizontally in the path of travel. The wheelchair frame and the height of the foot rest did not obscure the sensor 'view'. The problem of detecting the wheelchair structure became more significant when considering an increase of the SCAD scanning width. In later work (with the development of a wide angle scanning system) the sensor position needed to be placed forwards so that the scan did not detect the front caster wheels.

Figure 6.6 SCAD sensor mounting position

Therapists agreed that the SCAD could be used as a training aid, and a child was selected who had problems with maintaining concentration when she drove. She wanted to be independent but the staff were unwilling to let her drive on her own because of concerns about her crashing and having accidents with other students. A SCAD based training system was considered for her wheelchair and tested within a structured environment consisting of a road way made from plastic cups. The SCAD successfully detected the cups for guidance and this provided a driver training application that was used in the school.

The original SCAD audible warning system responded to an object anywhere within the scan. To provide directional (and some positional) information, the scan zone was divided into the three sectors of left, forward and right shown in Figure 6.1. Conditional logic was implemented that prevented a control direction from operating if an object had been detected in the same direction. For example an object detected in the left zone partition would lockout the left control direction. This was momentary, so when the object had stopped being detected the affected drive direction was restored.

Operation of the system was tested in the laboratory by attempting to drive into objects. Objects were detected within the scan sectors and collisions were prevented. It soon became obvious that the left and right scan zones did not sufficiently detect objects to be effective for use with some child drivers. The horizontal sweep needed to be expanded. The original 90° sweep angle was useful for detecting objects within the direction of travel but objects at the side (for example walls) were not reliably detected.

Figure 6.7 shows how the 90° sweep angle could not detect a wall when running parallel to it, due to specula reflection causing dispersion. Detectible ultrasonic sound energy was reflected away from the receiving transducer.

Figure 6.8 shows the approach angle at which the wall was first detected. The reflected sound energy was bounced back to the transducer.

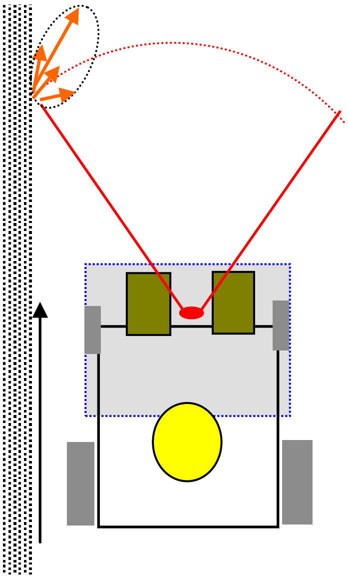


Figure 6.7 Specula reflection prevents detection of the wall

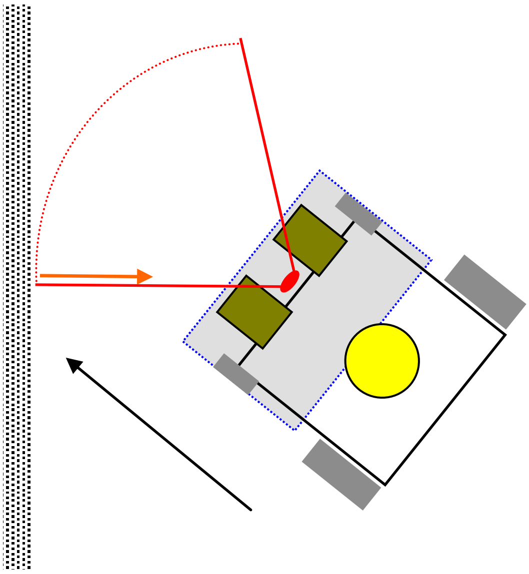


Figure 6.8 Angle of approach that the wall can be detected

Detecting walls became significant when drivers advanced from using the track system. Many children that were using the track had been improving their driving skill and were becoming increasingly frustrated by the limited number of destinations provided by the track routes. The first SCAD system had been used as an object warning device. There had been problems, (for example spurious detection issues caused by multi-path echoes) but they tended to be momentary and the occasional blip caused by these spurious or ghost echoes were generally ignored by users. When considering automated guided control and automated assistance these occasional blips had an invasive effect, causing the wheelchair to halt. Modifications were required for the SCAD to operate properly as a guidance system. The following changes were made; firstly the scan angle was increased. Secondly, the scan zones were segmented, and thirdly, the scan time cycle was reduced.

6.2 Increasing and segmenting the scan

The original SCAD scan angle of 90° did not detect objects at the side of the path of travel. For example, Figure 6.9 shows that when a left turn was applied then the right drive wheel rotated clockwise about the stationary left drive wheel and the wheelchair collided with a cone object on the left side.

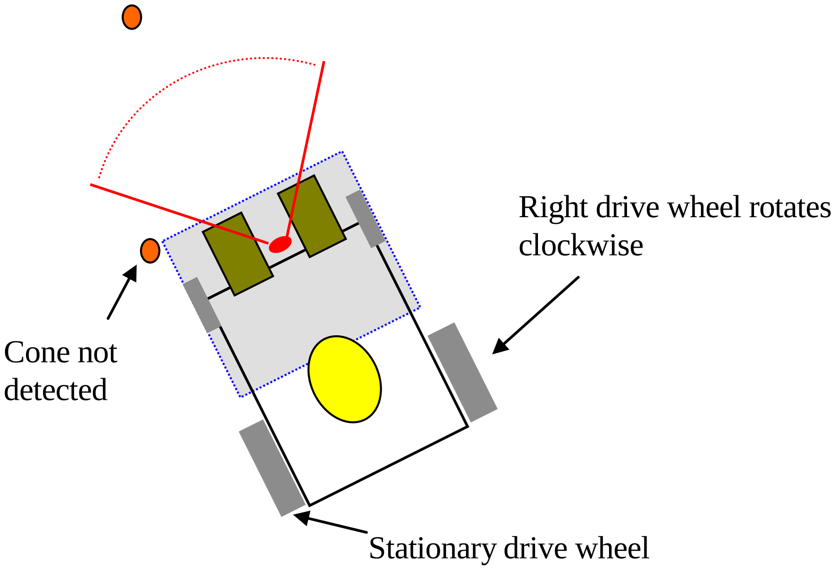


Figure 6.9 The 90° scan with was not usable for the training system

Problems were caused by increasing the number of sectors to widen the horizontal scan, particularly as this increased the scan cycle time. For early trials the wheelchair speed was reduced to maintain control. This provided extra time for the wheelchair to stop or change course when an object was detected within range.

Zone discrimination was intended for drivers who wanted to come off of the track but who were not quite able to master driving without assistance. Drivers sometimes returned to situations where helpers intervened and took control away from them. To provide a continuum of progression for children who had previously been on track, but who felt restricted by it, SCAD was selected as the next stage for their development.

Testing began using three scan sectors, left, forwards and right. The logic was simple, as each sector was ANDed with each switch direction control. For example, if an object was detected in the left zone, the logic prevented the left driving operation. If an object was detected in the forward zone, then forward driving would be disabled and reverse enabled etc.

There were problems with wheelchair control when sensing its local environment and how an object was approached could be significant. For example, if an object was approached at a slight angle then only a small steering correction was necessary because the angle of incidence from the wall was small. If the approach was ‘head on’ then more significant avoidance was required. This was not just a matter of cutting motor power when an object was detected and then restoring the power when the object was no longer detected. There needed to be specific levels and specific rules about how power was applied. The first SCAD system did not have this feature but consisted of ‘on-off’ relay logic (Niadex, 1995). This system did not perform well in real environments because of the narrow scan field and poor dynamic control of the wheelchair. This used crude relay control without any motor speed compensation. Although this setup performed a basic object avoidance function in the laboratory environment, when a child sat in the wheelchair then the increased weight affected system control. These problems significantly reduced the effectiveness of the first prototype SCAD.

6.3 Joystick emulator

Joysticks were the primary form of control that was used for wheelchair steering. The joystick provided a two channel voltage output that changed in proportion to the joystick movement. Standard wheelchair power controllers used these voltages to control the power in each of the wheelchair motors, allowing a driver to control the speed and direction of his or her wheelchair. It was necessary for the SCAD system to emulate these joystick control voltages in order for the power controller to operate.

An emulator interface was developed that generated the required joystick control voltages. When a forwards drive control was operated, then the joystick emulator provided the same voltage as that of a joystick when the stick was pushed forward. Similarly if a turn switch was selected, then a joystick turn voltage was generated.

There were problems when a fixed joystick control voltage was applied to a power controller when, for example, a wheelchair stopped during a manoeuvre or going up an incline. Sometimes staff manually pushed a wheelchair because it had stopped. This required a increase of motor power for the wheelchair to keep moving.

Commercially available power controllers incorporated in-built motor speed compensation. This increased the motor power when the motor experienced an increase in loading. The application of motor speed compensation was of great benefit and effective for a wheelchair (particularly around sharp turns without halting).

6.4 Automatic obstacle avoidance

The first SCAD system was based on switch controlled wheelchairs. Although performance was poor, that testing established the principals of object avoidance. Using the commercially available speed compensating wheelchair controllers for the SCAD application required further development of the interfaces that converted the switching control voltages generated from SCAD, into compatible joystick analogue voltages.

There were further problems with the first prototype SCAD. It had a slow scanning speed and long object detection update times. There were also inherent problems with long response times when interfacing the commercial proportional control units because these tended to have inbuilt damped control characteristics. This was necessary to avoid over responsive control characteristics when using a joystick. The SCAD interface needed a faster closed loop response time. This contradicted the more desirable acceleration and deceleration time that joystick drivers preferred. So there were two problems: firstly, long object detection time required for a wider object scan, and secondly, wheelchair power controllers had long dynamic response times. Work began to speedup the environmental sensing of objects in order to avoid collisions and to reduce the system response time. The first prototype SCAD system was useful for the initial experiments and for training the first group of children (who had previously been using tracks).

Plastic cups were painted bright orange and were used to create a detectable roadway. Driving experiments with children started using the SCAD within the cup roadways. One young child had been using the track with switch controls. She became frustrated by the track and wanted to drive with more freedom and greater opportunity, but she had problems with concentration and would often not be looking where she was going and crash into things. The therapists worked with the child to help her drive the prototype SCAD wheelchair within the roadway of cones. When she drove using automatic guidance, she just operated her forwards control and the system guided her within the cones.

There was not much functional difference between the track system and the SCAD cone roadway. This proved that the systems worked technically but did not train the young driver or make her think about problem solving. It became necessary to incorporate extra modes (operating functions) to stop the wheelchair and to automatically avoid objects. A lockout mode was tested that stopped the wheelchair when an object was detected. The driver was required to make control manoeuvres and select the correct direction in order to proceed. For example, if an object had been detected on the right of the wheelchair, then the right and forwards steering controls were disabled and the driver could only proceed by operating the left or reverse control switch. Pressing the forward drive control and letting the system do the work was no longer the only option. The child tried driving with this direction lockout function, but it became clear that she did not understand the driving process, particularly why the chair would stop. She tended not to apply the correct steering manoeuvres.

There were also questions about her understanding of the artificial driving environment using the cones (orange cups). It was not clear whether she actually saw the cones and could identify them as requiring her to drive within their boundaries. This presented a different situation to her that was not her usual school driving environment and she wanted to go back to driving on a track. It became clear that the new systems meant much more to children when they were driving around their own familiar school environment instead of in a laboratory setup. From then on, the laboratory was only used for technical testing and all user testing took place in real environments.

The original prototype SCAD could not be used effectively around the general school environment because it did not detect the variety of different objects reliably and it had a slow speed of response. Trials continued with children driving within a more structured but real environment. Light and sound prompts were added to the system in order to encourage children to make a control selection when the wheelchair was stopped by the SCAD system.

The cones were reliably detected and the children were kept safe within a controlled but real environment with little risk of going astray, although some still did.
The initial driving sessions with child drivers forced future research work out of the laboratory and into the real world, typically the school environment. To continue the training work that had been started using the roadway of cones, some children used switches that were made as part of the research. These were made with transparent covers that incorporated light bulbs. These were coloured coded to give each control direction an identity. When an object was detected then the opposite corresponding control would flash, for example if a child drove into an object on the right, then the left hand yellow switch would flash whilst the object was being detected. If a child could not proceed in any forward direction then the reverse control would flash.

When this first prototype system was used in the school buildings problems were reported about the system stopping when there were no objects close at hand. This was mostly because of ghost return echoes and ground / slope edge effects. The most significant problems were caused by doorways as the SCAD was not effective at detecting doorframes and other objects at the side of the chair. When the system was tested for doorway navigation in the laboratory it corrected the steering of wheelchairs by detecting objects close-by the door frame and the edges of the doorframe. The majority of the tests were successful. This was not the case when children used the system and they often crashed into the side of the doorframe.

During the test runs without a driver the forward control was continually operated so the chair could perform the necessary steering control corrections. When the children drove the wheelchairs then they would perhaps do unpredictable things. For example, they might stop midway through a door frame and try to make a turn. At that point the doorframe was not detected by the SCAD sensor and a collision would result. Children sometimes stopped and turned midway because they were not perceptually aware to realise that the rear of their wheelchair had not yet cleared the doorframe.

6.5 Side detectors

Some children could drive using a single SCAD sensor at the front of the chair. For others that was not sufficient. The child’s understanding (and sometimes training) for the task of driving needed additional work. Some needed more sensors. Additional side detectors were considered. An optical system was selected for this purpose because acceptable tolerance concerning specula reflection could be obtained. The main target types in this case were walls and doorframes. It was desirable to keep the number of sensors to a minimum to reduce maintenance requirements and system vulnerability.

A side detector consisted of a collimated infra-red beam transmitter and narrow angle optical receiver that detected objects by triangulation as shown in Figure 6.10. The acceptance angle of the receiver was restricted by a reflector to provide background suppression. This limited the detection range to stop objects being detected outside of the wanted area.

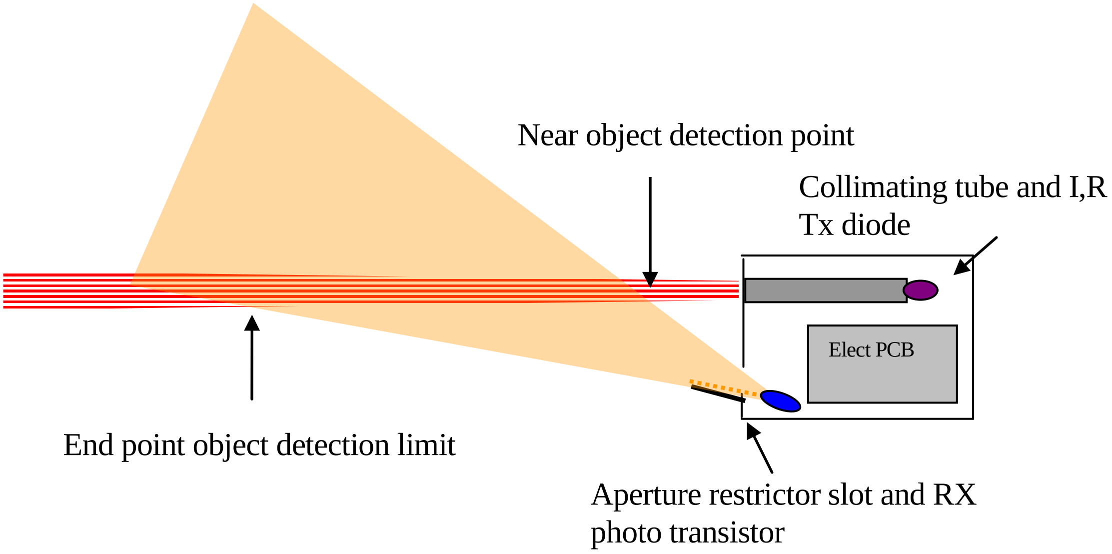


Figure 6.10 Side detector mounting position

It was also necessary to ensure that an optical detector could still detect objects at all distances up to the limited maximum. This could be achieved by placing a slot in front of the photo transistor that admitted the reflected IR light from the target object at close range, but cut-off at the set distance angle. The selected mounting position for the detector unit was above the rear drive wheel.

Figure 6.11 shows the mounting position of the infrared detector above each drive wheel (one side only shown). The beam was set to fan-out to provide early detection of the wall at point A. The wall is still detected at point B. The centre axis of the drive wheel coincided with the infra red beam to prevent the drive wheel scuffing past the wall aperture. The infra red detector did not give distance information but detected objects within a set triangulation. It was important to provide a definite distance cut-off to prevent unwanted detection of objects that were not in the path of the wheelchair. Consideration was given to object colour and reflectivity as it was noted that the cut-off point was shorter for matt black objects in particular.

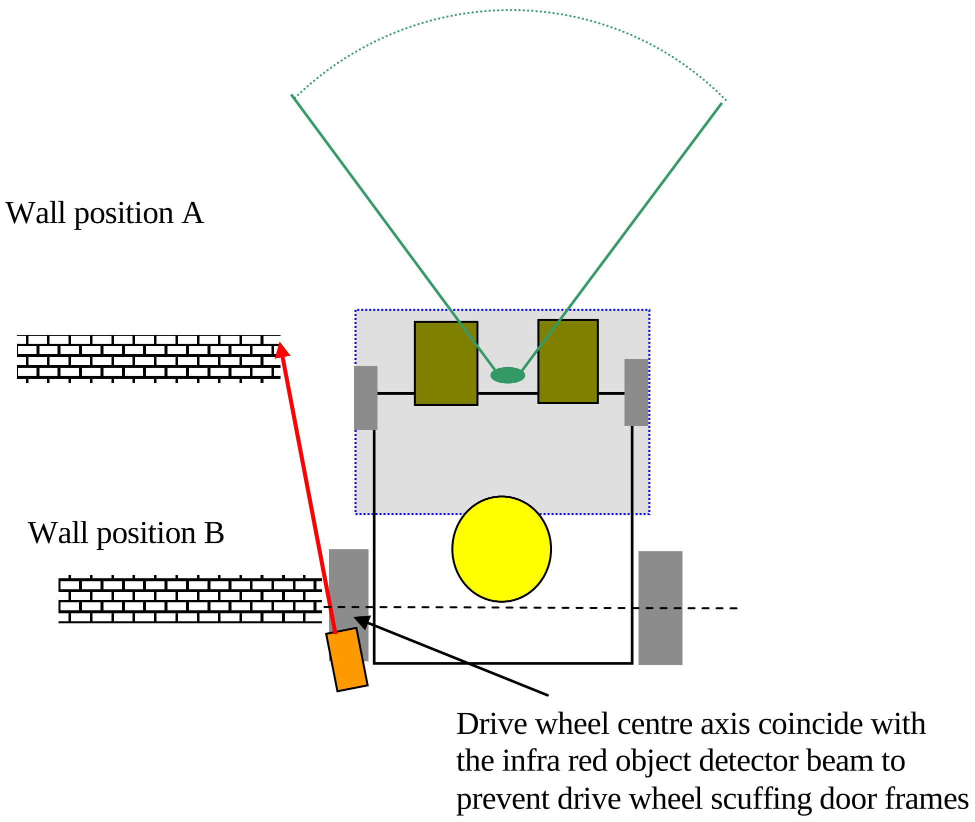


Figure 6.11 Object detection by triangulation

The primary reason for adding optical side detectors was for doorway detection and navigation. The infra-red beam had a nominal diameter of approximately 5mm. Doorframes were generally characterised by a solid surrounding structure.

There were a number of object sensing conditions where the narrow beam was a problem.

Figure 6.12 shows the differences in the cross sectional area between doorframes and other objects in a typical wheelchair operating environment.

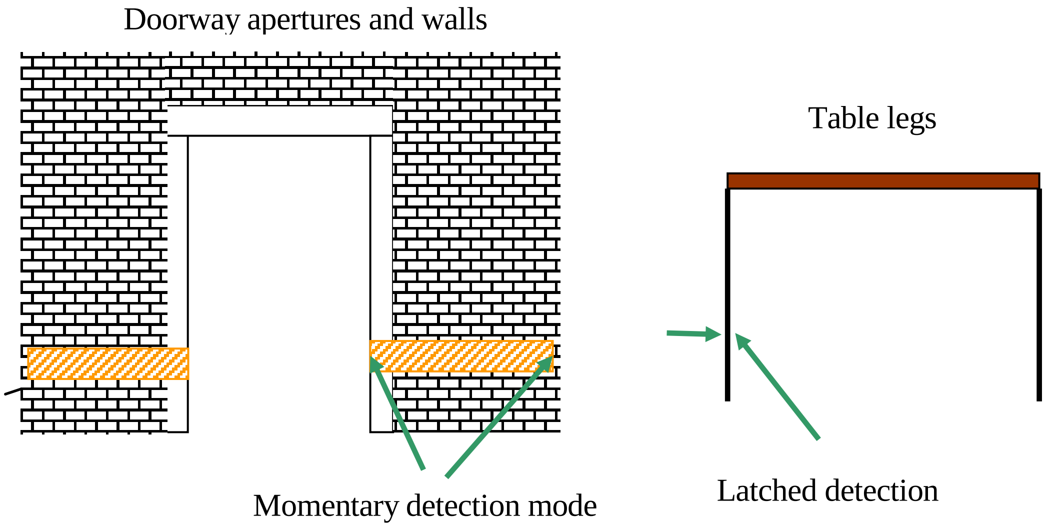


Figure 6.12 Differences in cross-sectional area between objects in the operating environment

Momentary (continuous) detection was sufficient to avoid collision with wall structures but narrower structures had detection problems. This was because the wheelchair stopping time was significantly longer than the object detected time.

An electronic latch was implemented to catch the transitional object detected output from the sensor. This functioned for left or right turning only. When driving forward, the control function of the side detectors was momentary.

Figure 6.13 is a functional logic diagram of the associated side detector control system.

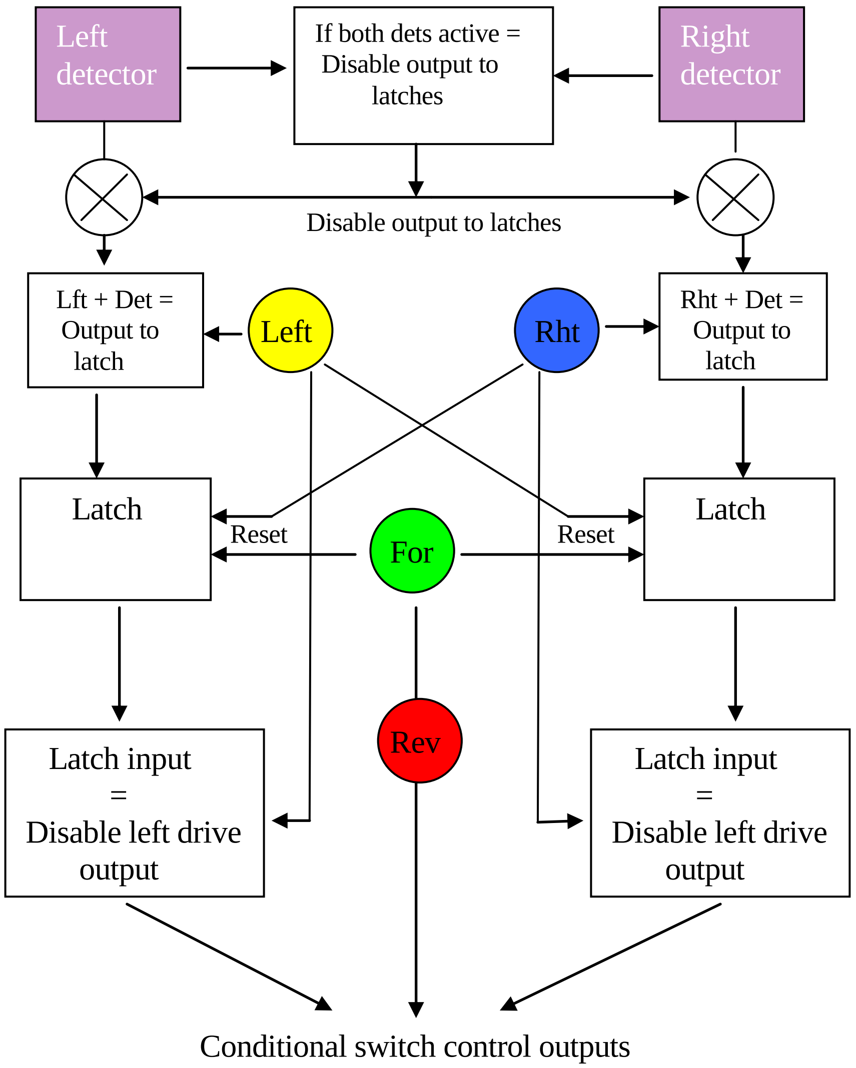


Figure 6.13 Side detector control function system diagram

The choice between selecting infra-red sensor or ultrasonic was mainly determined by testing the range of various objects as shown in Table 6.1.

Where there was an angle involved then the ultra-sonic energy was more prone to specula reflection problems. The object surface texture was also more significant for ultrasonic sensors. Table 6.1 shows a comparison between ultra-sonic and infra-red detectors.

Type of Object	**Ultra-Sonic**	**Infra-Red**
Doorframes	Good	Good
Table legs	Good	Good
Wall guidance applications	Poor	Good
Table cloths	Medium	Good
People	Medium - Good	Good

Table 6.1 The detection comparison between various objects

The most significant factor was the reliability of object detection. This was affected by the angle of the object surface and how much signal energy returned to the sensor as shown in Figures 6.14 and 6.15.

Reflectance tests determined differences between IR and ultra-sonic sensing systems. Both systems performed well when sensing objects that were perpendicular to the radiated energy.

The most significant parameter influencing the choice of sensing medium was the detection of walls for guidance. Most walls tended to have a smooth texture and most of the radiated energy was sent away from the sensor.

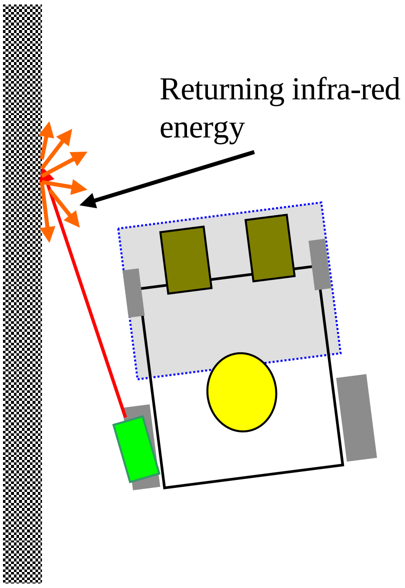


Figure 6.14 Infrared detection

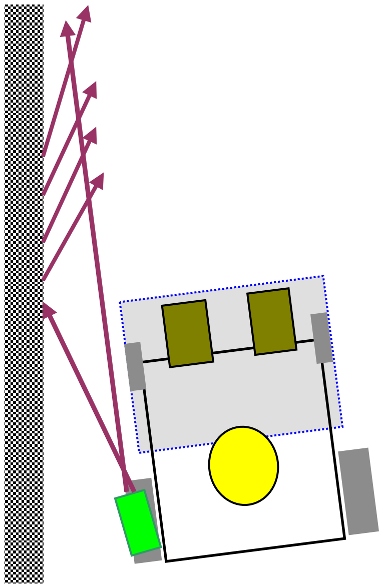


Figure 6.15 Ultrasonic detection

Testing provided the limits for object detection as shown in Figure 6.16. A slot was placed in front of the optical detector to control the field of view. The intersection between the infra red transmitting beam and the reception window determined the set range of the detector unit. In Figure 6.16 the distance indicated by the two blue lines indicate the operating detector range.

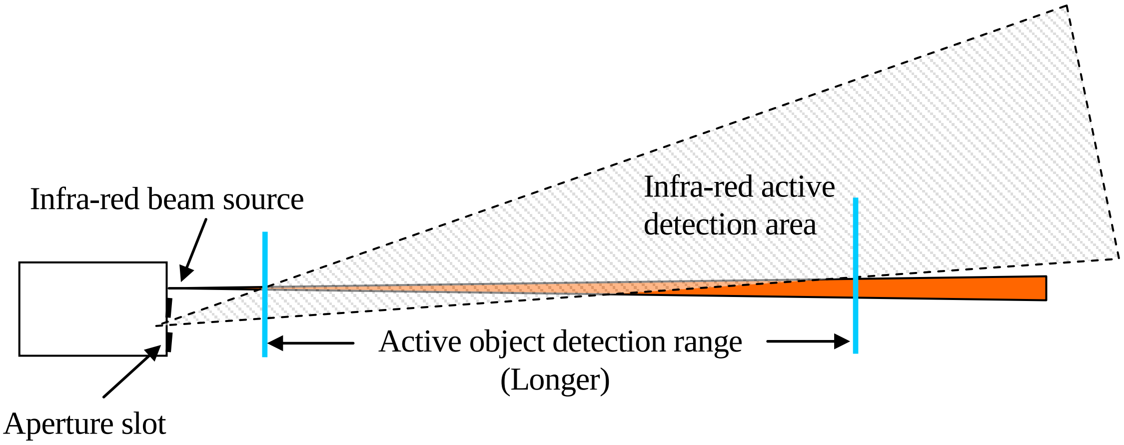


Figure 6.16 Testing to provide the limits for object detection

In Figure 6.17, the angle of the transmitting IR beam was changed and the intersection points were set to reduce the detection range.

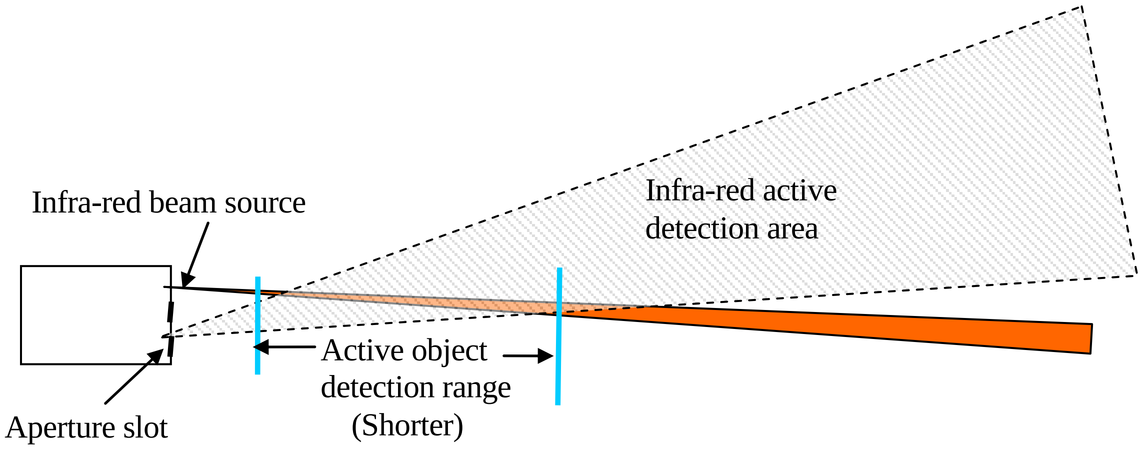


Figure 6.17 The angle of the transmitting IR beam had been changed and intersection points were set to reduce detection range

Side detectors suffered from ghost problems. Background suppression functioned by restricting the angle of the received infra-red from reflected object so that it would only accept the angle providing the set limit distance. The infra-red detector was still sensitive to reflections within its acceptance angle. Consequently multiple path reflections could occasionally be detected. Various tests were conducted to establish the causes of detecting false objects. A typical wheelchair system had armrests each side of the occupant and generally a tray around the front of the driver and over the side detectors. The reception angle of the infrared receivers looked upward. The shiny underside of a tray could act as a reflector to stray object reflections.

The infrared sensor unit was changed to angle down so that the received infrared could not bounce off the underside of armrest or trays. The ghost problems reduced. The power of the transmitted IR beam was also significant. The level of output intensity was established by using small black targets at the maximum intended object detection range. Object reflectivity and colour also affected detection distances. Light shiny objects extended the detection distance and dark matt objects reduced the distance. Generally the worst case was for black matt objects such as black trousers or dresses. Increasing the power of the infrared beam was considered, particularly because of the problems associated with stray reflected infrared from objects other than those in the intended target range. To reduce the intensity of the transmitted IR beam, a fine grating was made using photographic high contrast metalised film as shown in Figure 6.18. It was placed over the infrared receiver and transmitter lens apertures as shown in Figure 6.19.

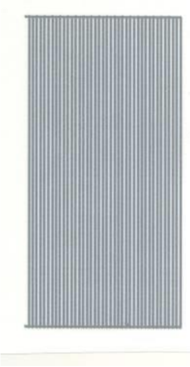


Figure 6.18 Grating bars

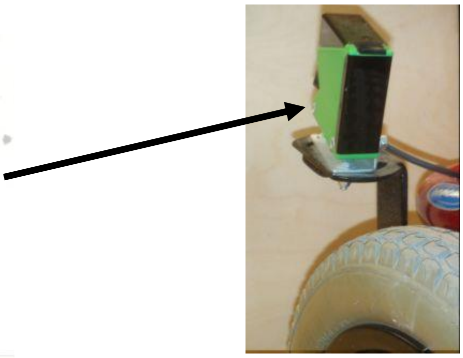


Figure 6.19 Optical side detector

The width and spacing of the grating bars were refined by successive tests ensuring that black target objects could be detected up to the defined cut-off distance as shown in Figure 6.20.

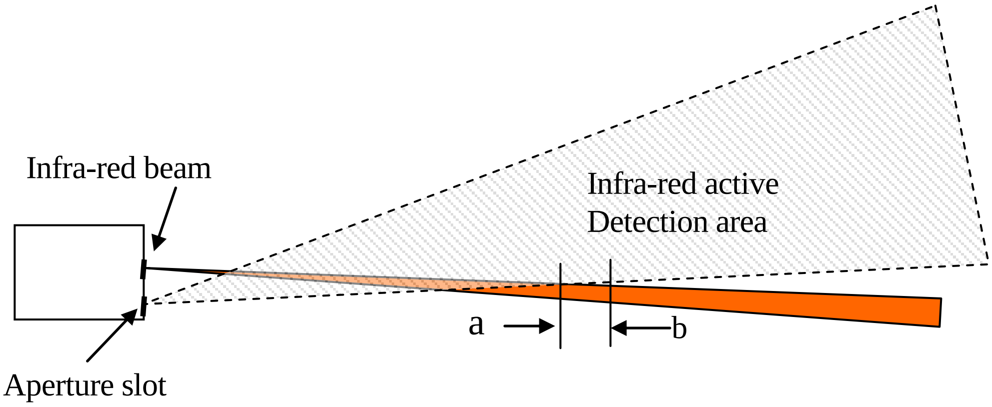


Figure 6.20 Refining the width and spacing of the grating bars by successive tests

When a target object was moved towards the detector, the object would be detected at a set range (a). When the target object was moved away, the point at which non-detection occurred was different. It was for example at point (b). The distance between points a and b (shown in Figure 6.20) were dependant on colour and reflectivity. The gap was smaller for light (whiter) objects whilst darker (black) objects increased the gap. The surface (texture) affected the object reflectivity for example, when testing and comparing black shiny objects against matt white objects the (a-b) gap showed little difference. The worst case was the reflectivity obtained from matt black objects. In a typical environment where the system was operating, the most commonly encountered black objects were clothes.

The a-b variation was not considered to be critical to the application of detecting objects at the side of the wheelchair, particularly as detected objects were not given a range value, but were either detected or not detected. It was necessary to provide an overlap between the optical sensors 'cut-off' point and the side SCAD scan zones, particularly to take account of the optical sensor variances.

The side detectors were implemented to increase object detection capabilities at the side of the wheelchair, particularly where a blind spot occurred with the scanning ultra-sonic SCAD detector.

There were situations in which the SCAD and side detector responded to objects at both sides of the wheelchair. This potentially caused a sensor lock-out situation as shown in Figure 6.21. In this example the side detector blocked the left direction and the SCAD prevented right turns.

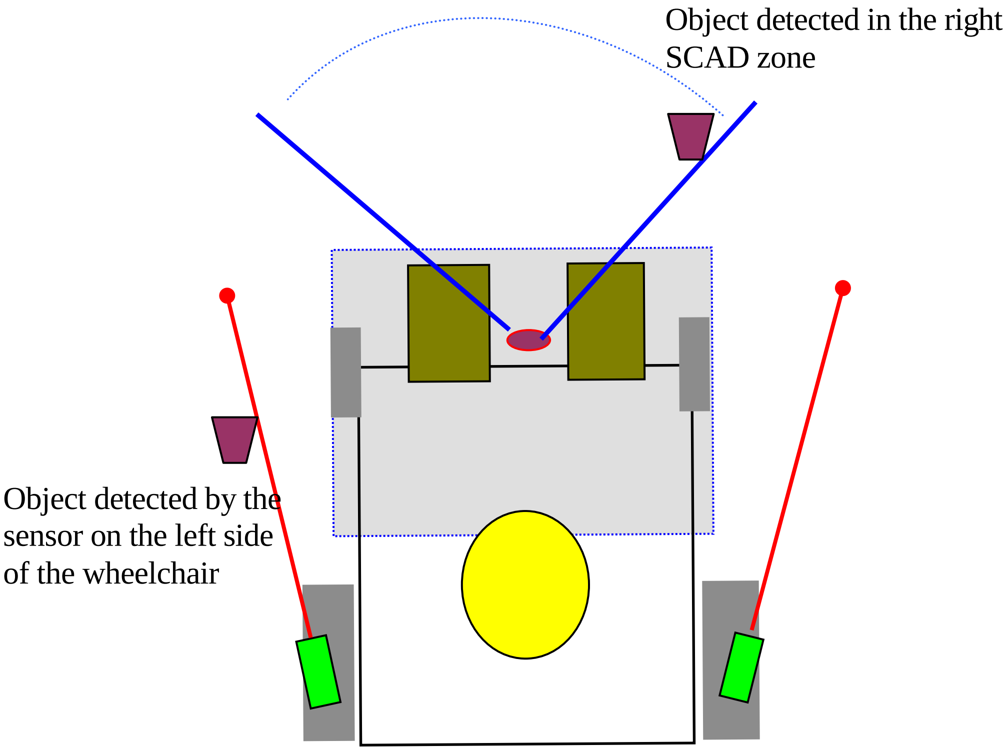


Figure 6.21 An example of sensor conflict

There was concern that this could be a significant cause of frustration for child drivers. Importantly the development of a collision avoidance system should provide increased independence and not hamper driving. Conditional logic was implemented to prevent the wheelchair from becoming un-drivable. The SCAD sensor operation disabled the functional outputs of the side detectors when the forward drive control was operated.

This suppressed object detection function at the sides of the wheelchair until the SCAD detector was free of detected objects. Paradoxically this meant that the wheelchair would continue to drive but may have collided with a potentially detectible object at the side.

6.6 Developing the guidance system for an unstructured environment

The initial work with the children strongly indicated the need to move away from laboratory testing conditions. It did not appear to be beneficial to take children out of their normal environment and put them into an engineered environment (for example into a roadway of cones) and then to expect them to understand. Once the testing moved into real environments then the children would often push forward developments by their willingness to explore new environments. It became important to develop and incorporate systems for people living their normal lives (or living pattern). The initial work did provide a test bed and highlighted the need for further technical developments but taking the system out into a young person's familiar environment highlighted its deficiencies.

Disabled people exposed weaknesses in the system (more so than non-disabled people). The most significant deficiencies exposed by drivers with disabilities were: the SCAD had insufficient scan width, long object update time, ghosting and problems with dynamic wheelchair control.

The problems with the 120° SCAD scan width, object detection update time and ghosting were inter-related. Work began to evaluate a suitable increase in the number of pulse echo samples for the improved horizontal object detection.

Figures 6.22 and 6.23 shows a comparison between detecting roadway marker cones and typical walls with the current system.

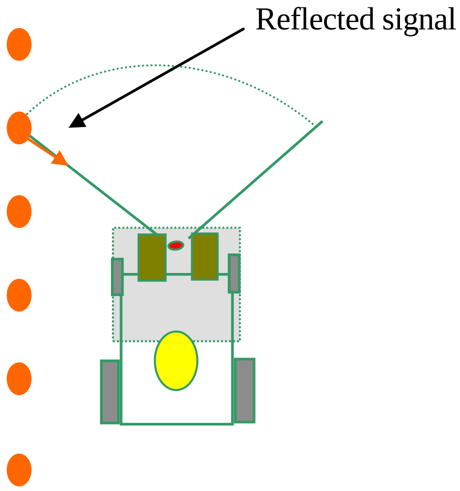


Figure 6.22 Cones detected for steering guidance

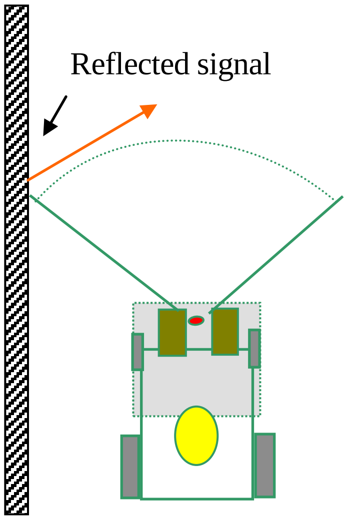


Figure 6.23 Wall not detected

In Figure 6.22 the cones were detected because they had a round shape which provided a reflected signal that was perpendicular to the transmitted signal and therefore offered a high guarantee of a reflected signal being returned back to the transducer. The wall shown in Figure 6.23 was not detected because the sound energy was reflected away from the transducer.

Some tests established the limits of wall detection when the wheelchair approached the wall at different intercept angles. Figure 6.24 shows a representation of the testing of the wheelchair system with a wall. The lower limits of collision angle were determined by the scan limits with respect to the wheelchair structure.

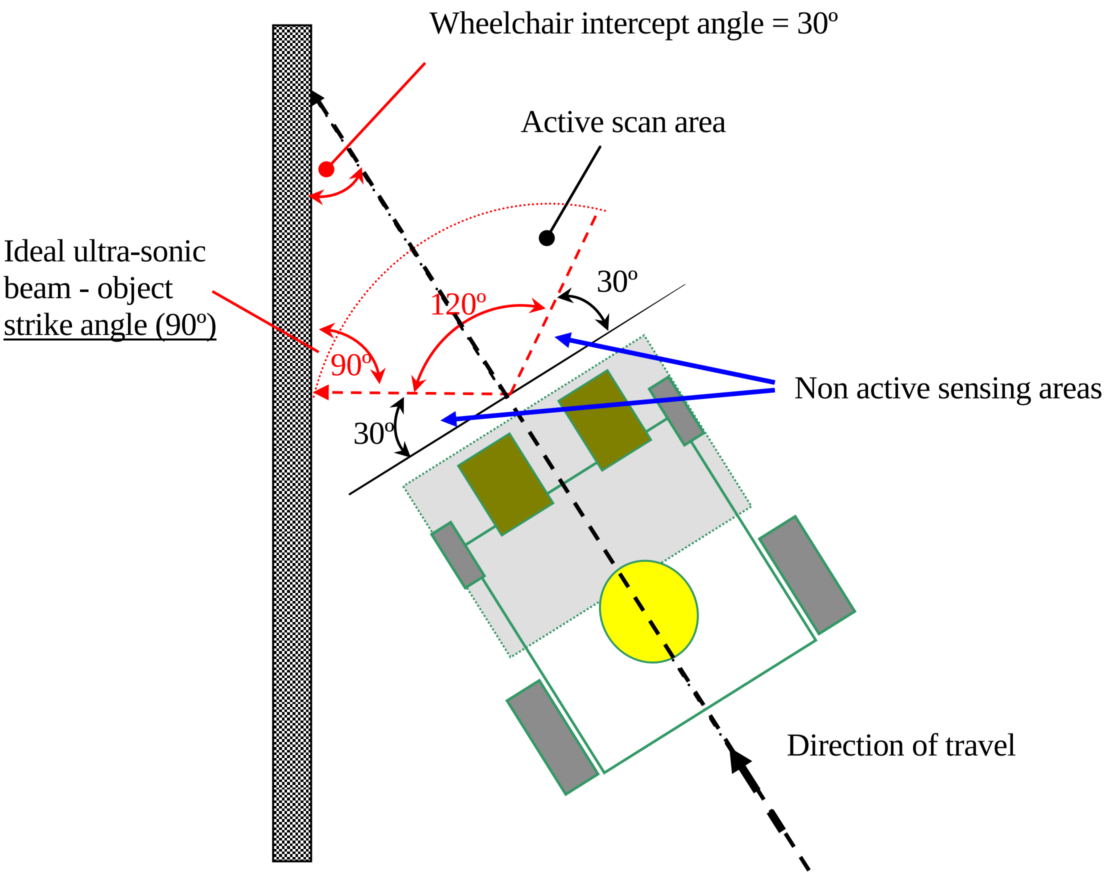


Figure 6.24 A representation of the testing of the wheelchair systems with a wall

Figure 6.24 shows the potential collision angle with a wall where the detection was reliable. The example shown represents the left side only, but was regarded as symmetrical for the right hand side of the wheelchair. Figure 6.25 shows testing for both sides.

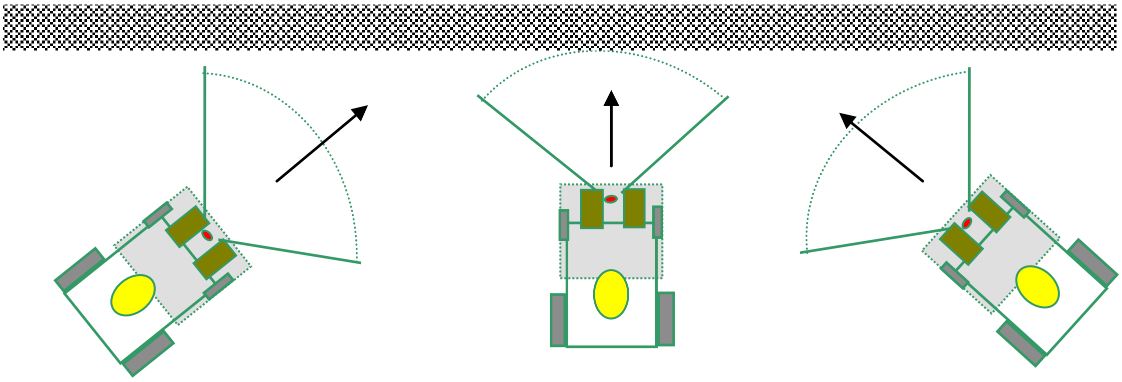


Figure 6.25 Collision angle testing

The next phase of testing was to determine the boundary between reliable and unreliable wall detection. The effects of specular reflection were significant and therefore when the collision angle was reduced then the wall avoidance was less reliable. Three conditional states were tested:

- Certain (reliable detection)
- Uncertain (50% detection) and (50% non-detection)
- No detection

Higher collision angles from 90º reducing to 30º as represented by Figure 6.26 returned reliable collision detection because generally the reflecting surface was perpendicular to the ultra-sonic transducer. The certainty of detection was related to the ultra-sonic beam with respect to the object strike angle and object surface texture and is referred to as the critical angle. This affected the amount of returning sound energy reflected from the object.

Object reflectivity testing revealed that smooth surfaces presented a narrow critical angle. This was consistent with smooth plastered walls and glass structures within buildings and was the worst case situation. Brick walls and concrete structures presented a wider critical angle which was attributable to their rougher texture having surface elements that reflected directly back to the receiving transducer. Brick structures had a level of uncertainty of detection and could exhibit narrow critical angles.

Uncertainty of object detection occurred where the wheelchair could be expected to collide or not collide with the wall.

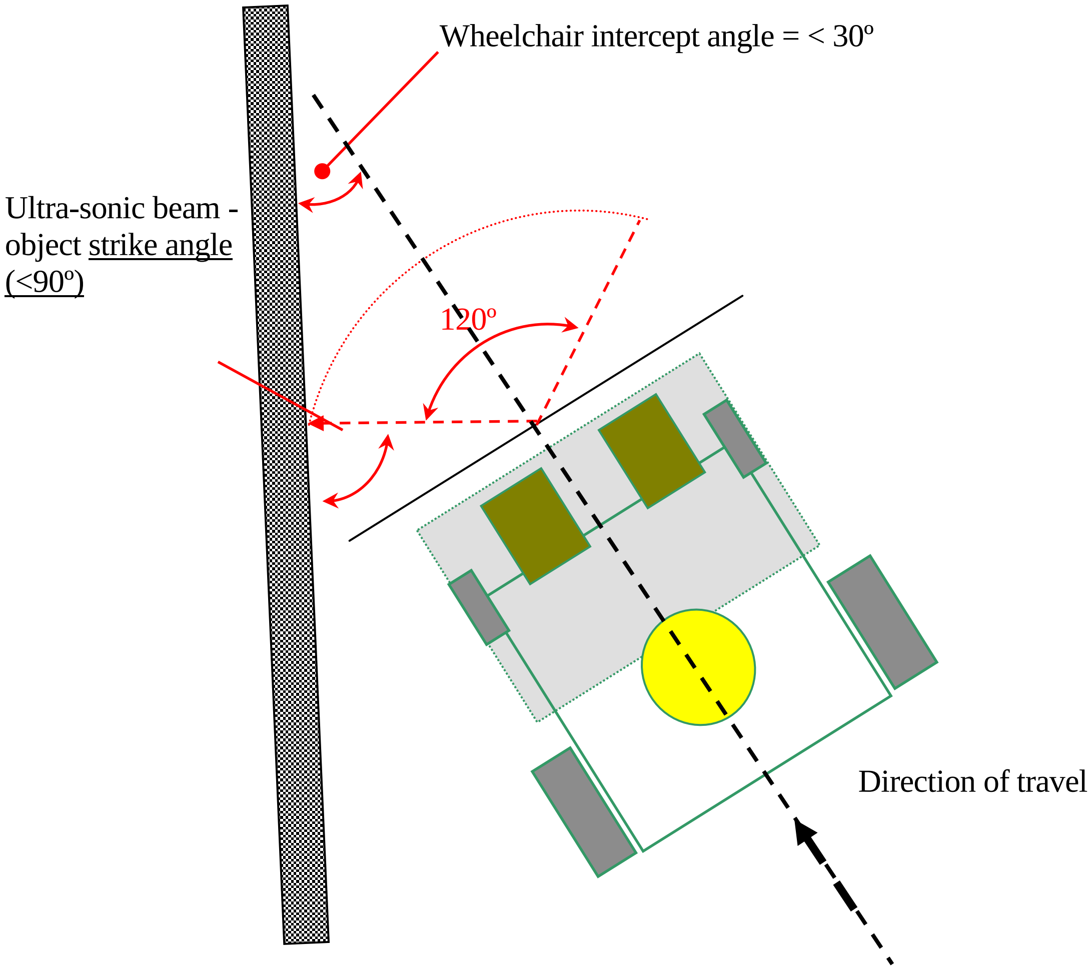


Figure 6.26 Critical angle of uncertainty

Figure 6.27 shows the intercept angle that was < 90º at which the wheelchair did or did not collide with the wall, this being the angle of uncertainty. The uncertainty of detection became the 'non-detection' condition.

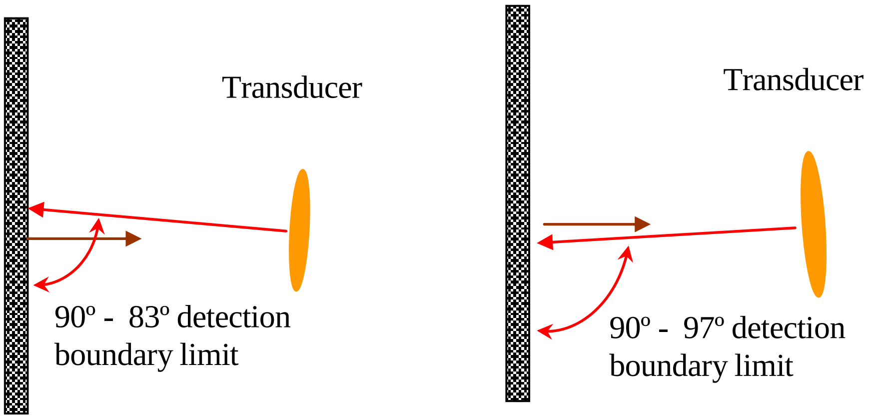


Figure 6.27 Wall detected between the limits 83º – 97 º

Figure 6.27 shows that practical tests revealed that there could be sufficient reflected energy from the ultra-sonic sound pulse to be detected between the limits up to (83º - 97º) angle of strike with respect to the wall surface. For the purpose of example the applied limit relates to 90º – 83º. Observations of children driving in their normal environment indicated that this limitation of the collision angle detection was a significant system weakness. Children and young adults often approached walls at low angles.

Children with perceptual problems would sometimes not react to these (subtle) low angle collisions, where as they would react more positively to head-on collision situations and stop the wheelchair for themselves. In Figure 7.28 the SCAD detector predictably failed to detect the flat wall surface because insufficient reflected sound energy could be detected.

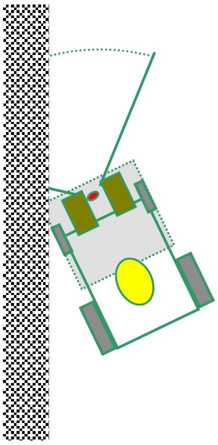


Figure 6.28 Wall not detected, resulting in a collision

The wall was not detected in Figure 6.28 because the flat wall surface reflected the detectible sound energy away from the transceiver. A simple test was performed by rotating the whole SCAD sensor assembly with respect to the wheelchair frame to determine a workable SCAD intercept angle for reliable wall detection, particularly when the chair was driven parallel to the wall. Figure 6.29 represents the test set-up.

The system was tested to determine the limits of object detection when approaching a wall at different trajectories.

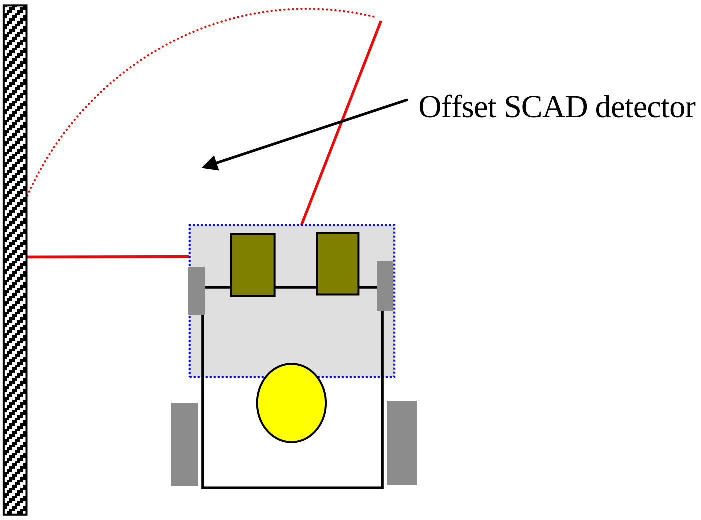


Figure 6.29 The off-set sensor detected the wall

The test was successful in so much that the ‘SCAD sensor detected the wall on the left whilst the wheelchair was parallel to the wall. The issues concerning low angles of wall intercept were much improved by offsetting the SCAD head and wall collision avoidance was significantly improved for the left side of the wheelchair. There were insufficient samples for object detection to also cover the right side of the wheelchair. This amounted to a deficit of 4 sample sectors having a width of 15° totalling 60°. The scan angle is shown in Figure 6.30.

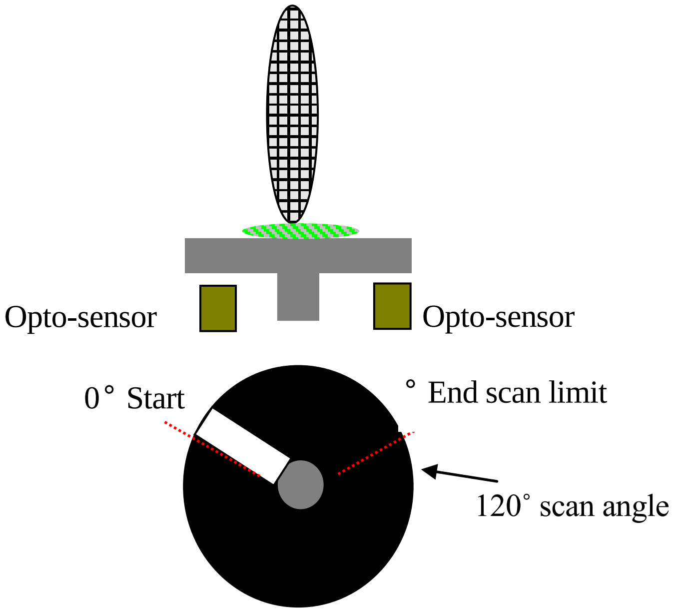


Figure 6.30 Transducer optical position maker mounting disc

The system operated with the stepper motor rotating the transducer assembly 120°

reciprocally and optically detecting the start of scan marker and then applying a count value to provide 8 sectors. When at this count value the transducer disc was reverse rotated back to the start position. The end of scan position optical sensor provided a reset function for start up and over scan limiting.

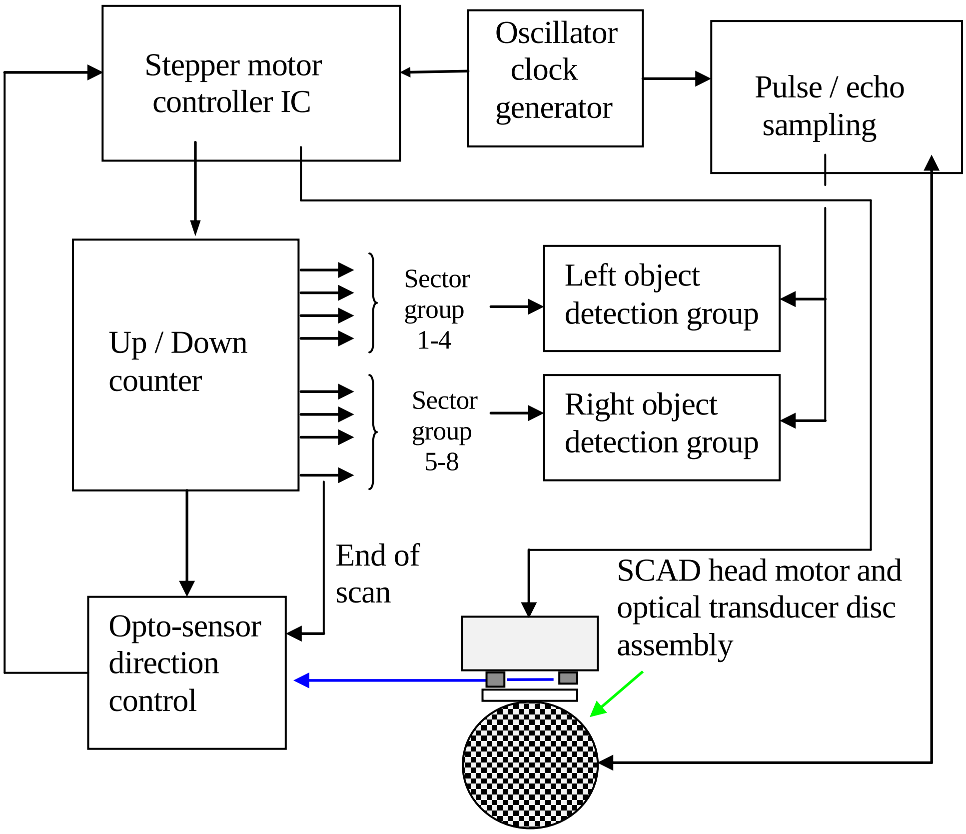


Figure 6.31 Functional diagram of the reciprocal stepper motor control

Figure 6.31 is a functional block diagram of the reciprocal stepper motor control. When the system was first powered up, the position of the transducer and optical disc markers was indeterminate between the two optical position sensors. The motor rotated to find the home position (left side of the scan). When the optical marker was detected by either of the opto-sensors, the disc was returned to the home position. After the first motor step a sound pulse was fired from the transducer, and then listened for a returning sound echo. The next step occurred after the listen period had expired. This process continued and when the count value of the right sector group = 8, the stepper reversed direction toward the home position. Figure 6.32 shows the complete sweep cycle and the number of echo samples involved for a full sweep cycle. The time taken between each step was 33.3 ms.

There were fifteen pulsed / echo samples taken for a complete sweep. The pulse frequency was set to 30Hz and therefore the time taken for the sweep cycle was (15 x 33.3) = 499.5 ms or 2 sweeps per second.

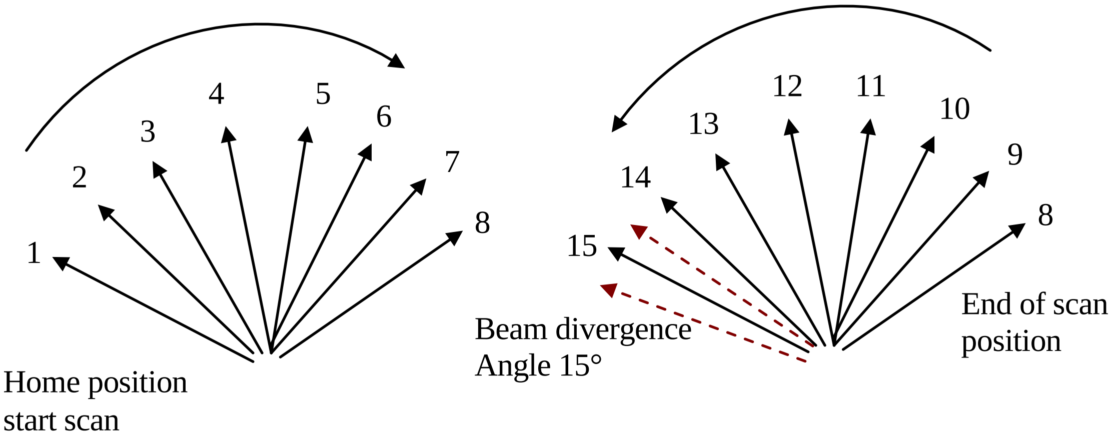


Figure 6.32 Pulse / echo samples 120° step span

To ensure that the transducer was not moving when a pulse echo sample was required, the reciprocal stepper motor control generated a sequence within a time of 33.3 ms to complete a pulse echo sample / step to the next sector. Figure 6.33 shows the order of events necessary for the system to sample the environment for an object in a scan sector. A sound pulse was sent on the rising edge of the timing control. The timing control also provided a set blanking period of 1ms. The transducer membrane still had residual energy (ringing) after the pulse transmission. The blanking period assisted in damping before switching to receive mode for a period of 14.15 ms before the next step.

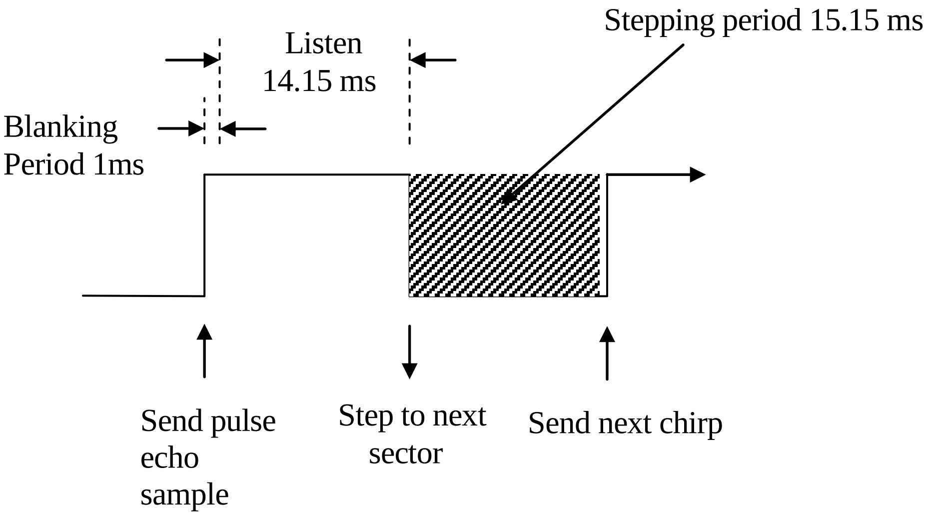


Figure 6.33 Pulse / echo step sampling cycle 33.3 ms

The step period had a time window of 15.15ms. Some magnetic bounce between the poles of the stepper motor was noted and this was affected by the stepping frequency and mass of the transducer and mounting assembly. Work started to increase the number of pulse / echo samples for the complete scan to provide the required 180° sweep.

Increasing the number of pulse echo samples for the object detection scan increased the time required for the complete object detection sample sweep. This was significant in terms of how far the wheelchair moved between object detection updates. Adding the required four sectors provided a total of twelve and increased the scan time by 33%.

The stepper motor control electronics was modified to provide the additional sectors. The scanning process remained the same and Figure 6.34 shows the modified scanning control electronics and the re-grouping of the scan sectors from four to six sectors in each group and the end of scan count number that was similarly changed from eight to twelve. This necessitated making changes to the position of the end of scan opto-detector because the transducer disc now rotated the extra 60º or more (to detect the disc marker).

As the transducer rotated to the end of scan point the count value of 12 triggered the change of transducer rotation to return to the home position. The end point optical detector would not be triggered unless an abnormal condition occurred.

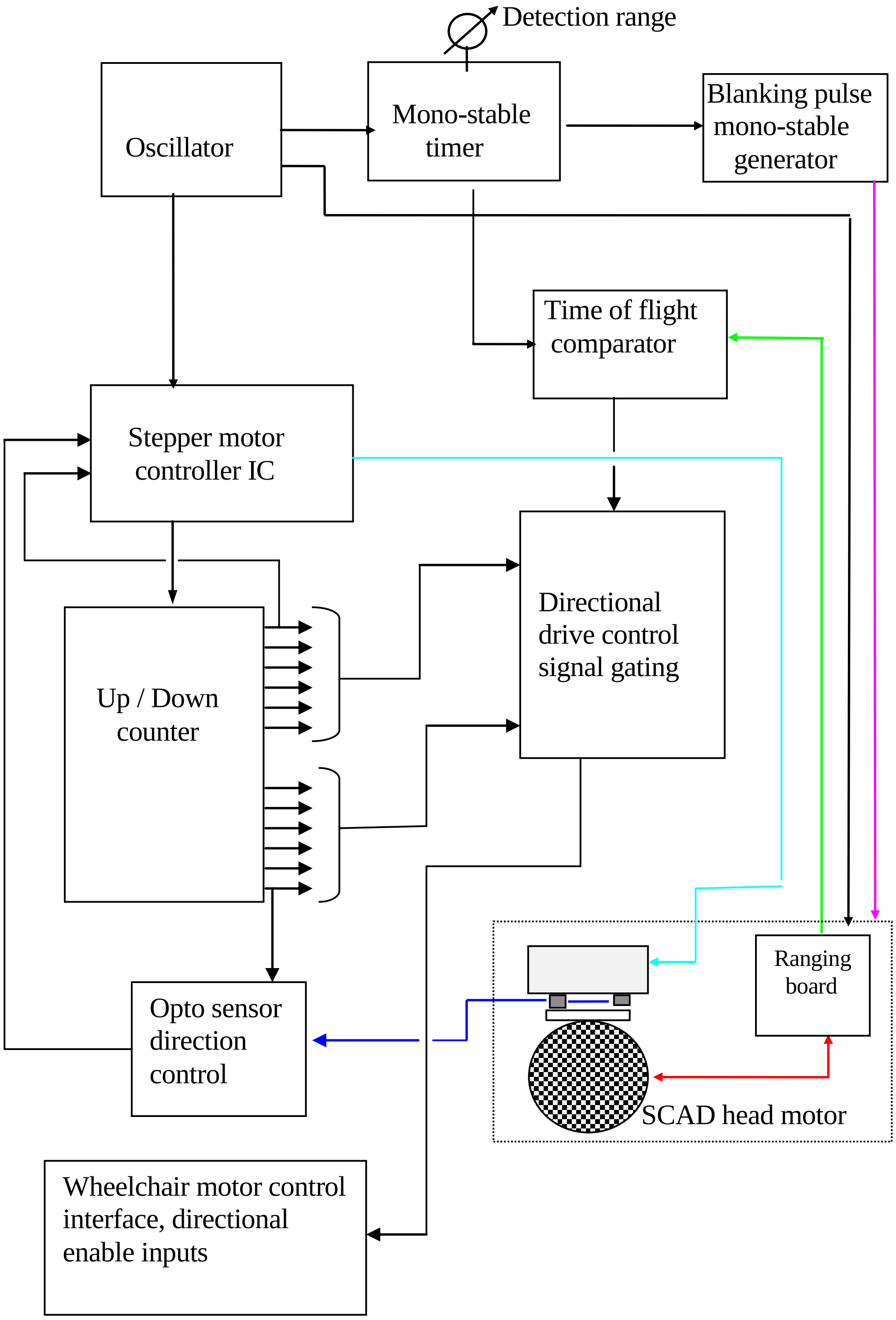


Figure 6.34 Scanning control re-development to provide twelve scan sectors

The modified scan pattern is shown in Figure 6.35

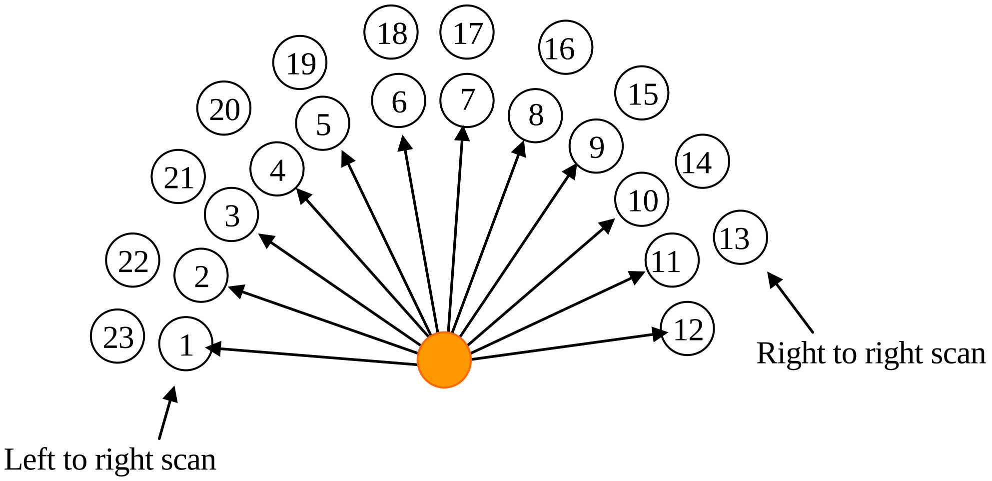


Figure 6.35 Adding sectors to provide a 180° scan

Although adding in the extra sectors provided the required symmetrical detection on the left and right side of the wheelchair, the slower update time caused the chair to get closer to objects before they became detected. Consequently collisions occurred because of late detection. The advantage of the increased scan width provided notable benefits to the system functionality. Late object detections were partially compensated for by increasing the detection range as opposed to decreasing the wheelchair speed, which would have frustrated many users. This improved the guidance function, but restricted driving through doorways, because the total scan was greater than the doorway width. A method needed to be developed to permit doorway navigation without reducing the detection range for wall detection guidance.

There were a number of interrelated factors that affected the speed at which objects were detected in the path of travel: The wheelchair speed, sporadic object detection and where the object was first detected with respect to the scan cycle.

The wheelchair speed was a critical factor in collision control. It was also notable that some children preferred to go at a slower speed as this provided them with more personal time to take control actions for themselves. Some people became frustrated by these imposed slow speeds. Later research work developed systems that applied a pre-slowdown function before collision control action occurred.

Occupational therapists, teachers and carers would feedback information about how children were coping with their driving and the most appropriate driving speed was determined. Measurements were obtained by driving a wheelchair between two points of known distance and recording the time taken. Wheelchair drivers were divided into 4 skill groups and their range of speeds in (meters per second) were recorded and put in Table 6.2.

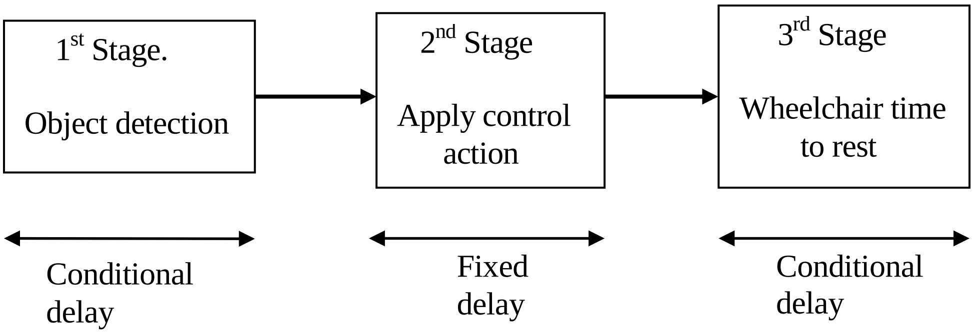
Driver type	**Low speed**	**Ave speed M/ Sec**	**Higher speed**
First timers	0.2	0.34	0.48
Improvers	0.30	0.475	0.65
Competent drivers	-	1.1	1.1
Highly skilled drivers	-	1.8	1.8

Table 6.2 Wheelchair driver speed table

It was noted that the drivers who were competent and highly skilled were provided with variable speed joystick controls and therefore their lower speeds were not recorded, because this was conditional upon the driving situations. It was also observed that young people using specialised control systems for example, single switch direction control scanners did not attain the higher speed values and consequently fell within the improvers group, but clearly demonstrated high order driving skills.

Those that were first introduced to powered mobility were provided with speeds that measured in the region of 0.3 meters per second. This provided more time for system control. Problems were encountered with speed stability as the wheelchair driving speeds were now operating at the lowest speed range capabilities of the wheelchair controller.

When the wheelchair was travelling forwards and first detected an object there were three stages of control action and each of these stages imposed delays.



Object detection delay was comprised of several variable factors. They were of different importance. Small variables were: Time of flight object ranging delay small variables; Propagation of sound in air at 3.33 ms/meter; Atmospheric pressure changes; and temperature / humidity. These small variables were not considered further because they appeared to be too insignificant for any changes that could be made through system development.

A medium variable was the pulse repetition rate of sample echo. The Polaroid Ranging interface circuit board generated a burst of 16 needle pulses necessary to resonate the transducer membrane at approx 50 KHz for the transmission of the sound chirp. Figure 6.36 is a signal trace that shows the 1 ms blanking period in relation to the transducer pulse burst.

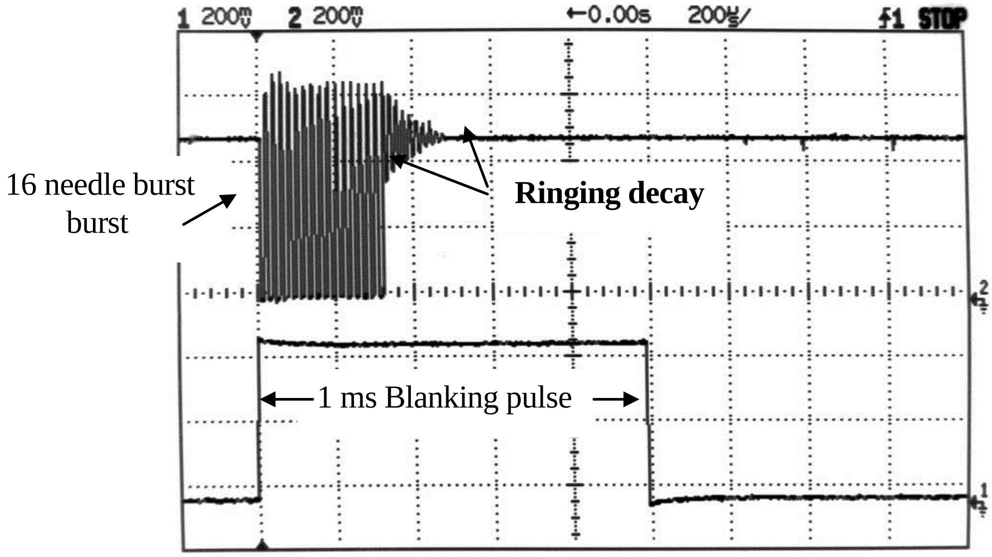


Figure 6.36 Oscilloscope timing trace transducer signal burst

The trace shows the transducer still has some ringing energy that decayed after the burst. This must not trigger the receive output latch once the blanking period had expired and the receive mode enabled.

Due to the problems associated with false echo detection (ghosting) time was discarded in the process of pulse / echo sampling and in the test development system the pulse echo sample time was limited to 33.3 ms. Figure 6.37 shows the chain of events for a single object detection sample for an object detection range of 1 meter and the amount of time (33.3 – 8) 25.5 ms, that was available for the transducer stepping period.

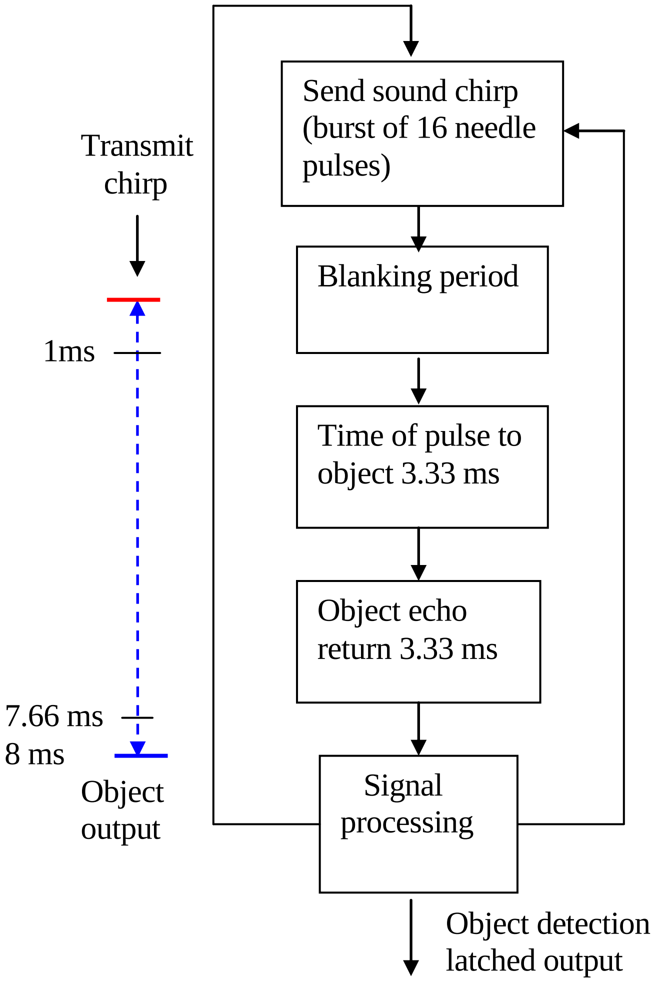


Figure 6.37 Pulse / echo sample events delay event diagram

A significant variable was the sweep cycle delay. The largest single factor contributing the object detection delay was where a potentially detectable object was placed in relation to the transducer scan position prior to its first detection. Figure 6.38 shows the scan sectors and the time values for the purposes of a general assessment of the maximum time before detection.

An assumption is made in statements (a) and (b) that an object appears at 1 meter from the transducer in two separate situations:

a) The object appeared in the sector 1 at the time the chirp was transmitted. This resulted in the object being detected after 8 ms.

b) The object appeared in sector (1) 8 ms after the chirp was transmitted. The object would not be detected until a full sweep had been completed (22 X 33.3) = 732.6 ms. This represented the worst case.

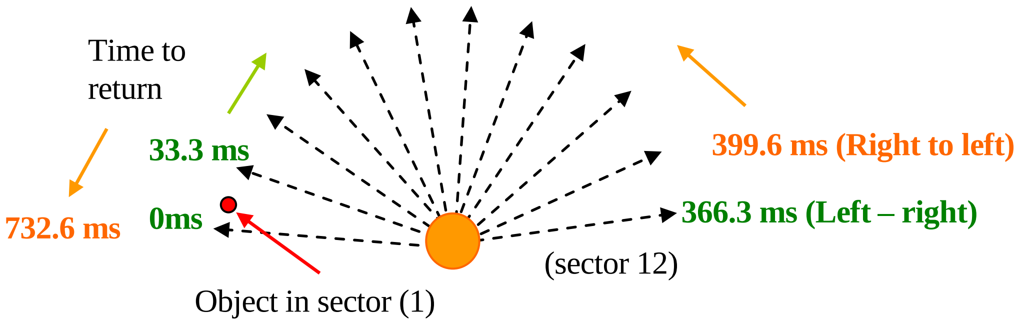


Figure 6.38 Scan sector timing

Figure 6.38 shows that there was considerable variability in the time taken for an object to be detected. The worst case value of 732.6ms for object detection referred to the extreme side sectors. The most significant issue was how far the wheelchair moved before the object was detected. When the wheelchair was being driven forwards the closing speeds for objects at the side of the wheelchair was less than if the object was directly in front.

When the wheelchair was turning the closing speed was more significant for the side sector positions due to the rotational speed of the chair. Figure 6.39 shows a measured value of turning radius obtained for a practical spin and arc turn for a test wheelchair.

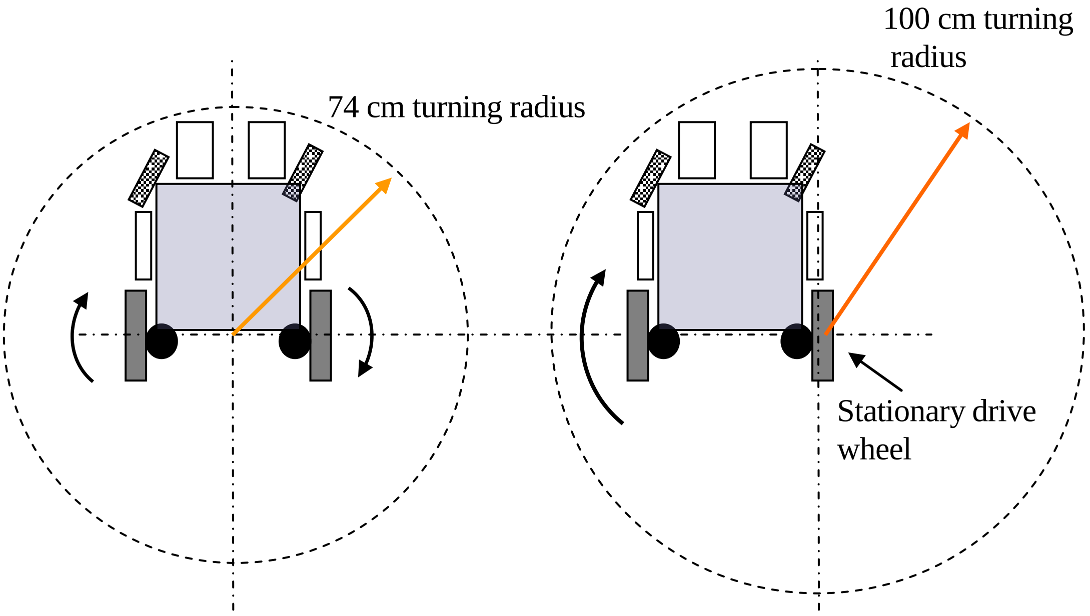


Figure 6.39 Spin and arc turn comparison for the test

When the two drive wheels were contra-rotated at the same speed an arc turn was produced and provided the smallest practical turning circle. When the wheelchair rotated about a stationary drive wheel the turning radius increased to produce an arc turn.

Observations of children driving indicated that that a fixed turn was not ideal for all driving situations. For drivers that had proportional control, the turn radius was applied according the driving situation and varied from a straight line, where both drive wheels rotated at the same speed, through to contra-rotating drive wheels that provided a spin turn. This translated into independent control of turn speed and turn radius. For the purpose of comparison, commercially available systems (Dynamic Controls) provided control of a wheelchair via switches. It was noted that there were two distinct turning modes. When operating a single turn control switch the system applied a ‘spin turn’ as shown in Figure 6.39. When the forward and turn controls are jointly operated the system applied an arc turn. Interestingly this provided a choice of turn mode that could be used for turning on the move and turning when stationary. Observations indicated that the spin mode applied a hard turn whilst the arc mode applied a soft turn.

For the purpose of evaluation the test wheelchair control interface was developed to provide a selectable mode of turn for a hard or soft turn respectively. Young drivers were tried with the options of a hard or soft turn and their driving was observed. The differences were subtle. It was noted that drivers using hard turns tended to drive with more start stop cycles than when driving with soft turns. Interestingly there was a perceived forwards component to a soft ‘arc turn’. A spin turn was perceived as a rotation and consequently required greater precision for steering corrections. The general feeling amongst young drivers and assistant helpers was that the soft turn option was generally more user friendly and accordingly the soft turns were applied on the research wheelchair for further work.

The suitable turning speed for drivers who were novices or improvers was measured and was in the range of 10 – 15 seconds for a full 360° turn. Interestingly many drivers preferred to keep their turn speed the same even when their forwards drive speed was altered of increased, particularly for those who stopped after each directional control action. It was important for the object detectors to be able to operate effectively at the driving speeds that were suitable for a young person. For switch control, the wheelchair speeds were held at a fixed value. The distance between the centre axis of the right or left drive wheel to the scanning detector was measured to be 0.8 meter on the test wheelchair and shown in Figure 6.40.

Three right side sectors only are shown for illustration

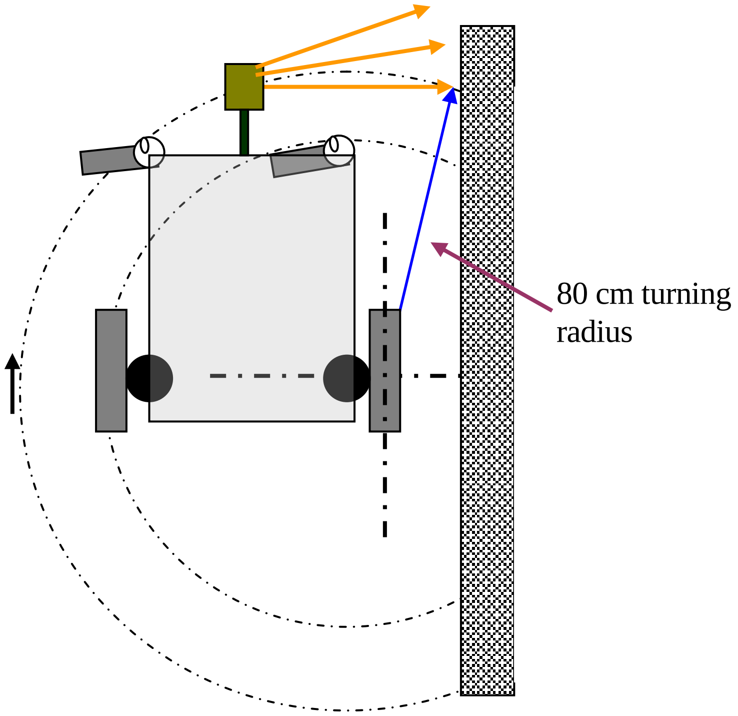


Figure 6.40 Approximation of turning speed for object detection

Due to the differing individual preferences and driving habits of young people, accurate closing speeds to objects was difficult to obtain. It was noted that results obtained for system testing in the laboratory differed to those obtained with children. Young drivers did not have system testing and colliding with objects in mind and observations of children driving suggested that they could spontaneously change their control actions which made system operation less predictable.

An approximate evaluation is shown in Figure 6.41. This reflected the practical performance obtainable from the test system when the intention was to collide with an object.

To determine the circumferal speed, the turning radius on the test wheelchair was 80 cm x 2 (Pi) = 502cm. The test wheelchair took approx 12 seconds to complete a full turning circle. The circumferal speed = 12/502 = 41.83 cm / sec. To derive the late detection variation distance, the worst case time for object detections was 732.6ms therefore 41.83 x 0.732 = 30.6 cm. This large variation was a significant system weakness, and was often responsible for collision with objects particularly at the side of the wheelchair.

When the wheel chair was turning the scan sectors covering the opposite direction did not serve any purpose as they would be moving away from a potential object. During a turn, only six of the scan sectors provided a detection function in the direction of the turn. Time was wasted in scanning the unnecessary sectors during the turn.

Figure 6.41 shows the left group of sectors did not provide a useful function for the right turn where the arc of the turn moved the left hand sectors away from objects.

This reasoning was also applied for a left turn when the right six scan sectors are moving away from objects on the right side of the wheelchair.

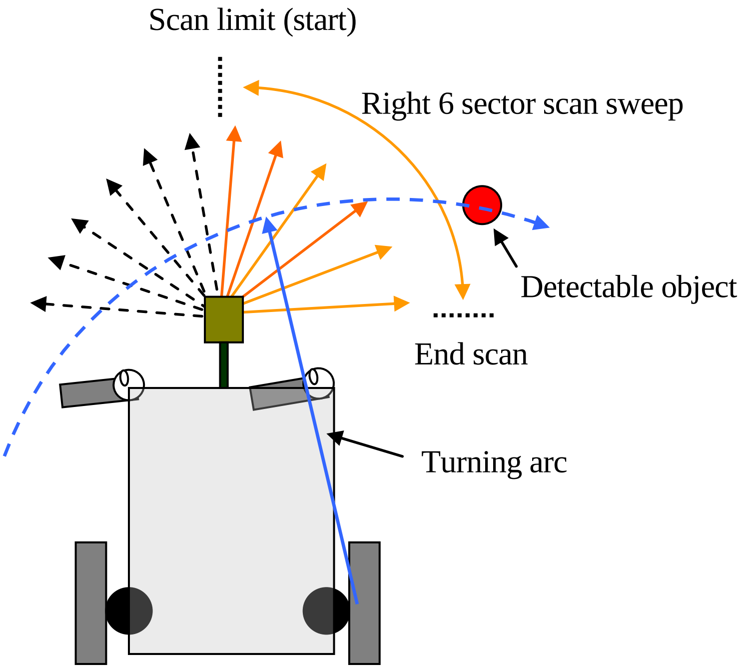


Figure 6.41 Right turn side sector scanning

6.7 Adapted object scanning control logic during turning

The scanning control electronics was modified to shorten the scan cycle time whilst turning in order to reduce the object detection time when the wheelchair was turning. Adapting (halving) the number of scan sectors was applied only when a turn control switch was operated. The pulse echo sampling rate and step frequency remained the same.

The scan cycles reverted to the full sweep of 12 sectors when the forwards control was operated. Figure 6.42 shows the modified part of the scan scanning control system. The resulting adapted scan function reduced the scan cycle time from 732.6ms to 333 ms.

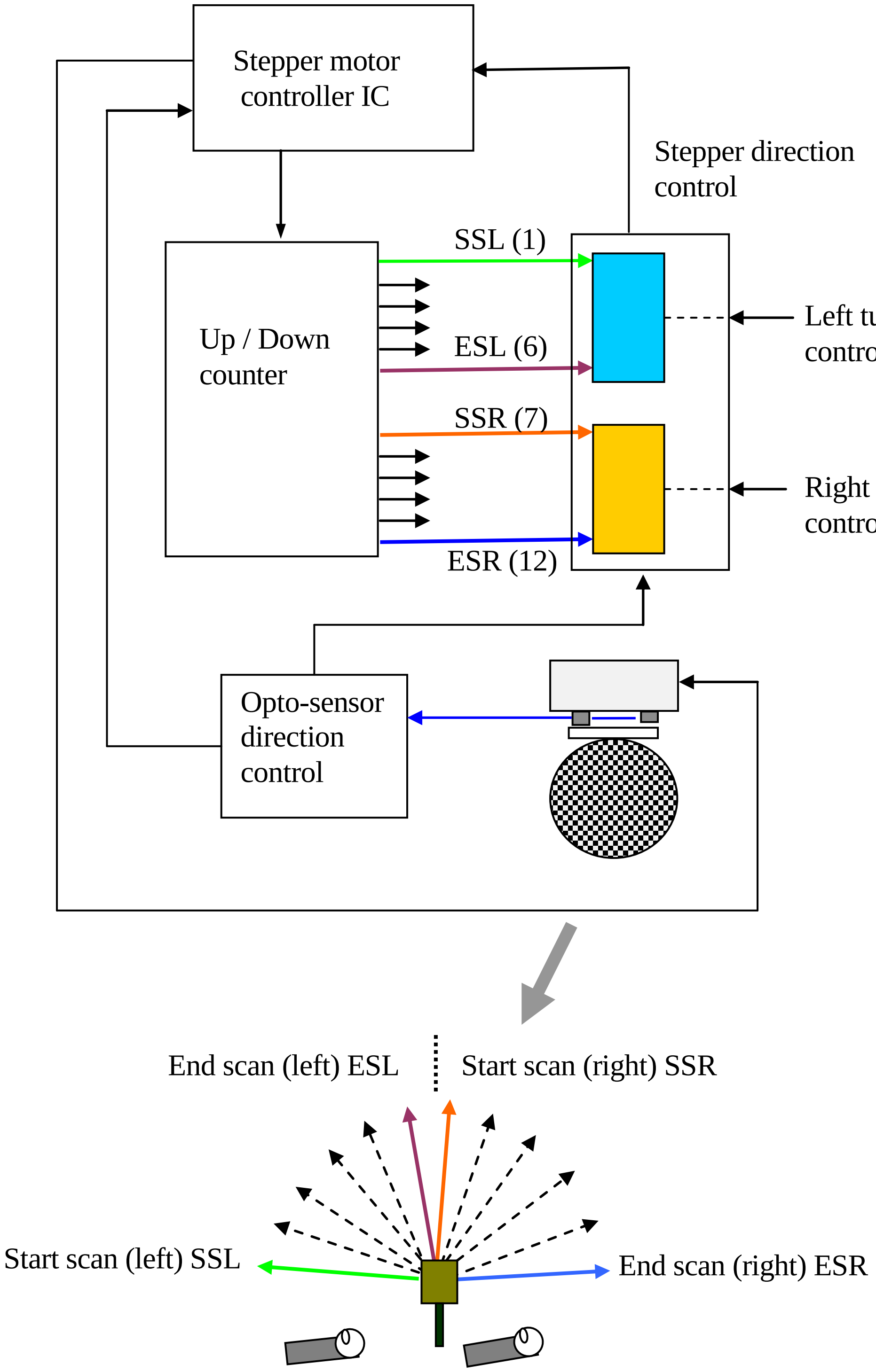


Figure 6.42 Adapted half scanning control diagram

Scan operation for a left turn. When the left turn control switch was operated the control logic was set to scan between a count value of 1-6. The start scan point corresponded to the normal home (reset) point on the transducer optical disc. The end of scan 'left' was represented by a count value of (6). This acted as a reset point and the stepper motor direction was reversed and returned the transducer disc back to the (home) start point of the scan. This process continued for the duration of left switch control operation.

Scan operation for a right turn. When the right turn switch was operated the end of scan point remained at the normal scan end point count value (12). When the transducer disc rotated to this point the direction the transducer direction was reversed to rotate the transducer back to the home position. This was set to the count value (7) at start of scan ‘right’. The scan was operating between count values of 7 – 12, and this continued for the duration of right switch control operation. When the turn control was released the scan reverted to the full twelve sector sweep and operated between the normal home position at start left scan point (1).

The object detector was sending pulses at 33.3 ms intervals. If an object was detected in a particular sector there was 33.3ms until the next pulse echo sample. A large object could be detected in the next sector and therefore the object detection period could span 66.6 ms. 33.3ms was the minimum time for a momentary object detection. This time period was not sufficient to apply a sustained control action for wheelchair collision control. It was necessary to stretch the object detection period to enable the wheelchair control system to respond. When an object was detected during the sweep an object detect latch was set, but only for the complete sweep period. If the object was detected again in the next successive sweep, the latch was re-triggered and the object detection state was held active for the control system to apply a steering correction or stop the wheelchair.

Not all objects were ideal reflectors and the reflecting surface of the objects could vary with respect to the sensing transducer particularly when the wheelchair and sensor system was moving. Due to the cyclic nature of the object scan, some objects that either had a small reflecting cross sectional area or those that were larger but reflected most of the ultra-sonic energy away were not detected repeatedly for each scan sweep. If an object was detected on every sweep, momentary control was applied for collision control.

Evaluation of the scanning method highlighted factors that increased the object detection time and this was related to where the object was with respect to the scan cycle. The most favourable object position was the mid point of the scan.

The SCAD was scanning for objects in the path of travel. When an object first became in range the point of detection was dependant on where the transducer was looking in the sweep cycle. There were delays that all contributed to the time taken for the wheelchair to stop or change heading to avoid a collision after an object had become within the detection range. Other conditions were:

- Scan cycle to object detection delay
- Time of flight echo ranging echo delay
- Speed of the wheelchair
- Deceleration time, when switch released
- Applied system damping
- Motor compensation
- Payload

6.8 Determination of the wheelchair steering avoidance control

Video recordings were made of a group of skilled wheelchair drivers that used variable speed control joysticks and those that used switches. When a young person had well developed hand function (fine motor skills), joysticks had the advantage of translating personal control actions into accurate speed and steering control.

Many children taking part in this research did not have sufficient ability to use a joystick effectively. Observations of how children used switches to control their wheelchair steering highlighted many differences. Due to the complex nature of a young person’s disabilities, some critical factors affected how children operated their switches. The design of the control system needed to take account of this. The wheelchair was operated by pressing a switch to activate driving for forwards, backwards or turning. The control was momentary in which driving operation at a fixed speed occurred so long as the child sustained enough operational force to activate the switch.

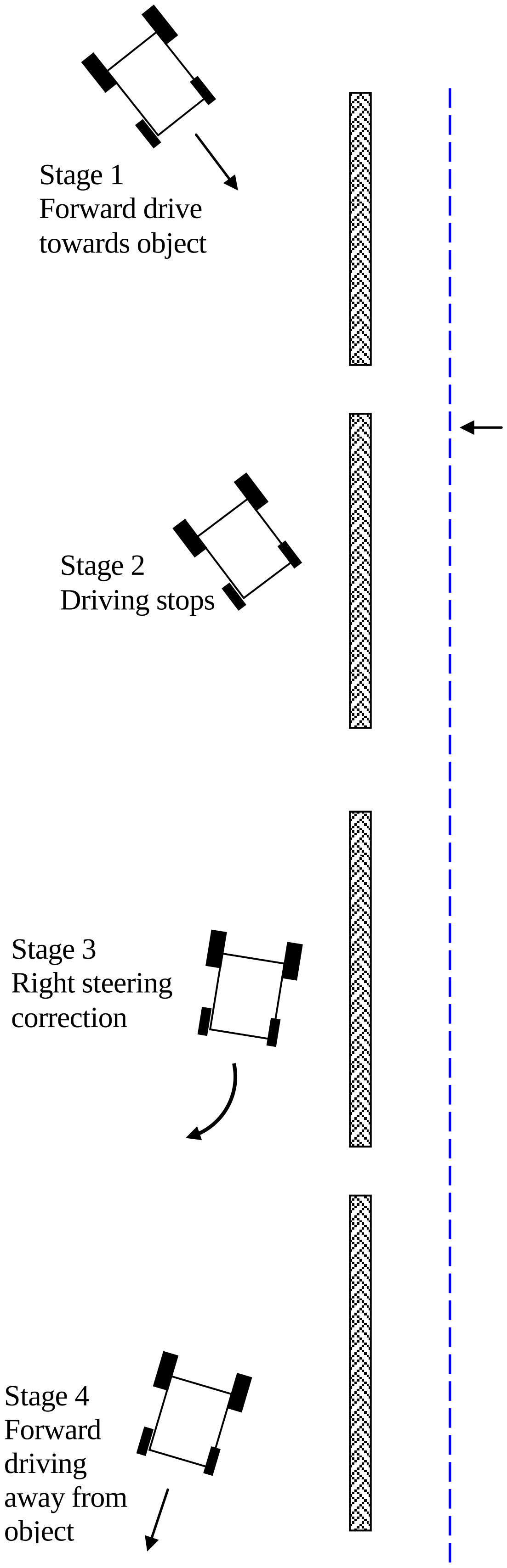


Figure 6.43 Stopping after each control action

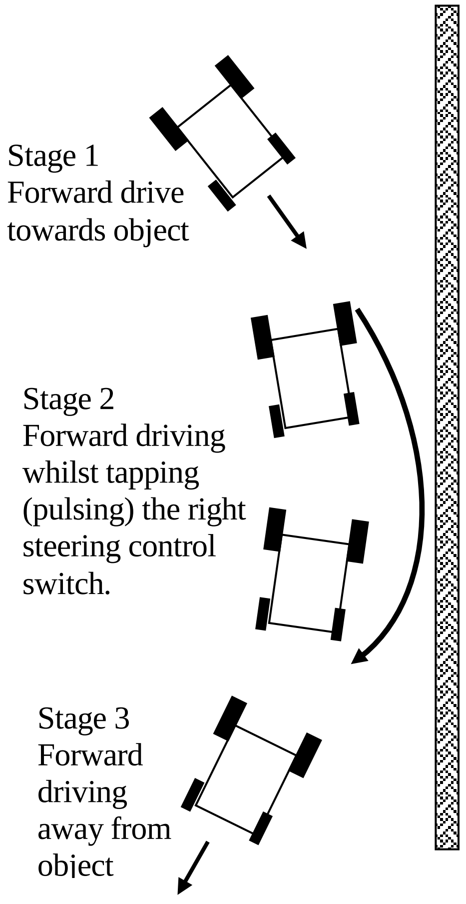


Figure 6.44 Forwards driving whilst pulsing the right steering switch

Interestingly, proficient drivers using switches managed to control their driving speed similar to joystick users. Switch control demanded accurate timing and anticipation skills, because there was no gradation of speed. Children learnt to control their speed by varying switch press time intervals and effectively pulsing switch operation. Further observations showed that some drivers would stop after each control action. Figures 6.43 and 6.44 show possible control sequences that would be exhibited by proficient child drivers who used switches. The example shown in Figure 6.44 progressed more quickly and smoothly than the example shown in Figure 6.43 where time was lost because of starting and stopping.

The logic of switch control was examined and there were three basic interfacing differences:

- Forward + Turn = Forward
- Forward + Turn = Turn
- Left + Right = Forward

} Favoured by advanced drivers for steering on the move

An understanding of the effects of switch control logic was significant for the application of the collision avoidance system. The first system was based on an interrupting switch control function where: Left + Right = Forward. Figure 6.45 is a simplified functional diagram.

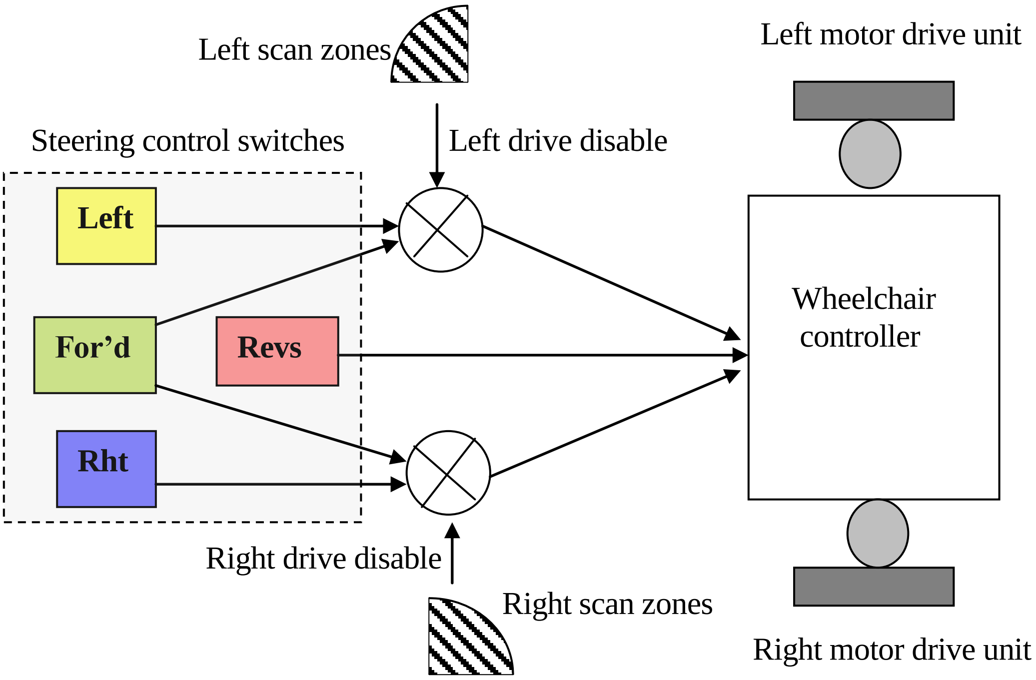


Figure 6.45 Simple direct test collision control interface

The rudimentary control system shown in Figure 6.45 provided steering control commands in response to detected objects. For example, if an object was detected in the right scan sector, the driving control output from either the right or forward switch was disabled thus stopping the right direction wheelchair drive motor. The process was the same for the left control detection zones. If an object was detected in both of the scan zones, all forward drive functions were disabled and the only active control was reverse. A simple interface was constructed. The first collision avoidance systems applied the wheelchair steering control action when an object had been detected. The avoidance control continued to be applied so long as the object was detected and the driver was operating their control switch. The wheelchair was steered away from the object. Steering control ceased when the object was outside of the set range. The position and size of the object affected collision control. The control action was applied in bursts as a natural result of the transducer scanning action.

The application of the steering avoidance control affected the wheelchair trajectory after the control intervention. The collision control system avoided the collision, but the exit course was uncontrolled and children were over deflected and consequently ‘cut up’ other drivers and people in the corridor. It was necessary to consider the effect of collision control intervention, particularly the post collision intervention course that was an un-intentional result of driver control and regarded as an ‘intervention hangover’. The approach angle to a wall was variable and this affected the leaving angle. Figure 6.46 and Figure 6.47 show the observed results of collision control interventions for the early test system.

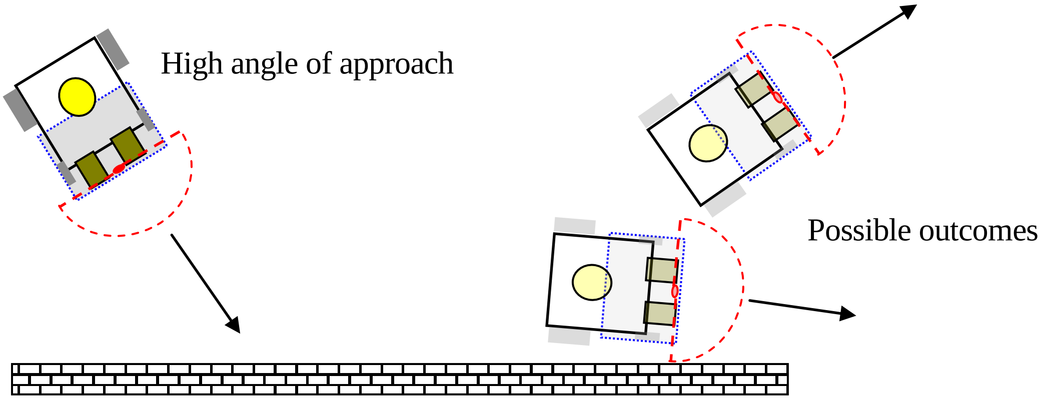


Figure 6.46 High angle of approach with variable outcomes

The over correction problems often resulted from the application of sufficient avoidance steering control necessary for the wheelchair to avoid a collision when on a steep 'head-on' type collision angle. In a situation where the approach angle was small, the avoidance system applied a harsh correction which resulted in an over-correction, as shown in Figure 6.47.

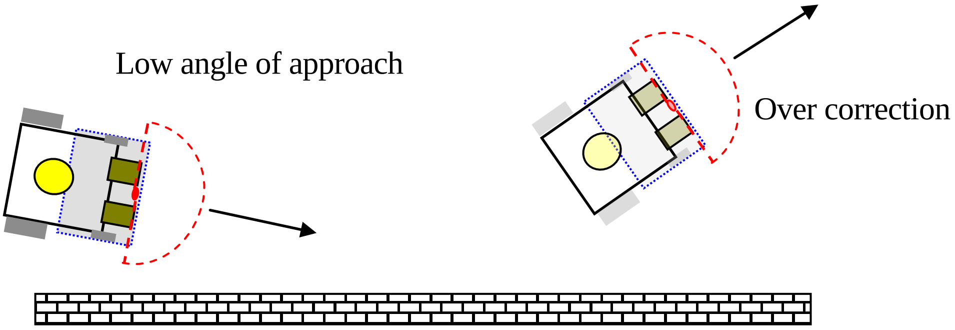


Figure 6.47 Low angle of approach over corrected outcome

Considerations about the desirable leaving angle trajectory were based on not knowing the intention of the driver. The applied control action needed to be as neutral as possible and based on the system applying the minimum necessary amount of correction. Sometimes drivers wanted to steer into objects and sometimes wheelchair veering caused the driver to make extra unwanted control actions. Veers were often caused by casters swivelling due to surface gradients (slopes), carpet piles and motor control imbalances. Some work on veer control is described in Chapter 3.

The control system was modified to apply a proportionate amount of collision avoidance control depending on the approach intercept angle. Collision control was applied by retarding one or both of the drive wheels.

When the wheelchair was being propelled forwards, both drive wheels were rotating at the same speed as shown in Figure 6.48. To implement a turn function, Figure 6.49 shows that when an object had been detected, one of the drive wheels rotated at a slower speed with respect to the other.

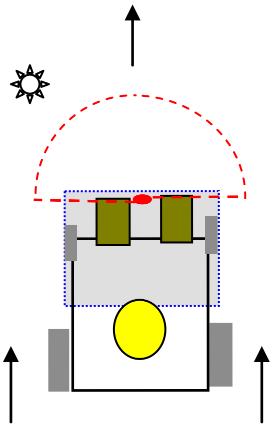


Figure 6.48 Object not detected, both drive wheels rotated at the same RPM

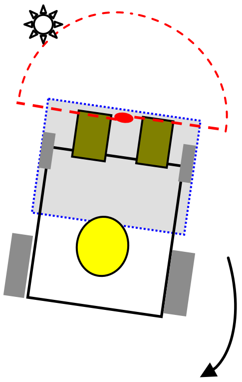


Figure 6.49 Object detected on the left, system responded by reducing Right drive wheel RPM

The resulting turn function enabled the wheelchair to avoid the object. To provide effective system control, the amount of drive wheel slowdown (retardation) was related to the sector where the object was detected within the scan field.

Figure 6.50 shows the system response variation between the object placement sector and the drive wheel retardation rate for the left side object detection. (For the purpose of simplification the left scan zone only has been shown).

The function is similar for the right scan. This has been colour coded for each of the six scan sectors.

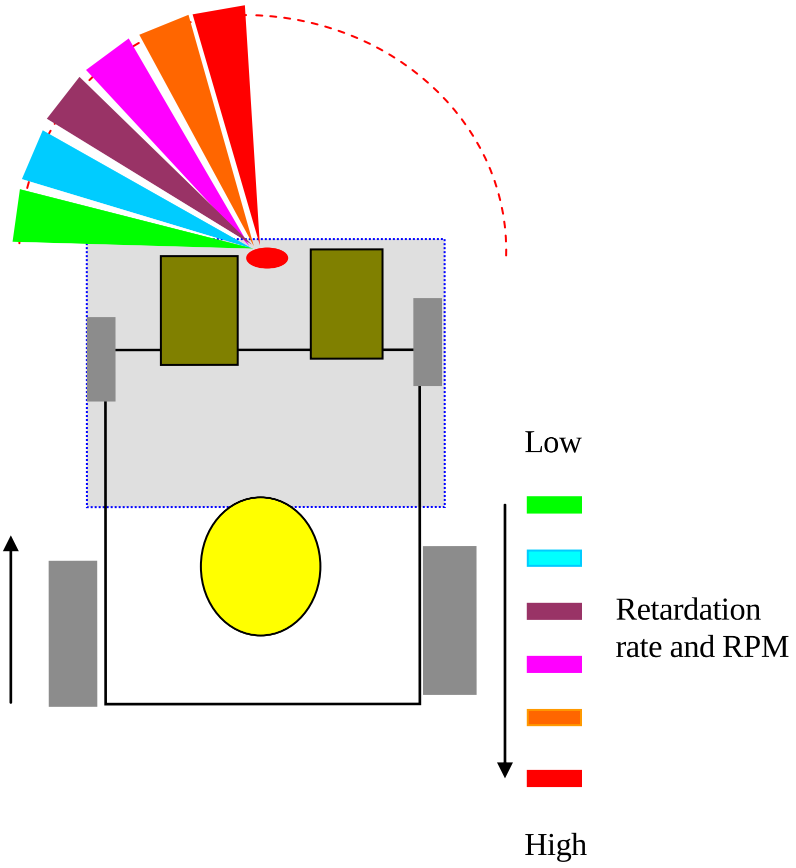


Figure 6.50 Proportionate collision turn avoidance

An object detected in the red sector represented the maximum retardation rate. This forced the drive wheels to contra-rotate. The green sector provided the minimum drive wheel retardation and therefore the system applied the minimum amount of avoidance turn. When an object was detected across both of the left and right sector zones, both of the drive wheels were forced to reverse rotate and consequently the wheelchair backed away. The retardation control was applied in bursts with a defined mark-space ratio.

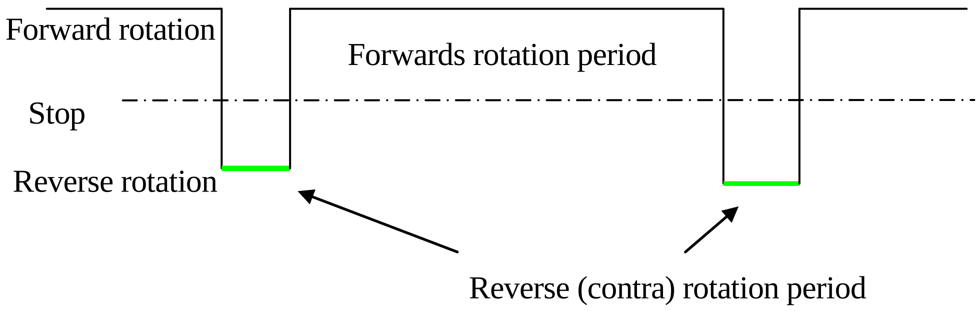


Figure 6.51 Gentle object avoidance turn

Figure 6.51 shows the applied (minimum) avoidance direction control in which the forward rotation period is significantly longer than the reverse rotation period represented by an object detected in the green sector.

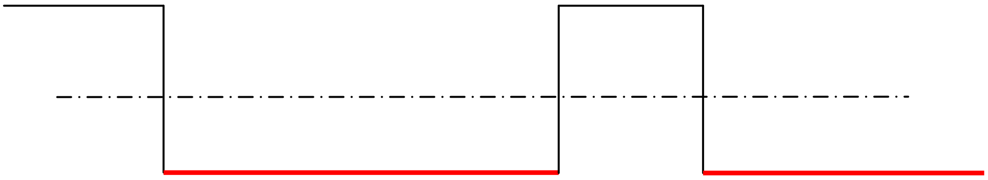


Figure 6.52 Maximum object avoidance control

When an object was detected in the red (front) sector, the period of applied reverse control was greater than the forward period, therefore the drive wheel was forced to reverse rotate and applied maximum object avoidance as shown in Figure 6.52. Figures 6.51 and 6.52 show the instantaneous control voltage change that was applied for motor control. These step changes translated into an acceleration and deceleration period that was necessary for the drive wheels to change their speed of rotation. The DX control programming tool is shown in Figure 6.54. This enabled the system to apply pre-programmed acceleration and deceleration times. The amount of drive acceleration and decelerations were set by this system programme value and this was set within the DX control power module. The acceleration and deceleration tendencies are shown in Figure 6.53.

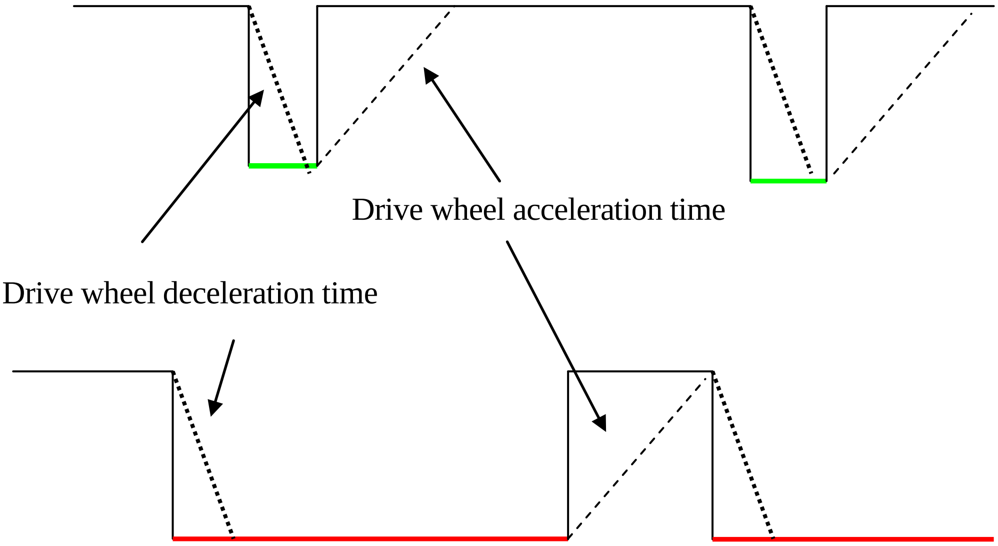


Figure 6.53 Wheelchair drive wheel rotation acceleration and deceleration time constants

Figure 6.54 is a picture of the Dynamic DX hand programmer used to set the parameters.

Setting the turn deceleration time to 100 % provided the fastest system response.

Figure 6.54 DX controller hand held programming tool

6.9 Non-steering intervention SCAD

A Variation of a trackless SCAD object detection system was created for a young boy driver who was competent but had lapses in concentration and would drive into things. He used a standard proportional joystick controller. The SCAD system limited his drive speed in confined spaces, particularly when entering doorways. Profiling the scan zone reduced the restrictive nature of the system but crucially provided advanced warning of an approaching object in the forward line of travel. The SCAD object detection intervention applied a speed reduction when an object had been detected within the profiled scan zone that had three separate range values. The complete scan sweep consisted of 12 pulse /echo samples.

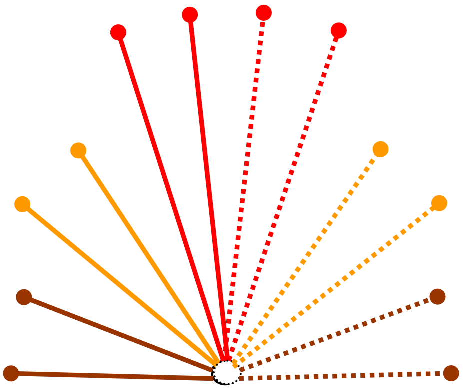


Figure 6.55 Three left side scan zone pairs and three right side (mirrored and shown dotted)

This was divided to provide a left group of six samples and a right group of six. The zone profile consisted of sector pairs. Figure 6.55 shows the pair grouping and the three range zone groups. Figure 6.56 shows the zone conditioning electronics to generate three preset range values.

The left scan zones in Figure 6.55 are shown as solid lines and the right zones are shown as dotted lines; they were a mirror image of the left. The slow-down mode of operation did not require positional detection of the object with the horizontal SCAD field.

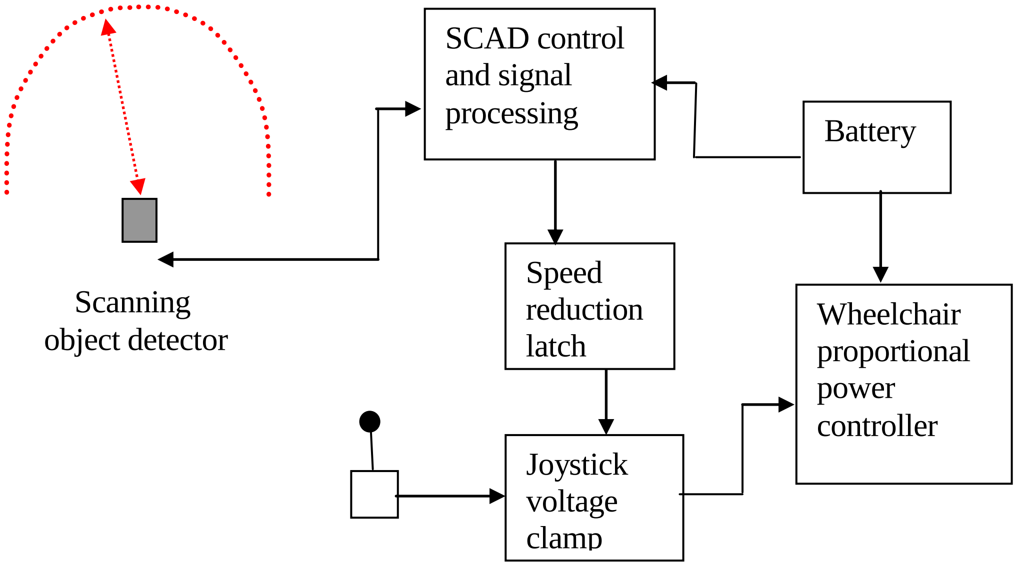


Figure 6.56 Object detection and speed reduction system

Figure 6.56 show a control interface for the slow down system that was built. The zone ranges were set by using a timer that generated a delay period for the time of flight object ranging. A time comparator provided an object detect pulse if an object was detected before the set time period had elapsed. When the transducer assembly was stepped through each zone sector pair, the pulse/echo time delay interval was switched to provide three separate target distance values for the zone groups.

When an object had been detected then the maximum speed for the wheelchair was limited. The electronic interface clamped the joystick output voltage, therefore reducing higher speed. Once the speed reduction system had been triggered it could be reset by releasing the joystick knob so it could return to the neutral stop position. The speed reduction latch was reset only when the joystick was at neutral and no objects were detected. If an object was being detected then the system reduced and limited maximum drive speed.

The latch was necessary to prevent drivers being taken unawares when acceleration (to return to a faster speed) could be suddenly restored when not close to objects (as there could be momentary gaps in object detection particularly concerning confined areas).

Chapter 7

Initial testing of the SCAD

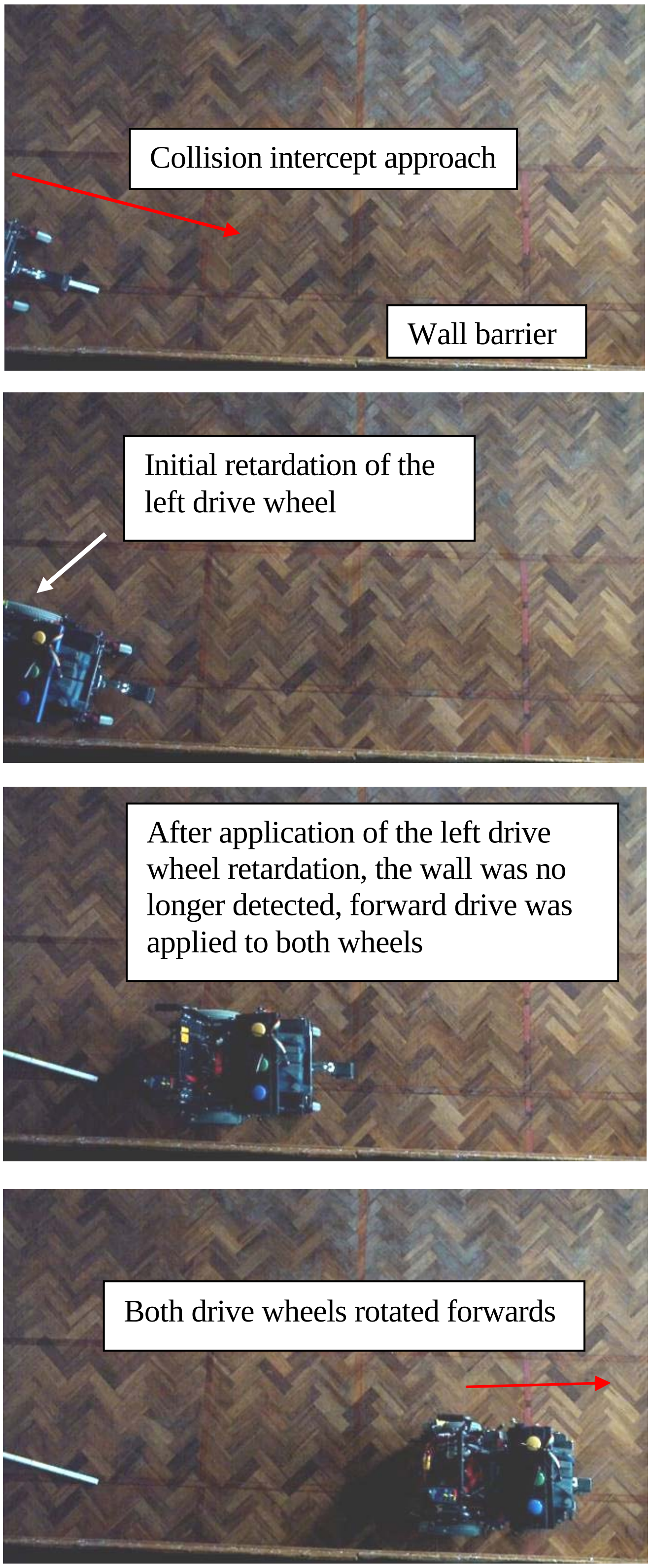
This Chapter describes the transition of the collision avoidance system from the laboratory environment to real world; the children's familiar environment. The collision control system was developed by successive trial applications including collision avoidance testing. Real life driving issues are discussed, in which the SCAD system needed to provide an adequate level of driver support.

An understanding of the human versus automatic system was formed and professional people concerned with child development had strong views regarding the application of assistive technology. A main parameter of SCAD operation was that it offered a variable level of driver support. There was a requirement for the system to be adaptable, particularly to take account of the complexities of the children's personal difficulties and obstacles encountered in the real environment. An example of this, was the creation of automatic object range contraction to enable the wheelchair to pass through doorways, which would have been prevented by a fixed range system. The concept of effort reduction began to develop when collision avoidance control was provided for young drivers using single switch direction selection.

7.1 SCAD before and after avoidance control intervention

Collision avoidance tests were conducted in a school hall and recorded using a digital video camera operating at 30 frames per second. The camera was mounted eight meters above the floor over a stage wall that provided a detectable surface. The wheelchair was set on a collision course with the stage wall at various intercept angles. Forward drive control was operated by a lump of blutac that enabled selection of sustained driving. Multiple trajectory tests were carried out. Three of the test runs are shown for low angle in the range of (0˚ to 20˚), mid angle (20˚ to 45˚) and high angle (45˚ to 80˚) wall collisions. Repeated collision tests were carried out and some are shown for the purpose of illustration. The amount of collision intervention has been shown in Figures 7.1 to 7.4.

Low angle collision control sequence



Phase 1
Wheelchair enters collision situation, pre collision intervention

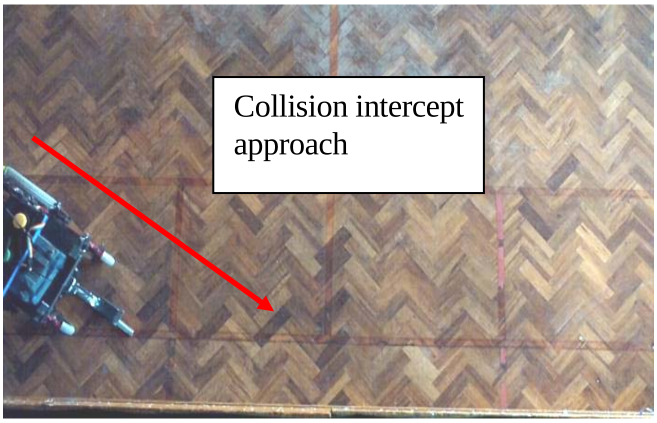
Phase 2
The wall object was detected and initial proportionate turn correction was applied

Phase 3
Completion of the initial proportionate avoidance turn. The wall object ceased detection

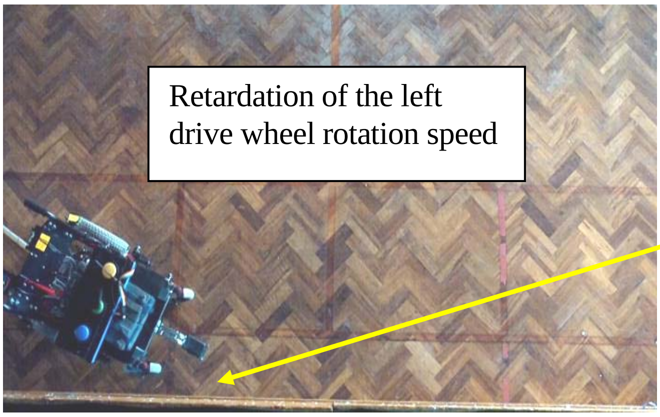
Phase 4
Wheelchair exit heading after the collision intervention. Forward drive was applied to the left and right drive wheels

Figure 7.1 Low angle collision intervention

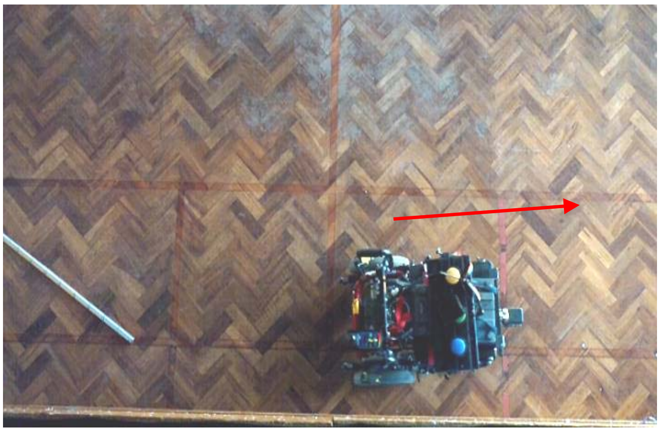
Mid angle collision control



Phase 1
Pre-collision control
Intervention



Phase 2
The wall was detected,
and the castors swivelled
in the direction of
wheelchair turn

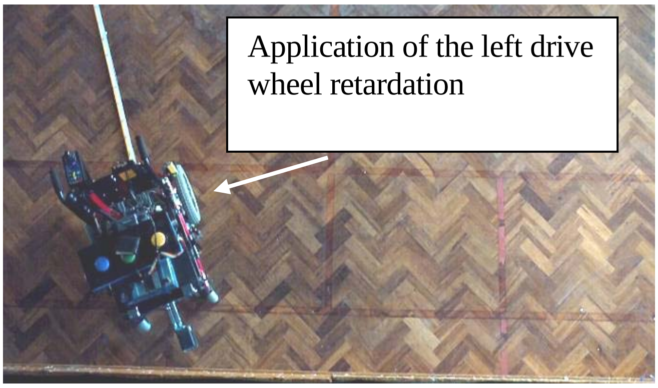


Phase 3
Wheelchair on
exit heading

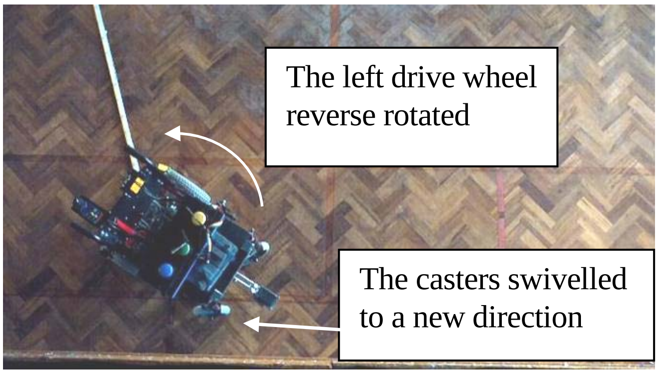
Figure 7.2 Mid angle collision control

High angle collision control

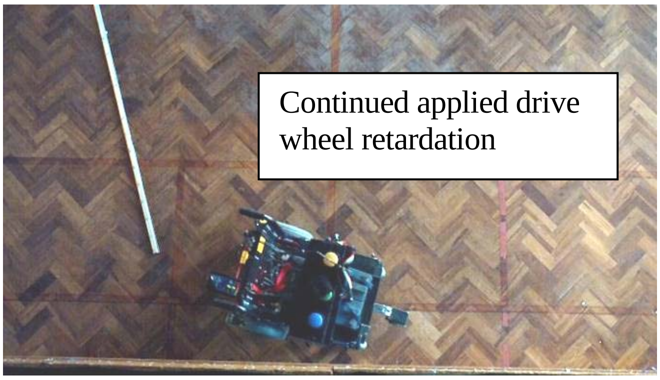
Phase 1
Pre- collision control intervention



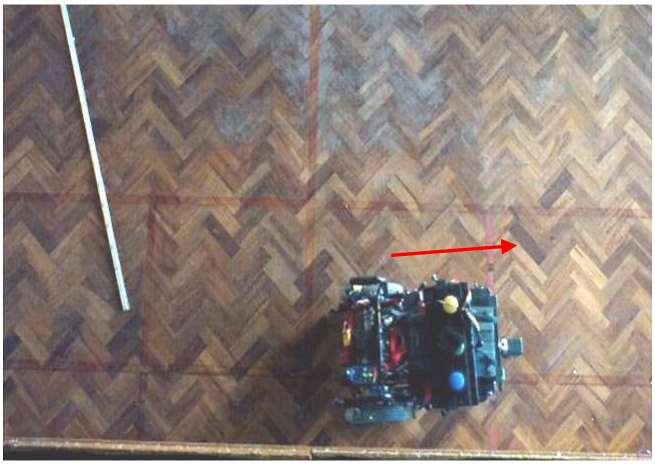
Phase 2
The wall object was detected and turn avoidance was applied



Phase 3
The wheelchair executed a right collision avoidance turn



Phase 4
Wheel retardation was reduced as the collision angle became less than at phase 2



Phase 5
The wheelchair exit heading after intervention (the wall was no longer detected)

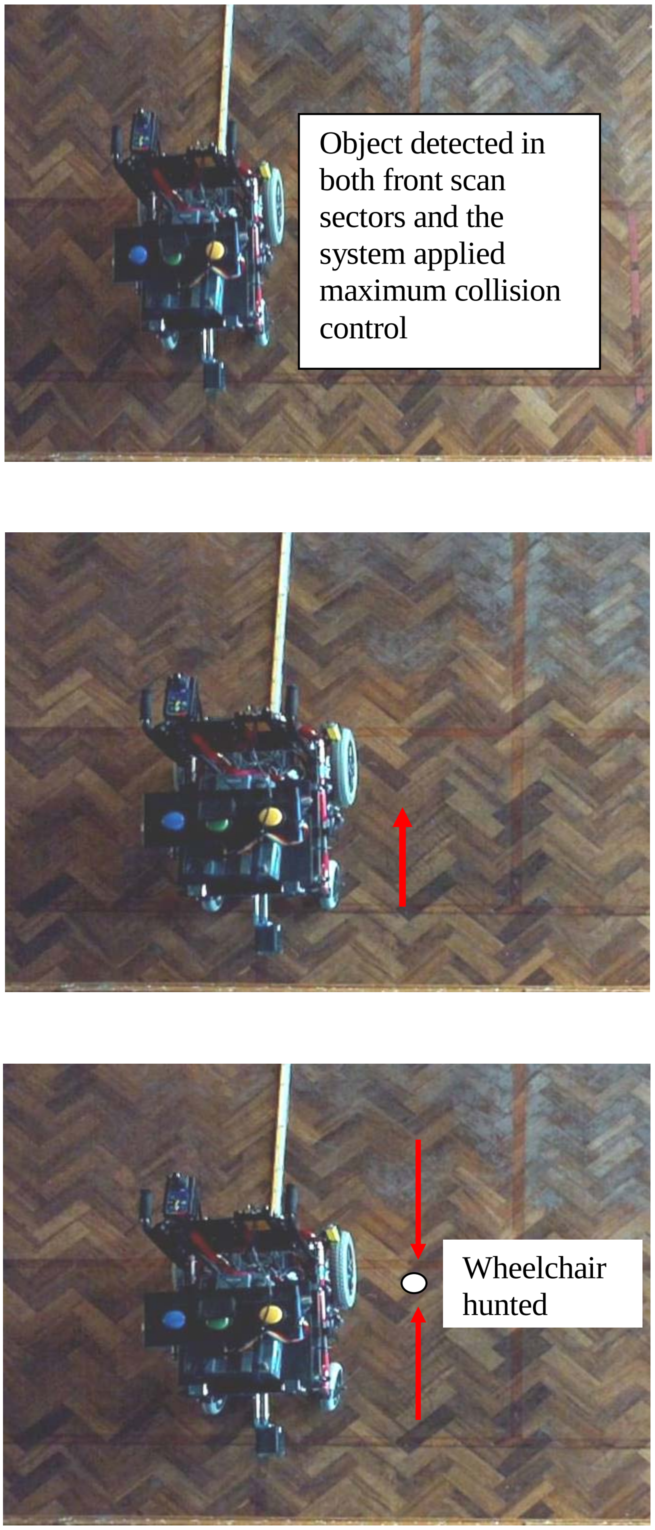
Figure 7.3 High angle collision control

At this collision angle greater demands were placed on the system collision control. Phase 2 and phase 3 pictures show the first application of the left drive wheel retardation.

Head On' impact collision control

The wheelchair was set on a perpendicular collision course with the wall object as shown in Figure sequence 7.4.

Phase 1
The wheelchair approached the wall before detection occurred



Phase 2
The wall was detected and collision control applied reverse and retarded the forward rotation of both drive wheels

Phase 3
Both drive wheels were reverse rotated and the wheelchair backed away from the wall

Phase 4
The wheelchair reversed until the wall was no longer detected

Figure 7.4 Head-On trajectory

At phase 4 the wheelchair was observed to oscillate backward and forward indefinitely until the forward control switch was de-activated.

7.2 Difficulties with motor speed compensation

There were problems with wheelchair driving speed, particularly when controlled by switches. When a suitable driving speed had been determined for a young driver, the intention was that the wheelchair would be driven at that set speed. In practice this set speed become variable depending on the driving environment. The Penny and Giles power wheelchair controller had inbuilt motor speed compensation and this was designed for a proportional joystick.

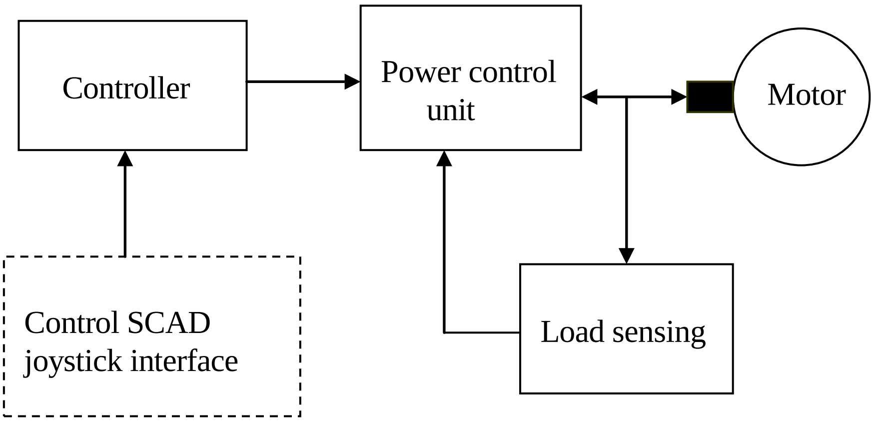


Figure 7.5 Applied load compensation

When the joystick function was emulated and a pre-set speed applied, the compensation was insufficient to keep the speed at the set value for various driving conditions. Consequently the effect of slopes and ground surface drag resistance increased the driving difficulty. In later work the Penney and Giles controller was replaced by a programmable wheelchair control system (Dynamic Controllers DX) that could interface with switches without the need for a specific joystick emulator function. The motor speed compensation value could be programmed into the system. Figure 7.5 shows the type of load compensation system implemented by Dynamic Controls for a powered wheelchair using permanent magnet DC motors. The control system used electro-motive-force (EMF) feedback as a method of load sensing. The feedback enabled the system to adjust motor torque to maintain a near constant speed while the load varied due to changes in the terrain caused by: slopes, concrete, tarmac and carpet surfaces. The practical performance of the load compensation at slow speeds (needed by novices and improvers) was not satisfactory. The terrain induced speed changes that frustrated drivers. There were two observed situations where the applied load compensation feedback responded:

- Firstly, when the wheel chair was driven over an object, for example a shoe; the load compensation enabled the chair to hold a straight line. This was a relatively sudden change in motor loading
- Secondly, gradual changes in motor loading, for example driving the chair over sloping ground. In this case, the applied compensation was not sufficient to hold the chair on a straight course

Increasing motor compensation also increased system instability and the longer term course drift problem became the subject of later work that investigated methods to reduce wheelchair veer that was described in Chapter 3.

7.3 Range reduction to pass through a doorway

The main reason why the wheelchairs found it difficult to pass through a doorway was because of the range necessary to detect walls. A simple method was created to reduce the sensor detection range when the SCAD approached a doorway. The complete scan comprised 12 object detection sectors. These were divided into left and right groups having 6 sectors each.

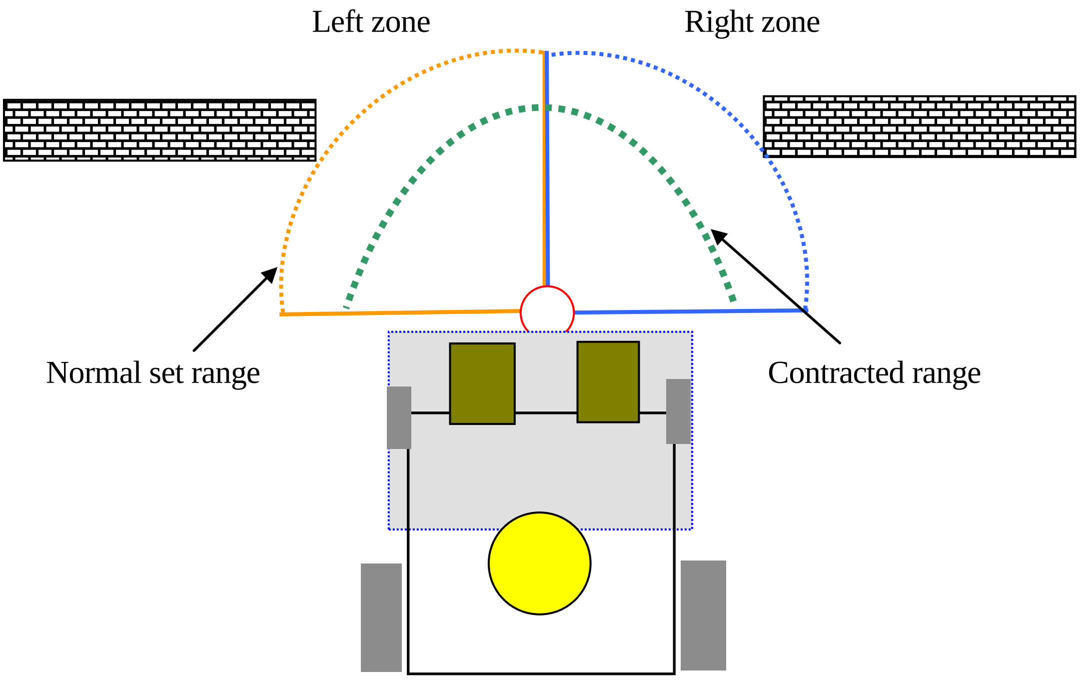


Figure 7.6 Left and right zone detected the aperture

Figure 7.6 shows the situation where both left and right zones were in the detected state and therefore driving was halted. To allow a wheelchair to pass through the aperture, the scan range was reduced to cover the basic wheelchair width, represented by the green dotted line. A logical '&' function between the left and right zones provided a conditional output to trigger the contraction period (set by a timer function). This was held at the short range setting for four seconds. After this period the range was returned to the normal value. The system was re-triggered if the wheelchair was still within the doorway structure. Applying this range contraction allowed children to drive though narrow doorways. The SCAD function for collision avoidance was not compromised unless both of the left and right scan sectors detected an object at the same time. The range reduced period was timed and the normal range was automatically re-set after that period. A significant problem affected some child drivers who drove directly at objects 'head-on'. Figure 7.7 represents the situation when a SCAD sensor detected a wall. The range reduced and that increased the chance of a collision into the wall.

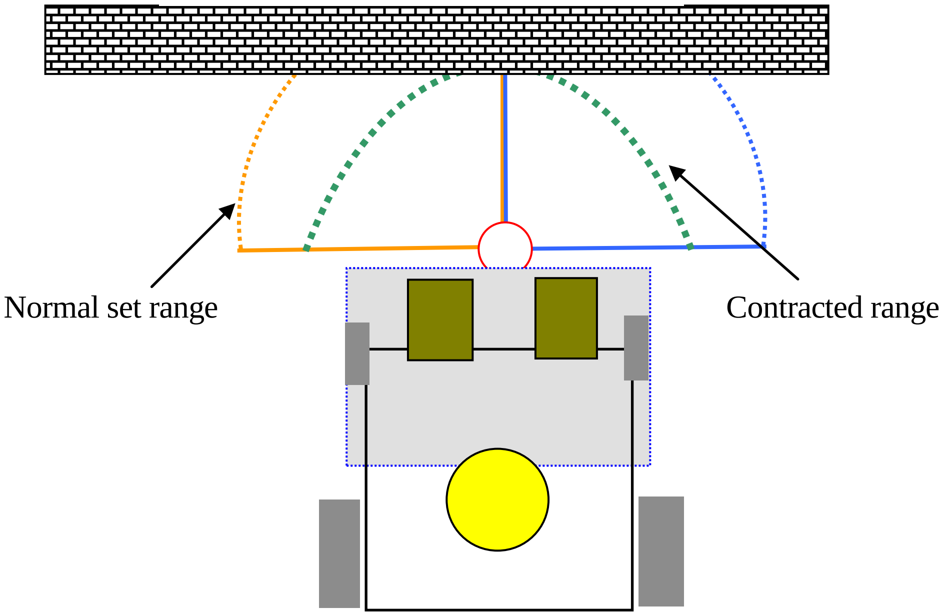


Figure 7.7 The reduced range allowed the wheelchair to get closer to a wall

The reduced range did not always provide sufficient time for a chair to decelerate without colliding. Some protection was provided by the system in the reduced range state after the wheelchair had stopped. Continued detection of the wall prevented the control system from powering the wheelchair motors when the forward drive was selected. The range contraction feature was working against the desired function of object avoidance, but it provided the useful function of driving through a narrow doorway. A method was considered, tested and then applied to enable the system to discriminate between a doorway and a wall when driven towards them. The doorway aperture was characterised by a specific signature and so a simple rule could be defined. A doorway could be recognised by grouping the twelve sectors into three sector groups as shown in Figure 7.8.

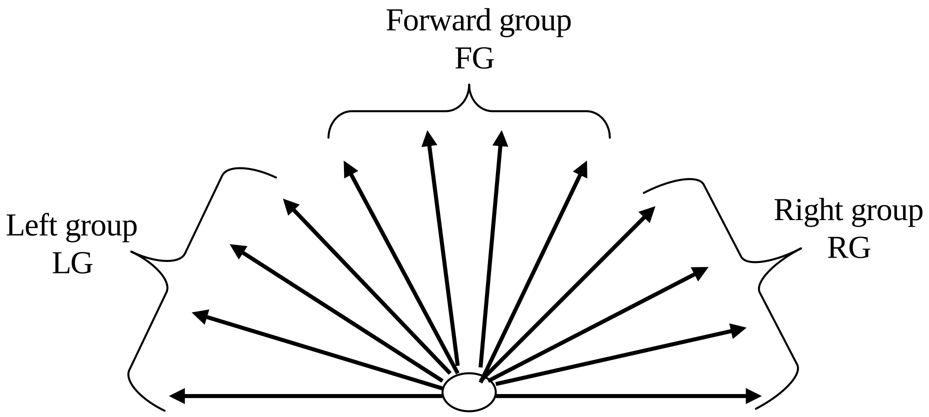


Figure 7.8 Sector grouping

The three sectors had a combined width of 4 x 15°. The following logical conditions were applied to the three 60° sectors and a simple logical function determined when to reduce range.

Table 7.1 shows the logical function.

Left group Det	**Right group Det**	**Forw'd group Det**	**Function**
Yes	Yes	No	Range contract
Don't care	Don't care	Yes	No Contract
No	Yes	No	No Contract
Yes	No	No	No Contract
No	No	No	No Contract

Table 7.1 Doorway discrimination logic function

The function placed an angle of tolerance limit on the angle of approach. Figure 7.9 shows a practical limit at which the range would still contract from a point taken from a 'dead centred' approach. The aperture is shown as having an approach on the right side. An approach from the left functioned in the same way.

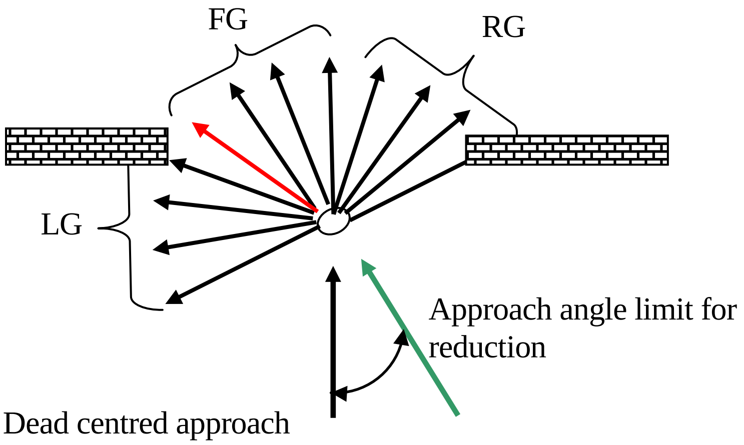


Figure 7.9 Range contraction within approach limits

The red arrow indicates the sector most likely to stop range reducing and therefore set the approach limit angle. Figure 7.10 shows the practical operation limit.

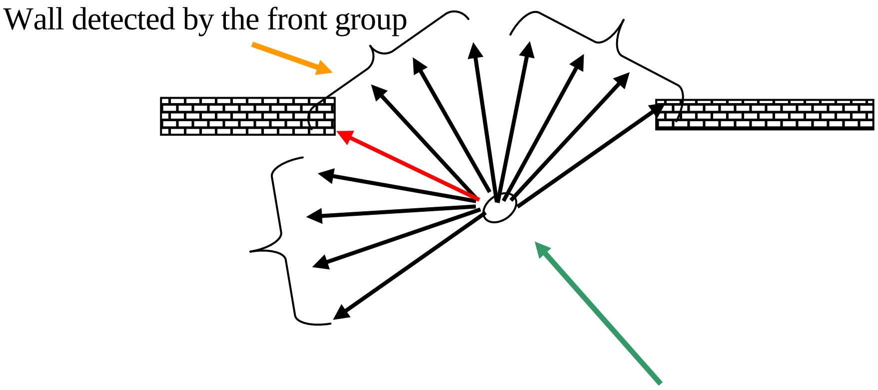


Figure 7.10 Range reduction not logically possible

The sector marked in red triggered the logical condition when an object was detected by the front group and therefore the range was not reduced so driving was stopped in the direction of the object. This 'extreme' angle of approach did not give the wheelchair sufficient manoeuvring space to pass though the aperture without the rear drive wheels becoming caught by the aperture side wall.

7.4 Children learning to drive

There was a conflict regarding user control of the wheelchair and system control. Some therapists believed that system intervention blurred the boundaries of wheelchair control. This made if difficult to determine what level of control was being applied by the child driver. Other therapists believed that assistive technology improved the chances of young child drivers, who would not normally drive without helpers close at hand or even be provided with wheelchairs. The personal child achievement of getting to places and moving themselves (even with technical help) provided increased confidence.

Stages of child driver development were observed, in which children progressed through stages of driving with a normal wheelchair to experience crashing, direct wheelchair steering and control feedback. The effect of collision control on the driver was considered. For example, did they understand why their wheelchair had altered course when an object had been detected? Therapists at CHS developed a driving programme in which young people were put through training with basic switch controls, for example, simple straight line driving and circling. This helped link cause and affect with the child's own understanding of the task.

The therapists had specific driving sessions with child drivers on a weekly basis. The time the therapist spent with each child was short compared to the time the child had available to drive throughout the school day. Sometimes continuity of control for young drivers could be different for the training session. An example was when a child was familiar with their switch controls and the therapist wanted to introduce joystick practice. In the longer term a child may gain the skills for joystick control. There could be a transition period in which the child was more proficient with switches.

Opinions varied about whether an assistive system took part of the decision process away from the child, as the system would do the work of avoiding the object without the child having to do it. Some believed assistive technology made it possible for young people to have an introduction to driving without the constant need for bystanders and helpers. There were questions being asked, for example, 'are we creating child robots'?

Observations of child drivers showed differences in personal driving skill and anticipation. There were situations in which the system acted or responded in order to stop a collision. Interestingly, who or what acted first. The system might cut power to avoid a collision, or the driver might act before the system.

It was important to consider what effect collision control had on the child driver, for example, did they understand why the wheelchair altered course when objects were detected. Sensations of acceleration and deceleration were felt during collision control. Importantly the child always initiated the driving function. No process occurred without the switch being operated, apart from a system controlled stop.

There were issues relating to children being pushed when they could be driving themselves. Did children understand when they were being pushed and not driving under their own control, when they still had access to switch controls in front of them? The child might not understand why a switch was not operating, even though it was making a clicking sound when the child pressed it. The motion of the chair became independent of switch control when it was being pushed. The nature of how human help was given was considered.

There was a conflict of interest between children and helpers. Children needed to be allowed to make mistakes and not to be always be told where to go or drive. The school time table imposed the need for children to reach specific destinations within time set frames and this also sometimes compromised the amount of freedom given to drivers.

The level of applied SCAD operation needed to be suitable for individual requirements and changes. It was important that the child's own ability was not swamped by system interventions. System control options were incorporated that enabled system functional operating changes to be made. These were graduated to progressively offer increased or decreased autonomous driving functions.

Operation of the wheelchair when lockout mode was selected was intended to be a training mode in which a child was expected to problem-solve during driving situations. This lockout mode was regarded as a minimal intervention. An operational example was where an object was detected on the right side of the wheelchair. The control system disabled the function of the right turn and forward control switch. The child driver was expected to work out for them self which switch should be operated in order to drive away from the object. In the example where an object had been detected on the left side, the control options available to a child were right and reverse. Operation of the forwards control caused the wheelchair to head for the object and that was therefore disabled for the period in which the object was detected. In situations of open space where no objects were detected within the set range of the detector, the wheelchair reverted to normal steering control.

When auto-steer was selected, the system applied increased collision avoidance control. Using a similar example where an object was detected on the right side of the wheelchair, operation of the right turn control switch was disabled. Operating the forwards control enabled the system to apply collision control intervention. This system intervention stopped at the point at which no objects were detected in the path of travel. The wheelchair control system reverted to the normal function of momentary steering control similar to lockout system operation.

7.5 Enhancement of avoidance control

Many young children that had been driving using a track guided system were generally required to operate three switches: a forwards drive switch, and left and right junction turn controls. Sometimes it was necessary to simplify the controls, for example, just a single switch could be used for some young drivers. When drivers developed their cognitive understanding and control of the task then more control options could be provided (typically junction turn selection control switches). It was not considered practical to provide track drivers with a reverse control. One particular concern was that a young driver would not be able to see their driving direction and consequently would collide with objects. Additionally it was not justifiable to add the extra hardware and control systems required.

There was a need for the application of a reverse function when driving in a free situation. The term ‘free driver’ was used by staff helpers and therapists to describe a driver who was not guided by a track. To help a young person with their transition from driving a track guided wheelchair to becoming a free driver, their familiar driving control set-up remained the same. In many cases a reverse control was not provided. When driving using collision avoidance, inevitably a young person would need a reverse function, perhaps to escape from a bottleneck situation. The control interface for the SCAD system incorporated a reverse input. Where a young person had the ability to operate a reverse control they could use it. The test systems did not have a sensor to detect objects behind the wheelchair in order to reduce system complexity. The reverse function was time-limited. When the reverse control was activated the wheelchair responded for a set period (typically three seconds). After this period, reverse driving stopped even though the reverse switch might be activated. Some drivers learned that they could continue reversing by re-activating their reverse control. Later developments incorporated a latch circuit that prevented re-triggering of the reverse direction control when no objects were being detected.

An automatic reverse and turn mode was created that provided a systematic reverse process so that a young person could manoeuvre their wheelchair out of a bottleneck with their turn control switches. This mode of control operated when an object had been detected to the left or right side of the wheelchair. For example, if an object had been detected on the right side of the wheelchair and the user operated their right switch, the system responded by applying a reverse control function. The wheelchair backed away to a point where the object was no longer detected. This cycle continued until the wheelchair was clear of the object and the driver maintained operation of the right turn control.

A turn delay was incorporated when the automatic reverse and turn manoeuvring functioned after the delay period had expired. This provided a window of time that prevented the wheelchair engaging reverse in order to provide a driver with thinking time. There were some situations, in which a driver may not have required the automatic reverse function, particularly corridors.

There were different operational parameters that could be applied as part of a collision control strategy. The amount of system support needed to be flexible and responsive to the changing needs of the children. The application of specific operational modes helped classify the system operation. Two system controls were provided that preset collision intervention and the functional collision avoidance was set by a mode number.

- Mode 1 Object detection driving lockout
- Mode 2 Object detection driving lockout + automatic reverse and turn
- Mode 3 Driving collision avoidance
- Mode 4 Driving collision avoidance + automatic reverse and turn

The distance the wheelchair was from an object before a control intervention occurred was set by the range control number.

- Range (0) = Short (system protection non-collision control)
- Ranges (1 – 4) = Short increasing to long object detection distances
- Range (5) = Extended range + automatic range reduction for doorway navigation

Detection operation was retained for range (0) to provide some minimal system protection, to reduce damage if the system was driven into walls. The object detection range was set by a range control number. The range value (0) indicated no practical system support. To protect the sensor a short detection limit was applied, typically 20cm. Even with this residual level it should be noted that the therapists preferred an all-off state. They believed that the collision system should be switched off so that it did not function in any way.

The inclusion of side detectors provided additional object detection support, although some drivers did not necessarily need this. For assessment applications the side detectors were mounted on the wheelchair and their outputs switched off when not required. To provide system flexibility the SCAD or infrared side sensors could be switched in and out of operation independently.

The concern of the therapists was noted and later systems incorporated a kill option. Even at the shortest object detection range (system protection), system operation blurred the boundaries between human control and system control. It was further noted that some children in particular wanted to drive close to an object of interest and collision control intervention hindered this, for example a child wanting to operate a wall mounted light switch. The range control settings could only be adjusted by attendants and not the drivers themselves.

7.6 A first proportional SCAD

A young driver who had a self destructive disorder, LeschNyan syndrome started driving his wheelchair using a switch joystick. He needed a collision avoidance system because he would sometimes be intent on harming himself or crashing. The switch joystick became frustrating for him and was not a suitable match for his abilities. He had demonstrated finer personal hand control (provided he was suitably restrained). The SCAD system only operated with switched inputs. Therapists assessed him for a proportional joystick and he demonstrated a high level of competence and a definite preference but therapists, school staff and carers were unhappy to let him drive without an appropriate collision avoidance system.

The main considerations involved with the application of collision control for proportional joystick drivers were object detection controlled wheelchair slow down (deceleration) and collision control steering intervention.

A new control interface was created. The existing ultra-sonic scanning control system remained the same. The object detection signals were used with comparators that blocked the joystick direction and speed output when object detect signals were present. Proportionality was applied for speed control of the wheelchair and not in proportion to the detected object distance. When an object had been detected, steering control towards that direction was blocked. A definite cut-off point was preferred in order to provide firm feedback to the driver so that they knew that a system control intervention had occurred. Lessons were learnt from previous work in which system intervention had blurred the boundaries of human and system control.

A driving control interface was developed that used a method of direction blocking. This was placed between the joystick voltage outputs and the power control joystick input control lines. The joystick shown in Figure 7.11 provided a forward control speed voltage and a direction control voltage. For system safety, particularly in a safety critical application such as powered wheelchair control, the joystick provided dual decode outputs. The joystick was made of two separate circuits where each axis had a complimentary (mirror) output. A joystick fault could be detected and false uncontrolled system operation was prevented.

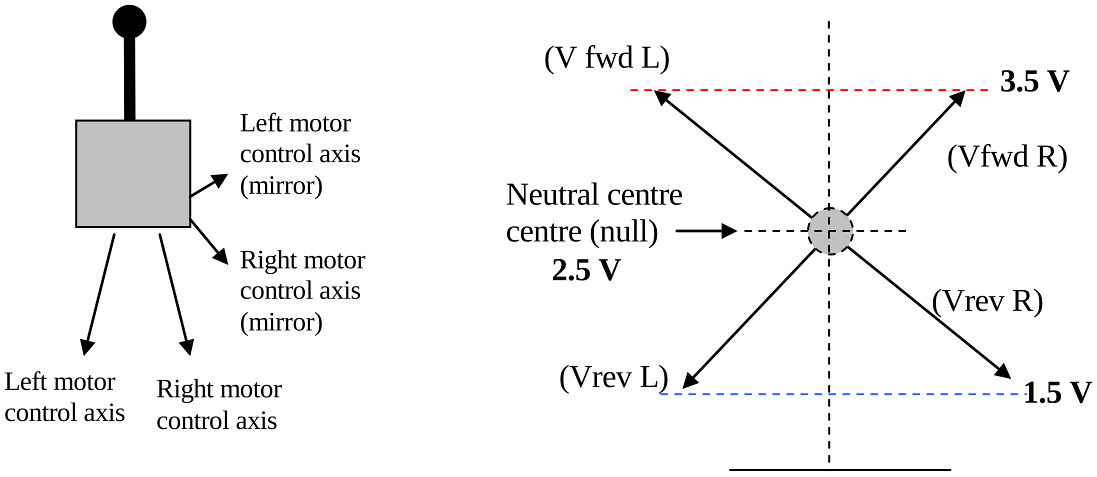


Figure 7.11 Inductive joystick output voltage against joystick displacement

The test SCAD interface used the V (forwards left) and V (forwards right) joystick control outputs. The V (forward L) mirror and V (forward R) mirror signals were fed to signal comparators that provided an out of balance signal. A system disable latch was triggered if there was a joystick problem or a disconnected wire.

The system disable latch was used if other elements of the interface system had a simple fault condition. For example, a disconnected peripheral sensing component. If these became disconnected the wheelchair could not be driven. The joystick had a neutral midpoint (null) position and this was both mechanically and electrically central.

7.7 Joystick control voltages

The joystick provided control voltages for motor speed in forward and reverse directions in response to movements of the joystick. The joystick applied a mix of direction and speed voltages depending on the wanted driving direction. Figure 7.12 shows the wheelchair motors responding to the joystick direction control.

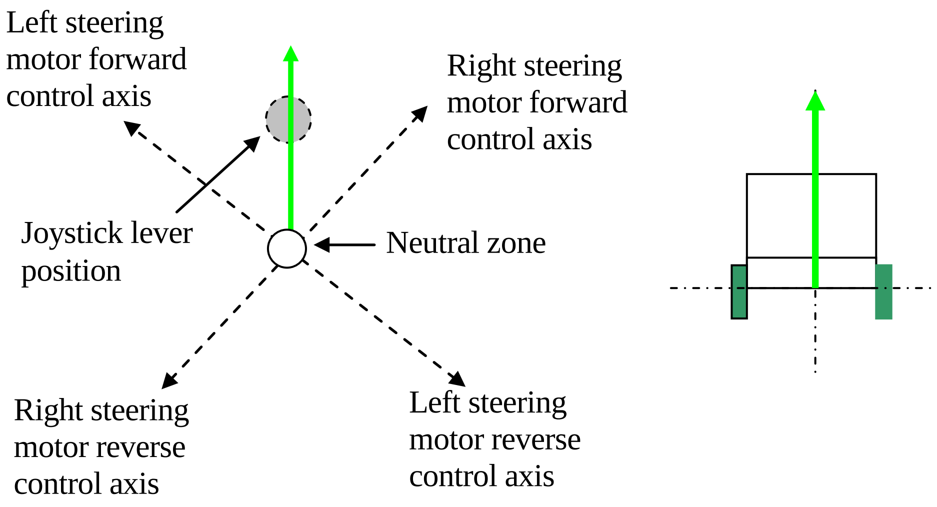


Figure 7.12 Resulting forwards directional control, both drive wheels rotated forwards at the same speed

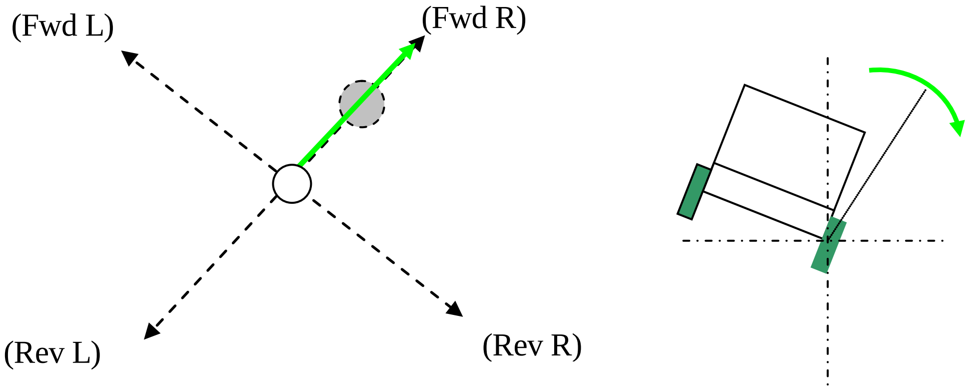


Figure 7.13 Resulting right arc turn

Figure 7.13 shows the wheelchair executed a right arc turn by rotating the left drive wheel forward about a stationary right drive wheel. The joystick displacement only affected the left drive wheel forward control voltage.

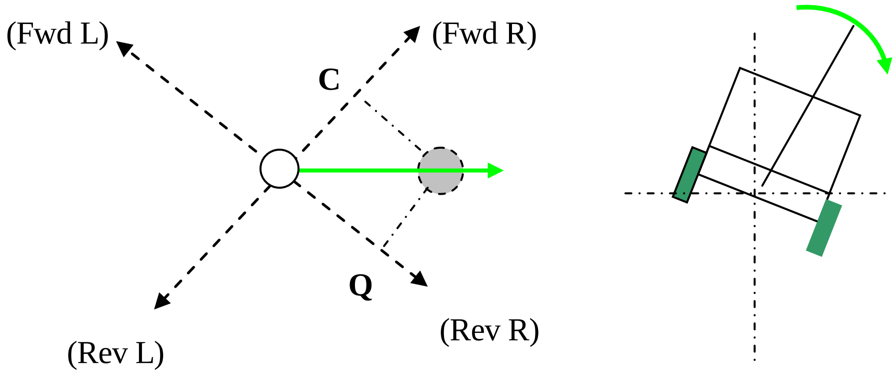


Figure 7.14 Resulting right spin

At this joystick position a spin turn resulted from contra-rotating drive wheels. Figure 7.14 shows point C on the joystick forward control axis controlled forwards rotation of the left drive wheel, whilst point Q controlled reverse rotation on the right drive wheel. A method of control voltage blocking stopped the progressive change of joystick output voltage beyond a certain point. When an object was detected, control blocking voltages were generated that were in opposition to the driving direction that would take the chair towards the object.

The object scan sectors were divided into two areas (left and right shells respectively) as shown in Figure 7.15. Each shell had six scan sectors for the left detection zone and six scan sectors for the right detection zone.

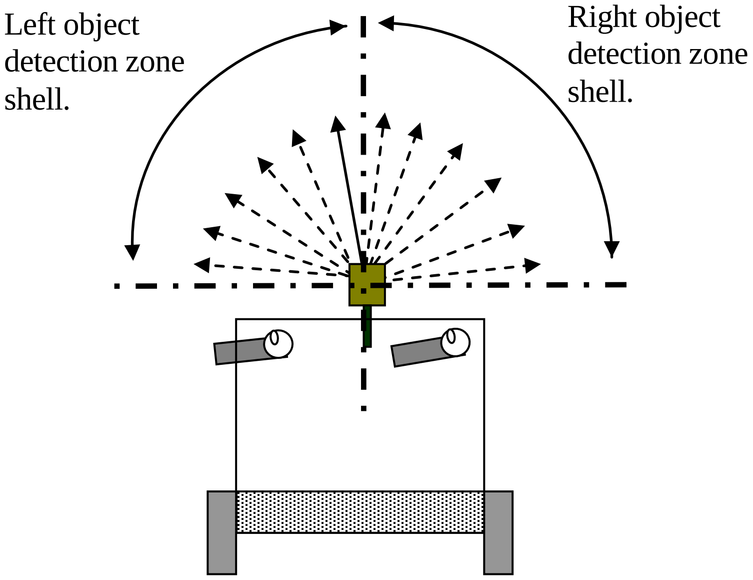


Figure 7.15 Left and right scan sector grouping

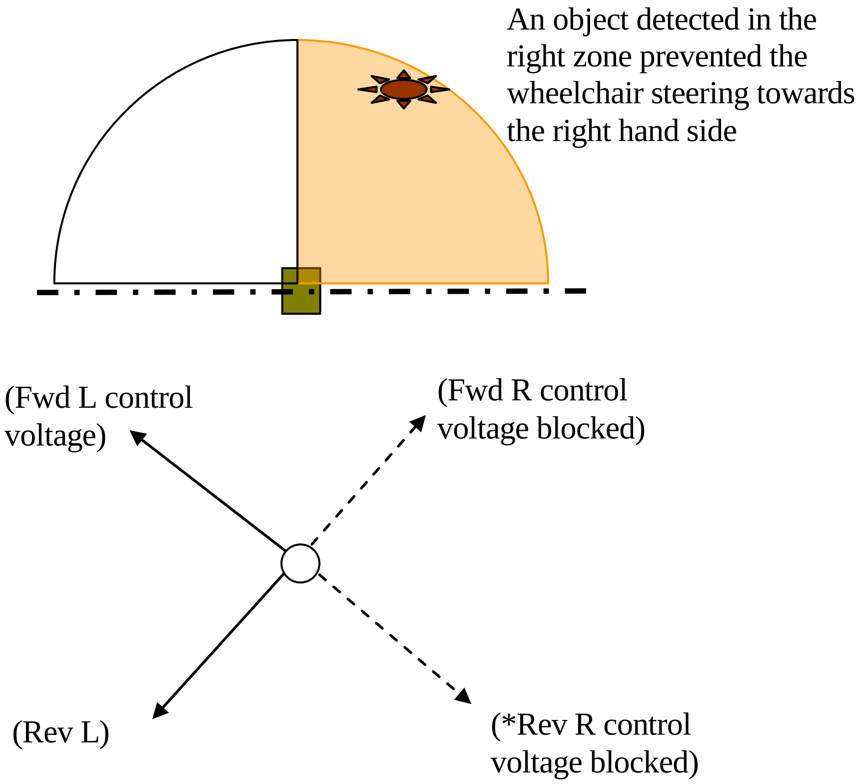


Figure 7.16 Object detected right steering blocked

Figure 7.16 represents an object being detected in the right zone. The right forwards steering control and right reverse functions were electronically blocked. In this condition, the only operating drive direction was forward left or reverse left.

Consequently, the system applied collision control and prevented the wheelchair hitting the object.

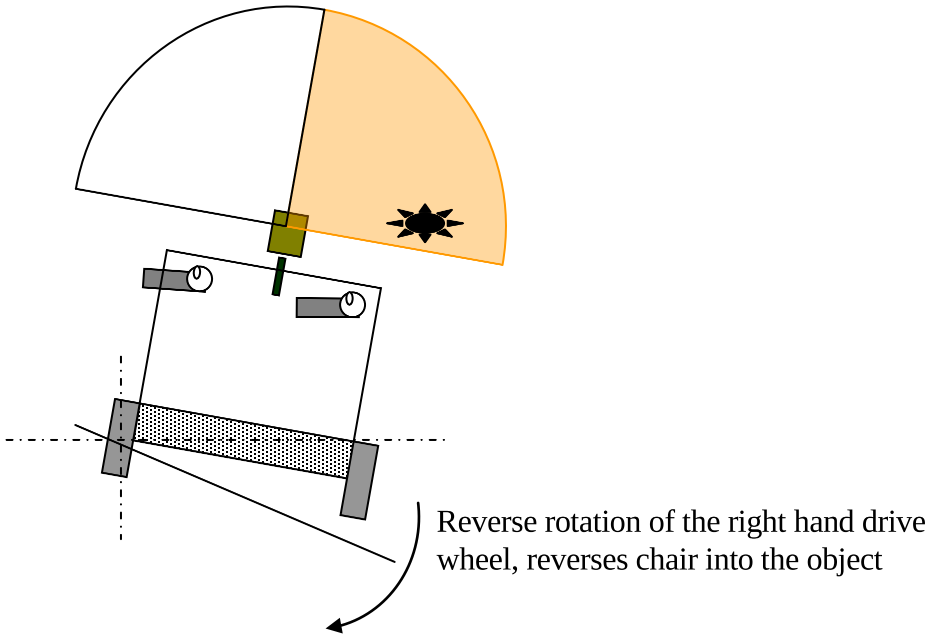


Figure 7.17. Reverse right turn into the object

It was necessary to prevent reverse rotation of the right hand wheelchair drive wheel shown in Figure 7.17. Without this blocking, the chair could be reversed turned into an object.

The proportionality of speed control was retained for the enabled control (left) direction, in the example shown where the object was detected on the right. The speed of turn was controlled by the child driver.

If an object had been detected directly in front of the chair and occupied both left and right detection zones then the left forward and right forward drive directions were blocked. Consequently both reverse directions would also be blocked, rendering the system un-driveable, as shown in Figure 7.18.

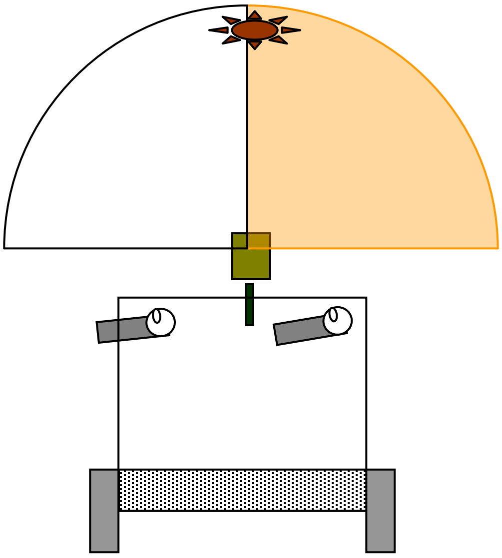


Figure 7.18 An object detected in both front zones stopped driving

To prevent this condition, a logical rule was applied that unblocked the reverse driving directions when both forward zones detected an object. This allowed the chair to be driven backwards away from the object.

Some later work addressed this issue concerning a driver using a proportional joystick control system. He became frustrated by not being able to get close to objects of his interest. Proportional joystick's had a specific advantage when compared to switches because they could translate graded control from the operator.

A test development was considered that linked the detection range with joystick displacement so that when the driving speed was increased, the detection range was also increased.

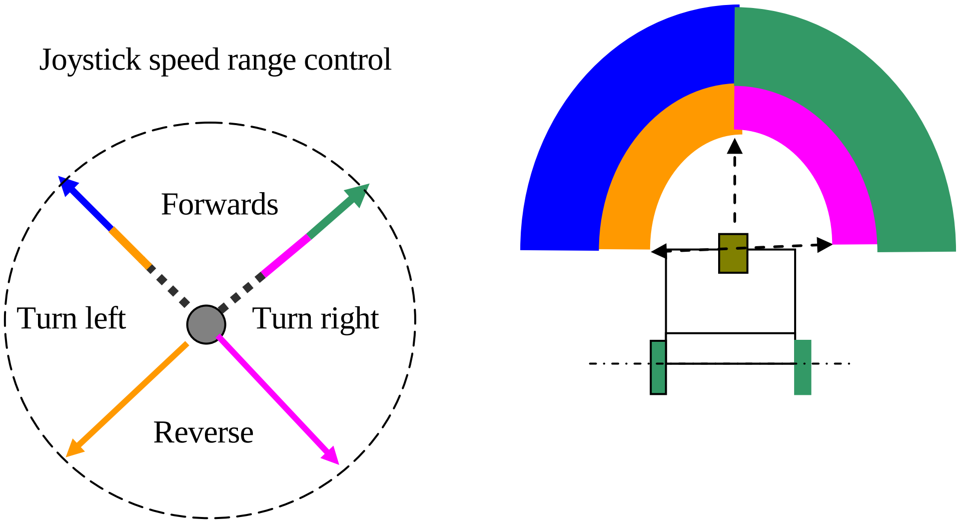


Figure 7.19 Linking speed and range together

Figure 7.19 shows how the detection range was applied in three stages. Each of the object detection zones had a separately switched detection range that was controlled by each separate joystick axis. When a driver moved the joystick for slow speed, the object detector was completely switch off, and therefore provided close contact at slow speed. When the joystick control was moved into the mid-band position, the object detector was switched to a mid range value providing intermediate collision intervention. If a driver then moved the joystick toward maximum speed then the object detector would switch to long range.

It was noted that during testing, the system needed to be reversed considerably more than was desirable before the detected object became out of range. For this reason an object range reduction was applied to reduce the clearance distance when the joystick voltage entered the reverse control region. This was similar to the range reduction for doorway navigation used on the switch control SCAD system described previously. Infrared side detectors were also incorporated into the control system. They provided an additional blocking function to reinforce the SCAD side zone areas. To simplify the control interface, the side detector outputs were connected in parallel with the SCAD to reinforce the basic functional process.

7.8 Single switch control

There were young people who were not able to operate more than a single switch. Driving a wheelchair could be made possible for them by using a single switch direction control scanner. This made driving hard work because each direction for the wheelchair had to be individually selected and this could be time consuming and frustrating.

A major part of the effort reduction work described in Chapter 3 consisted of developing systems to reduce driver fatigue and frustration. Good personal timing skills were a prerequisite as control button activation needed to happen in a window of time in which a selected direction was highlighted. There were two distinct issues when setting up a scanning system: firstly: the scanning frequency and secondly, the dwell time. If direction scanning was fast with a short dwell time then the operator missed their intended direction. If the scan rate was significantly slower then an operator had better success with direction selection, but they needed to wait for longer periods for the next required selectable direction.

Commercially available systems used a predictive scan pattern that would scan the next most likely wanted direction. Even with a predictive scan pattern the drivers spent considerable amounts of time selecting and reselecting directions to make driving progress.

Figure 7.20. A prototype direction scanner coupled with SCAD sensors on a wheelchair detected the walls and objects in the path of travel and provided electronic steering guidance

A test system was created as shown in Figure 7.20 to evaluate to the SCAD systems by driving a wheelchair along a short 40 meter route through corridors. The first wheelchair run was conducted using the prototype direction scanner operating conventionally. The driver needed to select each direction individually with a single switch to reach the target destination. The time recorded was 2minutes: 11 seconds.

A second wheelchair run had the SCAD system engaged. Driving along the same route with the same switch and scanner, the recorded run time was 1 minute: 7 seconds. It was noted that the second run needed only 10% of the number of switch operations to reach the destination when compared to the first run. Some child drivers had a significant visual impairment so the test direction control scanner had talking outputs in addition to visual indicators. The audio output provided prompts for a driver.

Figure 7.21 Time comparison at the end of the test

This experiment was videoed, shown in Figure 7.21 and it showed that the amount of effort required to drive along a route was significantly reduced and required half the time to complete the run when compared to the standard unassisted control system.

For future work, the time required for the scan of available drive directions could be reduced. A direction skip mode would not indicate a direction in which an object had been detected. Therefore the scan options would adapt to the change in the detected environment. For example, if an object was detected on the right, then the forward and right scan option would be temporarily disabled, providing left and reverse only as selectable directions. This could reduce the scan cycle time during which the drivers needed to wait before selecting a direction.

7.9 Further development and future work

Merging SCAD and Anti-veer systems together could create a scanning driving direction system for young people using a single drive control.

The attitudes of therapists varied in their views; some were supportive of assistive systems and some felt it could hinder the child’s learning. At Chailey Heritage

School, therapists felt that collision avoidance reduced the need to learn driving skills. Crashing and contact with the environment was an essential part of the learning process.

Therapists in other centres believed that assistive driving systems helped a young person build their confidence. To give a child an opportunity to experience driving under their own control (in terms of switch control operation) and providing a steering function that was more independent from helpers. Young people who would not normally be considered (or who were excluded from driving) were given an opportunity to drive by using a guided system.

The way SCAD was used (and how it was used) was dictated by the philosophy of the people that used it, and this fed back into how the system changed and developed over time. Proportional switch controls eased the transition to a joystick. Switch control users found it a big step to transfer their skill to standard proportional joystick devices. Sometimes it was necessary to increase the control movement by mechanical methods to match the ability of the young person's control actions. Most reported operational problems were caused by cables, interconnection weakness and sensor obscuration because of securing straps and shoe laces hanging over the sensors. These were temporary problem that could easily be fixed.

At Chailey Heritage School, wheelchair drivers would carry considerable amounts of luggage hanging off the back of their wheelchair handle bars. It was advantageous to keep the number of required sensors low to reduce obscuration and reliability problems. For this reason the implementation of a specific object reversing sensor was not rigorously pursued and a time protected reverse function was provided instead. It was important that the implementation of a SCAD system did not put extra demands on the driver. The intention was to reduce the amount of effort required and the level of helper intervention.

There were problems with the first test systems that under or over corrected when an object was detected and sometimes collided with an object that the wheelchair was trying to avoid. If the system over corrected, then the wheelchair would steer a course that was disproportionate to the direction desired by the driver. Collision control development reduced the number of inappropriate collision interventions by considering where the object was in relation the wheelchair.

Pre-collision and post collision avoidance trajectories were monitored. Test runs were conducted in which the wheelchair was set on various collision angles with a wall. The pre and post trajectory directions were recorded to assess system performance.

The difference between an automated system helping and a human helping was considered. People were not always on hand to help drivers. Children knew that the SCAD system was always available and this had a positive effect on the children's self confidence. Getting out of trouble with automated help and not human help became a matter of personal pride.

There could be a conflict of interests, a clash of wills (agendas) between where the child wanted to go and where the helper wanted the child to go. System neutrality, where the system applied basic rules and control functions was reasonably predictable. The problem solving methods applied by humans varied and outcomes were not predictable.

Applying SCAD with a scaleable amount of collision control (support), allowed a record (or back marker) to be kept of ability level. Child progression was considered using the analogy of bicycle stabilizers, as initial support enabled some independence from helper support. Stabilisers reduced the possibility of toppling, and damaging confidence, crashing or becoming tangled with objects. When a child improved and built up confidence then the stabilizers could be adjusted to provide increased latitude. Over a period of further use, the stabilizers became a hindrance and restricted a child from gaining further independence.

Observations showed that when children had developed better balancing skills then they depended less on the stabilizer support. There was a balance between extra freedom from not having the stabilizers against the child dependence and the level of risk involved.

With the SCAD system, the level of assistive support was not as obvious as the bicycle stabilizer analogy. The amount of system support could be varied either immediately or gradually, to help a driver make the transition to un-supported wheelchair control.

One of the major weaknesses of the collision avoidance system was slow progressive object detection having many sectors in which pulse / echo samples were taken. Doubling the scanning speed also doubled the number of pulses sent into the environment whilst the wheelchair was moving. This increased false detection problems because of the extra (previously sent) returning echoes coinciding with recent samples.

A new scanning method was created that halved the scan time but did not double the echo sampling frequency. Figure 7.22 shows the progressive scan cycle that consisted of 12 complete pulse echo samples for the left (transducer home position) to the right scan.

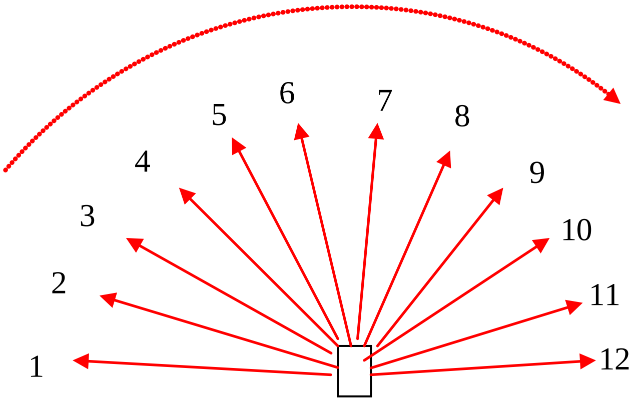


Figure 7.22 Progressive scan

At the (end of scan point) the scan motor returned the transducer back to the home position when another 12 pulse echo samples were taken. The transducer was stepped 15° and the time period before the next step was 33.3 ms. A period of approximately 15.15ms was allowed for residual transducer motion wobble to decay and then a sound pulse (ping) was sent.

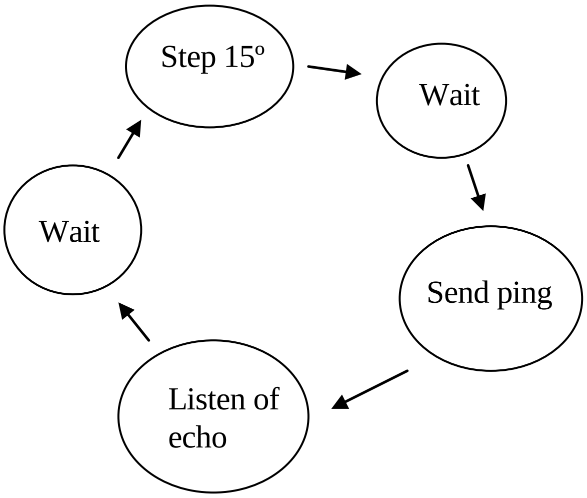


Figure 7.23 Object detection cycle scanning

The system waited again for a returning echo, after this the next transducer step was taken and the cycle continued. As shown in Figure 7.23.

To increase the scanning speed but keep the 30 Hz pulse echo sampling rate the same, the transducer step / ping cycle was modified to provide the alternate scan shown in Figure 7.24. The stepping time was reduced to 15.15 ms per step. The time between the pulse echo samples remained the same at 33.3ms.

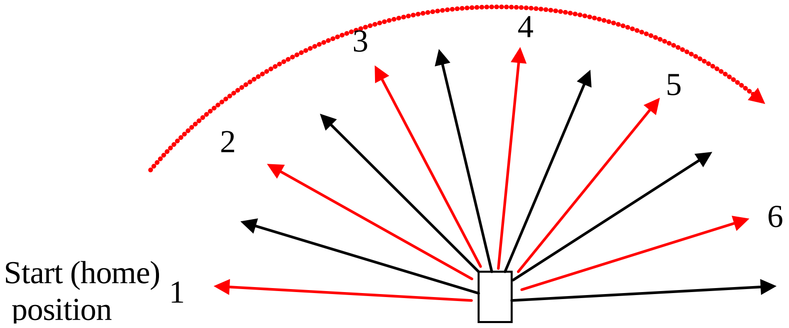


Figure 7.24 Alternate left to right sweep

Figure 7.25 shows that six samples were taken for a left to right sweep. The scan sweep started at the home position with pulse echo samples taken on odd sectors (Red).

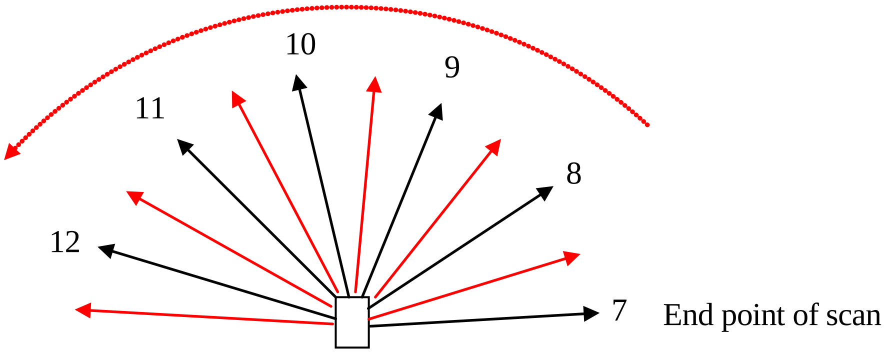


Figure 7.25 Alternate right to left scan

At the scan end point, the sound echo samples switched to even sectors (black) to complete the full 12 pulse echo samples for the complete scan and this is shown in Figure 7.25.

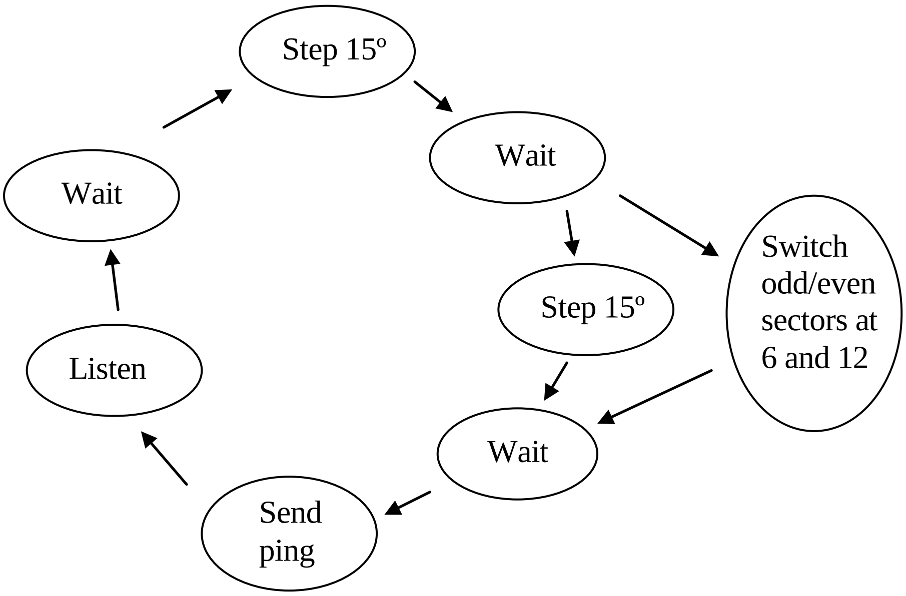


Figure 7.26 Alternate scan cycle control

Applying the modified alternate scan cycle control shown in Figure 7.26, meant that the transducer on average was moving at a faster rate than with progressive scanning, although the pulse / echo sample rate remained the same. This provided a significant reduction in the complete cycle time.

The most important aspect was that the transducer could sample the extreme side sectors in half the time when compared to the progressive scan method. What was particularly interesting was the rapidly moving transducer reduced false detection due to ghosting. Subsequently the sample frequency was raised to 50Hz. This further reduced the sweep cycle time. Therefore an approximation for a 20ms sample rate was 20ms X 12 sectors for a complete sweep of 240ms. This was an improved figure when compared to the 732.6 ms for the progressive full scan time and 333ms for the progressive half scan method. The signal scattering in the sensed environment was reduced by lowering the transmitted power of the ping by adding a current limiting resistor to the transducer pulse transformer. This also limited the effect on other near-by systems.

7.10 Connections to the moving transducer

The rapidly moving transducer placed an increased strain on the transducer connecting wires and consequently the system failed to detect objects due to wire fatigue. A new method of connection was created that was similar to the spiral wire connection used in moving coil meters. This consisted of a small wire bobbin which formed part of the transducer mounting base. Several turns of narrow gauge twin insulated wire was wound onto the bobbin and fixed to a stationary point for making the connection to the ranging circuit board. The other end of the twin wire was connected to the transducer. The reciprocating motion of the motor and associated mounted transducer caused the wire to wind and unwind without causing bending that could cause a wire fracture. Long term testing of this connection method concluded that this was a satisfactory method and at the time of writing there has not been a failure due to wire fatigue after five or more years of use.

7.11 Sensor vulnerability

The SCAD head enclosure was constructed to provide acoustic transparency and robustness. Construction of the enclosure incorporated mechanical scan limit stops. The protection bars were angled to reduce internal signal scattering and self pick-up. The position of the sensor head with respect to the wheelchair frame required an adjustable mounting to enable it to scan the extreme side sectors with sufficient clearance to avoid detecting the castor wheels when they swivelled forwards, for example, when the chair was driven backwards.

When wheelchairs were loaded into and out of transport vehicles the SCAD sensor could get damaged, becoming caught on tail lifts for example. Additionally, children were pushed around places where there were curbs and un-even ground. Ongoing work incorporated dual sensor mountings for both SCAD and track sensors and consideration was given to the design of swing away sensor mountings. Detachable sensor mountings were built for both track and the SCAD sensor enclosures, including the electrical interconnections. This was particularly needed for drivers who had their own wheelchair that went home with them.

Methods were considered to reduce sensor vulnerability. The sensor was vulnerable because it needed to protrude beyond the front castor wheels, particularly when they swivelled forward during reversing. If the sensor was mounted further back (so it did not protrude) then when driving forwards, the castors would be trailing and did not cause problems. From a functional perspective, the guidance system would operate. It was only after a reverse manoeuvre that this mounting position became impracticable because the castors swivelled back and obscured the side sectors.

The main reason that the SCAD sensor was placed at the front wheelchair was to provide detection clearance when the chair was driven backwards and the castors swivelled forwards. After a reverse manoeuvre, the chair could not be driven forwards because of the detection of the front castors. For this reason the sensor head scan needed to be clear and this made it vulnerable. Two methods were considered to reduce the problem of castor detection when they swivelled forwards, castor position switch and side sector muting.

Castor position switch. A magnet was attached on the castor swivel bearing and a reed relay on the wheelchair frame provided two switching points to denote the obscuring position. The switched output disabled the extreme left and right side object detection zones to stop castor detection. The castor angle switches detected when the castors swivelled back to a trailing position after the chair started to move forwards.

Side sector muting. The extreme side sectors were affected by the castor. A muting distance was considered that electronically blocked detection for objects at the distance that the castor was detected. The SCAD head was positioned near to the ground. Ground clearance and the functional sensing position were considered. The castor detection distance was constant and within a defined (castor) limit or range band. The extreme side sectors would detect a castor, but they might respond to a detected object within the defined limit, thus creating an exclusion zone. Control action would not be applied if an object was detected in the exclusion zone but collision intervention would occur if the object was detected outside of the exclusion zone.

The castor position switch and side sector muting options were not incorporated into the systems and work continued with a fixed mounting system. The footrests tended to be above the SCAD sensor. Taller children needed their footrest lowered to accommodate leg length. This caused problems with detection of the underside of the footrest fixing assemblies. Detection of the underside of the footrest was reduced by fixing a flat metal sheet on the under side of the footrest. The sheet covered irregular mounting attachments, the flat surface did not reflect back to the sensor.

Sensor ground clearance was a balance between the unwanted detection of ground surface irregularities and slopes. The low level SCAD mounting was good for the detection of shoes, people and animals at ground level. Importantly the sensor was vulnerable to damage from skimming and striking ground objects, door thresholds, and loading in and out of transport vehicles. The SCAD head could get damaged when being pushed around by helpers. Resilient mounting structures using shock absorbing exhaust (type) flexible rubber bushes were also investigated. This could all be considered in future work.

Chapter 8

Technical testing of SCAD

The first SCAD system described in Chapter 5 was used as a test bed to establish the principle and functionality of a scanning ultra-sonic detector to detect objects in the local environment. Further testing was undertaken to gain a better understanding about the practical operating and functionality issues.

8.1 Collision avoidance control

Tests were conducted to consider the SCAD collision avoidance operation with respect to the object approach and post collision angles of trajectory. The angle of departure was not the same as the approach angle as shown by Figure 8.1.

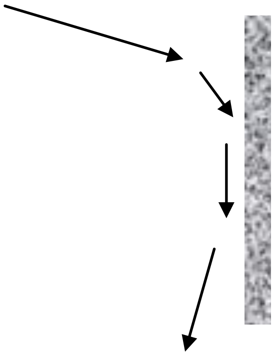


Figure 8.1 Different approach and departure angles

The angle of departure was less controlled and predictable because the system was not intended to function as a wall follower as described in [Goodwin 2000]. Part of the SCAD system function was to keep a wheelchair away from a wall but it did not track parallel to the wall. A driver could alter the trajectory with their switch steering controls. The effect of collision avoidance altered the course of a wheelchair when an object was detected. The SCAD responding to an object, caused an intervention that the user might not have intended and this was auto-steering.

Therapists were concerned that this could hinder the learning process of a child with complex needs if systems took away control from the driver, even when avoiding a crash [J Durkin 2004]. Where it was determined that a driver had sufficient understanding of collision avoidance and the reason why, then this became less controversial. Then the operation was referred to as ‘energy conserving’, where the driver was relived of some of the burden of steering and crashing.

During the research, the collision strategy was reviewed so that the auto-steering function could be switched ‘off’. This meant that when a chair was on course for a collision, the associated direction was halted without any applied automatic correction. This intervention strategy did not alter the course of the wheelchair when an object had been detected, instead it halted the wheelchair. The driver was required to problem solve in order to proceed. Introducing a wall following mode of operation was not considered because it might confuse a child about how their wheelchair was functioning. That could be the subject of future research.

8.2 Angular resolution of the scanning system for object detection

The SCAD system was intended to function as a reflex system where the driver provided the course planning and the intention to drive to selected places. The SCAD system intervened at the closest point to avoid a collision or provide a short term course correction. This minimised the system bias upon the driver’s intent to control their wheelchair. The system bias relating to the collision avoidance system formed a major part of the work involved in the creation of the SCAD.

Other supportive systems intended to provide environmental clues where the driver was within their environment. This was the subject of subsidiary audio signpost systems developed by the author of this Dissertation.

The dispersion angle of the transmitted sound pulse varied depending on the object distance from the transducer. The greatest sensing width occurred at the extremes of the set sensing distance.

8.2.1 Specular reflection and transducer polar response

The polar response diagram for the transducer is shown in Figure 8.2.

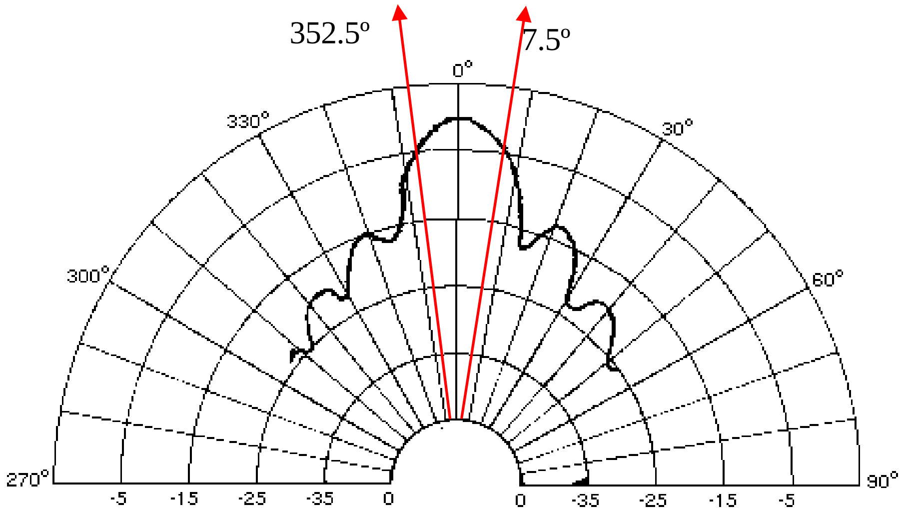


Figure 8.2 Polar response plot for the SensComp 600 instrument grade type electrostatic transducer showing the -3db points as red lines

The transducer was stepped at increments of 15º. According to the plot, the step boundaries approximated to points -3db down from the transducers peek at 0º as shown by the red line in Figure 8.2. The angle of the target object relative to the transducer affected how much reflected sound energy was returned to the sensor. Figure 8.3 shows a transducer working as a transceiver having a low angle of incidence with respect to the target object.

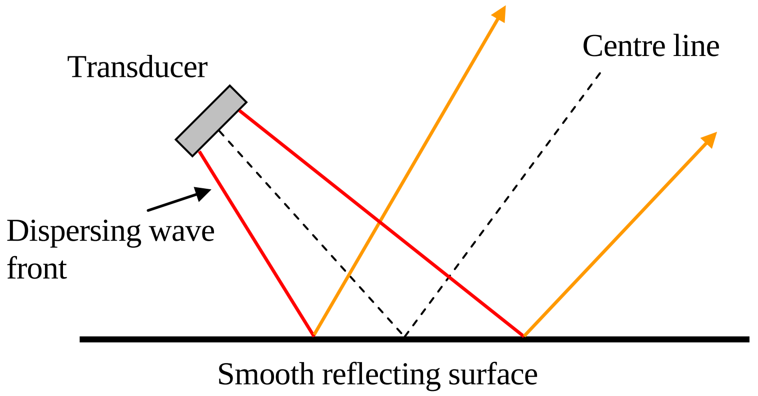


Figure 8.3 Target not detected because much of the sound pulse did not return to the transducer

Most of an echo pulse radiation did not return to the transducer, thus an object was not detected. In Figure 8.4 the angle of incidence was such that a sufficient amount of the dispersing sound energy was reflected back to the transducer.

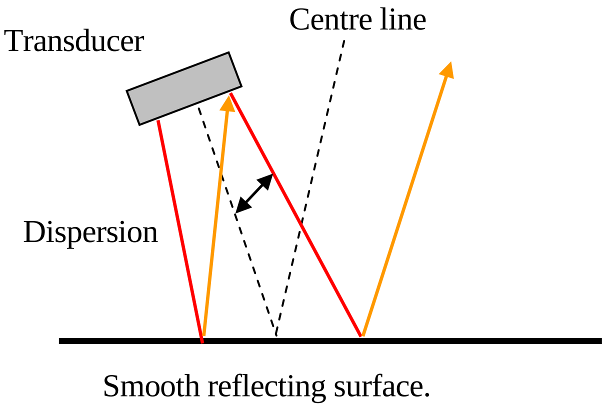


Figure 8.4 Target detected because sufficient sound energy returned to the transducer

8.3 Separation between the detection of wanted and unwanted objects

The angle of the transmitted pulse with respect to the ground and the effect of back scatter affected the response. This related to the tolerance of the detector and to changes of the ground surfaces. The type of ground surface considered were:

- Concrete, tarmac and brick
- Soft ground surfaces: carpet, lino and mats
- The effect of specula reflection by smooth surfaces
- The effect of specula reflection by rough surfaces

Before these tests were carried out, an object detection reference was established. The transmit power and the receive gain were set to detect an object of known cros-sectional area. An object that could be reliably detected was a 6mm diameter wooden dawl and this was used as the object marker.

A smaller wooden pin of 2mm cross sectional area was used to determine the maximum sensitivity limit of the transducer. The gain and transmit power was set so that the smaller object could not be detected (thus limiting over sensitivity).

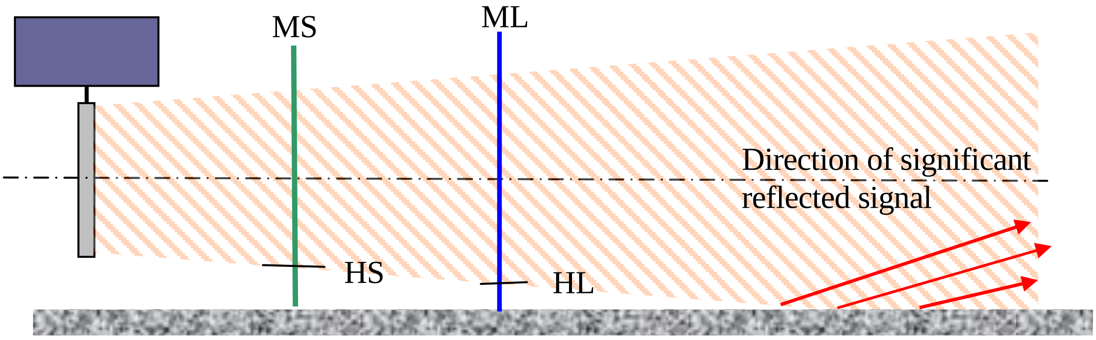


Figure 8.5 Back scatter testing

Figure 8.5 shows the transducer positioned at a height where the dispersion of the ultrasonic wave front coincided with the ground surface beyond the object detection range span settings. Marker (MS) = Short range and Marker (ML) = long range. The amount sound energy reflected back to the transducer was affected by:

- Transducer dispersion angle
- Height above ground surface
- Ground surface texture

The markers HS and HL shown in Figure 8.5, represent the change of detectable object height as a function of object range setting. The most concerning parameter was point HL, this determined the lowest operable sensor mounting height above the ground.

8.4 Ground surface edge testing

The borders between different sections of ground surface could cause ridges and small ledges. Depending on the direction of travel the edge could be facing the SCAD detector and could result in unwanted detection. The tolerance of the detector was tested and optimised to reject the differences in ground surface variations. An evaluation of typical ground surface variations in the test areas was conducted.

This determined a practical sensor mounting position with respect to the ground surfaces. A scanning ultrasonic detector was mounted on a typical powered wheelchair between the front casters. The mounting was height adjustable.

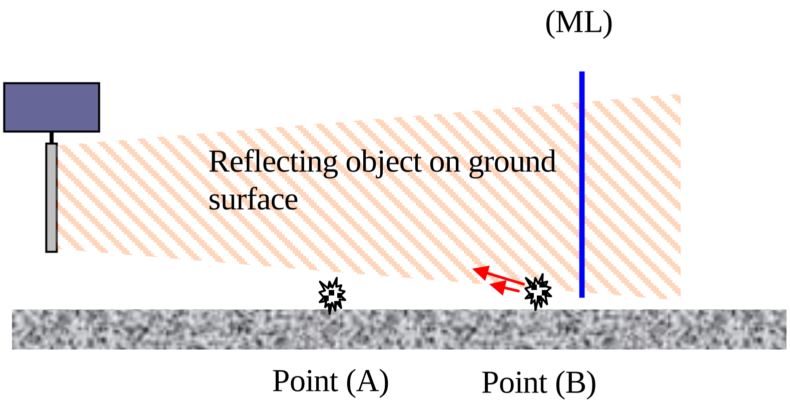


Figure 8.6 Back scatter testing with object detected

Part of the selection of sensor height involved a consideration of potential objects on the ground surface that could be detected; particularly if they had irregularities that made them good reflectors. Figure 8.6 shows an object that is not detectable at point (A) but is detected at point (B) within the set range limit.

Tests were carried out to determine ground characteristics along various routes around internal and external school areas. The level of back scatter from the following different types of ground and floor surface was assessed:

- Ground / floor irregularities e.g. crack and ridges, ground repairs
- Door thresholds, carpets stays, matting edges and rugs
- Ramps

The SCAD sensor was mounted on a platform. The angle of the sensor assembly could be tilted to test when the amount of the reflected signal became critical. Tests were carried out with the transducer platform placed on level ground as shown in Figure 8.7.

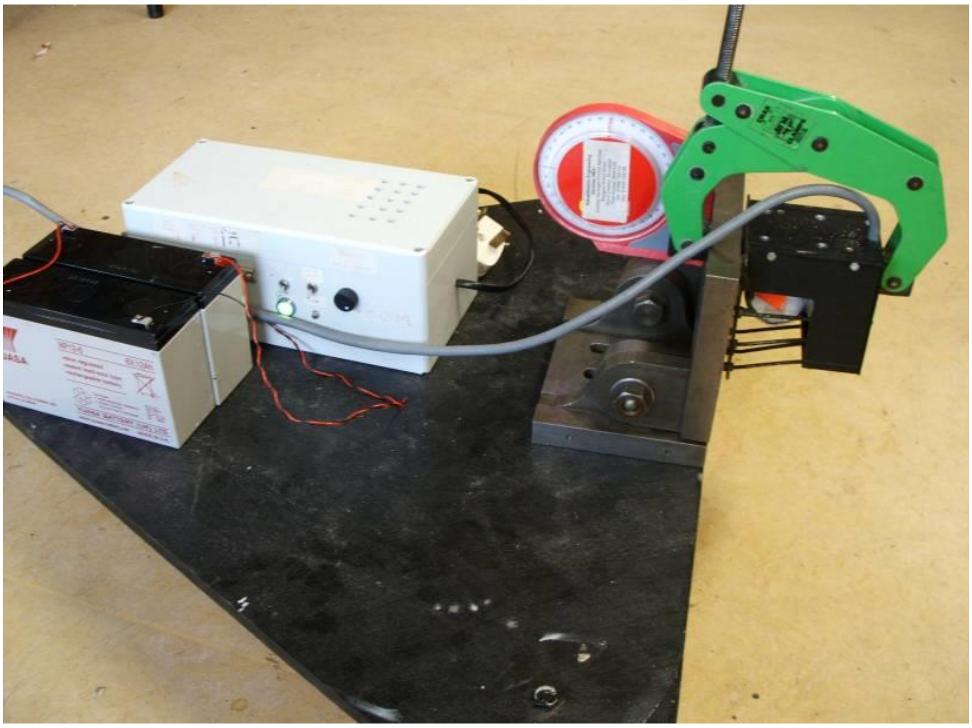


Figure 8.7 Ground reflection test platform

The transducer assembly was initially set perpendicular to the ground and then tilted to obtain a signal cut-off angle. The test setup consisted of a machine milling adjustable angle plate and SCAD transducer assembly enclosure. The SCAD was connected to a test unit that was built for electronically testing and calibrating the transducer and control electronics.

A gravity angle measuring device was attached to the angle plate that was mounted on a mobile platform having three castor wheels. The critical angle was established by tilting the angle plate to a position at which the detected signal became sporadic and intermittent as shown in Figure 8.8.

The angle reading was obtained from the red angle measuring indicator at the point at which the object received indictor of the SCAD test unit blinked. Figure 8.8 shows a door mat being tested at the critical angle.

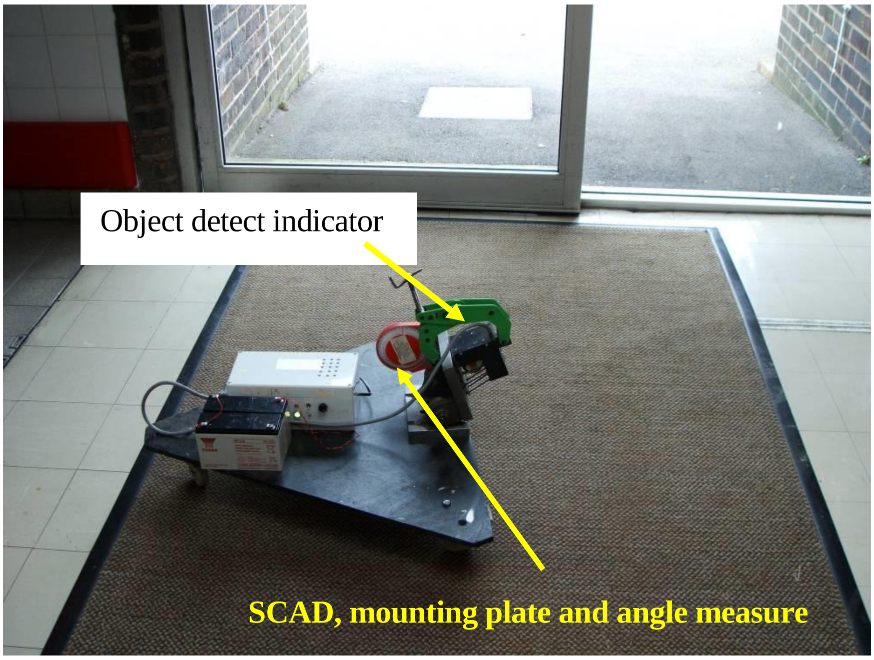


Figure 8.8 Doormat critical angle testing

The sensitivity of the SCAD transducer was calibrated by setting the SCAD transducer gain adjustment to discriminate between two objects of known diameter. The table shows the different types of ground surfaces that were tested and the critical detection angle for internal environments. The ground surfaces were tested when in a clean dry condition. The results are shown in Table 8.1.

Ground Surface Type	Critical Angle °
Unpolished Lino (soft smooth)	77 - 78
Polished Lino (hard)	79 - 78
Polished Lino tiles	79 - 78
Polished hard wood block	79 - 76
Carpet (short pile)	82 - 81
Matting (medium coarse)	60 - 65
Various door mats	60 - 70

Table 8.1 Ground surfaces testing to determine the critical detection angle of detection

A similar test was conducted in external areas. Although the SCAD system was primarily developed to operate and detect indoor environments, inevitably young drivers ventured toward external areas.

Table 8.2 shows the variations encountered from external ground conditions and provided a level of confidence about the system functionality. For this test the surfaces were free of any loose material. The test was constrained by factors that gave anomalous results due to broken surfaces and irregular surface texture, particularly tarmac and concrete that had become old and weathered. Some concrete paths were only just suitable for wheelchairs because of ground irregularities such as holes, bumps and cracks.

Ground surface type	Critical angle °
Paving slabs	59 - 65
Concrete	54 - 56
Fine Tarmac	55 - 57
Med coarse Tarmac	52 - 55
Soft play compound	55 - 56

Table 8.2 Variations in the critical angle of object detection

8.5 Auto steering collision avoidance

The angle of a wheelchair approach to an object varied from being ‘head-on’ to a “side-glance”. The amount of steering correction needed to take account of the approach angle.

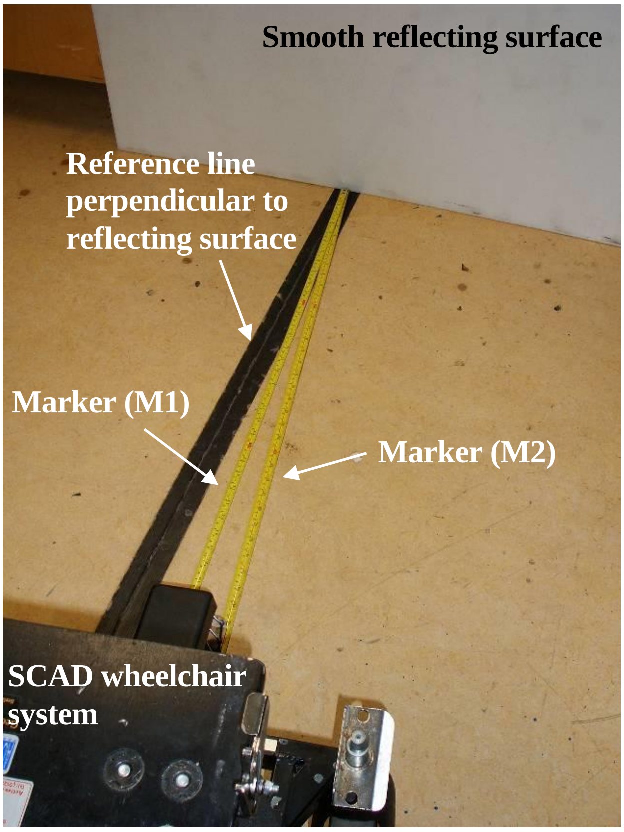


Figure 8.9 Critical angle avoidance testing

To determine the practical system response, critical angle tests were carried out as shown in Figure 8.9, by driving a powered wheelchair equipped with the SCAD detector towards a flat smooth surface. The angle of approach was referenced to a black line perpendicular to the object surface. In Figure 8.9, the two tape measures were placed at angles found to be the critical angles at which the system would not repeatedly start an avoidance turn to the left. The angles were measured with reference to the black centre line. The system response between marker lines M1 and M2 was indeterminate. The wheelchair would either stop, or perform a left avoidance turn. Factors that could affect the critical angle were:

- Object detection range
- Specula reflection angle
- Object surface texture and irregularities
- Speed of approach
- Which part of scan cycle the object was first detected

Figure 8.10 shows when this angle became critical and the system would not correct predictably.

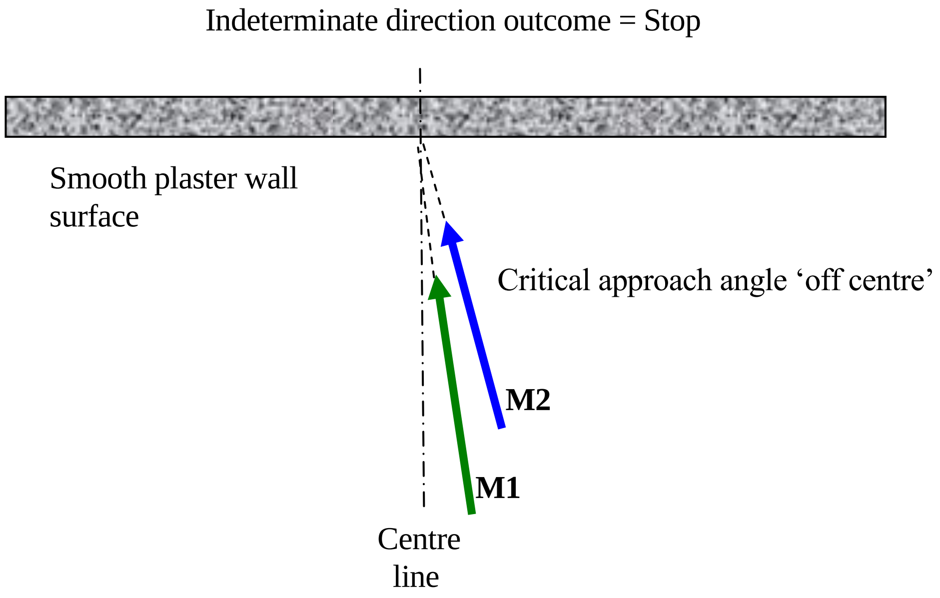


Figure 8.10 Critical object approach angle

When the angle of approach was greater than M2 (82°) as shown in Figure 8.10, the system would predictably complete an avoidance turn towards the left. If the approach angle was less than M1 (86°) the system would predictably stop.

The SCAD scan was symmetrical so that avoidance turns to the left and right resulted from the approach angles shown in Figure 8.11.

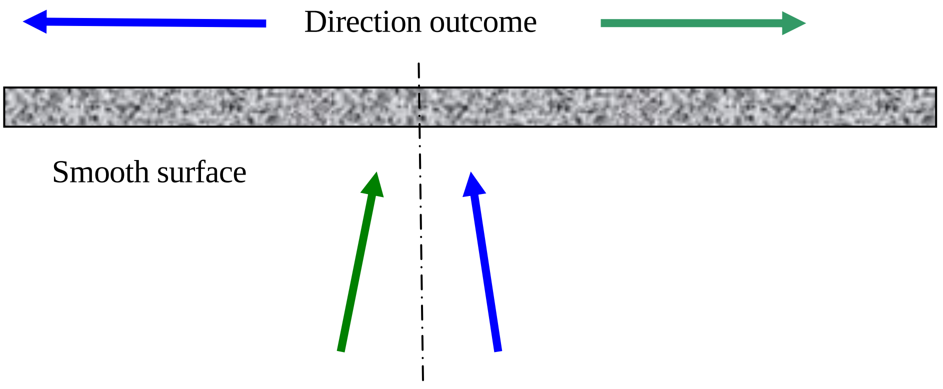


Figure 8.11 Approach angle > than critical angle (82°)

The practical range of approach angles over which the system would correct is shown in Figure 8.12. The functional correction angle was between 82° to a near parallel course when approaching the wall as shown by the green arrow.

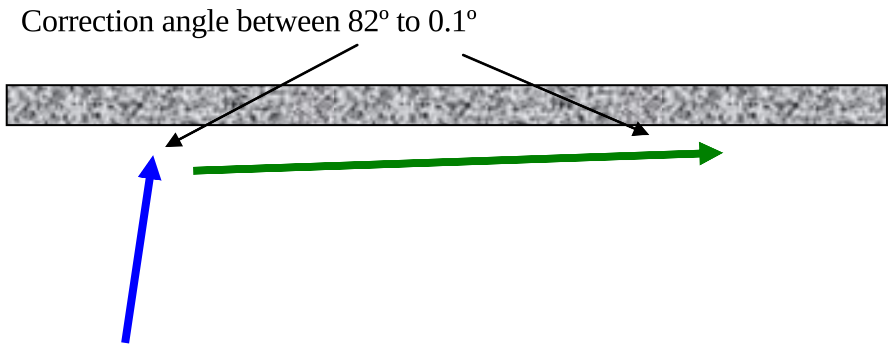
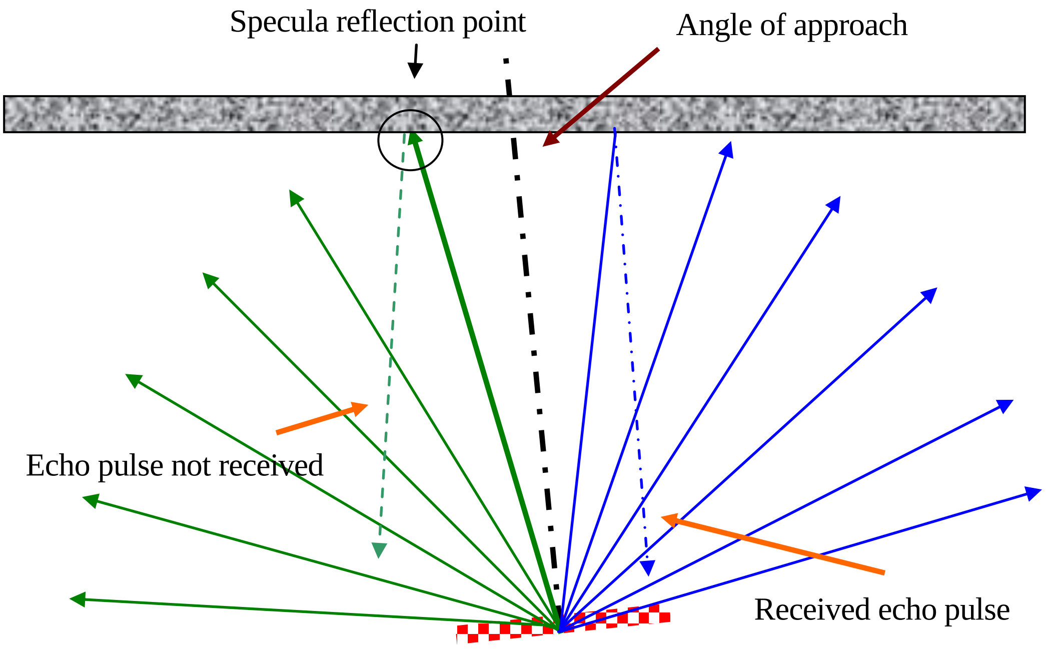


Figure 8.12 Shows the approach angle tolerance of the system

The critical angle was mostly determined by the effect and angle of specula reflection off the object surface. Figure 8.13 shows a complete SCAD scan sweep.

When the wall object was detected in the blue zone only, the wheelchair drive control steered to the left to avoid a collision.



8.13 The effect of specula reflection on the critical angle

The specula reflection point occurred when the reflected energy from the echo pulse became insufficient for detection so the object was not detected in the green zone, therefore producing the critical angle. The angle of specula reflection and critical angle varied according to the texture and irregularities of the wall surface. The following surface types were tested to determine the average critical angle and the results are shown in Table 8.3.

Type of wall / barrier surface	**Critical angle (°)**
Smooth plaster wall	86° - 82°
Brick / breeze / concrete block wall	85°- 80°
Wooded doors	86 - 82
Glass	86 - 83
Table cloth (fabric)	87° - 85°
Table cloth (Plasticized)	86° - 83°

Table 8.3 The effects of surface type on the critical angle

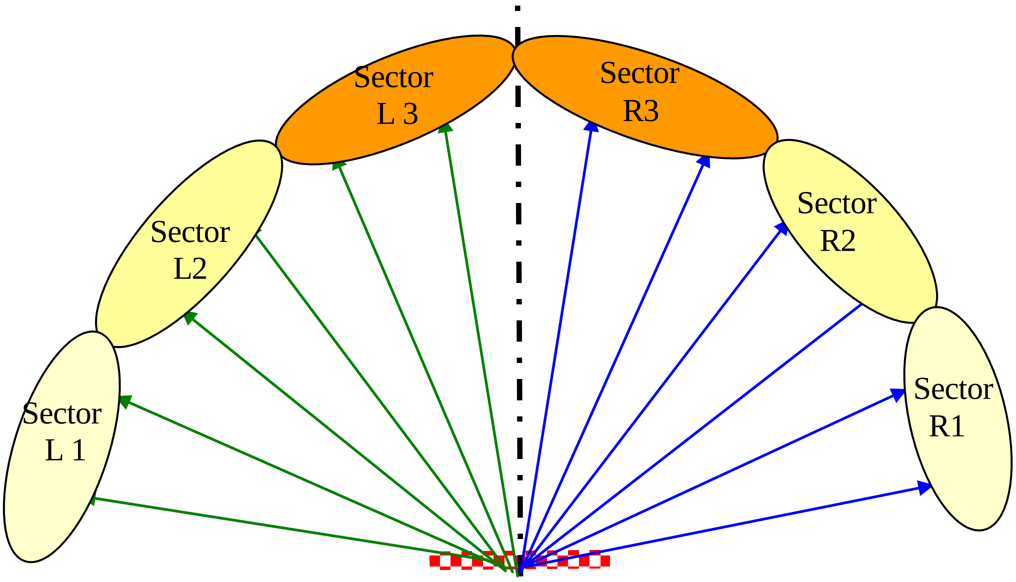
8.6 Object approach angle object avoidance compensation

The angle of approach varied with different driving candidates. The system was required to control the anti-collision course of the wheelchair over an approach angle range of 82° to 0.1°. The amount of steering compensation was pre-set, relating to the SCAD zone in which the object was detected. If, for example, the angle of approach was low then a small amount of correction was necessary, the applied correction was considerably greater for a 'head-on' approach.

The grading of steering correction was applied by altering the retardation of the wheelchair drive wheels in response to the detected object. When the wheelchair was driven in a straight line forwards, both drive wheels rotated at the same speed.

The way in which the system corrected the wheelchair steering to avoid a collision was considered, particularly how the driver became aware that a correction had occurred. The initial systems used wheelchairs steered and controlled by switches. The drive speed and turn speeds were set at levels considered suitable for the abilities of the child drivers who were tested. Operating the direction switches caused the wheelchair to turn at a pre-defined speed. The drive motion was controlled by programmable parameters (mainly) for acceleration, deceleration, forward speed and turn speed. Normal wheelchair motion was generally smooth. When an object was detected the SCAD controller steered the wheelchair to avoid a collision. The method selected was pulsed retardation of one of the drive wheels. This caused the wheelchair to veer away from the object. The duty cycle of the retardation pulse changed conditionally depending on where the object was in the object scan field. Figure 8.14 shows the scan sweep which is comprised of 6 pulse echo sample zones for the left and 6 zones for the right. The effective area of each zone spread over an angle of 15º and these were grouped together in pairs to give a 30º combined sector.

The pulsed object avoidance steering control was not a smooth steering function. This provided movement feedback to the driver that the system was acting to make a correction.



Transducer swept at 15º

Figure 8.14 Scan sweep zone allocations

The reverse retardation pulse duty cycles were:

Sectors L1 and R1 = 10%

Sectors L2 and R2 = 30%

Sectors L3 and R3 = 70%

The system was tested to obtain these functional duty cycle values. The reverse rotation control was applied in bursts synchronised to the scanning motion of the transducer. Factors that affected the avoidance steering control were:

a) Combined system response time (power control system + SCAD)
b) Burst pulse / retardation rate of the drive wheel
c) Pay load of the wheelchair
d) Wheel grip
e) Object detection range (warning before action)
f) Object detection update time (where object was in relation to sweep position)
g) Wheelchair to object approach speed

a) Combined system response time

Standard manufactured wheelchair control systems incorporated programmable response times and speed values that could be tailored to a driver's ability and requirements. The SCAD system required fast response times, particularly deceleration, so the wheelchair could be controlled after object detection. Some drivers did not like the harsh deceleration, particularly for general driving. It was decided to incorporate a SCAD interface with two separate modes of deceleration:

Driver decelerate. Some drivers preferred a gentle slowdown of their wheelchair after they released their drive switch. When nothing was detected the deceleration was controlled by the SCAD interface, which applied a gentle slowdown.

System decelerates. When an object was detected, the SCAD object detection response took priority and imposed a faster deceleration rate to stop the chair and avoid a collision.

b) Burst pulse / retardation rate of the drive wheel

To convey a sense of applied control to the driver that avoidance control action had been applied, the SCAD applied control action in short bursts. This burst pulse caused a drive wheel to change from forward to reverse rotation to effect steering control. To alter the collision course, the wheelchair turn function was applied to retard the forward speed. The rate of the applied retardation was governed by the ultra sonic sector in which the object had been detected. The amount of time required for the drive wheel to change of direction was dictated by the length of the burst signal. It was noted that this was affected by wheelchair loading.

c) Pay load of the wheelchair

The dynamic control of the wheelchair, particularly deceleration, was affected by the weight of the child and seating system. This was particularly apparent when the same assessment chair was used by small and large children; this had a direct effect on the amount of energy involved for effective control. It was noted that there was more overshoot and collision problems with heavier children and sometimes the drive speed was slower.

d) Wheel grip

The weight distribution of the person and seating system on the wheelchair affected the combined weight over the drive wheels. The seating system placed more weight towards the front of the chair. This reduced the amount of grip available from the rear drive wheels and increased the drag imposed by the front castor wheels. There were problems with skidding and wheelchair steering control could be lost. The dynamic characteristics of the drive control (damping) affected skidding, for example rapid decelerations. Less aggressive control was preferred and minimised the amount of skid although this could extend the control response times.

e) Object detection range

The response time of the system introduced a delay between the time the object was detected and the time at which the wheelchair responded. Advancing the object detection range compensated for this by an earlier object detection.

f) Object detection update time

The update time was dependant on when an object first became detectable within the set range and where the transducer was looking during the scan cycle. Subsequent object detect updates were subject to the scan cycle time. Due to the alternate scanning method, an object of small cross sectional area may not be detected by one half of the scan, thus the update time was equal to the complete scan cycle time including the time of flight delay. Larger objects could be detected on both halves of the scan; therefore two updates would occur for a complete sweep cycle.

g) Wheelchair to object approach speed

To increase the control time for object avoidance the scan range was increased and this restricted some drivers. The slow speed of driving frustrated many drivers. To provide a solution for this an additional scan zone was applied and is shown in Figure 8.15. This provided an extended outer zone that acted as a pre-slow-down prior to control intervention. This provided a compromise for accessibility, increased speed in less confined areas and provided more time for the control system to exercise a control manoeuvre.

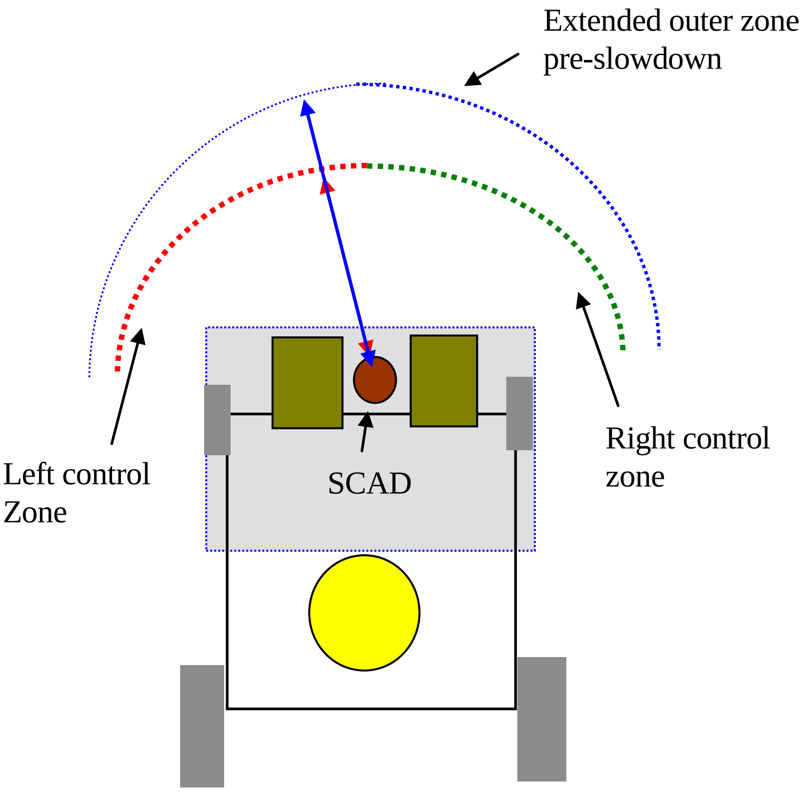


Figure 8.15 Extended outer zone

8.7 Mounting position for the SCAD head

When children and young adults used their powered wheelchair they were usually supported by special seating systems.

Figure 8.16 Adjustable CAPS system

Chailey Heritage Engineering had conducted some research and developed the Chailey Adjustable Posture Seat (CAPS) systems shown in Figure 8.16. These also incorporated a tray that was detachable from the seat. The child and the CAPS needed to be transferable to enable the child access to their powered wheelchair.

A multi-element sensor array was considered. Multiple transducer units had been used on smart systems. Multi-element sensor arrays needed an enclosure for each transducer and twelve would be required to provide the same combined sensory field angle that could be obtained from one single scanning SCAD transducer. Considering individual transducer matching and overlap characteristics, multiple arrays had the advantage of firing pulses in different directions at the same time. SCAD had the advantage of compactness and possible agile scan sequences and profiled range shape. A single transducer also simplified the amount of required electronics and inter-connections.

Consideration of SCAD mounting positions included:

a) To cause minimal obstruction when transferring children and seating systems
b) Not affected by the occupant
c) Structural integrity of mountings

d) Obscuration of the sensor. (Overhangs e.g., strap fixings, shoelaces, etc.)

a) To cause minimal obstruction when transferring children and seating systems

It was important to mount the SCAD detector head so that it was un-obtrusive and did not interfere with moving the child and seat in and out of the wheelchair. It did not require repositioning or attachment by staff each time. It was considered that a removable sensing system carried the extra risk of being damaged, (particularly during plugging and unplugging connections), or from being lost.

b) Not affected by the occupant

When a child and seat were in a powered wheelchair, there could be aspects that affected the sensing system. Problems were caused by children with long legs that had their footrests adjusted to be closer to the ground and consequently the footrest mounting clamps were detected. It was necessary to raise the seating base to provide additional clearance to stop this unwanted detection. It was noted that placing a thin smooth flat rectangular plate between the under side of the footrest and the sensor reduced unwanted pickup. Any reflecting mounting structures were shielded.

c) Structural integrity of mountings

Wheelchairs generally operated in a busy environment and were not always treated carefully. Any additional attachments needed to be robust. It was not possible to rely on people treating wheelchairs more carefully because they were equipped with sensors. The mounting structures were made to be as robust as possible. Future work will look at compliant mounting structures that could pivot out way if they were hit.

d) Obscuration of the sensor

There have been problems with straps and shoe laces that dangled in front of the sensor. The SCAD detector field needed to be clear of the front castor wheels when they swivelled forwards during wheelchair reverse or turn manoeuvring.

The casters were detected by the sensor as shown in Figure 8.17.

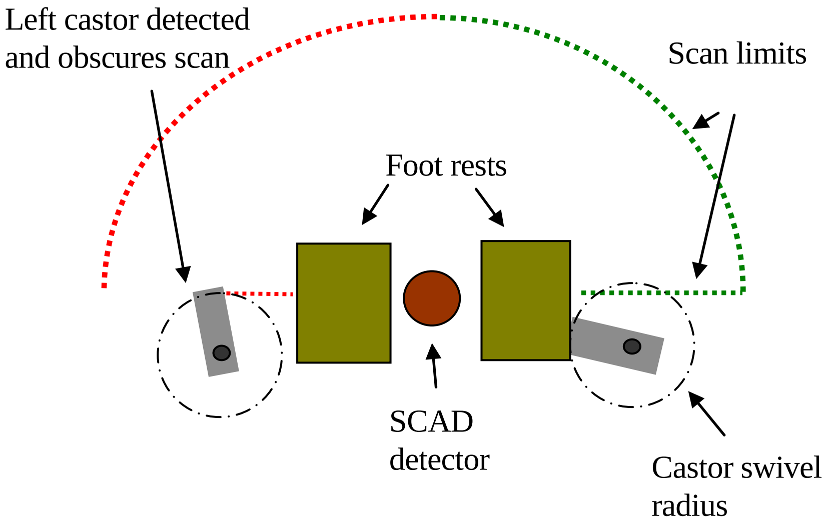


Figure 8.17 Obscuration of detection by caster swivelling

The detection of the castor wheels blocked the sensing of objects in forward driving directions. Figure 8.17 shows the left front castor that has swivelled forward and has been detected by the left part of the scan.

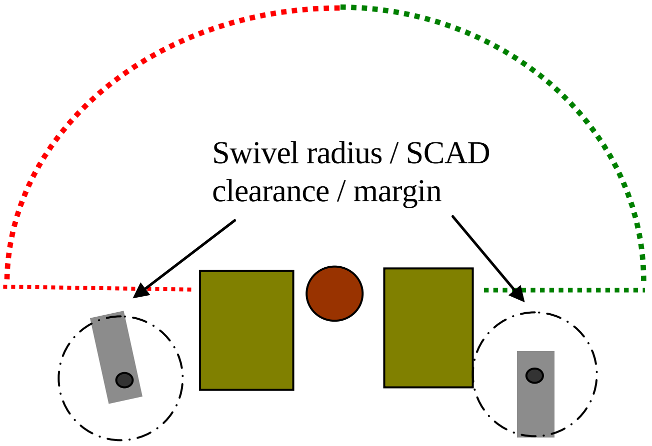


Figure 8.18 The SCAD detector was moved forwards to provide castor swivel clearance

Figure 8.18 shows the SCAD detector moved forward to provide clearance of the castor swivel radius. This had the disadvantage of increasing the sensor vulnerability at the front, particularly if the footplates were removed.

Mounting the SCAD sensor in the tray was considered. The tray was a removable item and sensor interconnections would be required. Manual handling issues and plugging and un-plugging sensor cables militated against this option and the tray mountings may not have been suitable for long term sensor operation. Furthermore the higher sensing position lost the advantage of sensing objects near to the ground.

The SCAD system used for assessment used a ‘clip-on’ mounting for the scanning head, either on the tray or the footrests. With ongoing work the SCAD could be permanently mounted to the wheelchair structure, or made detachable (e.g. similar to a removable curb climber). Having the detachable feature was helpful when the wheelchair was transferred into transport vehicles and pushed on and off steep ramps and curbs.

The sensor position needed to have a minimal effect on the operation or the mechanical specification of the wheelchair and did not add to the overall dimensions of the chair.

8.8 Testing the SCAD

The SCAD ultra-sonic transducer was tested in the lab and in the real environment. The transducer enclosure needed to be compact, especially in height, because of being mounted under the footrests to provide satisfactory ground clearance. The first prototypes were damaged and the delicate transducer assembly needed to be protected by an enclosure that was robust and acoustically transparent. Figure 8.19 shows an enclosure design that had a mesh wrapped around transducer scanning window.

Figure 8.19 the first SCAD prototype enclosure

Having a mesh over the front of the transducer degraded the sensitivity. There was a cumulative build up of dirt, on the fine types of mesh. The sensor housing could then cause internal reflection and consequently problems occurred with false detection.

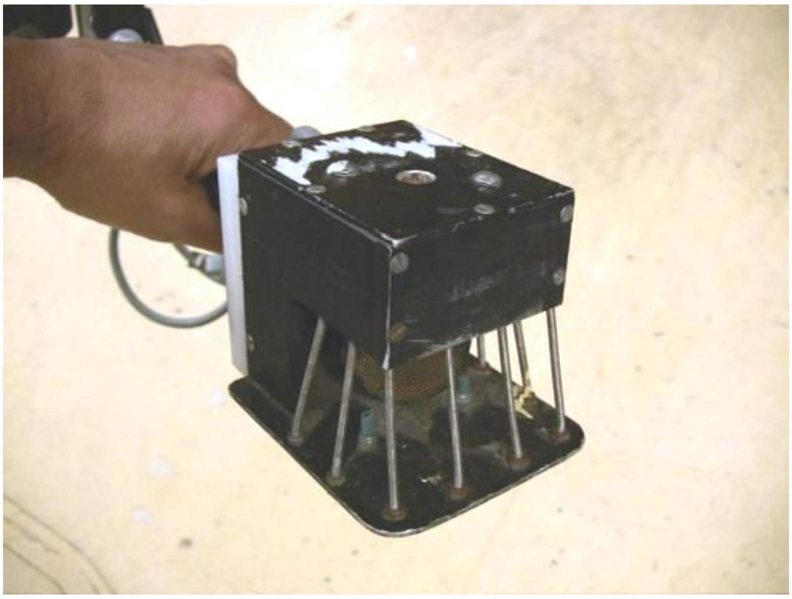


Figure 8.20 The robust aluminium

Sometimes the edges of enclosure aperture caused stray reflections. Figure 8.20 shows an enclosure that was made of 6mm thick aluminium and was robust enough to withstand daily use. As the enclosure height was the most critical dimension, the top and bottom plates of the enclosure were made of 1mm aluminium. The protection bars were made of stainless steel and were set at an angle to reduce sound pulse energy reflected back to the transducer. There were problems with the acoustic transparency of the enclosure.

The design of the enclosure needed to have an aperture window sufficiently clear to reduce any stray reflections, this could structurally weaken the enclosure. This meant that subsequent designs were larger than the first prototypes.

The moving transducer was connected by two thin wires to a Polaroid ranging transducer signal processing board and there were problems with wire fatigue. Figure 8.21 shows the connecting wires that were subjected to the reciprocating movement of the transducer.

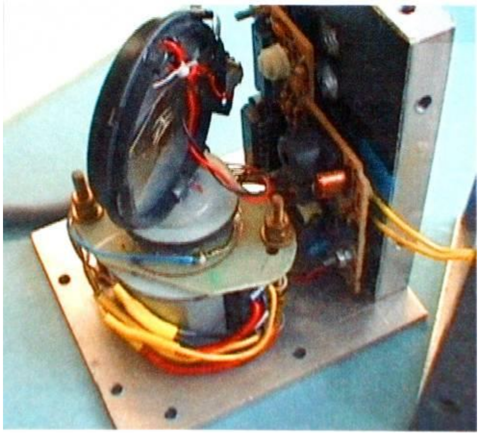


Figure 8.21 Loose transducer twin wire connections

Figure 8.22 The transducer was mounted on a bobbin with wires spiral wound

A method was developed to increase the reliability of the transducer connection. A small bobbin was made so the delicate wires could be wound into a spiral and held captive as shown in Figure 8.22. It can also be seen that the bobbin formed the transducer mounting. The reciprocation motion would successively wind and un-wind a small section of the wire spiral similar to a mechanical clock escapement.

Experiments were conducted to reduce the standard transmit power that was primarily for single pulse application for the purpose of object / ranging for camera focusing up to a range of 10 metres. For repetitious pulse echo sampling, the standard transmitter power value was too high and there were problems with environmental pulse scattering. This caused ghost echo pulses and multiple bounces that caused false detection problems. Tests were carried out to determine the best power level. The power level of the transmitted pulses was set. Higher power levels provided reliable detection of reflecting objects, particularly with a smaller correctional area but was susceptible to anomalous false detection problems.

A test was carried out to determine the extent of practical detection of objects around the school that children in their wheelchairs would most likely come into contact with. A scanning ultra-sonic detector was mounted on the front of a push wheelchair. This was wheeled around the school and an assessment was made of which object types could be detected reliably and those that were not. Specula reflection caused problems with some objects having slopping surfaces and gaps between furniture legs, soft furnishings, hard walls, people clothes and chair legs at different angles. Tests were carried out to evaluate the environmental variations in the type of object texture and how it affected detection.

- Furniture, hard wood, walls and metal objects
- Soft objects, table cloths, clothing, trousers and dresses
- Medium hardness objects, shoes and fabric covered furniture

An optimal receive sensitivity was set. The Polaroid ranging board incremented the receiver gain with time to compensate for signal decay. High receiver gain provided high sensitivity for object detection but it provided a low tolerance to environmental noise. A test was carried out to assess the effect of high frequency environmental noise. When the Polaroid ranging circuit board was switched to receive mode, a high gain amplifier was connected to the transducer. When the amp output increased beyond a preset level, a voltage comparator provided an output signal. An oscilloscope was attached to monitor the noise floor (the signal level below the triggering threshold). Rattling loose change (coins) provided a common source of sound that contained high frequency sound components. Dropping hard objects onto hard floors, clashes of cutlery and high frequency (sibilance) components of speech and mechanical noise from wheelchair motors and gearboxes were also evaluated.

Collision avoidance operation restricted how close individuals could get to things and places of interest. An example was when the system prohibited access through narrow doorways and spaces (narrow apertures). The system range setting was fixed at a level that was based on factors such as: the driver's ability, skill and confidence.

The set object scan width was wider than the width of the wheelchair. This caused the system to halt when driving through a confined space or doorway. Environmental range conditioning was considered to enable the system to continue without halting.
When two objects were detected at extreme left and right zones and when no object was detected at the front zones. When these conditions were met the system would contract the sensing range for a fixed period of time. After this time had elapsed the range would revert to the set value. If the driver was still in the confined space within the range contraction conditions, then the process would repeat. This feature was incorporated into later SCAD systems. The system was extended to provide an option for children who did not have sufficient personal switch control ability to master a reversing control. The SCAD system implemented a conditional reverse manoeuvre

when in a situation where a driver became trapped without the use of a reverse function. When in a confined space, whilst activating a turn control, the system performed a sequence of reverse turns. This incrementally rotated the wheelchair in the selected direction and out of the confined space.

A reverse switch input was provided. No reverse direction detector was used on the wheelchair to keep the number of additional peripheral detector units within the constraint of one front centre SCAD sensor and two side detectors.

Consideration of additional sensors:

- Maintenance
- Vulnerability to damage
- Cost of additional devices

An alternative to a backward sensor was the implementation of a reverse timer. This allowed the driver to withdraw from an object or confined space. The time factor limited the distance travelled in reverse in order to reduce collisions.

A method was developed to evaluate the SCAD scanning segment overlap / under lap characteristics. Figure 8.23 shows the testing board to determine the uniformity of object detection. The test used a pencil (of width 6.25mm), which was chosen as it had a small area compared to the 15° sectors of the scan zones.

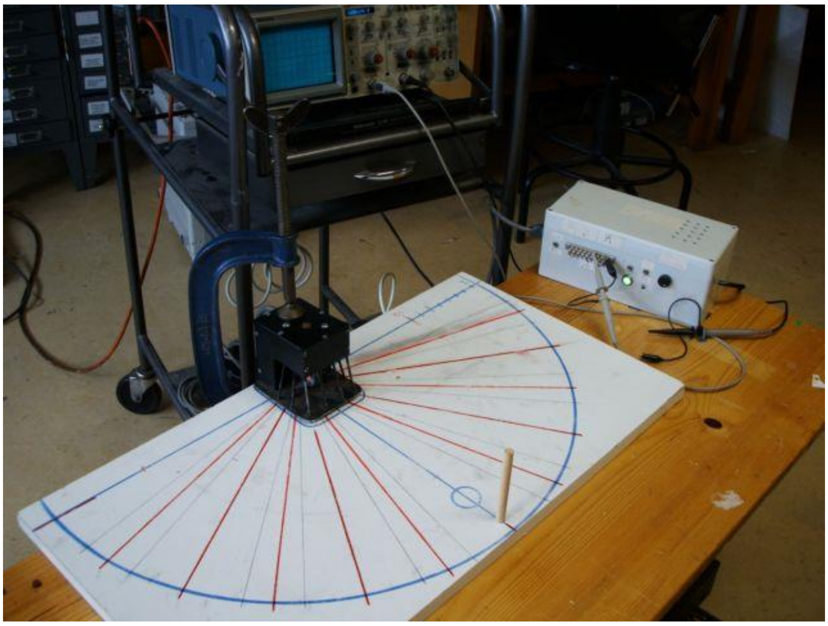


Figure 8.23 Testing for dead spots

To assess dead spots within the sweep, the pencil was moved across each sector and dead spots were recorded. The stepper motor, with the mass of the transducer exhibited resonances that caused changes in the step angle. Tests were carried out to change motor excitation levels, half stepping, damping, step rate and the mass of the transducer to improve the uniformity of the sweep zones at a 50Hz pulse sampling rate. Using reciprocal scanning, the update time for object detection varied depending on the position of an object within the scan. At the centre, an object was swept twice as fast as at the extreme sides. Experiments were conducted to increase detection speed by half scanning when turning corners, but this work was not continued, as half scanning caused a blind spot on the opposing side of the full scan field.

The first SCAD system used progressive scanning. An assessment was made of the over and under laps between the sectors in the scan sweep on both clockwise and counter clockwise scanning directions. There were problems with ghosting. This worsened when the pulse repetition rate increased, and the chair would stop inappropriately. This caused significant restrictions with the usable pulse repetition rate. Problems were encountered by children colliding with objects because of the slow response of the detection sweep. The speed of the wheelchair was reduced to provide more time for the system to respond, some drivers became frustrated, and wanted to drive faster. The detection range was extended to provide an increase in the time margin for object detection, but this caused problems by restricting access throughout the driver's environment.

Experiments were undertaken to decrease the scan cycle time. During turning, the scan was switched to a half scan sweep to reduce update time. The update time for object detection varied depending on the position of the object within the scan. At the centre, the object was swept in less time than at the extreme sides. Experiments were conducted to increase detection speed by half sweep scanning when turning corners.
A faster complete sweep was needed. Alternate pulse / echo sample was developed, but that had alternating sector gaps in each scan direction. A full sweep cycle was twice as fast as sequential / progressive scanning. This effectively interlaced the sector gaps. Therefore if the left to right sweep missed an object then the right to left sweep would detect the object. The alternate scan method had an advantage of increased detection speed.

The polar response of the transducer was a significant factor in the choice of scanning method. A Polaroid 600 series transducer was selected because it had characteristics that suited the 15° step angle when it was incrementally rotated. For a sequential scan, the transducer moved 15° for each pulse and 30° for alternate pulses. When the system was tested for doorway navigation it performed reliably, except when children tried the system. On approach to a doorway children could alter course or steer into a door frame whilst only halfway through. This highlighted a problem because the scanning sensor was limited by castor wheel obscuration and could not detect objects at the side.

8.9 Supplementary detectors

Children that had been using the SCAD system with the main scanning ultra-sonic sensor for guidance sometimes had collisions by turning into an object at the side, mainly because this was out of the SCAD scan range limits. Additional side detectors were created that covered the blind spot at the side of the wheelchair.

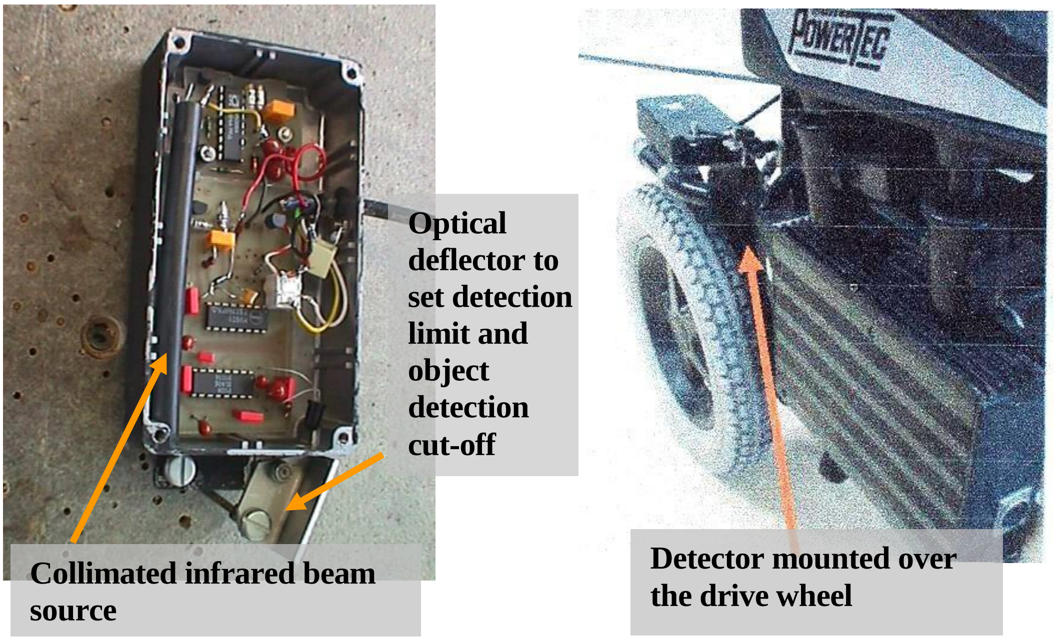


Figure 8.24 Infrared side detector with background suppression

Infra-red detectors were selected because infrared reflected back sufficiently to detect objects at low angles of incidence with greater certainty than sound. Also the requirement for ranging was less critical. Figure 8.24 shows an optical infra red side object detector that was created to supplement the ultra-sonic system. This provided detection of objects at the side of the wheelchair by triangulation.

This detector used a coded infra-red beam that reduced problems with environmental interference. Optical methods were selected because of their acceptable tolerance to high angles of specula reflection. The limit of detection was set by a deflector that 'cut-off' the target reflection at a pre-determined distance. Two optical detectors were required to provide a balanced system for the left and the right sides of the wheelchair. The limit of detection was affected by the colour of the target object. Objects that were dark or had a matt surface were poor reflectors and the cut-off point became closer than objects having higher reflectivity, for example white. The object detection range is shown in Figure 8.25.

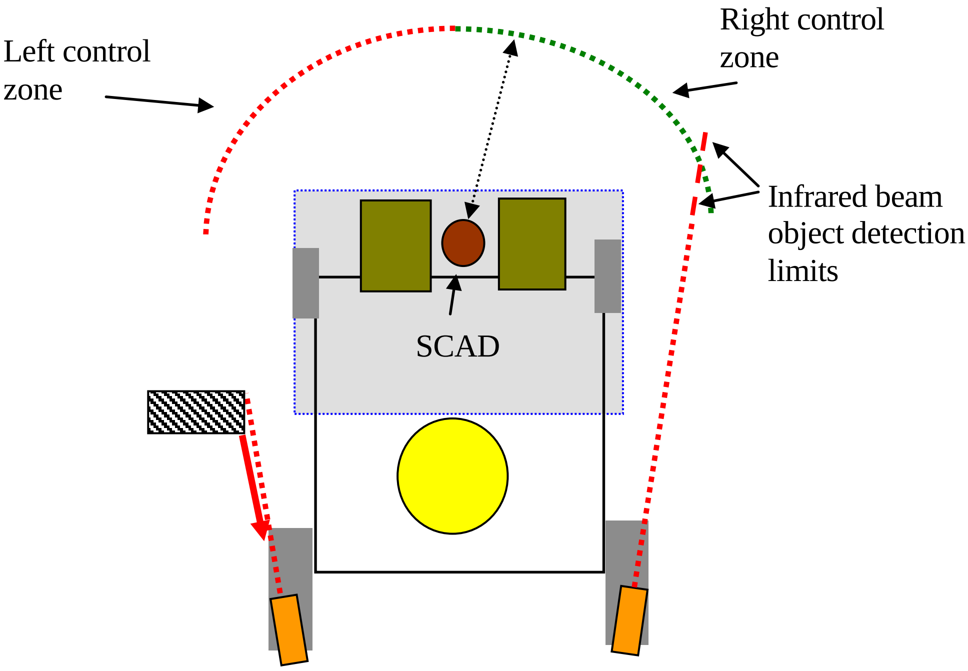


Figure 8.25 Side detectors mounted over the rear drive wheels

Figures 8.26 and 8.27 show a powered wheelchair fitted with a pair of optical detectors. The optical side detectors detected walls and door frames with sufficient reliability to reduce collisions.

Figure 8.26 Left door frame was detected

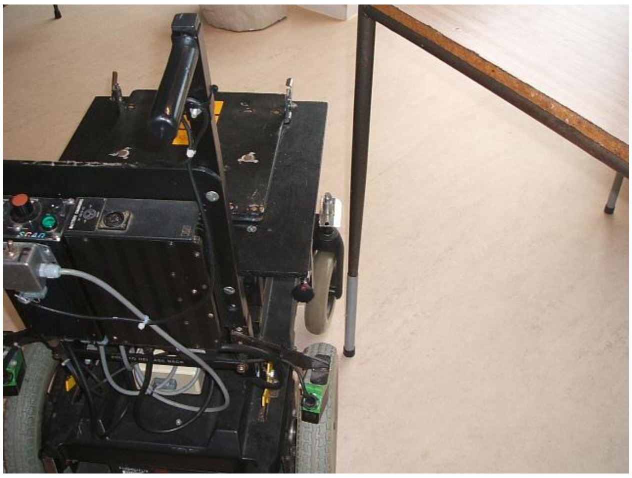


Figure 8.27 Momentary detection of a table leg

There were problems with objects that had a small cross section area, for example, table legs as shown in Figure 8.27. The legs would pass through the beam that provided only a momentary output, causing the chair to pause momentarily and then continue to crash into the table. A latch system was developed that halted the affected direction when the detector was triggered. This was reset by selecting a direction on the opposing side. The side detector modules were vulnerable and were damaged when the drive wheel brushed against the side of the door frame. Detector vulnerability was reduced by careful positioning of the detector within the outer edge of the drive wheel as shown in Figure 8.28.

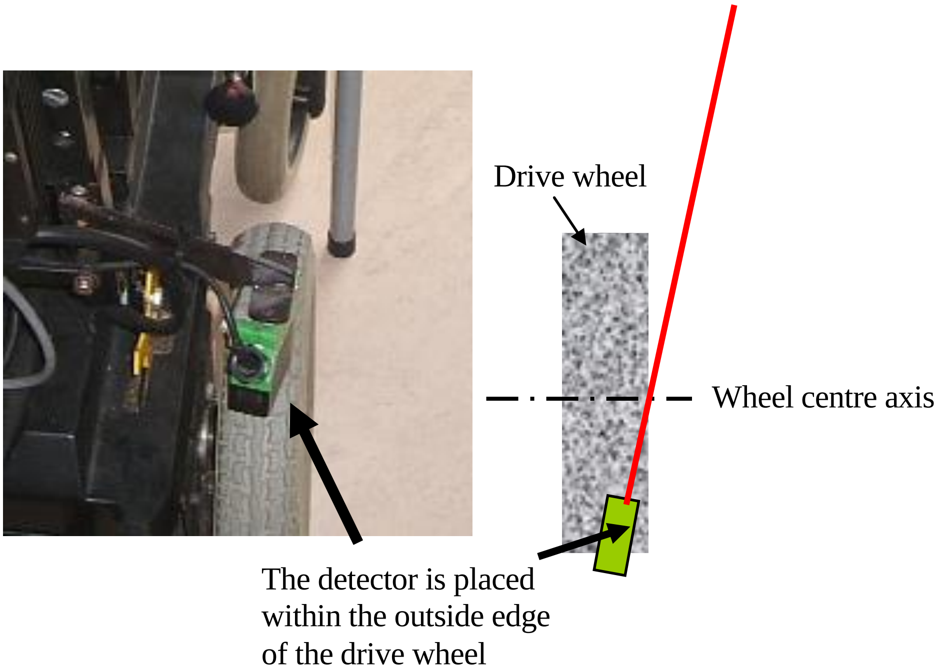


Figure 8.28 Optimised side detector mounting position

The infrared beam crossed the centre axis of the drive wheel so that objects were detected at the side of the wheel and problems with scuffing through door frames were reduced. The side detectors proved to be a valuable addition to the SCAD system. Commercially available infra-red background suppressed detectors were obtained that had an adjustable range of between 0.2-1.0 metres and an acceptable tolerance to object reflectivity and colour.

These were not without their problems. It was noted that these were susceptible to interference from high frequency fluorescent lighting and the infra-red door entry systems.

8.9.1 Integration of the side detectors in to control system

There were two modes of operation to be considered:

Momentary or latching operation. The momentary mode came into operation when the forward drive control was activated. When a side detector responded, for example a wall, the control function steered the chair away from the wall in a way similar to SCAD side detector zone application. Secondly the latch function occurred when a steering control was operated. When a side detector momentarily responded to an object, for example the table leg shown in Figure 8.27 the latch function disabled the direction into the table.

Re-setting by operation of the opposite steering direction. When the steering direction latch had been triggered it was necessary to encourage the driver to steer away from the object. Therefore the latch function was reset by the driver selecting a steering direction that was away form the object. All of the steering directions were restored providing no object was being detected.

8.9.2 Sensor conflict

There were driving conditions in which the SCAD sensor and side detector would detect objects that would stop driving, causing the system to freeze. An example was when a side detector responded to an object on the right and the SCAD detected an object centre and left. The system would lock any forward driving and this frustrated drivers. The sensors were prioritised so that when the SCAD detector had responded to an object the side detectors were disabled.

Striking an object was possible and driving could proceed. Collision avoidance was compromised in favour of not restricting access. Accordingly if both side detectors responded simultaneously, i.e. narrow doorway aperture, driving would not be halted.

8.9.3 Detection of overhanging objects

The SCAD had a horizontal width of 180° and much less vertical width 15°, the detection of objects at increased height when referenced to ground was limited. Specula reflection problems limited effectiveness issue when considering increasing the vertical width by using more that one ultra sonic transducer within the same enclosure. An experimental supplementary optical detector was tested that was mounted at 45° upwards. This was mounted alongside the SCAD head to detect over hanging objects, e,g. table tops and ledges. Commercial sensors retro-reflective background suppressed types had problems with high frequency fluorescent lighting. Particularly as the sensor was looking upwards.

Chapter 9

Human trials testing with children

9.1 Introduction

Mechanical bumper systems created by this research provided a starting point for object detection. A primary reason for the bumper developments was to increase the amount of independence provided by track guided systems to young people. The first step was enabling drivers to reach destinations without constant helper intervention. This was compromised because children collided with objects causing helpers to intervene.

Figure 9.1 A young driver using a track guided wheelchair fitted with a prototype mechanical bumper

The young girl shown in Figure 9.1 was based in the primary department of the school and used a track guided wheelchair because of her visual and physical disabilities. Her chair was fitted with a mechanical bumper system. When the bumper struck an object, driving was stopped and an audible warning was sounded. This did not offer a total solution to reduce helper intervention because the bumper was triggered when the driver had collided with an object and often helpers were needed to remove the obstruction, particularly if the drive function was disabled. The main advantage provided by the bumper was object collision warning and damage limitation.

When applying the bumper system to wheelchairs with an increased frame size, the bumper did not provide any advance warning as shown in Figure 9.2, in fact, the tray and the foot rests were outside of the bumper detection area.

Figure 9.2 The bumper was less effective for larger wheelchair frame sizes

The only practical benefit provided by the bumper was detecting low level objects lying on the ground, for example children sitting or crawling.

Initial tests with children indicated that bumpers provided positive feedback to drivers about collisions. Children and helpers felt more confident that the bumper provided a margin of safety and warning. The bumpers had fundamental limitations, as they were vulnerable to damage when accidentally ‘stepped-on’ by helpers placing the child in or out of their seats. Protruding bumpers made wheelchair handling difficult. Although the purpose of mechanical bumpers provided a valuable function, they had significant practical disadvantages. This led to the new work that started to create a contact less SCAD object detection system created by the author of this Dissertation.

9.2 Testing the new contact-less SCAD system

The first practical application of a compact SCAD system was for a warning device to help a blind girl who drove a track guided wheelchair. Figure 9.3 shows the SCAD system enclosure mounted above the track guidance sensors. Object detection provided an interim between line guidance and no guidance. Although the first track driver developed her independence by using track guidance she wanted to be able to detect possible collision situations involving people and objects. Most of the time, she needed a helper with her even though she was guided by a track. The helper would provide warnings of congestion and possible collision risks.

This young track driver had acute hearing and she was able to discriminate certain places along her track routes but she was at risk of collisions with objects and other children. In many cases her driving was stopped through non availability of staff.

This put her at a disadvantage as the amount she drove was compromised through staffing issues.

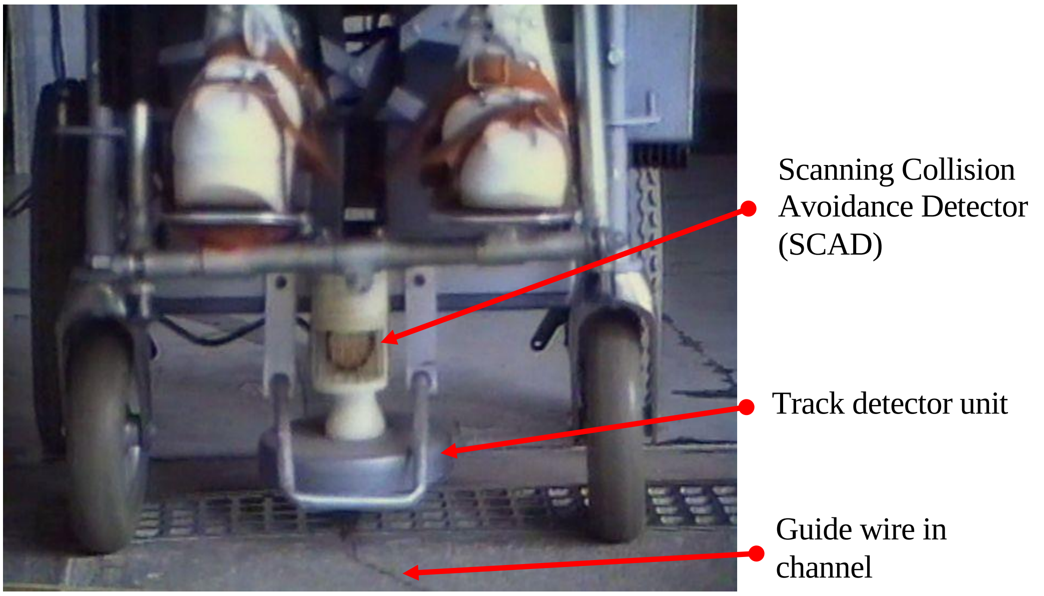


Figure 9.3 SCAD and track detector mounted on the powered wheelchair

This young driver used a set of experimental adjustable chin switches that was developed as part of a control development project funded by the Spastics Society at Chailey Heritage.

Figure 9.4 Driving towards a person

Figure 9.4 shows her track driving by operating the forwards control that was placed centrally under her chin, although she was aware that someone was close, she did not know how far away.

Figure 9.5 She responded to the sound chirp

She was able to make turn selections at junctions by operating switches mounted either side of the forward track drive control switch. The guide wires were set in a channel in the flag stones and the SCAD had detected the person in front. Figure 9.5 shows the driver had lifted her head away from the chin controls and stopped driving when she heard the SCAD generated object warning chirp.

The purpose of the SCAD was to warn about possible hazards in front of her wheelchair when she was driving. This system did not intervene or apply control to the wheelchair directly, for example cut the drive power when an object had been detected. This was not necessary because she responded well to verbal prompts from people close at hand to stop driving if she was going to hit something.   The list below outlines some considerations.

a) Generating a warning sound chirp in response to the detected object
b) The driver understood what the sound chirp indicated
c) She learnt to distinguish different sound signatures

a) The first application of object detection was the creation of a compact warning system (SCAD) for a blind girl who was an experienced track user. The detector repeatedly sent out ultrasonic sound pulses in front the wheelchair. When an object provided an echo, the system generated a short chirp. She heard this from a small loud speaker placed near to her head.

b) The scanning ultra-sonic device scanned for objects in front of the wheelchair, because the pulse echo samples were repeated continuously, the sound chirp was also repeated until the object was clear. She soon learnt that repeated chirps indicated an object was near. The chirps were short duration of approx 100 m/s.

c) The short sound chirps resulted form a positive pulse echo sample. The reciprocating object scanning meant that if an object was at the side of her chair she heard a repeating chirp. If the object was placed at the front centre she heard a repeating double chirp. This was because the object was double scanned. This subtle change of chirp timing provided a crude sound signature. If there was a large obscuring object that occupied many scan sectors the chips merged into each other and this provided an extended chip.   She learnt to distinguish these differences, for example, she would know if there was one, two or a large object in front of her.

Through general observation the children who were using the track were also restricted by it. The development and application of the track guidance systems provided children with a mobility opportunity that enabled them to reach specific destinations through line guidance. The tracks also imposed a barrier to children who wanted to go to other places and explore.

Therapists were asking and wanting children to come off the track and go free drive (no tracks), but many children still had problems with controlling their wheelchairs and were driving much shorter distances than they had been when they were using the track system.

These are observations of the track guidance:

a) The track provided a high of level driver support
b) The track system provided a child with a secure pathway
c) The track prevented the child going astray; staff would know in advance where a child was going and their destination options
d) Children wanted more options and choice of destinations (free drive)
e) Children became restricted by the track

a) The high level driver support given by the track provided a driving opportunity for young people who otherwise needed cares and helpers to continually guide their wheelchairs. The track gave a young driver personal space so they were able to develop a sense of independence. A young person was able to operate a single switch to control starting and stopping. The track provided steering and a safe passage to a specific destination, but the track was highly controlling and restricting.

b) The track provided fixed guide routes. Many children were able to learn the route destinations through practice and staff were secure in the knowledge that young people would only be able to drive along specific routes. The secure path provided by the track enabled young drivers to practice and develop awareness of their driving environment particularly because the control feedback was consistent.

c) The fixed nature of the track prevented children from going astray. Staff and cares felt confident that children would only be able to travel in specific areas. An important aspect was to increase the general confidence and reduce the vulnerability of the child, particularly from driving into potential hazardous situations.

d) Choice of destinations became an issue with the track system particularly when areas of the school were expanded to include residences and new classrooms. There needed to be a balance between the number of junction choices and destinations that were available. Some drivers could be confused by too much choice. Others needed more choice. Track drivers spanned the complete age range of young people at the school.

e) When drivers were advancing with their driving many became frustrated by the restrictive nature of the track system because they wanted to explore and access areas where there were no active track lines. Where there was no track, children became immobile and this added to frustration. This could be an indication of a young person’s personal progress because they were starting to outgrow the track system.
The restrictive nature of the track system became the focus of new work to create a support system that could provide young people with a free-drive capability. The concept of ‘free-drive’ was a term used by Occupational Therapists and related to a wheelchair that was track-less. The next phase of the SCAD developments was to provide driving support to ex- track drivers. The initial SCAD development had been to create a warning device but it did not provide any operational control functions to guide a wheelchair. A new SCAD system was created that was intended to apply direct collision control for a powered wheelchair.

The SCAD was created to provide an early warning of possible collisions, so that drivers were not so staff dependant. The concept of providing an object detection sound queue was tested and the effect on driver independence was noted.

9.3 The SCAD with a driver control interface

One of the most encouraging aspects about the SCAD was that it did not get damaged and its operation was reliable when compared to the mechanical bumper systems. The operating position of the SCAD was behind any protruding wheelchair components which provided physical protection. The first practical experiment with a self steering SCAD system was for a girl who had problems with concentration whilst driving her powered wheelchair and often she collided with objects, people and other wheelchairs. She normally drove a powered wheelchair with four separate button type hand switches mounted on a tray in front of her.

New work was started to provide a training environment and supportive driving systems.

9.4 Training areas

Driving training and practice using a SCAD assisted powered wheelchair began in the main school hall at Chailey Heritage. This offered sufficient space and seclusion from normal distractions within the school environment. A simple roadway lined with plastic cups sprayed with bright fluorescent orange paint provided markers and boundaries for a road way. The cups were separated by twice the width of the wheelchair to replicate the normal average corridor width around the school complex. The young driver was placed within the artificial roadway scheme as seen in Figure 10.6. Initially she drove though the roadway with the SCAD turned off. Her driving was then monitored without SCAD to see whether she would stray out of the road markers. Some cups were squashed as can be seen in Figure 9.6.

Figure 9.6 Roadway cones

When the SCAD was turned on, she became captive within the roadway and could only progress by driving to the end of the road way or by operating her reverse control. There was no practical reversing object sensor fitted to the system. A drive timeout gave a small amount of limited reverse driving. The reverse drive time period

provided enough driving distance for her to get the chair clear of objects that may be in front of the wheelchair and therefore provide manoeuvring space.
A video record was taken of these first SCAD driving sessions. It was clear that this was a double learning curve, not only for the child but for the research and practical application of driving training systems.

Some therapists had concerns that the child drivers could become lazy and develop a reliance on the system guidance and perhaps disengage from the active personal control. It was observed on occasions that this driver activated her forward drive switch and happily let the SCAD control her steering. For this reason two modes of SCAD operation were implemented. These were (auto-steer mode) and (lockout mode). In general, auto-steer became regarded as an energy conservation mode for driving. This was particularly suited to users with a single switch drive scanner. With this the driving directions could sequentially be selected and provided full manoeuvrability in all selectable steering directions.

The single or double driving switch scanner control system incorporated features to help the driver with direction selection. Speech output was incorporated so that each possible selectable direction was spoken by the system. To be age appropriate the authors own children made the recordings. To help drivers see the display in varying ambient lighting conditions an automatic indicator intensity control was developed that adjusted the brightness of the direction indicators that were suitable for the ambient lighting conditions.

A reverse skip function short cycled the selection of reverse to reduce the scanning loop time. Reverse could be supplemented by the auto-reverse SCAD system mode.

9.5 Auto-steer

This was originally intended to replicate the function of a track guided system in which the wheelchair followed a pre-determined route. In the case of the SCAD shown in Figure 9.7, this was the roadway of cups. The forward drive switch was the ‘go button’. In its simplest form (similar to track guidance) this single switch was used to introduce an individual to powered wheelchair driving. It was possible to keep the wheelchair captive within a large ring of markers (cups) in which the driver could circle around using the auto-steer facility. The auto-steer reduced the amount of work required from the driver and the necessity to make steering corrections.

9.6 Direction lockout training mode

After an introduction to driving in auto steer mode, the lockout mode provided a more progressive functional training. When an obstacle was detected, the chair ceased to move toward the object and there was no applied automatic correction. The young driver needed to select a new direction to drive away from the offending object as shown in Figure 9.7.

The intention was that this would exercise her mind and help her to concentrate on driving control. When she used the system in the lockout mode, at first she did not instinctively correct herself when the system was driven into a detected object barrier. Video was taken showing how she experimented with pressing different switches in order to escape. She was encouraged to find her way out of the situation.

Figure 9.7 Deciding which switch to operate

As a result of these early trials, further development work was undertaken to provide extra system based help (prompting) for the driver. Some of these early experiments consisted of illuminated beacons placed at the appropriate side of the wheelchair tray.

For example, if an object was detected on the left, a beacon would light to the right to indicate the direction to drive away from the object. The lights were made to blink at a slow rate (2Hz) as shown in Figure 9.8. This was similar to a car signal indicator frequency.

It was noted that when seeing the lights she actually placed her hand directly onto the light domes. This observation of her reaching out and targeting onto the light source necessitated the development of integrated light switches. The switch was made to light up when it should be chosen, when in an object collision situation.

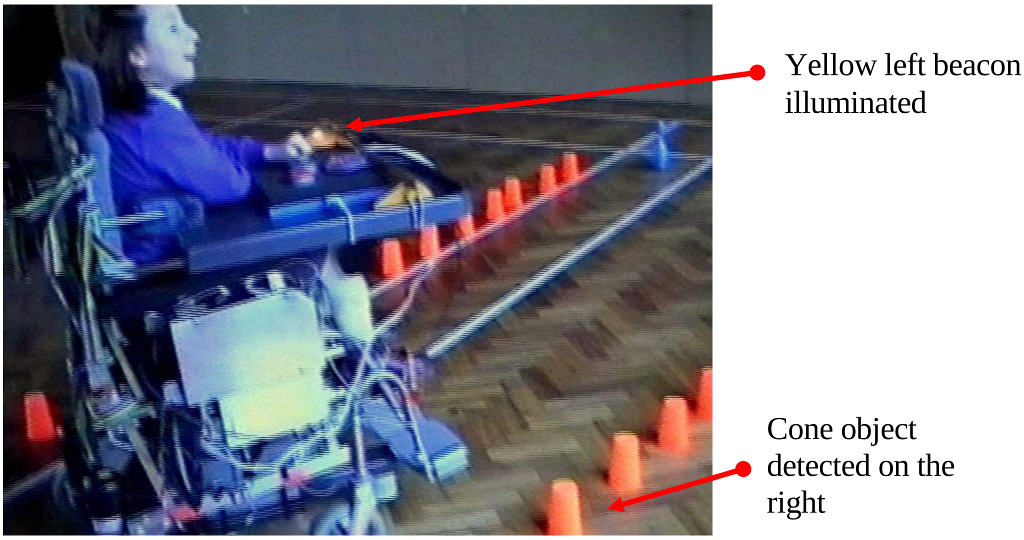
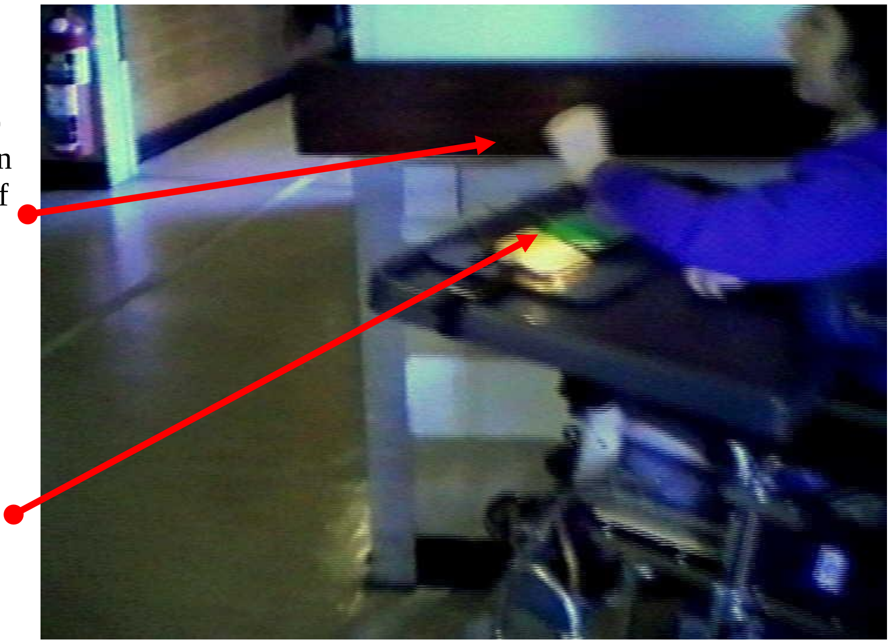


Figure 9.8 Object beacon indicator lights

The switches themselves were made in the workshop by the author of this Dissertation. Illuminated switches were built that incorporated small light bulbs. Transparent switch covers were produced with coloured strips to help reinforce switch identities. A switch colour code was used to help train pupils associate switch operation and direction:

- Red controlled reverse
- Yellow controlled left
- Blue controlled right
- Green controlled forward



A wall (object) was detected on the right side of the wheelchair

Yellow (left turn switch) illuminated

Figure 9.9 Driving around the school using illuminated drive control switches

Figure 9.9 shows a picture from a sequence of video taken of her driving out of the hall into a corridor. The lights only operated when an object had been detected. In this case the wall had been detected on the right.

Further work with automatic system prompting led to the inclusion of speech output devices as there were some children who did not like or responded positively to the light switches.

Audible prompting of switch operation and was provided as an alternative to the light system. The sound message was triggered when the system was driven towards an object. Digitally recorded phrases e.g., “press the blue switch” were used as prompts.

An object detected
message sounded
from the right
'blue' speaker.

Figure 9.10 Using auditory sound direction prompting

A two speaker system was used to provide a stereo effect to give a sense of object position. If the object was on the right, the sound would emanate from the right speaker, correspondingly a left object would cause the sound to come out of the left speaker. In Figure 9.10, the yellow & blue speakers can be seen on the corners of the drivers tray. If the object was detected straight ahead both speakers would provide a "go backward" message.

With ongoing SCAD driving trials it became increasingly clear that it was better for the children to drive around their real environment instead of a situational set-up using the road cones. For the initial tests using the SCAD, the cones worked well, particularly for providing detectible boundaries. Although the road cones provided a functional barrier, they were not liked by the children and did not suit the children's longer term training requirements.

The SCAD system was then subsequently used around the school, although this system did not detect all of the objects found in the general school environment and was not reliable when compared to the artificial roadway cups set-up. The normal driving routine for young people going from one place to another at specific times formed ongoing assessment criteria.

9.7 Considerations about crashing

a) Too much crashing was hampering children who wanted get to places
b) Not enough crashing was hampering the learning experience
c) Children were impeded through not having a reverse control

a) Often children would not be allowed to drive because of staff and helper concerns about their safety and crashing into things and people. The track system [Langner (2004)] provided a means for young drivers to drive without constant helper support and enabled young people to reach destinations. The track became restrictive for advancing drivers who wanted to drive free. The tests with SCAD (particularly the road cones) demonstrated that helpers could step back and allow the children to drive and problem solve with a reduced fear of crashing.

b) The first practical applications of the SCAD with young people provided some practical feedback that reduced the amount of crashes. Some therapists were concerned that SCAD control interventions took control away from the driver and that children needed to learn to control their wheelchair through the crashing experience. The technical development of the SCAD took account of this and incorporated adjustable parameters that reduced or increased the amount of SCAD collision control. The therapists still wanted to be able to completely disengage the SCAD.

The author of this dissertation was reluctant to implement this because, a residual level of object detection provided some self protection for the system. A system kill switch was provided and this removed any doubts about system intervention when the young person was driving.

The therapists became more relaxed when young people demonstrated that they understood the concept of driving, the therapists became less concerned with the conflict of child learning and system support and became encouraging about SCAD support to reduce the amount of effort needed from young people to control their wheelchairs. This formed the subject of work presented here or possible future work to create effort reducing systems.

c) Observations showed that children drove into situations in which they were not able to free themselves, most particularly room corners so children become stuck with their wheelchairs and helpers intervened. Helpers would pull back the child's wheelchair, or operate a reverse control if this was available.

Many children did not have sufficient personal physical ability to use a reverse control and were not always provided with one, furthermore, there were issues concerning some children not being able to look in the reverse direction.

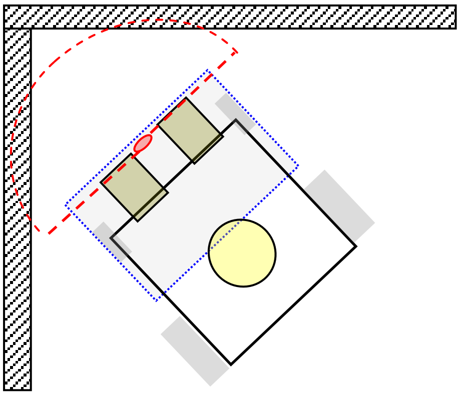
A reverse control was given to children when they were ready. At this stage children needed to learn about when to use reverse and problems with crashing whilst going backwards. Considerations about control function selectivity and targeting necessitated the child learning a control strategy in which accidental reverse operation was minimised in favour of deliberate operation.

9.8 Adding a reverse turn manoeuvring function to the SCAD

A reverse function was necessary to enable children to back themselves away from obstructions or situations where they had become trapped, for example in a room corner. When the driver did not have a reverse switch, the SCAD control system applied a reverse turn manoeuvring control sequence.

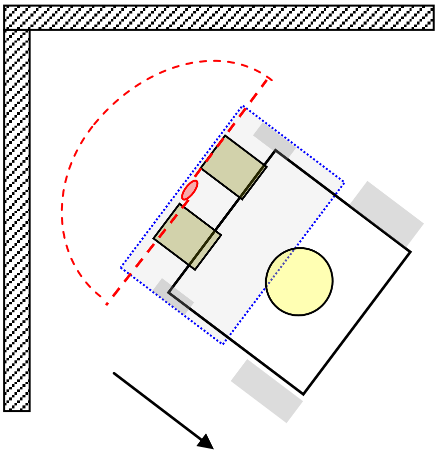
Figure 9.11 shows a reverse turn manoeuvring turn sequence that started when a turn switch (left) was operated. Figure 9.11 also shows the sequence of automatic events that provided the reverse turn manoeuvring function. It can be seen that this operation is repeated and at stage 3, the wheelchair has started to turn out of the confined area in the direction of the selected (left) turn control.

The stages 1, 2 and 3 continued until the chair was free of the obstruction whilst a turn control (left) was operated. A delay was provided to stop the reverse function acting immediately when an object was detected and this reduced the chance of the reverse turn manoeuvring acting when not required.



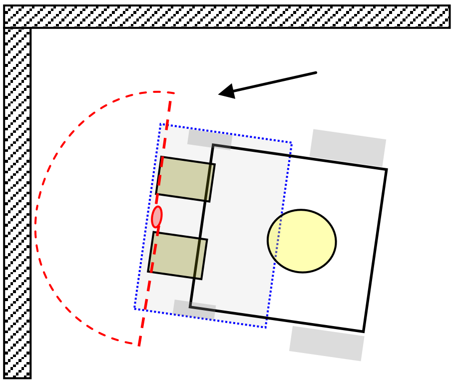
Stage 1

Wall detected =No forward, left or right turn possible. The system implemented reverse when a turn switch is operated after a delay period <u>but only until the wall is no longer detected</u>



Stage 2

The system applied reverse when the left turn switch is operated until the wall was not detected



Stage 3

The chair moves forward left until the wall is detected, then reverse is applied until clear of the wall

<u>Figure 9.11 Automatic reverse turn manoeuvring</u>

During the operation of the reverse turn manoeuvring the switch operation was contradictory to normal (unconfined operation) e.g., when operating a turn control the wheelchair responded by going backwards.

It was noted that a child being able to get free from trapped situations was preferred by people in general.

Some staff commented children maybe confused when avoiding objects. Did the children understand what the SCAD was doing and why their wheelchair responded differently during the function of collision avoidance? The switch control function changed, for example, in pre-collision, the forward drive switch controlled the forwards motion. When the SCAD detected an object on the left, pressing the forward control caused the wheelchair to steer to the right to avoid the object and vice versa.

This reflected the child's understanding about what control manoeuvres were necessary in order steer around objects and the associated resulting motion of the wheelchair. Switching off the automatic collision control function was preferred by the occupational therapist, as this to some extent, converted the SCAD into a learning tool. When the SCAD stopped the chair by the detection of an object, the driver needed to operate the correct switch in order to proceed. In this situation the child was suspended in a pre-collision state but not physically trapped or in contact with an object. Occupational Therapists preferred a bias towards a child problem solving when driving. There was a conflict of opinion because some school staff also valued child autonomy.

For flexibility the SCAD control system was subsequently developed to incorporate a range of functional modes. These modes were selectable.

- Auto steer
- Non-auto steer (lockout mode)
- Object detection range
- Pre-slow down
- Automatic reverse turn manoeuvring
- No system object detect function

Children that had been using a track guided wheelchair were not provided with a reverse control. Reverse driving on the track was deemed counter productive as prolonged reverse travel with the driver facing in the forward direction was not linked to normal mobility. Interestingly, some children liked reversing in their un-guided wheel chair. Children having early exposure to going backwards in rear facing car chairs or prams and push chairs, where the child was facing the person who is pushing them are factors in early child development.

- Incorporation of the automatic reverse functions for turning (non-reverse switch).
- The avoidance control modes were adapted to suit the learning phases and stages of the children.

It was noted that automatic steering guidance could enable children to become trapped in confined space, for example, in room corners or amongst clusters of furniture. When the auto steer was turned off, as favoured by therapists, the chair would be difficult for the driver to steer within the scan detection boundaries. The child’s driving corridor was narrowed by the system. This was a significant problem with SCAD in the non –auto steer mode and this is the subject of future work, particularly as it made the chair more difficult to drive and young drivers were stopped by the system in confined spaces.

9.8.1 Child understanding of what the SCAD was doing and why

The normal control operating parameters of the powered wheelchair were being learnt by drivers using the system. When drivers were operating switches or joysticks the relative control functions translated into wheelchair movement. With the interventions applied by the SCAD system the control response relationship changed conditionally. Concerns were raised by some therapy staff about the child’s understanding of these interventions. Children were told that the chair had stopped because there was an object close in front or to the side of their chair. The driver pressed the switch and the chair did not move. Normally before the application of track or SCAD assistance staff guided the child if they were there at the time.

Observed common human interactions with child drivers:

- Giving verbal commands to the child to correct an aspect of driving
- Telling the child to stop prior to an impending collision, verbal prompt

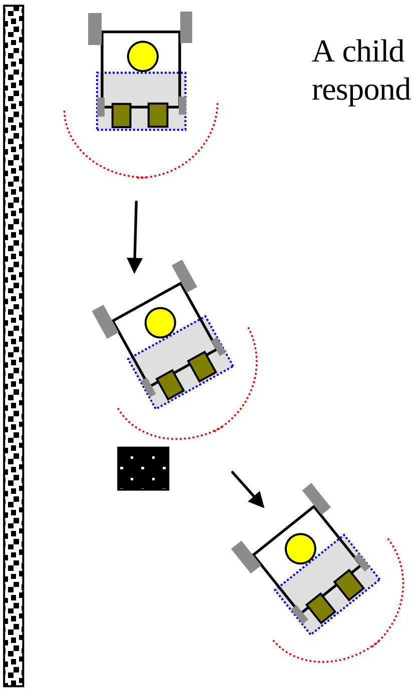
warnings
- Praising the child for good progress
- Physical gesturing
- Removing a child who became stuck by physical intervention by disengaging the drive wheels so the chair can be manoeuvred into the clear
- Operating the child's controls directly to manoeuvre the chair
- Exerting control actions by holding the child's arm or hand
- Conflict of needs, e.g., the child wanted to go somewhere that the helper did not want the child to go

Observations showed that helpers changed the drivers coarse by steering the chair by its push handles whilst the child was driving. This was a common practice mostly to expedite the child's progress. On many occasions the child was not asked and may not have been aware of what was happening.

9.8.2 Course restoration

The wheelchair altered course after collision avoidance operation. Figure 9.12 shows that a new heading would often result when the SCAD control system had intervened. It was necessary to consider the child understanding and confidence in the system.
To restore the chair to the previous heading required a system memory of the previous pre-collision heading.

For the system to do this it would be performing a manoeuvre not directed by the driver. This represented a different form of intervention compared to the SCAD avoiding or stopping before a physical object. Post detection course restoration required an intervention control sequence from system memory without detecting a physical object.



A child pressed forward drive control and the chair responded by going forward

Figure 9.12 The wheelchair trajectory during object detection

A concerning issues was: would the child understand what was happening if the wheelchair coarse was restored, as the drive controls would not respond directly until the preceding heading was re-established. Course restoration was not implemented during this research.

9.9 Discussion

The creation of track and SCAD systems provided support to help young people drive their wheelchairs with reduced reliance on helpers. Where ever possible, including the child at the earliest stage of the research provided meaningful and true feedback about the impact of any applied strategy or system. Often children exposed weaknesses in system operation and sometimes the by product of the original concept was more useful. An example was a young boy driver who became highly motivated when trying to knock the fire extinguisher off the wall by exploiting a weakness in the SCAD sensor when it sometimes did not detect the corner of the wall. He learnt the best angle of approach to do this. This was a valuable lesson for a researcher.

Through observations such as this, a system weakness became an advantage and perhaps a totally safe system created a false sense of security. Preserving personal awareness was still needed for some individuals to reach their goals and not through a ‘totally’ automated approach.

When testing systems, the assumption that it worked in the lab environment and it would also work for the child was proved wrong. The testing of the SCAD doorway control guidance operated reliably when in the lab. When tested with a child it crashed into the side of the doorframe.

It was assumed the driver wanted to get through the doorway, but the child changed their mind at a critical moment when passing thorough and made a turn. The frame was beyond the SCAD detector range and consequently collided. Perhaps also the child’s physical awareness of space was a problem in that he thought he was clear of the doorframe when in reality he was halfway through. A practical solution to this was made by adding side detectors because of this valuable trial.

The application of SCAD systems started with an artificial road environment. This tested the system operation but children soon wanted get into and around their real environment. The application of this research made minimal changes to the child’s wheelchair equipment and the environment. A priority was given to adapting the research based systems in preference to wheelchair modifications, particularly as these were used on a daily basis.

Therapists asked if the system could be switched off as they may want to assess a particular child driving without any form of assistance. Providing system function controls, particularly the most appropriate was learned through the system application and user feedback. ‘Backing off amount’ of system help at the earliest opportunity gave young drivers an option to demonstrate their skills. The SCAD system provided steering guidance and crash protection but this could reduce the ability for drivers to get close to objects, for example, draw handles and pushing open doors. Using SCAD systems showed that preventing close contact with objects frustrated some drivers. Significantly reducing the wheelchair speed instead of halting the wheelchair proved a useful exercise in combining restrictions and access requirements.

Chapter 10

Staff discussions and interviews

The research described in this dissertation was primarily targeted at reducing the number of control actions required by a driver. There were human issues that influenced the system development and the direction of the research and these are discussed in this Chapter. For example, how did the system affect young people and their associated teachers, helpers, carers and therapists? The author generated an initial suggestion list to highlight some general points concerning young people using the new systems when driving and interacting with their local environment.

The list was used to guide interviews with twelve professional people working with children in clinical, educational and caring roles in order to get feedback about the impact of the research and to validate the work.

Subjects discussed were:

10.1) The benefits of mobility for young people
10.2) The value of assistive technology
10.3) Do young people need help with their mobility?
10.4) Human help versus technical assistive support
10.5) Assistive technology taking control over a young person
10.6) Raising expectations
10.7) Learnt helplessness
10.8) A young person leaving the school
10.9) A child (young person) understanding of the task
10.10) Wheelchair control and frustration
10.11) Risk
10.12) Other discussion points

Interview sessions were recorded and converted to text using a keyboard and voice recognition software. The context of what was said has been interpreted as accurately as possible.

The subjects are considered in the following sections and interviewees are identified by a simple three digit code. All interviewees were aware of the SCAD assistive technology created during this research.

10.1 Benefits of mobility for young people

The interviewees were positive about a young person's need for mobility, especially independence and how this was central to other aspects of life. Mobility was considered to be a pivotal aspect to learning and achievement.

- (RM1) "I would say absolutely vital. I think the kids here need to explore as much of life as they possibly can. I think if they can move themselves that is an ideal situation and if they can have some control over where they go, that is giving them something which is inestimable really. But in any case, mobility is part of life and we should be able to offer everything that they can take up really. It's giving them a choice isn't it. I think in everything that we do for the kids we need to be able to give them as much choice as possible. And if it is self powered mobility that is giving them a choice of going where they want to. I know that might be restricted, but it is giving them a choice. It is opening up other aspects of life and experience."
- (KD1) "I think initially it is of value because they can use it to do something for themselves. That might just be driving round in circles going in and out of the room. The other end is that there are students who can usefully get safely from A and to B. That's kind of very functional driving so there is a difference between a kind of play and function. It replaces toddler and baby freedom to explore at their own volition I think. I think primarily it is important because it's a sense of going where they want to go and looking at what they want to look at, not just independence in terms of going from A to B, independence in terms of finding out about things. Some of our students might not start driving sometimes until they are 11 or 12 years old, so they are miles behind".
- (HC1) "I think it is essential in terms of developing independence, confidence, personal autonomy and being able to do those things which other children would be doing at the same age. It enables them to vote with their feet if they want to. Other children if they don't want to do something, they can get up and walk away. It enables students to make choices themselves and to do that independently without relying on somebody else to assist them. Children have one life and they should be given every opportunity to enjoy every moment of their life and even when they move and things aren't followed through, that is

tremendously unfortunate but surely should not prevent them achieving with the help of whatever technology that can be provided for them here. I would say that we need to be looking at improving what happens when they move on rather than not doing so much now".

- (AB1) "I think it can offer them independence and the degree of independence can depend on the ability of the child but it is something that gives them an opportunity to move from A to B, where they couldn't possibly otherwise. The benefits are they can go where they want to, they can choose where they want to go, especially a child that has no verbal communication, he/she is at the complete mercy of who is pushing them where and when".
- (SO1) "Yes because it develops their perceptual awareness, it develops their social skills and their independence. I think for some of our children who are not going to have mobility under their own steam, powered mobility is essential, if they are going to have any mobility. It rates very highly but I think some children are learning a lot of other mobility skills with their walkers, biking, horse riding , swimming to a degree, there's other things as well that feed into that process, but I still think children should have independent ability to move from room to room within their environment".

The general view expressed by the interviewees was that personal mobility was important for the well being of young people. Some complex disabilities required constant personal help. This validated the need to undertake research that could create new systems to provide supportive mobility systems to increase the independence of young persons.

10.2 Value of assistive technology

The interviewees thought the new research based systems were beneficial because they helped young people explore and offered increased independence. They moved about with greater freedom from helpers, particularly encouraging non drivers to become drivers.

- (SO2) "I think its independence. I think some children will find driving at a young age or older very difficult if they got a degree of physical disability or visual disability that is not going to allow them to drive. That should not stop them driving. We should enable them to do as much as possible”.

- (F2) “Being able to give these children means and ways of being independent and to explore is so, so important. Because every moment of their life is governed by other people. For students that are learning to drive to build up their confidence, because if they have an accident it is going to knock their confidence in driving further. And a lot of these children are not given such a scary task. I think that the basic functionality of assistive mobility is amazing, but it needs to be more personal to the actual child and how they use it. Take for example a child in this class who uses a head switch to drive; when he uses his head switch, he has to turn his head to the side, so when he is moving forwards he cannot actually see where he's going. These children are amazing because they have to be patient throughout their entire lives. Particularly because of their communication difficulties, they don't often speak up. Unless they are asked a question maybe repeatedly you can't get to the bottom of things”.
- (RM2) “Yes, I think apart from the choice, enabling children to have achievements is good. So I think if by some means you can give them control, they otherwise would not have the opportunity for an achievement. I personally feel that everything we do at Chailey is a learning experience and I think that for certain children, some of those benefits are greater than they might get in a classroom. So I think, you know it’s horses for courses, for some children giving them that control and choice is so valuable that time from other activities would be justified”.
- (PB 2) “You can't possibly put the child into a wheelchair, give them a control system and expect them to be able to drive it. And some children learn that very quickly, given the joystick they very rapidly work out that pushing the joystick forwards takes you forward and what have you. But some children don't have enough muscle control to stop and to turn corners and to get through doorways. So you have to be able to assist them with that so that they would hopefully build up to driving by themselves. But if they don't, at least they can still drive”.
- (DC 2) “The majority of children at Chailey Heritage cannot walk independently or at least functionally walk. Therefore, the answer to that is yes, they do need help with their mobility. I think the children have a wide

range of needs, both physical and cognitive, and therefore a range of assistive technologies can be brought to bear in order to assist them with either becoming independent, becoming partially independent within a set environment or using mobility as a therapeutic fun thing, a plaything”.

- (LM2) “I think for young people with complex physical medical difficulties we have in our population here at Chailey, there will always be room for assistive technology. It's getting the balance between how much help we are giving them and whether we are then taking away any kind of control development from them”.
- (MW2) “I think it is more important for our children than it is to you or I, basically because we should have that ability to actually look, assess and make decisions to a point, whereas I think perhaps the decision-making process for some of the children is slow or slower and the assistive technology would be of great assistance to them. If you go back to the children where their motor control is not that precise, the turn right or turn left is left on too long and therefore they have to overcompensate to come back. Any technology which is actually going to make driving smoother has to be of benefit to them. I think it must be enabling for the people to be able to say I want to go to point A, and to be able to get there if as you say there is an obstacle in the way, the device can help steering guidance. If they could override the system where it may block them getting to things and then turn it back on, that would be brilliant. Then we have to think about everybody else that might come into contact with it whether it be furniture or whether it be people, there is the safety aspect as well. I was going to mention the likes of J who currently has a chair fitted with a track. That is fine whilst it is around the site here but the attendant controls on the back are very, very delicate, it is very easy to over steer with a very slight movement, all of a sudden you're shooting off to the left. This is like Nintendo controls. The other thing which is a real problem is the fact that when you're away from the site you cannot get used to the attendant control. A lot of people are frightened because it is so precise and so volatile I suppose in its movement. They turn it off. But then of course you don't have any handles with which to actually push apart from the two verticals in the frame of the chair. So if there was something which was more of a conventional grip it would make it easier”.

- (KD2) “Well, as far as my understanding is, if the child has not got their hands on a switch or head on a switch or joystick, the chair is not going to move. It depends if the child wants to use it as a way to get from A to B, because that's what it would be in that situation wouldn't it, because it would not be so much of a plaything because it would be so much driven by the technology, so if they were interested in that aspect of getting themselves from A to B with technology then I think that would be good”.
- (AB2) “At the very top. At the very, very top. You know, what better thing than to be able to go out independently, but that is at the very top. In a school like this I would put it far above everything, I would, like communication. I understand that some people, if they are on the track that can't be transferred outside. Better to have loved and lost than to never have loved at all”.
- (HC2) “Is this the chair that detects the environment it is in? The almost in between stage, having seen the beginnings of research on that line it offers those children the next step on in terms of their independence. I think it is absolutely crucial and at no stage should a child be held back if technology can in some way support them on to the next step”.

The interviewees suggested that the application of the work described in this dissertation was of value to young people, particularly for increasing their autonomy and freedom within their local environment. It helped them to gain confidence and personal achievement. The new research based systems enabled young people with a visual disability to have a driving opportunity and reduced the need for helper intervention.

10.3 Do young people need help with their mobility?

The immediate response of the people interviewed was that this question had an obvious ‘yes’ answer. Two particular interviewees added comments that mobility systems had a definite value for young people because they had not attained independent mobility skills or abilities within the normal developmental age range.

- (JD3) “Yes they need help with their mobility, because the majority of them from babies, don’t get the normal experience of exploring their environments, that moving around not being able to crawl or to be able to touch, to be able to explore the objects, to be able to understand what is hard and soft and to get the autonomy to develop as a typically developing child can to explore their environment”.

- (LM3) “Yes I do. I don't think they have the cognitive ability necessarily or the control expertise to make full use of potential independence though. One of the big problems again is with the SCAD is that it does not pick up voids, like under a table. There is the issue of veer of the wheelchair, which I know you are thinking about. I think that confuses them sometimes because they are expecting to get to do something and actually it’s how they deal with camber etc. I don't know if the technology is there, something that could be a vertical scanning as well as the horizontal scan. Some children who seek to get into trouble because they think the SCAD will be protecting and actually it has not picked up something and so they may be driving into something like a table”.
- (SO) “To me, I think when they first start, you want to make it as easy as possible for them to use the switches. They've got to learn to negotiate and they got that ability to move. For a lot of children, starting off on a track which cuts out a lot about decision making and makes it simple and also it is quite exciting to get to somewhere and for them to make a positive choice at a junction. I have no problem with a young child starting on the track, and then once they have got the idea with switches, making choices which might take you one way or the other switch may take you the other way, you are learning all those skills, but you are safe and you can't crash. But you are also learning to pass things and you're learning to stop. You've actually got all skills you are learning even though you’re supposedly just on the track”.

The general conclusion from the interviewees was that technical assistive help was needed because the young person’s personal disabilities prevented them from normal exploration and personal interaction through their own coordinated movement. The general feeling was that mobility should be introduced at the earliest opportunity.

10.4 Human help versus technical assistive support

The responses from the interviewees indicated that there were many issues affecting the learning development of a young person. A significant concern was the understanding of a young person to the applied assistive support and where this fitted in with their learning stages and driving with increased safety. There were also issues of conflict where helpers may have different agendas to the young person driving.

- (LM4) “I think there's merits to both. I do think staff need training as to how much assistance they can give, when not to give assistance and to allow the child to make their own decisions and work things out themselves and for how long. I think as staged progression, I think they have to have a person to start with. And then I guess it depends on the cognitive ability of a child as to whether they understand what is happening when they activate a control. That they actually do understand that cause and effect, that this is me doing that, and if I do it that way this happens to me, or I am trying to do that, nothing is happening. Why? Problem solving? I think that's quite a cognitive leap. I think when children have the time to drive independently, the system helps them there, because then the helper tends to back off and allow them the time. I think you see people being helped when time is short and there is a time pressure because they have to get back to class in time for lunch, or down to the residential bungalow, or whatever. Where there is no time limit on it then I think people are much more prepared to allow pupils to make their own choices and then the system helps them. I think some of them are denied personal control, some of them are very aware of that and I do know because some pupils have said it, that they resent that, because I am perfectly capable of driving up here and whether it is a school assistant or it is an escort, because they want to get on the bus quickly, they overrule them. You know, if I just got my independence I would be very frustrated about that. I think there is frustration there, somehow within systems we have to build in that time to allow these children that time. Is it that they had to leave 10 minutes ahead of the rest of their class because they can then independently drive to lunch. I would argue that that is a very valid reason to do that”.
- (KD4) “I hate seeing a child who is being driven along by their joystick

because somebody is in a hurry to get to somewhere”.

- (PB4) “It's not the same because the child is not in control then. It is just an adult human doing it, because they can do so little, so few things for themselves, to be able to sit in a wheelchair and okay people are watching them, there's always somebody around, but at least they are doing it themselves. Even those children who are perfectly able to drive and to drive as fast as he wants to get there very often has his joystick control take over by able-bodied grown-ups and being driven there because they haven't got the time to let him drive there himself; he's got to get on a taxi, as soon as a taxi driver sees him he's driven somewhere”.
- (DC4) “I think, it is very difficult to determine the effects on our children because of the limitations of their communication and so sometimes there is a lot of interpretation which has to be made within their communication. So I think to get to the heart of it would obviously be good to ask the children themselves, but there are issues around that. I think the assistive technology can certainly enhance their ability to be mobilised efficiently. I think like some others, there can be concerns that when you just apply technology in a sort of blanket form to see how it falls with different people. You can find it falling very unevenly, such that you find some kids are being maybe not cognitively up there in terms of what it is that they are doing and why things are happening, and we went through that process of trying to unravel some of that and had got out of the habit of just blanket applying technology. It works for so and so, let's see how it falls with little Johnny and little everybody else, and I think that is a positive thing, more of an analysis of where the children are at and introducing things by steps”.
- (JD4) “I think it is a huge area when you talk about human approach because again that was part of what I looked at and researched, in that everyone talks about training a child to learn powered mobility, and what they are realistically talking about or what you can gather from research data because there is very little in there, people are talking about training, the chance to use the powered wheelchair as a machine and how to operate the machine. When you look at electronic mobility guidance systems, you've got to look at where the child is in their learning process and if you introduce them to soon then you're not allowing the child the opportunity to cognitively learn what each of the

switches or buttons do when they press them, and that is something that came out in the research. When I was working with typically developing children, they got very confused if the chair suddenly took over and the chair did not do what the child was expecting.

Where electronic assistive technology was helpful for the children was at stages where they did not have the refinement skills and they could not get through a doorway and they were not prepared to work out how to get through the doorway. It became too frustrating and the chair taking over helped those children but they had been through a basic pre-learning where they understood and had worked out what each of the switches did. It was down to their refinement skills that they weren't able to achieve that, until they've had more practice. So it is looking at when you put in this equipment and when you take it away and that has to be worked out with the child and the child has to be in control of that".

- (RG4) "The one advantage of the controlled system is that it might often be incorrect but it has the advantage of never being biased. In other words a technical solution never brings anything to help in a problem other than what it can provide. Whereas a person can bring preconceptions to what the child wants".
- (RM4) "Well again I think I suppose we're talking about safety aren't we? Human help is a very safe way of getting about but it is denying choice to a great deal. With very good human help then choices are avoided as much as possible. At its basic level, a person who is pushing has got control. Hopefully they are extending choice with the person they are pushing but ultimately they have got control. With a robotic system, you are to some extent handing the control to the child so that really it is their choice. So for the right children there is obviously a huge benefit for them being able to choose if they can. It is the grey areas in between the two where it is difficult. I think that children here have benefited enormously from some of the systems we've offered".
- (HC4) "The difficulty is, it is a school and therefore the school has targets and curriculum's they have to teach to time and have to get from A to B in order to be doing the curriculum. Therefore there are pressures of time and as much as possible we do support the students in their mobility. At the same time we

have to be present at certain times to do lessons, but that is where Chailey comes into its own as a whole community, because although within perhaps a school day on a time table, a lot of the students live in a bungalow and there are activities like scouts, where they are given opportunities then, and I guess that is where as much time should be given and encouragement given to their mobility. The children that go home perhaps don't necessarily get given those opportunities. For one thing, home is often small, so driving potential or time to drive at home may be not be as much for the students that are at home compared to the ones that stay on site".

The research work was validated because the interviewees felt that it provided young people with their own means of control. Using assistive systems provided young drivers with opportunities to make driving choices without the continual presence of helpers who might intervene and override them. The creation of the research based systems described in this Dissertation was mindful of the learning stages of the young people.

10.5 Assistive technology taking control over a young person

Some interviewees highlighted particular factors. For example, a young person's understating of why the machine had applied a control action was important, whilst other interviewees felt that the combined function of personal control and machine control enhanced the driving process. It was important that the young person achieved a goal, and that this was the young persons own achievement even with applied technical assistance.

- (HC5) "I think we are looking at this from an able-bodied mind in that we might think it is taking over but for some of the children in the school every movement of their head or arms take such a huge amount of effort. I think perhaps you have to look at it from what we might think the machine is taking over still involves quite a lot from the children in the school".
- (DC5) "That is a tricky one isn't it because it is like the chair has to suddenly start absorbing all sorts of different factors as well as the child's personality and wants and dislikes. Short of just applying lots of semi-rigid rules to the

logic of that chair, you could very easily start it doing something, or just as easily misinterpret what the child is doing; there is no way of linking into the child's intent, that is the thing”.

- (HC5) “Not so much that it becomes too difficult for them and they wanted to give up, but just enough to move on. At the end of the day, if it is improving the quality of life then surely it has to be important and it has to be significant”.
- (JD5) “I feel that during the child's learning, it is very important for them to be able to bang and crash into walls and if you take that away then you are taking away a whole area, and people on the whole tend to want to avoid that piece of learning because it is seen to be physically destructive, and also tends to be an adults agenda. From clinical experience of watching the children where they go through a process of needing to crash, bang, scrape, that is a very important feedback mechanism for children to be able to work out depth perception and to be able to work out directional control. If you take that away then they don't ever get that very valuable learning experience”.
- (RG5) “I am not aware that we ever go for a solution where the machine is ever in control. I am aware that many developments are perhaps trying where the equipment does everything but I'm not aware that our alternative solutions in fact were ever based on that premise. So I would say no, I don't think we do too much. It would only be in the minutiae of the smallest aspect could you say the equipment is doing something which the child ought to be doing. We have in the past offered options”.
- (MW5) “Well it's not just with wheelchairs that this is happening. Just within the last couple of weeks they are talking about collision avoidance been incorporated and commonplace within vehicles that you and I drive in the next 10 years. It’s technology that is actually affecting everything we do where there is control of a vehicle, but then at some stage the device is going to cut in and if the child is aware of that then they are going to say, I can just drive it anywhere and if I get overloaded it will stop me anyway. Unless you allow a certain amount of danger and a certain amount of injury to occur. In which case what to you do?”
- (F5) “I would hope; that before that system was put in place then the child's abilities would be evaluated. And at the end of the day, in this situation we are

talking about children and young people, and as a parent you have to at the end of the day let them do things, but you need to guide them. If you have to make a decision on their health or safety then it is your duty to do so. Again it is at an individual basis".

- (PB5) "It depends where you are with the wheelchair thing, if they know they cannot crash, they never had to learn not to crash but because of the way you've done it, so they are taken off that system, so they are put on a more reduced crash ability type system like SCAD. So they have got those steps of moving up to independent mobility but if you simply left them on the track which you could do and it went places. They are not going to learn a thing after a while are they?"

The comments from the interviewees indicated that the applied research work helped young people perform tasks that they were otherwise not able to perform without helper intervention. The work described in this Dissertation helped young people drive through doorways and along corridors, and enabled young drivers to refine their skills through practice. The systems reduced the chances of young people giving-up because driving was too much hard work. Safety was also a factor in which the research base systems acted to stop collisions where objects and possible hazards were detected. This therefore protected driving opportunities, and reduced the chances of young drivers having control taken away from them by the application of human help.

10.6 Raising expectations

In general the interviewees thought that raising expectations was a consequence of providing new systems and providing young people with new experiences, preferably under their own control.

- (RM6) "I don't think it's wrong to raise expectations but I think we need to invest in systems that they can take away with them because otherwise we could be frustrating them. There is one line of thinking which is that everyday counts and particularly if some of the kids here are not going to have long lives so that any day's achievement is good. But I think a lot of them are going to leave Chailey and not have the facilities they've got here so we must also bear that in mind, I think. So I would like to see assistive systems that they can take away. The track system is honestly not something they are likely to encounter elsewhere, so maybe that could be used for sort of limited achievements but not building towards a particular goal but I think if we are inventing or investing in systems that are going to be possible for them to take away, then that would be great. So I think there are two things, one is a limited goal for a day-to-day achievement and the other is building to increasing skill which could go on through life. They are rather different things really”.

- (LM6) “I think these young people have a right to get the best provision they can possibly have. The fact it might not happen outside is no reason for us not to give it to them. They need to know what they can do, what rights they have and then they can do. We, to a certain degree, can influence what else is happening. To me there is no point in doing what we do at all, if we're just going to say, well there is no point in doing it because they are not going to have it afterwards. It's all part of promoting disability and the equality”.
- (SO6) “You could say that about me using a magic mix to chop like a chef! Is that wrong? A lot of children are not getting the experiences that a young child would get and by assistive technology, learning to negotiate a doorway first of all on the track system and then maybe a SCAD, then they do. Children need lots and lots of experience”.
- (RG6) “Quite simply (and it's incredibly simple) we should always provide as much of a similar experience to the so-called normal child. In other words, that any technology that is put in to help must never be an end in itself but should only be a step towards a normal experience of the world”.

Many of the interviewees said that raising expectations was of positive benefit, as this placed an expectation on the young person to achieve as opposed to being a passive onlooker, even when the research based systems gave the appearance that a child was driving by providing the driving control function. Some interviewees suggested that this put pressure on other organisations to provide extended support in other centres and services.

10.7 Learnt helplessness

The responses from the interviews varied in their interpretation of learnt helplessness. For example: taking the easy way to do things, being passive or learnt behaviour. Recognising an individual’s achievement and building progressive steps in child learning was considered important.

- (F7) “You have got to look at these things and remember that inside there is a child and we were all children and if there is an easy option we can take it. And again each child is different and cognitive ability needs to be taken into consideration again during the evaluation period. And for some children, that learnt behaviour is the only option and that's as far as they are going to get. I don't see why if they have learnt behaviour, why they should not be given the chance to do things”.
- (PB7) “It depends on the child, and that's where you have to build in progressive steps, in some ways to keep making it harder and harder for them, but not to a point where say the control of what they're doing becomes so hard that they give up driving altogether. But you've got to get to a point where they are happy driving. And it strikes me that when you see children who have left here or other children like these children here, very often they don't drive once they become adults because it becomes too much of an effort and they have a full-time carer and they'd rather be pushed than drive”.
- (LM7) “The experience with children with disabilities is that they can be very passive and we work hard to give them control or give them a choice. That actually the child isn't making the choice, it's all being done for them, so they can just sit there and not make any decisions. The child just presses a switch and it will get them somewhere and something will be looking after the child. I think we have to be sensible to where we are overstepping that line. I was going to say that if I wanted to go through the door and the SCAD won't allow me because it's sees it as an obstacle because the door is shut, I don't know how we get over that. Is there an override button or something like that, that can be provided? I think the collision avoidance device keeps them safe. It also comes down to agendas again. What is the helpers agenda as opposed to what is the pupil's agenda? What is it that they want to do? A young person

may decide, I don't want to go back up to the hall, that is why I want to go this way, but perhaps for whatever reason, somebody will override that and say I'm sorry you can't make that decision, you have to go this way. We don't have time to do that or you're going the wrong way without perhaps exploring the reasons why that young person wants to go that way. And again that to me, whether its technology or its human assistant, overrides their independence”.

- (RM7) “Well I think there are two aspects. One is that they've got to be able to recognize the achievement, so they have got to have sufficient control themselves with the help of whatever technology you can give them to get that achievement and then I think it's very valuable indeed. But the other aspect is the possibility of continuing with that after Chailey, because otherwise it can be very frustrating for them if they make that achievement here and then have no possibility of following it up. So I think whatever technology, it must be something they can take away with them. That is my feeling”.
- (AB7) “I don't agree that any system can totally do it for the child, they've got to press a switch for themselves. I think things like a SCAD chair, okay if the SCAD chair stops children bumping into walls, fantastic. It does not matter that it is the technology helping. If a child had no legs and he was fitted with an artificial whatever, they're not his real legs and he couldn't do it without them, that's fine. It's the goal of getting where you want”.
- (MW 7) “That's what I said about the cars. There was something in the news recently about a car in America that they are currently developing and possibly be in production within 10 years where literally you just get in and you press the button and it takes over. Because it is laser guided, and will travel at 30 or 40 miles an hour and will actually detect other moving objects within the carriageway, and will stop and break or accelerate coming up to junctions. It will detect other vehicles moving in front and go left and right, it is an incredible thing. But as I said, it is a lazy way of doing things”.

None of the interviewees thought that the systems created by the research added to learnt helplessness. Helping young people to reach goals and, importantly, being able to back-off the amount of applied system support were important factors concerning child development and independence. One particular comment was that “I don’t agree that any system can totally do it all for the child they’ve got to press a switch for themselves". This was true, as at some point a child had to operate a control to make things happen.

10.8 A young person leaving the school

The interviewees thought that the new systems for the young people may not be supported or provided in other places. Concerns were raised about some young people who may not have continued access to facilities and support structures that they had been using as part of their learning and development at the school.

- (DC8) It is a difficult one, because they get an opportunity here to do something that they probably won't get once they leave. And therefore I think it has to be weighed up in terms of how that might affect that child, and again that is a really difficult one because you don't know how it is going to affect them, so you see how well they actually get on with something. I guess in general, one would go for giving a child an opportunity to experience something rather than not. However I do think there has to be quite a measured approach in terms of just limiting expectations of what then can be picked up outside. I think it is big enough of a fall once they leave here, certainly for the children themselves and their families in terms of what adult services they move into and I think perhaps just better preparation, perhaps it can be met. Perhaps it is about preparing parents and children much earlier about how things are out there in the rest of the world in terms of services. Because if they were a little more motivated, a little more empowered to actually take things into their own hands, they would be aware of what could happen and therefore either foresee it and decide, well let's just say no to this now, or indeed say, we know there's not going to be anything out there but maybe this can happen at weekends at home still, or that kind of thing.
- (HC8) And that's the problem with the future placements and the future wheelchair companies and not what is provided here, but that is about educating the public sector in a way. I guess Chailey is seen as being one of a kind and a great many people never come into contact with the sorts of technology that are used here but my guess is that disability is changing because of the disability discrimination act that is coming in to support

disabled people in the community. I would guess there is scope there in moving things forward to educate the wider world than Chailey Heritage.

- (F8) I would bring up the issue of equal opportunities with that, I think just because these children have disabilities and differences to us, it should not mean that they have to put up with what is on the market. People should be going further to make sure these children have the best.
- (SO8) It does not go out into the community. It is limited to probably institutions where things have been set up, but I'm not saying you should not have it just because it is not everywhere. It's really only the track that doesn't go out into the community. The SCAD goes out.

Although the interviewees had concerns about the on-going provision of technological support that this research provided, the general opinion was that this should not stop the creation of bespoke research based systems. Furthermore some interviewees stated that the imposition of the Disability and the Equality Act [2010], helped reinforce the need to research and create systems to help enhance a young person’s independence.

10.9 A young person understanding the task.

Interviewees felt that the young person’s understanding of the reason and purpose they were driving was important. Some interviewees said it was sometimes hard to determine if the young person was driving or if the assistive system was driving the child.

- (DC9) Whose needs are you meeting in terms of giving the child this assistive technology? Yes they might be able to be in the chair with everybody else in the class. That's fine, but actually, as long as it is not raising people's expectations and the family around them, in terms of suddenly they hear so and so, he's driving he's doing really well and the expectation is that if he is driving then he's functionally driving and therefore he can be independent, or achieve some level of independence with it, and that is not always the case.
- (KD9) Yes, I suppose I think if a student understands that. I think it would be good if the student understood that. They found it difficult to avoid obstacles

and therefore understood they were using a SCAD because of that reason. I think if the student knows and understands the process of it, like for instance the student I have in mind, understands. He knows when he's had a SCAD and it is useful for him and I think that's a really useful way ahead. I just think it might be a bit odd for students who don't really understand what is going on and I don't know how you know whether they understand or not, unless it's very clear.

- (JD9) The wheelchairs themselves are not designed to be user-friendly. The appearance of the chair was undoubtedly important for the child and also the parent because a parent reacted positively to a powered chair when it looked like a toy as opposed to the typical NHS wheelchair that was provided. When you talk to children and young people further along the line who have got past using the chair and realise it is part of their lifestyle skills it is a very important part of how they move around their environment and I am having to use things like single switch control scanners, that is very frustrating for them in that often it is not reliable, the switches are not reliable. The connections aren't reliable and it is all very precarious at times and when you're getting into that level of sophistication of electronic equipment it certainly does not meet the needs of the young people. Using a powered wheelchair with a scanner and the amount of veer and the amount of correction that they have to make and the head switches and sometimes the unreliable nature of the head switch when they hit they had to wait for the scanner to go all the way round again, there are lots of areas.

  What the children described back was working with systems that don't do what the children asked them to do because they are inconsistent and they are unreliable and they have to constantly keep adjusting and realigning the chair.
- (LM9) Difficult one! Again, it has to be based on the individual experience I think, and how quickly they develop those skills. It may be that they don't ever develop a skill where they are going to be independently able to control their environment. But they are going to either need somebody there or some help there. I don't think you can say there's an end point, perhaps take each individual, it is very difficult to say.
- (PB9) That is where you start taking the controls off isn't it? So the child is having to learn.

The responses from the interviewees suggested that child understanding was a difficult area because the research systems could give the impression that the young person was steering their wheelchair, when in reality the system was. The interviewees felt it was important that the young person understood the reason they were driving and the value of personal independence.

This suggested that the new work described in this Dissertation about audio and visual prompting systems needed to be taken further to help young drivers understand the reason when, for example, a wheelchair had altered course because an object had been detected.

10.10 Wheelchair control and frustration

The interviewees commented that there were aspects of wheelchair driving that needed investigation, particularly wheelchair steering.

- (JD10) Those children who were using switches have got very gross movements and may have not been able to refine there fine motor skill. Children who are learning to operate joysticks may not have had refined manipulation of the joystick. Although it appears switch users take longer I suspect that some joystick users are constantly having to refine their movements and they are constantly having to use their motor skills to correct the chair rather than steering the wheelchair to where they want to go.
- (F10) Yes I think the kind of problems such as veering wheelchairs need to be looked at. The young man I was talking about earlier, his front wheels were off, so every time he drove, he was not driving where he wanted to go, plus the fact he could not see where he was going. But it was not until I had asked him, your wheels are going in the wrong direction, I know I'm going in the wrong direction, but he had not told anybody, he was just saying I don't want to drive, I don't want to drive.
- (PB10) Partly because the conditions here, that they know they cannot control that veer to the left say. They are not fast enough to respond to the way the chair is behaving. I think the things that I would like to see improved is that factor of the wheelchair veering on a very small slope and it makes it impossible for a child to learn and those that have learnt, they know full well

that they pressed forward and may start going left. You are building in a huge amount of problems for the child whereas, if the chair would just go forward when you press forward it would just make life easier. The chair lets them down doesn't it? If it means they don't have to make so many adjustments, if you could do that to the chair so they don't have to do it through the switches that would improve things, yes make it much easier.

- (AB10) Yes veers, veers is the obvious one, and that is really frustrating.
  Well, I think that must be so frustrating. Take one particular child who is doing exactly the right thing, he is pressing forwards and it is just going way off the point where he wants to go. Then it's becomes such hard work.
- (MW10) The presentation you did on the anti-veer device that you were trying to put forward for certain children, that would be an enormous benefit. It really would. Not only around the site here but even when we are out at other colleges. The corridors are narrow to gain access around the site and there are lots of left-hand, right-hand and 90° turns all of the time. It must be frustrating when they are having to make little contact with their controls to steer and yet that is too much for the restriction of the corridors. It must be very frustrating for them.
- (SO10) Some children will learn to drive. They have become automatic because they physically find it easy and they have got a degree of mobility around on the floor and they have learnt to negotiate. They don't have visual problems. They don't have any other problems like that so they can now drive. I don't think they get quite so tired as children who are constantly changing switches and are having to control their bodies with an enormous amount of effort. They are never really going to become very good drivers because it is so hard for them. Whereas perhaps if we make it easier they will become more independent.

The most significant problem reported by the interviewees was wheelchair veers. Many of interviewees had spent a lot of time helping young people steer their wheelchair because of the effects of slopes and uneven terrain had caused a driver to drift off line. This generated a lot of frustration to the young drivers and helpers. The variability of wheelchair control did not provide consistent feedback for young drivers to refine their driving skills.

A new anti-veer system was created by the author during the research and wheelchair trials demonstrated that wheelchair veer was significantly reduced. This formed the subject of later work and the system is described in Chapter 4.

10.11 Risk

The interviewees thought that the nature of a young persons disabilities put them at risk, particularly wheelchair driving. They took the view that this risk needed to be balanced against providing a young person with opportunities to do things. Health and safety legislation could act against the purpose of providing independence in a special school.

- (RM11) We are increasingly more conscious of risk aren't we and risk assessment, personally I think sometimes too much but you have got to weigh the benefits to the child against the risk to them. Obviously outside of a controlled environment the risks are likely to be greater so any system we are offering has got to be either used within a controlled environment or won't add greatly to the risk of injury. For some kids the sky's the limit. For others you have got to be very conscious of the risk. I think the benefits of choice and freedom outweigh the risk on balance but I think one of the problems you are going to have is, it is very hard to know what environment some of the kids here are they're likely to end up in, so it's very hard to get a picture of where they like to be five years after leaving Chailey. So it is a difficult choice. My own feeling is that we should allow them to do things if children have positive attitude and the systems suit them. We should encourage them to use equipment to their best ability and invest in the right equipment. I think that you should not be over depressed by thoughts of risk. Because choice is more important than risk, I think then presumably they will be with adults who can help them make those decisions.
- (LM11) Initially as a safety issue for a young person. So that they can't drive themselves into a wall or into somebody or into an object say, like the collision avoidance device. I think that is perhaps the next stage. Again we have to understand whether the child understands safety issues and knows when they are putting themselves at risk. I think the track gives some people a

security feeling, that they know they are not going to get into any trouble, that they know that if they do this and do that they will get to a certain place. Certainly children with visual impairments; I think some of them have found that reassuring. It can be that they then move from that secure thing because they then want to explore the boundaries but again I think there are these stages where we have to give them as much security as we can and then judge it that they are ready, or they themselves can make the choice; are you ready to move off the track and try free driving? It's like learning to drive a car yourself. You don't want to go out without anybody who’s got dual controls initially until you've got the skills yourself and you become more comfortable.

- (M11) You know, with your own children you have to start somewhere and actually to instruct them and show them the element of danger. Perhaps we could make an obstacle course around here so children can try and find their way around. On the one hand you want the pupils to achieve their own independence but only where they are in the confines where there is no danger to themselves or other people. Do you allow them to control crash so they can experience what it is like? You have got the classic going down to the bungalows. The fencing was put up as a result of the youngster going off-road and tipping over his wheelchair. That could have been fatal. Do you introduce a system of controlled crashing, where you know they are going to experience the jolt, or a tipping of the wheelchair to a degree but there is built-in safety so that where you know it is only going to go over a little bit, is not going to go right over? You put your tilt platform on gala day. Could you incorporate some form of technology like that into a sort of crash scenario, so that, this is what's going to happen if you do whatever? Perhaps you could build a power point presentation or something and link it to that so they can see where they are going to feel what they have learned because they had driven off course.
- (PB11) Some of it is safety. There are very few children you can trust completely to go off somewhere and not have to watch some of them that they are not going down a ditch somewhere. The SCAD doesn't pick up spaces under tables and there are a lot of spaces under tables. It doesn't always pick up people's legs sometimes and where as it will pick up walls and things you don't want it to pickup. It's not just a matter of driving towards walls and

doors is it? There's lots of other stuff around as well it needs to be able to intelligently suss out, there's a table in front and now I know that there is a gap but I can't keep driving under the table.

- (F11) Yes driving under tables. You are never going to have perfection. I think you can protect children too much. Again coming back to the parent issue you have to give a level of protection. Obviously if they are cognitively able again it is the individual child. There are dangers.
- (AB11) What makes me really annoyed is I do have a mobility group and we used to go all the way around the site, but we are not allowed to now because of health and safety. I'm sorry, you know, but how can you ever, just because one day nothing to do with school one evening a car was seen to come up the wrong way so we're not allowed to go that way now? That's another issue. There should be more opportunity for mobility groups. On a Friday, I used to have about four students, and never got beyond driving to and from the bungalows but at least we could explore other environments, but now they're not allowed to go there on there own and it was a choice, it was an option.
- (SO11) I think crashing. I think for a lot of our children the very young ones probably don't need to crash because before you had all this lovely technology they went crash bang wallop and everybody used to jump to grab them take their hands off the control and try to save them. And I think that was really scary so I think what they need to do first is a bit like learning to drive a car you don't take away the dual control until you have got some idea as to what you're doing and then you can organise them to have a safe crash or two. But I think for some children it is very scary because they've never been able to make mistakes. In fact they're making mistakes. Where they're going mentally, thinking I'm going there and gone off there is quite enough of a mistake in their psyche to begin with. I don't need to crash. That is another whole concept. I mean they're not used to making mistakes. Otherwise I think they could very easily and very quickly just switch off. That was a really nasty experience i'm not doing that again. Children are given so few opportunities to make mistakes. In fact you would have to count out the times they make mistakes and are allowed to make mistakes. I think they need to make mistakes and take risks.

The interviewees thought that the research improved the chances of young people driving because it reduced the risk associated with driving. Through the application of the research, crashing was provided as an option. For example, the collision avoidance system gave a choice of allowing children to crash or not to crash. This could be for reasons of preserving a young person's self confidence that could be damaged by a bad driving experience. It was recognised that systems created by this research provided new driving opportunities to young people with visual impairments.

10.12 Other discussion points

A variety of topics were discussed further. Many of the interviewees worked with young people having complex disabilities. It was difficult to capture the wide spectrum of issues by using a questionnaire with specific subjects. The following statements resulted from open discussion and provided a broader picture of the issues relating to people working in a school and caring environment:

a) Why are we not sure of what the child wants to do?
b) Giving the control to the young person to turn the assistive system off
c) Can AT have side effect problems?
d) Assistive Technology masking what the child is doing
e) Integrating assisted mobility into the curriculum
f) Priorities
g) Cost influencing people decisions
h) Define the term 'energy conservation'
i) Future developments

> a) Why are we not sure of what the child wants to do? (RG) The obvious barrier is language ability. It's such a basic one. For conventional children it is such a basic statement because you can ask somebody what they wanted to do now and the answer is reasonable. Not necessarily totally explicit but it's a reasonable answer. Children with disabilities, all too often people say, do you want to do this do you want to do that and unless you ask or correctly identify what the child is really thinking about, almost everything from then on tends to be a bit of a disaster, because you never really tried to measure against what the child wants, which is the only point of the whole thing, you are measuring against your own preconceptions that you bring to the task.

b) Giving the control to the young person to turn the assistive system off. (SO) I would not have a problem with that. It is probably very useful to have the ability to have the SCAD switched on in some environments and then, it's part of the learning process to either have very controlled areas where they learn to drive without the SCAD on, or to push a bit of furniture or to get really close to something so that they can reach it or what ever it is they want to do. I think the more we can grade their learning to drive in very small steps, the more successful the children will be. To me the track is actually the initial step and then you move gradually up to the SCAD and then to the normal.

c) Can assistive technology have side effect problems? (KD) I don't know actually, the answer to that, whether or not. I think definitely driving is something that most students really enjoy and find very valuable. Whether it is functional or not. Yes I think it would be good for most students to have the opportunity to see which way they wanted to go, but a student might not have the capability to free drive in a useful way. They might just enjoy going around and around in circles or something. Then they might not even want to go on the track but at least they had the chance to do that.

d) Assistive technology masking what the child is doing. (PB) Do you need to know what the child is actually doing, if they are getting from one place to another, you don't have to know what is inside their heads do you.

e) Integrating assisted mobility into the curriculum. (DC) I can see that it would be something really hard to change because I think the school has got quite used to using assistive technology in a certain way and there key areas where it comes in, for example, computer access to some children but not necessarily other bits of kit for others, and so I think there needs to be. I thought not just by a person like yourself who is the ‘AT’ person, the assistive technology developer person to come in. I think there has to be a concerted effort by actually the teachers at the school, to look out there and see how other schools might be approaching this problem, just do a sort of benchmark or reality check in terms of how well they are measuring up, in terms of allowing the development of these sorts of skills which are very key in terms of independence and life skills, socialisation skills which would be within any typical school. I think there is a need for maybe a working group as teachers as well as someone like yourself to actually go out there and see how well things are going, to take a measure of how things are going in other schools

f) Priorities. (F) Personally I think that communication, because you can make a singing and whistling chair but if the child cannot communicate to you that this is wrong or whatever, it is pointless. So communication should always be the key start point.

g) Cost influencing people decisions. (JD) From the research that I did and when I consulted with my peer professionals it was put forward by people in the NHS that it was costs and safety and finance and risk but what also came out quite clearly was there is a lack of knowledge and understanding and people are applying a very outdated medical model approach to provision of equipment which was traditionally set up for adults and not children. The children are dismissed because they say that the finances are not there, but it is not just about finance. It is also about looking at needs and looking at creative ways of finding partnerships to supply the equipment. It is not just down to money and finance there are other factors as well, which is attitudes and lack of knowledge.

h) Define the term 'energy conservation'. (JD) I would define it for a child who is looking at using powered mobility. That the amount of physical effort, coordination that they have to put in to operate the switch to get the chair to move, along with the time that it takes them to get from A to B.

i) Future developments. (JD) I think it is about research which is child led and that the children are the ones who decide where the areas of research need to take place, that they design the research program from the beginning. They are literally in the driving seat that they decide what is important and what is a priority and what needs to happen next.

10.13 Conclusion

This is a brief synopsis of opinions taken from discussions with the interviewees.
In general, the interviewees stated that the new assistive systems created in this research helped increase independence and provided new driving opportunities for young people at the school. It was noted that some interviewees felt that too much help could be provided and this risked “switching off” the young person from making an effort. When considering developments with automated sensing collision avoidance devices (SCAD), many interviewees stated it was important that a young person initiated the process of movement by pressing a control button.

It was noted from the interviewees that frustration was very evident from young people. Especially when a young person had their own powered wheelchair but was pushed around (particularly when they were able to drive themselves). One particular area of conflict was children being overridden by helpers. This could be because the young person’s rate of progress did not match the need for them to get to places in a set amount of time. Many young people got frustrated when they were overruled by helpers. It was suggested that when a powered wheelchair had an attendant control, helpers sometimes found it difficult to steer the wheelchair.

The school curriculum time table added constraints. Some interviewees suggested that the school establishment should build in more time to allow young people to self drive more. Although a conflict of agendas was always going to be a problem where the helper’s agenda was weighted in favour of the young persons agenda.

One interviewee stated there was a particular problem across the school “there are barriers of language ability” and there were issues about the accuracy of interpretation and jumping to wrong conclusions about what the child wanted to say. One interviewee stated that, “The School should provide as much of a normal school experience as possible”. In practice this was hard to achieve but many interviewees felt that amongst all the equipment there was a young person and the focus should not always be on the equipment.

Assistive technology needed to be more personal sometimes, to address specific personal issues such as a user with head switches. When he drove he had to turn his head away from looking where he was driving when selecting control directions.

Some interviewees felt that the systems created during this research should be introduced to young children at the earliest opportunity to help them gain confidence in making control decisions and learning to gain driving skills in a safer controlled environment. Children should be allowed to make mistakes and take risks, although in a controlled situation, using a SCAD system to grade the learning process, either by increasing or reducing the amount of guidance support.

Opinions differed from the interviewees about students and driving hazards. Some of them thought the system should be able to detect more things (for example under tables), whilst others thought it was wrong to apply too much protection or apply system intelligence. Again too much help may cause the young person not to apply their own best effort and become de-motivated and not apply or develop their own problem solving skills.

The new systems described in this research were regarded as energy conserving (in terms of the amount of applied personal effort) and this was considered to be a valuable asset for young people to have on their wheelchair drive system. The term ‘Energy Conservation’ was used by the occupational therapists and this was defined by one interviewee as “The amount of physical effort, coordination that they have to put in to operate the switch to get the chair to move, along with the time that it takes them to get from A to B”.

Young people with gross motor function had difficulty with fine controls, for example joysticks. Switches were used because they were more appropriate and because they were larger targets for control action.

Some interviewees felt that future research should be child led and to give children the choice to drive or not to drive. Many interviewees felt that the down side of the research based systems were that they did not go out into the community.

It was commented that some children may never develop the skills to become independent drivers. This may be because of age, issues with cognitive ability and profound physical disabilities.

Some interviewees felt that child intention was sometimes difficult to gauge when there were preconceptions about what a young person wanted or needed. One interviewee in particular felt strongly that child led research, was better by asking young people what type of research should be undertaken; however the researcher may think differently about what is good for the young person and what the young people themselves may want. The author posed the question, “surely any young person in a wheelchair would want an anti-veer system?”. The interviewee responded “Why don’t you ask them”, because it is possible they may want to work at control themselves. If the SCAD stopped a driver from going through a door, should the young person override the system? There is always room for assistive technology and future developments.

Many various issues relating to child independence were discussed and it was widely felt that the systems created for people with complex disabilities through research must have the involvement of the person they were designed to help. The opinions of the users, helpers and professionals and the experiences of the young people feed into the development and design process; this was regarded with particularly high importance.

Interestingly, when interviewees were asked ‘should the collision avoidance system be improved’? some commented that it did not detect gaps under tables. Interestingly, some interviewees suggested children could be over protected and in the real world environment, the child needed to develop its own self protection skills. This again reflected the importance of child inclusion in the system development process and creating systems that were adaptable and had changeable operational parameters.

In particular many interviewees felt that the scale and amount of systematic help should not “switch the child off” in terms of applying their own problem solving ability. Providing just enough help to encourage a young person to drive and build confidence through a positive experience was generally thought valuable, but in reality hard to achieve. Many interviewees said that the new research described in this dissertation was a significant step to meet this challenge.

Chapter 11

Discussion and conclusions

Through the research work conducted and described in this Dissertation children have been able to drive without intense ‘hands on’ supervision. This has enabled them to gain self confidence and further improvement of their personal control skills.

At Chailey Heritage (pre-1990) powered wheelchairs were only provided to children and young adults who could demonstrate suitable dexterity and fine control of joysticks because powered wheelchairs were usually fitted with joysticks. There were Automated Guided Vehicles systems in use in industry that used techniques which could transfer into applications for assistive mobility for disabled drivers.

A Multi-Junction Wheelchair Guidance System had been created before this research, specifically for users to drive in their living and school environment. This is included in appendix C. The new work carried out and described in this Dissertation drew strength from that previous work and from the knowledge of working examples of automated guidance systems used in industry and the Swedish Slingan project

A track system existed at the beginning of this research Langner [2004] and no new claims are made in this Dissertation about the creation of that system. It provided a form of mobility and an assessment tool for use with a range of postural support systems and provided an opportunity for children to safely venture away from helpers with greater autonomy. Once children started to demonstrate improved driving competence using track guidance, the restrictive nature of the track routes became evident. Children wanted to break free of the system constraints. The new research work described in this Dissertation started here and aimed to create a system that could enable guidance by detecting the local environment (and not have to use tracks).

11.1 Effort Reduction Systems

Test runs with and without the new veer correction system demonstrated that a simple feedback system could reduce the amount of effort needed by a driver to counteract the tendency for a wheelchair to veer. The experimental system was primarily intended for switch users. Feedback could be adapted and incorporated into proportional control systems as these provide continuous feedback operation rather than on-off signals.

The limit of veer correction seemed dependant on the traction capabilities of the wheelchair, power of the motors coupled with the wheel grip characteristics and weight distribution over the ground surface [which could be rough or smooth]. The system would still try to correct the veer even if the drive wheel skidded. This could be a problem it the feedback was too aggressive, as a sharp response could cause a skid (loss of traction). If the response was as shown in the experiments so far, then the veer is not completely removed but significantly reduced.

Changing from a set of digital switches to a set of new variable switches improved performance for some powered-wheelchair users. This was helpful for people that did not have sufficient hand-grasp and release ability and sufficient targeting skill to be able to use joysticks effectively. In Chapter 3 a simple input device was presented that isolated gross motor function and was tolerant to involuntary movements. The device was tested for more than a year and shown to assist powered-wheelchair users with poor targeting skills. This offered a proportional control medium for users that would otherwise be given a digital switch.

A case study was described as an example. The new variable control enabled one driver in particular to control and reduce veers on slopes and to provide proportionate control of turn-speed. They provided a means to successfully control forward speed, turn speed and radius while reducing frustration, effort and improving personal energy conservation. Users became more independent and said they did not want to return to digital switches. Through the introduction of variable control it is hoped that people will be able to learn, distinguish and exercise progressive control. Vari-switches still retain the virtue of switch operation in that they can enable other combined functions.

11.2 Object detection devices for powered wheelchairs

The creation of a guiding system for children in powered wheelchairs provided them with an opportunity for independent exploration and independence. This was beyond the boundaries and restrictions imposed by the young person's physical disability and the necessary requirement for a personal helper. With normal un-guided systems the helper would naturally steer the young persons chair as a means to help and tracked guidance system reduced this need. There was still a need for the helper to stop the driver from colliding into objects in the path of their travel. Again the helper would act to protect the child and others close by and reduce impact damage to the environment.

Chapter 4 described work on the development of mechanical bumper systems. The potential independence gained by young people using the track was compromised by their inability to stop in critical situations. Crashing into objects was regarded as a matter of child safety. Some therapists believed that crashing was a learning experience and they had concerns that systems developed to stop the child automatically would reduce their need to learn. Teachers shared the view that they would like to see children driving with increased independence.

Because trainers, teachers, carers and child drivers responded differently during and after collisions, different responsive modes of operation were needed. In addition, visual impact of bumper systems was not a positive image for a young person. The bumpers appearance accentuated aspects of disability. Ironically, the physical dimensions required a bumper to absorb impact energy and the size of the bumper systems added to the footprint of a wheelchair. This unfortunately increased difficulty for wheelchair drivers, although for a guided system this was not such an issue. Later research created a contact less (proximity) object sensing system that provided the basic contact bumper function and contact less collision avoidance.

11.3 The new Scanning Collision Avoidance Device (SCAD)

Chapter 5 described the creation of the first prototype Scanning Collision Avoidance Device (SCAD). This early system was created as a successor to the mechanical bumper system used for track and limited driver training. The major disadvantage with the mechanical type bumper was its footprint size. This became larger when increasing the amount of advanced warning. Non-contact proximity object detection (provided by ultra-sonic ranging) reduced the need for large over- hanging physical bumper detectors. The events in which drivers would collide and misjudge object distance became the focus of further work.

The principal of rotating the ultra-sonic transducer & sending ultrasonic pulses through stepped periods of rotation had been used and evaluated with the first prototype SCAD single field detector. This had originally been intended as a wide angle audible warning device for people (such as a blind girl). There were notable anomalies with the detector, mostly arising out of the repetitive pulse echo sampling. Old returning echoes could sometimes conflict with nearby in-range targets, the sample time was slower than desired etc. In spite of some of these drawbacks the system worked well enough to be of some value in detecting nearby objects.

Ultrasonic sensors were cheap and during testing they worked quite well when using time of flight measurements. A single transducer was used and samples were taken individually. Placing the transducer at a lower level (under the footrests) allowed the objects at low level to be detected, for example curbs, shoes and low lying objects (small children and animals).

It was desirable to increase the sample rate as the wheelchair would move less distance between samples and provide earlier detection. That became the subject of some later work. Experimenting with the ultrasonic detection of objects determined a number of important conditions that needed to be respected in order to obtain an understanding of operational effectiveness. Although factors such as object surface (sound absorption) and area could have an effect on the received echo, other conditions (for example object-shape) were also significant.

A wheelchair was tested with an ultrasonic detector on the front and that provided valuable information about the best mounting position and performance (how well it detected objects in real environments). Much time was spent in pushing wheelchair set-ups around laboratories and schools to assess their ability to detect the environment. The prototype system was given to a blind girl and the SCAD provided a warning sound when it detected an object ahead of her. The young driver responded well to the warning sound.

For wider use, the prototype SCAD systems needed to be able to cut off power; mainly because all the children with mechanical bumpers could not be relied upon to stop with only a sound warning. The focus became contact-less sensing, especially as it became “un-cool” to have a mechanical bumper on your wheelchair. The essential requirements of the SCAD detector head were to be compact and simple. The construction of the SCAD scanner enclosure, particularly the protection bars, could have an effect on performance. Due to the delicate nature of the transducer & motor assembly, damage could result if hit, poked or kicked etc. Experiments were carried out using protective meshes and gauzes to wrap around the sensor system.

11.4 Assisting with steering

Chapter 6 described developments to the scanning collision avoidance device to assist with steering. This enabled the SCAD to offer children an opportunity to drive without needing a helper to intervene (except perhaps verbally). The effect of system intervention had to some extent been tested by the use of the track guidance system, where children had become more independent from helpers when driving between track destinations. Many children demonstrated they could safely venture away from helpers (and many enjoyed doing that).

A SCAD based training system was tested within a structured environment consisting of a road way made from plastic cups. The SCAD successfully detected the cups for guidance and that immediately provided a driver training application that was used in the school.

This first SCAD system was based on switch controlled wheelchairs. Although object detection performance was poor, testing established the principals of object avoidance. Using the commercially available speed compensating wheelchair controllers for the SCAD application required further development of interfaces that converted the switching control voltages generated from SCAD into joystick analogue voltages.
Some children could drive using a single SCAD sensor at the front of the chair. For others that was not sufficient. Some drivers did not have a well developed sense of spacial awareness and appreciation of the wheelchair physical size. Although the front sensing SCAD guided the wheelchair it did not detect objects at the side (for example

a doorframe). Additional optical detectors with background suppression were used. Infra-red was selected because of a higher tolerance concerning specula reflection compared to an ultra sonic system. The main target types in this case were walls and doorframes.

It was desirable to keep the number of sensors to a minimum. The initial work indicated the need to move away from laboratory testing. It did not appear to be beneficial to take children out of their normal environment and put them into a structured and artificial environment (for example into a roadway of cones) and then to expect that the task would be understood. Once testing moved into real environments then children would often push developments by their willingness to explore new environments. It became important to develop and incorporate systems for people living their normal lives (or living pattern). The initial work provided a test bed and highlighted a need for further technical developments but taking the early systems out into the young person's familiar environment highlighted some deficiencies. Disabled people exposed weaknesses in the system (more so than non-disabled people).

11.5 The initial testing of the SCAD

Initial testing is described in Chapter 7. The collision control system was developed by successive trial applications including collision avoidance testing. Real life driving issues were discussed, in which the SCAD system, needed to provide an adequate level of driver support. There was conflict regarding user control of the wheelchair and system control. Some therapists believed that system intervention blurred the boundaries. This made if difficult to determine what level of control was being applied by the child driver. Other therapists believed that assistive technology improved the chances of young child drivers who would not normally be provided with wheelchairs or drive without helpers close at hand. The personal achievement of getting to places and moving themselves (even with technical help) provided increased confidence.

Stages of child driver development were identified in which the child progressed through stages of driving with a normal wheelchair to experience crashing, direct wheelchair steering and control feedback. Opinions varied about taking part of the

decision process away from the child, as the system would do the work of avoiding an object. Some teachers believed assistive technology made it possible for young people to have an introduction to driving without the constant need for bystanders. There were questions being asked about, were we are creating child robots?
Observations of child drivers showed differences in personal driving skill and their anticipation. There were situations in which the system acted or responded first in order to stop a collision.

There were issues relating to how well children understood when they were being pushed and not driving under their own control when they still had access to switch controls in front of them. Some children might not understand why a switch was not responding, even though the switch was still making a clicking sound. The motion of a chair became independent of switch control when it was pushed. The nature of how human help was given varied. The level of SCAD applied needed to be suitable for individual needs and changes. It was important that the childs own ability was not swamped by the system interventions.

System control options were incorporated. These were graduated to progressively offer increased autonomy.

A test system was created to evaluate the SCAD system by driving a wheelchair along a short 40 meter route of corridors. This provided proof that the SCAD significantly reduce the amount of driver control actions need to reach a destination.

Some therapists believed that assistive driving systems helped a young person build their confidence. Young people who would not normally be considered (or who were excluded from driving) were given an opportunity by using a guided system. The way SCAD was used (and how it was used) was partly dictated by the philosophy of the people that used it, and this fed back into how the system changed and developed through the research.

One weakness that became evident was slow progressive object detection having many sectors in which pulse / echo sample were taken. Doubling the scanning speed also doubled the number of pulses sent into the environment whilst a wheelchair was moving. This significantly increased false detection problems because of extra (stray) returning echoes coinciding with recent samples.

A new scanning method was created that halved the scan time but did not double the sampling frequency. The transducer moved at a faster rate, although the pulse / echo sample rate remained the same. This provided a significant reduction of the complete cycle time.

The most important aspect was that the transducer could sample the extreme side sectors in half the time when compared to the progressive scan. What was interesting was that the rapidly moving transducer reduced the problems of false detection due to ghosting. Subsequently the sample frequency was raised to 50Hz and this further reduced the sweep cycle time. The rapidly moving transducer placed increased strain on the transducer connecting wires and consequently the system failed due to wire fatigue. A new method of connection was created, similar to the spiral wire connection used in moving coil meters. Long term testing of this connection method concluded that this was a satisfactory method and to date there has not been a failure due to wire fatigue.

The SCAD head enclosure was constructed to provide acoustic transparency and robustness. Construction of the enclosure incorporated mechanical scan limit stops. The protection bars were angled to reduce internal signal scattering and self pick-up.
Steering avoidance control affected the wheelchair trajectory. The collision control system avoided the collision, but the exit course was uncontrolled and children were sometimes over deflected and consequently ‘cut up’ other drivers and people who were also travelling along a corridor.

11.6 Technical testing and functional considerations

Chapter 8 described further technical testing undertaken to gain a better understanding about practical operating and functionality issues. During the research, the collision strategy was reviewed so that the auto-steering function could be switched ‘off’. This meant that when a chair was on course for a collision, that direction was halted without any automatic correction. This intervention strategy did not alter the course of the wheelchair when an object had been detected, instead it halted the wheelchair.

The driver was required to problem solve in order to proceed.

The way in which the system corrected the wheelchair to avoid a collision was considered, particularly how the driver became aware that a correction had occurred. The initial systems used switches. The drive speed and turn speeds were set at levels suitable for the abilities of the child drivers who were tested.

When an object had been detected, a wheelchair would steer to avoid a collision. The method selected was pulsed retardation of one of the drive wheels. This caused a wheelchair to veer away from an object. The duty cycle of the retardation pulse would vary conditionally depending on where an object was in the scan field.
The pulsed nature of the applied correction provided feedback to the driver that the system was acting to make a correction.

The dynamic control of the wheelchair (particularly deceleration) was affected by the weight of the child and seating system. This was particularly apparent when the same assessment chair was used by small and large children; this had a direct effect on the amount of energy involved for effective control. It was noted that there were more overshoot and collision problems with heavier children and sometimes the drive speed was slower.

When children and young adults used their powered wheelchairs, they were usually supported by special seating systems. Chailey Heritage Engineering had conducted some research and developed the Chailey Adjustable Posture Seat (CAPS) systems. The mounting position of the SCAD detector head was considered so that it was un-obtrusive and did not interfere with normal operations when putting a child and seat in and out of a wheelchair. Wheelchairs generally operated in a busy environment and were not always treated carefully. Any additional attachments needed to be robust in order to survive. It was not possible to rely on people treating wheelchairs more carefully because they were equipped with sensors, therefore the mounting structures were made of materials similar in gauge to that of the wheelchair frame.

An environmental survey was carried out to determine the extent of practical detection of objects around Chailey Heritage School that children would most likely come into contact. Tests were carried out to evaluate the environmental variations in the type of object texture and how it affected detection. The optimal receive sensitivity was then set. The Polaroid ranging board incremented the receiver gain with time to compensate for propagation signal decay. High receiver gain provided high levels of object detection, but it provided a low tolerance to environmental noise.

Collision avoidance restricted how close individuals could get to things and places of interest. An example was, that the system sometimes prohibited access through narrow doorways and spaces (narrow apertures). The system range setting was fixed at a level based on factors such as, the ability and estimated skill and confidence of the driver.

Environmental range conditioning was applied to enable the system to drive though a confined space (doorway) that was less than the set scan width. The system would contract the sensing range for a fixed period of time. After this time, the range would revert to the set value. This enabled drivers to get through doorways that were narrower than the normal object range setting. A reverse timer allowed a user to withdraw from an object or confined space. The time factor limited the distance travelled in reverse in order to reduce collisions and provided a satisfactory reverse limiter function.

There were driving conditions in which the SCAD sensor and side detector would detect objects that would stop driving. An example was, when a side detector responded to an object on the right and the SCAD to an object centre and left. The system would lock any forward driving and this frustrated drivers. The sensors were therefore prioritised so that when the SCAD detector responded to an object, the side detectors would be disabled. This prevented a driver from becoming stuck because of the sensors detecting objects.

11.7 Human trials

Chapter 9 described human trials with children. The first introduction of object detection was a mechanical bumper system. These successfully increased the level of independence of young people and reduced the need for helper intervention. Initial tests indicated that bumpers provided positive feedback to drivers about collisions. Children and helpers felt more confident that the bumper provided a margin of safety and warning although it had fundamental limitations, particularly because the bumpers themselves were vulnerable and were sometimes damaged.

The first practical application of the compact SCAD system was as a warning device for a blind girl who drove a track guided wheelchair. The SCAD provided a warning to her about possible hazards in front of her wheelchair. Through general observation, the children who were using the track were also restricted by it. Therapists wanted children to come away from the track but children still had problems with controlling their wheelchairs. An encouraging aspect of the SCAD used on a child's wheelchair was that it did not get damaged and it's operation was reliable, compared to the earlier bumper systems.

Children tested the first prototype SCAD systems. A simple roadway lined with plastic cups sprayed with bright fluorescent orange paint provided markers and boundaries for a road way. A video record was taken of these first SCAD driving sessions. It was clear that there was a double learning curve, not only for the child but for the development and practical application of the driving training systems. As a result of these early trials, further development work was undertaken to provide extra system based help (prompting) for the user. Some of these early experiments consisted of illuminated beacons placed at the appropriate side. For example if an object was detected on the left, a beacon would light or make a sound to the right in order to indicate the direction to drive away from an object.

With ongoing SCAD driving trials it became increasingly clear that it was better for children to drive around in their real environment rather than a situational set-up using the road cones.

An improved system was created and the SCAD system was subsequently used around the whole school. This formed a better training format for the children as their driving gained extra purpose. The normal driving routine of young people going from one place to another at specific times then formed on-going assessment criteria for the next part of the research.

The research work described in this Dissertation started because of observations of the difficulties young children had with driving. Often they would not be allowed to drive because of staff and helper concerns. Children generally had a strong desire for independence, but this was heavily reliant on personal helpers to guide their chairs. The track system provided a means for young drivers to drive without constant helper support [Langner (2004)]. The test with SCAD (particularly the road cones) demonstrated that helpers could step back and allow children to drive.

A reverse function was implemented to enable children to back themselves away from obstructions. Many young drivers did not have a reverse control because of their limited physical or mental ability. The reverse function was important for the young person to master because it provided them the means to manoeuvre out of situations where they became trapped.

Some staff noted that SCAD collision avoidance may confuse some children. Did the children understand what the SCAD was doing and why their wheelchair responded differently during collision avoidance. The switch control function changed, (for example in pre-collision, the forward drive switch controlled the forwards motion); when the SCAD detected an object on the left, pressing the forward control caused the wheelchair to steer to the right to avoid the object and vice versa. This change of control function confused some children. This reflected the child's understanding about what control manoeuvres were necessary in order steer around objects and the associated resulting motion of the wheelchair. Switching off the automatic collision control function was an option for occupational therapist's, and to some extent converted the SCAD into a learning tool.

11.8 Validation interviews and discussion groups

Some staff discussions and interviews were recorded in Chapter 10. Twelve professional people working with children in clinical, educational and caring roles were interviewed. The general view was that personal mobility was important for the well being of young people. Some complex disabilities required constant help. This validated the need to undertake the research. The interviewees suggested that the researched was of value to young people, particularly for increasing their autonomy and freedom that helped them to gain confidence and personal achievement Technical assistive help was needed because a young person’s personal disabilities sometimes prevented them from normal exploration and personal interaction. A general feeling was that mobility should be introduced at the earliest opportunity.

The interviewees felt that assistive systems provided young drivers with opportunities to make driving choices without the continual presence of helpers who might intervene and override them. The creation of the research based systems was mindful of the learning stages of the young people. Some comments from the interviewees indicated that the applied research work helped young people perform tasks that they were otherwise not able to perform without helper intervention. The research helped young people drive through doorways and along corridors, and enabled young drivers to refine their skills through practice. The systems reduced the chances of young people giving-up because driving was too much hard work. Safety was also a factor in which the research systems acted to stop collisions where objects and possible hazards were detected. This protected driving opportunities, and reduced the chances of young drivers having control taken away from them through the application of human help.

Many interviewees said that raising expectation was a positive benefit, as this placed an expectation on a young person to achieve, as opposed to being a passive on-looker, even when the research based systems only gave the appearance that a child was driving. Some interviewees suggested that this put pressure on other organisations to provide extended support. None of the interviewees thought that the new systems created by the research added to learnt helplessness. Helping young people to reach goals and, importantly, being able to back-off the amount of applied system support, were important factors for child development and independence. One particular comment was that, “I don’t agree that any system can totally do it all for the child. They’ve got to press a switch for themselves”.

Although the interviewees had concerns about the on-going provision of technological support, the general opinion was that this should not stop the creation of bespoke research based systems. Furthermore, some interviewees stated that the imposition of the DDA (Disability Discrimination Act) helped reinforce the need to research and create systems to help enhance a young person’s independence. The interviewees felt it was important that a young person understood the reason they were driving and the value of personal independence. This suggested that the new work described in this Dissertation about audio and visual prompting systems needed to be taken further to help young drivers understand the reason when, for example, a wheelchair had altered course because an object had been detected. The most significant problem reported by the interviewees was wheelchair veers. Many of interviewees had spent a lot of time helping young people steer their wheelchair because of the effects of slopes and uneven terrain had caused a driver to drift off line. This generated frustration.

A new anti-veer system was created by the author during the research and wheelchair trials demonstrated that wheelchair veer was significantly reduced. The interviewees thought that research improved the chances of young people driving because it reduced risk. Through the research, crashing was provided as an option. For example, the collision avoidance system gave a choice of allowing children to crash or not to crash. This could be for preserving self confidence that could be damaged by a bad driving experience. It was clearly recognised that systems created by this research provided new driving opportunities to young people with visual impairments.

Some interviewees felt that the new systems created during this research should be introduced to young children at the earliest opportunity. Children started to be allowed to make mistakes and take risks, although in a controlled situation. A SCAD system could be used to grade the learning process, either by increasing or reducing the amount of guidance support.

Some interviewees felt that child intention was sometimes difficult to gauge. One interviewee in particular felt strongly that child led research was better. The author posed the question, “surely any young person in a wheelchair would want an anti-veer system”. The interviewee responded “Why don’t you ask them”, because it is possible they may want to work at control themselves.

11.9 The train, adventure playground and interactive systems

Appendix D described the train, adventure playground and interactive systems.
The creation of Track and SCAD systems provided support to help young people to drive their wheelchairs with reduced reliance on helpers. A reason for the creation of

a track guided train was to motivate individuals to try a new activity not centred on wheelchairs. Drivers took responsibility for their passengers and the train provided a choice of being a driver or a passenger. The group mobility aspect of the train also provided disabled and able bodied young people an opportunity to take part together in a combined activity.

The author was involved in the design and creation of an environment to offer a choice of switch operated devices that a child could select. Multi-sensory environments had relied on facilitators to setup the child with the necessary hardware in advance to enable the individuals control switch to operate a chosen device. If different choices were required then the facilitator would have to change the set-up, so that a different device could be connected. New research work described in this Dissertation involved the creation of interactive systems to extend the personal autonomy of young people beyond driving. Enabling young people to take control of (remote) devices coupled with mobility became the focus of new work. A train was an icon of mobility; traditionally the driver was responsible for the transportation of his passengers and therefore had a sense of power and purpose. Associated with this was the responsibility of control. Children were given an opportunity to be a ‘train driver’ and transport other children as passengers.

The train was used by competent and experienced drivers who wanted to try something different. Child drivers acted as demonstrators and this often encouraged first time drivers to have a go. The train was operated by a single switch to control starting and stopping. Junction control select switches provided operators with left or right turn selection. A switch input control interface was built that could accept a variety of commercially available switch controls. The adventure play area was used as a common resource. The technologically assistive systems were created predominantly for children with disabilities but non-disabled groups were not excluded. The design of the locomotive and the tenders incorporated the mounting assemblies required for specialist seat and non specialist seats or chairs. Children from either group were able to operate the train.

The versatility of the seating systems in the train allowed children of different abilities to take part in the activity of driving or being a passenger. A choice of position was offered to the children and some elected to be drivers and some wanted to be passengers. There were also some who wanted to spectate, although this was often because there were not enough tenders to accommodate all who were interested. As the number was restricted to three, it was interesting to note that some children who had their own powered wheelchair would follow the train, also members of staff would push children in buggies behind. By observation, this was a group activity. The driver had responsibility for moving and controlling the train. The driver's actions would therefore affect the transportation of fellow passengers. Some children clearly understood what was happening, especially those who were already competent drivers. Non-disabled children could take control of the train to give rides to non-disabled or disabled children passengers. This could be changed so that disabled children could be drivers and assume responsibility.

The adventure tunnel and playground were created and offered children an opportunity to drive powered mobility devices and to take control of devices. The technology created and described in this Dissertation provided increased autonomy. The adventure tunnel introduced and established possibilities for individuals to control devices in their immediate environment or space. A novel system was created that enabled the change of function between wheelchair control and remote device control when within a specified operating distance of the chosen device. This provided an opportunity to take control and operate more than one mode through a single switch.
The physical and cognitive abilities of the young people that used track guided wheelchairs varied. It was necessary to integrate mobile interactive control with driving control as a strategy that enhanced independence. The most important aspect was that the children understood when the control function changed from wheelchair control to device control and many children demonstrated this understanding.

The adventure tunnel and playground enabled children to control their powered mobility systems, (wheelchairs, locomotive train and a motorised platform to support children in their standing frames), to take control of devices in their immediate environment and significantly reduced the need for helper intervention.

Chapter 12

Future work

The research described in this Dissertation identified several new areas of research, some of which have been started during the write up phase of this dissertation. These are described in the following sections.

12.1 Veer detection and correction systems
12.2 Track based audio (talking) sign post system
12.3 Power stander base developments integrating guidance systems
12.4 Single switch scanning controlled SCAD based control system
12.5 Potential commercialisation

Other work to be considered in the future is:

- Proportional wheelchair control system incorporating SCAD
- Proportional switch controls (including force feedback)
- Merging track and SCAD systems together on a wheelchair
- Tilt in space motional feedback platforms
- Integrating veer detection and SCAD systems
- Mobility devices for sporting activities (robotics for ball retrieval / collection / throwing)
- Personal energy tapping systems for student powered activities and energy measurement applications
- Haptic (force feedback) joystick linked to object detection feedback

12.1 Veer detection and correction systems

Theses systems are described in Chapter 3 and development work is continuing.

There were problems with the experimental anti-veer sensor. The castor swivel and veer conditions were detected and fed back to the electronic wheelchair steering control. The first anti-veer system shown in Figure 12.1, consisted of rotation sensor created to fit over the front castor bearing.

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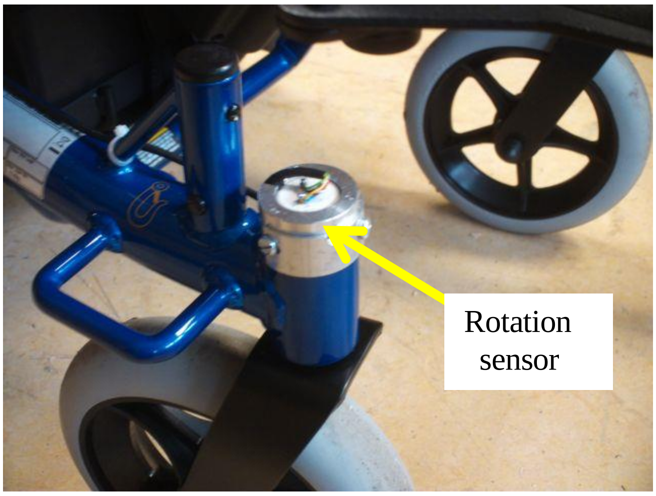


Figure 12.1 Castor rotation sensor

This system demonstrated that troublesome wheelchair veer could be detected and significantly reduced but there were problems if the wheelchair castor became caught in a pothole or lost contact with the ground.

Figure 12.2 The inflexible wheelchair frame

Observations showed that wheelchair frames were generally not flexible and did not have any form of usable suspension. There were occasions when the wheelchair was driven over uneven ground and castor angle feedback was unreliable (as seen in Figure 12.2). This caused errors that resulted in indeterminate operation.

Work has started on developing a new system using swivel detectors on both castors to reduce problems if one castor was lifted off the ground; the other would still be in contact. This presented a new issue of how the system would know which castor was providing correct information and which erroneous feedback. Castor to ground contact force sensing was considered but this time the system engineering was becoming complex and time consuming and a better method needed to be found. Gyroscopes have been used extensively in aircraft to obtain heading information and provide stabilized flight. The cost and engineering requirements to adapt mechanical gyroscopes for wheelchairs has not been realistic. Over the last few years micro miniature electronic sensors have become available. An extensive search on the internet was carried out to find a suitable device. These devices were becoming affordable and a small electronic gyro was purchased for evaluation.

Tests were conducted to determine if the new sensing device had sufficient sensitivity for veer detection. The original electronics developed for the first castor swivel anti-veer system was re-engineered to work with the gyro. Initially the results were not as good as the castor swivel detection system.

The complete anti-veer control system was redesigned to operate in a different feedback control mode to enable improved anti-veer performance. The original castor swivel system acted as a benchmark for the trials. The gyro based system went through several design and test cycles and was extensively trialled using laser guided markers.

The solid stage gyro was placed inline with the wheel axis

Figure 12.3 The testable gyro based anti-veer system

After testing, the anti-veer performance of the new system was superior to the original castor swivel system and had the advantage of simplicity of installation on the wheelchair (shown by the red arrow in Figure 12.3).

Two test systems have been given to Chailey Heritage School students for evaluation and the feedback has been positive. Many switch drivers who have improved their driving skill are often tried with proportional joysticks. This may also be an area where the anti-veer system could be applied.

12.2 Audio (talking) sign point system

Figure 12.4 shows an audio sign point system that was created to help a young girl with a visual impairment, identify where she was within the CHS complex whilst driving her track guided wheelchair. She specified where she wanted the audio markers along her track routes.

Figure 12.4 A young track driver hearing a sign post identification beacon

When she drove past a place with a marker beacon, the messaging system provided the place identity. Some other students have started using the same system and there were various marker beacons positioned around the school (internal and external).

Figure 12.5 Young people testing the audio sign system

A new pupil information system called ‘audio / visual sign points’. Figure 12.5 shows young people at CHS testing the system. They have suggested new message formats that mean the most to them. Sign points can be placed in any area of the school and if necessary can be programmed by a student with their own messages.

The method of activation is non mechanical and has a number of different possibilities depending on the young persons abilities. For example, students who can reach out, can operate the system directly, others who may have more restricted movements can activate the system by having small pendants they carry with them, so they will get a message when they pass by. An experimental setup of this is shown in Figure 12.6.

Figure 12.6 Testing a remote triggering message system

The work on the development of contactless activation technology can be extended to provide simple direct control of local lighting and power devices local to the young person within their environment.

12.3 Power stander base developments integrating guidance systems

Many children at Chailey Heritage School use mobility systems. Trikes, walking gait trainers and walking aids are used. Some of the young persons' physical impairments mean that their energy requirement can be high and often they require physical assistance from helpers.

Mobility provided by powered wheelchairs is often the only real opportunity children have to travel large distances under their own control but in that case the children are seated. Mobile standers (shown in Figure 12.7) enable a young person to have periods of mobility whilst standing but then the child loses a major part of their autonomy and freedom; becoming totally reliant on people pushing them around. It is important to consider that a young person's access to independent mobility is a normal aspect of their life.


'Clip-on' power module

Figure 12. 7 A young wheelchair driver testing a power stander combination

The creation of a specially developed power module restored a child's personal control of mobility and provided them with a new opportunity to drive whilst in a standing position. The power module has initially been designed to partner some Active Design standers that are in use around the school.

A child's familiar control was used in the same way as their powered wheelchair. The power stander module could also be equipped with standard switch controls and new variable switch systems that are under development.

Figure 12.8 Children using their switch controls

Young people at Chailey used a range of control systems. The power module shown in Figure 12.8 can operate with switch controls in the same way as a standard power wheelchair. Some require assistive driving support to help them with their personal mobility. The development of a purpose made power base is underway.

Figure 12.9 Developing a purpose built power base

The power base shown in Figure 12.9 has been optimized for young drivers. The base unit has a small foot print and low centre of gravity and has been designed to incorporate track guidance or SCAD assistive driver support systems if required.

Future work will concentrate on developing an agile system to match skilful drivers so that young people can take part in sporting activities.

12.4 Single switch scanning controlled SCAD based system

Driving is hard work particularly for those who use a single drive control. Each direction for the wheelchair has to be individually selected and this can be time consuming and frustrating. A major part of the new effort reduction work has considered merging SCAD and anti-veer systems together and then creating a scanning driving direction system for young people using a single drive control.

Figure 12.10 Video picture of the test run destination

A prototype test system has been created and evaluated by driving a wheelchair along a short (40 meters of corridors). The first wheelchair run was conducted with the direction scanner operating conventionally. The driver needed to select each direction individually with a single switch to reach the target destination.

The time recorded was 2 minutes:11seconds. The second wheelchair run had the

SCAD system engaged.

Driving along the same route with the same switch, the run time was reduced to 1 minute:7seconds. It was noted that the second run needed only 10% of the number of switch operations (when compared to the first run) to reach the destination.

This experiment was videoed and a clip is shown in Figure 12.10. The video showed that the amount of effort required to drive along the route was 90% less in terms of the number of control actions and it took half the time when compared to the standard control system. The next phase of the effort reduction project is to create a working system for students to test around the school complex and to monitor their reactions and progress.

12.5 Potential commercialisation

During the process of this research interest was shown by visitors to the school, parents of children and those who had attended presentations and seminars about this research. Although this research was primarily applied to children, there were enquiries about applications that could involve older people and possibly those in care homes.

There were often questions and enquiries about the commercial availability of track and SCAD systems. Indeed the author of this Dissertation had built systems privately in his own home workshop, however the numbers produced were limited and did not meet the numbers of enquiries.

At the time of writing Chailey Heritage School are perusing ways to make the SCAD and track based assistive technology commercially available. This involved Author working with enterprise organizations and people within the school with business connections.

Appendix A

A.1 Ethical considerations

The aim of the research described in this Dissertation was to improve the independence and self confidence of young people at Chailey Heritage School; children with multiple complex disabilities. The young people were asked if they wanted to take part in testing and trying new systems. It was carefully explained to them, often by a person they knew and trusted, that they were taking part in new work to help them drive. Many children could not communicate verbally and communication with some children was a personal process. It was critical that a child understood as best they could and that the children's responses were interpreted correctly. Sometimes special symbols were used and methods of eye gaze and specific head movements or gestures were involved.

The work undertaken in this research was conducted under the guidance of the NHS Chailey Clinical Services Organisation. The occupational therapists would oversee research aspects, in particular identifying potential candidates and arraigning driving practise sessions with the young people. Additionally Chailey Heritage School applied strict safeguarding and child protection policies. This helped ensure that every young person having special needs was being fully supported. Also a school governing committee was kept informed throughout the progress of the research.

Children were not the only participants in the research. It was important to inform the staff who were associated with the young people. Presentations and demonstrations were given to therapy, teaching, caring staff and parents to explain the purpose and the structure of the research work. At these meetings any concerns or views from the staff were noted, particularly if there were any issues regarding children who had a significant medical condition.

Parents or guardians were informed and their consent or otherwise was obtained. Parents, family members and key workers were invited to visit or be present or involved with driving sessions.

Photographic permission was obtained for all of the children shown in this Dissertation. At the time of this research most children at Chailey Heritage School had photographic permission for their picture to go into the public domain. Often video recordings were made of the sessions and copies made and given to parents and therapy staff.

There were some young people who had photographic restrictions. Accordingly, any video recordings or pictures taken for research purposes were kept alongside the young person's medical record files. These were held in a secure place for which only specific members of staff had access.

In all driving research based sessions an occupational therapist, physiotherapist or specific key worker was present. A young person sometimes responded positively when a particular person was with them. Conversely sometimes particular people had an adverse effect and this was noted.

Teaching and medical nursing staff were informed about the times children would be taking part in the research so they could find them if needed. Accordingly any disruption to school lessons or child related activities was minimised wherever possible.

If a child became distressed or anxious during a driving session, they would be taken away from the situation unless the issue could be resolved by communication at the time. Sometimes children were uncomfortable in their seating or posture support system, so it was important to establish the cause of their discomfort.

As the research progressed the SCAD and track systems were used by more young people. The requirements for a therapist and researcher to be around was reduced. Generally the research based systems became integrated within the general school activities that the children were involved with. Reporting structures were setup so that the children's progress or problems could be reported or monitored by nominated members of staff.

Appendix B

B.1 Intelligence in robots

Robotic applications in industrial environments have tended to be specialised and require highly structured environments. Any change in the environment, or to the specific task to be undertaken, has tended to require off-line re-programming. [Lozano-Perez (1990)], [Goodwin (1992)], [Sanders (1993)] and [Tewkesbury (1994)].

[Brooks (1991a)] described how work in Artificial Intelligence has had a strong influence. The Von Neumann model of computation has influenced the application and structure of Artificial Intelligence systems. Intelligence in biological systems is different. Work in behaviour-based Artificial Intelligence has produced new models of intelligence that are closer in spirit to biological systems. [Eunjeong K (2009)] developed an intelligent wheelchair for severely disabled people using a vision recognition method. The proposed system enabled a user to control the intelligent wheelchair using his mouth shape and face movement. Ten range sensors were used to detect and avoid obstacles in the environment.

[Kezhong (1996)] introduced the intelligent mobile robot key technique for an intelligent mobile robot. The robot exhibited path planning and simulation, transfer and multi-sensor fusion techniques. [Galt (1999)] considered the most productive mobile robots to be predominately wheeled or tracked vehicles. That is, they all have wheels and some have the addition of their own "rolling road". The majority of basic wheeled vehicles have been confined to environments with an ideal walking surface, for example, flat, smooth with no stairs or other major obstacles. [Yuki K (2011)] proposed robotic/intelligent wheelchairs that employ user-friendly interfaces or autonomous functions. Although it is often desirable for a user to operate wheelchairs on their own, they are often accompanied by a caregiver or companion. When designing wheelchairs, it is important to reduce the load on the caregiver. This robotic wheelchair moved with a caregiver side by side.

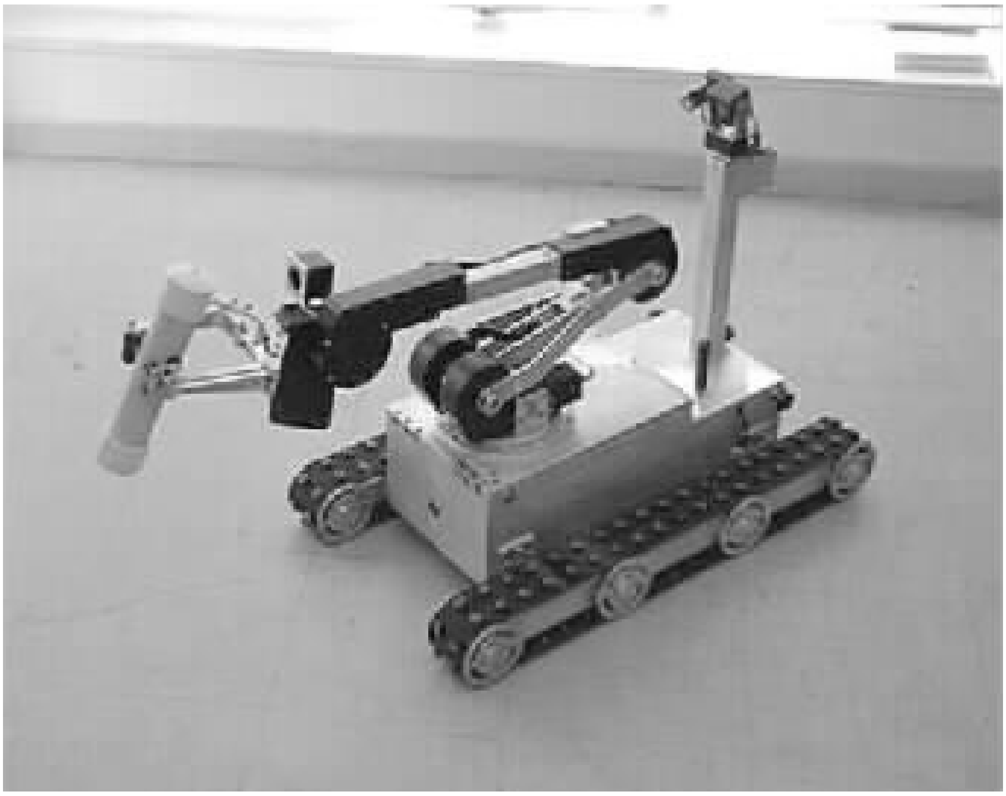


Figure B.1 The Merlin robot, reproduced from [Stott phd 2002] originally from [Galt (1999)]

[Galt (1999)] reported that the most versatile mobile robots employ sets of tracks for locomotion. Tracked vehicles have had much success on difficult terrain that may be a problem for conventional wheeled vehicles. A good example of tracked wheel technology can be found on one of the most capable of terrain locomotion devices in operation, the Merlin robot shown in Figure B.1. [Alqasemi (2007)] considered a wheelchair mounted robotic arm system that was designed and built to meet the needs of multiple impaired persons with limitations of their upper extremities. The control system was designed for teleoperated or autonomous coordinated Cartesian control and offers expandability for future work.

[Zhihua (2009)] introduced the main design concept of a novel, movable service robot prototype for the elderly and the disabled. The robot had the characteristics of simple structure, low cost and vision-based guidance. Key technology points of the robot are double working arms, visual positioning equipment, movable platform, control system and path planning etc.

The work described in this Dissertation, built on this previous work on automated applications for persons having disabilities and problems with wheelchair control.

B.2 Communications

For wire guided systems it could be convenient for fixed control computers to communicate with the vehicle. This was achieved by combining the communicating signals and guidance signals on the same wire [Langner Thesis (2004)]. A vehicle picked up both and unscrambled them. Similarly the vehicle could transmit information back through the same medium to a computer, providing a two-way link. Two mediums were considered in sections B.2.1 and B.2.2.

B.2.1 Radio

Frequency modulated radio links could be installed that provided near-continuous communication with all vehicles. [Hartley (1987)] used radio instructions to change the path of some vehicles. Real time wireless sensor networks have been developed to help provide information to visually impaired people to help give them more independence within in their local environment. [Sevillano (2009)] describes the availability of inexpensive low power hardware including, low power Cmos cameras and wireless devices that make it possible to deploy a wireless sensor network to function as a navigation aid for wheelchairs.

B.2.2 Infrared

Infrared links were also used for local interactive communication. Infrared had advantages when compared with radio because the areas covered could be tightly controlled and contained within operational areas or cells.

B.3 Force feedback

A human and a robot could carry out a task which was not attainable by themselves. In particular, a human recognizes environments and plans a trajectory without collision with obstacles. A robot can generate a controlled force more consistently than a human. [Katsura S(2004)] considered a combination of human ability and robot capacity based on force commands from a human.

Another technique for assisting a user to steer a powered wheelchair was described by [Brienza, Angelo (1996)], with a force feedback joystick and control algorithm for wheelchair obstacle avoidance. Common tasks such as traversing through doorways, turning around in halls or travelling on a straight path were described as being complicated by an inability to accurately and reliably control the wheelchair with a joystick or other common input device. Or, by a sensory impairment that prevented the user from receiving feedback from the environment". An active joystick with force feedback to indicate obstacles in the environment was developed.

An active force feedback joystick was used to assist a user to navigate in an unknown environment. Sensors were fitted to the wheelchair to sense that environment. The wheelchair system had two modes of assistance; passive assist where the joystick became stiffer to discourage trajectories which would cause a collision, and active assist where the wheelchair system moved the joystick to degrees of freedom (moved the central position). Active assist steered the wheelchair away from objects. Passive assist tried to make the user steer away from an object.

The paper led to the suggestion that this system could be connected to a device that could assist in unknown environments and to help in pre-mapped environments along predetermined paths. A related application using power assist control by repulsive compliance control of an electric wheelchair was described by [Shabita (2008)], who described a power assist control to assist in the pushing task of an electric driven wheelchair. Wheelchairs were widely used in the daily lives of disabled people. A new power assist control for the pushing task was proposed as an intelligent function of wheelchair. This was called a repulsive compliance control. In this strategy, the reaction force of human input into object is estimated and was utilized to generate the power assist torque for the wheels and made it easier to carry out the pushing task by wheelchair users.

Further work was undertaken with the aim of implementing a force feedback joystick system with a set of range sensors. [Bourhis (2007)] considered a system intended for people with a disability for whom a traditional joystick control (or any other adapted sensor control) was difficult or impossible because of their severe motor disabilities. The force feedback was calculated according to the proximity of the obstacles and helped the user, without forcing them, to move towards a free direction.

B.4 Sensor fusion

A single sensor system working in isolation typically could provide limited information for the system. Sensor arrays may be used to enhance data rate and accuracy of the system. Sensor fusion methods are described in [Purcell, Huisoon (1993)], [Chang, Song (1996)], [Fatemi, Lecocq (1996)], [Guey *et al* (1997)]and (Sanders (1993)].

[Song (1996)] described a navigation system that allowed a robot to travel in an environment about which it had no prior knowledge. Data from multiple ultrasonic range sensors were fused into a representation called Heuristic Asymmetric Mapping to deal with the problem of uncertainties in the raw sensory data caused mainly by the transducer's beam-opening angle and specular reflections. A potential field method was used for on-line path planning based on the constructed grid based sonar map.

The problems faced by users of ultrasonic sensors include the high incidence of misreads which was typical of these systems. Histogrammic In Motion Mapping (HIMM) and Vector Field Histograms (VFH) have been used to reduce the effect of misreads. [Murphy(1996)] compared HIMM/VFH and Dempster-Shafer techniques for obstacle detection for a moving robot. The HIMM/VFH methodology worked well for a robot navigating at high speeds, but the algorithms showed poor performance at lower speeds in cluttered areas as the beam width created a wide, slow moving area in which the object could be located. The number of grid elements updated varied as a function of the robot's velocity. In addition, varying the beam width with the velocity of the robot improved the updating of an occupancy grid using Dempster-Shafer theory versus that of HIMM. The Dempster-Shafer method tended to handle noise better and make smoother and more realistic maps.

[Gilbert ,Johnson (1985)] and [Khatib (1986)] applied the method of representing obstacles by distance functions, in the case of Khatib, who was motivated by the electrostatic repulsion between like charges. For example, the mover and obstacles could be represented by positive charges. This artificial potential repulsion approach was aimed at the local, short-term avoidance of obstacles in real time rather than automatic planning of paths. Although the algorithm did not quite solve the find-path problem, the use of a repulsion force made this algorithm original and the system worked in near real time. The function tended to infinity as the point approached the surface and was zero beyond a certain distance from the obstacle. This representation had the advantage that the task of calculating the distance between a robot and an obstacle was replaced by the task of evaluating the simpler function. Compared to solid geometry or polyhedral models, these calculations were relatively fast.

The repulsion force was generated by a fictitious potential field around each obstacle due to a potential assigned to it. When any link of a robot arm approached an obstacle, a repulsive force pushed the link away from the obstacle.

B.5 Navigation

Navigation is primarily concerned with path selection. It uses the terrain and information from other sensors to chart the most appropriate course for the vehicle [Kumar, Waldron (1989)]. In path planning, a prerequisite to circumventing any obstacle is to detect it. Various methods for detecting obstacles have been proposed by different authors including [Doty, Govindaraj (1982)], [Sanders *et al* (1992)] and [Fu, Gonzalez ,Lee (1987)].

Many researchers were interested in electric wheelchair automation because of the mobility problems met by a certain number of young disabled and older people. [Njah M (2009)] proposed a system equipped with unit control and sensors to extract some information.

A fuzzy controller generated control information to the wheelchair wheels to reach the target position. An example of retrieving location data universally was via the (GPS) Global Positioning Satellite System. Originally developed by the US defense department for military purposes, twenty four satellites were launched at high cost. The system accuracy was purposefully degraded for military purposes, but potential accuracies to within one meter could be achieved [Borenstien *et al* (1997)]. This navigation system has found a wide commercial market and is used for shipping, aircraft and general transportation of goods and personal transport.

Appendix C

Track systems

C.1 Introduction

This Chapter describes the track system that existed at the beginning of this research [Langner (2004)]. It provided a form of mobility and an assessment tool for use with a range of postural support systems. It had a single switch to control starting and stopping to give driving more purpose and meaning. The concept of an electronic railway line 'Track' was created. This provided an opportunity for children to safely venture away from helpers with greater autonomy. The system could be driven free from the track if additional switches were provided. The inductive method described in Langner 2004 was selected because it provided flexibility of performance and it was not affected by visual obscuration.

C.2 A first mobility platform and simple track

A low level mobility platform was built for a young driver who had spatial awareness problems and needed a compact system to make the best of available driving space. Particular attention was paid to keeping the height of the platform as low as possible to reduce the risk of toppling.

The track was primarily intended to offer a driver support using a single switch for starting and stopping. This enabled a driver to reduce their reliance on helpers and a gain sense of individual achievement. Children who were given powered mobility became more active and engaged in the world [Butler (1996)]. It was observed that young children gained self confidence and some attempted more challenging free driving that required additional switches for the selection of turning and reverse.

A traceable signal was provided by a wire taped on the floor which was connected to a signal generator. Two reed relay operating coils were used as pickups under the wheelchair with their respective outputs amplified by a single stage op-amp circuit. A standard wheelchair power control unit was used to power the drive motors.

The control system was designed such that signals in each sensor coil would remain in balance at the mid-line centre tracking position. When a deviation occurred (for example a bend) the signals were no longer in balance due to one coil signal being higher than the other. These relative signals controlled the individual motor speeds. One motor slowed and the other increased speed by the correct amount, the system maintained a balance and therefore kept track.

One of the deciding factors in determining the track signal level was the effects of EMC on the quality of performance. With a higher track signal the pickup amplifier gains could be reduced and the effects of locally generated interference were reduced in proportion. This did not entirely solve the problem, but it made it possible to use a working system for the purposes of the research. A track was created that was made of thin ABS plastic and wire conductor as shown in Figure C.1.

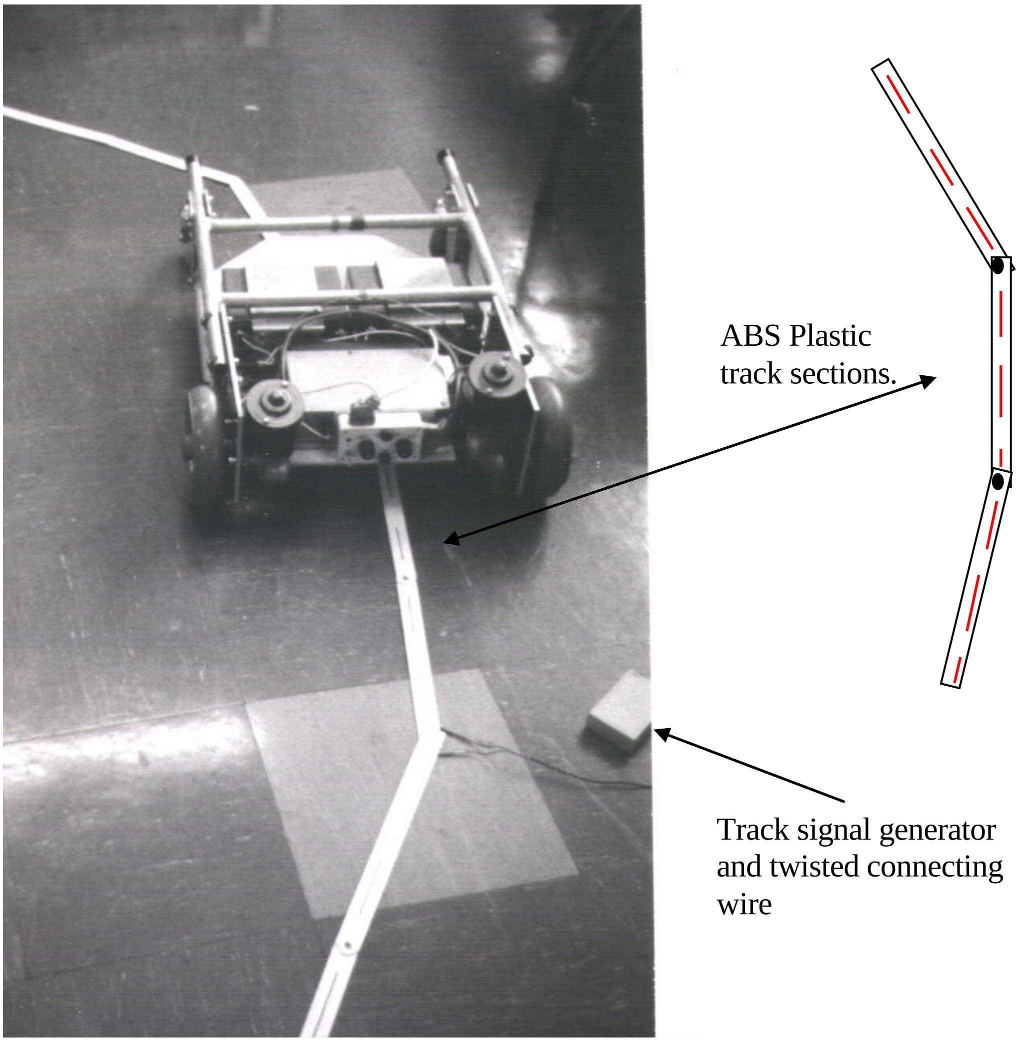


Figure C.1 Non permanent plastic track sections

The track could be connected up and put down quickly to enable young drivers to start driving in a short space of time.

C.3 Incorporation of track junctions

A junction format was selected that was simple and direct so as to reinforce the concept of turning. Other users with different needs were also considered, as well as differences in the types of powered wheelchairs. There were two areas of particular interest concerning an approach to a junction. The first was how the user would interpret that he / she had a choice and accordingly command the system to carry out that choice. Secondly, how the system would respond logically, that is recognise the junction and control the chair to enable a change of track line. As part of the control system a junction identifier was created to inform a user that a junction had been reached. The amount of automation at a junction was considered, particularly as some users may not have been able to steer at the junction points. The variation in the number and type of switches was considered to ensure sufficient flexibility of operation for different users. An appropriate junction format was selected that was simple and direct so as to reinforce the concept of turning. The variation in the number and type of switches was considered to ensure sufficient flexibility of operation for different users. Initially, three switches were used.

The creation of a tracked guidance system embodying junctions presented problems. The track layouts could become electrically complex in terms of energising the track branches. The variable nature of the junctions was of concern.

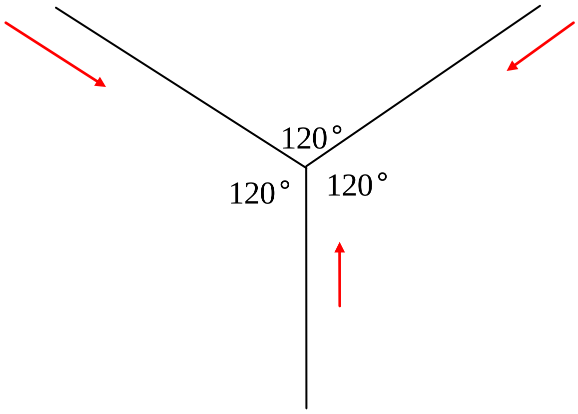


Figure C.2 Star junction

For a young new user, a simple and repeatable choice was desirable, for this reason a simplified junction was created that offered the same left or right direction selection for any approach spur. This is shown in Figure C.2.

The guidance system needed additional detectors and control logic for junction detection and control but it proved difficult to use or alter the existing tracking components for the junction detection process. Figure C.2 shows a star type junction that had the same options for any approach spur. These were always left or right. This was a simple starting point for users to learn direction selection. The star had a recognisable signature that simplified the detection process. Although the junction was symmetrical by appearance, the electromagnetic field strengths were not. The feed wire or the source conductor connected to the track generator divided into two, to form the junction spurs. This also divided the signal in each of the spurs to half the feed level. Spurs would be different lengths and accordingly have different relative resistances. Figure C.3 shows the termination resistors were used to equalise the path resistances and signal levels.

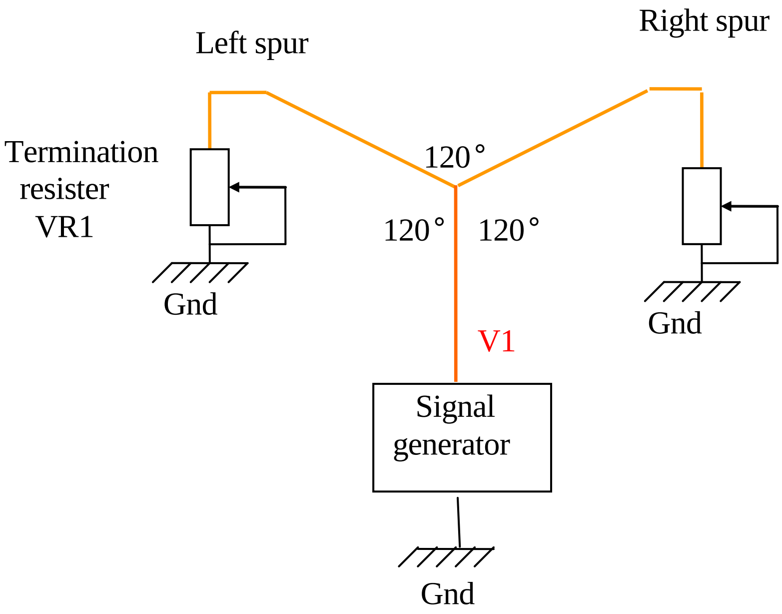


Figure C.3 Track termination resistors

The return signal paths from the track end points to the signal generator used the electrical mains earth cable for convenience. Detecting a junction required additional pickup coils that did not produce any meaningful output during normal track following. When at a junction they both produced a significant signal output from the two spurs. The outputs from the junction coils were fed into signal amplifiers and the outputs were combined. A valid junction condition was obtained only if both junction coil outputs were above a pre-set limit. This helped prevent spurious activation due to general tracking conditions. The orientation of the sense and junction coils was optimised through experimentation and by observing the working performance of the wheelchair.

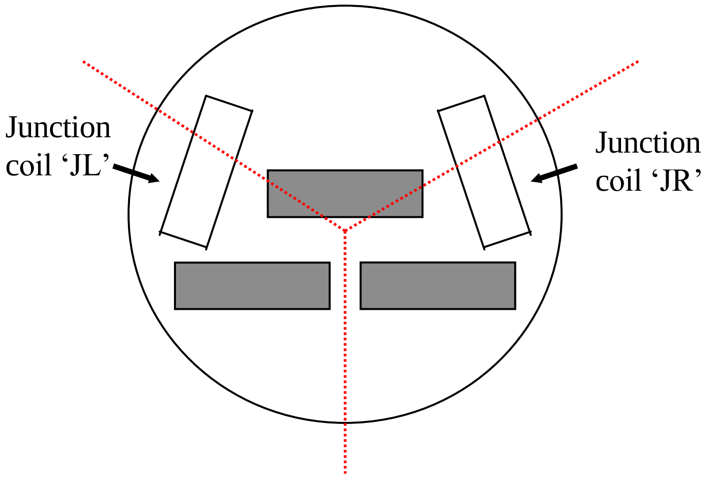


Figure C.4 Track sensor head incorporating junction

Figure C.4 is a representation of the sensor array sitting over a junction. Both of the junction coils were positioned so that they provided a large induced voltage from the track spurs. To provide a stop condition at the junction, the outputs from both junction coils needed to be high.

C.3.1 Detecting a junction

The stopping point over a junction was critical for the system to work reliably. This could be affected by the handling performance of the wheelchair. In addition to problems with overshoot, the sensor position on approach could be slightly 'off-line'. This resulted in improper junction coil alignment with respect to the track signal. Consequently one of the junction coils would not have sufficient induced voltage for the detection of a valid junction. The physical layout of the track junction affected the predictability of system performance. In particular the track lead-in to the junction had to be as straight as possible to allow the tracking system to stabilise (centralise) itself before the junction. This was sometimes difficult due to space constraints within buildings. Approach speed affected the amount of over or under shoot. Problems were noted particularly if drivers stopped just before the trigger point. The momentum of the chair was lost and often resulted in an undershoot. Problems encountered in the first prototypes became the subject of later improvements. When the wheelchair and sensor assemblies had stopped over the intended junction, a decision was required on which direction to take. To proceed the wheelchair driver had to select a turn switch.

The track control system needed to have a pre-defined control sequence when at a junction. Normal driving was 'dead mans handle', (the wheelchair moved as long as the control switch was operated). The exception to this was at the junction when a junction turn switch was operated. This was a timed function in which the wheelchair control system implemented a turn mode to align the wheelchair over the selected junction spur.

C.4 Junction control

After a junction turn had been completed, the sensor should have been positioned within the capture range of the track follower sensors. This was significantly affected by the radius of the spin turn.

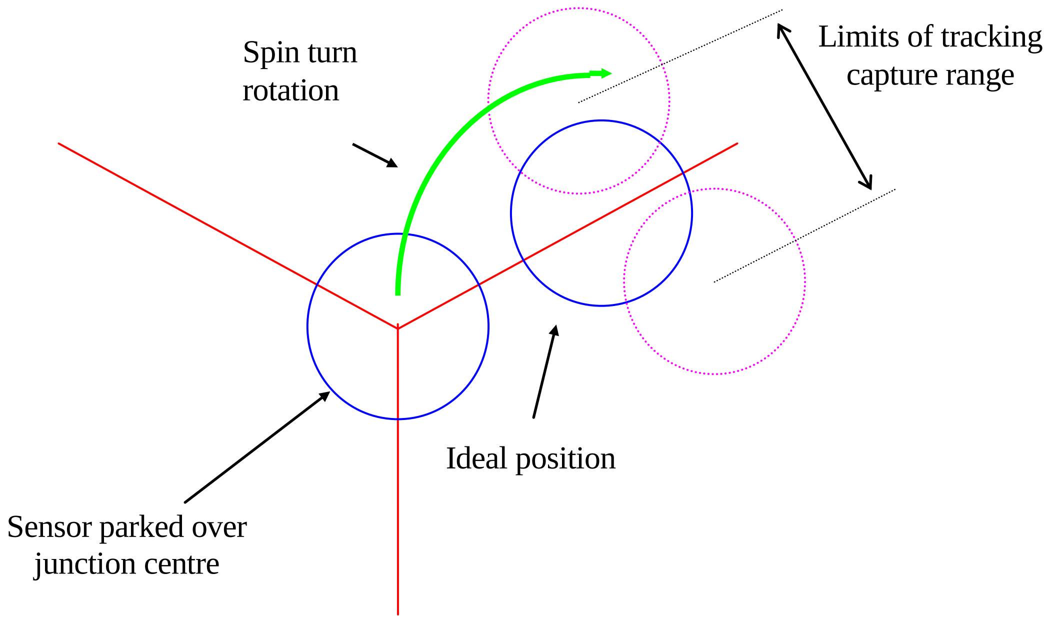


Figure C.5 Junction manoeuvre control

Figure C.5 shows the possible workable sensor position tolerance after a right spin turn had been completed. If the position of the sensor after the junction spin turn was outside of the ‘capture range’ the induced voltages in the tracking coils were too low to provide the necessary control voltages for guidance tracking and the system failed. In practice the junction overshoots were mainly caused by fast approach speeds. To counter this, the deceleration time of the wheelchair was shortened to reduce the over shoot. This produced an abrupt stop when driving at an acceptable speed when the junction trigger point had been reached. Similarly when the user stopped by deactivating the drive switch then the wheelchair stopped abruptly.

C.5 Multi-junction systems

There were fundamental problems limiting the number of junctions due to signal division at junction spurs. When the track conductor divided to produce a junction, so did the tracking signal current. This put a severe limit on the number of junctions.

Early research was mainly targeted at a small group of individuals. During this time, the concept of guided travel for children started to provide opportunities for others who were having difficulties driving or who had not been introduced to powered wheelchair driving before. Further research work was undertaken to expand the number of users on the track and to increase the number of junctions.

C.6.1 Two channel multiplexed tracks

A new multi-junction wheelchair guidance system was created. The new multi-junction system used a different method of signal branching where track signal was time distributed. The spurs of the junction were sequentially energised with a signal level that was set to be equal for each limb of the junction.

A different method of energisation was applied to address the problem of signal division as shown by Figure C.6.

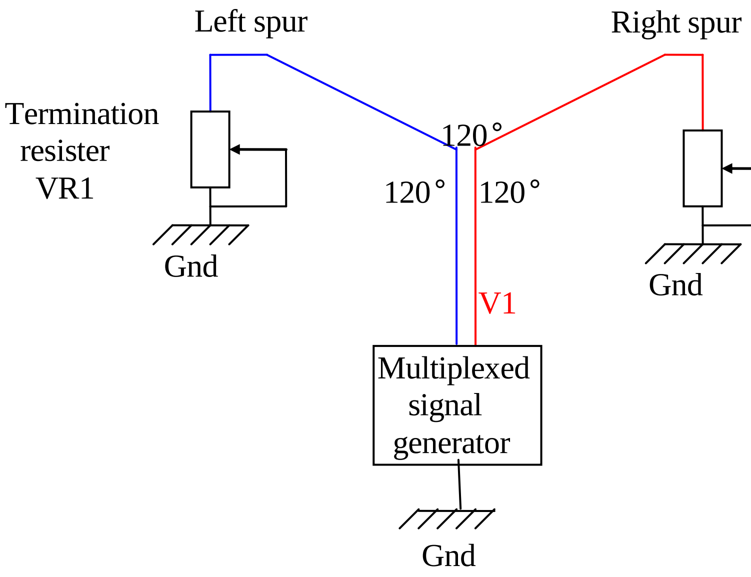


Figure C.6 Multiplexed junction energisation

The signals applied to the blue and red spurs were alternately switched, so only a single spur was energised at a given time. Both spurs were not energised simultaneously and therefore signal division or addition could not occur. The resulting track signal was pulsed. This required a revision in the method of tracking and control for wheelchair systems.

A coded signal multiplexing method was created. The resistance loss related to the length of the track spur was compensated by individual termination resistors.

In the example shown in Figure C.7 the generator sequentially sent out 5 separate binary codes; these have been coloured to represent each binary code. The multi coloured lines show the presents of multiple signals. Each respective line receiver had been designed to respond to a specific code by lowering its line impedance to a pre-set level. The pulsed nature of the track signal updated the tracking detectors for track guidance.

C.6.2 Binary coded multiplexed track

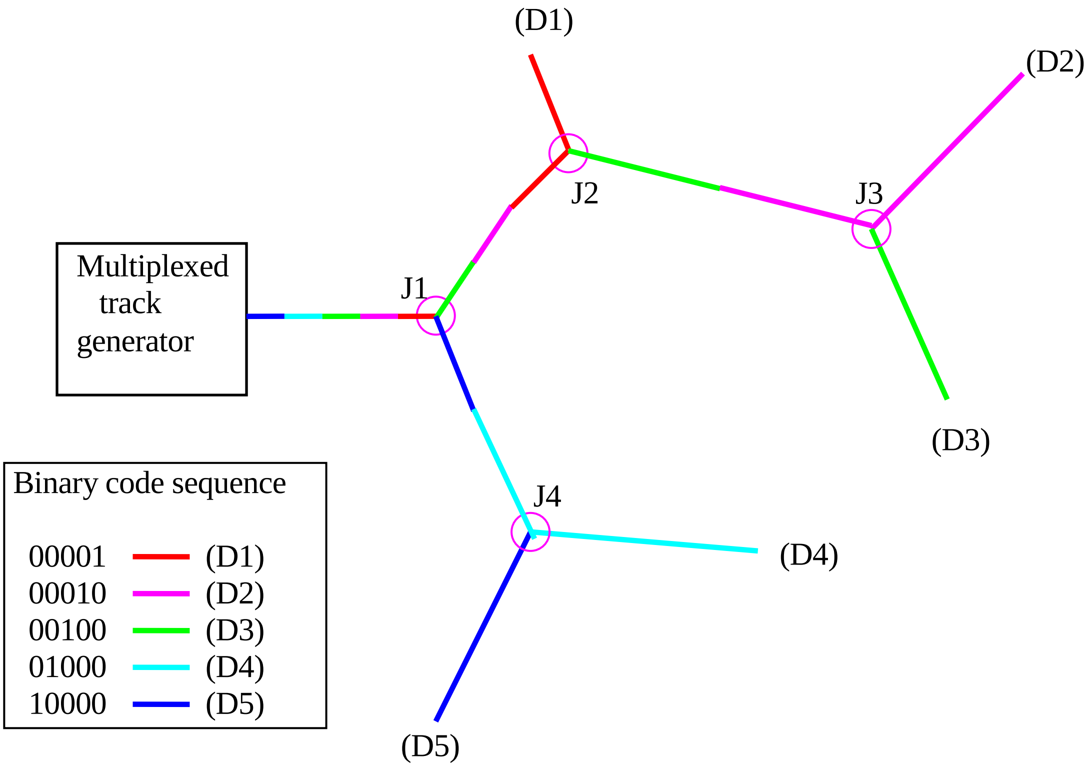


Figure C.7 Coded multiplexed structure

The creation of the new multiplexed track energisation methods required the redevelopment of the tracking guidance system. It was not possible to use the previous track following systems on the multi-junction system, due to the pulsed nature of the track signal. Reliable detection of a track junctions required sample and hold signal processing. A new multi-junction wheelchair guidance system successfully addressed the problem of signal division at junctions. Each section of the track signal remained consistent because the multiplexed signal generator used coded signals to energise each section of the track at the same level sequentially. The track generator coding structure resulted in a pulsed track signal and these put constraints on the minimum track bend radius for acceptable tracking speed performance. The track pulse updated the wheelchair tracking position. Multi-junction track pulse frequency distribution affected the sample rate. Sections of the track system had different track pulse and branch time distribution characteristics. The wheelchair tracking quality would be notably smoother on sections having more pulses per second. The tracking update timing related to the number of pulses that occurred in the branching sections of the track scheme. The lowest number of update pulses per second occurred at the end point destinations of the track and this was the least. Coded multiplex developmental included semi automatic destination seeking. This was not developed but has potential future research work. The coded track signal generator and associated line receivers utilised the existing electrical earth lines within the building to complete the track return circuit. This significantly simplified track installation and reduced the requirement for splitting and making connections of the track conductors to form the junctions. The coded track generator shown in Figure C.8 provided a stable tracking signal, functional control code transmission and the power required by the line receivers. For sine wave generation a waveform generator voltage controlled oscillator (VCO) integrated circuit provided a sufficiently stable output. The remote control encoding and decoding operated with pulse position modulation.

C.6.3 Track driver generator design

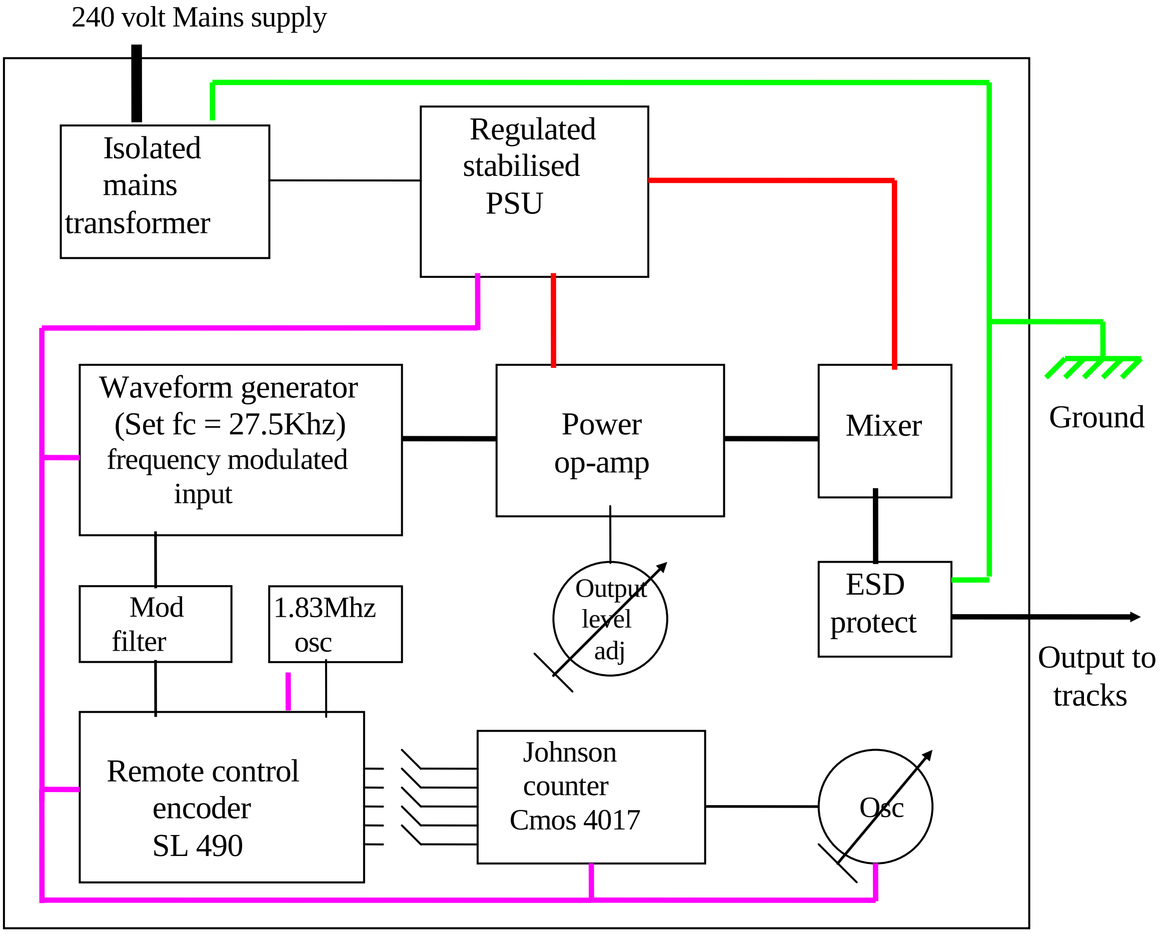


Figure C.8 Schematic of the FM coded track generator

A filter modulation shaping circuit controlled a VCO that provided a frequency modulated track signal on to which pulse position coding was applied. EMC considerations in the circuit design reduced the incidence of track radiated interference to nearby radio receiving apparatus, particularly with the frequency modulated switched track signal. In the track generator, a power operational-amplifier and mixer provided the combined alternating track signal (AC) and the direct current (DC) required for operating the line receivers.

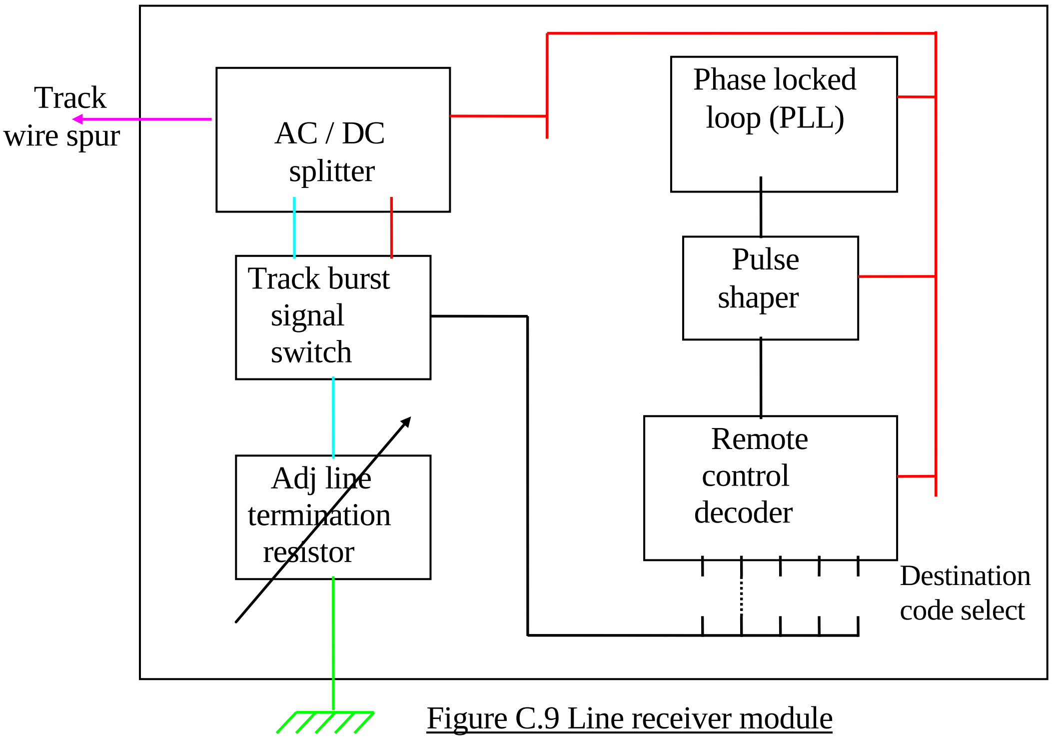


Figure C.9 Line receiver module

The generator coded sequencing repeatedly sent the control codes for each line receiver shown in Figure C.9 (in turn). The DC component of the track line signal powered the line receiver electronics. The phase locked loop (PLL) demodulator extracted the FM modulated remote control PPM codes from the tracking line signal. A pulse shaper circuit converted the PLL output to the correct logic level required by the remote control decoder. The frequency of the track signal switching was restricted by the remote control coding and de-coding time PPM frames. 10 Hz was the practical limit for the switching frequency of each line receiver. The track burst signal width related to three or four valid decoded remote control PPM frames. The track burst signal switching noise caused problems with the FM demodulation and corrupted the PPM codes.

C.6.4 The un-coded track generator

The un-coded track system generator is shown in Figure C.10, superseded the coded generator and did not require line receiver modules. The un-coded generator operated with separate signal return lines and did not use earthed signal returns belonging to building electrics or plumbing. The system was therefore self contained and isolated from electrical earth grounding. The un-coded generator operated with 5 output channels sequenced by a clock timing generator. The output channels were connected to destination points via signal routing cables installed in school buildings. Track signal switching was controlled by modulator burst signal profiling which limited unwanted radiated emissions and switching spikes. The generator incorporated a low distortion sine wave oscillator.

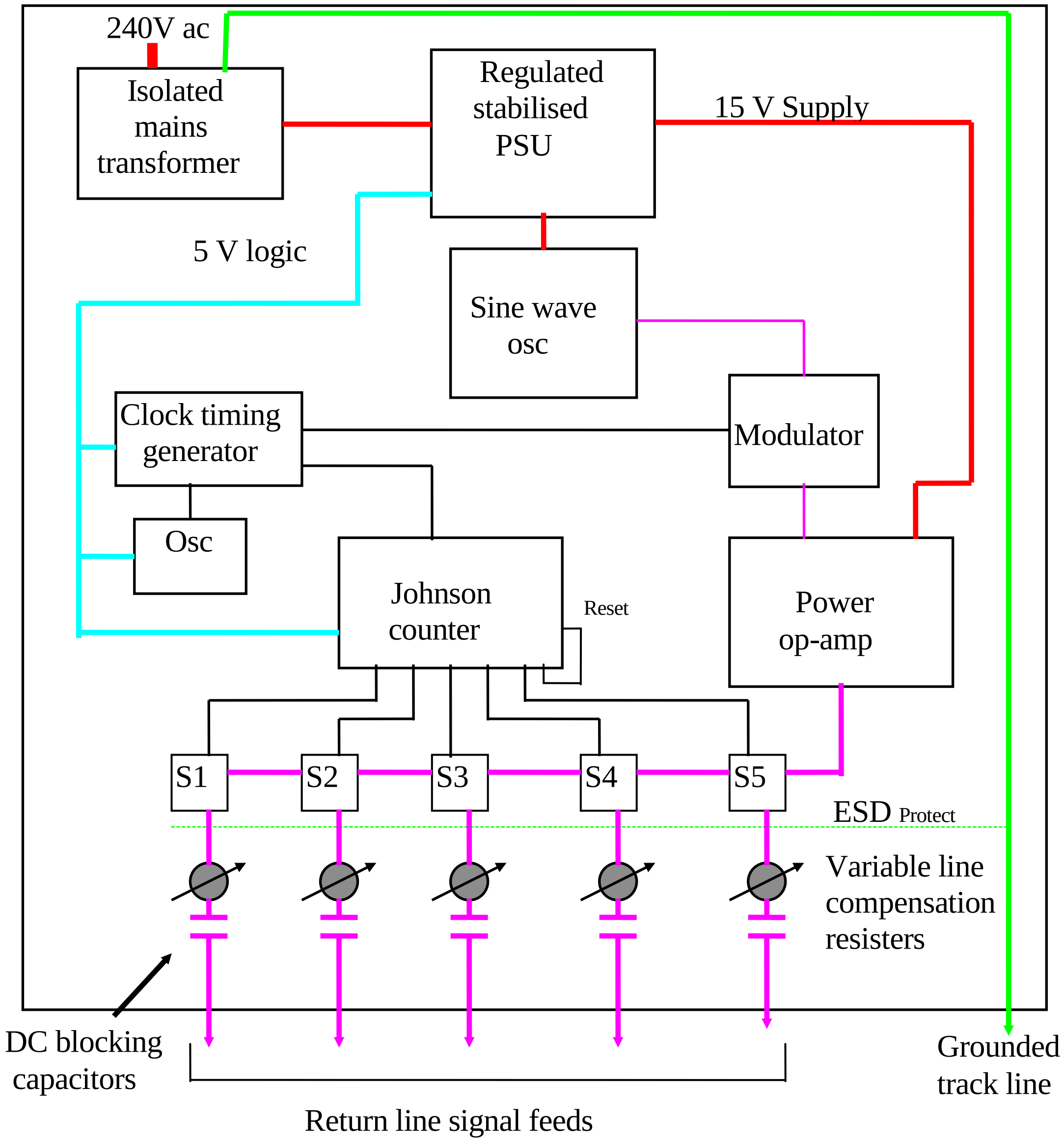


Figure C.10 Schematic diagram of the un-coded track generator

The generator outputs were protected from electro static discharge by transient suppression diodes.

C.6.5 Wheelchair track control

The continuous carrier tracking based wheelchair systems would not operate on the new pulsed multi-junction track system. The inclusion of sample & hold signal processing held the pickup coil voltage levels between track signal pulses was necessary. The signal sampling technique updated the tracking position with every track signal pulse. Factors that affected the gating (sampling period) included the speed of response of the charge capacitor used for signal level retention. Optimizing the rate of response to a fall in the detected pickup signal level improved tracking around bends.

Accurate synchronization of the signal sampling system with the track signal pulses captured the track burst signal level the moment it occurred. The application of a sample and hold circuit to sensor coil designations included the left, right and sensor pickup coils and not the junction detect coils.

C.6.6 Positional tracking

At a junction the distribution of junction signals included track signal busts required by other sections of the track layout. The junctions were symmetrical in terms of the magnetic intensity of the separate signal bursts. Ongoing problems with junction control resulted in the implementation of positional feedback. Pickup signals were referenced against a fixed value so that an overshoot margin could be derived. The system would then implement reverse drive that repositioned the sensor back over the junction. The practical junction detection and system triggering made further use of positional feedback for junction control that spotted selected track spurs and terminated the post junction turn control sequence. The processes of signal extraction from the outputs from the junction sensor coils provided the functions of automatic junction pullback including the pullback start and release triggering process. The system no longer operated on a hit and miss basis.

The applied amplification and filtering provided optimized tracking sensitivity and had sufficient bandwidth to accommodate the frequency modulated track signal. The sensor enclosure shape, size and coil geometry evolved because of available mounting space on the wheelchairs. The effects of ferrous mounting materials close to the sensor head distorted the detection of the tracking signal. Plastic mounting materials reduced the problem, but were not robust. Improvements in the mounting assemblies resulted in an adjustable mounting structure made of aluminum that was physically robust and caused little distortion of the magnetic field. Sensor balance testing could be accomplished by fine adjustment of the sensor mounting. The balance affected how the system performed in terms of symmetrical operation. Out of balance conditions resulted in un-equal tracking performance on left or right bends and possible miss-queuing at junctions. With the growth, particularly, of the external track sections, some users wanted to travel faster. There were problems caused by track following over runs.

The practical method for bend slowdown retarded the wheelchair speed at the initial part of a bend. This used an additional track signal level pickup coil positioned in advance of the main tracking coils. The detected signal would drop, which enabled the slowdown function on the bend approach. The sensor head enclosure was extended to incorporate the optional slow down sensor.

C.7 The expanding system

The continued improvement of one young girl in particular led to the addition of more junctions in the track route to extend her choices of destination. Track guided mobility proved useful and daily routines were set-up to drive from the classroom to the toilet area and vice versa. The first practical application of a junction provided drivers with access to the classroom, toilet and breakfast areas. The guidance system needed additional detectors and control logic for junction detection and control. The stopping point over a junction was critical for the system to work reliably. The physical layout of the track junction affected the predictability of system performance. A dedicated track generator was created to provide a permanent track signal. An essential part of the track systems was the signal return lines. It was found that earth return lines consisted of general plumbing as well as other routes and mains cables could exist under some floor sections. When near the track runs it was noted that signal cancellations occurred causing the wheelchair to stop at these points. During later track installation work it became important to carry out an electromagnetic survey using test track lines to assess any interactions along a proposed route.

A thin PVC hazard warning tape was used and protected the track conductor. When the tracking wire is out of sight, for example under a carpet, surface identifiers were required to visually indicate the track line, coloured round circles over the junctions and a wall map for staff information.

Track following wheelchairs were used for an increasing number of children. At the time of writing approximately 60 young people were driving and 15 of those were using and sharing track guided wheelchairs. Additionally, the amount of track routes around the school increased to provide access via internal and external paths and corridors leading to classrooms, toilets, dinning and living skill areas, nurses, residential bungalows and adventure play areas. At the time of writing approximately 1 Km of tracks had been provided.

The system needed improvements, particularly to the smoothness of tracking and cornering reliability. Although there was a proportional element in the control interface, the system drove in a 'jerky' manner. The speed of driving affected the stability of tracking, particularly along a straight piece of track. At faster speeds there could be problems with smoothness. The weight loading of the wheelchair could affect stability. Mechanical wear in the motor drive system also caused problems, in particular drive slack. This resulted in movement that could not be controlled, and generally became worse with ageing.

C.8 Moving children away from the track

Once children started to demonstrate improved driving competence when using track guidance, the restrictive nature of the track routes became evident. Children wanted to break free of the system constraints, but some needed the benefit of guided support to preserve their personal achievement and self esteem. New research work began to create a system that could enable guidance by detecting the local environment and not relying on tracks. The remainder of this dissertation describes that new research work.

C.9 Summary

The development and application of track guidance system provided opportunities for young people to drive who were not normally given a wheelchair because of their physical and visual impairments. Interestingly many children were motivated to drive and this forced the necessity to create a system that incorporated multiple track junctions to provide track driving within and around the whole school complex.

Drivers who had been advancing their driving skill whilst track driving wanted new driving opportunities but they were not competent to drive an un-guided system to safely reach destinations.

New research described in Chapter 5 provided trackless guided support for young people who wanted to advance their driving opportunities.

Appendix D

The train locomotive, adventure playground and interactive systems

This Appendix describes the practical use of the new knowledge produced as a result of this research described in the previous Chapters.

D.1 Introduction

The creation of track and SCAD systems provided support to help young people drive their wheelchairs with reduced reliance on helpers. A reason for the creation of a track guided train was to motivate individuals to try a new driving activity not centred on wheelchairs; they could exercise personal control and achieve movement through space. The functionality of the train provided an early driving control experience and introduced powered mobility as a fun activity. The train provided a choice of being a driver or a passenger. Drivers could take responsibility for their passengers and the group mobility aspect of the train provided disabled and able bodied young people an opportunity to take part together in a combined activity. This involved turn taking and shared control.

D.2 Multi sensory room

The author was involved in the design and creation of an environment to offer a choice of switch operated devices that could be selected by children. Usually multi-sensory environments had relied on facilitators to setup the child with the necessary hardware in advance to enable an individual to control switches to operate a chosen device. If different choices were required then the facilitator would need to change the set-up so that a different device could be connected. Figure D.1 shows the multi-sensory room built at Chailey Heritage School that was equipped with a range of switch operated devices that could be pre-selected providing up to 16 choices.

Figure D.1 Multi-sensory room at Chailey Heritage School

The multi-sensory room at Chailey Heritage School was equipped with soft padded flooring and light proofing. The author developed a universal control system to enable pupils to operate four selectable devices via a four channel coded radio transmitter module. The multi-sensory room provided an environment in which a child could be taken out of their special seating systems and then be laid on cushions or allowed to crawl of move. Helpers were there to aid the child. This was essentially a static environment. Figure D.2 shows a set of two switches connected to a remote radio transmitter.

Selecting a radio link provided freedom from long connecting wires to the various devices. Radio also offered electrical isolation from mains powered devices. Figure D.3 shows the electrical distribution panel, remote control receiver and the operational control centre that was created and built by the author of this Dissertation.

Figure D.2 Two switch set connected to radio module

Figure D.3 Remote controlled distribution panel

Different switch modes of operation could be selected to suit individual preferences:

- Latched function: (one press = 'On') (next press = 'Off')
- Momentary: Device functioned so long as the switch was operated
- Two switch: One switch activated the device, another switch deactivated the same device
- Time function: The device remained active for a specified time when the switch had been operated and again after the switch had been released
- Combined: All of the devices could be operated with any switch

The multi-sensory room was useful for enabling a child to experience the control of devices in their local environment; but they were heavily dependent on helpers to make selectivity changes.

The new research work described in this Dissertation involved the creation of interactive systems that extended the personal autonomy of young people beyond wheelchair driving. Enabling young people to take control of remote devices coupled with mobility became the focus of new work.

D.3 The Train

A train was an icon of mobility; traditionally a driver was responsible for the transportation of his passengers and therefore had a sense of power and purpose. Associated with this was the responsibility of control. Children could be given an opportunity to be a 'train driver' and transport other children as passengers.

Figure D.4 shows some children experiencing the new train for the first time.

Figure D.4 The first train locomotive trials

The track guided train offered new opportunities for children with complex needs:

D.3.1 Operation by children at different levels and stages of development
D.3.2 Enabling non-disabled and disabled children in a combined activity
D.3.3 Taking responsibility for others
D.3.4 Shared control
D.3.5 Group working
D.3.6 Turn taking

D.3.1 Child drivers at different stages of their development

The train was used by competent and experienced drivers who wanted to try something different from powered wheelchairs. Child drivers acted as demonstrators and this often encouraged first time potential drivers to have a go. The train could be operated by a single switch to control starting and stopping. Junction control select switches were provided so that an operator could select left or right turns at junctions.

A switch input control interface was built that could accept a variety of commercially available switch controls, including custom made controls. Figure D.5 shows the switch control types that were available at the time of writing.

Figure D.5 Switch selections

These control input devices were binary switches (non-proportional) and generally mounted on adjustable structures. Pad type switches were often mounted using Velcro that provided a versatile fixing method, particularly as the movement pattern and motor function exhibited by some children required a subtle and adaptable approach to switch positioning. The use of Velcro allowed refinement of switch position and was a soft fixing. Although Velcro provided adaptability for the short term, there could be problems when the switch position changed through continued use and manual handling. A hard fixing method was used for longer term use once the suitability of switch use had been determined. This involved engineering the switch mounting platform to incorporate clamps and securing bolts in slots and this became a specific switch set that would belong to a user.

D.3.2 Non-disabled and disabled children in a combined activity

The environment in which the train was used had a mix of children due to an onsite nursery. Children from the age of six months to five years were accommodated and looked after by nursery staff. The Nursery was NHS funded and resided alongside Chailey Heritage Pre-school. Many nursery children belonged to teaching and care staff that were employed by the school and were not there for reasons of a stated disability. There were some youngsters that were going be assessed as potential candidates for the pre-school. At the time of writing the youngest acceptable age for pre-school child entry was four years old.

The adventure play area was used as a common resource. The technologically assistive systems were created predominantly for children with disabilities but non-disabled groups were not excluded. When the first trials of the train began, interest was noted from both disabled and non-disabled children and the requirement for multiple seating was identified. With few exceptions, all of the children at Chailey Heritage School were equipped with their own special CAPS (Chailey Adjustable Postural Support Seating) system. An example of an infant and junior CAPS is shown in Figure D.6, and these would be provided and setup specifically for the child's postural support requirements.

Infant CAPS

Junior CAPS

Figure D.6 Child CAPS inserts

The design of the locomotive and the tenders incorporated the mounting assemblies required for specialist seat and non specialist seats or chairs. Children from either group were able to operate the train.

D.3.3 Children taking responsibility for others

The versatility of the seating systems in the train allowed children having different abilities to take part in an activity of driving or being a passenger. A choice of position was offered to the children and some elected to be drivers and some wanted to be passengers. There were also some children who wanted to spectate, although this was often because there was not enough tenders to accommodate all of those who were interested. The number was restricted to three. Some children who had their own powered wheelchair would follow the train, also members of staff would push children in their buggies behind. By observation, this was a group activity.

The driver had responsibility for moving and controlling the train. The driver's actions affected the transportation of his or her fellow passengers. Some children clearly understood what was happening, especially those who were already competent drivers. Non-disabled children could take control of the train to give rides to non-disabled or disabled child passengers. This could be changed so that disabled children could be drivers and assume responsibility.

D.3.4 Shared control

A distributed control system was developed that provided multiple control input points. Aspects of driving control could be separated to allow each child within the train to perform a different control task. The main operator control was the driving switches and these could be separated so that the driver and passengers could take part in a combined activity. Additional control features were added to enable an individual to control of devices in their immediate environment.

Tender buggies were quipped with infra-red transmitters. These could interact with toys and responsive systems in the adventure tunnel as shown in Figure D.7. The path of the infra-red beams has been indicated by the yellow arrows. The infrared beam was detected by a receiver unit that was protected by a low level steel conduit. In this example the light curtain had been activated by the child pressing the switches.

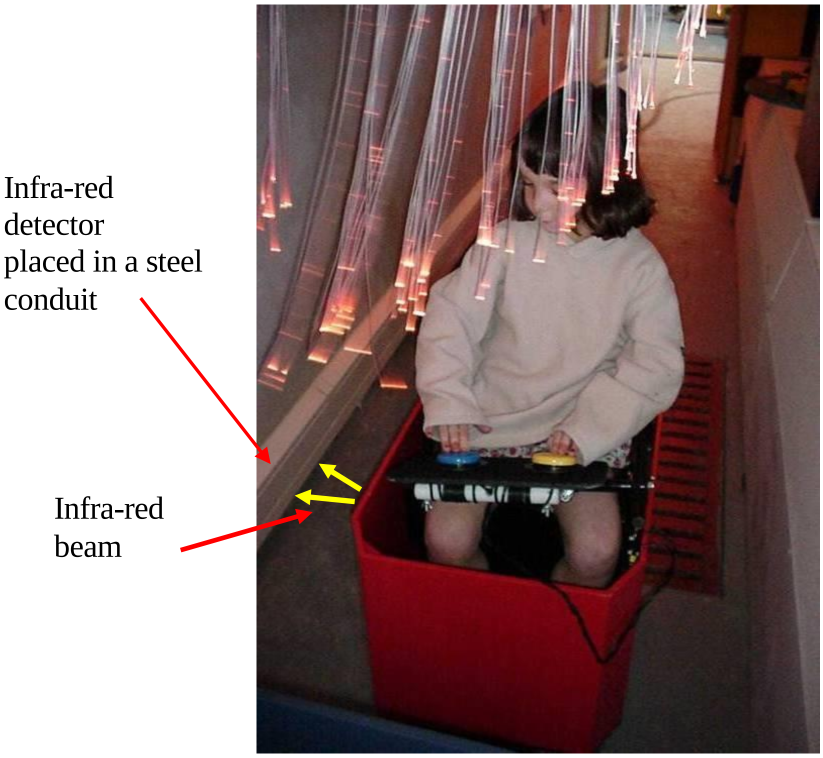


Figure D.7 Tender buggies and the author's daughter testing out the system

D.3.5 Group working

Dividing the control options provided children with the option to control separate functions throughout the train. The driver could be responsible for start and stop control and a first passenger could be responsible for selecting turning points at junctions. The other passengers could be given operational control of environmentally controlled devices. The train included a whistle and a specific individual could be given control over this. The locomotive also included a sound generator to provide a sound of a steam train. This was activated in parallel with the tracking control.

D.3.6 Turn taking

The assignment of the control functions could be changed so that children could be given different control opportunities. The control of driving and additional control options was distributed so that any child on the train system could operate different features. A direct method of switch connection was chosen to simplify electrical connections. The process of loading the children onto the train was time consuming. The switch interface needed to be plug and play to avoid adding extra time to the process. The time taken to ready the train could be three times longer than putting a single child into a wheelchair. An option was provided to override the infra-red switch control input so it transmitted continuously. This triggered the infra-red activated devices when the tender buggy went past without a child having to operate a switch. This was intended to stimulate those who were unaware or did not immediately understand the cause and effect aspect of switch control. The adventure tunnel and playground were created to offer children an opportunity to drive powered mobility devices and to take control of devices in their immediate space. A problem with providing multiple control opportunities had been a requirement for helpers to connect and disconnect the children’s operating switch to the devices. The technology created and described in this Dissertation provided increased autonomy for a child. The choice and number of operable devices being an important factor.

D.4 The adventure tunnel

An adventure tunnel was created to enhance mobility and integrated environmental control resources. The tunnel was three meters wide and eighteen meters long and its purpose was to introduce and establish the possibilities for individuals to control devices in their immediate environment or space.

Figure D.8 A selection of remote controllable devices built into the tunnel

Figure D.8 shows a selection of controllable devices that was provided within the tunnel environment. When a device responded to a control it was important that the responsive device provided direct operational feedback. Devices and features were chosen or developed that provided movement for visual stimulation, sound, hot and cold air streams and aroma discharge devices and a felt sensation. An example of a ‘felt sensation’ was driving over a vibrating platform.

Transponder systems were created as part of this research work to provide a control interface. This enabled standard powered wheelchairs including manual (pushed) wheelchairs to interact with controls via coded infra-red. The design of the train and tender buggies incorporated these interactive controls.

Figure D.9 Environmental (MIC) Mobile Interactive Control

Figure D.9 shows that some of the transponder units needed to be placed in external environments and it was necessary to provide all weather protection for the electronic systems and internal shielding to reduce the effects from direct sunlight.

Track guided wheelchairs provided a means for individuals with complex needs to drive within their environment with greater independence from helpers. Wheelchairs were the most common form of powered transport. This was also the most common stereotype that marked out a person with physical or mental disability. The new train was created to be a fun object and was used to introduce individuals to driving, but also to arouse natural curiosity and to inspire individuals to try a new activity. When guided track systems were developed at Chailey Heritage School it was anticipated that it would be used by wheelchairs. The design and construction of the new train needed to operate within the constraints imposed by wheelchairs as it was not desirable or practicable to alter the existing track layouts.

D.5 The development of a mobile interactive control system (MIC)

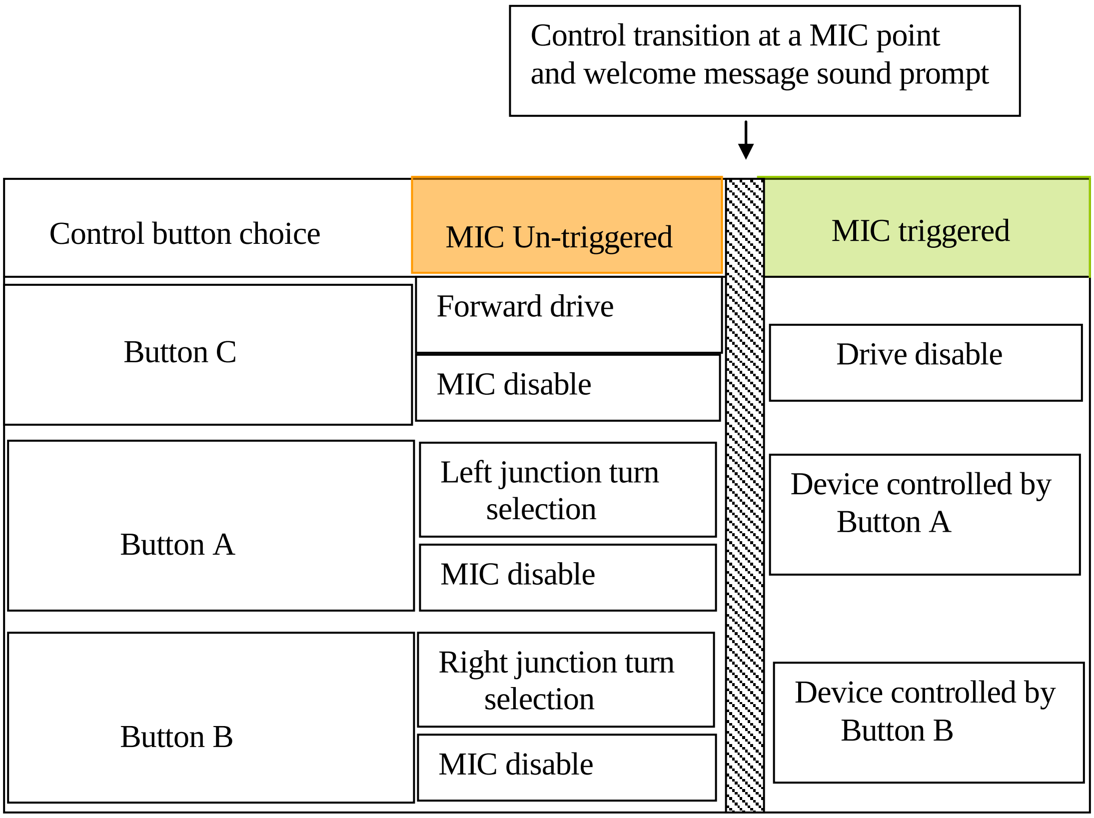
A novel system was created during this research that enabled a change of function between wheelchair control and remote device control when a wheelchair was driven within a specified operating distance of a chosen device. The intention was to offer an opportunity for children to take control and operate more than one device by using their switch. The switch control function changed so it operated a selection of devices. Children varied in their ability to understand the change the switch operating mode. Some children could operate a change of function selector switch and others did not because of their limited physical dexterity or not understanding the process.

An activity arch was constructed to test the notion of combining remote device control and powered mobility. The arch shown in Figures D.10 consisted of a structure with trays having motorized toys placed at a child's eye level. The powered wheelchair was quipped with a mobile interactive control transceiver.

Figure D.10 A young child using the activity arch

When this chair was driven through the arch, an infrared beam triggered the wheelchair to stop. A change of control function occurred at this point.

To help a young person understand the MIC process the numbers of operational stages were kept to a minimum and this has been defined as stages. The first system was developed to operate with a wheelchair using a track following system that was created by the author of this Dissertation [Langner (2004)]. In later work as part of this research, the MIC systems were adapted to operate with wheelchairs using a SCAD system. The physical and cognitive abilities of the young people that used track guided wheelchairs varied. It was necessary to integrate mobile interactive control with driving control as a strategy to enhance independence. The most important aspect was that the children understood when the control function had changed from wheelchair control to device control. Children who were able to operate three separate control switches needed to understand that the switches had dual functionality. The change of function conditions are shown in the table.



Control transition at a MIC point and welcome message sound prompt

Control button choice	MIC Un-triggered	MIC triggered
Button C	Forward drive MIC disable	Drive disable
Button A	Left junction turn selection MIC disable	Device controlled by Button A
Button B	Right junction turn selection MIC disable	Device controlled by Button B

Figure D.11 Control function transition from driving to environmental control

Figure D.11 shows that the switch control function changed at a MIC transition point and the control of the wheelchair was diverted to remote external device control. A sound prompt was triggered with a welcome message at the MIC transition point.

Figure D.12 shows the operational time delay applied when the child wanted to leave the MIC point and resume driving and cease operating the external remote devices.

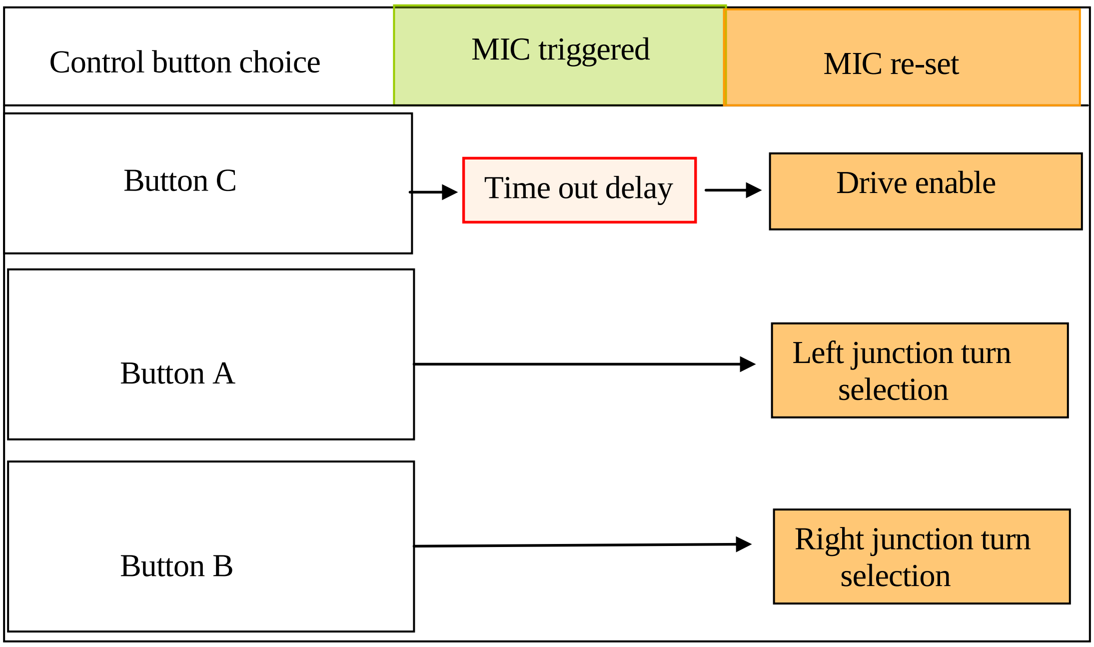


Figure D.12 Returning control to wheelchair drive

There were many occasions when a young person operated a device by pressing the control button, but un-intentionally flicked the forward (MIC disengage control). This triggered the system to drive out of the MIC operating zone. A time out delay was introduced to prevent this. Some children learnt to count down the seconds until the system reverted to drive control and in some cases they had fun with this, but more importantly it helped children concentrate and maintain contact with their controls. This was particularly helpful for sustained driving practice.

It was also necessary to consider a child that did not want to operate a device. For this reason the time delay was adjustable. When children improved their switch discrimination skills, the time delay was reduced and in some cases removed.

When a young person was driving their wheelchair, the operation of the MIC caused an abrupt stop to driving. Sometimes a young driver was confused. The addition of a sound prompt provided a welcome message or chime. This helped the child identify the change of control from wheelchair driving to device control. For example, when at the location of the fan the system announced, “Would you like to operate the fan”. A leaving message, for example, “goodbye” was also provided during the transition form device control to wheelchair driving. The sound messaging system provided reinforcement to the young people to help them make choices. User feedback suggested that the consistency of the message defining an object had helped children to learn, whereas helpers varied their description of the object from one time to another.

Observations of young children using the system showed that when they wanted to drive away from a MIC control point it could sometimes become re-triggered because some young people did not press their drive control for a sufficient time and also due to stray infra-red beam reflections. A hop feature was developed that enabled the wheelchair to clear the MIC point. The system then provided extended drive activation after the transition from MIC control to drive control.

The following diagrams show the operational steps that occurred in order for the control to change from wheelchair control to external device control and returning control back to the wheelchair.

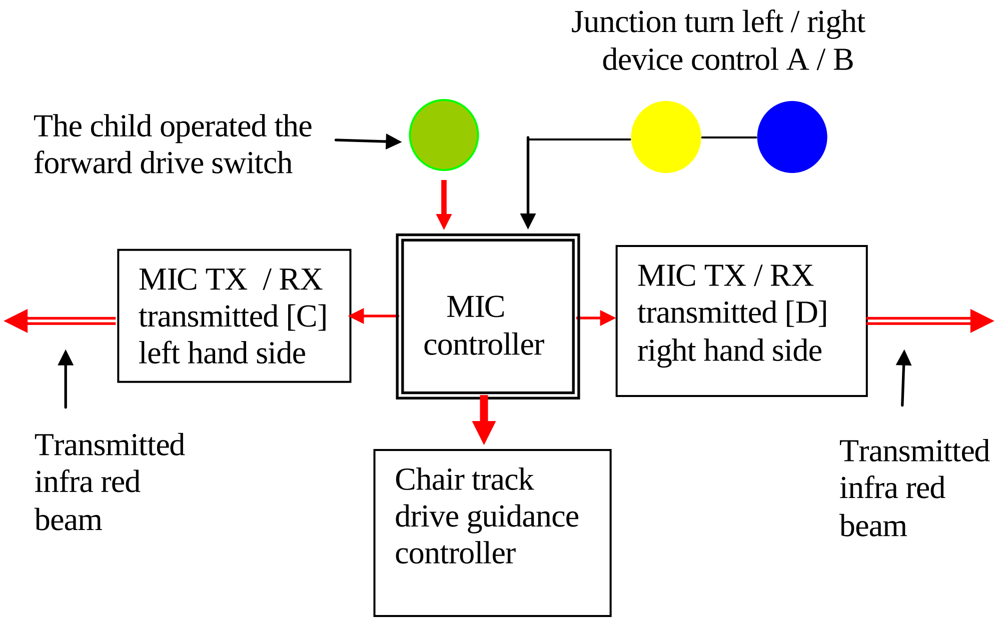


Figure D.13 Stage 1, wheelchair drive mode

When a child operated their forward control the wheelchair moved forward. The MIC system shown in Figure D.13 was operating in the wheelchair drive mode and transmitted separate coded infra-red beams for the left hand side [LHS] and right hand side [RHS] of the wheelchair.

The active components of the system are shown by the red arrows. When the driver stopped pressing their drive switch, the wheelchair drive and the infra-red transmitter also stopped until the driver pressed the switch again.

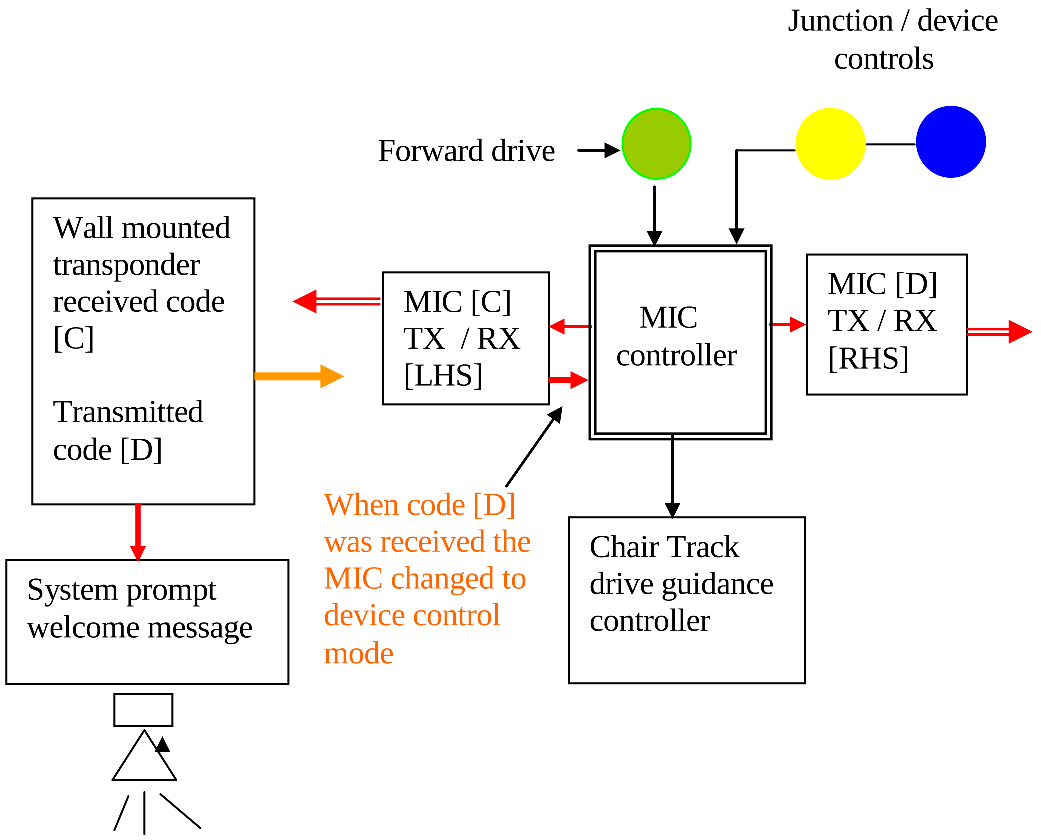


Figure D.14 Stage 2

Figure D.14 shows the system at stage two when the MIC had passed a wall mounted transponder. It was necessary to ensure that the transmitted codes were complimentary, so when code [C] was received by the wall transponder it transmitted back code [D]. This was necessary to prevent false triggering due to direct reflections form objects at the side of the wheelchair. After the wall unit had sent the stop and change of function code, a digitally recorded message unit was activated. This was specific to the devices that were controlled, for example it said, “hello press your yellow switch to control the fan”.

Stage 3 was triggered when code [D] had been received by the MIC system and this is shown in Figure D.15.

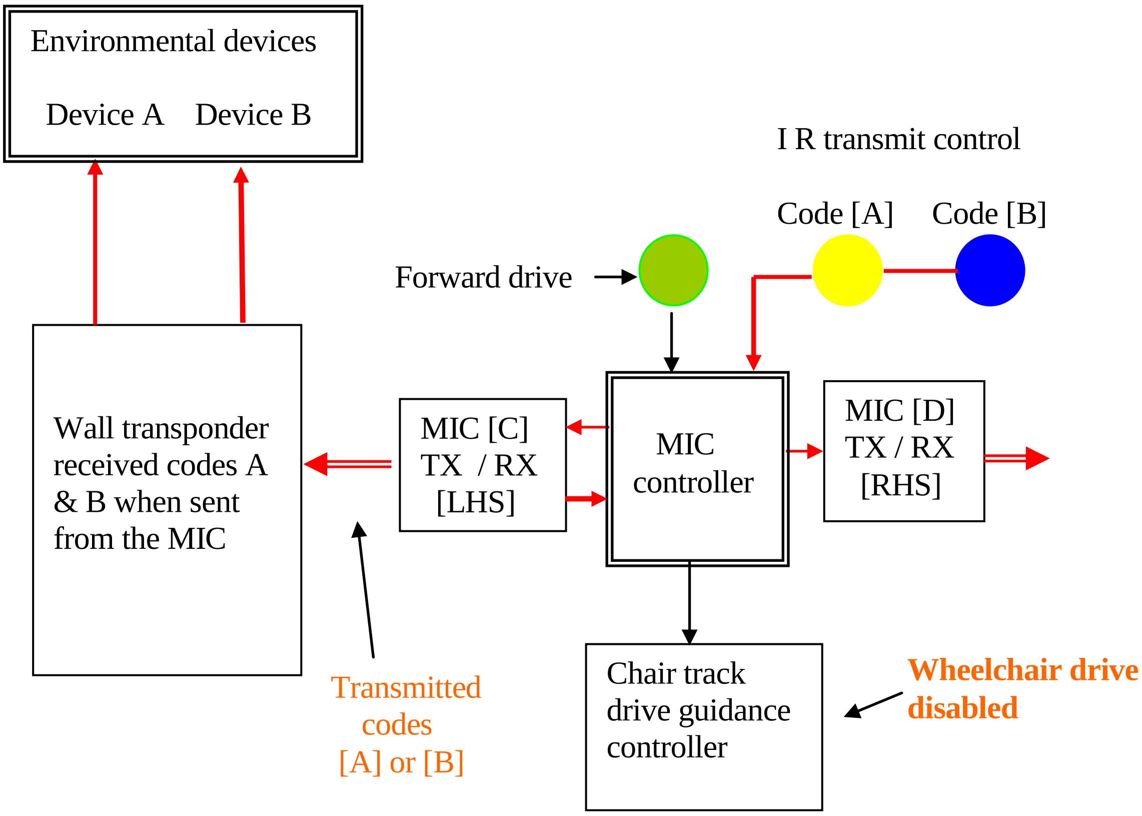


Figure D.15 Stage 3, the MIC had switched to environmental device control

Figure D.15 shows that the MIC had switched to environmental device control. The junction control switches now operated the MIC transmitter and sent codes [A] and [B] when operated by the driver. At this stage all wheelchair drive control functions had been disabled.

Stage 4 is shown by Figure D.16. To switch the MIC back to drive mode and leave the device control point, the forwards control was activated. When the young person wanted to change back to wheelchair drive it was necessary to apply an accidental operational delay period because some children momentarily activated their forward drive control when trying to operate a device. The accidental delay period prevented the system reverting to drive control. This delay could be set between 1- 5 seconds.

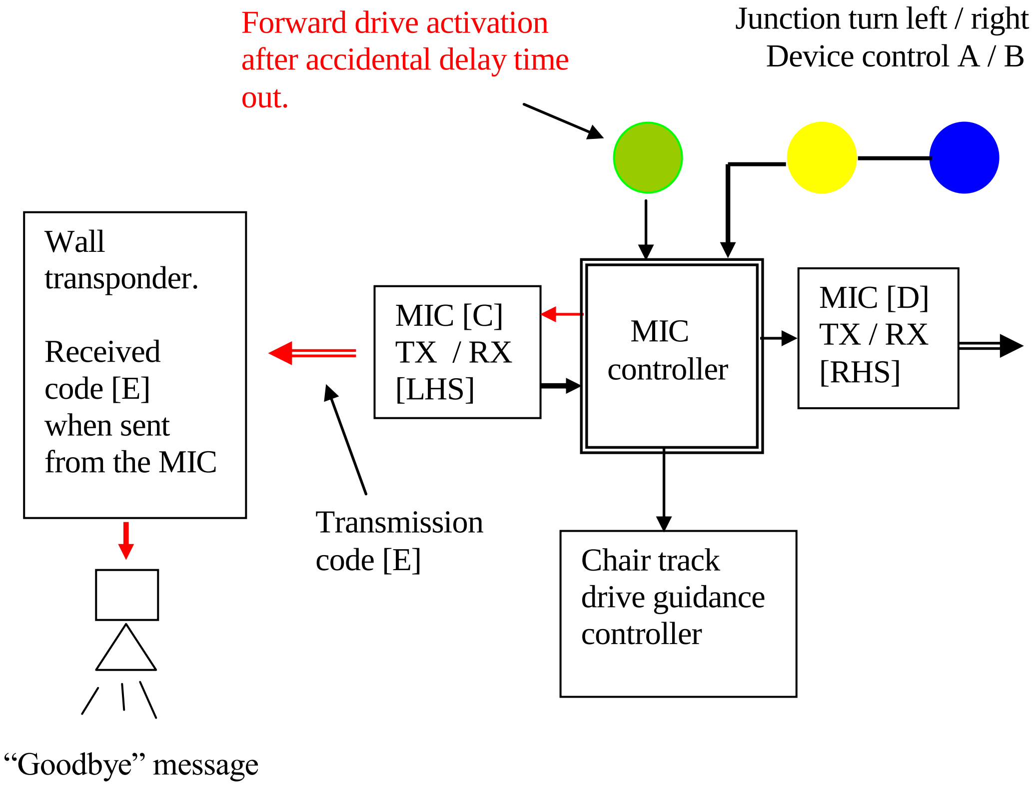


Figure D.16 Stage 4, reverting back to wheelchair control and leaving device control

Some children had learnt to count down the seconds until the wheelchair started to move. The accidental delay was only applied when the MIC reverted to drive mode.

D.6 Bidirectional object control selectivity

The control output from the child's switch was converted from left or right driving control to the transmission of a coded two channel infra-red transmitter. The arch incorporated infrared receivers Rx (C) and Rx (D) as shown in Figure D.17 and the infra-red coded transmitters.

Figure D.17 Coded infra-red transceivers

The arch could be entered from either side. When entering the arch there would be a pair of devices at the front right and front left of the driver. There was also a set of devices behind the child on both the left and right sides. When the change of switch function occurred, it was important to ensure that the correct set of devices were operable, (those in front and facing the child). If a child wanted to operate the second set of devices, he or she would need to enter the arch form the opposite side.

To provide a selection process to take account of a child's orientation with respect to the chosen device, a mobile interactive control was created. Not all children were able to drive powered wheelchairs. Children might be seated in a manually propelled buggy seat or a manual wheelchair. If a child did not have the requirement for motor drive control via switches, the switches could still be used to control devices in close proximity. Small battery operated infra-red two channel transmitters were built to enable a child to engage in all activities.

Pendants were built to be quickly attached to trays used by children in their seating systems. Figure D.18 shows a two channel remote control transmitter pendant being attached to a child's tray. Figure D.18 also shows the pendant in relation to the infra-red transponders fitted into the white low level steel conduit identified by a red dot.

Figure D.18 Remote pendants

The design of the locomotive and tender buggies was intended to be universal for children with special needs. There were practical problems with the seating systems that ranged from the smallest CAPS to junior size II. Each group required a specific seat adaptor PLIB (Passive Locking Interface Board). Three sets of PLIB were required to accommodate the complete range of seating systems. There were concerns from staff that the number of PLIBs caused issues with equipment handling, particularly as there would be three sets of PLIBs. A seating shell was created that could accommodate the different seat sizes in one unit. It was important to reduce the amount of staff time involved in system access when loading and unloading children from the locomotive and tender buggies.

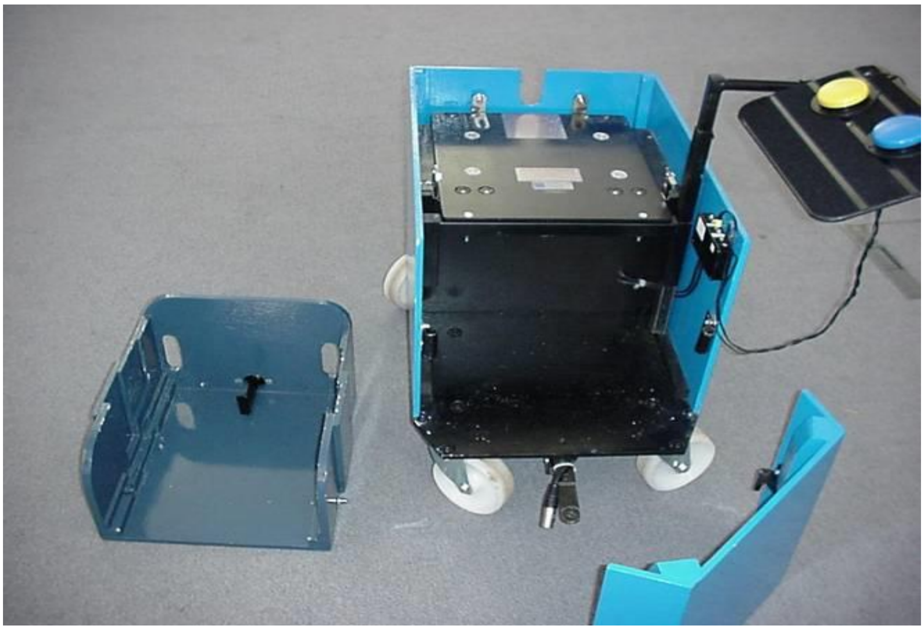


Figure D.19 Buggy open access

Figure D.19 shows a tender buggy with the adaptable seating shell and the front cover removed. A standard child CAPS has been mounted onto the seating pedestal. This accommodated the largest CAPS seat which did not require the shell adaptor. The front cover was secured by pushing it into position and this was held in place by using tapered locking pins. Figures D.20 to Figure D.23 show a range of CAPS within a seating shell including a standard child 14 inch CAPS and a purpose made adjustable padded seat for nursery children. Other considerations included the design of the locomotive and tender buggy surrounding structures which could hinder a child's installation. Removable structures could be heavy or lost. The main shell of the locomotive was constructed out of wood and was hinged at the front end to provide open access to the seating pedestal.

Figure D.20 Mini CAPS B1-B3

Figure D.21 Mini CAPS A1-A3

Figure D.22 Child CAPS II

Figure D.23 Adjustable padded seat for nursery children

The main locomotive body shell was not removable as the front chassis section was not heavy and could tip up. This was due to the necessary weight being concentrated over the rear drive wheels for satisfactory traction and grip. Figure D.24 shows the locomotive in the open position.

The restraining straps can be seen and were necessary to protect the chimney from damage by hitting the ground.

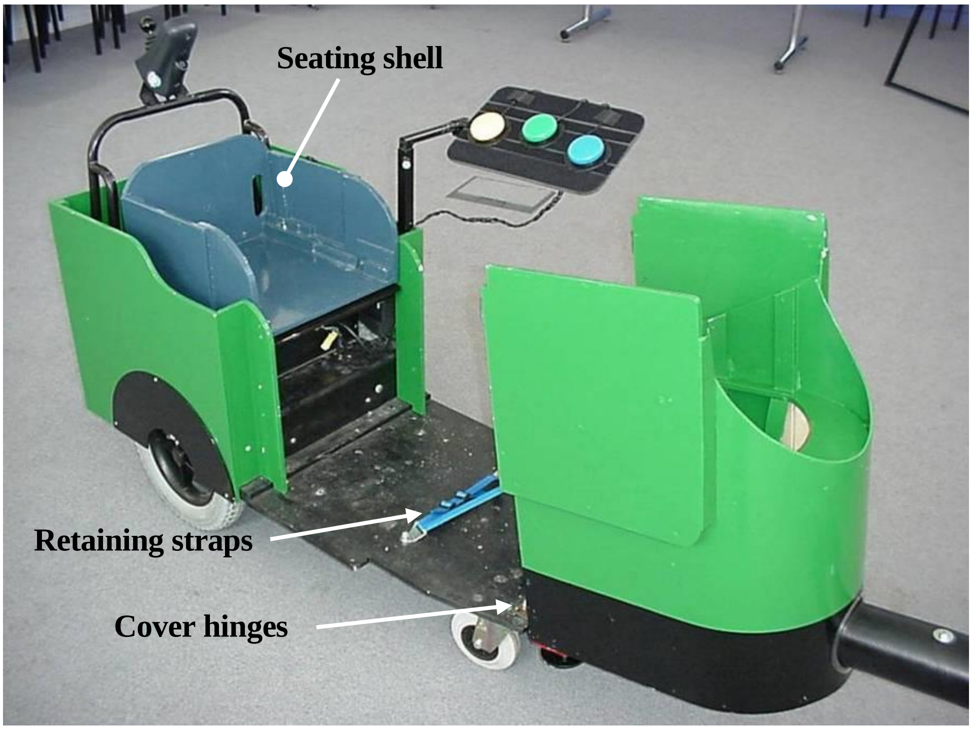


Figure D.24 Locomotive in the open access position

Two options were considered before making the locomotive. Firstly, building a locomotive body shell onto a standard powered wheelchair, or secondly, making a purpose made sub frame and structure. The following considerations were applied to using a conventional powered wheelchair base and building the locomotive bodywork onto it. The extra width associated with the imposition of the body shell. The weight distribution to enable effective traction. The functional position of the coupling tow point, position of the child's seat base within the locomotive body shell. The amount of possible space available for leg room and the aspect ratio of body shell that may cause overhangs. Appearance and the functional wheelbase dimensions of the locomotive body. Many of these issues could not be adequately satisfied and therefore it was decided to build a purpose made sub frame and chassis for the locomotive. Conventional wheelchair motors, power controller and batteries were suitable and were supplied by a powered wheelchair manufacture. This was subsequently equipped with a track following sensor.

A standard wheelchair chassis for a ‘Newton Badger Vixen’ was used for the sub-frame of the locomotive. It was necessary to make changes to the standard wheelchair wheelbase dimensions to take into account the following:

- Effects of multiple loads with passengers in buggies, mis-tracking, overshoot at junctions and role back on inclines
- Drive tracking, weight distribution
- Length to width ratio to provide a realistic locomotive appearance

This was all necessary to minimise any problems when driving along established track routes. Practical assessments were carried out to test for clearances, particularly in the adventure tunnel where space was critical. It was important to try to keep the looks of the locomotive conventional. The body length to width ratio required careful optimisation to allow passage through the tunnel environment and school corridors. Figure D.25 is an outline drawing of the locomotive sub assembly. The green arrow shows the concentration of weight over the drive wheels to provide effective traction, particularly for pulling the cargo load of tenders.

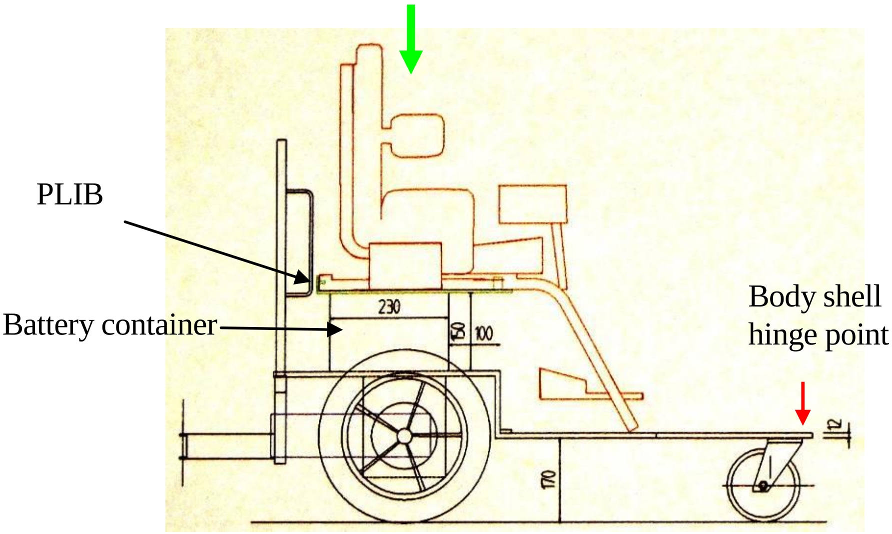


Figure D.25 Locomotive sub-assembly

The drive batteries were contained in the seat box immediately under the PLIB (Passive Locking Interface Board). The locomotive body shell is not shown. The hinge points are indicated by the red arrow. This body hinging provided the necessary counter weight for the front castors. If the locomotive body was removable, then the lack of sufficient weight over the front castors caused instability. Figure D.26 shows the construction of the body shell.

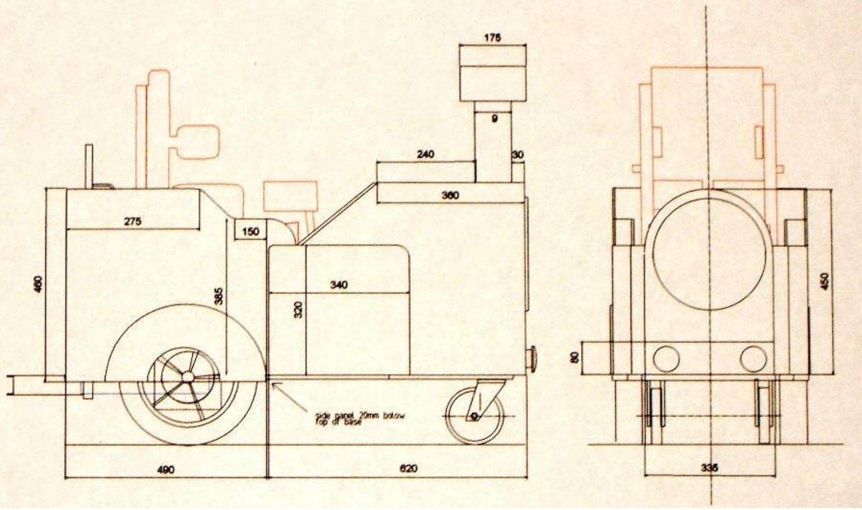


Figure D.26 Locomotive body shell

When the locomotive body was in the operating position, it was necessary to ensure that space was provided to accommodate any trays that a child may require. There were two options for trays.

- The CAPS with moulded tray. This had the necessary tray mounting structures integrated into the seating system
- Locomotive integrated switch tray. The locomotive sub-assembly incorporated a tray mounting support that was independent from the CAPS structure

The locomotive tracking system and control distribution is shown in Figure D.27.
The brown outlined area was constructed from commercially available components that were used for standard wheelchair drive and control. The area marked in green was the track following system [Langner (2004)] and is described in Chapter three of this Dissertation. The additional components marked within the blue outline were included to provide sensory feedback to young drivers and were specific to the train and the control distribution.

D.7 Control distribution

An important new aspect of guided mobility control that was provided through this research was a group centred control activity. In Figure D.27 the blue outlined area shows the inter-connection interface required for switch control distribution. This provided each young person on the train with a control opportunity. Additionally the incorporation of a sound effect generator was linked to drive operation.

The control options were provided by single jack sockets into which switches were directly connected.

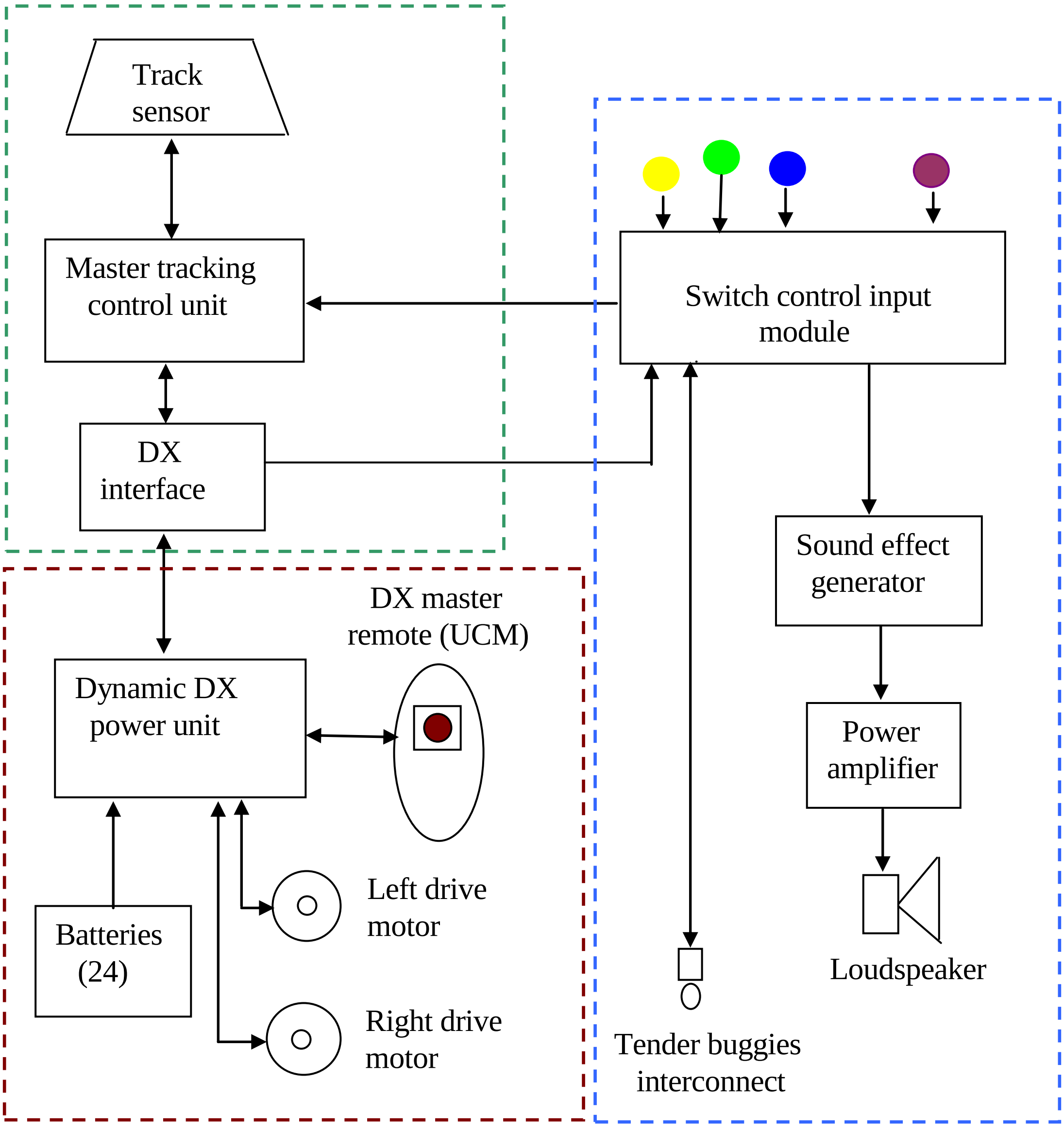


Figure D.27 Tracking control distribution

This enabled young people to control any part of the train system. For example, a child in the rear buggy controlled junction turn selection, whilst a child in the middle buggy operated the whistle and a child in the locomotive operated the drive control. These options could be swapped around according to preference.

D.7.1 Sound effects generator

The sound effect generator consisted of a digital recorder integrated circuit ISD [1416P]. This had addressable sections of non-volatile memory that was used for the sound recordings and could be separately addressed to provide a selectable choice of recorded sounds.

A printed circuit board was made, that incorporated the necessary supporting components, typically a microphone and record playback switching. Unfortunately the ISD recorder was not able to play back two recorded sounds simultaneously and therefore two separate dedicated sound player / recorders were made.

A minidisk recorder was used to make a sound recording of a steam train operating at the Blue Bell Railway. This was edited to provide the characteristic chuffing and whistle sound of a locomotive and then re-recorded onto the digital ISD [1416] recorder chips.

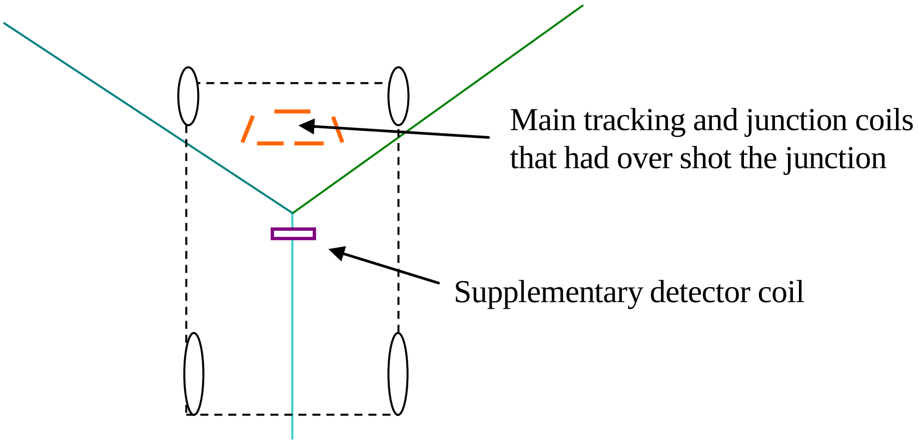
The playback function was looped providing a continuous stream of chuff sounds and this was triggered when the forwards drive control was operated. The sound of the whistle was similarly looped and was triggered by a child in another part of the distributed system. One ISD recorder could not playback the sound of the whistle and chuffs simultaneously.

A printed circuit was made for the digital sound recorders and this incorporated a 5 Watt audio power amplifier to provide sufficient volume from a loud speaker mounted in a space at the front to the locomotive body shell. The outputs from the two ISD recorders were separately adjustable. The sound level of the whistle was set higher than the chuffs.

During trials of the track train it was noted that the loading effects due to the coupling of the passenger tenders sometimes caused overshoot at track junctions. This triggered the carrier fail system to inhibit driving operation. The track control system was primarily intended to operate with standard powered wheelchairs but development of the locomotive and buggies presented some additional operational challenges.

It was not preferable to develop a new tracking control system if the present design was able to meet the need, but modifications were required. The most significant issue was junction overshoot. A supplementary detector coil and signal amplifier was added to detect and provide a carrier holding signal at the point of junction overshoot. Figure D.28 shows the position of the locomotive when it had over shot the junction.

Figure D.28 also shows the position of the main tracking coil sensors that did not provide sufficient detected signal from the junction wires. The supplementary carrier fail pickup coil detected the track signal that maintained and provided the holding signal to enable junction control operation.



FigureD.28. Additional supplementary carrier fail detector coil and signal amplifier

In Figure D.28 the locomotive had over shot the junction and the main tracking coils had became out of limits, at this point the carrier fail trip threshold was above the detected tracking signal level; therefore the carrier fail facility stopped driving.

When the disabling effect of the carrier fail circuit was removed, the junction control system operated. This demonstrated that removing the carrier fail system restored junction control.

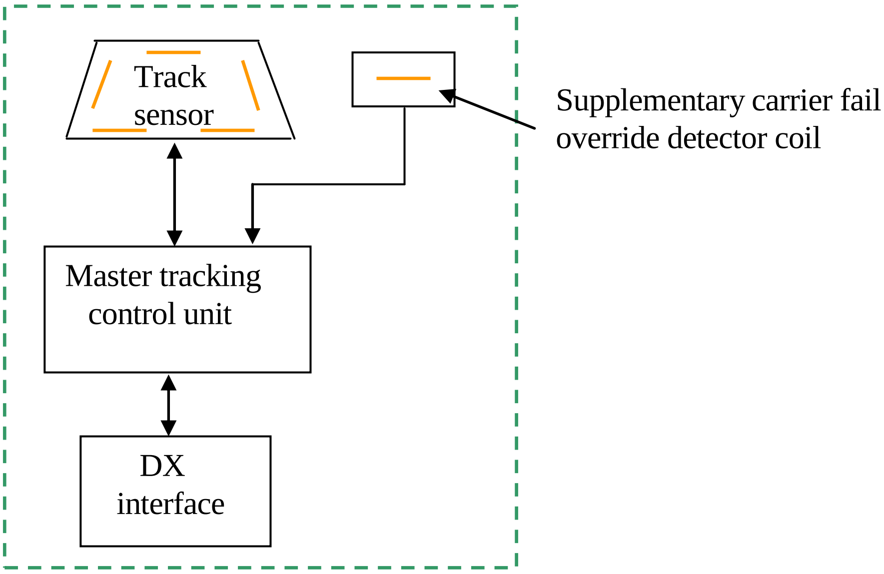


Figure D.29 Modified front end electronics and carrier fail override

The reason for the carrier fail system implementation was to stop the system driving in an un-controlled state if there was no track signal. Figure D.29 shows the additional modified ‘front end’ track and control guidance schematic with the inclusion of the supplementary detector coil.

The amplifier preserved carrier fail function and provided the overshoot carrier fail holding signal for enabled junction control.

D.7.2 Mobile interactive control distribution

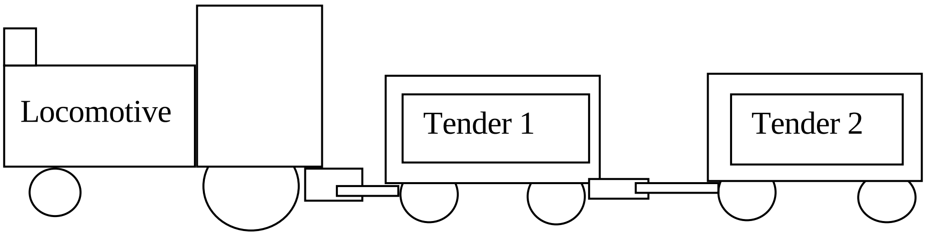


Figure D.30 Locomotive and tender buggy mechanical linking

Locomotive control options

- Forward drive
- Left junction turn
- Right junction turn
- Locomotive whistle

Tenders 1 and 2 control options

- Forward drive
- Left junction turn
- Right junction turn
- Infra-red TX channel 1
- Infra-red TX channel 2
- Locomotive whistle

Figure D.31 Locomotive and tender buggy switch control

Figure D.30 shows the mechanical linking arraignment between the locomotive and the tender buggies. Figure D.31 show how the drive and auxiliary control functions were shared between the locomotive and tender buggies, an in-line connector was provided at the buggy coupling point. Staff and helpers were familiar with how switches were plugged in to devices and computer systems around the school. The locomotive control system connections were made to be in the same format. The locomotive had various connective options so it could be used as a stand alone device, or with one or two tenders attached.

D.7.3 Powered mobility systems incorporating mobile interactive control systems

A standard powered wheelchair was used as an assessment system and equipped with track guidance, SCAD and MIC (mobile interactive control) systems. Figure D.32 shows this chair fitted with a small CAPS seat and assessment switch joystick.

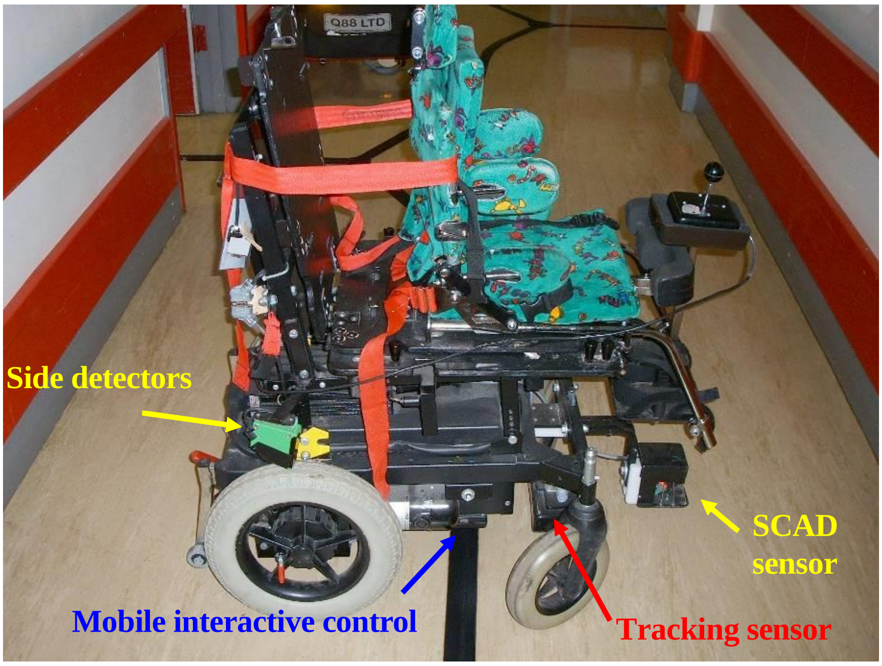


Figure D.32 Assessment SCAD powered wheelchair

Figure D.33 show the MIC printed circuit board and enclosure. The optical cut-out windows can be seen for the left and right hand sides respectively. Optical window slots were cut out of the enclosure to control the field of view and reduce false triggering from adjacent units. Only the left hand side optical devices are shown by the arrows in Figure D.33. The same configuration is used of the right hand side.

The infrared photo diode was set back from the transmitting infrared LED to reduce unwanted detection of the transmitted infra red.

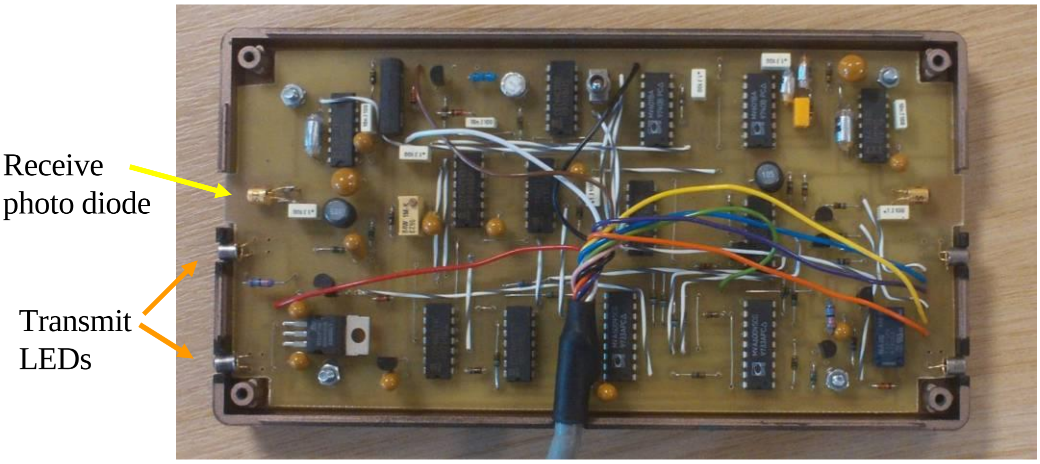


Figure D.33 Mobile MIC unit

It was necessary to incorporate two transmitting LEDs to provide advanced triggering for the infrared wall units to help reduce wheelchair overshoot.

D.7.4 Power stander mobile base unit

The power stander base unit was developed to offer children guided powered mobility in a functional standing position. A standard Chailey type stander could be mounted onto the platform. The power stander base unit was equipped with a track following guidance system [Langner (2004)]. It was also equipped with a MIC (mobile interactive control system). Children could sometimes operate their switch controls in a different way when they were setup in a standing position. They were supported differently when they were seated.

The child had a higher view when standing and this could change a young person’s outlook and perspective, particularly when they had an element of personal movement control.

Figure D.34 Power stander base

Figure D.34 shows the power stander base used with a ‘Chailey Child Size’ stander secured by straps. The child can be seen operating the green drive switch, which controlled forward track driving. To integrate the drive control function and environmental control, a MIC unit is mounted at the front of the mobile base unit. Fixed behind the MIC unit is the track following guidance sensor. Figure D.35 shows a child operating the waterwheel when the MIC changed the mode of function to device control. The infra-red transponder unit was built within a white box and can be seen fixed to the pond wall adjacent to the child.

Figure D.35 Power stander mobile interactive controls

The adventure tunnel and playground enabled children to control their powered wheelchairs, mobility platforms and take control of devices in their immediate environment and significantly reduced the need for helper intervention.

D.8 Summary

Track and SCAD systems provided support to help young people drive their wheelchairs with reduced reliance on helpers. This Chapter described the creation of interactive systems intended to extend a child's personal autonomy beyond guided and SCAD assisted wheelchair driving. A reason for the creation of a track guided train was to motivate individuals to try a new activity not centred on wheelchairs. Drivers took responsibility for their passengers and the train provided a choice of being a driver or a passenger. The group mobility aspect of the train also provided disabled and able bodied young people an opportunity to take part together in a combined activity. Disabled children could take control of the train to give rides to non-disabled child passengers. This could be changed so that non-disabled children could be drivers and assume responsibility. Enabling young people to take control of (remote) devices associated with mobility became the focus of new work. The train was operated by a single switch to control starting and stopping. Junction control select switches provided operators with a left or right turn selection. A switch input control interface was built that accepted a variety of commercially available switch controls.

The technologically assistive systems were created predominantly for children with disabilities and non-disabled groups were included. The versatility of the seating shell systems that were built for the train allowed children having different abilities to take part in the activity of driving or as a passenger. An adventure tunnel and playground was created. This offered children an opportunity to drive powered mobility devices and to take control of devices that were nearby. The technology created and described in this Dissertation provided increased child autonomy. The adventure tunnel introduced and established possibilities for individuals to control devices within their close environment or space. A novel system was created that enabled the change of function between wheelchair control and remote device control when within a specified operating distance of a particular device. This provided an opportunity for a child to take control and operate more than one mode by a single switch. An important aspect was that the children understood when the control function changed from wheelchair control to device control and many children demonstrated this understanding.

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