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Improving wheelchair-driving using a sensor system to control wheelchair-veer and variable-switches as an alternative to digital-switches or joysticks

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Text - Abstract

Structured Abstract Page

Purpose

Powered-wheelchair transducers and systems are presented that provided more control, reduced veer on slopes, and improved energy conservation, while reducing effort. They are especially significant for people with movement disorders who lack sufficient hand-grasp and release ability or sufficient targeting skill to use joysticks.

Design/methodologies/approach

Laboratory test rigs were created to test the proportional switches and to teach potential users. Then a rolling road was created and trials were conducted with the road and real situations. Caster angle measurement was selected to provide feedback to minimize drift away from a chosen course and an electronic solution was created to match driver control to caster steering position. A case study is described as an example.

Findings

Results and advantages are presented from changing from using a set of digital-switches on a wheelchair to a set of new variable-switches and then adding a sensor system to prevent veer on slopes. The systems have been tested for more than 18 months and shown to assist powered-wheelchair users with poor targeting skills.

Research limitations

The research used typical wheelchairs with caster wheels but systems could easily be used on other wheelchairs.

Practical implication

Simple input-devices are presented that isolate gross motor function and are tolerant to involuntary movements (proportional-switches). A sensor system is presented that assists users in steering across sloping or uneven ground.

Originality/Value

The proportional-switches and sensors were shown to reduce veer and to provide more control over turn and forward speed and turn radius while reducing frustration and improving energy conservation. The simple and affordable systems could be created and attached to many standard powered-wheelchairs in many organisations. . The powered-wheelchair users became more independent when using the new systems.

Key words: Assistive technology; mobility; self-help devices; wheelchair; joystick; electronics; transducers.

1. INTRODUCTION

This paper presents simple systems to enable people to begin using powered-wheelchairs and to become more independent. Advantages are presented of changing from using a set of digital-switches on a powered-wheelchair to a set of new variable-switches. The work is then extended by adding a sensor system to prevent wheelchairs from veering off course on slopes. These improvements are especially significant for people with movement disorders who lack sufficient hand-grasp and hand-release ability or sufficient targeting skill to use joysticks. Instead, simple variable input-devices are presented that isolated gross motor function and that was tolerant to involuntary movements.

Interacting with the variable controls was a success for several students but problems with the common caster-wheel configuration repeatedly occurred when a wheelchair was driven along sloping ground because the casters tended to swivel in the direction of the slope and gravity caused the wheelchair to start an unwanted turn or ‘veer’. The driver usually sensed this and applied correction to counter this veer. This caused extra work for the driver as the chair went in an unintended direction. This situation was exacerbated for digital switch users, as switches could not provide fine control to trim and compensate for veer. Switch users frequently needed to hop between directions and forward control switches to maintain the intended direction. Wheelchairs could also veer when driven over a flat surface. This could 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 could electronically trim and compensate so that a chair could hold a straight direction on level ground, however they would not automatically correct for changes in wheelchair loading and sloping ground effects.

To correct the problem, a sensor system was created that assists powered-wheelchair users in steering across uneven or sloping ground without veering off course. Several systems were considered to model the environment around the wheelchair (Sanders, 1995a; Stott, 2000b), predict terrain ahead of the wheelchair (Urwin-wright, 2002 and 2003; Stott, 2000a), use artificial intelligence systems (Sanders, 1999, 2000a and 2000b; Tewkesbury, 1999a) or machine intelligence (Hudson, 1997, Sanders 1996 and 2008b; Tewkesbury 1999b) or to plan paths for the wheelchair (Goodwin, 1997; Sanders, 1995b). These all could have worked but were rejected as too complex and / or to expensive for this application. Other researchers had also investigated the use of safety restraints to assist in wheelchair use (van Roosmalen, 2005) but it was considered better to investigate ways of assisting users in steering their wheelchairs to keep them safe.

Caster angle measurement was selected to provide feedback to minimize drift away from a chosen course and an electronic solution was created to match caster steering position to driver control. Both the variable controls and the sensor systems have been tested for more than eighteen months and shown to assist powered-wheelchair users with poor targeting skills.

The paper begins with some background to discuss the way that engaging in an active lifestyle is beneficial for maintaining quality of life (Pate RR, 1995) and especially the way that a powered wheelchair can help towards providing that lifestyle for some people (U.S. Department of Health and Human Services, 2000). After that, the paper explains the systems and goes on to describe testing and a case study. A rolling road was created to test the systems. That was used as an assessment tool and trials were conducted with both the test-bed and in real situations. The new proportional switches and sensors were shown to reduce veer on slopes and to provide more control over turn and forward speed and turn radius while reducing frustration and effort and improving energy conservation; for example, by avoiding switch-hopping. That was similar to the systems recently created for fork lift trucks (Sanders, 2008a).

The research involved the creation of simple and affordable systems that could be attached to many standard powered wheelchairs and that could be constructed or replicated in the laboratories and workshops of most medical institutions. The simple and affordable systems could be created and attached to many standard powered-wheelchairs in many organisations but examples described here are for common powered-wheelchairs that steer by having two swivelling caster wheels.

To avoid subjectivity in the results, 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. All tests and studies were conducted with the approval of the appropriate ethics committees at the University of Portsmouth and Chailey Heritage.

2. BACKGROUND

Independent mobility such as crawling, walking, and running is 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 completed a study to measure the effects of individually prescribed wheelchair systems (Trefler, 2004). 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 (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 possible in wider society (Brandt A, 2004). The transition to a powered wheelchair enhances occupational performance, competence, adaptability, and self-esteem for persons with severe mobility impairments (Buning 2001).

As wheelchair technology becomes increasingly sophisticated and complex, so do decisions regarding the type of wheelchair that people are able to obtain (Hubbard SL, 2007). Evaluating the use of powered wheelchairs is important because of the increasing number of people with disabilities who have access to one (Pettersson I, 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).

The control interface is one of the most critical components of a powered wheelchair (Cooper, 2000a). There is a patient population for whom mobility is severely limited if not impossible given currently available power wheelchair control interfaces (Fehr, 2000; Langner, 2008). 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 can reduce or prohibit control over a powered wheelchair (Cooper, 2000b).

Pellegrini described how changing interfaces could dramatically improve performance (Pellegrini N, 2004) and the initial research described in this paper created 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 at Chailey Heritage indicated that 9 to 10 percent of residents who receive powered-wheelchair training found it difficult or impossible to use their wheelchair for daily living (Fehr L, 2000).

Dicianno reported that an estimated 125,000 Americans (with movement disorders that preclude independent mobility in a powered-wheelchair) could benefit from improved control devices (Dicianno, 2006). Woods wrote a short history of powered wheelchairs (Woods B, 2003), a survey of wheelchair providers was completed by Guerette (Guerette P, 2005) and a survey of wheelchair-use by residents of nursing homes was completed by Fuchs (Fuchs RH, 2003). These are included as useful further reading.

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

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

Krishnamurthy suggested that some people who cannot achieve fine enough movements to control a joystick with their hand may be able to use their tongue(Krishnamurthy, 2006), Gosain suggested foot control (Gosain, 2007), and Taylor suggested head movement (Taylor, 2003). Langner (2004) suggested using a track system, Goodwin and Stott suggested navigation systems to assist (Goodwin, 1997; Stott, 2000a), Begasa-Suso discussed human computer interaction (Bergasa-Suso, 2005) and Sanders listed some force sensing systems that might help (Sanders, 2007) … but in practice simple switch input devices have tended to be used; often digital (on-off).

The initial research work aimed to explore methods and ideas to help users to derive a sense of proportionality within a digital switch medium by introducing proportional switches. Once the proportional switches had been successfully incorporated then a new problem became apparent. The new wheelchair users were finding it especially difficult to steer their wheelchairs across sloping ground without veering off course. A new sensor system was created to address that problem.

Wheelchairs generally steer by having two swivelling caster wheels. This simple system provides manoeuvrability. The drive wheels rotate at speeds determined by joystick operation. To go forwards in a straight line then 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, 1986; Sanders, 2008a). 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.

Gaal stated that aspects of wheelchair stability, particularly the effects of wheelchair configuration are important (Gaal, 1997). 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, although some studies report advantages (Brubaker, 1986). More recent studies suggest little or no advantage with cambered wheels to improve veer (Buckley, 1998), although Trudel suggested that camber could improve manoeuvrability and stability on a side slope (Trudel, 1997) and recent results of user preference surveys appear to support this finding (Perdios, 2007) 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, 1994; Trudel, 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, 2001; Ruggles, 1994; Brubaker, 1986; Reid, 1990; Rudins, 1997). 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 (Webster, 1988).

3. PROPORTIONAL SWITCHES FOR POWERED-WHEELCHAIRS

Powered wheelchairs are normally supplied with a proportional joystick but that could be replaced with the new proportional switches described in this paper as they also enable a user to control speed and direction. A small amount of joystick movement or pressure on a proportional switch in the selected direction and a wheelchair would start a gentle turn in that direction. If the driver applied more joystick movement then the wheelchair would turn more sharply. Similarly for speed, when a joystick was progressively moved forward or more pressure placed onto a variable switch then a wheelchair progressively increased speed.

A switch can provide:

- A simple input device in the first instance that is 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.

Fifteen potential powered wheelchair users were provided with some proportional control over a period of a year. If they did not use any of the proportional range but instead only operated at the extremes (flat-out or ‘off’) then they were not considered to have sufficient graded control to allow them to operate the new proportional switches.

For the twelve users able to use a proportional range, 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; however 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, how hard you brake is controlled by depression of the brake pedal, 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 then timing becomes more crucial so consideration was given to methods that might be used to introduce some proportionality (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 with switches it was necessary for wheelchair users to develop timing skills. For example, switch users controlling their wheelchairs only tended to use a fixed speed for a given time. People don't always want to go at one fixed speed because driving situations can change. Speed selection by a wheelchair driver using switches is possible; however it has to be set in advance. There are situations where time constraints do 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. Conversely a proportional control driver could seamlessly change the wheelchair speed without stopping.

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 proportionality within their movements and this area of work could help to train them to exercise graded control and develop a sense of proportionality.

Some complicated Human Computer Interaction Systems (Sanders, 2005) and some Virtual Reality Systems (Stott, 2000a) were available for training but these were complicated and expensive. Cheaper and simpler devices were available that could be produced in most organisations and that responded in a variable way so that tests could be conducted to discover if potential system users could change parameters in response to movement. 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. Figures 1, 2, 3 and 4 show how the image changed in relation to varying control (as the control was progressively pressed down from figure 1 to figure 4). The image disc could be changed to provide, for example, a colour spectrum. Other systems used included an electric light with a potentiometer so that the brightness changed and different discs that changed colour or increased the size of objects in response to movement.

Figure 1 here

Figure 2 here

Figure 3 here

Figure 4 here

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 can increase or decrease the amount of control movement to widen out the band of proportionality. Technically ‘high-end’ contact-less systems can be too vague and undefined for some people. The work described here aimed to create a new control that looked like a switch that people were familiar with (or perhaps had already been introduced to).

The new proportional switches were easier to operate than a joystick but for the first time, provided a similar input device that isolated gross motor function for users with poor targeting skills and involuntary movements. Control directions were separated but provided immediate control output to a responding device. These variable switch controls (vari-switches) were a new development for controlling powered-wheelchairs.

The vari-switches 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. Generally the only medium through which proportional (graded) control is given is by a joystick. A joystick tends to have a set movement span and often the control area is confined to within only 9 Sq cm. For those with physical impairments this can be difficult to manage, where in particular, holding the joystick control knob can be difficult, challenging and unreliable. The vari-switch can be placed in similar operating positions to those used by standard switches. Through the introduction of variable control, some users have been able to learn, distinguish and exercise progressive control. Vari-switches still retain the virtue of switch operation, enabling combined functions (for example driving and computer or environmental control).

Figure 5 shows a typical simple paddle switch used by students at Chailey Heritage School. This is shown in the Off position. The main armature consisted of a high impact polystyrene vacuum formed cover and the switch base plate was made of Delrin. When the switch is operated the cover acts against the micro switch lever arm as shown in figure 6. The return spring provided sufficient return force to ensure the switch deactivated when not pressed.

Figure 5 here

Figure 6 here

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 magnet attached to its underside as shown in figure 7. The angle of cover movement was increased to provide the required movement span for graded control. Figures 7 and 8 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 7 here

Figure 8 here

To enable the variable control to operate a powered wheelchair it was necessary to provide an appropriate signal to a wheelchair power controller. A variable control interface was built 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.

4. WHEELCHAIR-VEER

Early experiments showed that carefully setting up wheelchair control for straight line balance and optimizing motor compensation was not enough. Young people expend considerable energy, become frustrated and could end up crashing as a result of un-controlled wheelchair veer and for this reason it was considered dangerous.

Most wheelchair drivers reported veer problems with their wheelchairs and figure 9 shows a young person trying to control his veering wheelchair. This might be corrected by control programming; however 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.

Veer problems were still reported even when a 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. 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. In many cases a wheelchair could become un-drivable due to problems with veer. 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 level of caster-drag. Wheel slip could also be a problem on even mild slopes (up to 5°) and could contribute to loss of control.

Normally a veer would be detected by a wheelchair driver using visual sensory input (eyes), processing control (human brain), bio mechanical interface (muscle action) 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.

Some simple veer detection methods were considered, including: sensing of the drive motor Electro Motive Force (EMF), odometer, gyro and caster-angle-measurement and

Sensing drive motor EMF relating to motor speed is the most common form of speed compensation and tends to be used in some relatively expensive and complicated commercially available systems.

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

Optical: Ground movement sensing is similar to an optical (ball-less) mouse. Surface texture variations and reflectivity of ground surface caused problems (particularly in wet conditions). The ground detection range could have been extended by using an optical magnifier but this was not attempted during this research.

Inertial: Gyro / rate of rotation sensor measuring the precession of a gyro to the rotation of the wheelchair when veer caused turning downhill. Consideration was 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 remained high compared to using caster-swivel-detection.

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. That method could be considered as a mix between that recently suggested for use with forklift trucks (Sanders, 2008a) and some ideas recently suggested for wheelchairs (Langner, 2008).

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.

A rolling-road was built as an assessment tool to study the effects of wheelchair loading in a controlled environment. For a wheelchair to go in a straight line, both drive wheels needed to rotate at the same speed (assuming they were equal in diameter). An accurate assessment could have been obtained by using tacho measurement wheels coupled to the main wheelchair drive wheels but tacho sensing of the motor drive shaft speed would not take into account variances of wheel diameters and wheel slip. Remote tacho sensing provided sufficient accuracy for the straight line test but could not control the drive loading. The rolling-road test-bed shown in figure 10 was built 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 each of the motor/drive speed characteristics separately.

Figure 10 here

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 incorporated programmable load compensation. This helped to keep wheelchair speeds constant when driving up or down slopes. For example, if increased load was applied to the drive motor, the control system applied more power to keep the speed constant. Motor compensation was applied in equal amounts to both motors. When testing 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 in a corridor was only valid in that environment. A problem with conventional wheelchair control systems was how 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 odometer methods, there could be issues with changes in wheel diameter and wheel slip. The casters provide steering manoeuvrability, however they also cause 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 would become less of an issue but manoeuvrability would be lost.

To address these problems, some systems were considered to model the environment around the wheelchair (Sanders, 1995a; Stott, 2000b), predict terrain ahead of the wheelchair (Urwin-wright, 2002; Urwin-wright, 2003; Stott, 2000a), use artificial intelligence systems (Sanders, 1999, 2000a and 2000b; Tewkesbury, 1999a) or machine intelligence (Hudson, 1997, Sanders 1996 and 2008b; Tewkesbury 1999b), to consider forces (Sanders, 2007) or to plan paths for the wheelchair (Goodwin, 1997; Sanders, 1995b). These all could have worked but were rejected as too complex and / or to expensive. Other researchers had also investigated the use of safety restraints to assist in wheelchair use (van Roosmalen, 2005) but it was considered better to investigate ways of assisting users in steering their wheelchairs to keep them safe.

The intention was to create an electronic solution to lock the caster steering position to the driver's 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 Fig 11). This provided left, right and centre swivel direction outputs.

Figure 11 here

Correction feedback was applied when the caster swivelled from the centre position. The amount of compensation feedback determined how accurately the wheelchair held its course against gravity pulling against the chair. 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 effects could induce a veer even on level ground, for example changes to carpet fibres.

5. CASE STUDY

Vari-controls development was undertaken in parallel with the introduction of the concept to the young people using them. That engendered a co-operative and collaborative result. As a case study, one of the 16+ pupils at Chailey Heritage School (called Chris) is considered as an example.

Chris had been using a set of lever pad binary 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 Fig 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). Chris's 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. Chris had learnt to reach and pull back on his reverse switch to implement reverse (similar to pulling back on a joystick).

Figure 12 here

Switch controls were held in place by Velcro. This provided a convenient means to anchor the binary switches; however their positions could move when in use and therefore could be a source of frustration. To help accommodate Chris's 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 Chris sometimes had trouble with the operation of all of his switches with the same ease. To accommodate Chris's range of movement, the switch mounting was off-set but this position increased vulnerability when passing objects on his left side. Recently the controls had gradually been moved to be within the confines of the tray structure. Chris's continued use of the switches enabled him to develop the finer elements of his control movements. Figure 13 shows the arrangement of the controls.

Figure 13 here

Chris 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 with binary switches or driving on slopes).
- Unable to change speed or turn his drive controls on or off while moving.

Once Chris had become a proficient switch control user, then he was given an opportunity to try proportional switches. This provided a gateway for him to practice more finely graded wheelchair control. This also had the advantage of improving energy conservation and allowing him to exercise better control of the wheelchair on slopes and turns.

Another problem encountered by Chris (and the other wheelchair drivers) was veer (Langner, 2008). This occurred when one of the drive motors rotated at a slightly different speed or one wheel was worn more than the other. This could cause the wheelchair's caster wheels to turn instead of going in a straight line. The problem especially occurred on sloping ground where gravity pulled one end of his chair down a slope. Even with the proportional switches, Chris had to work hard to keep correcting his wheelchair in these situations. Variable controls did allow some drivers to trim and counteract unwanted veer by shifting the position of their hand but that was only possible with the variable or proportional controls (and it made them a valuable asset in improving energy conservation).

Chris was not ready to use a standard proportional joystick. Instead his binary switch controls were replaced by variable control devices. This allowed Chris to grade his speed in all directions and was similar to a standard proportional joystick (but without the need to hold a control stick). Proportional Vari-switch controls were selected for Chris 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.

Chris tested the prototype control system with the variable switches and demonstrated that he could control speed using them. This is shown in figure 14. Chris had a good understanding of how to drive but he was not able to use a joystick. The original arrangement of digital-switches (the horse-shoe arrangement shown in figure 12 and figure 13) 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 Chris's range of moment 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 Chris 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 Chris had with controlling his wheelchair 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 Chris 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. Chris needed to work hard to counteract this drift by applying his left control more than his right in order to continue along the path.

A first problem was that the switch-function responded asymmetrically by turning faster to the right and slower to the left. Chris's reactions to control to the right were not always fast enough. A second problem was that the wheelchair could stall when commanded to turn up a steep 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. A second change was to introduce the new sensors to reduce wheelchair veer.

- Insert figure 14 here -

6. TESTING

Chris 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 Chris 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 Chris was able to sequentially select through the operational functions. These are shown in table One.

6.1 TESTING OF THE PROPORTIONAL CONTROLS

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 tests are still taking place to confirm this. Reverse and Mode select were used less often and this mounting position may help to reduce accidental operation. Figure 14 shows a video still from film of Chris trialling his new vari-controls .

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 Chris felt comfortable with. The drive program was reviewed periodically and, if necessary, adjusted to suit his current needs.

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-centre'. When forward drive was selected the fast acting correction system tried to restore the wheelchair to a straight-line direction quickly. 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. This was similar to results reported in (Sanders, 2008a) for forklift trucks.

Chris 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 15, 16 and 17 show a sequence of video still pictures of Chris driving along a sloping path. Many drivers have problems driving along this path because of the 3 degree slope (in particular those using switch controls). The picture sequence shows that Chris was able to maintain control against the slope. This was achieved without stopping to correct directions as was the case when he used switch controls. Chris significantly reduced the amount of switch-hopping between directions and this reduced energy expenditure and frustration.

Insert figure 15

Insert figure 16

Insert figure 17

The general outcomes have included a reduced initial reaction time and movement time but have greatly improved driving accuracy.

6.2 TESTING OF THE VEER CORRECTION SYSTEM

The new veer correction system was initially tested in the laboratory. Later the systems were tested on sloping ground that was used regularly by children and young adults at Chailey Heritage School. The number of steering corrections needed to complete an outside test run was counted and a small video camera was mounted behind the driver to provide a dynamic record of events. Figure 18 shows a video still of a driver testing the veer compensating system during an early outside test. The systems are now in permanent use by drivers at Chailey Heritage School.

Figure 18 here

Figure 19 and figure 20 show video stills from an indoor veer test in the laboratory on a 4 meter ramp (with a left slope of 3°). 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.

Figure 19 here

Figure 20 here

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 degrees. 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.

A typical set of test results is shown in Table Two and Table Three. Table Two shows a set of results from an outside test on a path of length 30 Meters and an average camber / slope of 3º without the new veer system and sensors engaged. Table Three shows the improved results from the same slope with the systems engaged.

The case study was described as an example but ten children have now successfully been using the systems.

7. DISCUSSION

This paper firstly described how changing from a set of digital switches to a set of new variable switches could improve performance for some powered-wheelchair users. This was especially the case for some people with movement disorders that had precluded independent mobility in a powered-wheelchair before this work, for example if people did not have sufficient hand-grasp and release ability and sufficient targeting skill and therefore were unable to use joysticks.

A simple input device was presented that consisted of four variable (proportional) switches that allowed for the isolation of gross motor function and was tolerant to involuntary movements. The devices assisted powered-wheelchair users with poor targeting skills; providing a more proportional world rather than digital for a switch user. For example, at the time of writing, Chris had been using his variable control for eighteen months and had achieved a high level of driving independence. He learnt to mix his control directions which helped in controlling wheelchair veer and he could grade his speed in critical situations.

The new switches reduced some veer on slopes and provided more control over turn-speed. They provided a means to successfully control forward speed and turn speed and radius while reducing frustration and effort and improving energy conservation. The ten users have all 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.

During the introduction of the new veer correction systems, tests 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, however the method was easily ported to proportional control systems as these provided a continuous feedback signal rather than on-off signals.

The limit of veer correction was dependant on the traction capabilities of the wheelchair and 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 a drive wheel skidded. This was a problem it the feedback was increased so far that the correcting movement became too aggressive, as a sharp response could occasionally cause skid (loss of traction) on a slope

8. CONCLUSIONS

Results have been especially significant for people with movement disorders who lack sufficient hand-grasp and hand-release ability or sufficient targeting skill to use joysticks. The simple input-device successfully isolated gross motor function and was tolerant to involuntary movements. This has been shown to assist powered-wheelchair users with poor targeting skills. The second new sensor system assisted powered-wheelchair users in steering across sloping ground without veering off course.

Caster angle measurement was shown to successfully provide feedback to minimize drift away from a chosen course and an electronic solution was successfully created to match caster steering position to driver control. This was proven on a rolling road and later in real situations.

The new proportional switches and sensors were shown to reduce veer on slopes and provided more control over turn and forward speed and turn radius while reducing frustration and effort and improving energy conservation; for example, by avoiding switch-hopping. The powered-wheelchair users became more independent. The two systems are simple enough and affordable enough to enable the systems to be created and attached to many standard powered-wheelchairs in many organisations.

All the wheelchair users have become more independent with the new systems and have said that they do not want to go back to on-off switches. Users are exploiting the subtleties of proportional control for different drive conditions.

REFERENCES

Barker DJ, Reid D, Cott C (2004). Acceptance and meanings of wheelchair use in senior stroke survivors. American Journal of Occupational Therapy 58 (2), pp 221-230. ISSN: 0272-9490

Bergasa-Suso J, Sanders DA and Tewkesbury GE (2005). Intelligent browser-based systems to assist Internet users. IEEE TRANSACTIONS 48 (4), pp 580-585.

Bootsma RJ, Martenuik RG, Mackenzie CL, Zaal FTJM (1994). The speed-accuracy trade-off in manual prehension – effects of movement amplitude, object size and object width on kinematic characteristics. Experimental Brain Research 98 (3), pp 535-541.

Brandt A, Iwarsson S, Stahle A (2004). Older people's use of powered wheelchairs for activity and participation. Jnl of Rehabilitation Medicine 36 (2), pp 70-77. ISSN: 1650-1977

Brubaker CE, McLaurin CA, McClay IS. (1986). Effects of side slope on wheelchair performance. J Rehabil Res Dev. 23 (2), pp 55-58

Buckley SM, Bhambhani YN. (1998). The effects of wheelchair camber on physiological and perceptual responses in younger and older men. Adapt Phys Activ 15, pp 15-24.

Buning ME, Angelo JA, Schmeler MR (2001). Occupational performance and the transition to powered mobility: A pilot study. American Journal of Occupational Therepy 55 (3), pp 339-344. ISSN: 0272-9490

Cooper RA, Jones DK, Fitzgerald S, Boninger ML, Albright SJ (2000a). Analysis of position and isometric joysticks for powered wheelchair driving. IEEE Trans Biomedical Eng 47 (7), pp 902-910.

Cooper RA, Widman LM, Jones DK, Robertson RN, Ster JF (2000b). Force sensing control for electric powered wheelchairs. IEEE Trans Control Systems Technology 8 (1), pp 112-117.

Cooper RA, Thorman T, Cooper R, Dvorznak MJ, Fitzgerald SG , Ammer W, Song-Feng G , Boninger ML. (2002). Driving characteristics of electric-powered wheelchair users: How far, fast, and often do people drive? Arch Phys Med Rehab, 83 (2), pp 250-55

Denison I, Shaw J, Zuyderhoff R. The effect of components on manual wheelchair performance. In: Denison I, Shaw J, Zuyderhoff R, (1994). Editors: Wheelchair selection. British Columbia rehabilitation equipment evaluation. 1st ed. Vancouver (British Columbia, Canada): BC Rehab; pp. 31-40.

Dicianno BE, Spaeth DM, Cooper RA, Fitzgerald SG and Boninger ML (2006). Advancements in power wheelchair joystick technology: Effects of isometric joysticks and signal conditioning on driving performance . American Jnl Physical Medicine & Rehabilitation 85 (8), pp 631-639.

Fehr L, Langbein WE, Skaar SB (2000). Adequacy of power wheelchair control interfaces for persons with severe disabilities: A clinical survey. Jnl of Rehabilitation Research and Development 37 (3), pp 353-360

Fuchs RH, Gromak TA (2003). Wheelchair use by residents of nursing homes: Effectiveness in meeting positioning and mobility needs. Assistive Technology 15 (2), pp 151-163. ISSN: 1040-0435

Gaal RP, Rebholtz N, Hotchkiss RD, Pfaelzer PF (1997). Wheelchair rider injuries: Causes and consequences for wheelchair design and selection. Jnl Rehabilitation research and development 34 (1),pp 58-71. ISSN: 0748-7711

Goodwin MJ, Sanders DA, Poland GA, et al (1997). Navigational assistance for disabled wheelchair-users. Jnl Systems Architecture 43 (1-5), pp 73-79.

Gosain, D, Jyoti, D, Asiwal, D, Singh, S, Maheshwari, S and Agarwal, SK (2007). Design and development of a foot controlled mobility device. Proc' of 2nd Frontiers in Biomedical Devices Conf, pp 83-87. ISBN: 978-0-7918-4266-9

Guerette P, Tefft D, Furumasu J (2005). Pediatric powered wheelchairs: Results of a national survey of providers. Assistive Technology 17 (2), pp 144-158. ISSN: 1040-0435.

Hubbard SL. Fitzgerald SG, Vogel B, Reker DM, Cooper RA, Boninger ML (2007), Distribution and cost of wheelchairs and scooters provided by Veterans Health Administration Volume 44 Number 4, pp 581 — 592

Hudson AD, Sanders DA, Golding H, et al. (1997). Aspects of an expert design system for the wastewater treatment industry. IEEE Int Symp on Circuits and Systems, Vols 1-11, Proceedings, pp 5551-5554. ISBN: 978-0-7803-9389-9.

Krishnamurthy, G and Ghovanloo, M (2006). Tongue drive: A tongue operated magnetic sensor based wireless assistive technology for people with severe disabilities. 2006

Langner MC (2004). A Wheelchair guidance system for people with complex needs. MPhil. University of Portsmouth.

Langner MC and Sanders DA (*In press*). Controlling wheelchair direction on slopes. Journal of Assistive Technologies.

Pate RR, Pratt M, Blair SN, Haskell WL, Macera CA, Bouchard C, Buchner D, Ettinger W, Heath GW, King AC, et al. (1995). Physical activity and public health. A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. 273 (5), pp 402-7.

Pellegrini N, Guillon B, Prigent H, Pellegrini M, Orlikovski D, Raphael JC, Lofaso F (2004). Optimization of power wheelchair control for patients with severe Duchenne muscular dystrophy. Neuromuscular disorders 14 (5), 297-300.

Perdios Angeliki, Sawatzky J, Sheel W (2007). Effects of camber on wheeling efficiency in the experienced and inexperienced wheelchair user. Journal of Rehabilitation Research & Development, Volume 44, Number 3, pp 459 — 466.

Pettersson I (Pettersson, Ingvor), Ahlstrom G (Ahlstrom, Gerd), Tornquist K (Tornquist, Kristina) (2007). The value of an outdoor powered wheelchair with regard to the quality of life of persons with stroke: A follow-up study. Assistive Technology 19 (3), pp 143-153. ISSN: 1040-0435

Reid M, Lawrie AT, Hunter J, Warren PM (1990) The effect of steering on the physiological energy cost of wheelchair propulsion. Scand J Rehabil Med. 22 (3), pp 139-43

Rudins A, Laskowski ER, Growney ES, Cahalan TD, An KN (1997). Kinematics of the elbow during wheelchair propulsion: A comparison of two wheelchairs and two stroking techniques. Arch Phys Med Rehabil. 78 (11), pp 1204-1210.

Ruggles DL, Cahalan TD, An KN (1994). Biomechanics of wheelchair propulsion by able-bodied subjects. Arch Phys Med Rehab. 75 (5), pp 540-44.

Sanders DA (1995a). Real time geometric modeling using models in an actuator space and cartesian space . Jnl of Robotic Systems 12 (1): 19-28.

Sanders DA (1995b). The modification of pre-planned manipulator paths to improve the gross motions associated with the pick and place task. ROBOTICA 13: 77-85 Part 1.

Sanders D (1999). Perception in robotics. Industrial Robot – an international journal 26 (2), pp 90-92.

Sanders DA (2007). Viewpoint - Force sensing. Industrial Robot – an international journal. 34 (4): 268-268.

Sanders D (*2008a – In press*). Controlling the direction of “walkie” type forklifts and pallet jacks on sloping ground. . Assembly Automation (in press as AA-08-014 - to be published in Cecember 2008).

Sanders DA (*2008b – In press*). Progress in Machine Intelligence. Industrial Robot – an international journal (in press for IR 35-6 - to be published in November 2008).

Sanders DA, Haynes BP, Tewkesbury GE, et al (1996). The addition of neural networks to the inner feedback path in order to improve on the use of pre-trained feed forward estimators. Mathematics & computers in simulation 41 (5-6), pp 461-472.

Sanders DA and Hudson AD (2000a). A specific blackboard expert system to simulate and automate the design of high recirculation airlift reactors. Mathematics and com puters in simulation 53 (1-2), pp 41-65.

Sanders DA, Hudson AD, Tewkesbury GE, et al (2000b). Automating the design of high-recirculation airlift reactors using a blackboard framework. Expert systems with applications 18 (3), pp 231-245.

Sanders DA, Urwin-Wright SD, Tewkesbury GE, et al (2005). Pointer device for thin-film transistor and cathode ray tube computer screens Electronics Letters 41 (16), pp 894-896

Stott IJ and Sanders DA (2000a). New powered wheelchair systems for the rehabilitation of some severely disabled users. International journal of rehabilitation research. 23 (3): 149-153.

Stott IJ and Sanders DA (2000b). The use of virtual reality to train powered wheelchair users and test new wheelchair systems. International Journal of Rehabilitation Research 23 (4), pp 321-326.

Taylor PB and Nguyen HT (2003). Performance of a head-movement interface for wheelchair control. Proc' 25th Int Conf of IEEE Eng in Medicine and Biology Society, Vols 1-4 - A new beginning for human health 25, pp 1590-1593 (Part 1-4). ISSN: 1094-687X

Tewkesbury G and Sanders D (1999a). A new simulation based robot command library applied to three robots. Jnl of robotic systems 16 (8), pp 461-469.

Tewkesbury G &Sanders D (1999b). A new robot command library which includes simulation. Ind Robot 26 (1), pp 39-48.

Tolerico ML, Ding D, Cooper RA, Spaeth DM, Fitzgerald SG, Cooper R, Kelleher A, and Boninger ML (2007), Assessing mobility characteristics and activity levels of manual wheelchair users, Journal of Rehabilitation Research & Development, Volume 44, Number 4 Pages 561 — 572.

Trefler E, Fitzgerald SG, Hobson DA, Bursick T, Joseph R (2004). Outcomes of wheelchair systems intervention with residents of long-term care facilities. Assistive Technology 16 (1): 18-27. ISSN: 1040-0435.

Trudel G, Kirby RL, Bell AC (1995). Mechanical effects of rear-wheel camber on wheelchairs. Assistive Technology (2), pp 79-86.

Trudel G, Kirby RL, Ackroyd-Stolarz SA, Kirkland S (1997). Effects of rear-wheel camber on wheelchair stability. Arch Phys Med Rehab 78 (1), pp78-81.

Urwin Wright S, Sanders DA and Chen S, (2002) Terrain prediction for an eight-legged robot. Journal of Robotic Systems, Vol 19, No 2, pp 91-98, published by Wiley.

Urwin-Wright S, Sanders D and Chen S (2003). Predicting terrain contours using a feed-forward neural network . Engineering applications of artificial intelligence 16 (5-6): 465-472.

U.S. Department of Health and Human Services (2000). Healthy people 2010: Understanding and improving health. 2nd ed. Washington (DC): U.S. Department of Health and Human Services.

Van der Woude LH, Veeger HE, Dallmeijer AJ, Janssen TW, Rozendaal LA (2001). Biomechanics and physiology in active manual wheelchair propulsion. Med Eng Phys. 23 (10), pp 713-33.

van-Roosmalen L, Reed MP, Bertocci GE (2005). Pilot study of safety belt usability for vehicle occupants seated in wheelchairs. Assistive Technology 17 (1): 23-36. ISSN: 1040-0435.

Verburg G, Snelle E, Pilkington M and Miller M (1984). "Effects of powered mobility on young handicapped children and their families". Proc. of the rehabilitation engineering Soc. of N. America. June 1984 Ottwa. pp172-173.

Webster JS, Cottam G , Gouvier WD, Blanton. P, Beissel GF, Wofford J (1988). Wheelchair obstacle course performance in right cerebral vascular accident victims. J Clin Exp Neuropsychol. 11 (2), pp 295-310.

Wolf E, Cooper RA, Pearlman J, Fitzgerald SG & Kelleher A (2007), Longitudinal assessment of vibrations during manual & power wheelchair driving over select sidewalk surfaces. Jnl of Rehabilitation Research & Development, 44 (4), pp 573-580.

Woods B, Watson N (2003). A short history of powered wheelchairs. Assistive Technology 15 (2): 164-180. ISSN: 1040-0435.

Figures

Figure 1 Image on the light projection box when the control switch was pressed

Figure 2 Image on the light projection box when the control switch was pressed further.

Figure 3 Image on the light projection box when the control switch was progressively pressed further.

Figure 4 Image on the light projection box when the control switch was pressed as far as possible.

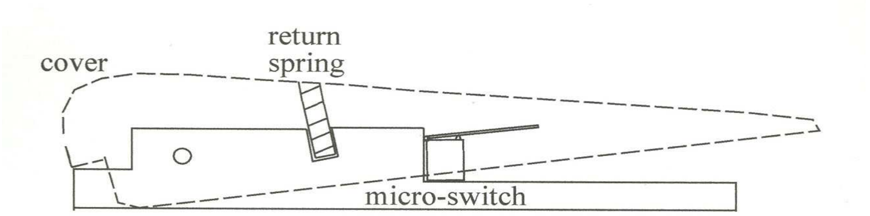

Figure 5 Typical simple paddle switch used by students at Chailey Heritage School - shown in the Off position.

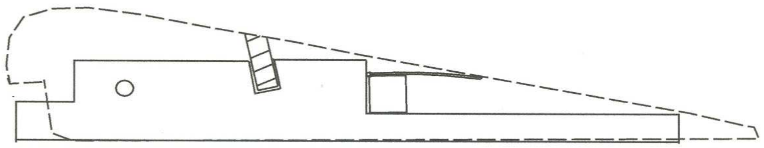

Figure 6 When the paddle switch is operated then the cover acts against the micro switch lever arm.

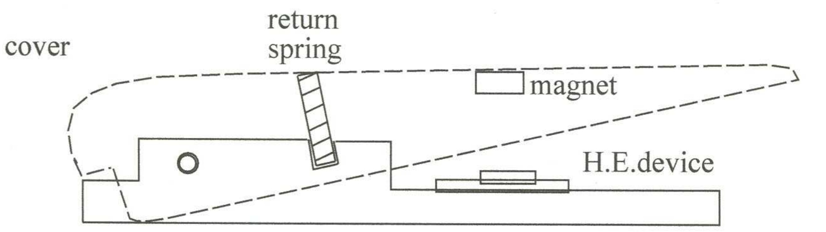

Figure 7 New variable switch with a Hall Effect integrated circuit and a small magnet - - shown in the Off position.

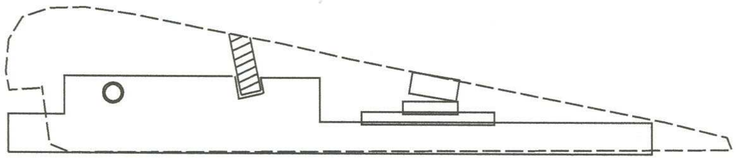

Figure 8 The extreme of the operating position for the new variable switch with a Hall Effect integrated circuit.

Figure 9 - Young person trying to control his veering wheelchair.

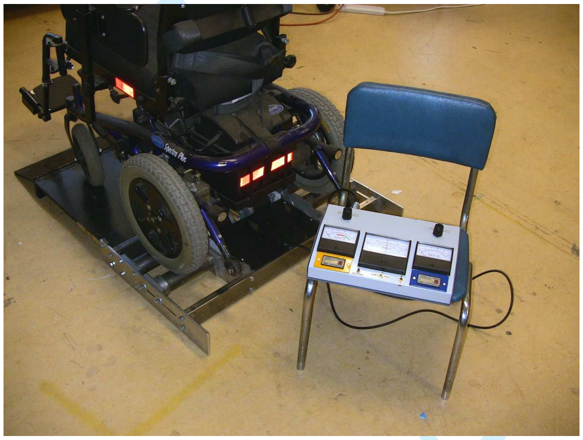

Figure 10 Rolling-road test-bed

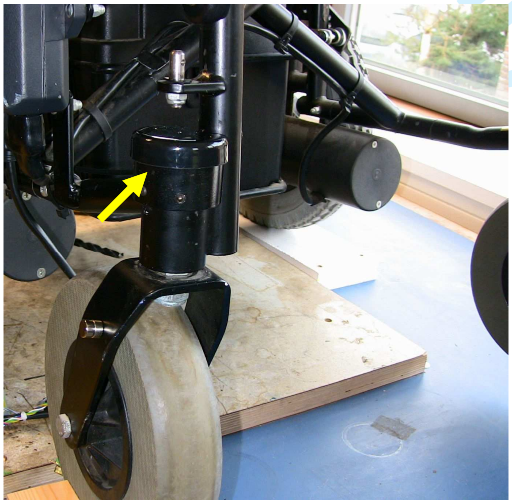

Figure 11 Small swivel detector attached to the caster swivel bearing

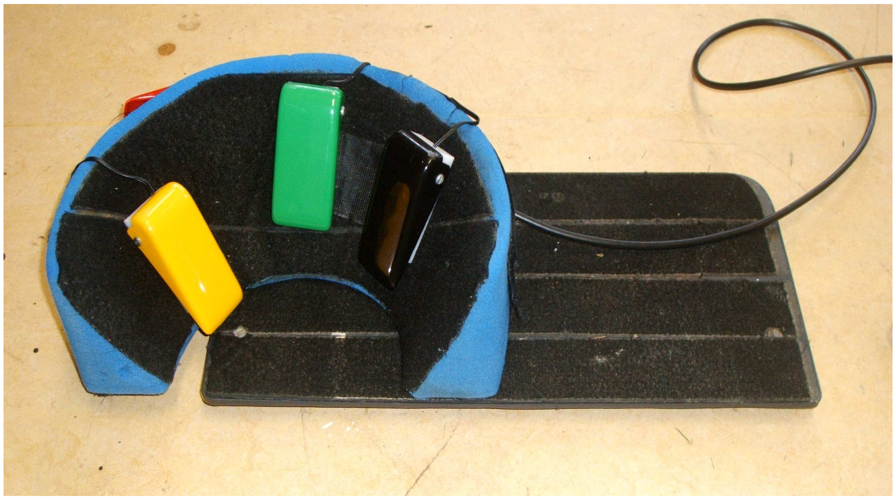

Figure 12 - Chris's switch controls.

Figure 13 - Chris's horseshoe switches.

Figure 14 - Chris trialling his new vari-controls.

Figure 15 Chris at the beginning of a sloping path.

Figure 16 Chris driving along the sloping path

Figure 17 Chris at the end of the sloping path.

Figure 18 Video still of a driver testing the veer compensating system during an early outside test

Veer not compensated

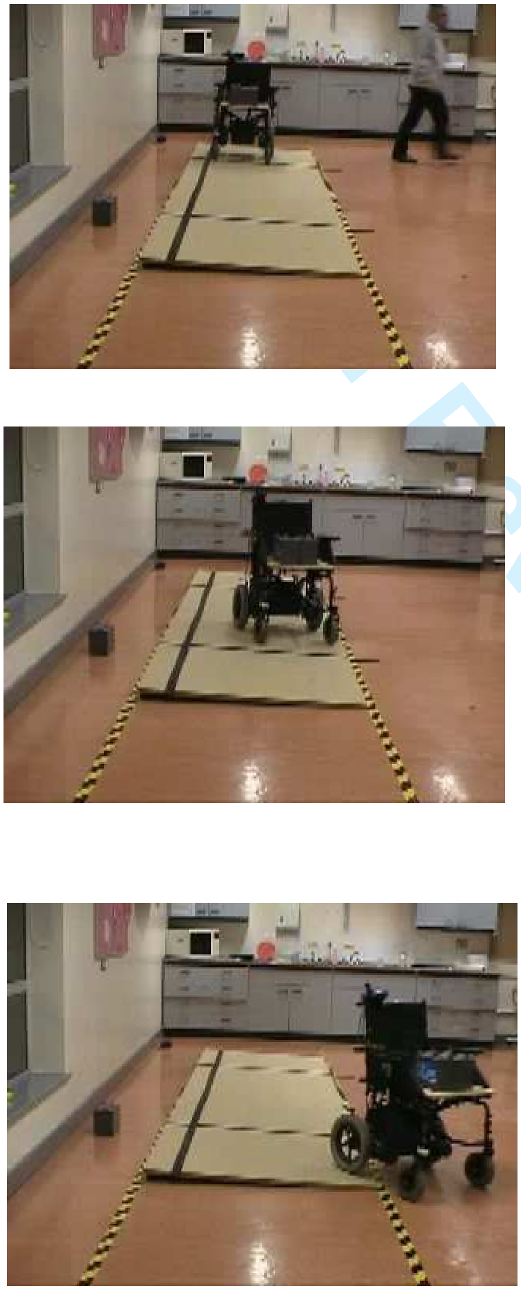

Figure 19 Video stills from an indoor veer test in the laboratory on a 4 meter ramp (with a left slope of 3º) with only the forward switch control activated.

Veer compensated

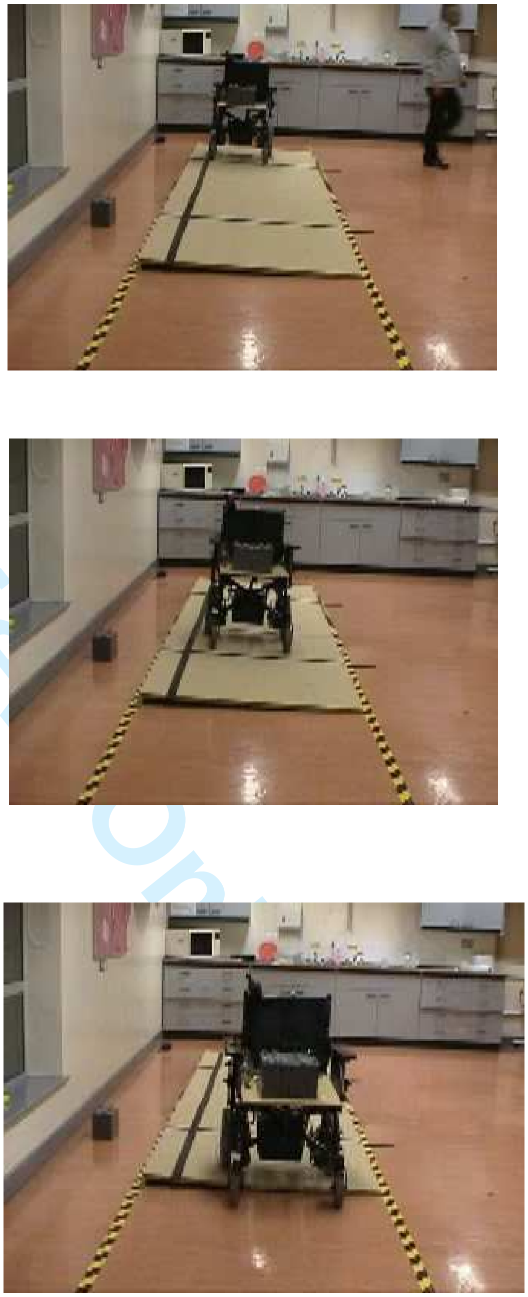

Figure 20 Video stills from an indoor veer test in the laboratory with the forward switch control and sensor system activated.

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 ONE

Run test with no applied veer correction test.

Time to complete run = 2 mins : 6 secs

Total number steering corrections required = 9 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 = 3.4
2nd = 6.2
3rd = 11.9
4th = 14.2
5th = 15.5
6th = 18
7th = 21.4
8th = 24.4
9th = 26.9

TABLE TWO

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 = 2 (1 right and 1 left)

Approximate correction distance in meters (m)

1st Right correction distance = 9

1st Left correction distance = 20

TABLE THREE