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Haptic interfaces for wheelchair navigation in the built environment
(2004) CS Harrison, M Grant, BA Conway
Presence: Teleoperators & Virtual Environments 13 (5), 520-534
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Haptic Interfaces for Wheelchair Navigation in the Built Environment

Abstract

Many countries have recently introduced legislation aimed at ending discrimination against disabled people. In the UK, the Disability Discrimination Act (1995) provides the disabled community with new employment and access rights. Central to these rights will be an obligation for employers and organisations to provide premises which do not disadvantage disabled people. Many disabled people rely on wheelchairs for mobility. However, many buildings do not provide conditions suited to wheelchair users. This work reports on the development of instrumentation that allows wheelchair navigation within virtual buildings. The provision of such instrumentation assists architects in identifying the needs of wheelchair users at the design stage. Central to this project is the need to provide a platform which can accommodate a range of wheelchair types, that will map intended wheelchair motion into a virtual world and that has the capacity to provide feedback to the user reflecting changes in floor surface characteristics and slope. Integrating, visual and non-visual sensory feedback that correlates with the physical effort of wheelchair propulsion augments the perception of self-motion within the virtual world and creates an effective instrument for use in the study of wheelchair accessibility within the built environment. The project represents a collaborative effort between architects, bioengineers and user groups and research related to platform design, construction, interfacing, testing and user evaluation are presented.

Keywords:

- Virtual Wheelchair Access,
- Disability,
- Discrimination,
- Motion Simulation,

- Building,
- Instrumentation.
- Perception of effort

Introduction

Over the last 30 years there has been an increasing awareness of the lack of provision of rights for people with disabilities and this has led to the introduction of a number of important legal devices. For example, in the USA the Americans with Disability Act (ADA) (http://www.usdoj.gov/crt/ada/adahom1.htm/) has introduced legislation aiming to end the discrimination in education, employment, access to public and private accommodation and transport faced by the disabled community. Similarly, in the United Kingdom the Disability Discrimination Act (1995) (http://www.disability.gov.uk/dda/) has begun to phase in legislation that by 2004 will require service providers and employers to make reasonable adjustments to the physical features of their premises in order for disabled people to overcome physical barriers to access.

Improved access to the built environment has therefore become, not only an important issue to the disabled community, but also an issue that must be addressed by professionals involved in the design, construction and management of the built environment. Many disabilities relate to problems of mobility, and assistive technology in the form of wheelchairs can dramatically impact on the ability of users to engage more fully in society. In the USA, estimates based on data collated in 1994 indicate that across all age groups 1.5 million people use wheelchairs (REF Russell et al., 1997) while in the UK the Prosthetic and Wheelchair Committee (1996) reported that more than 1.5% of the population use wheelchairs. With current demographic trends towards an older population (REF Tuljapurkar et al., 2000) and the high incidence of mobility problems in seniors it is anticipated that the total population of wheelchair users will continue to grow. Despite forming a sizeable population, many features of the external and internal built environment fail to accommodate the access needs of wheelchair users and this significantly limits the standard and quality of living achieved by many individual wheelchair users. Adoption of inclusive design together with the enforcement of current legislation should offer equal opportunities for disabled people and through their full integration in society lessen social security and welfare cost. Accordingly, there are important social and economic reasons for the development of tools, which could allow architects and others to explore access issues early in the design process of new buildings or in the redevelopment of existing domestic and commercial building stock .

Virtual reality (VR) simulations of the built environment may provide the basis for such tools through accurate visualisation and user interaction. However, to capitalise on the potential for using VR as a tool to improve building accessibility it is vital that navigation through the VR world should be driven by systems that accurately reflect the mode of transport used by intended users. Immersion in VR systems is principally generated by optic flow driven by a navigation device. However, as wheelchair accessibility is constrained not only by the architectural layout of an environment but also by the physical features of the ground that the chair is moving across it is apt that VR environments designed for assessing wheelchair access should provide non-visual sensory feedback to the user that relates to the effort associated with propelling a wheelchair over changing terrains.

Users of manual wheelchairs depend on upper limb function to initiate and control wheelchair speed and direction of motion via actions imparted to the chair's wheels. A trained wheelchair user will therefore have experiential knowledge of the dynamic upper limb muscular effort needed to control wheelchair motion across different surfaces or inclines. Thus for VR to be useful in assessing wheelchair accessibility the user must be able to sense through their upper limbs the effects of changes in floor surface and slope as they occur during VR navigation. It is therefore essential that user interfaces not only generate realistic graphical displays of wheelchair motion but also simulate the variations in resistance to wheel rotation encountered as ground conditions change. Implementing a haptic interface that achieves this would insure that the physical effort of propelling a wheelchair in the virtual world is matched with expectations learned through actual wheelchair usage. For experienced wheelchair users presence within the virtual world will be enhanced if the integration between visual and proprioceptive feedback mechanisms are matched to expected outcomes of the users acquired motor behaviour. Accordingly, we report here on the development of a haptic interface which allows wheelchair users to navigate within VR simulations of buildings through the use of their own wheelchair and which provides the user with visual and proprioceptive feedback that directly relates to the task of wheelchair propulsion and control. The paper presents an outline of the development of the haptic wheelchair interface, its integration within a virtual reality laboratory and the results of a wheelchair user group evaluation on its use. The incorporation of haptics into VR simulations of the built environment provides a powerful tool that should allow wheelchair users to directly participate in the design and testing of accessible environments.

System Overview

The entire system is comprised of three mutually inter-linked components;

- the motion platform
- the graphics system
- the control system

Each of the above elements forms a linked system that is controlled by the bidirectional flow of information from the wheelchair to the virtual environment, and from the virtual environment to the wheelchair. The feedback loop is via the user’s visual perception of progress through the virtual environment and by the perceived effort associated with alterations in the rolling resistance of the wheelchair.

<Figure 1 near here>

By closing the feedback loop with a human rather than a further pair of sensor connections, it was found that any minimal latency or hysteresis in the rest of the communications path can be compensated for by the user.

Motion Platform

The design of the interface between the manual wheelchair and the virtual environment has been specified so that the wheelchair remains fixed in place, with movable driving wheels. In this way the user is not limited within the virtual environment by the constraints of their physical environment. This interface was required to fulfil two main functions.

- **Firstly**, it had to be able to transfer the rotation of the driving wheels to provide realistic navigation around the virtual world (REF Hofstad and Patterson, 1994,).
- **Secondly**, it was to provide additional non-visual (proprioceptive) feedback to the user on the basis of their interaction with the virtual environment. This served to match optic flow and motion perception with voluntary motor effort, and thereby enhance the users experience of navigating the virtual world.

- **Finally**, in order that a user could retain their own wheelchair whilst navigating in the virtual environment, the interface has been designed to accommodate a wide range of manual wheelchairs.

<Figure 2 near here>

The physical structure of the wheelchair platform is based around a pair of rollers. These are mounted on separate shafts so that one roller is under each driving wheel of the wheelchair. The rollers are 300 mm long so that a range of wheelchair widths can be supported. The roller shaft is supported by a pair of single row radial ball bearings mounted in support pillars, fixed to a solid base plate. The roller, and space for an inertial mass, is situated between the two bearings. The maximum size of the mass that could be accommodated was a cylinder 65mm long with a diameter of 240mm. Outside the lateral ball bearing, the shaft was machined to accommodate a hollow shaft encoder. The body of the encoder is held with respect to the base plate, while the hollow shaft has been clamped to the roller shaft. Brakes are rigidly mounted coaxial to the roller shaft. Motors are geared to each roller shaft using a toothed belt and coupled through an electromagnetic clutch.

The disposition of these components is shown in Figure 3.

<**Figure 3. near here**>

The entire structure is enclosed by a wooden cover so that the user is protected from the moving parts. Two rectangular holes in the cover allow the rollers to stand slightly proud of the surrounding surface allowing wheel contact. Adjustable straps and bars ensure that the wheelchair is rigidly held in place on the rollers, and a ramp allows the user to gain access to the facility.

<Figure 4 near here>

Note from Figure 4 the size and strength of the base plates and shaft supports required to bear the weight of the user and wheelchair when transmitted through a small contact patch.

Graphics System

The role of the graphics system is to generate a virtual world that can realistically represent the built environment both visually and physically and so provide feedback along two separate paths.

Visual Simulation

The virtual environment is visualised using a three-projector system that provides a 150 degree by 40 degree, high resolution image on a five metre diameter cylindrical screen. Each of the three image channels is edge blended to provide a seamless display. When viewed from the design eye point the image fills most of the users field of vision providing a highly convincing sense of visual immersion within the scene as indicated by the results of our user evaluation (see Figure 6 and related text) . Graphics are generated on a twelve- processor Silicon Graphics ONXY II with two graphics pipes. This is capable of processing detailed architectural models at high frame rates in order to provide the desired degree of realism. At each time-step in the simulation the graphics are rendered to three separate output channels, each channel sharing the same eye point but with a different angular offset in azimuth, corresponding to the offsets in the projection system. This circumvents the geometrical distortion inherent in large field of view displays.

<Figure 5 near here>

The software used to drive the virtual environment is based on the Silicon Graphics Performer API. This is a high performance 3-D rendering toolkit for multiprocessed interactive applications. The graphics component is closely coupled to a separate asynchronous module that interfaces between the incoming data from the motion platform control system and the rendering software.

Physical Simulation

The graphics application requires the Cartesian co-ordinates of the eye point, plus the yaw, pitch and roll angles of the direction of view. Given the yaw angle the remaining two parameters can be calculated based on the wheelchairs attitude on the floor plane. In the database traversal three rays corresponding to the contact patch of each of the rear wheels and the midpoint of the front axle, are intersected with the floor. The normal vector of the ground plane at these points can then be used to calculate the roll, pitch and altitude of the chair and hence the corresponding view. The same intersection procedure can also be used to identify the surface under each wheel, this information then being used to index material properties, such as rolling resistance and surface texture which can be passed back to the control system. Because the system does not support object to object collision detection a further class of intersection appraisal was implemented. This provided a matrix of randomly "jittered" rays aligned with the current direction of motion which proved to be capable of detecting collisions between the wheelchair and even relatively narrow vertical or horizontal obstructions. The length of these rays was varied according to the distance traversed by the wheelchair between frame updates. On detecting a collision condition a flag is also passed back to the control system.

Control System

A large number of environmental features were identified for which accessory haptic feedback could enhance the perception of the virtual environment. These included object collisions, slopes and cambers, kerbs, uneven surfaces and different ground surfaces.

Motion Simulation

As outlined previously, the motion simulator and the graphics software form a closed loop system. . The motion simulator communicates with the graphics system over a TCP/IP network. The task of the motion simulator is to accept incoming data from wheelchair platform, this data relating to the individual incremental angular displacement of both wheels on the motion platform. The current data values are compared to the previous increment, to determine whether either wheel is rotated forward or backward, this information then being passed to the next stage of the algorithm. The basis of the motion control algorithm is the determination, through an analysis of similar triangles, of any translation and also, using the location of the centre of rotation along the rear axle of the virtual wheelchair, the angle through which is turned. These values are passed to the graphics system where the transformation of the eye point and rotation of the view vector can be determined. As the angular motion of the rollers is used to calculate wheelchair displacement the motion of the visual field can be calibrated in relation to actual displacement. Feedback from the graphics system determines whether the brakes, clutch or motors should be actuated to provide a physical level of feedback to the user.

Platform Control

The platform control system is based on a standard Personal Computer, running purpose written software, interfacing with the virtual world via a network link using TCP/IP and also with the platform instrumentation via a General Purpose Interface Board (GPIB). The control system monitors the user input by taking incremental readings from the rotary encoders on the motion platform whilst simultaneously controlling the feedback stimuli to the wheelchair on the basis of feedback data received from the graphics system.

The motors are independently controlled for each wheel by setting suitable voltages on the motor control unit, this can be achieved by using the GPIB card and controlled via the software drivers. Thus control of the entire wheelchair platform is accomplished at the physical level by simply writing values on the GPIB card which are generated by software logic controlled by events in the virtual world. Since the user controls the position of the chair in the world realistic force feedback is provided by the actions directed to the platforms rollers.

Ascending and descending a steep gradient.

In order to achieve realistic simulations of changes in slope and surface conditions data on how these variables influence the rolling resistance of a wheelchair was collected using an instrumented wheelchair. This data was then used in setting the parameters for the control variables used in altering the platform roller motion. Based on the data collected variations in floor surfaces can be simulated by simply altering the resistance to motion of the rollers, using the brakes. Simulation of the wheelchair moving down or up a slope requires active input into the system, providing a torque against which the user can control their movement. A variable torque motor is used to provide this input for different grades of slope. Thus if a wheelchair user is positioned at the top of a slope the motors will activate, the wheelchair wheels will rotate and the chair will roll down the slope. If the wheelchair is facing upslope and the user does nothing the wheelchair wheels will be rotated backwards. As roller motion is used to drive the graphics system the user sees the visual world moving in the appropriate direction. The user can control their rate of descent downhill by manually braking the wheels but uphill motion requires increased physical effort to overcome the action of the torque applied by the motors. When the graphics system detects a collision event a flag is passed back to the control system which then resets the users position to the last "non collided" location and cycles the brakes on the rollers. This temporarily locks the wheels on the wheelchair and this mechanical block to the platform generates an audible event that also indicates a collision event. The user therefore sees, feels, and hears collision events.

User Evaluation

Fifteen volunteer manual wheelchair users were recruited to participate in an evaluation of the interface. The evaluation was conducted with the approval of the University of Strathclyde Ethics Advisory Committee and written and informed consent was obtained from each participant. All volunteers were people with spinal cord injuries affecting their lower limbs and were considered to be experienced users of manual wheelchairs Summary details of the volunteers and the type of wheelchair used by individuals is given in Table 1.

<Table 1 near here>

In evaluating the system volunteers were asked to navigate around the VR model described previously and on completion were asked to rate how realistic various features of the simulated environment compared with ‘real life’ experiences/expectations. This was done via a questionnaire which allowed a range of features relating to the performance of the wheelchair platform, the sensation of self motion within the VR model and the degree of effort expended in navigating the virtual world to be assessed. Table 2 gives a summary of the areas assessed by the questionnaire and provides a key to the rating scales used in the response to individual questions.

Data from the completed questionnaires were then collated and the results are summarised in the histograms shown in Figures 6-8. Out of the 15 subjects, a single user reported sensations of nausea due to motion sickness and this subject was unable to complete the evaluation. The data from this subject has been included in Figures 6-8 but the majority of responses made were in the ‘unable to judge’ category. Importantly, when asked about susceptibility to motion sickness the subject indicated that he often became ill during car, train and boat journeys. However, the remaining 14 subjects reported no incidences of motion sickness and their feedback from the questionnaire provides an important pointer to the performance of the system.

<Figure 6near here>

Figure 6 illustrates the user responses to questions relating to the integration between the wheelchair interface and the visual representation of the built environment (row 1 of Table 2). Importantly, the majority of users reacted positively to the system and rated both the visualisation of the built environment and the perception of self-motion within the virtual world to be realistic.

<Figure 7 near here>

The combination of high quality graphics and realistic wheelchair kinematic simulation being key features in generating positive user feedback. This is further emphasised in Figure 7 which summarises the users' responses to questions on the performance of the wheelchair platform during navigation (see row 2 of Table 2). From Figure 7 it can be seen that for most features that could be considered to be contributors to wheelchair mobility within the build environment the interface performed to a satisfactory level. The negotiation of kerbs was the least realistic feature of wheelchair motion simulated (Figure 7j). The method of depicting a wheelchair traversing a kerb in our system relies exclusively on a transient visual stimulation that correlates in time with the change in wheelchair tilt that would accompany rolling off or over a kerb. However, because the platform itself is stationary and does not actively tilt the normal non-visual feedback associated with kerb negotiation does not occur. The lack of key non-visual sensory input in this case fails to reinforce the visual simulation and limits the realism of the event. It is because of the lack of non-visual feedback that features such as kerbs are rated less realistic than those in which the visual and non-visual sensory cues are matched. For example, features that utilise haptics such as changes in floor surface(Figure 7e), changes in slope (Figure 7g,h) and collisions (Figure 7i) are all considered as realistic and it is the combination of the sense of effort experienced by the user together with an accurate visual representation of expected motion that provides the perception of reality and is a vital component in making the overall VR simulation truly immersive. This is further emphasised in Figure 8 which shows the response to a series of questions relating to the level of physical effort needed to navigate through the simulation of the built environment,

<Figure 8 near here>

Based on the responses to the questionnaire illustrated in Figures 6-8 we believe that the developed interface can provide an important tool for examining access issues within simulations of the built environment. The system also has the ability to provide quantitative information on the navigation path a wheelchair user employs as they manoeuvre within the simulated built environment. During a test session data relating to the position and heading of the wheelchair are continuously logged by the system creating a file that can be used to recreate the navigation pathway taken by a user. This file also logs the collision points that occur between the wheelchair and the features of the VR world (e.g. walls, desks, doorframes etc.). Figure 6 illustrates a map of the VR model used in our evaluation with the navigation paths of the 15 subjects participating shown.

<Figure 9 near here>

Importantly, the logged data can be used to analyse the kinematics of the users wheelchair motion and because collisions with objects, walls, doors etc are also logged (see Figure 10, circles indicate collisions) the potential exists to explore in a rigorous and cost effective way how wheelchair users cope with different building layouts.

<Figure 10 near here>

Conclusions

The Visual Simulation

The realism of even a simple model proved to be adequate in generating a sufficiently complex, built environment, which could provide all the necessary visual cues required for surface recognition and spatial navigation. The display system demonstrated a mix of positive and negative aspects relating to the technology employed. The wide angle of view was a benefit as this allowed the users direction of view to be decoupled from the direction of motion of the wheelchair. This enabled a user to look around within the environment rather than be constrained to the narrow view frustrum common to conventional graphics displays. The downside is that this form of display provides an "out of the window" view which separates a user from objects, which would otherwise be within arms length. This had been thought to be a drawback as wheelchair users tend to make reference to the extremities of their chair when negotiating obstacles. However, in practice this did not seem to disadvantage users of the system. A possible reason for this is that the user can sense the environment through the addition of the haptic feedback provided by the wheelchair platform.

The Physical Simulation

The physical simulation is based on the interaction of geometry within the virtual world. As such, refinement or extension of these capabilities would usually be just a matter of writing additional software. However the project did highlight some fundamental limitations with this concept in that the system was primarily related to the interaction of the wheelchair with the environment as opposed to modelling the users personal interactions. This is exemplified by the manner in which a user might negotiate swing doors. In this event a wheelchair occupant might tend to use their knees, or the chair itself, to wedge the door open while manoeuvring for a favourable position from which to exert additional leverage. This was beyond the scope of the current implementation. In general, users regarded the physical feedback as "moderately" to "very" realistic with the exception of the treatment of kerbs. Kerbs represent a singular challenge to wheelchair users and are either avoided or negotiated by a unique manoeuvre. In the simulation this feature was represented by making the upstand of the kerb a very short, but steep, incline as opposed to being truly vertical. This allowed the software to treat kerbs in the same manner as all other inclines, requiring substantial input to climb the obstruction, but not faithfully mimicking real world practice.

The Control System

The control system is responsible for interfacing between the motion platform and the virtual world. One of its tasks is to translate the sensed wheel rotations from the incremental movement of the rotary encoders into translation and rotation of the wheelchair via a motion model. This function accurately modelled the gross behaviour of the wheelchair but initially neglected to account for the subtle influence of the castoring front wheels. This castoring action induces two further complications to the model. Firstly, the castors tend to transfer torque between the driving wheels. This tends to stabilise the heading of the chair, an effect that increases with speed. Secondly, the orientation of the castors is a function of the previous direction of motion; any subsequent movement on a new heading must first re-align the castors with the new direction. This can result in unexpected deviations from the desired course, especially among new wheelchair users. When the simulation failed to take account of the first feature it was difficult to maintain a constant heading but a simple algorithm was introduced to mimic the effect of torque transfer and this succeeded in damping out the oscillations. The second feature is more subtle and perhaps of greater concern to powered wheelchair users. In the event this was not corrected and the trial users did not comment on its omission. This will be addressed in a future phase of the project.

The Motion Platform

The motion platform proved to be a complicated electro-mechanical device. Throughout the project it performed to its design potential but also exhibited some limitations. The rollers, brake, clutch, encoder and motor drive all shared the same axis of rotation which necessitated the use of a composite axle shaft. In practice it proved to be difficult to maintain the perfect alignment of all these components. In order to provide minimal friction so as to allow freewheeling, the clutch and brake had to rotate with minimal drag. This meant that they had to be aligned with no more than 0.1 mm axial run-out and therefore required frequent adjustment. Other than the mechanical issues the platforms contribution to the realism and perception of immersion within, and interaction with, the virtual world proved to be the key issue in allowing users to explore the (virtual) built environment in a manner which would allow them to make qualitative judgements on issues of accessibility.

Sensory integration and the perception of self-motion in VR.

Without feedback on the physical characteristics of the surfaces encountered during wheelchair VR navigation key elements of the built environment that limit manual wheelchair mobility are neglected. In this regard it becomes crucial in designing virtual environments for wheelchair users that the physical factors that influence wheelchair motion can be perceived through the ‘feel’ provided by the combination of visual and non-visual feedback. The haptic VR interface developed in this project attempts to solve this problem by reacting to the changing floor conditions specified within the virtual world. To the user of the interface changes in roller resistance (or an applied torque) are perceived primarily through the sense of muscle effort which is informed by proprioceptive feedback from the upper limbs during movements directed toward the control of wheelchair motion (see Cafarelli, 1982; McCloskey et al., 1983; Sanes & Evarts, 1984). The altered mechanical properties of the rollers are therefore perceived by the user as a change in ground conditions. Proprioceptive feedback together with vision is recognised as an important component in the perception of self-motion (Beer et al., 2002; Harris et al., 2000; Bard et al., 1995). Hence, the perception of self-motion during VR wheelchair navigation results from the integration of the visual detection of the optic flow generated by graphics system and the proprioceptive feedback arising from the arms during wheelchair propulsion. In the system described in this study our user evaluation highlights that when visual and non-visual feedback are matched (e.g. uphill or downhill motion) a highly realistic simulation is generated. In contrast, simulation of kerb negotiation does not produce the expected combinations of sensory stimuli and is therefore not considered as a truly realistic simulation. In designing VR systems that require the user to perceive self-motion consideration should therefore be given to the provision of haptic interfaces that not only measure action but can provide direct feedback to the user and thereby through feel aid in establishing presence within the VR environment.

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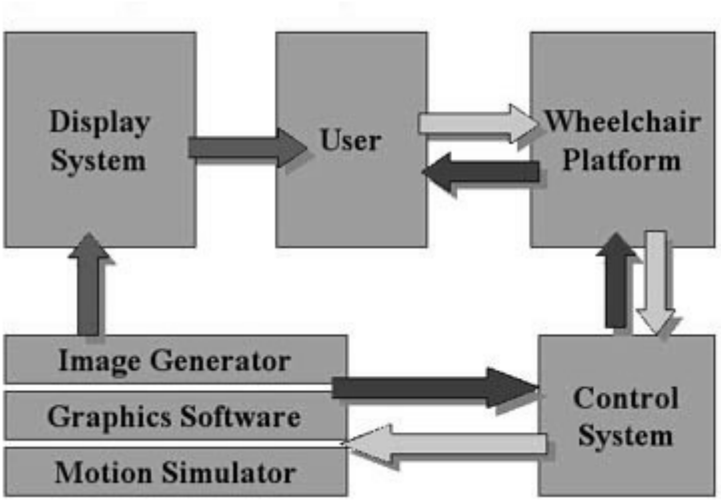


Figure 1. System overview highlighting the main routes of information flow during operation.

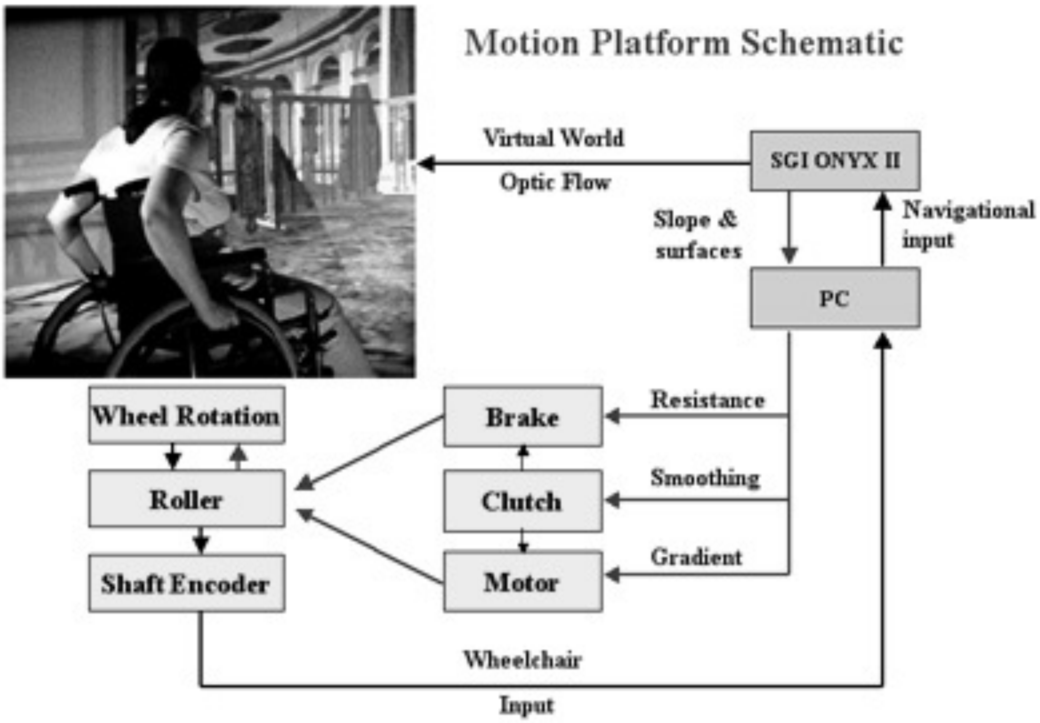


Figure 2. Diagram illustrating components and control elements within the complete VR system.

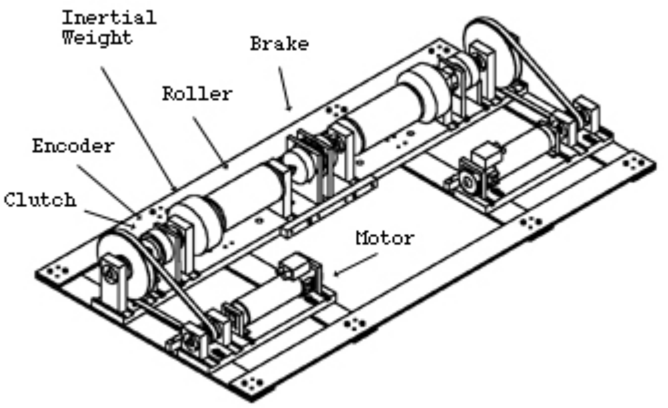


Figure 3. Detail layout of principle wheelchair interface components.

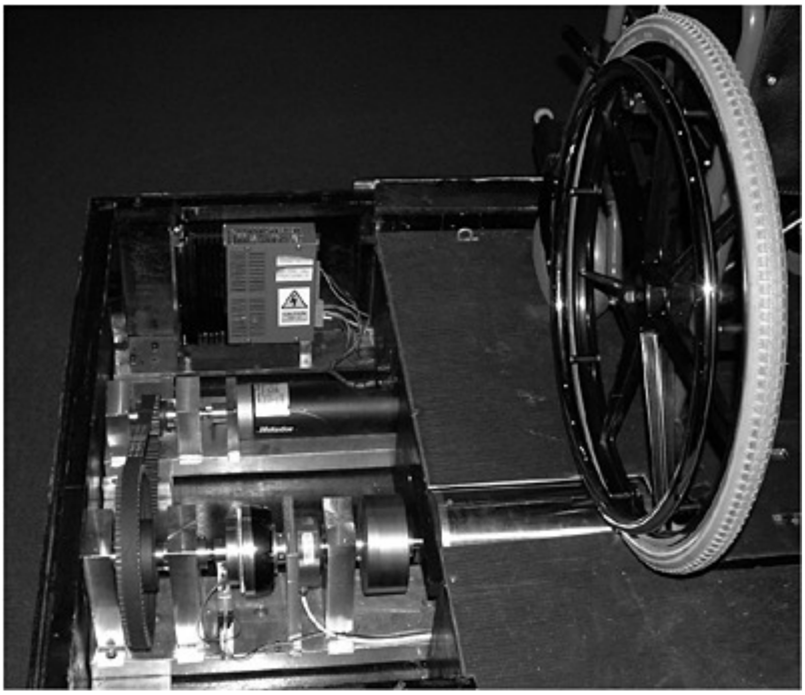
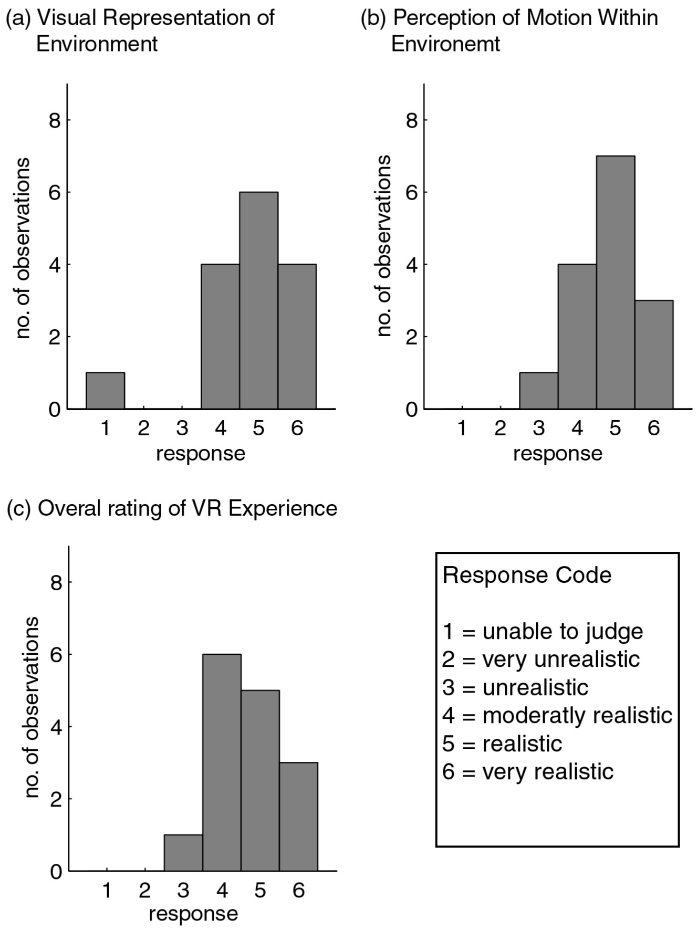


Figure 4. The motion platform roller assembly. During operation the main drive components of the system are fully enclosed thereby providing protection from moving parts.

Figure 5. Illustration of wheelchair platform within the virtual reality laboratory.


(a) Visual Representation of Environment

(b) Perception of Motion Within Environemt

(c) Overal rating of VR Experience

Figure 6. User evaluation of wheelchair interface in respect of (a) the realistic visualisation of the built environment, (b) the perception of motion within the VR simulation and (c) an overall rating of the integrated VR system.

Figure 7

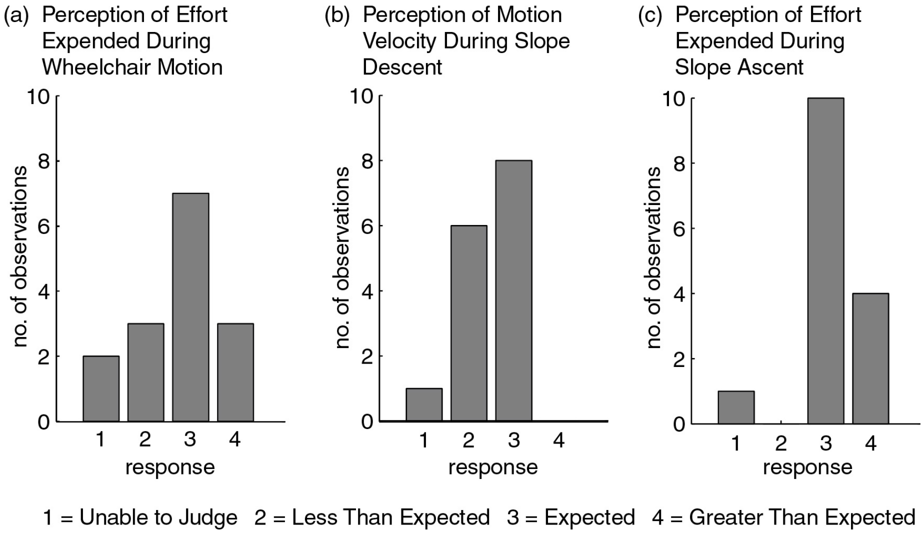


Figure 8. Histograms depicting the responses collated from the user evaluation questionnaire in respect to (a) the perception of the level of effort needed to produce wheelchair motion, (b) the perception of motion during slope descent and (c) the perception of effort associated with slope ascent. The key to the response code used in each histogram is provided at the bottom of the figure.

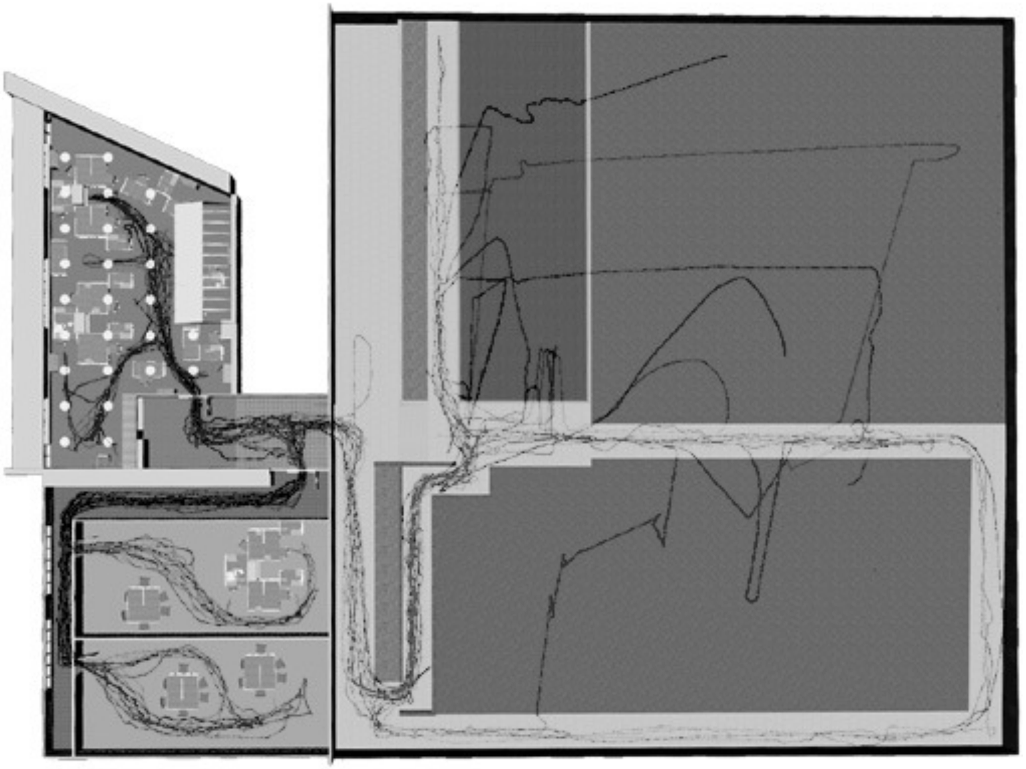


Figure 9. Navigation paths within the Virtual Environment. Tracks illustrating the navigation routes used by the 15 volunteers are shown superimposed on an architectural plan of the Virtual Environment.

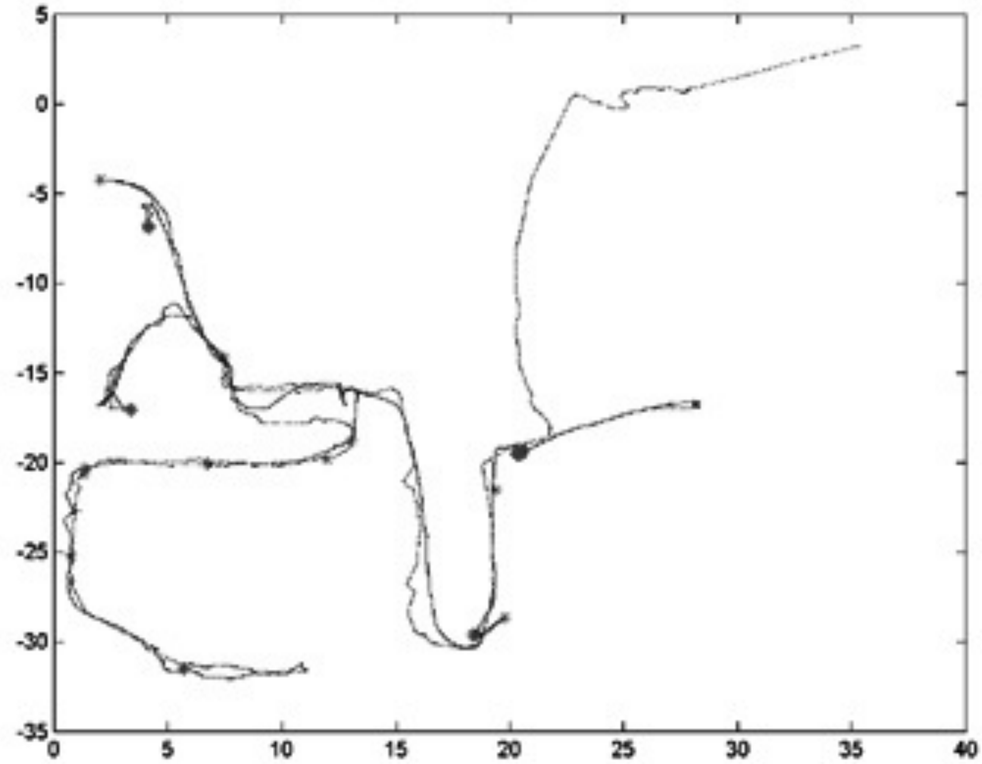


Figure 10. Log of Wheelchair Collision Points. Motion within the virtual environment for one subject is mapped to illustrate the spatial coordinates of collision points (circles) encountered during navigation within the virtual environment.

Age Range (years)	Duration of wheelchair usage (years)	Wheelchair models used by volunteers
19 - 59 (mean 41)	0.75 - 54 (mean 18)	Quickie (n=8) RGK (n=3) Elite (n=2) Suntec (n=2)

Table 1: Summary of volunteer profiles.

Questionnaire Category	VR System Feature Evaluation	Rating Scale Response
System Integration	a. Visual Representation of Environment b. Perception of Motion Within Environment c. Overall Rating of Virtual Reality Experience	1. Unable to judge 2. Very unrealistic 3. Unrealistic 4. Moderately realistic 5. Realistic 6. Very realistic
Interface Performance	a. Level Ground Propulsion b. Freewheel motion c. Motion along corridors d. Turning Manoeuvres e. Changes in Surface f. Negotiation of Doorways g. Descending Slopes h. Ascending slopes i. Object Collisions j. Negotiation of Kerbs	
User Effort	a. Perception of Effort Experienced During Wheelchair motion b. Perception of Motion Velocity During Slope Descent c. Perception of Effort Expended During Slope Ascent	1. Unable to Judge 2. Less than Expected 3. As Expected 4. Greater than Expected

Table 2: List of features rated by the users and the rating scales used.