Development of a wheelchair virtual reality platform for use in evaluating wheelchair access

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[1]*http://www.strath.ac.uk/Departments/Architecture/VEL/intro.htm*
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ABSTRACT

In the UK the Disability Discrimination Act 1995 aims to end discrimination against disabled people. Importantly the Act gives the disabled community 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 project aims to provide instrumentation allowing 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. The project represents a collaborative effort between architects, bioengineers and user groups and will be comprised of stages related to platform design, construction, interfacing, testing and user evaluation.

1. INTRODUCTION

With the increasing age profile of developed nations due to the improved health care coupled and reducing mortality rates (Tuljapurkar et al.,2000) there will be a continual increase in the number of people becoming reliant on wheelchairs for mobility as a consequence of disease or injury. In most societies wheelchair users are often discriminated against in areas such as employment and education due in large part to inadequate access provision to the built environment. This can lead to a below average standard of living and the need for a lifetime of state support. The development of a virtual reality facility which allows wheelchair users to explore virtual representations of the built environment should, if appropriately utilised by user groups and architects, lead to socio-economic benefits to a large group of disabled people through improved building design and therefore equal opportunities. In addition, the use of virtual reality systems where navigation is integrated with the sensing of intended motion of wheelchairs (or other forms of assistive devices) will be of benefit to those groups who need to examine compliance with the requirements of equal opportunity legislation. This could lead to the establishment and widespread adoption of design standards relating to building design for wheelchair access.

The long term objectives of this project are to provide a virtual reality facility that can be used to generate, via an interaction between architects, designers and wheel chair users, guidelines which address the issue of wheelchair access to, and within, the built environment. The project aims to design and build a wheelchair motion platform through which wheelchair users can explore virtual representations of buildings. It is envisaged that such a facility would form a powerful and cost effective means of evaluating wheelchair access provision early in the design of new buildings and in the redevelopment of existing buildings (Forest and Gombas 1995). Accordingly the following preliminary objectives need to be met:

- The design and construction of a manual wheelchair motion platform that can accurately monitor intended wheelchair motion and can provide physical and optical feedback to the wheelchair user on the presence of virtual obstacles or changes in floor coverings or slope.
- Interface the platform with a Silicon Graphics virtual reality facility to provide an immersive virtual environment within which navigation is linked to the intended wheelchair motion.
- Generate virtual representations of a range of building types in order to test and calibrate the performance of the platform and perform an evaluation of the system by wheelchair users.

2. WHEELCHAIR DRIVEN VR SYSTEM

The facility is comprised of seven functionally separate elements: projection system; image generator; graphics software; motion simulator; roller system; control system; user. An overview of the system is shown in Figure 1.

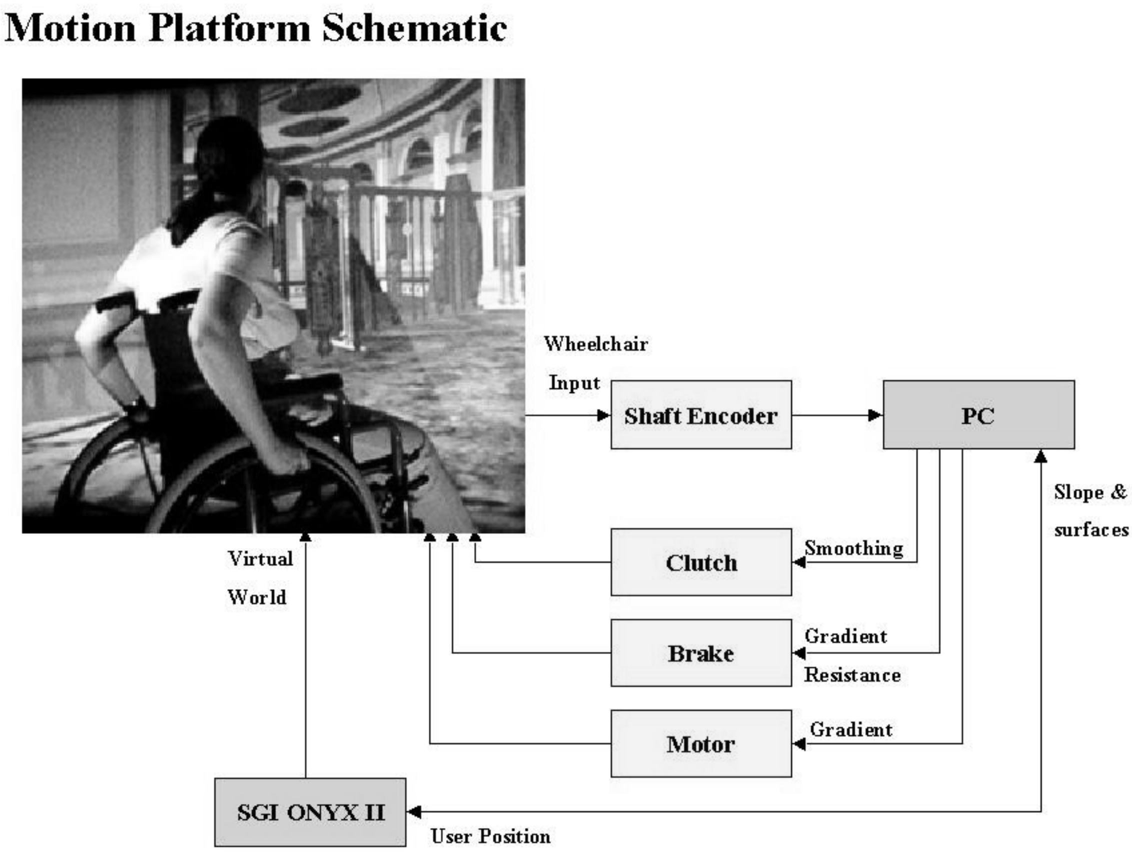

Figure 1. *Layout of the wheelchair motion Platform and Virtual Environment Laboratory (VEL)2.1 Projection system*

2.1 Projection system

The virtual environment is visualised using a three-projector system that provides a 150° by 40°, 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 immersion within the scene.

2.2 Image Generator

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.

2.3 Graphics Software

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.

2.4 Motion Simulator

As outlined above, the motion simulator and the graphics software are a close-coupled system. The motion simulator communicates with the control system over a TCP/IP network, and the link between simulator and graphics is via a shared memory segment. The task of the motion simulator is to accept incoming data from the control system. This data relates to the individual incremental angular displacement of both wheels on the motion platform. This data is compared to the previous increment, to determine whether the wheel is rotated forward or backward, and to pass this information to the next stage of the algorithm. The basis of the motion control algorithm is the determination, through an analysis of similar triangles, of the location of the centre of rotation along the rear axle of the virtual wheelchair and the angle through which is turned. From this the transformation of the eye point and rotation of the view vector can be determined.

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 and pitch of the chair and the corresponding view. The same intersection procedure can also be used to identify the surface under each wheel, this information can then be used to index material properties, such as rolling resistance, which can be passed back to the control system.

2.5 Roller System

The roller system is housed within a framework that supports the wheelchair and occupant, and converts wheel motion into an instrumented rotation of the main shaft. The system is duplicated for each wheel of the wheelchair. Mounted on each shaft are the brake, clutch, encoder, inertial mass and the take off for the motor drive. A detailed discussion of the design rationale and function is given in section 3.

2.6 Control System

The control system is based on a standard PC with purpose written software, that interfaces with the image generator via a network link using TCP/IP and with the instrumentation via a General Purpose Interface Board (GPIB). The control system feeds the motion engine of the image generator with incremental readings from the rotary encoders on the motion platform whilst controlling the feedback stimuli to the wheelchair on the basis of data received from the simulation in order to effect changes in floor conditions or collisions.

2.7 Wheelchair User

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 by the users visual perception of progress through the virtual environment and by the perceived proprioceptive changes associated with alterations in the rolling resistance of the wheelchair. By closing the feedback loop with a human rather than a further pair of sensor connections, it is expected that any minimal latency or hysteresis in the rest of the communications path will be compensated for by the user.

3. DESIGN OF MOTION PLATFORM

3.1 Manual Wheelchair Interface

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 the 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 (Hofstad and Patterson 1994 for modelling characteristics). Secondly, it was to provide additional non-visual (proprioceptive) feedback to the user of the environment represented by the virtual world, in order to match optic flow and visual 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 shows the detailed layout of the principle components of the wheelchair interface.

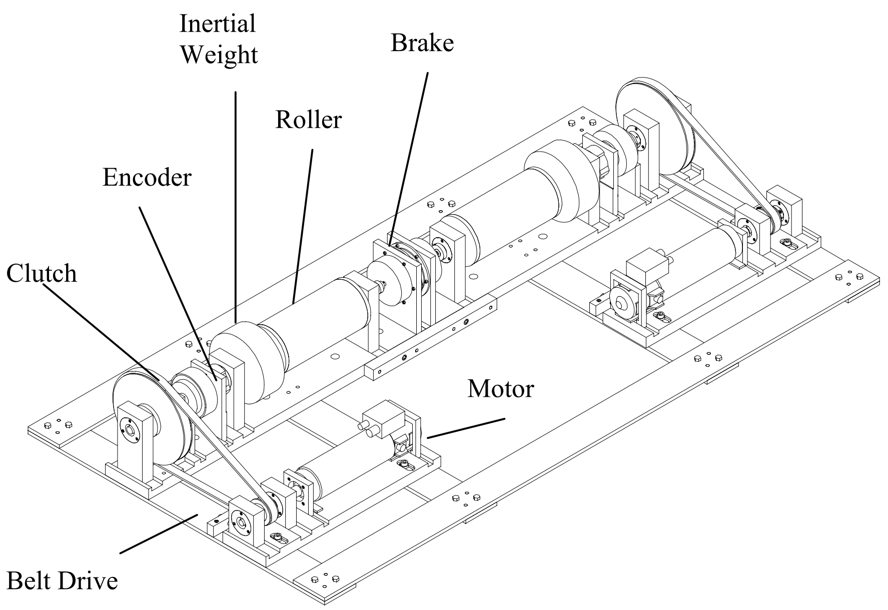

Figure 2. *Physical Components of the Wheelchair Interface without the Cover*

The physical structure of the wheelchair interface is based around a pair of rollers mounted so that one roller is in tangential contact with each of the driving wheels. Frictional contact between the tyre and the roller is sufficient to ensure that the roller rotates simultaneously with each wheel and so could then be used to navigate within the virtual environment. The use of two rollers was required so that differential motion of the driving wheels of the wheelchair could be distinguished to detect turning.

A large number of environmental features were identified for which accessory physical feedback could enhance the visual feedback of the virtual environment. These included slopes and cambers, kerbs, uneven surfaces and different ground surfaces. For the initial design of the wheelchair interface it was decided to concentrate on providing feedback for different ground surfaces and different grades of slope, as these are the features most commonly encountered by the wheelchair user. Different floor surfaces are simulated by altering the resistance to motion of the rollers, when pushing the wheels. A variable torque hysteresis brake is used to provide resistance to motion at each roller. The brake is used to provide increased resistance and so simulate the effect of gravity on the wheelchair when moving up a slope. Simulation of the wheelchair moving down a slope requires active input into the system, providing a torque against which the user can control their movement down the gradient. A variable torque motor is used to provide this input for different

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grades of slope. Switching between use of motor and brake is accomplished by monitoring the position of the rollers.

An early design proposal suggested that the wheelchair platform should tilt in response to changes in gradient within the computer model. This may have been advantageous because users often vary their seating position to alter their centre of gravity when traversing slopes. However due to the increased complexity of such an implementation, and the level of visual feedback already available, this feature was discounted.

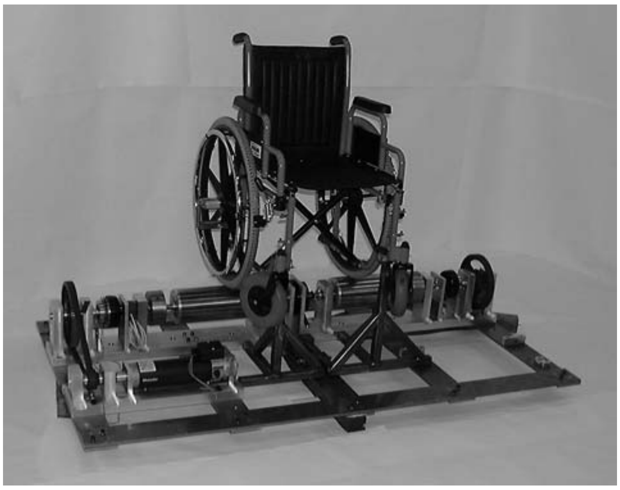

Figure 3. *Photograph of Wheelchair Motion Platform*

3.2 Physical Structure of the Wheelchair Interface

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. Each roller is constructed from seamless steel and aluminium discs were inserted into the ends of each tube to close the roller, and to provide a bush to which the axle could be secured.

The roller shaft is supported by a pair of single row radial ball bearings mounted in support pillars, fixed to a solid base plate, as illustrated in figure 3. The roller and space for an inertial mass is 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. Each brake is rigidly mounted coaxial to the roller shaft. The motor is geared to the roller shaft using a toothed belt and is coupled by an electromagnetic clutch.

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 held in place on the rollers, and a ramp allows the user to gain access to the facility. The system is electrically isolated.

3.3 Design Issues for the Wheelchair Interface

Normal translation in a manual wheelchair is a discontinuous motion. Between propulsive pushes the user needs to reposition the arms and during this period the wheelchair decelerates at a rate dependant on environmental and wheelchair characteristics. To simulate realistic navigation in the virtual world using encoder data from the rollers as the control input, requires that roller motion simulates real wheelchair motion with respect to kinematic parameters. These kinematic parameters are dependant on the interaction of the inertia and resistance to motion of the roller system. In the real environment, wheelchair motion consists of rotary motion of the four wheels, and linear motion of the wheelchair and user. When navigating in the virtual environment, the only physical motion is provided by the rotary motion of the rear wheels, the rollers, inertial masses, the brakes and, when engaged, the motors. To provide basic navigation through the virtual environment, a high inertia coupled with a low rolling resistance is needed in the physical interface.

The inertia of the roller system is predominantly determined by the fixed inertia of the contributing components. Provision has been made for the inclusion of an inertial mass for each roller. This allows the inertia of the system to be increased, should the basic inertia of the roller system prove too low, and provides a measure of adjustment to the system.

The biggest design issue has been the reduction of resistance of motion of the system to an acceptable level. The acceptable level was defined as that required for the system to decelerate with similar characteristics to the wheelchair and user when on a smooth level surface such as linoleum. A belt connection considerably increased the overall resistance to motion of the system and was avoided where possible, and therefore the brake was mounted directly coaxial to the roller shaft. The motor needed to be geared with respect to the roller and thus a belt connection was unavoidable. However counteracts the increase in system resistance by increasing the torque provided. An early prototype used needle bearings to mount the roller shaft. The characteristics of the needle bearings resulted in a failure of the roller to be able to match the required deceleration rates, and ball bearings were used in subsequent designs.

Additionally, a single roller per wheel was used rather than two. While a pair of parallel rollers per wheel would offer simple control over wheel positioning, a single roller system gives less rolling resistance. Therefore the platform has had to incorporate a set of adjustable bars and straps which fix the wheelchair in the correct position over the roller systems.

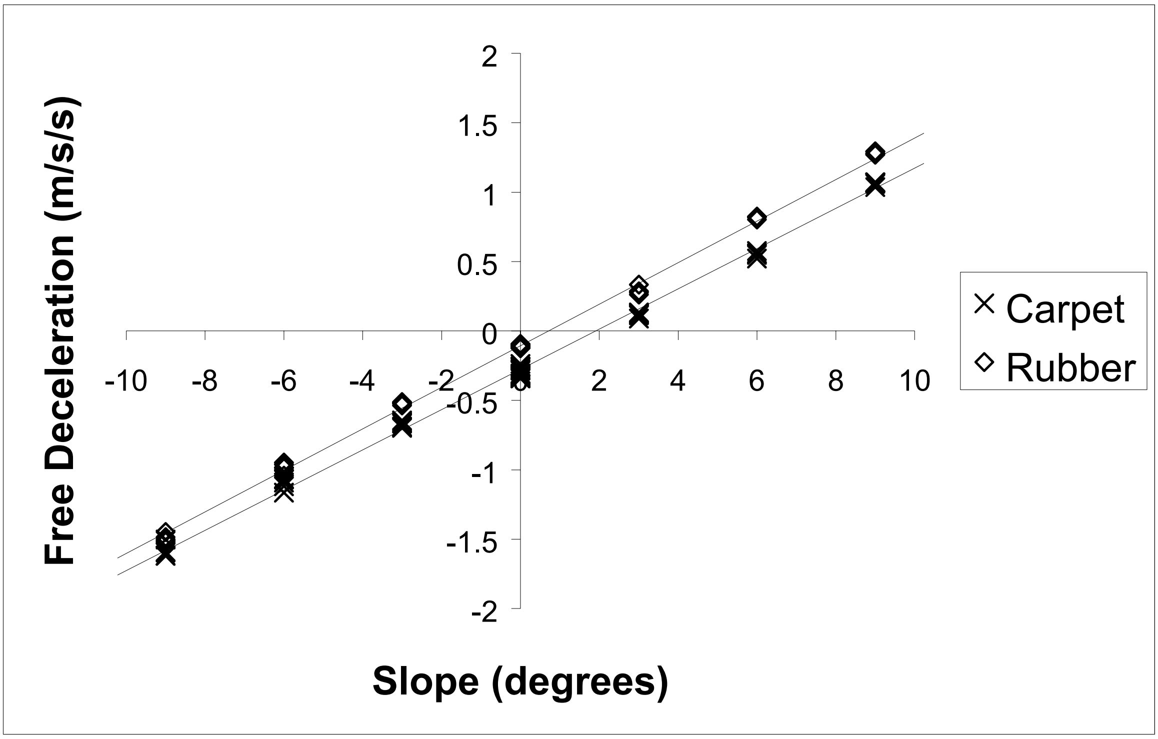

Figure 4 *Measured Free Acceleration for Carpet and Ribbed Rubber on Various Grades of Slope*

3.4 Matching the real world to the Virtual Environment

Defining the kinematics of wheelchair motion with respect to user input, surface and slope conditions, and different wheelchairs can be an involved task with many variables (Kauzlarich and Thacker 1985; Frank and Abel 1989; Hofstad and Patterson 1994). The creation of algorithms to encompass such variability was outwith the scope of this project, and an empirical approach was adopted towards the determination of control settings for various surface considerations. This involved the measurement of the motion of a single wheelchair when there was no user input, for real motion over various surface conditions and when on the wheelchair interface. The condition of no user involvement was used so that it could be reliably reproduced in all experimental circumstances. A rotary encoder was attached to the axle and spokes of one wheel of a basic wheelchair to investigate this relationship. The wheelchair was rolled with no external input over a range of surface coverings, for example ribbed rubber and carpet, and several different grades of slope. The acceleration of the period when there was no external input was calculated. Data has been collected for slope and surface combinations and a best-fit line for free acceleration against slope for each surface was calculated (figure 4). The graph shows a linear relationship between the free deceleration of the wheelchair and the grade of slope. This basic relationship is subject to an offset due to negative acceleration equal to the free deceleration of the wheelchair over each floor surface. A database of the free deceleration of a wheelchair in the real environment has been obtained from which the required free deceleration of the roller system for any particular surface and slope combination can be extrapolated. By knowing the free deceleration of the wheelchair and the roller system, the virtual environment can then be simulated by a range of voltage inputs for the brake and motor.

The kinematics of deceleration also vary depending on wheelchair characteristics, and these must be taken into account when setting up a session with the wheelchair interface. A calibration procedure is required when a user is introduced to the interface for the first time. The diameter of the wheel also need to be input into the control so that the ratio between roller and wheel for different wheelchairs is respected.

4. INTEGRATING MOTION PLATFORM WITH VIRTUAL ENVIRONMENT LABORATORY

4.1 Integrating Mechanical motion Platform and Virtual Environment Laboratory

It was decided at a relatively early stage to use a personal computer as the host for the motion platform and electromechanical devices, as this is a computer that is relatively straightforward to implement using commercially available software and peripherals. The PC could also provide a multi-role capability.

The team had earlier experience using sockets in a Unix to PC environment and this was one of the reasons for using this proven route again. For this reason a PC based solution was chosen, although many other integration routes are possible (Stredney et al 1995), the modular approach means that in the future interfacing to other VEL computers should be straightforward.

4.2 Host Personal Computer

Based on a networked Dell 220 Precision, the PC has a Digital to Analogue (D/A) card driving the clutches, brakes and motors through a purpose built power supply unit, and a commercial motor interface unit. The optical encoders provide feedback to the PC on the position of the rollers in space, and hence the position and orientation of the wheelchair, which is then be sent to the Silicon Graphics machine for conversion into 3D world co-ordinates. Standard geometrical treatments are available which describe the wheelchair dynamics (Stredney et al 1995).

4.3 Communications

The system uses sockets which provide either UDP (User Datagram Protocol) or TCP (Transmission Control Protocol) in order to establish communication between the PC and the VR Platform, currently a Silicon Graphics machine.

The use of this standard technology means that if the VR host is upgraded, the wheelchair motion platform will still be able to be commissioned with little or no difficulty.

5. CONCLUSIONS

The mechanical construction of the wheelchair motion platform is complete, although a certain amount of user calibration is required. The design and manufacture of the platform has proved to be a more complicated task than first estimated due to the requirement to provide low rolling resistance and minimal deflection when loaded by the user. This has meant working to high levels of machining accuracy, and assembly alignment for the eight separate bearings. Since in this application the user must be able to steer, the roller assembly is duplicated for each side resulting in a high quality assembly platform which can accommodate a wide range of wheelchairs, and which has good mechanical performance.

The design has enabled the independent use of brake, clutch, and motors which means that a wide variety of surface and slope conditions can be simulated in as natural a way as possible. These include uphill and downhill slopes combined with smooth and rough surfaces. The design can be evaluated by the user community, which includes architects, building design engineers and healthcare professionals as well as wheelchair users. Uniquely this system gives a sense of feeling of what a proposed design will be like to use in practice, which cannot be duplicated by any other method. Whilst it is possible to evaluate designs using conventional methods, none conveys the actual physical experience of wheelchair use in proposed buildings, which provides solid education and feedback outcomes for the user community.

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6. REFERENCES

G. Forrest, G. Gombas, (1995), Wheelchair accessible Housing: Its role in cost containment in Spinal Cord Injury, *Archives of Physical Medicine and Rehabilitation,* 76*, 5,* pp450-452.

T. Frank, E. Abel, (1989), Measurement of the turning, rolling and obstacle resistance of wheelchair castor wheels, *Journal of Biomedical Engineering*, 11, 462-466.

M. Hofstad, P. Patterson, (1994), Modelling the propulsion characteristics of a standard wheelchair, *Journal of Rehabilitation Research Developments*, 31, *2*, pp129 – 137.

J. Kauzlarich, J Thacker, (1985), Wheelchair tire rolling resistance and fatigue, *Journal of Rehabilitation Research Developments*, 22, *3*, pp25 – 41.

D. Stredney, W. Carlson, J. Edward Swan II and Beth Blonstein, (1995), The determination of Environmental Accessibility and ADA Compliance Through Virtual Wheelchair Simulation, *Presence: Teleoperators and Virtual Environments*, **4**, *3*, pp297-305

S. Tuljapurkar, N. Li and C. Boe, (2000), A universal pattern of mortality decline in the G& countries, Nature, *405,* pp789-792.