Shared Control Between Man and Machine in Brain Computer Interfaces

by

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Declaration

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

An immersive virtual reality electric-powered wheelchair simulator, controlled by a Brain-Computer Interface (BCI) has been developed at the University of Strathclyde. However, fine manoeuvring is difficult due to the limited number of commands that can be given through the BCI. This project aims to incorporate shared control between the user and an intelligent wheelchair controller to provide a better driving experience, while ensuring the safety of the user.

A shared control strategy was developed to provide three types of assisting behaviours - Obstacle Avoidance, Collision Avoidance and Wall Following. Reactive navigation strategies were devised with the help of user input from the keypad and information about the environment provided by sonar sensors, infra-red sensors and velocity levels obtained from ground truth. Respecting the importance of user autonomy, as re-iterated in the literature, the user has the power to override the assisting behaviour provided, except in the case of a risk of collision.

The shared control technique was evaluated with the help of five healthy volunteers who performed numerous wheelchair driving tasks in manual and shared control modes in the wheelchair simulator. They rated their driving experience using NASA Task Load Index (TLX) scales. In order to study the effectiveness of the shared control behaviours, a secondary task was used to simulate a state of suppressed ability in the able-bodied people. Average workload scores were calculated for all the tasks and revealed that while workload was decreased in the case of shared control for Wall Following behaviour, it was the opposite for Obstacle Avoidance.

The inferences made from the NASA-TLX assessment procedure and the observations made during the experiments have provided a useful insight into the limitations of the system and scope for improvement.

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Contents

List of Figures

Chapter 1

Introduction

1.1 Background

Spinal Cord Injury (SCI) occurs due to severe trauma to the spinal cord and has been considered as a catastrophic condition ever since it was first documented by the ancient Egyptians around 5000 years ago (Eltorai, 2003). In the U.K., the annual incidence of SCI is about 20 people per million of the population and in total over 36,000 people suffer from it (Department of Health, 2005). The corresponding statistics in the U.S.A. are 40 and 265,000 people, respectively (National Spinal Cord Injury Statistical Centre, 2010). An almost inevitable consequence of SCI is the loss of motor function of the lower and upper limbs, depending on the site and extent of the lesion along the spinal cord (Sie & Waters, 2003). Hence mobility of these patients is a major concern for their rehabilitation. The spinal cord may also be damaged due to factors other than trauma such as congenital or systemic disorders, infections, tumours etc., which account for numerous Spinal Cord Disorders (SCDs) such as multiple sclerosis, syringomyelia, arachnoiditis etc. (Woolsey & Martin, 2003a, 2003b). More than 52,000 people in the UK currently suffer from multiple sclerosis (Department of Health, 2005).

Wheelchairs provide mobility to persons with paraplegia and tetraplegia, i.e., impaired function of lower, and both lower and upper extremities, respectively. A range of manually operated or electric-powered wheelchairs are commercially available and are to be selected depending on the abilities of the user (Cooper et al, 2003). Manual wheelchairs can only be used by persons with functional upper limbs having adequate power to propel the wheelchair. Moreover, long-term use could also lead to fatigue and pain of the upper limbs (Somers, 2010). Electric-powered wheelchairs may be used by people with paraplegia as well as tetraplegia (Ding & Cooper, 2005).

The second half of the 20th century saw many developments in the fields of emergency medical services, surgical procedures, pharmacology, rehabilitation etc., in addition to technological advancements that improved the treatment and care of patients with SCI and SCD (Eltorai, 2003). Hence there has been a steep rise in the number of patients surviving with disabilities (Cooper, 1995). Since they would require the use of wheelchairs on a long-term basis, it is imperative that we strive to impart greater autonomy to the users and decrease their dependency on care-givers. Moreover the psychological aspects of being in control of one's life and having a sense of self-worth are critical for SCI and SCD patients to re-integrate with the community (Somers, 2010). Hence considerable amount of research and development is being done towards this end, worldwide.

1.2 Electric-Powered Wheelchairs

Though Electric-Powered Wheelchairs (EPWs) were created in the early 20^{th} century, their popularity increased only after the invention of the transistor, MOSFET and microprocessor, which enabled significant improvements in their design and control (Cooper et al, 2003). The main components of the control system of an EPW are the input device, the controller and motors (see Figure 1.1). The driving commands issued by the user with the help of the access device are translated into speed and directional commands by the controller and relayed to the motors that are coupled to the rear left and right wheels, resulting in desired movement of the wheelchair. Additionally, the controller may receive information about the environment from sensors placed on the wheelchair as in the case of robotic wheelchairs explained in section 1.2.2 (Ding & Cooper, 2005; Velázquez, 2010).

1.2.1 Wheelchair - User Interface

The design of the input device is critical for efficient control of the wheelchair as it is the interface for the user to convey his or her intentions for movement of the wheelchair. Moreover, the user interface must take the user's abilities into

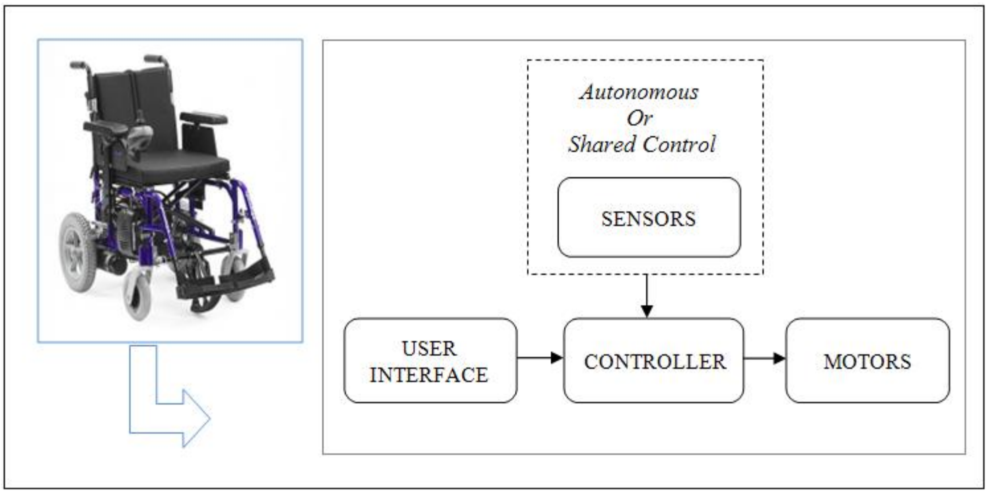


Figure 1.1: Main components for the control of an electric-powered wheelchair

consideration (Cooper et al, 2003). Joysticks operated by hand are the most common access devices for EPWs. Switches or keypads are also used. However, users with tremor or spasticity may not be able to manoeuvre the wheelchair appropriately with these devices, especially in narrow spaces (Philips et al, 2007). Such users or those with tetraplegia may opt for other input devices such as joysticks operated by chin, mouth, head or tongue, breath-controlled devices (sip and puff), tongue-touch keypads etc. (Somers, 2010). Many research groups have developed more complex wheelchair-user interfaces such as voice-controlled input (Simpson et al, 1998) and eye movement tracking (Yanco, 2000) or face direction tracking (Kuno et al, 2003). Graphical user interfaces have also been tested (Yanco, 2000; Zeng et al, 2006). Human-computer interfaces based on EMG (electromyogram) signals have also been developed. For example, Moon et al (2005) detected shoulder movements using EMG to deduce the intentions of the users. For people with severe disabilities such as locked-in syndrome, none of the above methods can be used for communicating with the wheelchair. Hence brain-computer interfaces have been developed to utilise EEG (electroencephalogram) signals for understanding the intentions of the user (Philips et al, 2007; Rebsamen et al, 2010). This is the type of user interface that is considered in this thesis and is detailed in section 1.3.

1.2.2 Modes of Control

An EPW may be controlled manually by the user, autonomously by an intelligent controller or in a shared manner by both the user and the wheelchair controller. Standard EPWs are manually controlled by the user with the help of any of the access devices mentioned in section 1.2.1. In this case, the controller does no more than converting the user input into translational and rotational commands to be given to the motors. However the safety of the user may be compromised if precise control of the wheelchair is not possible due to limitations of the input device and/or the user suffers from lack of physical dexterity, cognitive abilities etc. (Velázquez, 2010). Hence robotic technology has been used to provide navigational assistance to the user. Autonomous robotic wheelchairs (ARWs) are equipped with sensors to retrieve information about the environment. The controller in this case, takes inputs from the user as well as the sensors for decision making. The user needs only indicate the final destination and the control algorithms undertake global path planning and manoeuvre through obstacles. In the past two decades, there have been many projects across the world to develop autonomous wheelchairs. Simpson (2005) has provided a detailed review of 'smart' wheelchairs. Some of the wheelchairs capable of autonomous navigation using landmark recognition or internal maps include Bremen autonomous wheelchair and those developed in projects such as VAHM (Véhicule Autonome pour Handicapé Moteur), SENARIO (Sensor Aided Intelligent Wheelchair Navigation System), TAO, TinMan etc. The OMNI (Office Wheelchair with High Manoeuvrability and Navigation Intelligence for People with Severe Handicap) project developed an omni-directional wheelchair for vocational rehabilitation (Hoyer & Borgolte, 1996). The MAid (Mobility Aid for Elderly and Disabled People) project developed and tested control algorithms for manoeuvring a wheelchair in crowded public environments such as railway stations, malls etc. (Prassler et al, 1999).

The control algorithms used in ARWs serve the purpose of efficient manoeuvring of the wheelchair while ensuring safety of the user. However, the user of the wheelchair becomes a mere passenger and not the driver. As aforementioned, for people undergoing rehabilitation for SCI and SCD, a sense of independence is vital for their recovery and adaptation in society. Hence the assistance provided to the user must only *aid* their existing skills and not suppress them. With this view in mind, several projects described above and other research groups have sought to provide semi-autonomous or shared control of the wheelchair. Chapter 2 provides a detailed review of shared control approaches in assistive robotic wheelchairs.

1.3 Brain-Computer Interfaces

Brain-Computer Interfaces (BCIs) were first developed in the 1970s, though advancements in this field have been quite recent (Millán, 2003). Wolpaw et al (2002) have reviewed BCI research and explained its main components to be signal acquisition, signal processing, the output device and the operating protocol. Brain signals are acquired using EEG recording, either non-invasively from the scalp or invasively using electrodes implanted within the brain to pick up cortical neuronal activity. Both evoked and spontaneous potentials have been used by researchers. Evoked potentials are generated in response to external stimuli, while spontaneous potentials are due to intentional mental activity such as imagining limb movement, performing mental arithmetic operations etc. (Millán, 2003). Signal processing involves feature extraction, i.e., identifying the signals of interest which may contain the user's messages, and translating these signals into one of the several commands that can be issued by the user. In the case of a BCI-controlled intelligent wheelchair, the output device is the wheelchair and the user commands are hence used to navigate the wheelchair. The operating protocol refers to whether the communication is continuous or discontinuous, synchronous (brain signals are recorded in association with trigger signals) or asynchronous (user is free to generate commands at any time), method of turning on and off the system etc.

The Strathclyde BCI developed in the Neurophysiology Laboratory at the University of Strathclyde captures brain signals non-invasively using 14 EEG channels. The signals acquired in response to visual directional cues are classified and used to control a wheelchair on-line in a virtual reality simulator (Valsan et al, 2009). Chapter 3 provides further details of the simulator and wheelchair control.

In order to fully utilise the potential of brain-computer interfaces, the user must develop the skill to produce useful EEG signals (Wolpaw, 2002). Hence extensive training is required prior to operating wheelchairs controlled by BCIs.

In order to compensate for the lack of accuracy of signals, off-loading some level of control to the wheelchair would be favourable both in terms of safety and workload of the user. Moreover, the number of commands available to manoeuvre the wheelchair is limited - four directional commands in the Strathclyde BCI (Grychtol, 2010). Hence fine-steering requires great skill which may not be possible for many people with cognitive disabilities. In this case too, a certain degree of wheelchair autonomy would be advantageous. Therefore, shared control of the wheelchair by both the user and an intelligent wheelchair controller would be beneficial (Millán, 2009).

1.4 Project Objectives

Recognising the benefits of a shared control approach in a BCI-controlled intelligent wheelchair, the aim of the project is to incorporate the same into the virtual reality EPW developed in the Neurophysiology Lab by previous work (Grychtol, 2010). The following have been identified as the main tasks of the project:

- Review of shared control approaches in the field of assistive robotic wheelchairs
- Understanding the virtual simulator environment and control of the virtual EPW
- Equipping the wheelchair with appropriate sensors in an optimal arrangement
- Developing shared control algorithms for providing obstacle avoidance, collision avoidance and wall following assistance
- Evaluating the shared control strategy using an appropriate assessment procedure

Chapter 2

Review of Shared Control Approaches

2.1 Overview

In a shared control framework, both the human and the machine play an important role in the performance of the wheelchair. The degree of control imparted to the human driver should be decided based on his or her abilities. This may relate to physical or cognitive disabilities or temporal changes in skills due to stress, fatigue, type of environment etc. Hence the shared control system has to make three decisions on-line for continuously adapting to the user's needs - who is in control, when is assistance required by the user and what is the extent of assistance required. Vanhooydonck et al (2010) have identified a list of requirements for a personalised shared control strategy. These include useful navigational manoeuvres, user safety, independence from environment, good understanding between human and robot through adequate communication, predictable behaviour, respect for user autonomy, ability to predict user intention and adaptable to various disabilities of users. Most smart wheelchair developers focus on one or more of these requirements while designing their shared control system. However, it has proved to be difficult to satisfy all the requirements.

Some of the assisting behaviours provided by smart wheelchairs include obstacle avoidance, collision avoidance, wall following, docking, door passage, navigation through cluttered or crowded areas etc. The assistance may be provided in indoor or/and outdoor environments. Switching between these modes may be done explicitly by the user or implicitly by algorithms as in NavChair (Simpson et al, 1998) and Sharioto (Vanhooydonck et al, 2010).

Simpson's (2005) review of smart wheelchairs provides a helpful guide to understanding the various features provided by shared control approaches and their limitations. Most wheelchairs provide obstacle avoidance or collision avoidance assistance. Wheelchairs providing only these functionalities include Luoson III, TinMan, IntellWheels intelligent wheelchair (Petry et al, 2010), biometrically modulated wheelchair developed by Uridales et al (2010) etc. The CWA (Collaborative Wheelchair Assistant) however, depends on the user to detect obstacles, while the shared control module provides only path-following assistance (Zeng et al, 2006). The wheelchairs providing additional task-specific functionalities such as wall following, door passage, target tracking etc. include Hephaestus, Intelligent Wheelchair System of Osaka University, MisterEd, NavChair, OMNI, RobChair, SENARIO, Sharioto (Nuttin et al, 2002), VAHM, Wheelesley etc. These wheelchairs are capable of providing a wider range of daily manoeuvres required by people with disabilities or elderly people. However, the issue of mode switching must be handled explicitly or implicitly. The wheelchair developed in the MAid project was based on a different methodology for providing navigational assistance, as will be described in Section 2.2.

Various control algorithms have been adopted for implementing shared control. Section 2.2 provides detailed examples of a few interesting methodologies to illustrate the differences and similarities in shared control techniques. These include intelligent wheelchairs using Vector Field Histogram and Potential Field Methods for obstacle avoidance, implementation of BCI operated shared control, a biometrically modulated smart wheelchair, approaches where the environment has been modified for providing navigation assistance etc.

2.2 Shared Control Techniques

Obstacle avoidance is the major challenge in autonomous and semi-autonomous control of wheelchairs. Several methodologies have been developed to detect and avoid obstacles. Vector Field Histogram (VFH) and Potential Field Methods (PFM) are two popular obstacle avoidance techniques used by many smart wheelchair developers. Petry et al (2010) have summarised the advantages and drawbacks of these methods. VFH was originally designed for autonomous robots and have to be suitably modified for use in wheelchairs. The success of the VFH and PFM implementations are dependent on the accuracy of the sensor readings. They are also sensitive to local traps which may be overcome using global path planners. Oscillations in the wheelchair motion are commonly seen in PFM based systems, but not in those using VFH. In this section, examples of shared control approaches based on these concepts are first discussed, before moving on to other methodologies.

NavChair Assistive Wheelchair Navigation System (Simpson et al, 1998) provides a number of modes performing different behaviours and imparting different levels of autonomy to the user. NavChair is fitted with 12 ultrasonic sensors on the front of the wheelchair on a lap-tray. The obstacle avoidance mode provides the controller with the greatest level of autonomy. Minimum Vector Field Histogram (MVFH) and Vector Force Field (VFF) methods are used to implement general obstacle avoidance. MVFH is an improvised version of the VFH. It takes the rectangular shape of the wheelchair into consideration and also prevents jerky movements of the wheelchair by appropriate speed control. In this method, a map, known as certainty grid, is constructed of the possible locations of obstacles in the vicinity of the wheelchair, using data from the sonar sensors and wheel motion sensors. The certainty grid is combined with range data from the sensors to determine obstacle density in a particular direction. The direction requested by the driver is used as a weighting function to determine the path of least obstacle density in the desired direction. The speed of the wheelchair is altered depending on its proximity to obstacles in the path selected. In addition to the MVFH, NavChair uses VFF, a Potential Field Method, to determine the final direction of the wheelchair. This is based on the concept of imaginary repulsive forces exerted by obstacles on the wheelchair. Collisions are avoided by changing the direction of travel to encounter least number of obstacles, deduced from the magnitude of the repulsive forces. The obstacle avoidance behaviour maintains the wheelchair at the largest distance from obstacles compared to the other modes. The speed of travel is also the least in this mode since the wheelchair is slowed down by impending obstacles. The door passage mode imparts more control to the user and allows the wheelchair to move closer to obstacles. The MVFH method is used to achieve this behaviour by weighting the user input lesser than that done in the case of general obstacle avoidance. The automatic wall following mode uses the side sonar sensors to follow a wall. MVFH and VFF are inactive in this mode. Obstacles are detected by the front sonar sensors and those on the other side as that facing the wall. Mode switching is automatically done in NavChair.

The navigation of the Hephaestus Smart Wheelchair System (Simpson et al, 2002) is based on that of NavChair. The Hephaestus system was designed for commercialisation and can be attached to a standard power wheelchair to provide navigation assistance. The sensor arrangement is similar, though attaining a wider coverage area by positioning 13 sensors at the front on the lap-tray and 3 at the rear on the battery tray. Additionally, bump sensors have been added to bring the wheelchair to a sudden stop if they are activated by contact with an obstacle.

Sharioto, the intelligent wheelchair developed at KU Leuven (Nuttin et al, 2002) uses a modified VFH method for obstacle avoidance. It also provides other assistive manoeuvres such as collision avoidance and docking at a table. It has been equipped with 20 ultrasound sensors, 9 infra-red sensors, a 'lidar' (infra-red scanner) sensor and a gyroscope for estimating rotational velocity. In obstacle avoidance mode, a polar histogram is constructed using sensor data and current state of the wheelchair. This information is combined with the estimated user intent to determine a safe heading direction as required by the user. Collision avoidance algorithm computes the time to collision using current velocity of the wheelchair and slows down the wheelchair if a risk of collision occurs. If the user continues to point in the direction of the obstacle, collision avoidance will be deactivated. Docking is achieved by combining the estimated user intent with information about the environment, such as the tabletop, for docking at a table. Sharioto also has a simulated version.

A BCI controlled smart wheelchair providing adaptive assistance has been developed by integrating the IDIAP BCI with Sharioto (Philips et al, 2007). The focus of the research has been on activating assisting behaviours such as obstacle avoidance, collision avoidance and orientation recovery as and when required by the user, thus adapting to his or her needs. The shared control system receives the user input as estimated probability distribution values for three commands, Forward, Left and Right, from the BCI system. The command with the highest probability is identified as the user's intention and is converted into translational and rotational velocity values, which are combined with the current motor signal values to produce new wheelchair motor signals (Millán, 2009). Simultaneously, the shared control system receives an 'appropriateness level' for three assisting behaviours, namely, collision avoidance, obstacle avoidance and orientation recovery. These levels are calculated based on information of the environment obtained with the laser scanner. A winner-takes-all algorithm is used to select the assisting behaviour with the highest appropriateness level, which then modifies the motor signal obtained using the user input to create the final motor signal. Collision avoidance brings the wheelchair to a halt when it is within 0.4m from an obstacle. Obstacle avoidance uses a higher threshold of 0.5m. The orientation recovery behaviour adjusts the direction of the wheelchair if it is misaligned by more than 105°. Tests conducted in a simulated environment showed that accurate BCI performance was not necessary for efficient driving, provided that crucial situations are handled by a large number of accurate commands. The current shared control implementation can be made more adaptive by determining the activation thresholds based on the driving skills of the user.

Petry et al (2010) use the concept of PFM for performing obstacle avoidance in the IntellWheels smart wheelchair. The sensors used include two encoders, 8 sonar sensors and 8 infra-red sensors. Each sonar sensor reading corresponds to a virtual repulsive force acting on the wheelchair. The destination exerts an attractive force that is directly proportional to current user input. The resultant force is the sum of all the repulsive forces and the attractive force. To maintain user autonomy until facing a risk of collision, the repulsive forces are taken into consideration only when the wheelchair crosses a certain threshold of safety, which is determined using information about the distance to obstacles and speed of the wheelchair. The safety range designed also helps in eliminating oscillations, one of the previously mentioned limitations of PFM. Their approach does not require localisation and hence there are no dead reckoning errors. The obstacle avoidance algorithm was also tested on a wheelchair simulator, the IntellWheels Simulator.

Uridales et al (2010) have used PFM on a novel biometrically modulated shared control system. While Petry et al (2010) formulated only one resultant vector taking the user input as the goal direction, the approach here generates two resultant vectors. The human vector is derived from the user's commands. The robot vector is calculated as the sum of the repulsive forces from all the obstacles and the attractive force from the goal. To determine the final direction of movement of the wheelchair, these two vectors are then summed after applying weighting factors. Driving efficiency and the user's state are used to weight user and robot commands. The efficiency is measured by the smoothness, directness and safety of driving. Hence if a user's performance is good, the final direction of the wheelchair will be largely controlled by the user. Since the parameters of efficiency are measured locally, as and when the user performance changes, the proportion of the user's influence on the final direction of the wheelchair varies. The second weighting factor is the user's mental state. This is determined by measuring the pulse using a pulse oximeter worn on the wrist. Using heart rate as a marker for stress, more assistance is provided when the user's stress levels are higher. However, since performance is also taken as a weighting factor, the user will be in control if he or she drives well, in spite of being nervous. Hence their technique is very much adaptive in nature and upholds user autonomy. They claim that the aspect of deliberation contributed by the user input, when added to the reactive responses of the robot, helps to avoid local traps. However, the wheelchair is subject to oscillations, unlike the case in the work done by Petry et al (2010). Tests conducted using people with disabilities have provided successful results for collaborative control of the wheelchair. The tests also confirmed that stress reduced performance.

VAHM (Autonomous Vehicle for people with Motor Disabilities) was developed in a French project with work starting in 1989 (Bourhis et al, 2001). It provides manual mode, assisted manual mode and automatic mode. Two encoders provide information on position and orientation, while 16 sonar sensors are used for detection of obstacles, with three being placed on either side, two at the rear and the rest in front providing full coverage of the environment in front of the wheelchair. The access device is a GUI displayed on a LCD screen. Obstacle avoidance is used in both automatic and shared control modes. They use a method where independent activation of a sensor produces a particular behaviour of the wheelchair determined by its orientation with the obstacle. The direction followed when multiple sensors are activated is estimated by considering the respective behaviour associated with each sensor and the distance measured by them. The assisted manual mode provides additional 'local primitives' that allow performing specific tasks while avoiding obstacles. 'Free-space search' avoids obstacles while moving without a specific aim, 'direction following' does the same but maintains a particular direction, and 'wall following' allows moving in a straight line along a wall by formulating the equation of a straight line using data from the side sensors. Tests conducted in a rehabilitation centre proved the effectiveness of the semi-autonomous mode for people who could operate the wheelchair with a joystick. However, those who used a single switch operated by the head to move in an obstacle-filled environment, required autonomous operation that makes use of path planning and localisation.

Wheelesley (Yanco, 2000), a semi-autonomous wheelchair is capable of navigating in outdoor and indoor environments. Automatic detection of these environments is possible using a light-to-voltage optical sensor and a thermistor. Indoor navigation is provided with the help of 4 sonar sensors mounted on each side and 12 infra-red sensors, most facing the front. The wheelchair is also equipped with wheel encoders and 2 Hall effect sensors used as bumpers to detect obstacles escaping the vision of the other sensors. A reactive navigation algorithm is used for obstacle avoidance such that the wheelchair continues to travel in the direction commanded by the user, avoiding obstacles along its path, until a new command is given. Common sense constraints are used to navigate away from obstacles. If the wheelchair is blocked in front, it turns right by default or to the left if the right is obstructed. If blocked on either side, it reverses automatically. Hall centring assistance is provided by using side sensor readings to equalise the distance from either wall. Obstacles are detected while moving down the hall. Outdoor navigation is provided using a similar approach with the help of a vision system mounted on a lap-tray oriented 40° towards the ground.

The methodology adopted in the MAid project (Prassler et al, 1999), mentioned in section 1.2.2, differs from most of the smart wheelchairs discussed above. Their implementation was based on the opinion that developing specific strategies for behaviours such as wall following and door passage were not beneficial to people with disabilities who possess fine motor control. Hence they focussed on reducing the driver's fatigue while navigating in narrow spaces and wide crowded areas, by employing Narrow Area Navigation (NAN) using semi-autonomous control and the autonomous Wide Area Navigation (WAN), respectively. The sensors used by MAid include wheel encoders and a gyroscope for dead-reckoning, sonar sensors, infra-red scanners and a laser range finder for detecting moving obstacles. NAN uses a configuration space based planner (Prassler et al, 1998). The position estimation module provides the planner with a starting configuration composed of position and orientation information. The user provides the destination configuration. The planner then calculates all the sets of configurations to reach the goal without any collisions and finally selects those sequences of configurations that form the shortest path. The configurations are then converted into rotational and translational velocities by the path execution and position control modules. Users have the power to override the wheelchair movement at any time. It may be noted that in achieving the goals of NAN and WAN, the wheelchair automatically performs manoeuvres such as obstacle avoidance, wall following, door passage etc.

The Collaborative Wheelchair Controller (CWA) has been developed primarily for reducing fatigue or for drivers with physical and cognitive disabilities (Zeng et al, 2006). Their assumption is that users are capable of detecting obstacles and have not implemented any obstacle avoidance algorithms. Hence they require only two encoders and a barcode scanner as sensors. Bar code patterns affixed to landmarks in the environment are read by the bar code scanner placed under the seat of the wheelchair. Localisation of the system is achieved using these readings as well as odometry data from the encoders. Shared control is implemented using an 'Elastic Path Controller'. On a GUI interface, the user constructs a desired path to the intended destination, prior to driving the wheelchair. The user is then required to use only forward or reverse commands to move the wheelchair, since the collaborative controller guides it along the defined path to reach the destination. If obstacles are detected by the user, he or she can deviate from the path due to its 'elasticity' and the controller brings the wheelchair back to the guiding path. While this shared control strategy has yielded successful results in tests conducted on able-bodied volunteers and a person with cerebral palsy, its application is limited to familiar environments.

Another control strategy requiring modification of the environment has been designed by Carlson & Demiris (2008), which is capable of supporting both autonomous and shared control of the wheelchair. The concept of orientation recovery described previously (Philips, 2007) has been adopted to develop a 'safe mini-trajectory' generator. The arrangement of sensors was based on Sharioto, with a laser scanner and sonar sensors mounted along the front and sides of the wheelchair, respectively. Additionally, a camera was used to detect 2D markers fixed on the ceiling to aid in global localisation of the system. Prediction of user intent is performed using joystick input signals and the localisation data. It may be noted that user intention is recognised only in familiar environments by reverse modelling the route to be taken to fixed destinations in the environment. The safe-mini-trajectory generator uses this information to dynamically compute a safe path towards the goal. The decision to alter the joystick signals is made by considering the intention of the user and the safe paths generated. An obstacle avoidance module finally checks for obstacles in the selected heading direction and alters the signals to the motor control unit appropriately. A limitation of the methodology could be that if multiple starting points are required within the environment, the complexity of the inverse models would increase for large number of destinations.

2.3 Sensors used in Smart Wheelchairs

The discussion of various shared control techniques presented in Section 2.2 has provided examples of numerous sensor modalities employed for gaining useful information about the environment. Simpson (2005) has summarised the main advantages and limitations of commonly used sensors.

Ultrasonic sensors are one of the most popular types of sensors used, being cheap, easily available, light weight, compact, low powered devices etc. (Velázquez, 2010). They are based on the principle that sound waves incident on a surface are reflected back. Hence they provide accurate distance measurements provided that the angle of inclination of the beam is almost perpendicular to the object detected. If the angle of incidence is large, the reflected beam may not be captured by the sensor. Substances that absorb sound cannot be detected. Moreover, multiple reflections of a sound wave can cause perception errors due to ghost echoes and cross talk can occur due to sensors picking up sound waves from other sensors.

Infra-Red (IR) sensors offer all the advantages of sonar sensors but are cheaper and may not be as accurate. They are sensitive to background light and colour of obstacles since they work on the principle of transmission and reflection of infrared light rays. They do not detect transparent or refractive surfaces. Both sonar and IR sensors can detect drop-offs only if oriented directly facing the ground in order to be able to receive the echoes.

Laser range finders (LRF) or scanners provide more accuracy and overcome many of the drawbacks of sonar and IR sensors. They are capable of providing a 180° view and can detect drop-offs. However this comes at the expense of high power consumption, larger dimensions and high costs. As an illustration of cost, the laser range finder used in the MAid project cost approximately US$4000, compared to just a few tens of dollars for sonar or IR sensors. However it was deemed indispensable for detecting objects in a dynamic and crowded environment and hence incorporated in the system. The wheelchair used by Carlson & Demiris (2010) also uses a laser scanner. Sharioto (Nuttin et al, 2002) uses an infra-red scanner.

Machine vision is gaining popularity with smart wheelchair developers, being more robust and accurate. They provide wider and deeper coverage of the environment, are reasonably priced, have higher sampling speeds and are non-invasive (Velázquez, 2010). They are smaller compared to LRFs and hence easier to mount. They have been used as the access device for eye, face or head movements and also for sensing the environment (Kuno et al, 1999; Yanco, 2000; Carslon & Demiris, 2008). However, machine vision requires the use of image processing to extract useful information and hence the computational requirements are higher.

Wheel encoders are commonly used to provide odometry or ground truth data.

Most intelligent wheelchairs use multiple sensor modalities as seen in the discussion in Section 2.2. By utilising the advantages provided by each type of sensor and compensating for limitations of one type by using another, system reliability can be improved. Moreover, robust shared control algorithms that are not constrained by the accuracy of sensor data will also enhance the performance of the wheelchair.

Sensor arrangement on the wheelchair significantly contributes to the utility of the sensor data and the effectiveness of the algorithms used. All wheelchairs providing obstacle avoidance have one or another sensor modality placed on the front of the wheelchair. Collision with the sides and rear can be avoided by providing sensor coverage in these places as well. Another challenge is the height of mounting the sensors. Due to varied environments and different seating arrangements for wheelchair users, the sensors must be suitably positioned to prevent blind spots. This is also an important issue to be considered to enable commercialisation of smart wheelchairs (Bourhis et al, 2001).

2.4 Evaluation Methods

Appropriate evaluation of the shared control techniques is required to assess their merits and drawbacks. Nuttin et al (2002) and Parikh et al (2005) have listed a number of evaluation methods. Quantitative measures such as time to completion, speed of the wheelchair, number of collisions, number of stops, driver-wheelchair interaction, quality of trajectory, level of fatigue etc. have been widely used by developers to assess their systems. It has also been found that subjective evaluation in the form of questionnaires answered by the users or evaluation by observers, are useful sources of feedback.

Driver-wheelchair interaction can be measured by the number of times a user issues commands through the access device. Zeng et al (2006) conducted tests where volunteers were instructed to minimise the movements of the joystick to assess the effectiveness of their path guidance algorithm implemented in the Collaborative Wheelchair Assistant (CWA).

The five-point Likert scale (1 - strongly agreed, 5 - strongly disagreed) may be used for answering questionnaires (Carlson & Demiris, 2010; Petry et al, 2010). Another method of subjective evaluation is using the NASA-TLX workload assessment procedure (Parikh et al, 2005). The NASA Task Load Index (NASA-TLX) is an evaluation procedure to determine the workload of a task performed by the rater (NASA, 1986). Though originally developed more than twenty years ago by the Human Performance Group at NASA Ames Research Centre for the field of aviation, it has been applied for assessing subjective workloads in many other human-machine environments such as tele-operation of robots, automobile driving and military operations (Hart, 2006), as well as laboratory experiments such as memory tasks, grammatical reasoning etc. (NASA, 1986). Six subscales, namely, 'Mental Demand', 'Physical Demand', 'Temporal Demand', 'Performance', 'Effort' and 'Frustration', are rated on a scale of 0 to 100 for each task and the ratings are weighed by their contributions to the workload of the task. Hence the weighted average of the variable ratings provides the overall workload for the task. Moreover the weights of the component subscales may be compared in order to identify the source(s) of workload (Hart, 2006). Further details of the procedure for calculation of workload using the NASA-TLX scale are provided in Chapter 5.

Parikh et al (2005) and Carlson & Demiris (2010) have also used secondary tasks to assess the cognitive complexity of wheelchair driving tasks. These tasks are visual, auditory or cognitive tasks such as mental arithmetic problems, which aim to distract the user from the primary task of wheelchair driving. This can be compared to a scenario where the use of a mobile phone while driving a car can lead to accidents due to lack of concentration. Since shared control techniques are designed to handle these kinds of situations, creating these scenarios in the laboratory provides useful insight into the behaviour of both the user and the intelligent wheelchair in these conditions. Parikh et al (2005) used mathematical problems as secondary tasks and evaluation was based on the number of correct responses. Carlson & Demiris (2010) used a visual task requiring a physical response. The users had to respond to white images flashing on a blue screen at random intervals (between 100ms and 100ms), on one of the four quadrants of a tablet PC screen, by pressing the corresponding button on a joypad. Evaluation was based on the number of correct responses and the time taken to respond to each image.

Suitable evaluation methods should be selected depending on the implementation of the shared control strategies.

Chapter 3

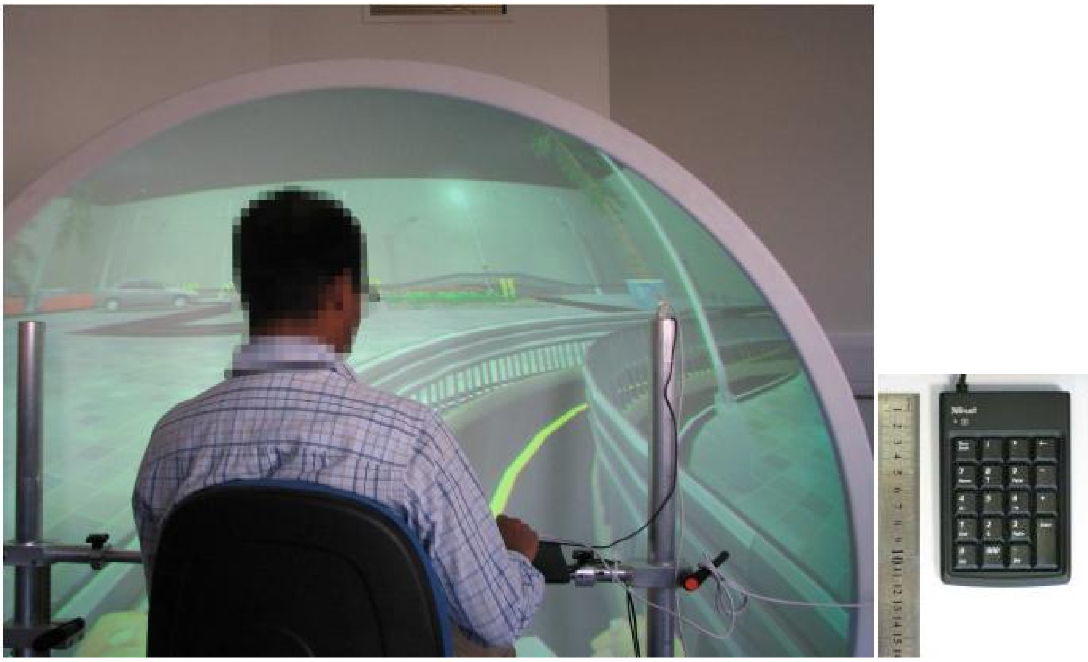
Immersive Powered Wheelchair Simulator

3.1 VR Wheelchair Simulator

An immersive Virtual Reality (VR) electric powered wheelchair simulator, serving a two-fold purpose of providing a safe environment for wheelchair-driving training as well as for the development of intelligent wheelchair controllers, has been developed in the Neurophysiology Lab at the University of Strathclyde (Grychtol, 2010). This environment is particularly useful in research related to BCI-operated wheelchairs since its use requires extended training and moreover, the safety of the drivers will not be compromised by classification errors.

This section and the next (Section 3.2) review the main features of the VR wheelchair simulator and its control, developed by Dr. Bartlomiej Grychtol (2010), which provide the foundation for development of shared control methods in this project. The modifications made to the existing framework for providing shared control of the VR wheelchair simulator are discussed in the final section of this chapter (Section 3.3).

The VR simulator wheelchair was developed with the help of USARSim, a robot simulator that runs on a commercial game engine, Unreal Engine 2.0 and using the game, Unreal Tournament 2004 (UT2004). The user inputs are translated into wheelchair driving commands by a controller that is explained in the next section (Section 3.2). These components, as well as the library for display rendering, are integrated into a single Visual C++ application using Mi-



(a) Volunteer driving the wheelchair (b) Keypad

Figure 3.1: A volunteer driving the wheelchair in the VR simulator environment using a keypad as the access device. *Adapted from Grychtol (2010)*

crosoft Foundation Class Library (MFC). It was developed in Microsoft® Visual Studio® 2005 following object-oriented programming. UT2004 communicates with the main application via a TCP/IP channel creating a client-server type architecture, wherein the former acts as the server. A graphical user interface (GUI) allows selection of the required parameters (such as map selection), spawning the wheelchair and controlling it using a suitable access device (keypad or joystick).

For this project, the access device of interest is the keypad as it can simulate the discrete commands issued in the Strathclyde BCI. Hence it can be substituted for the actual BCI to enable development of shared control strategies in a more efficient manner, with respect to both time, and error in input signals from the BCI classifier. Figure 3.1 illustrates the environmental set-up. A dome-shaped screen (2m diameter), providing a 160° view, helps in producing an immersive effect. A volunteer controlling the wheelchair in this environment with the help of a keypad is shown. The four arrow keys of the keypad, 8, 6, 2, 4 correspond to the commands 'Forward', 'Right', 'Reverse', 'Left' and the centre key 5 for 'Stop'. Control of the wheelchair using this access device is explained in the next section (Section 3.2).

3.2 State Control of Wheelchair

A finite state machine (FSM) controller was developed using the concept that wheelchair motion is achieved by controlling the left (L) and right (R) wheels separately. Equal L and R values correspond to forward-reverse movement of the wheelchair. A pair of different L and R values produces turning to the left if L is lesser, or right if R is lesser. This is based on the fact that to manoeuvre a turn in a given direction, left for instance, the velocity of the left wheel must be decreased and that of the right increased. A three-state Mealy machine was used to determine L and R values. L and R can take a maximum value of 100 and minimum of -50. ‘Stop’ is represented by null values of L and R. In any state, ‘Forward’ command causes the mean of the L and R values to be incremented by 25. ‘Reverse’ causes the same to be decremented and hence serves the purpose of decreasing the velocity step by step and then proceeding to reverse the wheelchair. While the wheelchair is turning left, ‘Left’ causes the L value to be decremented by 10 and the R value to be incremented by 10. If ‘Left’ occurs when the wheelchair is turning right, the mean of L and R is changed in the same way. A constraint of this Mealy machine is that the difference between L and R values must not be greater than 40. This condition is handled by preventing commands from being executed that would result in this scenario.

3.3 Alterations and Additions for Shared Control Functionality

3.3.1 Sensors

The wheelchair was originally equipped with ground truth and touch sensors. Additional sensors were mounted for providing more information about the environment, essential for implementing shared control. USARSim provides a host of configurable sensors that can be mounted on the wheelchair by including them in the system configuration file, through a line of code specifying the name, type, location and orientation of each sensor (Wang & Balakirsky, 2007). Sonar sensors and infra-red (IR) sensors were the chosen sensors for this project, being the cheapest and most easily available. The IR sensor emits a line in the direction of orientation of the sensor and provides a range value equal to the distance of

Figure 3.2: Top view of the sensor arrangement showing all 9 sonar sensors (encircled in yellow) and 4 IR sensors (encircled in red)

the first point of obstruction encountered by the beam from the sensor. The sonar sensor sends a number of lines within its beam cone and returns the closest point of obstruction. If no obstacle lies along the path of the beams emitted by a sensor, the maximum range is returned. The maximum and minimum range of the sensors can be configured. The beam width of the sonar sensor is also configurable. A point to note is that the IR sensor beam does not get reflected by transparent substances such as glass and hence such obstacles cannot be detected. Figure 3.2 shows a screen shot of the wheelchair in the simulator, illustrating the arrangement of the sonar and IR sensors.

Sonar sensors were chosen to provide Obstacle Avoidance assistance since, compared to IR sensors, they have a wider range and can be used in the outdoor environment, being insensitive to bright light. The total number of sensors was decided empirically, while trying to minimise the number through effective algorithms. Five sensors were placed in front of the wheelchair, two at either corners directed at an angle of 28° in the front-back wheelchair axis, and two were placed on either side. The height of the sensors above the ground was decided by taking into consideration objects such as chairs, beds, sofas etc. commonly seen in a

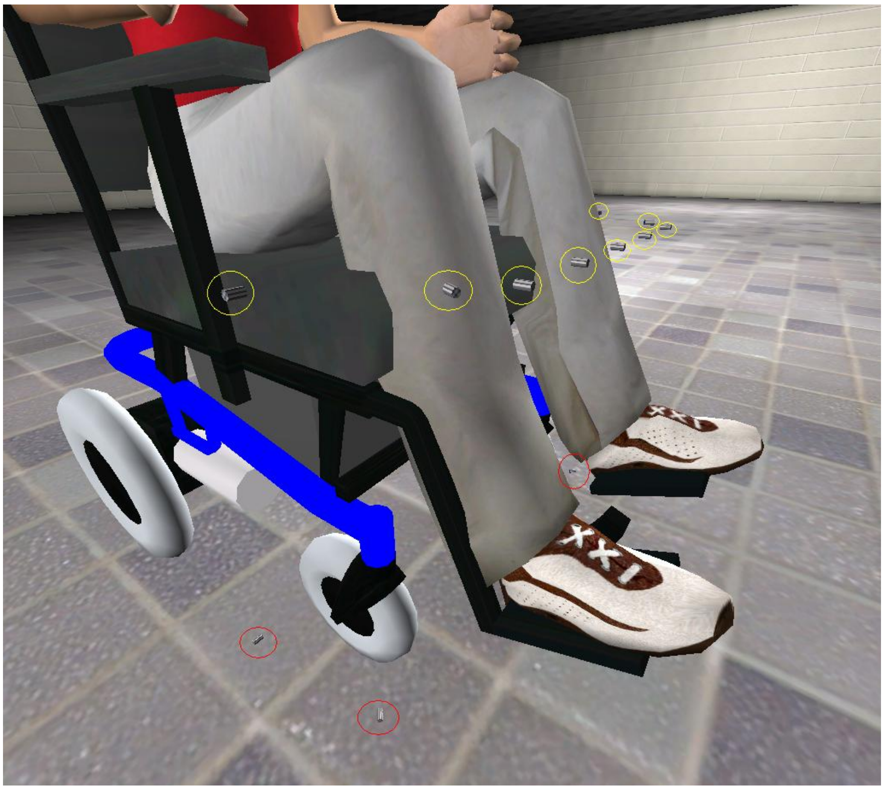


Figure 3.3: Side view of the wheelchair showing relative height of the sonar sensors, encircled in yellow. IR sensors are marked in red

household, which range in height from about 30 to 60 cm (from personal observation and measurement). However, since testing was done in an environment having other kinds of obstacles, the height was adjusted to be suitable for most obstacles in the map and was set at 53cm above the ground (see Figure 3.3 for relative height above ground). A suggestion for practically mounting the sensors at this height is to use the arrangement implemented in the MAid wheelchair (Prassler et al, 1999). The beam angle of the sensors was set at 30°. Higher beam angles caused incorrect behaviour of the Obstacle Avoidance assistance as it is based on fixed thresholds for determining risk of collision. The maximum range of the sonar sensor is 5m and minimum is 10cm. These were the default values provided in USARSim and since they were suitable for the current approach, they were not altered.

For providing Wall Following assistance, IR sensors were used since wide range was not required and the smaller size and cheaper cost of these sensors could be taken advantage of. Four IR sensors were mounted - one each on the right and

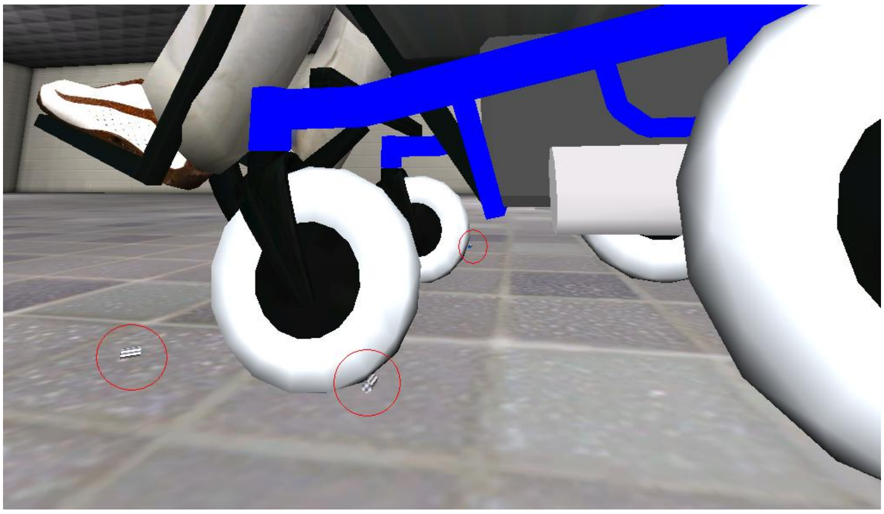


Figure 3.4: Side view of the wheelchair showing IR sensors marked in red - left side and corner IR sensors are clearly visible; right side IR sensor is partially visible

left sides and corners. They were placed at a distance of 5cm from the ground (see Figure 3.4). Placing the sensors close to the ground allows the use of Wall Following for following kerbs as well. The corner sensors were oriented at an angle of roughly 45° to the front-back axis of the wheelchair to facilitate the determination of wheelchair drift as explained in Section 4.1.3. The range of the IR sensors was set as 5cm to 1.5m in order to be able to detect a wall within 1m of it as well as to pull up close to the wall.

It was beyond the scope of this project to modify the centre of mass of the wheelchair that would have been altered by the addition of the sensors. Hence, it is assumed that the sensors are light-weight and do not affect the centre of mass significantly.

3.3.2 Modification in Graphical User Interface

The GUI of the wheelchair application was provided with an additional check box labelled, 'Shared Control', under the 'Control' field, that becomes active after spawning the wheelchair. If the box is checked prior to pressing the 'Control' button, shared control functionality will be enabled, else it operates in manual mode by default. This allows changing the mode on the fly between manual and shared control without having to spawn the wheelchair again.

3.3.3 Shared Controller

A new class, *SharedControl*, has been added as a friend of the main wheelchair application class, *CWheelchairApp*. If the 'Shared Control' check-box is checked in the GUI, an instance of this class is created by *CWheelchairApp* and sensor data is passed to the shared control object, which parses the message string and retrieves the velocity of the wheelchair from the GroundTruth sensor and range data from the sonar and IR sensors. The shared control routines are then called as described in Chapter 4.

3.3.4 Modifications to State Control

In order to retain the functionality provided by the existing state control, it was decided to create an additional function in the *StateControl* class for state control of the wheelchair initiated by the shared controller. The difference in implementation occurs for left and right commands by altering the turning radius of the wheelchair depending on its velocity. This has been achieved by making unit increments or decrements to the L and R values instead of adding or subtracting 10. The maximum velocity of the wheelchair has been temporarily restricted to less than 1m/s (second velocity level) due to the limitations of the obstacle avoidance algorithms. Another modification done to the state control routine involved the check for collision avoidance as explained in Section 4.1.2.. Details of the source code are provided in Appendix A.

Chapter 4

Shared Control Strategy

4.1 Shared Control Algorithms

After sensor data is collected every second, the shared control routines are called, which aid in assisting the user with three types of behaviours - Obstacle Avoidance, Wall Following and Collision Avoidance. In the former two assistive modes, the shared control functionality attempts to modify the direction of the wheelchair, if necessary, after the user has issued a command. Hence the user's commands are not directly modified and he or she can also override the commands issued by the controller. This approach maintains the superiority of the user over the wheelchair. Collision Avoidance, however, is in place to ensure the safety of the users and prevents them from moving in the direction of an impending obstacle by ignoring their commands. Obstacle Avoidance and Collision Avoidance are provided by default. Wall Following is an extra functionality that can be activated, provided that there are no obstacles in the path of the wheelchair, since the Obstacle Avoidance capabilities are not fully functional in this mode. Further testing is required to integrate them and verify their synergy in the shared control framework. In all assistive modes, shared control is not active when the wheelchair moves in 'Reverse' state due to the absence of sensors at the rear of the wheelchair. The assistive behaviours are explained in detail in the following sub-sections.

4.1.1 Obstacle Avoidance

Obstacle Avoidance assistance has been largely modelled on the technique used by Yanco (2000) as it provides a simplistic approach to shared control. Hence it was considered suitable for the scope of this project, particularly given the time-constraints. Sub-routines in the algorithm offer various corrective measures depending on the location of the obstacles. After describing some key considerations, the sub-routines are explained in the order in which they are run by the shared controller.

Assumptions: It is assumed there are no pits or sudden drop-offs and that the heights of the obstacles are such that they can be detected by the sonar sensors.

Thresholds: The shared control technique relies on fixed thresholds set according to the velocity of the wheelchair to determine risk of collision with an obstacle. This is in line with the implementation by Petry et al (2010), where the risk of collision is considered as a function of both distance to obstacle and speed as mentioned in Section 2.2. Considering that sensor data are updated every second, it was reasoned that the safety threshold for obstacles to the front and corners of the wheelchair be at least twice its velocity (in metres per second). This enables appropriate corrective measures to be undertaken by the controller within the next second while not bringing the wheelchair too close to the obstacle. An offset was added to this value to compensate for the distance of the sonar sensors from the periphery of the wheelchair (about 20cm from the edge of the foot). Final adjustments were made empirically. The side thresholds were set at half the front threshold in the interest of not being too far from obstacles on the sides.

Memory: The state requested by the user is stored in memory so that after a corrective action is made, the wheelchair can be set back to that state. This strategy proposes to minimise user intervention after the wheelchair has altered its movement.

Turning radius: The degree of deflection of the wheelchair to avoid an obstacle was determined empirically, taking into consideration both velocity of the wheelchair and the location of obstacles in its vicinity. For instance, for turning sharply to the left, the L value (or mean of L and R values) was decremented more than that required for a small deflection as discussed in Section 3.3.4.

Categorisation of obstacles: Obstacles have been categorised into three types and handled accordingly. The first and second categories include 'large' and 'small' obstacles situated to the front of the wheelchair, respectively. An obstacle is said to be 'large' with respect to the wheelchair if all its front and corner sonar sensors are obstructed by it. A 'small' obstacle obstructs only one or two of the middle three sensors. The terms 'large' and 'small' can be quantified by considering the arrangement of the sonar sensors at the front and corners of the wheelchair. Five sensors have been placed at the front, at a distance of 10cm from one another. Additionally, one sensor has been mounted at each front corner, oriented at 28° from the front-back axis of the wheelchair and at a distance of 4cm away from the adjacent front sensor. Hence a 'large' obstacle is wider than approximately 50cm or completely obstructs an area spanning 120° in front of the wheelchair. A 'small' obstacle is not wider than 30cm. The third category includes objects obstructing the corners of the wheelchair.

Obstacle Avoidance routines:

i Corner Navigation - This functionality is active only in the Wall Following mode, which allows a wheelchair that has been following a wall to negotiate a corner. When a corner is detected, the wheelchair makes a large deflection away from it. However, the logic used here is still rudimentary and does not take into consideration the angle of inclination of the wheelchair to the wall, which would determine the amount of deflection required. The routine can be improvised by appropriately handling different inclinations. Currently, the corner is negotiated properly if the front of the wheelchair is almost parallel to the wall in front and is within safe distance for negotiating the turn without hitting the wall in the process.

ii Large obstacles in front - If the wheelchair is completely blocked by an obstacle or numerous obstacles in the front and both right and left corners, as in Figure 4.1, it is brought to a halt and the driver is expected to issue a left or right command. The reasoning is that the user would wish to decide which way to proceed rather than the wheelchair being set by default to move either right or left. Hence the control strategy differs from Yanco (2000), where an obstacle in front causes the wheelchair to move right by default if that side is unobstructed. The wheelchair comes to a stop only if both sides are blocked. However, if the user had intended to go left and was not quick enough to

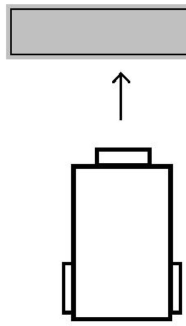


Figure 4.1: Wheelchair will come to a halt if it is completely obstructed at the front

stop the wheelchair before it turned right, he or she would then have to swing around to go in their direction of choice, which could be cumbersome to do all the time.

iii Small obstacles in front - If the wheelchair is partially blocked in front by an obstacle, it turns away in the other direction, provided that corner is free. If this safety check is not satisfied, the wheelchair will stop. In the example shown in Figure 4.2, an obstacle blocking the left part of the wheelchair causes it to turn right. If the obstacle is very small and located right in front of the wheelchair, the wheelchair moves to the right by default. If the right side is not clear, it moves to the left. In this case, the default behaviour does not cause the user to make any major deflections to get back to the desired path as compared to that required to avoid a large obstacle. For instance, if the initial state had been 'Forward', the wheelchair would turn away from the obstacle and continue forward by memory. If the initial state had been 'Right', the right turn made by the wheelchair causes a larger deflection to the right. It can be assumed that the driver had miscalculated the distance at which the right turn had to be made, causing the wheelchair to be brought into the vicinity of the obstacle. Hence deflecting it further to the right by the assistive behaviour would compensate for the erroneous decision made by the user.

(a) Small obstacle at the front (b) Obstacle at the corner

Figure 4.2: Wheelchair navigating away from obstacles partially obstructing its front or those obstructing its corners. The curve of the arrow indicates the turning radius - a larger deflection is required to successfully avoid an obstacle in the front as that for an obstacle at the corners.

iv Obstacles at the corners - If only one corner is obstructed, the wheelchair turns to the other side if it is devoid of immediate obstacles as indicated by the side sensors; else it stops. If both corners are obstructed, the wheelchair turns to the side where obstacles are more distant if the corresponding side sensor shows clear; else it stops.

4.1.2 Collision Avoidance

When the user commands the wheelchair to move towards the front, left or right directions, his or her command will be executed only if that direction is free from any imminent risk of collision. Since the user's command must be respected at all times except for emergency cases, the thresholds used in this assistive mode were taken as half of the corresponding thresholds used in Obstacle Avoidance. This relates to the condition where the wheelchair would collide with an obstacle within the next second. Hence, if the wheelchair has crossed the safety threshold of collision, the user's command to move in the direction of the obstacle is ignored. Any of the sensors located along the front of the wheelchair detecting an obstacle within the threshold of collision risk, will prevent the wheelchair from moving forward. The decision for moving left or right is made by checking the corresponding corner and side sensors. The user is expected to respond to this blocking behaviour by reversing the wheelchair and adequately adjusting its position to face a direction that is free from the risk of collision.

4.1.3 Wall Following

The key considerations for the Wall Following assisting behaviour are discussed below.

Assumptions: The wheelchair can be protected only from head-on collisions (Case ii, Section 4.1.1) in this mode since other Obstacle Avoidance routines have been disabled. This has been done since the safety threshold for the front and corner sensors is higher than the distance being maintained for wall following. This causes the checks for obstacles in the front and corner (Cases iii and iv, Section 4.1.1) to push the wheelchair away from the wall. Hence it is assumed that there are no obstacles in the path of the wheelchair. Two other assumptions made related to the sensor modality are that the wall is not a glass surface or similar transparent material as the IR sensors do not detect transparent objects, and that the velocity of the wheelchair is not greater than 1m/s, the threshold distance used to detect walls.

Threshold: The Wall Following mode strives to maintain the wheelchair within an arm's distance of the wall, i.e., about 65cm (determined by personal perception of a comfortable distance to maintain from a wall).

Wall Detection: If the wheelchair is brought within 1m of the wall and remains within this distance for 2 seconds (determined by checking both current and previous sensor readings), it will enter Wall Following mode. If a corridor is detected, the wheelchair will follow the closer side; or the right wall if equidistant from either wall. The approach adopted here allows the wheelchair to provide space for others to pass, particularly if the corridor is not wide. Yanco (2000), on the other hand, has chosen to centre the wheelchair in a corridor.

The main challenge in wall following is to correct for wheelchair drift. The technique to correct drift and stay within the threshold zone has been devised with the aid of trigonometry. It is known that the hypotenuse is the longest side of a right-angled triangle. The corner sensors are placed at approximately 45° to the direction of the side sensors. Hence, assuming the beams emitted by them to form the sides of a right-angled triangle if the wheelchair is parallel to the wall, it can be deduced that the corner IR sensor reading must be greater than that of the side IR sensor. In other words, if the wheelchair is parallel, the inverse cosine of the ratio of the side sensor and corner sensor should yield an angle of around 45° as shown in Figure 4.3. Providing for some degree of error in the direction of

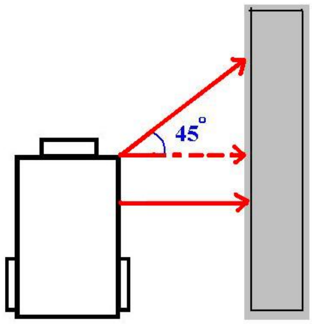


Figure 4.3: When the wheelchair is aligned parallel to the wall, the angle made by the corner and side sensors with the wall, must theoretically be equal to 45°. Also, the corner sensor reading must be greater than the side sensor reading.

the beams, it was expected that the inverse cosine would have some offset. Using this concept, experimental runs were conducted in manual mode to determine the range of the angles formed by the side and corner sensors. It was thus found that the inverse cosine value of the ratio of the sensor range values must be maintained between 48.5° and 51.5° to position the wheelchair approximately parallel to the wall.

The wheelchair is checked for drift every second. The method is explained considering the case of the right wall. Depending on the orientation of the wheelchair towards or away from the wall, it is turned left or right respectively. If side sensor reading is less than the corner sensor reading, it will go forward, provided that the angle between them is in the range 48.5° to 51.5°. The control strategy strives to maintain the wheelchair within about 40 to 65 cm from the wall depending on the velocity. The wheelchair is maintained at a greater distance from the wall for higher velocity. These values were determined empirically by trying to minimise the curvature of the path followed by the wheelchair. If the user issues a 'Left' command while being within this zone, the wheelchair is brought back towards the wall gently with a right turn. If the user issues 'Left' command again, it will move to the left again and if the threshold is crossed, it will exit the wall following mode. Hence the user is free to exit the mode quite easily.

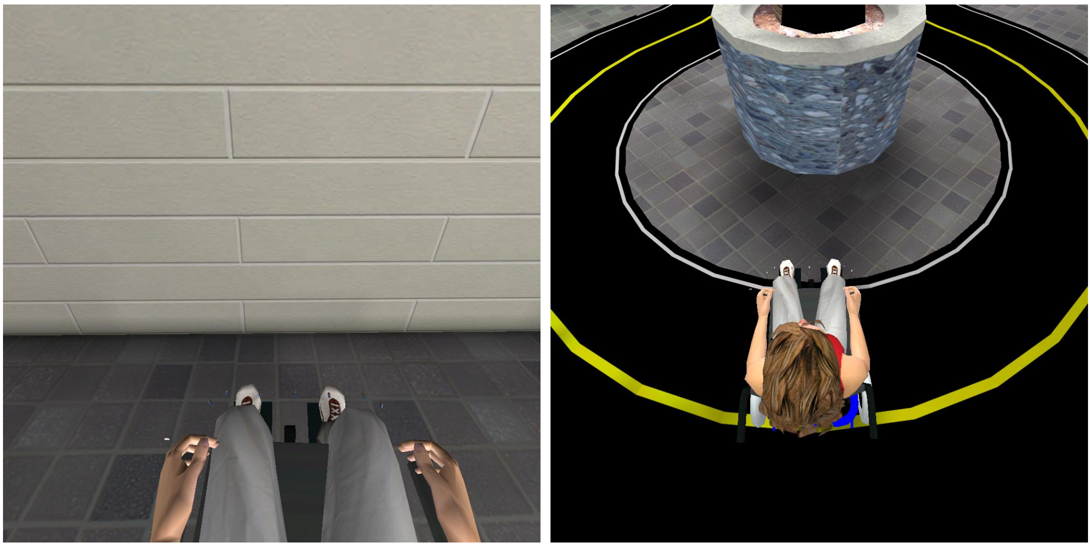


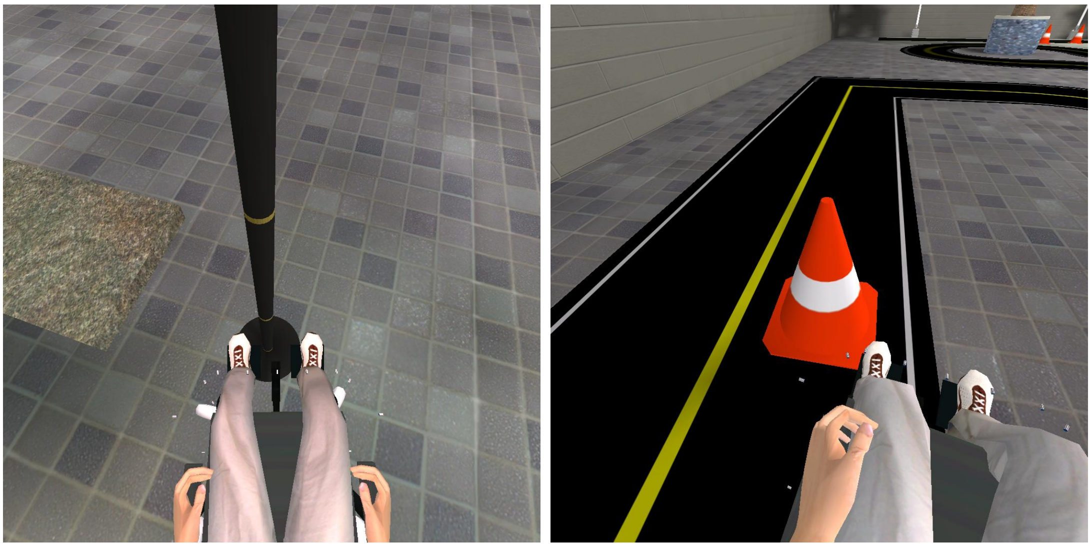
Figure 4.4: Examples of large obstacles appearing in front of the wheelchair, causing it to stop

4.2 Discussion of Wheelchair Behaviour

The behaviour of the wheelchair in the Wall Following mode was found to vary depending on the angle of inclination of the wheelchair to the wall, prior to starting the wall following behaviour. If the inclination was high (angle between side and corner sensors much lesser than 48.5° or much greater than 51.5°), the drift correction measures made the wheelchair follow a curved path or zigzag route, which took a few seconds to stabilise. Higher the velocity, more the curvature observed since the deflection of the wheelchair away or towards the wall is more, and greater distances are covered in the time between consecutive corrections (i.e., 1 second). It was found to follow an almost linear path when the angle of inclination was low. This behaviour occurs because the degree of deflection of the wheelchair, while moving right or left, was not handled separately for different inclinations of the wheelchair with respect to the optimal range of 48.5° and 51.5°. The curvature of the path followed by the wheelchair also depends on the distance from the wall, since the control algorithm strives to maintain the wheelchair between 40cm and 65cm from the wall.

The behaviour of the wheelchair due to the Obstacle Avoidance and Collision Avoidance assistive modes are explained with the help of a few examples.

Case 1: The response of the wheelchair to large obstructions directly ahead



(a) Narrow pole (b) Traffice Cone

Figure 4.5: The beam angle of the sonar sensors is not wide enough to detect all kinds of obstacles, such as the narrow pole or the tapering traffic cone, depending on the orientation of the wheelchair

of the wheelchair, such as those shown in Figure 4.4, depends on the angle of inclination of the wheelchair to the obstacle. If the wheelchair approaches the obstacle head-on, it will stop (Case ii, Section 4.1.1). If inclined to the right or left, it will move towards the other side (Case iii, Section 4.1.1).

Case 2: Some objects lie beyond the field of view of the sonar sensors, as illustrated in Figure 4.5, and are not detected by them, or detected too late to make a corrective action. The narrow pole belongs to the former category. The traffic cone escaped the beam of the sensor due to its shape. This behaviour is attributed to the narrow beam of the sonar sensors (30°).

Case 3: When both corners of the wheelchair are obstructed as shown in Figure 4.6, the wheelchair tries to move away from the closer side, right in this case, if the other side is free of obstacles. In this example, the left side is also obstructed and this causes the wheelchair to stop. The user is given the opportunity to slowly manoeuvre the wheelchair through the narrow passage without colliding with either side.

Case 4: A corridor containing columns, forming many narrow passages, is shown in Figure 4.7. This obstacle course forms the last part of the Training

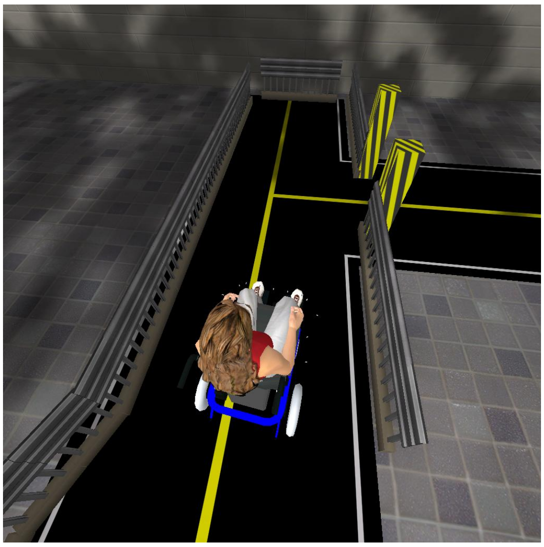


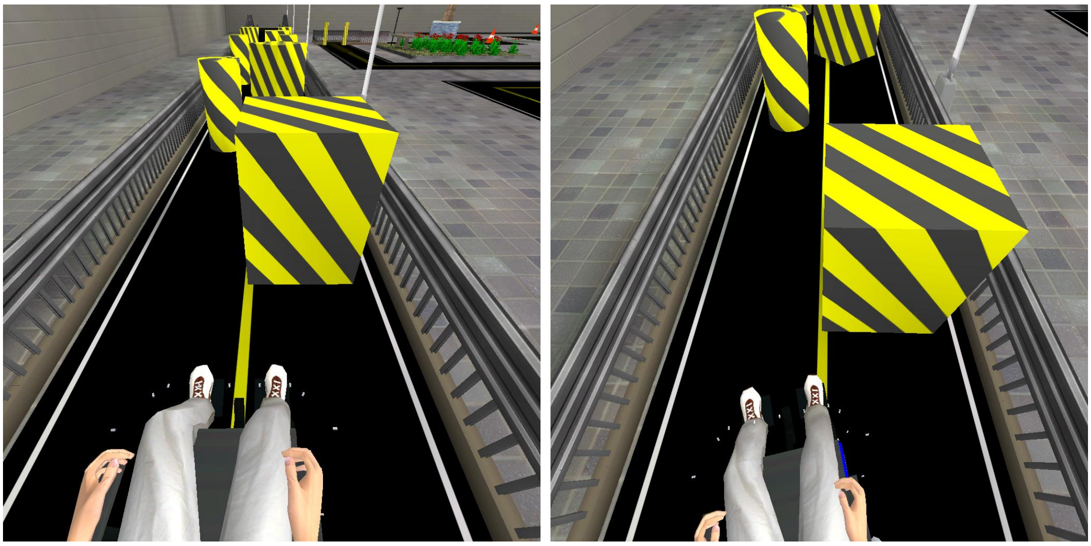
Figure 4.6: Navigating through a narrow corridor causes the wheelchair to stop frequently due to obstructed sides and corners

Course Virtual Environment map and was used for testing the behaviour of Obstacle Avoidance and particularly, Collision Avoidance. One of the major observations seen in this part of the circuit is collisions occurring between the side of the wheelchair and the columns or railings due to the lack of sensors on the sides.

Due to the maximum range restrictions of the IR and sonar sensors, the assistive behaviours were found to be more effective at lower velocities. As mentioned previously, the Wall Following mode can be executed only in the first two velocity levels, which are below 1m/s. Moreover, movement in narrow spaces would be almost impossible due to longer thresholds of higher velocity levels causing the Collision Avoidance to be activated more often. Hence the maximum velocity of the wheelchair in shared control mode has been temporarily restricted to less than 1m/s. After the algorithms are made more robust, lower thresholds may be used and higher speeds would be possible.

Figure 4.8 shows how an obstacle in front the wheelchair was detected and avoided well in time. Figure 4.9 shows an example of a case where collision avoidance prevents the user from going in the direction of obstruction. In this case, the wheelchair is obstructed on all three sides - front, left and right. The wheelchair user is required to reverse, re-align the position of the wheelchair and then proceed.

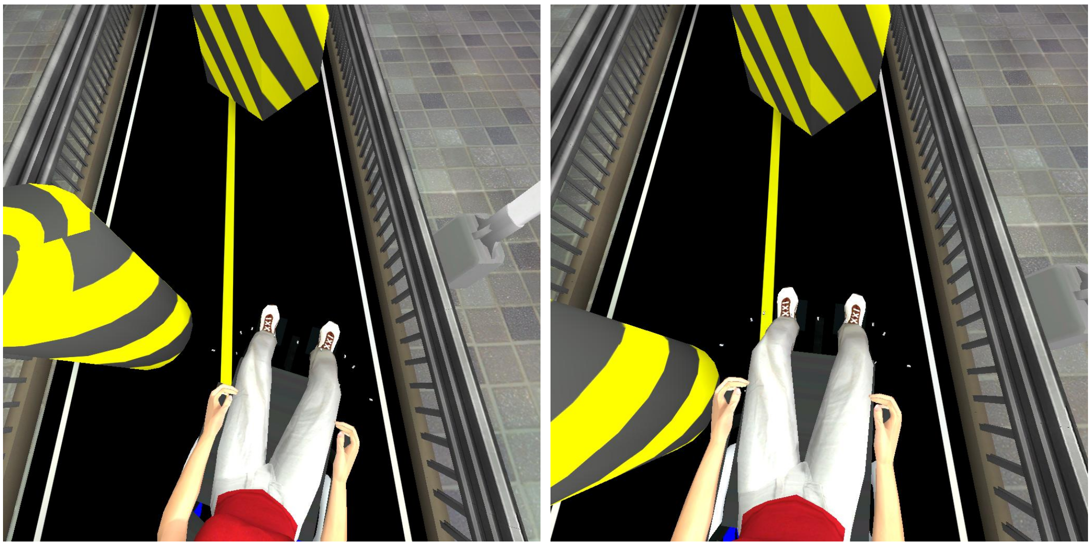
Figure 4.7: Obstacle course containing columns in the Training Course VE. The total width of the passage is about 1.8m. Some spaces, as shown here, are only as wide as the wheelchair, which spans about 0.65m



(a) Wheelchair oriented towards obstacle

(b) Successfully avoided obstacle

Figure 4.8: Example of successful obstacle avoidance assistance - The column ahead of the wheelchair (in (a)) is detected and the wheelchair is steered away from it (in (b))



(a) Collision avoidance activated

(b) Reversed and re-positioned wheelchair

Figure 4.9: Collision avoidance is activated due to obstructions on all three sides (in (a)). The driver reverses the wheelchair and re-aligns it to proceed in the forward direction(in (b))

Chapter 5

Evaluation

In order to evaluate the effectiveness of the shared control strategies developed, 5 able-bodied volunteers were asked to drive the wheelchair in the immersive virtual reality wheelchair simulator. They consisted of 3 men and 2 women aged between 24 and 42 (mean age - 31.60; standard deviation - 8.44). Three of them had no or insignificant previous gaming experience. One of them who belonged to this category had driven the virtual reality wheelchair for a few experiments using both the keypad and joystick about a year ago, but did not demonstrate any additional proficiency and hence was not advantaged. A number of driving tasks were carried out by each volunteer with and without the accompaniment of a secondary task. Following each task, they rated their experience using the NASA-TLX assessment tool. Prior to the start of the experiment, they were provided with an information sheet, consent form and definitions of the NASA-TLX subscales (see Appendix B).

5.1 NASA Task Load Index

The NASA Task Load Index (NASA-TLX), which was introduced in Section 2.4, has been created with the assumption that the variables, Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration, in one or another combination, account for the workload of most tasks performed by humans (Hart, 2006). This procedure was hence chosen to compare the workloads related with different wheelchair driving tasks. The influence of the individual subscales on the overall workload would also prove useful in assessing the shared control strategies and help in its improvisation.

The NASA-TLX scale involves measurement of the magnitude of the load, i.e., rating, as well as determining the sources of the load, i.e., weights (NASA, 1986). This two-step procedure ensures that the assessment is insensitive to the variability between different tasks and raters. Between-rater variability could be attributed to differences in the interpretation of the subscale definitions by different people as well as variations in their perception of the major factors contributing to the workload of a task. For instance, while some may consider performance to be the main criteria in gauging workload, others may find mental challenge to be the determiner of workload, irrespective of their own performance in the task. The evaluation of ratings and weights are described below.

Magnitude of Workload Evaluation: The rater is provided with a 'Rating Sheet' (see Appendix B.3) for each task performed by him or her. Each of the six subscales are to be rated on a scale consisting of a 12cm line representing a range of 0 to 100. It is divided by vertical tick marks into 20 equal segments. For all the subscales with the exception of Performance, 0 corresponds to 'Low' and 100 to 'High'. For the Performance subscale, 'Good' is represented by 0 and 'Poor' by 100. By placing a mark at the appropriate level on the scale, the user thus provides a numerical rating of that subscale, which is referred to as the 'Raw Rating'.

Sources of Workload Evaluation: Pair-wise combinations of all the subscales (e.g. Mental Demand or Effort, Performance or Frustration etc.) are provided to the user on separate cards arranged in random order for every task or set of similar tasks for which the sources of workload are the same. For each pair, the rater selects the subscale that contributed more to the workload of the task(s). Hence the maximum weight of a subscale is 5, signifying that it is the most important factor creating the workload, and the minimum 0 implying that it is irrelevant to workload.

While there are no right or wrong answers in marking these scales, the raters are asked to be consistent in their reasoning throughout the experiments in order to produce meaningful results.

Calculation of Overall Workload: The Sources-of-Workload Weights given to the subscales by each rater for a task are calculated by summing the number of times a particular subscale was selected by him or her. The Raw Rating of each subscale is then multiplied by its Weight to produce the 'Adjusted

(a) Red slide (b) White slide (c) Math slide

Figure 5.1: Screenshots of three consecutive slides of the slideshow used as the secondary task

Ratings' for that subscale. The overall or mean weighted workload equals the ratio of the sum of the Adjusted Ratings for all the subscales and 15, i.e., the total number of weights. Hart and Staveland (1988) have provided an example of the calculation of overall workload from the subscales ratings and weights.

5.2 Secondary Task

Secondary tasks, as previously mentioned in Section 2.5, provide a means of assessing the effectiveness of shared control. The wheelchair driver is deliberately distracted by an activity that requires him or her to divert his focus elsewhere while driving the wheelchair. This method of testing is particularly useful when the subjects are able-bodied volunteers, since they are capable of efficiently manoeuvring the wheelchair without shared control. Hence the benefits of shared control, if any, would be masked by their skills.

In this experiment, a secondary task was designed that required the volunteer to respond to visual stimuli displayed on a 14 inch laptop monitor positioned in front of or beside them, as per their convenience, without obstructing the view of the simulator screen. A slideshow was displayed on the monitor that consisted of three types of slides occurring in random order every two seconds. Snapshots of three successive slides from the slideshow are shown in Figure 5.1. The red slide required the volunteer to turn his or her head to the right so as to look away from the screen and then turn back again quickly. The white slide did not require any response from the volunteer. The third type of slide had mental arithmetic questions involving single digit addition or multiplication problems. Volunteers were asked to orally provide the solution for the problems without looking away from the simulator screen. In order to reduce any frustration caused by being unable to answer the questions correctly within the stipulated time, they were allowed to simply read out the question if they could not provide the answer immediately.

5.3 Experimental Procedure

The volunteers were briefed on the purpose of the study, i.e., to assess their wheelchair driving experience with manual mode and shared control assisting in Obstacle Avoidance and Wall Following. The keypad control (illustrated in Section 3.2) was explained to them and they were allowed to test the wheelchair for a few minutes in both manual and shared control modes to familiarise themselves with its control and the environment. They were also informed of the position of the sensors and the assistance provided by the shared control behavioural modes. Clarifications were provided for use of the NASA-TLX scales if any questions were raised about the same. The secondary task was explained as well. Volunteers then carried out 4 tasks per assisting mode of Obstacle Avoidance and Wall Following as listed below, in addition to performing the secondary task separately.

- Driving the wheelchair in manual mode
- Driving the wheelchair in shared control mode
- Repeating each task above while simultaneously performing the secondary task

The volunteers were told their priorities while performing these tasks were to avoid collisions, to drive as fast as possible, to respond to the slides of the secondary task (where applicable) as quickly and correctly as possible, in that order, respectively.

Considerations:

- Although speed was not used as a parameter to measure their performance in this study, the volunteers were asked to drive as fast as possible to prevent them from being over cautious. It is to be noted that the maximum speed allowed in the manual mode was made equal to that in the shared control mode, in order to reduce the obvious frustration associated with not being fast enough in shared control mode compared to the manual mode.

- Odd numbered volunteers started with Obstacle Avoidance tests and then went on to doing the Wall Following tests, and vice versa for even numbered volunteers. The order of performing the tasks using manual and shared control modes was also randomised. This was done to minimise any bias from learning effects (Carlson & Demiris, 2010). Randomisation also helped to decrease context effects associated with the NASA-TLX scales (Hart, 2006). These occur when the perception of workload of a task is influenced by previous tasks and the ratings are affected drastically.

- An exception to the randomisation was the order of the secondary task. It was expected that the workload in driving the wheelchair along with the secondary task would be higher than without it. Hence the feeling of workload would be greater if that particular task was being performed for the first time in a particular mode (manual or shared). It was hence reasoned that undue bias against the task would be avoided if the volunteer had already performed that task once in the respective mode before trying it with the secondary task.

Details of the experiment specific to Obstacle Avoidance and Wall Following assisting behaviours are provided in the next two sections.

5.3.1 Obstacle Avoidance Tasks

The obstacle avoidance tasks were conducted in the Training Course Virtual Environment (VE) shown in Figure 5.2. A well-defined path within this environment was pointed out to the volunteer. The first half of the path contained widely spaced obstacles, while the latter half contained very narrow spaces such as those explained in Section 4.2. The volunteers were told they were in control in both manual and shared modes, and had to guide the wheelchair through the path. However, shared control would step in if they were too close to an obstacle. It would also not allow them to proceed in certain directions if bound by obstacles, in which case, they were told to use the 'Reverse' command to reverse the wheelchair, alter its direction to find a clearing and then proceed.

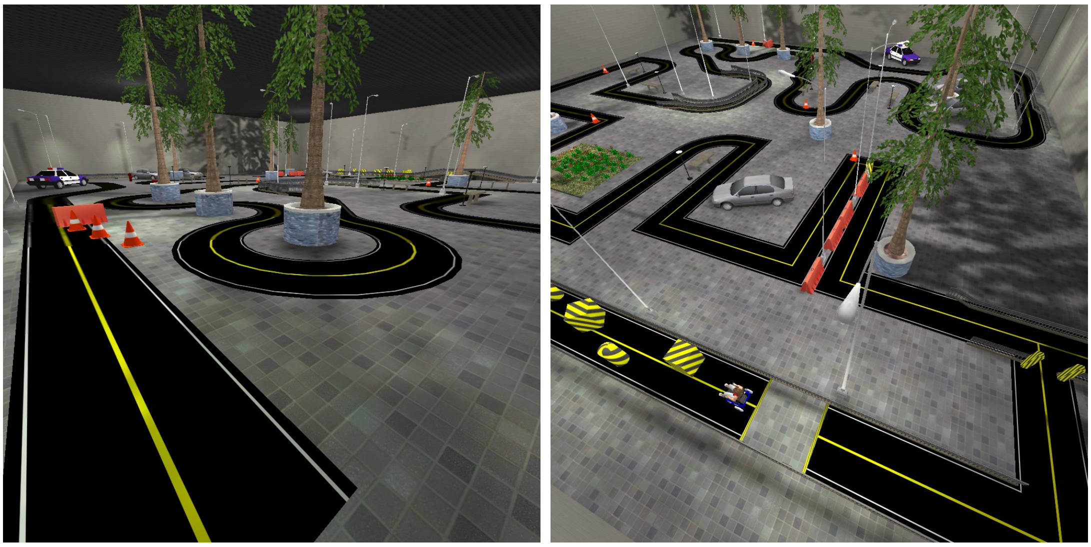


Figure 5.2: Two views of the Training Course Virtual Environment map captured from diagonally opposite corners of the environment

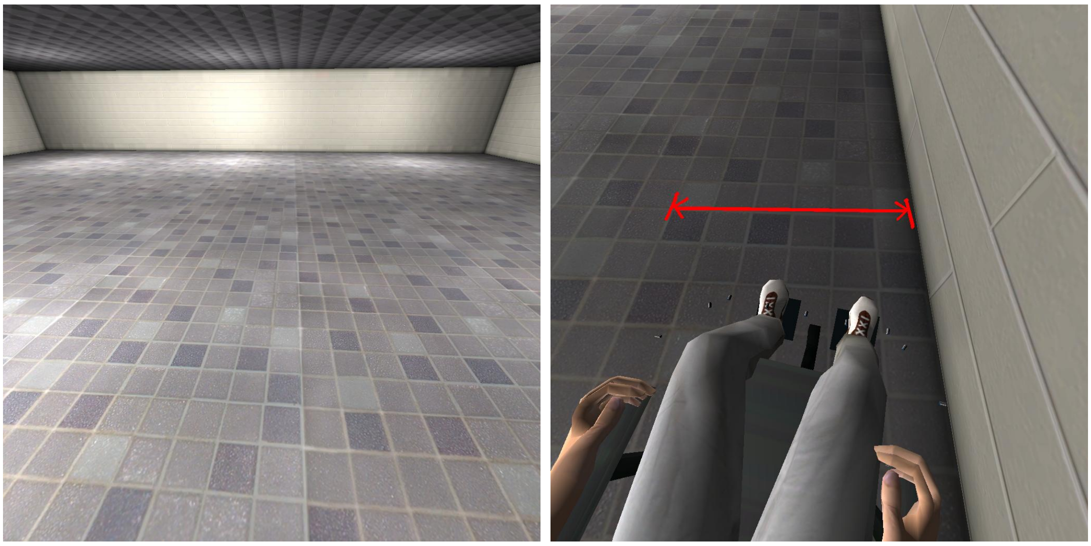


Figure 5.3: *Left* - A view of the Empty Hall VE. *Right* - Wheelchair following a wall in the Empty Hall VE keeping an arm's distance (approximately 65cm) from the wall, i.e., keeping within a zone of 6 tiles marked in red

5.3.2 Wall Following Tasks

The wheelchair was driven in the Empty Hall VE which consists of a large empty room bounded by four walls (Figure 5.3). The volunteers were asked to select a side for wall following and then instructed to move the wheelchair close to the

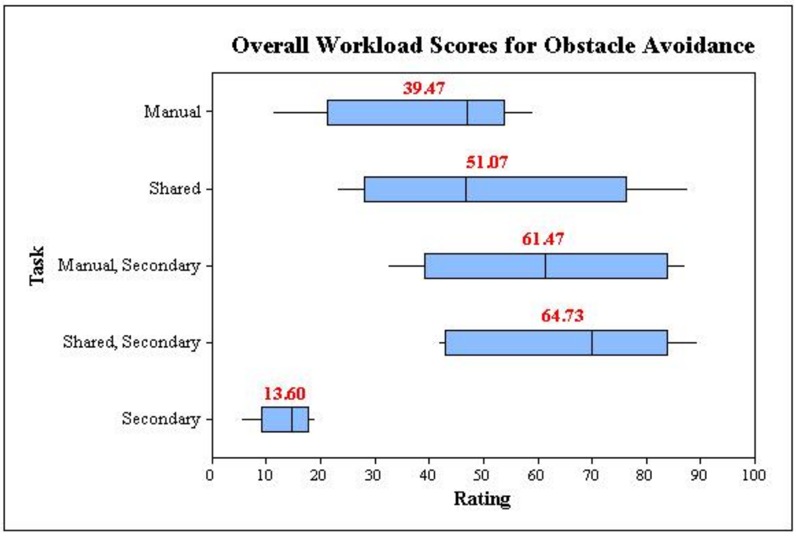


Figure 5.4: Overall workload scores for Obstacle Avoidance behaviour testing. 'Manual' and 'Shared' correspond to manual and shared mode, respectively. 'Secondary' refers to presence of secondary task. Mean workload values are indicated in red. Boxes represent the inter-quartile range, line within each box - the median, and whiskers - the range of data

wall appropriately. In manual mode, they were asked to follow the wall using minimal keypad inputs to maintain the wheelchair within an arm's distance from the wall (i.e., keeping the wheelchair within a zone of about 6 tiles from the wall as shown in Figure 5.3. The first three tiles from the wall span a distance of approximately 65cm and the width of the wheelchair is roughly 65cm. Hence the wheelchair was required to be maintained within 6 tiles to be at arm's distance from the wall. The task involved negotiating three walls and two corners. A similar route was taken in the shared control mode. They were asked to bring the wheelchair back within the prescribed zone if it exited it and also provide corrections to the corner navigation if required.

5.4 Results

The overall workload scores for all the five subjects were calculated and averaged to get mean overall workload scores for each task on a scale of 0 to 100.

The overall workload ratings for tests conducted to assess Obstacle Avoidance behaviour is shown in Figure 5.4. The variation in workload ratings between the volunteers is clearly visible. It is particularly high in the case of shared control

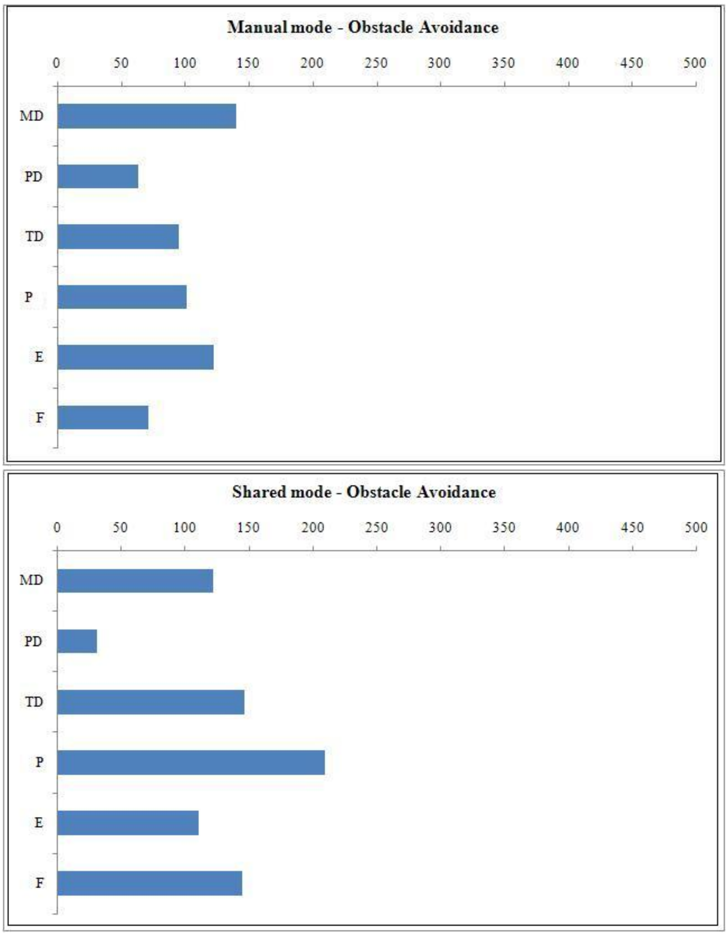


Figure 5.5: Sources of load for manual and shared control without secondary tasks. Each subscale is rated from 0 to 100 and given a weight from 0 to 5. Hence the maximum adjusted rating (rating x weight) for a subscale is 500. MD refers to Mental Demand, PD - Physical Demand, TD - Temporal Demand, P - Performance, E- Effort, F- Frustration

(without secondary task), with workload scores ranging between 23 and 87.67 (standard deviation - 25.8). The reasoning for this observation could be that the volunteers did not show the same response or have the same level of acceptance for the shared control assistive behaviours offered by the wheelchair.

It can be observed that the workload scores for shared control are higher than that for manual mode, with and without the secondary task. This can be attributed to the restrictions imposed by the collision avoidance behaviour, particularly in narrow spaces. Volunteers had to spend more time to re-position themselves in order to proceed in the required direction. This increased their frustration and sense of performance. These findings are represented in the graphs

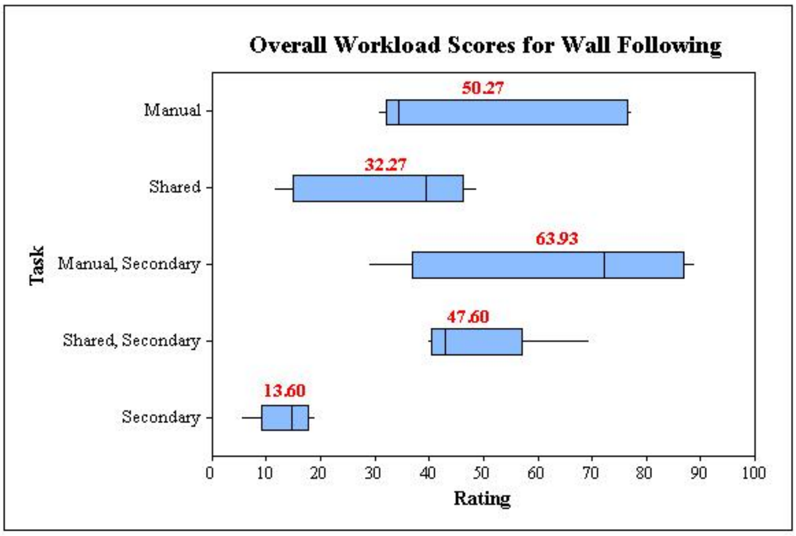


Figure 5.6: Overall workload scores for Wall Following behaviour testing. 'Manual' and 'Shared' correspond to manual and shared mode, respectively. 'Secondary' refers to presence of secondary task. Mean workload values are indicated in red. Boxes represent the inter-quartile range, line within each box - the median, and whiskers - the range of data

in Figure 5.5 showing the sources of workload for manual and shared control modes. Another observation is the perception of workload in the presence of the secondary task. While the workload of the secondary task alone is low, when combined with the manual mode driving task, the resultant workload is high. The change in workload in the case of shared control is not as much as in manual mode.

The results for testing the Wall Following behaviour is provided in Figure 5.6. Variations between different volunteers are observed in this case as well. Workload scores for manual mode with secondary task shows highest variability (standard deviation - 26.1). But the mean workload is highest for this task. This can be explained by the increased user intervention required to correct for wheelchair drift, in addition to performing the secondary task. User intervention was however required in shared control mode near the corners since the wheelchair did not always negotiate corners properly.

The effectiveness of the shared control approach is shown by the lower overall workload scores, both with and without secondary task. This can be attributed to the predictability of the shared control behaviour in this mode as opposed to the obstacle avoidance mode. Three of the volunteers found shared control beneficial in this task, one perceived no difference and one found manual control easier. The latter volunteer seemed unable to gauge the path followed by the wheelchair and frequently tried correcting its position.

Chapter 6

Discussion

The evaluation of the shared control methods with the help of the NASA-TLX assessment tool has provided a number of interesting results relating to the acceptance of shared control by different people, many of which have been observed by other researchers. It has also aided in identifying limitations of the shared control system and possible improvisations. Experience derived from the testing procedure has helped in formulating suggestions for a better and probably more accurate evaluation. This chapter explains these inferences in detail.

6.1 Acceptance of Shared Control Behaviours

A common feedback given by all the volunteers was that they preferred manual control of the wheelchair over shared control. It may be noted that all of them are able-bodied people who have sufficient skills and the confidence to perform the driving tasks without any assistance. The same may not be the case for people with disabilities as shown by the evaluation of the Hephaestus smart wheelchair system (Simpson et al, 1999), with the help of both able-bodied volunteers and those with disabilities, caused by conditions such as cerebral palsy and post-polio syndrome. While the able-bodied volunteers preferred not to be assisted by the smart wheelchair, the people with disabilities felt more secure driving with obstacle avoidance assistance.

In re-directing the control of the wheelchair from the driver to the wheelchair controller, shared control is expected to lessen the sense of control felt by the user. However, the degree of the loss of control perceived by the user seems to be related to the magnitude of unpredictability of the shared control behaviours. It was observed that users accepted the shared control assistance if it was as per their expectations. However, they expressed frustration when they were unable to understand the behaviour of the wheelchair. This was clearly noticeable in narrow spaces where the wheelchair had stopped and prevented the user from moving in certain directions due to the Collision Avoidance assistive behaviour. Parikh et al (2005) have linked sense of control and frustration as inversely related feelings. Carlson & Demiris (2010) have also provided a similar discussion relating to the lack of understanding of the system and the need for appropriate feedback.

An inference may be made at this point drawing from the discussion on 'feeling in control'. The fact that users prefer to have as much control as possible over the wheelchair elicits the advantage of shared control wheelchairs over autonomous wheelchairs in ensuring the driver's safety while still maintaining his or her superiority.

It was noticed that the volunteers responded in different ways while the experiments were being conducted. A few volunteers were more cautious than others and slowed down the wheelchair when approaching obstacles, resulting in lesser collisions. Others focussed less on speed control. Some volunteers got more frustrated than others. Those who were able to understand the shared control behaviours more quickly, adapted to the system more easily. Hence the level of acceptance of the assistance provided by shared control was not similar among the volunteers. This is proven by the varied workload scores depicted in Figures 5.4 and 5.6, in Section 5.4.

6.2 Training and Feedback

One way of providing a better understanding of the system is through adequate training. In the tests conducted, the users spent only few minutes test-driving the wheelchair, which has proven to be insufficient. This re-iterates the benefits of training environments such as the VR wheelchair simulator developed at the University of Strathclyde.

Feedback given to the user to indicate the reason for shared control behaviours would minimise unpredictability of the wheelchair movements. It can be quite beneficial in a training environment where users can learn to develop driving skills that make use of shared control effectively so as to minimise workload, while at the same time providing sufficient challenges. Previous studies conducted at the University of Strathclyde using human-in-the-loop design of BCI-controlled wheelchair operation has demonstrated the positive effects of appropriate feedback on user performance (Grychtol et al, 2010). A three-dimensional arrow displayed on the simulator screen was developed for this research to act as a cue. The use of this arrow can be adopted for the purpose of providing feedback in shared control operation of the wheelchair. The user could possibly be suggested the direction to take, for instance to navigate through a narrow passage when Collision Avoidance assistance is activated. Alternatively, in the same scenario, the arrow can be used to indicate the prohibited directions set by the Collision Avoidance mode, thus enabling the driver to use his or her decision-making abilities to tackle the situation.

6.3 Limitations and Recommended Improvisations

One of the main drawbacks of the sensor arrangement was side collisions due to insufficient sensor coverage. This was a source of annoyance for the drivers in spite of being told at the beginning of the experiment that this was to be expected. Others have also reported side collisions (Simpson et al, 1999; Parikh et al, 2005; Petry et al, 2010). This issue can be resolved in a number of ways. The most obvious way is by adding more number of sonar sensors. Use of other sensor modalities such as laser scanners may be considered, which could also help to eliminate blind spots currently present in front of the wheelchair. Moreover, multiple sensors may be employed as explained in Section 2.3, to overcome the short-comings of any one sensor. Another solution would be by improvising the shared control strategy using more robust and effective methods for obstacle avoidance such as Potential Field Methods, Minimum Vector Field Histogram etc.

The curvature of the path followed by the wheelchair in Wall Following mode may be eliminated by revising the algorithm so that it may follow a linear path. This would enable the user to predict its behaviour better and intervene less frequently to correct its path.

It may be noted that the sensors used in this project were those provided by

USARSim and hence limited their use to the functionality provided. One of the constraints was that the sonar sensors could not be individually configured to have different beam angles. Hence creating sensors that satisfy the requirements may be considered.

The level of user interaction has been used as a measure of the effectiveness of shared control as explained previously in Section 2.4. However, the current implementation of the obstacle avoidance is such that the user is in control until their safety is compromised. Due to this strategy, the volunteers were not asked to drive the wheelchair using minimal keypad inputs. In order to reduce the user interactions and hence workload, more level of autonomy may be afforded to the wheelchair. This may prove useful particularly in narrow spaces, the regions of the map which caused the greatest frustration, with the help of techniques such as path planning.

6.4 Discussion of Experimental Procedure

Testing was limited to a population of only 5 volunteers due to time and resource constraints and it was not possible to ascertain if the difference in mean workload scores for the various tasks are statistically significant. A more fruitful evaluation can be achieved with a larger subject pool of different age groups consisting of able-bodied volunteers and people with disabilities.

In the tests conducted for Obstacle Avoidance with secondary task, it was observed in the case of three volunteers that the wheelchair had been brought to a halt in front of an obstacle, waiting for their commands to proceed. Two inferences may be drawn from these observations. Firstly, since all three of them had no previous gaming experience it could be deduced that the benefits of shared control may be more visible for users with poorer driving skills and that there could be a correlation between gaming experience and wheelchair driving skills. This impact could be studied using a larger population with varied gaming practice. The second inference relates to the effectiveness of the secondary task in simulating a condition of reduced ability because while all the three volunteers were able to manoeuvre the wheelchair in manual mode, their skills were suppressed in the presence of the secondary task.

The volunteers' responses to the secondary task were also interesting to observe. One of the volunteers skipped slides to concentrate on his driving. Most of them gave wrong answers occasionally in the attempt to react as fast as possible, as was observed by Carlson & Demiris (2010). The design of the secondary task may be improved by studying the variability in volunteers' responses and devising a method suitable for testing across different population groups or using different sets of secondary tasks for different people depending on their abilities. In the tests conducted, between-rater variability was observed due to different interpretations of the NASA-TLX subscale definitions. In future tests, explicit instructions may be provided to the volunteers, citing examples of sources of workload within the tasks, to reduce the variability. For example, pressing the keypad can be identified as a physical task which would contribute towards the physical demand subscale. This would help to determine the magnitude of user interaction from the ratings of that subscale.

While testing Obstacle Avoidance mode, the rating of the tasks using the NASA-TLX scales was conducted immediately after the volunteer navigated the obstacle course containing the columns and narrow spaces, which were the main sources of frustration in the whole circuit. As this could have influenced their rating and choice of sources of workload, it is proposed that separate tests be conducted for different difficulty levels.

The Obstacle Avoidance tasks were conducted in the Training Course VE, which was created to test the mechanical functioning of the wheelchair such as its ability to negotiate ramps and corners, to verify the properties of inertia etc. It is suggested that testing be conducted in a map created to test various aspects of the shared control behaviours. The environment may contain obstacles of various sizes, passages of different widths etc. and arranged such that tasks with different difficulty levels can be tested separately.

Chapter 7

Conclusion

The objective of the project was to review shared control approaches used in electric powered wheelchairs and to incorporate shared control in the virtual reality wheelchair simulator developed in the Neurophysiology Lab at the University of Strathclyde. A shared control technique providing Obstacle Avoidance, Wall Following and Collision Avoidance assistive modes has been developed and evaluated with the help of a secondary task and NASA Task Load Index assessment procedure.

The wheelchair simulator provides shared control in unfamiliar environments with the help of sonar sensors to assist in obstacle avoidance and preventing collisions. The Obstacle Avoidance assistive behaviour is more effective in areas containing widely spaced obstacles as opposed to narrow spaces where side collisions occur more frequently. Collision Avoidance has been tested and though effective in increasing the safety of the user, it has been the main source of frustration in the tests conducted using 5 volunteers. Blind spots due to insufficient number of sensors must be removed. This would greatly enhance the performance of the shared control behaviours. Wall Following assistance has been achieved with the help of infra-red sensors. The assistance provided by this mode was better accepted by the volunteers. However, it follows a curved or zigzag path at times, which should be changed to a linear path by improvising the algorithm.

The use of secondary tasks has proven to be beneficial in assessing the shared control methods by imposing higher cognitive demands on the user and hence decreasing their wheelchair-driving efficiency. This brought out the effects of shared control, which would otherwise not have been detected since the volunteers were able-bodied people who did not require assistance. The design of the secondary task may be modified to yield better and more consistent results.

The workload scores obtained with the help of the NASA-TLX scales are satisfactory. The assessment procedure has provided a means of identifying the acceptable and annoying behaviours provided by shared control. In addition to these ratings, the feedback received from the volunteers regarding their driving experience in both manual and shared modes, as well as their perception of the usefulness of shared control behaviours, has provided valuable information in understanding the drawbacks of the system.

In conclusion, this study has provided a useful insight of how shared control may be integrated with the virtual reality wheelchair simulator and about the psychology of people interacting with intelligent machines. Future work in this domain can be based on the inferences obtained through evaluation of the shared control system.

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Appendices

Appendix A

Electronic Resources

The source code for the project is provided in the enclosed CD. A brief description of the files included is given below:

UT2004:

- ***USARBot.ini***, the configuration file in the *System* folder, has been modified to incorporate sonar and infra-red sensors in the wheelchair.
- ***IRSensor.uc*** in the *Classes* folder under the *USARBot* folder has been modified by changing the maximum and minimum ranges of the IRSensor.

Wheelchair Application:
The following files have been modified:

- ***resource.h*** and ***Wheelchair.rc*** files have been modified to include a new check box labelled 'Shared Control'
- ***WheelchairDlg.cpp*** and ***WheelchairDlg.h*** have been changed to allow the shared control check box to be activated.
- ***Wheelchair.cpp*** and ***Wheelchair.h*** have been modified to create a shared control object and pass sensor data to it.
- ***StateControl.cpp*** and ***StateControl.h*** have been changed to allow collision avoidance in the function, *TransFun*, prior to changing the state of the wheelchair. A new function has been added, *SharedTransFun*, to customise

the state control for shared control behaviour. The function *ModifyControl* has been added to limit the speed of the wheelchair in shared control mode.

The following files have been added:
SharedControl.cpp and ***SharedControl.h*** contain the implementation of the class *SharedControl*, which handles the shared control strategies for obstacle avoidance, collision avoidance and wall following.

Appendix B

Evaluation - Materials

B.1 Information Sheet

The information sheet provided to the volunteers contains details of the study and the experimental procedure. It also has attached a consent form which they are required to fill prior to the experiment. The definitions of the rating scales (Appendix B.2) are also provided to the volunteers along with the information sheet. These are shown in the following pages.

INFORMATION SHEET

Purpose of Study: In this project, shared control has been incorporated in the immersive Virtual Reality (VR) wheelchair simulator. The intelligent wheelchair controller assists the driver in times of need such as to avoid obstacles, prevent collisions and aid in following a wall. The effectiveness of the shared control behaviours will be evaluated based on the driving experience of the volunteers in this study.

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Participants: We are aiming to recruit male and females with no visual disabilities. *Please see next section for exclusion criteria*

Exclusion Criteria: Subjects would be unsuitable for the study if they suffer from any of the following:

- Visual disability that prevents them from viewing the wheelchair simulator on the screen or the slides shown on the laptop monitor
- Physical disability that prevents them from operating the keys of a keypad that is used as the access device to control the wheelchair

- Cyber sickness, which could be caused by the immersive effect created by the dome-shaped screen

Requirements: You will be asked to perform a number of tasks for which you need to know the following:

- NASA-Task Load Index assessment procedure: After performing each task, you will be asked to rate the 'workload' you experienced with the help of the NASA Task Load Index (NASA-TLX) scales. NASA-TLX is based on the concept that workload can be determined by considering the contributions of the six subscales, Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration, in creating the workload. Please read the definitions of these rating scales in the sheet attached. It is important that you understand them well. If you have any questions, please ask them now. For each task you will perform, you will be provided with a Rating Sheet that has six scales corresponding to each of the six rating scales. Each line ranges from 0 to 100 and you are required to put an 'X' mark at the point which, in your opinion, best describes the level you experienced. Note that performance ranges from 'good' to 'poor', on the scale from 0 to 100. After filling the Rating Sheet, you will given 15 cards, arranged in random order, each containing a pair of subscales. Select the subscale that contributed more towards the workload of the task. Please ensure that you are consistent in your reasoning for making these choices for all the tasks.

- Keypad control: The wheelchair is operated using this keypad. Key 8 is for moving the wheelchair forward - with every key press, you enter the next speed level. There are 2 levels of speed. Key 4 is for left, 6 for right and 5 for stop. Key 2 is for slowing down the wheelchair and then reversing it. Please familiarise yourself with the keys. The wheelchair continues to move in the direction of your last command until you give a new command.

- Secondary task: In addition to the primary task of wheelchair driving, you will be asked to perform a secondary task which involves responding to three different types of slides on a slideshow displayed on this laptop monitor, while simultaneously driving the wheelchair. A new slide appears every two seconds. The red slide requires you to turn your head away from the simulator screen and then quickly look back. When a slide containing a mathematical problem appears, please say the answer orally or at least read out the question. The white slide does not require you to do anything. Please adjust the placement of the laptop so that you are able to view both the simulator screen as well as the laptop monitor.

Instructions: Please keep the following in mind while performing the tasks:

- Your priority is to drive safely, avoiding obstacles, and to complete the task as fast as possible. The primary task takes priority over the secondary task at all times. In doing the secondary task, respond as quickly and correctly as possible.
- Modes of control: There are two ways of controlling the wheelchair - in manual mode, you are in full control of the wheelchair, and in shared control mode, you still control the the wheelchair, but it provides some assistance such as moving away from obstacles sensed by sensors placed along the front of the wheelchair. Obstacles to the sides and rear of the wheelchair cannot be detected. If the wheelchair stops and prevents you from moving in a particular direction, it is an indication that there is an obstacle in close proximity to you. Reverse the wheelchair and change your direction suitably to proceed.

Experimental Procedure: You will be given a few minutes to practice driving using the manual and shared control modes, following which you will perform the tasks listed below. At the end of each task, you will rate your experience using the NASA-TLX scales.

- Secondary task: You will perform the secondary task without the primary task.
- Obstacle Avoidance tasks: You will perform 4 driving tasks on the path shown to you in the Training Course map. These include driving in manual mode, with and without secondary task, and similarly for shared control.
- Wall Following tasks: You will perform the same set of 4 tasks involving following a wall in an empty hall. Perform all the tasks using as few keypad

inputs as possible. Decide on following either right or left wall. In shared control mode, the wheelchair detects the wall as you move close to it and follows the wall. It detects and negotiates corners as well. However, you may need to provide some correction if it does not turn properly or stops following the wall. At all times while following the wall, keep the wheelchair within an arm's distance from the wall. For a sense of distance, you can look at the tiles on the floor - keep within 6 tiles.

Withdrawal: Your willingness to participate is paramount. As a volunteer you can demand that the experiment be stopped at any point.

Risks: The possibility of developing cyber sickness, i.e., motion sickness caused by the immersive virtual reality environment.

Data Protection: Data will only be accessible via the researcher's computer or the departmental computer linked to the equipment, both of which require passwords to access and are stored in a safe location. Any data used will be anonymised before publication to protect the patients' identity.

Complaints: Should you wish to complain to an independent person, you may contact Mr. Brian Cartlidge, brian.cartlidge@strath.ac.uk, Bioengineering Unit, Room 4.02, *Tel*: 0141 548 3283 (Ext. 3283).

CONSENT FORM

Project: Shared Control Between Man and Machine in Brain Computer Interfaces

Researcher: Radhika Menon
radhika.menon@strath.ac.uk

Participant: Please enter your details below:
Name:...
Contact details: ....
Signature:..
Date: ....

Please read the following carefully and initialise each comment to signify your agreement:
I have read and understood the information sheet. ....
I have had opportunity to raise any questions regarding the study. ....
I am satisfied with the answers given to questions on the study. ....
I am aware that my participation in the study is voluntary and that I can withdraw at any time. ....
I agree to participate in the study. ....

Authorised:
Researcher signature:...
Date: ....

Participating in this study, or otherwise, will not affect your relationship with the University in any way.

B.2 Rating Scale Definitions

NASA has provided the following definitions of the six subscales used in the NASA-TLX workload assessment procedure. The volunteers are required to read and understand these terms before proceeding with the evaluation of the driving tasks in the experiments conducted. All definitions are quoted from Appendix A of the NASA-TLX Paper and Pencil Version Instruction Manual (Version 1.0) (NASA, 1986).

1. ***Mental Demand***: How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?

2. ***Physical Demand***: How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?

3. ***Temporal Demand***: How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?

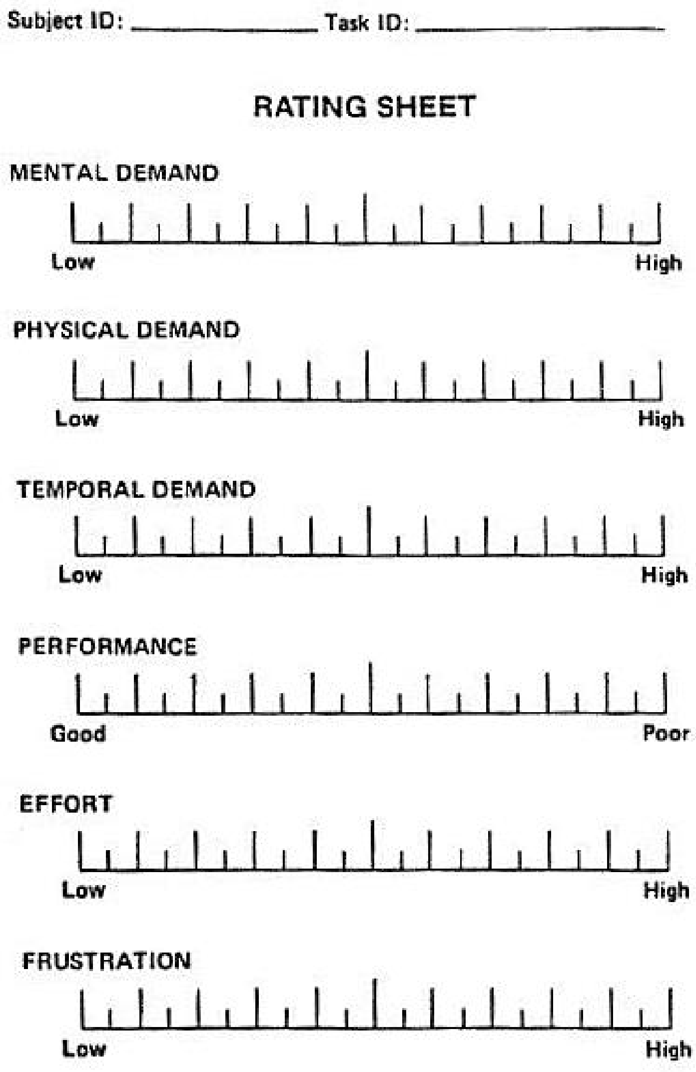
4. ***Performance***: How successful do you think you were in accomplishing the goals of the task set up by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?

5. ***Effort***: How hard did you have to work (mentally and physically) to accomplish your level of performance?

6. ***Frustration***: How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

B.3 Rating Sheet

The Rating Sheet shown in figure below, taken from NASA-TLX Manual (NASA, 1986), was provided to the volunteers for rating the six subscales.


Subject ID: ____________ Task ID: ____________

RATING SHEET

MENTAL DEMAND

Low High

PHYSICAL DEMAND

Low High

TEMPORAL DEMAND

Low High

PERFORMANCE

Good Poor

EFFORT

Low High

FRUSTRATION

Low High

Figure B.1: Rating Sheet for the six subscales. *Rating Sheet taken from Appendix C of NASA-TLX Paper and Pencil Version Instruction Manual (NASA, 1986)*