The enhancement of a virtual reality wheelchair simulator to include qualitative and quantitative performance metrics

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Abstract

The increasing importance of inclusive Design and in particular accessibility guidelines enshrined in the UK 1996 DDA act has been a prime motivation for the work on wheelchair access, a subset of the DDA guidelines, described in this paper. The development of these guidelines mirrors the long standing provisions developed in the USA although in the UK these guidelines have only become applicable since 2004. In order to raise awareness of these guidelines and in particular to give architects, building designers and users a physical sensation of how a planned development could be experienced a wheelchair virtual reality system was developed. This compares with conventional methods of measuring against drawings, and comparing dimensions against building regulations, enshrined in the Uk under British Standards[1]. Features of this approach include the marriage of an electro-mechanical force-feedback system with high quality immersive graphics as well as the potential ability to generate a physiological rating of buildings that do not yet exist. The provision of this sense of "feel" augments immersion within the virtual reality (VR) environment and also provides the basis from which both qualitative and quantitative measures of a building's access performance can be gained.

Key words: wheelchair, simulation, virtual reality, haptics, physiological cost

1. Introduction

Recent times have seen an upsurge in interest in the area of “inclusive design” within which access to the built environment has enjoyed a prominent position. There are a number of factors providing the impetus for this, not least a growing awareness of the quality issues incumbent within inclusivity. In the UK the Disability Discrimination Act (DDA) (DDA, 1995)[2] seeks to create a non-disabling environment which mirrors in part earlier work from USA under the ADA.[3] However, within the legislative framework there is an acknowledgement that prescriptive building codes do not always meet all the needs of those who rely on wheeled mobility. Indeed there is a growing awareness that adherence to design guidelines does not always result in the optimal, or even usable, environment. These factors have lead to the production and availability of a range of tools targeting design issues within the architectural sectors (Grant, 2004)[4], which can benefit quality of life and reduce cost Forrest 1995[5]. It is hoped that improvements in the design ob buildings may impact on the injury rate amongst users of manual wheelchairs over 50% of whom had completely tipped over, often resulting in injury, some serious, and many of these incidents are related to wheelchair ramps . Kirby 1994[6] MHRA[7] or reaching[8]. It may also be feasible to use the system partially to assess the safety of new wheelchairs as it has been suggested that design aspects may impact on injury.[9]

In the UK duties under the DDA came into force on 1st October 2004, after which the law states that, “*Service providers will need to consider making reasonable adjustments to the physical features of their premises to make their goods, services and facilities accessible to disabled people*”. A reasonable adjustment will be to remove, alter, or provide a reasonable means of avoiding a physical feature that prevents a disabled person from accessing goods or services. The tone of the legislation suggests that some physical intervention in the building could be sufficient to increase accessibility yet we would contend that "*reasonable adjustments*" should also take into consideration the ability of users to make good use of such refinements. However, the ability to base such a judgement on an analysis of the capabilities of the disabled population is hampered by the lack of data and design tools that can take this viewpoint into account.

Present design analysis methods consist mainly of comparisons against standard benchmarks and the codes inherent within building regulations and are not able to determine the "*reasonableness*" of a particular design decision. What is reasonable for a fit young person in a wheelchair may not be reasonable for an elderly one. The system described here may offer the potential to better inform architects, clients and the user base as to the benefits of proposed design scenarios and regulatory compliance and hence reduce expenditure through quantifiable measures minimising post occupancy rectification. The system can also uniquely give a sensation of how a building will be experienced in practice, both to the building specifier and potentially to the user. There is evidence of a consequent experiential learning effect based on work by Wilson [10] who used VR to navigate both virtual and real buildings.

Attempts at the simulation of an electric wheelchair are often represented by a joystick and PC screen or head mounted display, however systems that explicitly target the sensation of piloting a manual wheelchair are less common. One approach was taken by O'Connor et al 2000 [11] using a portable system for manual wheelchairs in order to encourage exercise via gaming. Another attempt was made by (Trimble 1992) [12] however investigation revealed that this was simply via the addition via mechanical attachment of different inertial weights rather than generating torque feedback, and was also slaved to a small personal computer screen which cannot give a convincing sense of immersion via optical flow or “vection”. Additionally the dynamic behaviour of electric wheelchairs is quite different from manual self propelled variants Bennet 1987[13] though there has been detailed work on the joystick interaction (Cooper 2002[14]) which indicates a “significant correlation” between driving an electric wheelchair in the virtual and real environments.

Another system that specifically aimed at the generation of realistic graphics for the investigation of stroke via wheelchair control was by Maxhall 2005[15]. The VR modelling system aspect of the same system was reported by Backman[16] and here the co-ordinates were driven from a pair of lightweight rollers attached to encoders with the addition of motion sensors. However experience at Strathclyde of the use of the particular head mounted display(HMD) a Virtual Research V8 used by Maxhall – briefly evaluated at Strathclyde, is that cybersickness in common with other units tends to result. With HMD’s the user is also presented with contradictions in the near field as it is difficult to represent oneself correctly in a virtual world. There is however a great deal of work in the field of wheelchair related ergometry relating to physiology such as that by Guo et al 2006[17], Cooper and et al 1998[18] , DiGiovine et al[19] and giving detailed descriptions of the experimental arrangement. The system presented here combines some aspects of ergometry, but was originally intended to generate a feeling for optical flow via convincing visual immersion, and an experience of how a building will present.

2. System Overview

This project aims to provide instrumentation through which wheelchair navigation within virtual buildings can be simulated. The provision of such instrumentation is designed to assist architects and building professions 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. (Harrison, 2000)[20].

The design of a wheelchair simulator can be considered as being derived from three main functional components which are all intrinsically linked:

- The motion platform and associated electromechanical devices
- The graphics system generating the virtual environment
- The control and communications software that links the above elements

The Wheelchair Platform

A photograph of the electromechanical system is shown in Figure 1 which illustrates the major components. These consist of a pair of Matador DC servomotors having 2.1Nm Stall torque, (DCM3F 30/14-A2) with 4:1 gearing to the roller via a toothed belt from Fenner. Each motor is controlled by a Control techniques single phase Midi-Maestro variable speed drive control unit (140 X 8/16) each slaved via a PC National

Instruments PCI-6704 D/A card. Two outputs from the NI card slave each Control Techniques drive, one of which is enable, and the other a proportional voltage to control the torque level generated on the pair of servo motors.

Figure 1 near here

The NI card output is driven by the VB program which is itself linked via TCP/IP to the Virtual reality orld. In short, the slopes of the VR world deliver controlled torque to the wheelchair rims to enable a feeling of slopes. The motors were able to be separated in non–slope situations originally by using a 24VDC BM400 Clark clutch, now replaced by an Ogura TMC 25Nm 24VDC electromagnetic clutch offering superior alignment capability and reduced drag, since this unit, like the brake, runs with no contact in the off configuration. Two steel inertial masses are used each having the dimensions 245mm diameter x 68mm wide with mass of 25.2kg per side. Each of the components is mounted on a series of roller bearings and the position of the rider is calculated by using a pair of Hohner (Model 5505-5500-0512) 512 line rotary encoders. Retardation can be supplied either by the torque action of the motors or the brake units (Ogura TMB 2.5) and collisions are generated by briefly activating the brakes when the user co-ordinate is in contact with a modelled wall. The brakes and clutches are controlled from the Windows 98 PC via the Ni card, operating via a power supply to increase the voltage and current from 10V, 20mA, to the 24V 3A, required. The 10V (20mA) to 24V 3A power supply was constructed in house.

Communication with the virtual world via the Silicon graphics computer was established using TCP/IP firstly by developing a “chat” application to communicate between the SGI computer and the PC. Thus a protocol for sending wheelchair heading, and position was established, using windows sockets under Visual Basic.

The sending information was in the format:

X_position, Y_position, incremental angle theta

where X,Y represent the centre of the chair and the incremental angle theta is the change in angle.

In return from Iris was the supplied string:

Actual Heading, slope value, Surface index

The chair is fixed in place using a four point strap arrangement onto purpose built mounts and is capable of accommodating sporting wheelchairs up to 0.91m, and potentially racing wheelchairs.[21]

The mounting means that the system cannot directly accommodate the “wheelie” in order to ascend kerbs, though this is a commonly used technique.(Kauzerlarich 1987[22]) The pushed, non-self propelled wheelchair variant cannot be evaluated in this arrangement, in common with many fixed chair simulators, however the platform can also accommodate electric wheelchairs. It would be a trivial matter to construct a wooden extension to accommodate racing chairs of up to width 0.91m x length 2.70m, the primary length limitation being only the position of the platform within the VEL. Additionally a ramp is provided for access and ethical processes and were required prior to evaluation. Written and informed consent was provided and the system was authorised by the appropriate University ethics and safety committees.

2.2 The Graphics System

The display driven by the Silicon Graphics computer is concerned with the generation and projection of the virtual environment. This relates not just to the visual simulation but also incorporates the physical characteristics assigned to the computer model. The data set which forms the virtual world is a conventional CAD model which allows the construction and display of any aspect of the built environment. Within this model each element of geometry is attributed with data that represents material and physical properties as found in the real world. In this manner objects can be classified not just with their innate geometrical properties, such as slope or position, but also with characteristics that determine rolling resistance or participation in collision detection.

2.3 The Control System

The control system written in Visual Basic uses the NI DAQ functions as well as USB encoder via a DLL, and is designed to complete the feedback loop between the motion platform and the virtual world. Integration with the SGI graphics machine is achieved by using Windows™ sockets.

Figure 2 near here

With the user and their chair mounted on the motion platform intended motion in the real world is mapped into the virtual world via software algorithms. The task of this feature of the motion simulator is to accept incoming data from the wheelchair platform, this data relating to the individual incremental angular displacement of both wheels on the motion platform. (Hofstadt 1994)[23]This is read by a Data Acquisition Card (DAC) in a host PC which is responsible for communications between the platform instrumentation and the VR system.

Each encoder is read using a driver supplied by the encoder manufacturer (Hohner Inc) and the value is read in to the Visual Basic program via two USB ports. Using the appropriate geometry the position of the wheelchair centre and the heading is recalculated. Here the approach taken is based on that described in Stredney, Carlson, Swan and Blostein 95[24]. Although Stredney defined the geometry for an electric wheelchair the wheel motion portion has some similarities based on the idea of two incremental moves on either side of a fixed length bar.

Figure 3 near here Wheelchair dynamics

In an equal move each wheel moves a distance given by $d_2 = d_1$ so that the eye-point moves straight ahead so the motion is simply along the distance of the vector. However if $d_2 \neq d_1$ then there is a little geometry to work out. Here the concept of a left wheel dominated move has taken place such that $d_2 > d_1$. The width of the wheelchair base is w. All that is required is to find the radius of curvature about the right hand wheel and the new heading angle given by ϕ. Since both wheels are attached to the chair, from similar triangles :

$d_1/r = d_2/(w+r)$ *hence*

$r = -(d_1w(/(d_1-d_2)$ *hence*

$\phi = \arctan(d_2/(r+w))$

In theory a further development based on some knowledge of the actual dimensions of the individual chair could be used but the authors took the approach that the centre of the chair and corresponding to the centre viewpoint of the VEL was sufficient. From this it is possible to determine what type of move the virtual chair is undergoing. Here the approach was to say that moves tend to be either right, or left wheel-dominated by magnitude, and then to transform the calculation of the X,Y point of the chair based on the incremental change in the movement of the wheels. Note that it was the *rollers* that the encoders were attached to and not the physical wheelchair itself. The magnitude of the differential move was calculated in terms of distance and angle through which the chair turned and then this was added to give the new heading angle and the position of the contact point of each wheel, based on the value of the moves of the left wheel move *(lm)* and right wheel move (*rm).* After detecting in which direction a move has been (clockwise or anticlockwise) then the magnitude of the move is found from:

$$m = USB\_delta *pi * roller\_dia/USB\_res$$

where USB_delta is the incremental move and USB_res is the resolution of the encoder which in this case was 512 counts per rev.

The basis of the motion control algorithm is the determination, through an analysis of similar triangles (Stredney 1995), 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 it is turned. (Hofstad, 1994). Note that the castoring effect has not yet been included though one possible approach is suggested in (Cooper 93)[25] The centre position of the chair is then determined (X,Y) as well as the heading value of the chair in degrees. The users eye-point is then calculated by assuming a standard height above the centre of the chair. This calculates a correct viewing position based on the top of the bridge of the nose. the centre of the is then se values are passed to the graphics system where the transformation of the eye point and rotation of the view vector can be determined.

Since the position and heading of the chair inside the virtual space was known at any point it will be seen that a sloping surface should be required to deliver a torque onto the users wheels. It will be seen that the magnitude of this torque is proportional to the slope of the surface and the direction of the heading of the chair. If the chair heading is pointing directly down the slope then the torque will be given by the following relation:

If C = compass heading of the slope: e.g. for a south facing slope $C = 180$

Let the angle of the chair $= \theta$

Then by inspection if $C = 180$ *and the angle that the chair makes with the slope is* θ.

So that we have maximum retarding torque (operating against the users impulse in other words facing up the slope)

So for a chair facing directly down the slope the accelerating torque will be at a maximum – tending to propel the user directly down the slope.

So $\theta = 0; C = 180; C - \theta = 180$ *then retard maximum*

If $\theta = 90; C = 180; C - \theta = 90$ *there should be no effect*

If $\theta = 180; C = 180\ C - \theta$ *then accelerate to the maximum*

Here it will be seen that the relation is based on the Cosine of the angle

So hence the angle can be specified by Motor slope angle. This means that the specified angle call it motor_slope_angle = Compass_heading-θ.

So that for the program calculation:

Motor_setting = Max_motor x Cosine(motor_slope_angle)

This relation was then included in the calculation of the setting for the control unit to control the value of the torque.

There are two solutions when zero torque is applied and this is when the wheelchair is heading directly across the fall line of a slope. It will be seen that minor differences in the torque of a wheelchair heading in the virtual downhill can mean that the chair if not constrained by the user by making a dragging effect on the descent the wheelchair goes into a fairly unstable turn one way or the other. If one imagines being parked at the top of a slope and facing down hill then a hands free rapid descent will result in a chaotic progress down the slope. This was observed to be the case in testing the platform.

Similarly ascending a slope gave most inexperienced people the popularly surprising result that driving a wheelchair up moderate slopes requires significant effort and failure to hold the torque or to use the brake will have the result that the chair will start to reverse down the slope.

Feedback from the graphics system then determines whether the brakes, clutch or motors should be actuated to provide a physical level of feedback to the user. If the world is flat, then the rider rolls the chair and the VR world gives a strong sensation of the world moving towards them. On slopes the motors provide torque dependant on heading so that the torque is maximum going up slope and similarly the user is accelerated down hill when the heading is down slope.

3. System Performance

The maximum torque capable of being supplied by the existing arrangement is 2.5Nm from the motor, giving 10Nm at the roller via the 4:1 gearing at the toothed belt. The maximum torque capable of being exerted on the rim is therefore approximately 43Nm. However practical testing has revealed that at these high values the friction between the rubber tire and the roller starts to break down – though this depends on the mass of the rider.

Figure 4 near here

The performance of some computer based tools for assessing wheelchair navigation can only be indicative in that their conceptual basis lies in implicit performance data. The system described above has been designed to provide an explicit simulation through the electromechanical reproduction of those physical factors that govern the interaction of a wheelchair with environmental situations. Data gathered from using the system may be classified as experiential, statistical or physiological.

3.1 Experiential data

The outcome of a session may be regarded as experiential if it is intended to be empirical and that the conclusion relates to or is derived from the experience of the user. If these experiences are to be regarded as real and the basis from which to make judgements then there must be a measure of confidence in the system performance.

In a previous system trial 15 experienced wheelchair users were asked to navigate around the VR model and on completion were invited to rate how realistic various features of the simulated environment compared with ‘real life’ experiences and expectations. In total thirteen features, relating to the performance of the haptic interface, system integration and perceived physiological effort were rated by each user. This was achieved by use of a questionnaire in which each user was required to rate each feature on a six point ordinal scale. The outcomes from this trial are reported in greater detail by Harrison et al. (Harrison et al 2004)[26].

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 user's 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 frustum 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 those 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 user's responses to features that could be considered as key contributors to wheelchair mobility in the built environment indicated that the system performed to a satisfactory level. 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. Other features that utilise haptics such as the variation in floor surface, changes in slope and collisions were all reported as realistic, and it is concluded that 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.

3. 2 Statistical Data

In parallel with the experiential output the system also logs all interactions between the user, their wheelchair and the environment. In this manner the system incorporates the ability to capture and store information on the route taken and speed achieved along a pathway including collision points, manoeuvre sequences and rest periods. Not only does this present the ability to playback in real time the navigational sequence of a session but it also offers a useful set of metrics for the determination of the safety and effectiveness of a wheelchair user. These data could be used to form outcome measures, such as those suggested by Kirby, taking account of a series of obstacles and the ease and efficiency with which a course could be negotiated. (Kirby,1997). This aspect has obvious benefits in the area of training and rehabilitation, (Stott, 2000), but can also be useful in a design context where the analysis of the data may offer a number of insights. The number of collisions or evidence of excessive manoeuvring might highlighting a particularly awkward section of navigation but also the evidence of preferred routes through a space could offer feedback on the designed appearance of the proposal.

3.3 Physiological Data

This aspect of the instrumentation is currently under development though some initial evaluation has been done and preliminary data is presented here. The intention is to provide a means of calculating a version of Physiological Cost Index (PCI) which can then be used to assess the energy expenditure required to navigate over features within the environment. With this goal in mind a series of physiological measures were been attached to the user with the intention of co-ordinating this with the virtual world. ECG electrodes were attached to the user and the conditioned and filtered signal supplied to the NI interface used by the platform control system, the heart rate in beats per minute were then logged. Some sample ECG output data from the neck and lower back is shown in figure 6 which is based on a number of varying positions based on the Einthoven triangle as a way to record heart rate, this being the optimal one. This protocol has previously been used to assess physiological performance metrics in wheelchair propulsion (Mukherjee, 2001)[27].

Figure 5 near here

The initial process was to request the subject to rest for 30seconds and then to follow a predetermined squared off track as seen in figure 5. ECG data was collected for 3 subjects in the measurement software Spike2 which can then export data as a text file. The data from the VR world was also exported as text files into Matlab which then allowed the combination of heart rate with position as shown in Figure 7.

It can be seen that as the user moves towards the downslope portion there is an increase in heart rate however when the transition is made onto level ground the heart rate reduces. When the torque action of the motors applies again on the up slope the heart rate again increases although the speed of the virtual travel is low – which is as expected as it becomes more difficult. When there is a transition to the level after completing the upslope, the hear rate again reduces however the speed of the chair increases. Finally there is a 30 second resting period in order to allow the heart to recover to its usual level.

Figure 6 near here

Hence the physiological cost index can be calculated from the following based on gait efficiency.

$PCI = (HR\ (w) - HR(r)) / S$

Where:

PCI = Physiological Cost Index.
HR (w) = Heart Rate Walking (heart beats/minute)
HR(r) = Heart Rate Resting (heart beats/minute)
S = Speed of Walking (meters/minute)

Figure 7 near here

This was adapted here to the following calculation:

$$PCI = \frac{\text{Heart rate(moving)} - \text{Heart rate (Resting)}}{\text{Speed}}$$

Though other methods of energy expenditure are possible[28]

The results of this calculation are shown in Figure 9 which shows the increase in "cost" when moving from the down slope to level ground and whilst moving to the up slopes. There is a corresponding decrease as the subject moves to level ground.

Figure 8 near here

This initial test data illustrates that it may well be possible to provide a scoring system for buildings – or more importantly for proposed changes in the built environment and to have these analysed in a quantifiable and verifiable manner. Existing methods minimally comply with established building regulations and are often audited by acess comitees based only on 2 D drawings and an assessment of what is reasonable based on experience. The approach described here could provide a legal framework for compliance which obviates the need for opinion – particularly where experts differ.

Figure 9 near here

The advantage of using the system described here is that the instrument, while being laboratory based, can still present all the navigational opportunities found in the unconstructed virtual world, as well as the real world and in complete safety, Stott[29] Cooper (2005) [30]. It is possible to construct navigational routes within which surface inclination or rolling resistance can be varied by known and incremental quantities so that building specifiers can experiment and obtain a feeling for alternatives as well as applying an independently verifiable test as to what is "reasonable" under DDA legislation.

4. Summary

In order to enhance the impression of reality a computer based wheelchair simulator should ideally mimic real world practice. The most important factor is that it must recognise and respond to real world constraints. Here the real world impacts on the feeling of slopes and surfaces encountered as well as a sense of optical flow or travelling through the model, achieved by having a 150 degree wide x 40degree high viewing optic. The real world genertates torque feedback and collisions and this gives a sensation of how a planned building is experienced. The system described here offers the potetntial to discriminate reasonableness in a quantifieable way by the use of heart rate monitoring via ECG matched to that virtual world. It has also been demonstrated that locomotion through the VR world helps to calibrate vision and can improve any decision making processes that rely on the judgement of distances or spatial qualities. (Iwata,1999)[31]. Previous work illustrates that there has been a realistic attempt to provide a convincing simulation based on the results of questionnaires) from 15 manual self propelled users and this has been augmented by some preliminary work with 3 non-wheelchair users in order to test the concept.[32].

Experiential data has proven to be of value in situations where user participation and the direct observation of results are required; the statistical output being of value where there is a need for the collection and classification of quantifiable data. The addition of physiological logging extends the capabilities of the system to monitoring not just the performance of the wheelchair in the environment but also the energy expenditure and effort required from the user.

While it is easy to equate the use of computer based design tools to the tasks of building code compliance and as an aid to investigating design guidelines there is a growing need to extend the capabilities of the investigation in order to make a repeatable and quantifiable judgement on the physiological cost of a particular feature. This is fundamental to a determination of what may or may not be "reasonable" as a measure of adjustment to the built environment and it is hope that this system offers potential towards that result.

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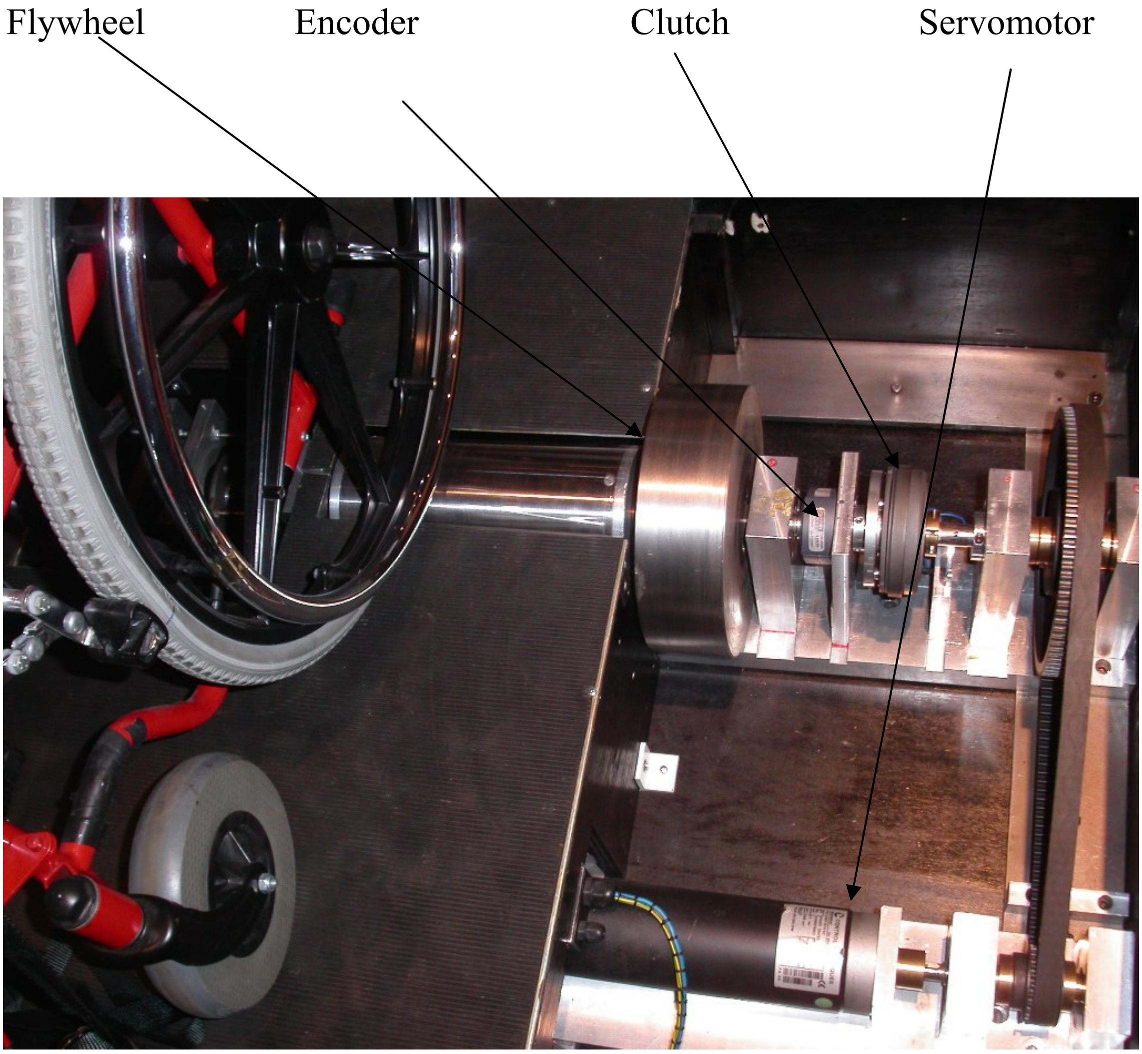


Figure 1 Arrangement of mechanical components on test platform

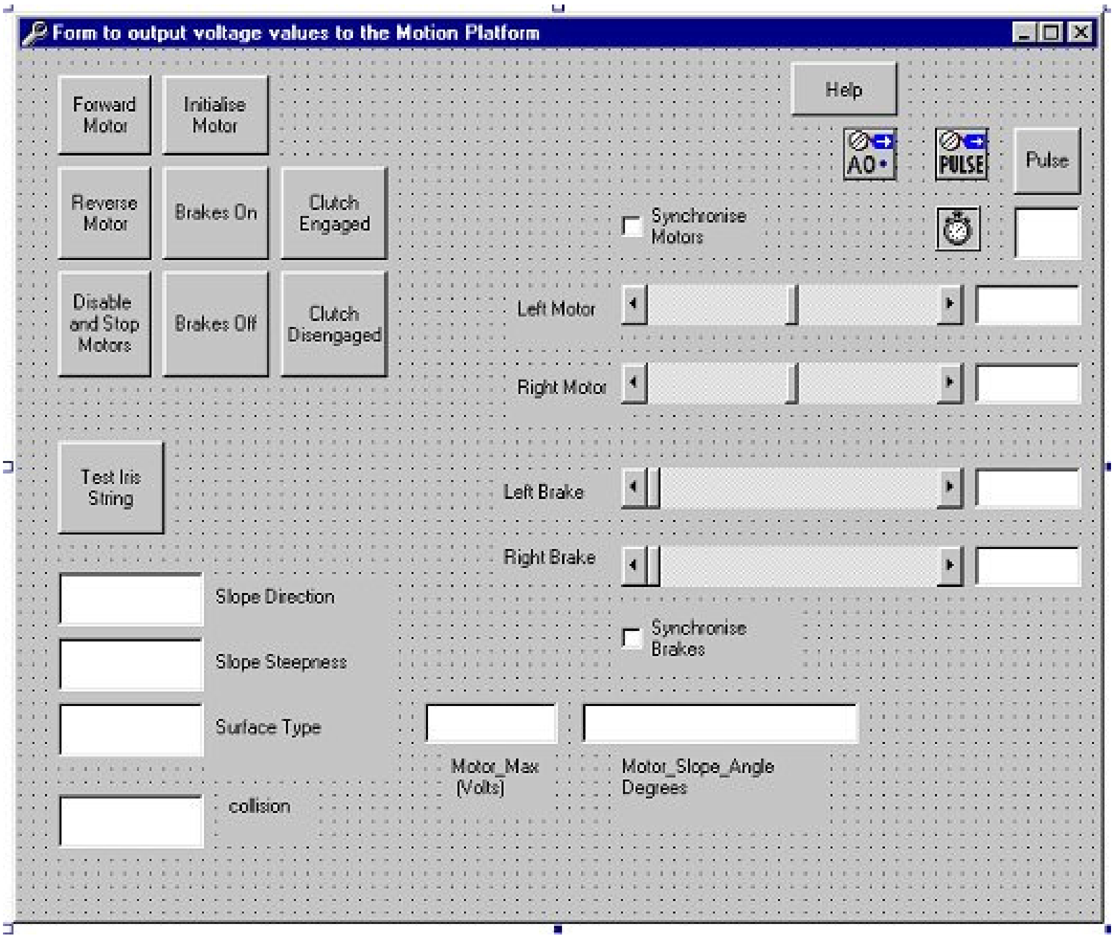


Figure 2 Form to control and test part of the electromechanical system

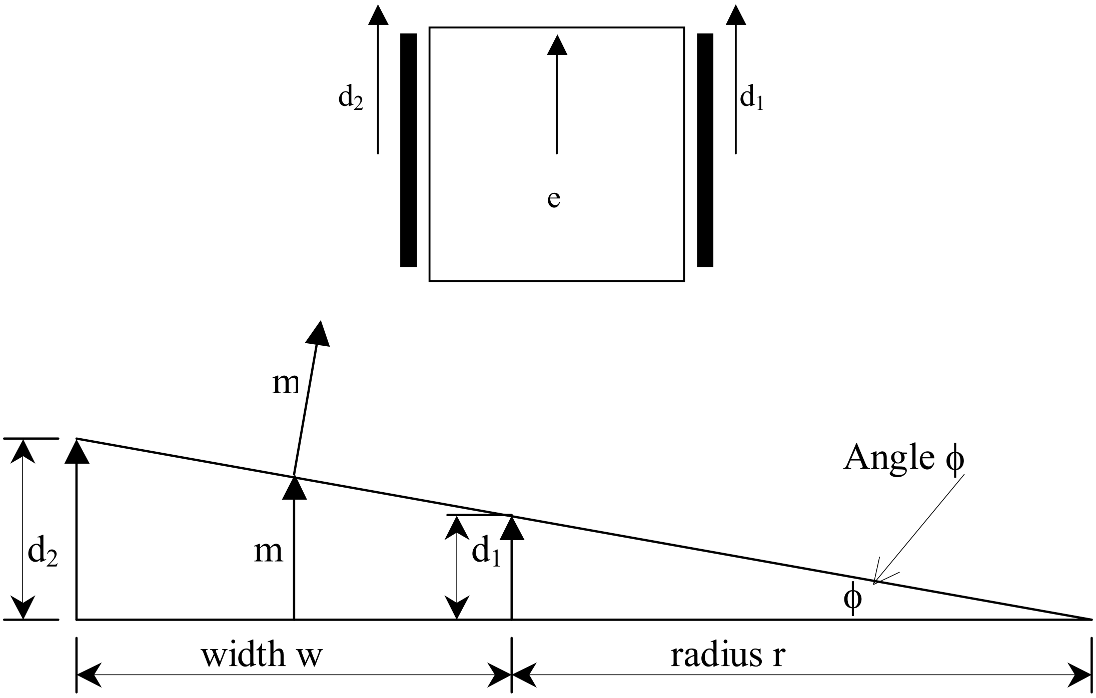


Figure 3 Wheelchair Dynamics (Stredney et al 95

Figure 4 Wheelchair simulator showing the curved screen of the VEL

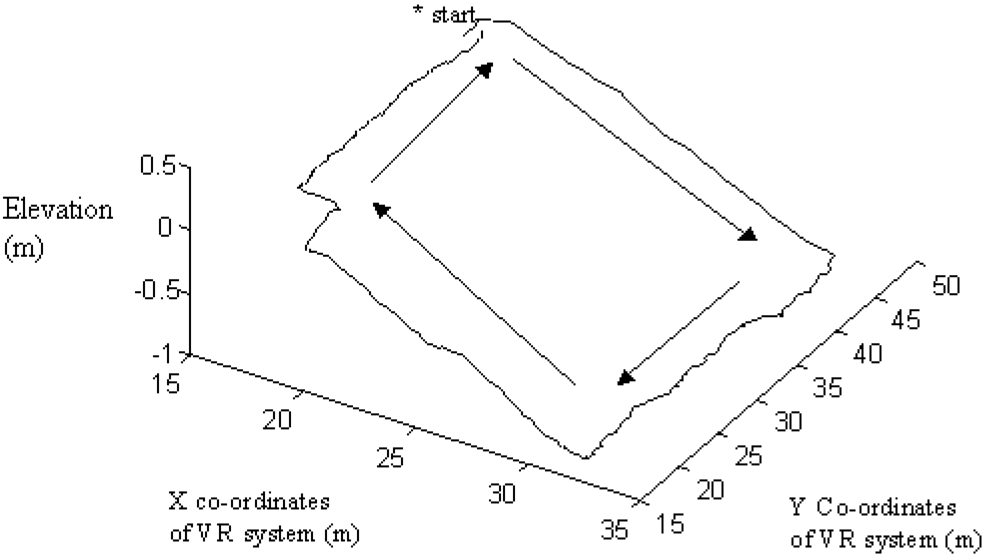


Figure 5 modelled surface within the VR world

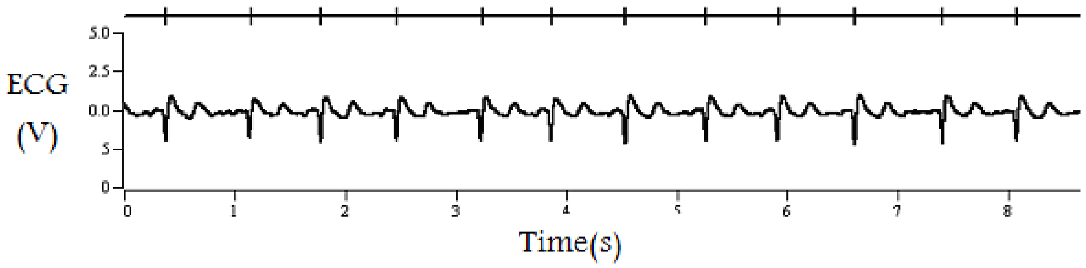


Figure 6 ECG output from upper and lower back showing clear heart rate

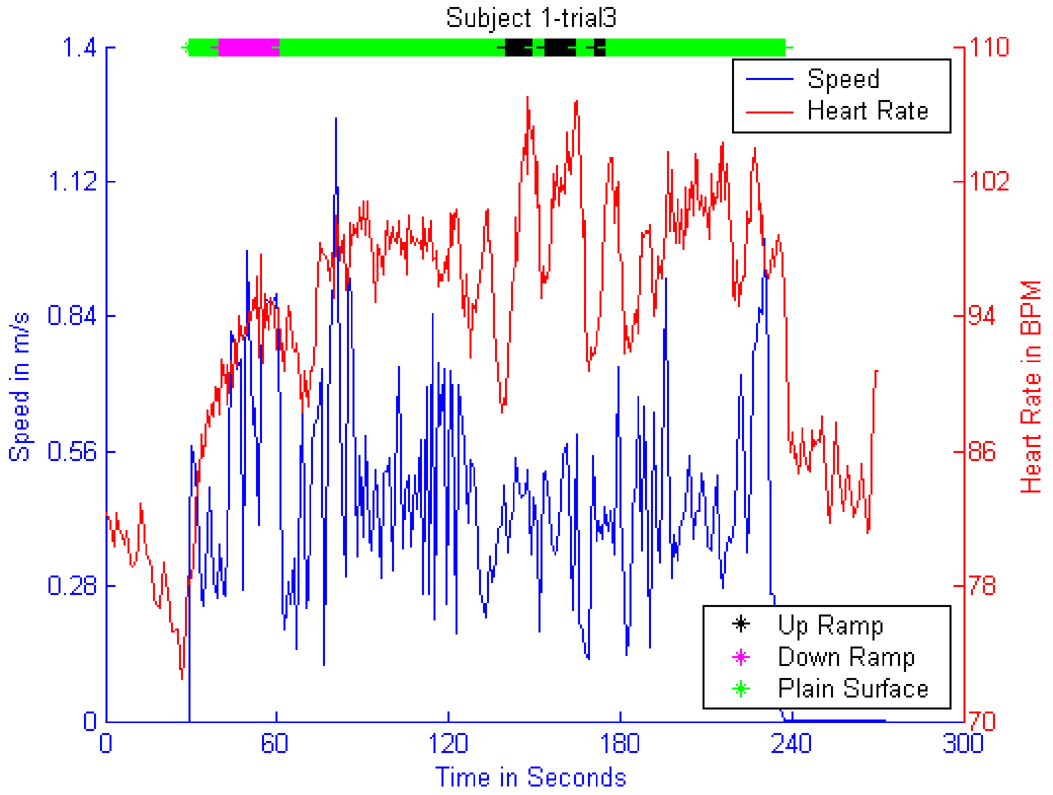


Figure 7 heart rate and speed travelling around model surface

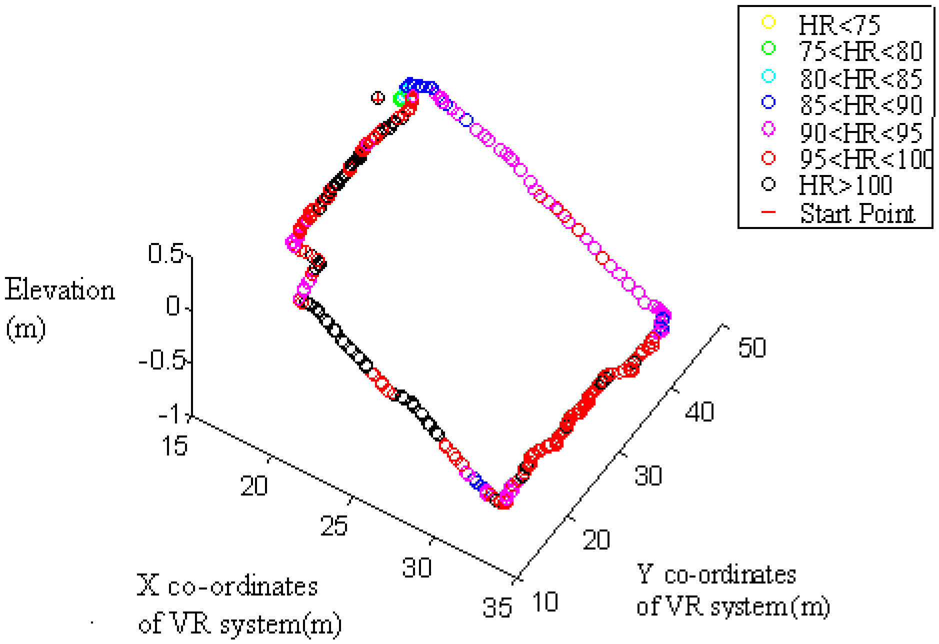
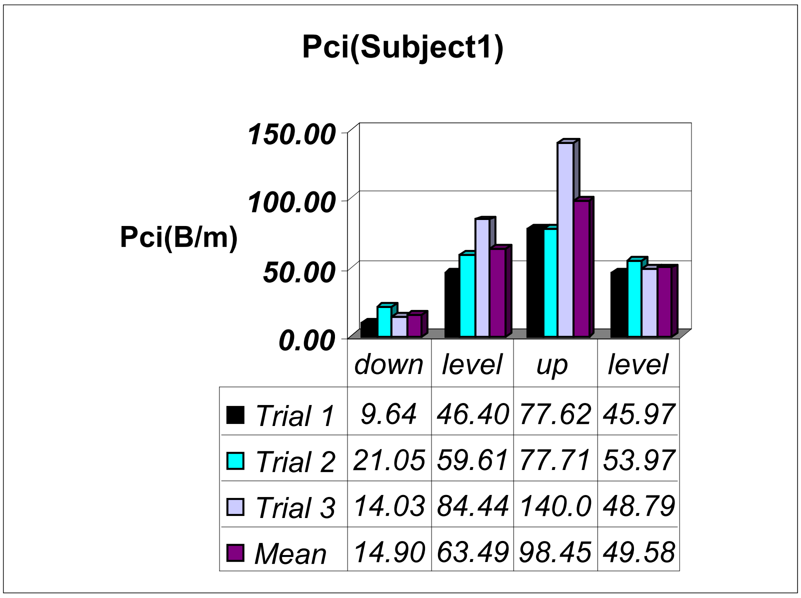


Figure 8 Heart rate mapped with position around test track



	down	level	up	level
■ Trial 1	9.64	46.40	77.62	45.97
■ Trial 2	21.05	59.61	77.71	53.97
□ Trial 3	14.03	84.44	140.0	48.79
■ Mean	14.90	63.49	98.45	49.58

Figure 9 Physiological Cost Index for sample user traversing track