Development of an Anti-Collision and Navigation System for Powered Wheelchairs

by

Tuck-Voon How

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science in Biomedical Engineering
Institute of Biomaterials and Biomedical Engineering
University of Toronto

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Abstract

Powered wheelchairs offer a means of independent mobility for older adults who are unable to walk and cannot propel a manual wheelchair. Unfortunately, cognitively impaired older adults may be denied this means of independent mobility. There is concern that these adults are unable to drive a powered wheelchair safely or properly. Intelligent wheelchairs offer an approach to address this problem. This research outlines the development and evaluation of an Intelligent Wheelchair System (IWS) that is proposed to make powered wheelchairs safer and easier to use for cognitively impaired older adults. The IWS has anti-collision and navigation functions. Hardware results show a 1000% increase in computational speed compared to the previous IWS. Clinical results with dementia patients show that the IWS has the potential to increase safety by reducing frontal collisions, and by promoting safe completion of movement tasks. Usability of the system may be an issue.
Acknowledgments

This project could not have been completed without the help of many.

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To IATSL: my colleagues and friends, your dedication always inspires me to push on.

To my friends and family: for supporting me throughout.

And lastly, to the participants and their families: thanks can only be offered now, yet your contribution paves the way to something more. Thank you sincerely.
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<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>2D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three Dimensional</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog to Digital Converter</td>
</tr>
<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>CALL</td>
<td>Communication Aids for Language and Learning</td>
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<tr>
<td>CAT6</td>
<td>Category 6</td>
</tr>
<tr>
<td>CWA</td>
<td>Collaborative Wheelchair Assistant</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to Analog Converter</td>
</tr>
<tr>
<td>DB9</td>
<td>D-subminiature 9</td>
</tr>
<tr>
<td>DCLM</td>
<td>Direction Control Logic Module (Joystick)</td>
</tr>
<tr>
<td>DDR</td>
<td>Double Data Rate</td>
</tr>
<tr>
<td>DOF</td>
<td>Degrees of Freedom</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>FPS</td>
<td>Frames Per Second</td>
</tr>
<tr>
<td>GB</td>
<td>Gigabyte</td>
</tr>
<tr>
<td>GHz</td>
<td>Gigahertz</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<td>-----------------------------------------------------------------------------</td>
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<tr>
<td>IATSL</td>
<td>Intelligent Assistive Technology and Systems Laboratory</td>
</tr>
<tr>
<td>iDAPT</td>
<td>Intelligent Design for Adaptation, Participation and Technology</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>IWS</td>
<td>Intelligent Wheelchair System</td>
</tr>
<tr>
<td>NASA-TLX</td>
<td>National Aeronautics and Space Administration Task Load Index</td>
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<tr>
<td>OCU</td>
<td>Onboard Computing Unit</td>
</tr>
<tr>
<td>OMNI</td>
<td>Office Wheelchair High Maneuverability and Navigational Intelligence for People with Severe Handicap</td>
</tr>
<tr>
<td>PALMA</td>
<td>Assistive Platform for Alternate Mobility</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>QUEST</td>
<td>Quebec User Evaluation of Satisfaction with assistive Technology</td>
</tr>
<tr>
<td>RS-232</td>
<td>Recommended Standard 232</td>
</tr>
<tr>
<td>SBC</td>
<td>Single Board Computer</td>
</tr>
<tr>
<td>SDM</td>
<td>Substitute Decision Maker</td>
</tr>
<tr>
<td>SDT</td>
<td>Signal Detection Theory</td>
</tr>
<tr>
<td>TBI</td>
<td>Traumatic Brain Injury</td>
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<td>USB</td>
<td>Universal Serial Bus</td>
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Chapter 1
Introduction

1.1 Problem Statement

Independent mobility is a critical component of an individual’s ability to engage in daily life tasks [1]. Without a means of independent mobility an individual may suffer from feelings of reduced self-esteem, social isolation, fear of abandonment, anxiety and depression [2] [3]. For older adults (65+) who have lost the physical ability to walk, the risk of losing independent mobility is a very real possibility. Fortunately, many of these older adults are able to use manual or powered wheelchairs to provide them with a means of independent mobility.

However, not all older adults who need powered wheelchairs for independent mobility are able or allowed to use them. Physical disabilities such as muscle weakness, spasticity, tremor, and vision impairment; and cognitive disabilities such as impaired attention, memory impairment, and deficits in executive reasoning, prevent adults from being able to use a powered wheelchair properly or safely [4]. With the growing population of older adults in developed nations, it is perceived that such barriers will prevent an increasing number of individuals from having a means of independent mobility.

In an effort to make powered wheelchairs more accessible for these older adults, there has been work from different health disciplines related to wheelchairs. For example, a better framework to assess driving skills of individuals using powered wheelchairs has been developed [5], and new wheelchair technologies aimed at accommodating different disabilities have been researched [6]. The barrier to powered wheelchair access is a multidisciplinary problem and each field has their role to play in the solution.

Within technology development, researchers have been pressed to develop more accessible and safer powered wheelchairs. This is done by improving wheelchair control interfaces and designing intelligent wheelchair systems [6]. Technology advancements offer one means of reducing barriers to powered wheelchair use, and thus promote an individual’s opportunity for independent mobility.
The goal of the IATSL (Intelligent Assistive Technology & Systems Lab) wheelchair project is based on that premise that technology can potentially reduce the barriers to powered wheelchair access for older adults. Specifically, this project is aimed at developing an intelligent system that will aid in the safe and proper powered wheelchair use for cognitively impaired older adults who may normally be denied a powered wheelchair [7] [8].

1.2 Objectives of Research

The objectives of this research were to:

1) Improve the performance of the existing IATSL Intelligent Wheelchair System (IWS) and adapt it to newer powered wheelchairs.

2) Evaluate the new system under hardware and clinical conditions to determine its viability of providing powered wheelchair use for older adults with cognitive impairments.

1.3 Research Questions

Three main questions were to be answered by this research:

1) Does the new intelligent wheelchair system provide an improvement, in terms of system performance, as compared to the previous IWS?

2) Does the design of the IATSL-IWS improve the safety and usability of powered wheelchairs for older adults with cognitively impairments?

3) What future improvements are needed for the IWS?
1.4 Overview of Thesis

This thesis has been divided into seven chapters. Following this introduction, chapter 2 will focus on a literature review about older adults’ use of powered wheelchairs, cognitive barriers preventing powered wheelchairs use, and intelligent wheelchairs. Chapter 3 will present the improved IATSL intelligent wheelchair system (IWS). Chapter 4 will describe the hardware trials used to evaluate the new system and will discuss findings related to the first research question. Chapter 5 will describe a clinical evaluation phase used to test the IWS with cognitively impaired older adults. Chapter 6 will discuss the findings from the clinical trials as they relate to the second and third research questions and limitations of the clinical study. Lastly, chapter 7 summarizes the completed research work.
Chapter 2
Literature Review

2.1 Powered Wheelchairs: Benefits and Use for Older Adults

Powered wheelchairs are known to provide benefits for older adults by enabling them to have a means of independent mobility. These benefits include: participation in self-care, productivity, and leisure occupations; as well as, socialization opportunities, and positive self worth [9] [10]. Overall powered wheelchairs are linked to an improved quality of life for older adults who have a reduced ability to walk and do not have the stamina, strength, or ability to propel themselves in a manual wheelchair [9]. Without a powered wheelchair these older adults would be dependent on others to complete life tasks [1], and unable to have independent mobility.

As age increases, the prevalence of wheelchair use in the population also increases [11]. Older adults are by far the fastest growing population within Canada [12], and therefore it is reasonable to state that the demand for powered wheelchairs is also increasing. In Canada, it is estimated that approximately 50% (or 96,600) of older adults in institutional settings and approximately 2.2% (or 81,300) of older adults in community based dwellings use wheelchairs (powered or manual) [11]. If any interventions are to be made to powered wheelchairs for older adults, it is important to understand the needs and demographics of both populations. In a national sample of 294 older adults living in institutional settings, approximately 65% had some form of cognitive impairment [13]. And in another national survey of 5287 older adults in community dwellings, approximately 19% were found to have cognitive impairment [14].

2.2 Required Skills for Driving Powered Wheelchairs

In order to drive a powered wheelchair a user must have: 1) adequate motor abilities for control of driving interfaces; 2) good cognitive reasoning to interpret and act upon the driving situation; and 3) sensory awareness of the environment around the powered wheelchair [4]. Specific cognitive skills required are: the interpretation of information from the environment (i.e. understanding when to stop), the recollection of knowledge from previous use (i.e. knowing how to navigate through certain obstacles such as door frames and ramps), and the ability to make
decisions and plans for mobility action (i.e. executive reasoning) [15]. Adequate memory, attention, and focus are also needed during driving. Together these skills allow an individual to drive a powered wheelchair properly and safely.

2.3 Cognitive Deficits and Powered Wheelchairs

Older adults (especially those in institutional settings) may have cognitive impairments that affect their ability to drive a powered wheelchair properly and safely. Cognitive impairments such as Alzheimer’s disease (most common dementia in older adults) and severe TBI (traumatic brain injury) are known to have symptoms of impaired attention, agitation, and poor impulse control [16] [17]. These symptoms could affect a driver’s ability to concentrate and could also lead to aggressive driving [4].

As well, cognitive impairments could negatively affect a driver’s ability for executive reasoning; this causes difficulties in judgment, problem solving, planning, decision making, and sequencing actions. With such difficulties drivers may not be able to plan driving routes and thus will have difficulties navigating in their environment. They may not also be able to understand when to stop, which could lead to collisions and injuries. Executive reasoning in older adults can be negatively affected by diseases such as: cerebral palsy, multiple sclerosis, severe TBI, and dementia [4]. Some of these diseases (cerebral palsy, multiple sclerosis, severe TBI) may also impact motor functioning. Lastly, memory impairment (which has been linked to diseases such as dementia) could cause difficulties in remembering how to drive to certain locations.

2.4 Risk and Concerns Related to Powered Wheelchairs

Older adults who have a cognitive impairment are at risk of being denied a powered wheelchair. Cognitive deficits increase the likelihood that the older adult will have accidents (collisions) that cause injuries to themselves and bystanders; or cause damage to the surrounding physical property [18]. It has been estimated that 25% of wheelchair injuries involve a powered wheelchair [19]. And 73-80% of older adults experience a trip or fall after being hit by a powered wheelchair [20].

Safety is a serious concern and some older adult institutions have restricted the use of powered wheelchairs altogether in order to manage their populations [21]. Other institutions have implemented assessment procedures that gauge whether individuals are suitable for driving a
powered wheelchair [22]. To date however, there is no standardized evidence-based method of distinguishing whether a potential driver is safe enough to drive a powered wheelchair [23]. The difficulty is that even though an older adult may have a cognitive impairment, this does not mean that they are unable to learn how to drive a powered wheelchair safely. Each individual is unique, and in institutions that allow powered mobility, clinicians have the task of balancing the need of allowing an individual’s independent mobility, with the safety of other residents. There are many stakeholders involved in the issue of safe powered wheelchair use.

If powered wheelchair use is denied due to cognitive deficits and safety concerns, then the older adult is left without a means of independent mobility altogether. A survey of practicing clinicians in United States reported that between 9% to 40% of their clients who desired powered mobility (powered wheelchairs or scooters) do not have the capacity to drive safely because their disabilities (sensory impairment, poor motor function, or cognitive deficits) cause them to have problems with existing powered wheelchair controls [24].

2.5 Addressing Concerns: Intelligent Powered Wheelchairs

To address concerns related to the usability and safety of powered wheelchairs, researchers have proposed the concept of intelligent wheelchairs. These wheelchairs use technology to improve the functionality of normal powered wheelchairs in order to make them safer and more accessible to use. By this definition, intelligent wheelchairs have the potential of allowing cognitively impaired older adults use a powered wheelchair by having technology make up for deficits in cognitive function.

There are many intelligent wheelchairs that have been developed – a literature review by Richard Simpson highlights main aspects of the field up to 2005 [6]. Intelligent wheelchairs can be divided by their functionality, sensing devices, level of autonomy, user interface, and form factor:

1) **Functionality** – different functions have been implemented in intelligent wheelchairs including collision avoidance (anti-collision), mapped based navigation to locations, wall following, and virtual path following.
2) **Sensing devices** – previous sensors that have been experimented with include: ultrasound, infrared (IR), laser, contact, and cameras. Each sensor has its advantages and disadvantages in terms of cost, accuracy, and robustness in detecting obstacles. Cameras are thought to be a promising option due to their lower cost and wide field of view.

3) **Level of autonomy** – intelligent wheelchairs differ in how much control is given to the driver. Some intelligent wheelchairs will have complete autonomy and will be able to drive a user to a pre-mapped location by itself. Other intelligent wheelchairs allow the driver to control the wheelchair, but will either help the user with navigation, or help the user avoid obstacles.

4) **User interface** – some intelligent wheelchairs use common interfaces such as joysticks, however other user interfaces have been developed to meet the needs of different disabilities. Some include: a vision based interface system [25], and a voice recognition system.

5) **Form factor** – some intelligent wheelchairs come as complete systems, while others use a robotic base with a wheelchair seat attached, and others have an add-on approach. The add-on approach allows the intelligent system to be attached to different powered wheelchairs that the user may go through.

The field is rich with different options of implementation, as intelligent wheelchairs have been intended for various disabled populations. For individuals with cognitive impairment, Simpson has described that autonomous navigation functions may be of benefit for those who cannot remember where they are going, how to get there, or have trouble problem solving; and anti-collision functions may be of benefit for those who are unsafe drivers [4].

Yet despite the proposed benefits, there are only a few projects have tested their functions with cognitively impaired individuals [6]. In fact, one shortcoming in this field is that many systems remain untested with their desired populations (partly due to the difficulty in coordinating trials with the desired population and also because the system may not be ready for clinical use). Because of this lack of testing, it is not truly understood if proposed ideas or prototype systems will help in the way they have been designed to. The need for clinical evaluation is critical in designing a system that will support the desired population it is intended for [26].
2.6 Intelligent Powered Wheelchairs for the Cognitively Impaired

This section will discuss intelligent wheelchairs that have been designed for and tested with cognitively impaired individuals:

2.6.1 OMNI

The OMNI (Office Wheelchair for High Maneuverability and Navigational Intelligence for People with Severe Handicap) is a standalone wheelchair developed with two goals in mind: 1) to allow high mobility in complex environments; and 2) to have modes of operation that will help the user have higher degrees of independence [27]. This wheelchair has been designed for individuals with severe mental and physical disabilities. It consists of mecanum wheels that provide 3-DOF (degrees of freedom) for the wheelchair; a specialized joystick for 3-DOF movement; a sensor ring around the wheelchair that has IR (infrared) and ultrasound sensors to provide obstacle detection capabilities; a bumper sensor for fail-safe detection of collisions; wheel odometers for knowledge of the wheelchair’s location; an elevating seat to raise the user; and a specialized display for the user select modes of operation. Modes of operation include: anti-collision, environment guided movements (e.g. following walls, driving through a door), complex maneuvers (e.g. back tracing a maneuver, or replaying a maneuver), and automated guided movements (e.g. using landmarks for automatic transport); these modes are selectable by
the user to provide customizability. Details of how the wheelchair functions in explicit algorithms have not been released due to confidentiality. The wheelchair underwent an iterative design process [28].

The wheelchair was tested with individuals with disabilities (type was not published), and was said to be advantageous because of its high maneuverability. It was also noted that the system could not prevent all collisions, and was meant only as a means of assistance to avoid collisions. Exact methods of testing were not disclosed.

2.6.2 Hephaestus Smart Wheelchair System

![Hephaestus Smart Wheelchair System](image)

Figure 2-2: Hephaestus Smart Wheelchair System (© IEEE, 2002).

The Hephaestus Smart Wheelchair system is designed as add-on system for existing powered wheelchairs [29]. The main goals of this system are to act as: 1) a *mobility aid* to help the user avoid collisions, and as a 2) *training system* to help users safely develop the necessary skills needed to drive a powered wheelchair without any technical assistance. To detect objects thirteen (13) ultrasound sensors are mounted in a semi-circle on a front facing tray, and three (3) ultrasound sensors are mounted on the rear. Due of this layout, the system has blind spots on the sides of the wheelchair. However there are also bump sensors (up to 24 can be mounted) that will immediately halt the wheelchair if contacted. The system analyzes user inputs from a joystick, and combines them with environmental information from the ultrasound sensors. From this, the system can either attempt to steer around obstacles by making slight adjustments to the user’s input, or slow down and stop the wheelchair at obstacles to allow “docking”. One disadvantage of the ultrasound sensors is that objects a few inches above or below the tray are unlikely to be detected.
The system was tested with four able-bodied and four disabled individuals (three with cerebral palsy, one with post-polio syndrome) [30]. All participants were asked to navigate through three simple object scenarios both with the smart system on, and without the smart system. All tasks were repeated four times in succession for each system condition. Subjective results showed that able-bodied participants preferred not to use the system and found the system intrusive rather than helpful; and disabled participants preferred to use the system as it provided a sense of security, although it did not lead to an immediate improvement in performance (as measured in time to complete the task).

2.6.3 Smart Wheelchair (UK CALL Centre)

![Smart Wheelchair](image)

**Figure 2-3: Smart Wheelchair developed by CALL Centre (© CALL Centre).**

The smart wheelchair developed by CALL (Communication Aids for Language and Learning) Centre is a standalone system [31]. The main purpose of the system is to provide a means of mobility training for children with severe and multiple disabilities. It has been developed into a commercial product and is currently available on the market. The main features of the smart wheelchair include: path following (using a line follower), and obstacle avoidance (using a bump sensor around the base of the wheelchair). With these two features, the powered wheelchair is capable of sharing various levels of autonomy with the user. The wheelchair can completely follow paths, bump and automatically turn away from objects, bump and let the user decide
where to go, bump and stop, or let the user have full control of the wheelchair. Conceptually, the level of control and independence of the user will increase with greater use of the system.

Because the system is commercially available there are now many records of use with cognitively impaired children. Most recently, the Centre for Cerebral Palsy in UK, conducted a study investigating the effectiveness of the smart wheelchair as a training tool for children with cerebral palsy [32]. Four children with cerebral palsy (between the ages of 4-14) were recruited to use the smart wheelchair in a six week training program (2 x 1hr sessions per week). Outcomes from the study showed that three of the four children gained independence in three of more driving skills. Psychosocial benefits for individual participants included: increased initiative, motivation, communication, and independence.

2.6.4 PALMA

![Figure 2-4: PALMA Autonomous Robotics Vehicle (© IEEE, 2005).](image_url)

The PALMA (assistive platform for alternative mobility) is designed specifically for children affected by cerebral palsy [33]. The goal of the PALMA is to provide the opportunity for these children to experience mobility in order to assist in their development. It is constructed as a standalone system using a modified children's toy car as its base (Boss by Hedstrom Co.). The system has eight ultrasound sensors to provide obstacle detection around the vehicle with a 90% sensor coverage rate. A child interfaces with the wheelchair through a control board made up of four direction buttons and a stop button; the system is also capable of plugging in additional controls, such as a joystick. This wheelchair is unique in that it has an interface for an educator.
to program the autonomy of the wheelchair. The autonomy of the wheelchair has six driving levels: 1) autonomous – random driving with obstacle avoidance, the child has no control over the wheelchair; 2) cause-effect relation – the child can start or stop the chair while it drives in autonomous mode; 3) simple decision – the wheelchair stops after detecting an obstacle, and the child must start the wheelchair again, if there is no response then there will be a audio prompt to do so; 4) control of direction – same as previous, but now the child must decide which direction to go into; 5) partially guided – same as control of direction, but now the child receives no prompts; 6) fully user guided – the child has full control over the wheelchair. Children can advance from levels of autonomy to levels of more user control based on how well the educator deems the child is driving.

Clinical trials were used to evaluate the system with children that had cerebral palsy. There were five participants (ages 3-7) and six evaluation runs were done for each participant over a period of two months. The child was allowed to drive in large rooms with obstacles, through doorways and corridors, to approach walls, and to complete other tasks. Exact testing methodology was not reported. Results showed that each child was able to advance to higher driving levels (each at different rates, judged by educators) by the end of the clinical trials.

2.6.5 Collaborative Wheelchair Assistant (CWA)

The Collaborative Wheelchair Assistant (CWA) is designed for people who find it difficult to use a normal powered wheelchair, yet still have the sensory ability to detect obstacles when
stopping is needed [34]. It is meant to complement the user, rather than the replace the user’s functional abilities. The system is driven by a joystick. For detection, it has wheel encoders to measure distance travelled, and a barcode scanner for localization of the wheelchair within the environment. The wheelchair functions by being able to create virtual guided paths between one location and another. Between these paths barcodes have to be placed on the floor in order to ensure that the internal map of the wheelchair is correctly calibrated. When using the wheelchair, users can select between two modes of operation: 1) free mode (no driving assistance), and 2) guided mode – the wheelchair automatically aligns itself and moves on virtual guided paths. During guided mode, the user has the ability to steer away from obstacles on the path, yet still remain “elastically” pulled to the path. Paths have to be mapped out by pushing the wheelchair through the environment or by defining them in software. Users input to a GUI (graphical user interface) which paths to drive on.

The system was clinically evaluated with five participants (age 16-48) with cognitive deficits from cerebral palsy or traumatic brain injury (TBI). These participants had previously been denied powered wheelchair use. Participants were first trained with modes of operation using a series of navigation tasks (e.g. driving along a straight line, avoiding a chair). After training, the participants were asked to complete a driving course, which involved driving through a door and around several tables. The participants completed the course ten times for each mode of assistance (free mode and guided mode). Results from detailed decomposition of joystick movements showed that the guided mode simplified joystick movement and reduced tremor content compared to free mode. All participants were able to drive a powered wheelchair with the guided mode, showing that they now have the opportunity for independent mobility. Four of the participants were able to drive in free mode after training.
2.6.6 Intelligent Wheelchair (Anti-Collision Skirt)

Figure 2-6: Anti-collision Powered Wheelchair with Skirt (© AOTA Press, 2009).

This intelligent wheelchair is a modified Nimble Rocket™ powered wheelchair (Nimble Inc., Toronto, Ontario) with a low force contact sensor skirt mounted around the base of the wheelchair [35]. The collapsible sensor skirt causes the wheelchair to stop if there is contact with an obstacle. Users are only permitted movement away from an obstacle; control is by joystick with no intelligent navigation assistance. There are also indicator lights mounted beside the joystick to show which direction of motion is allowed.

The wheelchair was tested as an intervention for an older adult male that had been diagnosed with dementia [36]. Twelve driving training sessions were conducted at the participant’s long term care residence in order to achieve one occupational performance goal: enabling self-mobility to increase social participation. This older adult was often limited in his social interactions with others due to his inability to physically move to other’s location. Results showed that the powered wheelchair encouraged independent mobility and social interactions of the participant. However the powered wheelchair was not able to sustain independent mobility for the user. The participant required ongoing support to use the wheelchair, and often needed verbal prompts (by the researcher), or hand-over-hand assistance for joystick control to help him navigate away from obstacles.
The intelligent wheelchair from University of Zaragoza is designed for users with cognitive disabilities [37]. To sense frontal obstacles the wheelchair uses a planar 180° laser mounted at a height of 0.75m (only objects at this height will be detected). For a control interface, a touch screen is used that acts both as an input device and a feedback (3-D visual representation) to the user of the local environment. The authors suggest that this interface will help situational awareness, and thus lower workload and errors. Users control the wheelchair using a final destination control strategy, in which they select a local point in front of the wheelchair via touch and the wheelchair navigates automatically to this point while avoiding obstacles. Navigation is based on input from the laser sensor and wheel encoders that measure the distance travelled. The wheelchair is capable of functioning in unknown environments with static and dynamic obstacles because it does not rely on pre-mapped environments.

Clinical evaluation of the wheelchair was done with four students (age 11-16) who had cerebral palsy. The study consisted of two phases: beginning with a training phase to allow individuals to familiarize themselves with the control interface (using a virtual training environment), and an evaluation phase to test the individuals’ use of the wheelchair in real-world setting (a hallway circuit within the students’ school). There was only one trial per student in the evaluation phase. System results showed that there were six collisions that occurred: three due to system errors, and three due to sensor errors (objects too low). Overall this was good, considering the experiment was carried out during normal school hours and in an uncontrolled and dynamic environment. All participants were able to complete the circuit successfully. It was noted that
individuals with higher degrees of cognitive impairment had more difficulty with the control interface (i.e. more time taken to complete course, greater number of touches required). Assistance was still required for individuals with higher cognitive impairment to complete complex navigation tasks (e.g. sharp turns).

It is noted that a previous iteration of this system used voice commands to control the wheelchair [38]. In-lab trials with two cognitively impaired children showed that voice was a poor interface (e.g. one child had less than 20% correct voice recognitions; there were errors due to incorrect order of words; and speech training in the lab environment was not adequate for control in other settings). The authors state that the new touch screen is a more robust control interface [37].

2.7 Discussion of Literature

The literature shows that there are innovative and promising intelligent wheelchairs that have been developed for and tested with cognitively impaired individuals (even though this represents a small portion of the field). These wheelchairs employ a variety of controls and sensors to assist users with powered wheelchair driving. It is unclear if one implementation is better than another because there is no standardized method of evaluating intelligent wheelchairs at the moment. Generally, more conclusive results were formed with longer trial periods and with systems that had been further developed.

Although, a number of intelligent wheelchairs showed promising results for children with cognitive deficits, only one project was known to target older adults with cognitive impairments (anti-collision skirt). This system was also unable to provide the older adult participant with a sustained form of independent mobility. Since the majority of wheelchair users are older adults, and since this population is growing, there is a pressing need to understand how intelligent wheelchairs could affect this population.

The purpose of this thesis is to further investigate the applicability of intelligent wheelchairs for older adults with cognitively impairments. In particular, it will look at the evaluation of a proposed Intelligent Wheelchair System (IWS) that has been developed by IATSL specifically for cognitively impaired older adults [7] [8]. This system has both anti-collision and navigation prompting abilities, which is an improvement over the anti-collision skirt system. Evaluation of
this project will form a better understanding of how navigation prompting may benefit cognitively impaired older adult drivers, and how the overall system can affect their mobility.
Chapter 3
System Development

3.1 Goal of IATSL Intelligent Wheelchair System (IWS)

The goal of the IATSL-IWS is to provide a safe and effective means of powered wheelchair mobility for older adults with cognitive impairments. The IWS is designed as an add-on system for existing powered wheelchairs. In this chapter a detailed look at the IWS will be presented: starting from an overview of the system, to limitations of the previous design, and lastly to the development of an improved IWS.

3.2 Overview of the Intelligent Wheelchair System (IWS)

A powered wheelchair’s hardware can be divided into three functional components for operation (Fig. 3-1).

![Diagram of powered wheelchair hardware]

**Figure 3-1: Functional diagram of powered wheelchair hardware.**

An *input device*, such as a joystick, is used as an interface for the user to send direction and speed commands to the wheelchair. The *motor controller* accepts these commands from the *input device* and transitions them into voltage signals that are used to drive the *wheelchair motors*. Finally, the *wheelchair motors* will turn and cause wheelchair tire motion based on the input voltage signals.

The IATSL-IWS adds three other functional components for intelligent operation (Fig. 3-2).
A sensor is used to detect the environment in front of the wheelchair. For the IWS this sensor is a stereovision camera: a special type of camera that has depth perception. The environmental information is then sent to an onboard computing unit that interprets the information and decides whether to stop/allow wheelchair movement in specific directions. If wheelchair movement is prohibited in a certain direction, the joystick DCLM (direction control logic module) will prevent any input device commands that cause the wheelchair to move in that direction from reaching the motor controller. In addition to controlling which directions of motions are allowed, the onboard computing unit can also use the environmental information to calculate the greatest area of free space in front of the wheelchair.

From this setup, the IWS has two capabilities:

1) **Anti-collision**: the IWS is able to stop the wheelchair from hitting obstacles (that are detected within a certain distance of the wheelchair) by preventing the wheelchair from moving towards those obstacles.

2) **Semi-autonomous navigation**: when the wheelchair is stopped due to an obstacle, the IWS can calculate the free space surrounding the obstacle, and the onboard computing unit will play audio prompts to help the user navigate to the area of greatest free space (i.e. “try turning left/right”). Prompting stops once the object is cleared. The navigation is considered semi-autonomous because the user’s control of the wheelchair is aided by the system.
3.3 Limitations of the Previous System

In April 2009, a previous version of the IWS [8] was tested in clinical trials at a long-term care center. Based on observations from these trials, several key areas of improvement were identified. These areas are summarized in the table below:

<table>
<thead>
<tr>
<th>Problem Encountered</th>
<th>Area of Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>• System had a slow update rate of 1-2 frames per second (FPS).</td>
<td>Computational system speed must be increased.</td>
</tr>
<tr>
<td>• Wheelchair could potentially drive too quickly and hit an object before the object is detected, or system could fail to detect moving obstacles before a collision occurs.</td>
<td></td>
</tr>
<tr>
<td>• System prevented all frontal joystick motion when an object was detected. This caused user frustration when their desired path of motion was blocked (ie. forward left/right).</td>
<td>Joystick direction logic must allow for more motion around obstacles and have allowance for slight errors in joystick direction.</td>
</tr>
<tr>
<td>• There were many areas of joystick “dead zone” (no movement produced) when the wheelchair was stopped to prevent a collision. The joystick had to be placed in a specific location (ie. far left/right) to produce movement. Users were confused when their joystick motion would not produce movement.</td>
<td></td>
</tr>
<tr>
<td>• False obstacle detection from lines/reflections on the floor. Users were frustrated when they perceived no obstacle in front of themselves and their motion was blocked.</td>
<td>Detection accuracy must be improved by better sensors or algorithms.</td>
</tr>
<tr>
<td>• Poor detection of non-textured surfaces (ie. plain table). Safety is a concern if the system does not detect certain obstacles.</td>
<td></td>
</tr>
<tr>
<td>• Incorrect prompting caused confusion to user. Sometimes the system incorrectly prompted the user to navigate into an obstacle.</td>
<td>Navigation prompts must have improved accuracy.</td>
</tr>
<tr>
<td>• There were occasions when the wheelchair sideswiped into obstacles because they were not in the stereovision camera’s forward field of view.</td>
<td>Detection of obstacles around the entire wheelchair is needed.</td>
</tr>
</tbody>
</table>
3.4 Requirements of the New IATSL-IWS

All areas of improvement from the clinical trials were taken as design requirements for a new version of the IWS. In order of importance the design requirements were: 1) improve computational speed, 2) improve joystick logic, 3) improve detection accuracy, 4) improve navigation prompts, and 5) have detection of obstacles around the wheelchair. The order of importance was chosen based on what improvements would make a high impact on the user’s driving performance, as well as what was feasible during the development timeframe (1 year).

A few additional design constraints were added to make the system compatible with newer powered wheelchairs. These constraints were that the IWS would be:

1) Able to **interface with proprietary signals of digital motor controllers** (used by newer powered wheelchairs).

2) **Compact** to fit on a mobility device.

3) Designed as an add-on system that is **adaptable to different powered wheelchairs**.

Lastly, the new IWS was designed to be modular and reprogrammable so that future changes to the system could be easily implemented.

Due to time constraints, detection of obstacles around the wheelchair was not implemented. However, all other design requirements were implemented.
Table 3-2 summarizes how the design requirements and constraints were implemented within the new IWS.

**Table 3-2: Implementation of Design Considerations for IATSL-IWS**

<table>
<thead>
<tr>
<th>Design Considerations</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Improve computational system speed</td>
<td>New stereovision camera with dedicated hardware to speed up processing.</td>
</tr>
<tr>
<td>2) Better joystick direction logic</td>
<td>New joystick DCLM that can block specific directions of forward motion independently of each other, and has reduced “dead zones” areas.</td>
</tr>
<tr>
<td>3) Improved detection accuracy</td>
<td>Blob collision detection algorithm that is less susceptible to noise, and can use a higher stereovision sensitivity for better detection of objects.</td>
</tr>
<tr>
<td>4) Improved navigation subsystem</td>
<td>Improved occupancy grid for better navigation prompting accuracy. Larger field of view with stereovision camera.</td>
</tr>
<tr>
<td>5) Interface/adaptability with newer wheelchairs</td>
<td>Limited implementation. IWS makes use a third-party product for interfacing with newer powered wheelchairs (Pride Mobility’s Q-Logic).</td>
</tr>
<tr>
<td>6) Compact system.</td>
<td>Hardware of IWS has a small form factor and is battery powered.</td>
</tr>
</tbody>
</table>
The following sections describe the new IWS’s hardware and software in detail.

3.5 Hardware of New IATSL-IWS

3.5.1 Sensor

The IWS uses a Focus Robotics stereovision camera [39] as a forward sensor. This camera was chosen because of its ability to perform depth calculations through hardware at real-time speeds (~30 FPS). The camera has a resolution of 720x480 pixels, with horizontal field of view (FOV) of 64°, and a vertical FOV of 41°. Figure 3-3: bottom left, shows an image of the camera.

The stereovision camera operates by taking two slightly different images of the same scene. Object locations within one image are matched to their locations within the other image. The greater the distance (or disparity) between these locations, the closer the objects are to the camera. This process is performed by a dedicated FPGA (field programmable gate array) board that is housed within the onboard computing unit. A CAT6 cable connects the camera to the FPGA board for data transfer.

![Camera Images](image1)
![3D Depth Image](image2)

Figure 3-3: [Left] Stereovision Camera captures two scene images (one from each lens) and transfers them to a [Right] FPGA board for depth processing. In the processed 3D depth image, brighter objects are closest to the camera.
Although the speed of depth processing is real-time, one disadvantage of using an FPGA for calculations is that the disparity values will be rounded off to the nearest whole. The result of this is that distances from the camera are quantized, or rounded off with some error. Quantization has a small effect on distances that are close to the camera (~5mm error), and an increasing effect as distances go farther from the camera (up to 10.4m error). With a 3.6mm lens, the stereovision camera has a detection range of 0.563±0.005m to 36.0±10.4m. Objects that are closer than this range have too high of a disparity to be calculated, and will cause occlusion on the 3D depth image (i.e. not be detected correctly).

3.5.2 Onboard Computing Unit

Figure 3-4 shows a picture of the onboard computing unit without its casing. The form factor of the unit is a PC/104 [40], which is a special board size (90 x 96mm) for embedded applications. PC/104 form factor has the advantage of being small and stackable. As mentioned previously, the stereovision’s FPGA board is housed within the onboard computing unit. This board is one of four components that are stacked together to build the unit.
In order from top to bottom, the four components of the stack are (Fig. 3-5):

1) **Single Board Computer (SBC):** Advanced Digital Logic’s ADL855pc is a computer with a 1.8GHz Pentium M processor; 1GB DDR-ram; 4GB compact flash hard drive; an audio output line to speakers; USB output line to a USB stick for data logging; and a serial RS-232 connection for real-time communication with the *joystick DCLM*. This computer is responsible for interpreting the 3D depth image outputted from the FPGA board.

2) **FPGA Board:** Focus Robotic’s nDepth FPGA board takes original images from the stereovision camera and converts them to a 3D depth image. It is connected to the stereovision camera via a CAT6 connection, and transfers data directly to the SBC.

3) **Power Supply:** TRI-M Engineering’s HESC104 is a 60W high efficiency power supply. It has an input voltage range of 9.5-19.5V; output voltages of ±5V, ±12V; and is capable of charging batteries. It is used to supply power to the computer and FPGA board, and it can be powered by an outlet socket or by the rechargeable battery in the stack.

4) **Rechargeable Battery:** TRI-M Engineering’s BAT-NiMh45 is a nickel cadmium rechargeable battery with a capacity of 4500mA-hr. At full capacity it has an energy backup of 37.8watt-hr, which is enough to power the stack for ~90 minutes.

The top three components of the stack are connected with a PC-104+ or PC/104 bus connector. These connectors allow power and data to be sent through the stack. The rechargeable battery is connected directly to the power supply via an 8-pin connector.
3.5.3 Joystick Direction Control Logic Module (DCLM)

As stated in section 3-2, the role of the joystick DCLM is to stop/allow the joystick signals that can reach the powered wheelchair’s motor controller. To accomplish this role, the joystick DCLM must first analyze what joystick signal has been sent, and then act on whether it should be stopped or allowed through the DCLM. The details of this process will be explained later in the software section. For now, the underlying hardware (Fig. 3-6) for this process will be discussed.

![Figure 3-6: Block Diagram of Joystick DCLM.](image)

The joystick DCLM is physically connected to a proportional joystick and a third-party interface device: Pride Mobility’s Quantum Q-Logic [41]. This interface device converts the joystick’s analogue signals into proprietary digital signals that are used by digital motor controllers in Pride Mobility’s powered wheelchairs. Two DB9 (9-pin connector) connections are used to attach the joystick and the Q-Logic to the joystick DCLM (Fig. 3-7).

![Figure 3-7: [Left] Joystick, [Middle] Quantum Q-Logic, [Right] DB9 Connector.](image)
Figure 3-6, shows that the *joystick DCLM* is made up of four functional blocks:

1) **Input Signal Conditioning:** The purpose of this block is to convert the incoming analogue joystick signals into a signal that can be analyzed by the microcontroller (by voltage level-shifting and scaling). This block is made of a precision voltage source, and a combination of operational amplifiers (op-amps), capacitors, and resistors (Fig. 3-8).

![Figure 3-8: One of the two op-amps within the Input Signal Conditioning block.](image)

2) **Microcontroller:** This block consists of an ATMEL Atmega644p microcontroller. The microcontroller performs ADC (analogue-to-digital conversion) on the input signals after their conditioning. Following this, the microcontroller analyzes the digital version of the joystick signals and determines whether to output them or to stop them from continuing on in the process. The microcontroller is also connected to the onboard computing unit via a serial RS-232; this allows the onboard computing unit to send commands to the joystick *DCLM* about which joystick directions are prohibited. Lastly, two digital lines connect the microcontroller to an emergency stop button. When this button is pressed the wheelchair will stop immediately.

3) **Output Signal Conditioning:** This block converts the output digital signals from the microcontroller back into analogue signals that can be sent to the Q-Logic. Hardware of this block consists of a DAC (digital-to-analogue converter), op-amps, capacitors, resistors, and a precision voltage source (similar to Fig. 3-8).

4) **Power Circuitry:** This block is responsible for supplying power to all other blocks within the *joystick DCLM*. It is made of a 5V and 10V voltage regulator, and several
precision capacitors. Power to the unit is drawn directly from the Q-Logic (ie. drawn from the powered wheelchair) via the DB9 connection.

Appendix A shows a complete schematic of the hardware for the joystick DCLM. Figure 3-9 shows the joystick DCLM after it was built on a custom designed printed circuit board (PCB).

Using a third-party device to interface with newer powered wheelchairs is a limited implementation of the IWS design goal of adaptability to new and different powered wheelchairs (since only one brand of wheelchairs is supported at the moment). However, with a modular design approach, further improvements can be made without changing much of the current IWS. In the future, the Q-Logic could be replaced by a custom interface device that is able to convert joystick signals into many different proprietary signals on the market; thus achieving the goal of interfacing with many different powered wheelchairs.
3.5.4 System Enclosure & Mounting

For evaluation purposes, the IWS was mounted on a Pride Mobility Quantum 6000z powered wheelchair. The stereovision camera was attached to the wheelchair using a custom camera mount. This camera mount was designed by iDAPT (Toronto Rehabilitation Institute), and it has the ability to swing open to allow access to sit into the wheelchair. The mount can also be tilted and laterally adjusted to change the camera positioning. For our purposes, the camera was mounted in the center of the wheelchair.

![Figure 3-10: Overhead view of camera mount with stereovision camera attached. The mount is an extension of the right arm wheelchair support.](image-url)
Figure 3-11: IATSL-IWS mounted on Pride Mobility Quantum 6000z powered wheelchair.

Two steel box enclosures were used to encase the joystick DCLM (4x4x2”) and the onboard computing unit (5x4x6”). These enclosures were mounted on the back lower-right of the powered wheelchair seat. The onboard computing unit has a power switch to turn on the IWS.

Figure 3-12: Enclosures mounted on back of the powered wheelchair seat; box on left is Joystick DCLM, right is Onboard Computing Unit.
3.6 Software of New IATSL-IWS

3.6.1 Anti-Collision

The anti-collision software runs on the single board computer in the onboard computing unit. This software analyzes the input 3D depth image, and determines if there are any imminent collisions. Anti-collision on the new IWS was first implemented using an updated version of the occupancy grid method from the previous IWS [8]. However due to noise issues, a new blob detection algorithm was developed for anti-collision. The next two sections describe the workings of each algorithm and the limitations of the occupancy grid method.

3.6.1.1 Occupancy Grid Method

The steps in Figure 3-12, describe how the 3D depth image is used to create an occupancy grid. During step 3, the value of each cell in the grid (\(G(i)\), for cell \(i\)) is updated by a constant \(K\). If the cell is in an occupied region, then \(G(i)\) is decremented by \(K\). If the cell is in a free space region, then \(G(i)\) is incremented by \(K\). Lastly, if the cell is in an unknown region (ie. behind another object), then \(G(i)\) is shifted by \(K\) back to a default \(G(i)\) value that represents unknown space. As a cell becomes more decremented/incremented then there is more certainty that the cell is occupied or in free space. A larger \(K\) value corresponds to a faster update rate of the occupancy grid.
grid; it also corresponds to an increased susceptibility to random noise. The K value was chosen to allow for fast updating of the grid, while maintaining low random noise within the grid. For the new IWS, each cell in the grid represents a 1cm by 1cm space; this is an increase in resolution from the previous IWS and improves the accuracy of collision detection.

Once the grid is mapped, zones of the grid are analyzed as depicted in Figure 3-13 to detect collisions.

![Figure 3-14: (Left) The closest forward-left and forward-right zones in the occupancy grid are scanned for obstacles. Object is detected in forward-right zone. (Right) Forward zone is scanned, an object is detected.](image)

If a zone has an obstacle, then a signal will be sent to the joystick DCLM to block the joystick direction that corresponds to that zone. Once the zone is free of the obstacle, then another signal will be sent to the joystick DCLM to allow joystick movement in the corresponding direction.

Although functional, the occupancy grid method suffers from its susceptibility to local noise. This is different than random noise that occurs over the 3D depth image. It has been described by Murray and Little [42] as small, stable regions of noise, that are due to mismatching between the two original scene images (ie. an object in one image is mismatched to a different object in the other image).

![Figure 3-15: (Left) Selected local noise spots are circled on 3D depth map. (Right) Resulting occupancy grid is severely affected by the local noise.](image)
Another disadvantage of the occupancy grid method is that it simplifies the external environment. Height data about the environment is lost because the occupancy grid is a 2D representation of a 3D world. This means that certain objects would appear similar on the grid. An example is a wall and a table, both would appear similar on the grid, yet in the real world the interaction between each is drastically different. A wall must be avoided in case of collisions, but a table could be approached to allow docking. With the occupancy grid method, there is no allowance for approaching the table, because in essence it is treated the same as the wall.

3.6.1.2 **Blob Detection Algorithm**

To compensate for the issues, a new collision detection method was devised to be less susceptible to local noise, and to be able to preserve height data (Fig. 3-16).

---

**Step 1**
Surfaces (or blobs) with high disparity (i.e., the closest objects) are found within the 3D depth image.

**Step 2**
Only surfaces that are larger than a certain threshold will be kept, this rejects local and random noise.

**Step 3**
The kept surfaces are encapsulated by boundary boxes. The location and size of the boxes gives information about where the obstacle is in the camera’s FOV, and the height of the obstacle.

---

**Figure 3-16: Blob Detection of Obstacles.**

**Figure 3-17:** [Left] Forward-left and forward-right zones are scanned for boundary boxes. The forward-left zone detects an obstacle. [Right] Forward zone is scanned for boundary boxes and detects an obstacle.
With the blob detection algorithm, the 3D depth map is scanned for obstacles (Fig. 3-17). Similarly to the previous method, if a zone has an obstacle or is free of obstacles, then a command will be sent to the *joystick DCLM*.

Since both local and random noises are rejected with this algorithm, the sensitivity to the environment can be increased to allow for better detection of true obstacles (and also more noise that must be rejected – Fig. 3-18). This is an advantage to the blob detection algorithm.

![Figure 3-18: [Left] Lower sensitivity and [Right] Higher sensitivity to the environment. Objects become better represented, but there is also more noise that must be rejected.](image)

3.6.1.3  *Communication to Joystick DCLM*

The communication from the single board computer (i.e. anti-collision software) to the joystick DCLM is implemented over a serial RS-232 communication line. Although this type of line is capable of thousands of commands (i.e. different serial combinations), only six commands have been implemented and encoded as 8-bit ASCII characters (American Standard Code for Information Interchange). These commands are described below:

<table>
<thead>
<tr>
<th>ASCII Command</th>
<th>Description</th>
<th>ASCII Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Allow forward-left zone.</td>
<td>q</td>
<td>Block forward-left zone.</td>
</tr>
<tr>
<td>2</td>
<td>Allow forward zone.</td>
<td>w</td>
<td>Block forward zone.</td>
</tr>
<tr>
<td>3</td>
<td>Allow forward-right zone.</td>
<td>e</td>
<td>Block forward-right zone.</td>
</tr>
</tbody>
</table>
3.6.2 Navigation

Navigation software is also run on the single board computer, and is initiated when zones have been blocked by the anti-collision software. When a zone has been blocked, this algorithm will calculate the direction of greatest freedom in front of the wheelchair, and will play an audio prompt after a short delay (Fig. 3-19). Audio prompting will continue to play until all zones are allowed (ie. the obstacle is cleared).

![Step 1) The sum of free space in the left and right zone is calculated by adding together G(t) cell values in the zone.
Step 2) The zone with more free space (a higher sum), will play its corresponding audio prompt (“try turning left”/“try turning right”).](image)

**Figure 3-19:** Navigation Software. Above, the left zone has more free space.

The new implementation of the occupancy grid improves the navigation algorithm by: 1) increasing the resolution of the grid, and 2) removing grid artifacts by updating unknown regions (Fig 3-20). Overall, the accuracy of prompting is improved.

![Figure 3-20: [Left Images] Grid artifacts are created when regions behind existing obstacles are not updated. Here an object approaches the camera. Artifacts skew the free space summation values. [Right] New occupancy grid updates regions behind obstacles.](image)
All software written on the single board computer was programmed with C++, using the OpenCV (Open Source Computer Vision) library, and a custom API (application programming interface) made by Focus Robotics to communicate with the stereovision camera and the FPGA.

3.6.3 Joystick DCLM Firmware

The Joystick DCLM firmware has two basic functions:

1) Real-time acceptance of commands sent by the single board computer.

2) Filtering of joystick signals based on free/blocked zones.

The first function is implemented using an interrupt routine that will accept the ASCII commands (see section 3.6.1.3) from the single board computer as they are sent to the joystick DCLM. As previously described, these commands are only sent when there is a change in the state of the collision zones (i.e. either an obstacle has appeared, or has disappeared).

Immediately after the command is accepted, this routine will analyze the command and will change the joystick zones that are free or blocked accordingly (Fig. 3-21). Each joystick zone corresponds to the collision zone that it could move towards.

![Diagram of joystick zones](image)

Figure 3-21: [Left] A joystick can be used to drive a powered wheelchair in 8 directions. [Right] Joystick zones are divided based on the directional movement they produce. Only the forward-left, forward, forward-right zones can be blocked in the IWS.
The second function is implemented by analyzing the input joystick signals after they have been converted into their digital values (described in section 3.5.3). There are two values associated with each joystick signal: an x-value, and y-value. These values correspond to how far the joystick has been pushed in the x or y axis. The values are used to determine which zone the joystick is currently pushed towards. Once the zone is known, it is checked against the status of which zones are free or blocked. If the zone is free, then the two joystick values are outputted without any changes. If the zone is blocked, then the two values are changed to values of the center joystick position (ie. the joystick position that produces no movement, essentially stopping the wheelchair).

Joystick “dead zones” are also reduced by this zone blocking feature. In the previous IWS, large portions of joystick motion were not allowed when a collision was detected (Fig. 3-22 – Left). In the new IWS a larger allowance on joystick motion has been given (Fig. 3-22 – Right).

![Figure 3-22: [Left] Previous IWS – when a direct frontal collision is sensed, only the light regions from the joystick would produce motion. [Right] New IWS – when a direct frontal collision is sensed, larger regions (shown as lighter regions) are allowed for motion.](image)

The firmware for the joystick DCLM is implemented on the ATMEL Atmega644p microcontroller. It was programmed using C and converted to assembly language using AVR Studio 4.
### 3.6.4 Summary of Completed Work

Table 3-4 summarizes the novel work completed for the new IWS.

**Table 3-4: Development Completed on New IWS**

<table>
<thead>
<tr>
<th>Module</th>
<th>Development Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onboard Computing Unit (OCU)</td>
<td>• Assembled computing stack (see section 3.5.2).</td>
</tr>
<tr>
<td></td>
<td>• Programmed collision detection algorithms.</td>
</tr>
<tr>
<td></td>
<td>• Programmed navigation prompting algorithm.</td>
</tr>
<tr>
<td></td>
<td>• Programmed communication code between OCU and Joystick DCLM.</td>
</tr>
<tr>
<td>Joystick DCLM</td>
<td>• Designed circuitry for joystick DCLM (see 3.5.3 and appendix A).</td>
</tr>
<tr>
<td></td>
<td>• Designed printed circuit board for joystick DCLM (see Fig. 3-9).</td>
</tr>
<tr>
<td></td>
<td>• Programmed firmware for joystick DCLM.</td>
</tr>
<tr>
<td>Overall</td>
<td>• Assembled enclosures and mount for OCU and joystick DCLM.</td>
</tr>
</tbody>
</table>

Outsourced work includes:

- Custom stereovision camera mount, designed and built by iDAPT (Toronto Rehabilitation Institute).

- Manufacturing of the printed circuit board by Advanced Circuits.
4.1 Objective

The objective of hardware evaluation was to compare the performance of the improved IWS with the previous system. Hardware evaluation was performed on the new IWS when it was mounted on a Pride Mobility Quantum 6000z powered wheelchair. The previous system had been built on a Nimble Rocket™ powered wheelchair, and results for that system have been published [7] [43].

4.2 Evaluation

The two methods of testing were: 1) hardware benchmarking, and 2) in-lab trials.

4.2.1 Hardware Benchmarking Methods & Results

Hardware benchmarking was conducted to measure differences in computational speeds between the old and new systems. The average processing frame rate of both systems were measured over 1500 image frames. Additionally, other properties were compared between the old IWS and the new system. The table below summarizes the findings:

<table>
<thead>
<tr>
<th></th>
<th>Previous IWS</th>
<th>New IWS (occupancy grid method)</th>
<th>New IWS (blob detection algorithm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Rate</td>
<td>2.25 fps</td>
<td>28.04 fps</td>
<td>24.47 fps</td>
</tr>
<tr>
<td>Image Resolution</td>
<td>320x240 pixels</td>
<td>720x480 pixels</td>
<td>720x480 pixels</td>
</tr>
<tr>
<td>Camera Horizontal FOV</td>
<td>50°</td>
<td>64°</td>
<td>64°</td>
</tr>
</tbody>
</table>
The new system has improved the processing frame rate by approximately 1000% with the blob detection algorithm. The blob detection algorithm has a slower performance than the occupancy grid method because it is more computationally intensive; however both perform better than the old system. With the new IWS, the image resolution has increased to allow detection of smaller objects, and the camera horizontal FOV has increased to allow a larger detection of the local environment.

4.2.2 In-Lab Trial Methods

In-lab trials were designed to test the system’s viability in a potential real-world setting: long-term care homes for elderly [6]. These trials evaluated the system’s anti-collision and navigation subsystems with real-world objects. The idea is that, if the system is capable of performing well with these objects, then it has the potential to be deployed in such a real-world environment.

The anti-collision function was tested by driving the powered wheelchair towards six different object scenarios: 1) a white wall; 2) a light green aluminum four-wheeled walker; 3) a silver-colored aluminum walking cane; 4) a stationary person; 5) a moving person; and 6) no object (to test for false detections). The wheelchair was driven from a distance of 3m towards the object in order to allow time for a constant velocity of 0.16m/s to be obtained (Fig. 4-1). Driving motion was allowed to continue until the anti-collision subsystem stopped the wheelchair, or the wheelchair hit the object. For the moving person scenario, the person remained outside the FOV of the camera until the wheelchair was within 700mm of the person. At this time, the person would step into the FOV and stop in front of the wheelchair. The anti-collision subsystem was set with a threshold distance of 700mm (i.e. if objects were detected within this threshold, then the system would stop; also refer to section 3.5.1 about detection issues when an object is too close). A threshold of 700mm was set to replicate previous methods used to test the old IWS [7]. This threshold was chosen based on experimentation of the required stopping distance for the Nimble Rocket™ powered wheelchair and the old IWS system. A 700mm threshold ensured that the previous IWS would stop the wheelchair before it hit an obstacle (if the obstacle was detected properly).
Figure 4-1: [Left] Anti-collision testing scenario, the powered wheelchair is driven towards the object. [Right] For the moving person scenario, the person remains outside the FOV of the camera until the wheelchair is within 700mm of the person.

The wheelchair was driven towards an object 20 times in each scenario, adding to a sum of 120 trials. In each trial, the response of the anti-collision subsystem was noted, and if the wheelchair was stopped by the system, the distance from the stereovision camera to the object was measured.

To test the navigation subsystem of the IWS, the powered wheelchair was driven towards three (3) different navigation scenarios: 1) an object placed left of center, 2) an object placed right of center, and 3) no object (to test for false prompting); see Figure 4-2 below. The object that was used was the light green four-wheeled walker. Each scenario was repeated 20 times, for a total of 60 trials. In each scenario, the prompting response of the navigation subsystem was noted. Driving motion was allowed to continue until the wheelchair stopped to prompt the user, or the wheelchair hit the object.
Signal detection theory (SDT) was used to group the responses of the anti-collision and navigation subsystems. There were four categories of responses for the anti-collision subsystem: 1) **Hit** (object present, object detected); 2) **Miss** (object present, no object detected); 3) **False Alarm** (no object present, object detected); 4) **Correct Reject** (no object present, no object detected). For the navigation subsystem, a **hit** would be given if the object was detected and direction of prompting was in the area of greatest free space (i.e. prompted to go right, if the object was on left). And a **miss** would also be given if the object was detected, but the prompting was not in the area of greatest free space.
4.2.3 In-Lab Trial Results

Results from the trials for the new IWS and the previous IWS are discussed below. These findings were performed when the new IWS was implemented with the occupancy grid method of collision detection.

Table 4-2 compares the performance of the old and new IWS (occupancy grid method) with each collision situation.

Table 4-2: Comparison of Old and New IWS’s Anti-Collision Subsystem Performance

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Hits</th>
<th>Misses</th>
<th>False Alarms</th>
<th>Correct Rejects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Old</td>
<td>New</td>
<td>Old</td>
<td>New</td>
</tr>
<tr>
<td>No Object</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wall</td>
<td>18</td>
<td>20</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Walker</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cane</td>
<td>18</td>
<td>20</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Person Stand</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Person Walk</td>
<td>20</td>
<td>19</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>96</td>
<td>99</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Two misses occurred in the wall scenario, and two misses in the cane scenario for the old IWS. One missed occurred in the moving person scenario for the new IWS. All other conditions were successfully detected or rejected.
The graph below shows the average stopping distances of both the old and new IWS (occupancy grid method) in each collision situation:

![Anti-Collision Stopping Distance](image)

**Figure 4-3: Anti-collision subsystem performance - Average stopping distance to object.**

In most conditions the stopping distance for the new IWS was closer to the desired stopping threshold than the previous IWS. The exception to this was the moving person condition, where the new IWS stopped on average ~8.4cm farther from the threshold than the old IWS. For all cases the standard deviation of stopping distances on the new IWS was less than the previous IWS.
Table 4-3 outlines the results for the navigation portion of testing.

### Table 4-3: Comparison of Old and New IWS’s Navigation Subsystem Performance

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Hits</th>
<th>Misses</th>
<th>False Alarms</th>
<th>Correct Rejects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Old</td>
<td>New</td>
<td>Old</td>
<td>New</td>
</tr>
<tr>
<td>No Object</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Object – left</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Object – right</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Both the old IWS and the new IWS had successful prompting results in all navigation scenarios.
4.3 Hardware Evaluation Discussion

The results from the hardware evaluation are used to answer the first main research question (see section 1.3):

**Does the new intelligent wheelchair system provide an improvement, in terms of system performance, as compared to the previous IWS?**

The new IWS has an improved computational speed, sensor resolution, and detection field of view (FOV).

From the in-lab trials, the new IWS outperformed the previous system in all collision situations except for the person walking situation. In this situation, the new IWS had one miss and a stopping distance that was further away from the desired threshold value than the previous IWS. The reason for the miss is likely due to the new stereovision sensor, and in particular the minimum distance that the sensor can detect (see section 3.5.1). The new sensor has a minimum detection distance of \(~56\)cm, which means that when the moving person comes into the camera FOV at \(70\)cm, then there is at best \(~14\)cm to detect the closest part of the moving person. Couple this with errors in judgment of when the wheelchair has moved past the \(70\)cm mark, and errors in step timing (i.e. stepping into the FOV too late); then this creates situations where the person will enter the camera FOV too late and will not be detected (leading to the miss that was seen). Change in stopping distance may be due to the texture of clothing between the walking person scenarios of the old and new system. Results from the previous system were published before, and it was not possible to replicate the exact walking person scenario. The texture tested with the new IWS could be harder to detect at farther ranges. Aside from clothing and the person used, all other conditions between the previous and current in-lab trials were the same (e.g. lighting, objects used, location).

Misses could possibly be avoided by changing the stopping distance threshold of the IWS. A greater stopping distance threshold would increase the scanning range of the anti-collision subsystem, and give more time for the IWS to properly detect an obstacle. Threshold distance is dependent on the wheelchair speed, and the distance needed for the powered wheelchair to stop safely without ejecting the driver. Moving objects would also require a greater threshold distance if they are approaching the powered wheelchair, because they approach the wheelchair
more quickly than stationary objects. It should be noted though, that if the stopping distance threshold is too great this will prevent users from maneuvering close to objects in their environment (e.g. tables).

The new IWS also improves upon the accuracy of stopping by lowering the standard deviations of stopping distances. This lowering of standard deviations is due to the increased computational speed of the system. Since the new IWS updates at a faster rate, it is able to detect objects at distances that are more consistent than the previous system.

The new IWS performed perfectly for navigation testing, although this was not an improvement over the previous system.

Due to project timing, in-lab trials were not repeated with the new IWS using the blob detection algorithm. Although the blob detection algorithm has a slightly slower update rate than the occupancy grid method, it is hypothesized that the blob detection algorithm will have stopping distances that are closer to the desired threshold and with smaller standard deviations. This is because the blob detection algorithm does not rely on a K value to update the certainty of whether an object exists in the environment. Rather, the blob detection algorithm detects objects in real-time since it rejects noise in real-time. Both methods of anti-collision will still be influenced by the stopping distance threshold in the same way (i.e. greater threshold for more time to detect objects).
Chapter 5
Clinical Trials

5.1 Objective

The objective of the clinical trials was to evaluate if the IWS could have a positive impact on the safety and usability of a powered wheelchair when driven by cognitively impaired older adults. Within this population, a subset was selected for practicality; this was older adults with dementia at an institutional setting. Although the end goal of the IWS is to provide independent mobility for cognitively impaired older adults, the current prototype was not suitable to test such a construct of mobility. This was due to the fact that the system could not prevent collisions in the left, right, and rear directions of a powered wheelchair. Meaning, safety would be a concern if the wheelchair was driven by participants in their living environments. As such, a prerequisite of independent mobility was chosen as the focus of this study: essential movements of powered wheelchairs. In order to have independent mobility, drivers of powered wheelchairs must first show mastery of the essential movements (e.g. left/right turn) related to powered wheelchair use. These movements are the basic building blocks for independent mobility in an individual’s living environment. The IWS must first have an impact on these essential movements before it can achieve the goal of independent mobility. This study would compare the safety and usability of a powered wheelchair with and without the IWS.

5.2 Research Questions & Hypotheses

The study focused on the following questions:

1) Does the IWS positively impact the safety of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?

**Hypothesis:** With the IWS enabled, the participant will have a reduced number of frontal collisions due to the anti-collision subsystem. The IWS will also help the participant complete essential movements without collisions. Subjectively, perceived safety is expected to increase when the IWS is used.
2) Does the IWS positively impact the usability of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?

**Hypothesis:** The IWS will increase the time of task completion due to stopping from the anti-collision function. Subjectively, the user will find the powered wheelchair with IWS easier to use and their perceived workload will be lowered due to navigation and audio prompting features.

3) Does overall user satisfaction of a powered wheelchair change if the IWS is enabled?

**Hypothesis:** Satisfaction will increase due to increase safety and usability when the IWS is used.

Two system specific questions were also evaluated to identify future improvements:

4) What is the effectiveness of navigation subsystem’s audio prompting on producing a correct joystick response?

5) Are there any errors with the anti-collision subsystem in identifying objects or imminent collisions?

5.3 Methods

The evaluation was conducted using a single-subject design methodology. Single-subject design was chosen for two reasons: 1) to identify the effects of the IWS on the individual, which could be averaged out in traditional group design; and 2) due to difficulties in recruiting large numbers of the desired population needed for powerful group design [44]. Under single-subject design a single participant acts as his/her own control. A participant is tested under a baseline phase and an intervention phase. For this experiment the baseline phase was the use of a normal powered wheelchair (phase A), and the intervention was the use of a powered wheelchair with the IWS (phase B).

In each phase, the participant was asked to drive a powered wheelchair through an obstacle course. The obstacle course consisted of six essential movement blocks, which were based from other tests used to assess powered wheelchair mobility [45] [46]. The six movement blocks were: 1) 90° left turn, 2) 90° right turn, 3) 3m straight line path, 4) stopping block, 5)
maneuverability obstacles, and a 6) 180° turn spot (see Appendix B for dimensions and spacing). To reduce the effects of course familiarity on the internal validity of the experiment, the order of the blocks were randomly assigned for every run through the course (see Appendix C for course arrangements). Below, Figure 5-1, shows an example of one obstacle course used in the study. Obstacles were built with 1-inch thick foam blocks to prevent injury to drivers when collisions occurred.

1. Start/End location
2. Turnaround location
3. 180° turn spot
4. 90° left/right turn
5. Maneuverability obstacles
6. Stopping block obstacle (will be removed when participant stops within 0.5m of block)
7. Narrow straight line path
8. Ideal pathway for participant

Figure 5-1: Obstacle course, each grid represents a 1m x 1m space. The participant drives through each object twice, with the exception of the turn spot.

Each phase lasted a total of five days, with a run through the obstacle course occurring once a day. There was a break of a few days before the next phase started due to scheduling at the testing facility.
For training, prior to the start of each phase the participant was shown how to control the powered wheelchair with the joystick. At first, the participant was trained at a reduced speed (0.083 m/s) until he/she had an understanding of the joystick directions that produced different motions for the wheelchair (i.e. cause and effect). Once the participant demonstrated this understanding and was comfortable with their familiarity of the joystick, the speed of the wheelchair was increased (0.16 m/s) and the participant was asked to perform several on-the-spot turning motions, forwards and backwards movement, stopping after driving forwards and backwards, and a figure-8 motion. When the IWS was added, a demonstration of how the system would block frontal movement if an obstacle was detected was given. The phase training lasted approximately 15 minutes. Every participant in the study received training from the same researcher.

Before runs in the phase, the participant was asked to perform several motions (left and right on-the-spot turns, forwards and backwards driving, stopping) to demonstrate that they retained their understanding of the joystick directions. Corrections were given as needed. If the IWS was used, the demonstration of how the system worked was given again.

To increase the external validity of the study, several single-subject trials were conducted with random phase ordering. Participants were randomly given a phase A/B ordering, or a phase B/A ordering. This ordering would help to investigate if the intervention was indeed causing the changes in the outcome measures (and not other factors, such as learning effects).

For each participant, the joystick was mounted on the side of their dominant hand. Participant’s comfort in the wheelchair was asked and confirmed before the run through the course began. Additionally, when the IWS was not being used, the stereovision camera mount was removed entirely to help the participant distinguish between the normal powered wheelchair and the powered wheelchair with the IWS.

### 5.4 Outcome Measures

Outcome measures were used to obtain an objective and subjective measure of safety and usability of driving a powered wheelchair. In addition, user satisfaction of the assistive technology was also measured. Several hardware related measures were also taken. The following describes the outcome measures in detail:
5.4.1 Collisions

Both the number of collisions and the area in which the collision occurred were measured with every run through the obstacle course. These outcomes were an objective measure of the safety of a powered wheelchair.

The definition of a collision was: a single point of impact between the powered wheelchair and an obstacle block. If several impacts occurred successively, each would be considered a collision. If the wheelchair hit an obstacle and dragged/pushed it without changing the point of impact, then this would be considered one collision.

Areas of collision were defined using the four sides of the wheelchair: front, left, side, rear. The location of the impact, as well as the way in which the collision occurred (i.e. turning or driving straight into an object) helped to identify which side of the wheelchair was hit.

Frontal collisions were also classified into: 1) outside of the stereovision FOV, and 2) within the stereovision FOV. Collisions within the FOV should be detected by the anti-collision subsystem.

5.4.2 Completion of Movement Tasks

Completion of every movement task was given a pass or fail grading. A pass would only be given if the movement task was completed without a collision. This outcome was an objective measure of safety as related to specific wheelchair movements. This measure was done for every run.

5.4.3 Time to Complete Course

The total time to complete the course was measured after every run. It was inferred that time to complete the course is related to the ease of using a powered wheelchair. If the wheelchair is easier to use, then the user should be able to drive through the obstacle course at faster times. This outcome was an objective measure related to the usability of a powered wheelchair.

5.4.4 NASA Task Load Index (NASA-TLX)

The NASA task load index is a subjective measure of workload imposed by a given task [47]. A total workload score is composed of six dimensions: 1) mental demands, 2) physical demands, 3)
temporal demands, 4) perceived performance, 5) effort, and 6) frustration. Three of the scores (mental, physical, and temporal demands) relate to the subject, and the other three scores (effort, frustration, and performance) relate to the subject’s interaction with the task. Each of the dimensions is self-graded through a questionnaire process on a scale that ranges from 0 to 20, with 0 relating to minimal workload and 20 relating to high workload (see Appendix D for questionnaire). Scores from the dimensions can then be added together to form a total workload score. By procedure, calculation of a total workload score involves weightings of each dimension. However, dimension weighting was not used in this study because it has a negligible impact and it would complicate the questioning process [48].

Descriptions of each dimension are as follows:

1) Mental demand – the perceived amount of mental and perceptual activity required for the task.

2) Physical demand – the perceived amount of physical activity required for the task.

3) Temporal demand – perceived time pressure related to the task.

4) Performance – how successful the subject felt they were at accomplishing the goals of the task.

5) Effort – how hard the subject felt they had to work (mentally and physically) in order to achieve their level of performance.

6) Frustration – how insecure, discouraged, irritated, stressed, or annoyed the subject felt when performing the task.

For this study, the task was defined as: maneuvering a powered wheelchair through an obstacle course with as few collisions as possible. The NASA-TLX was given to the participant immediately after they completed each run. In this study, the TLX scores are subjective outcome measures related to the usability of a powered wheelchair.

NASA-TLX was stated to be a reliable and sensitive measure of perceived workload in an analysis of its psychometric properties [48]. It has been used to study adults (including some over 65) with TBI and their response to driving tasks [49].
5.4.5 QUEST 2.0

QUEST 2.0, or the Quebec User Evaluation of Satisfaction with assistive Technology (version 2.0), is an outcome measure related to user satisfaction of their assistive devices [50]. QUEST is a questionnaire composed of 12 satisfaction items. Eight of the items relate to the device, and four of the items relate to the service of the assistive technology. For the scope of this study, only the eight device items were considered. These items of satisfaction were: 1) dimensions, 2) weight, 3) adjustments, 4) safety, 5) durability, 6) simplicity of use, 7) comfort, and 8) effectiveness of the device. Each item was graded by the user through a 5-point Likert scale ranging from not satisfied at all (1), to very satisfied (5); see Appendix E for the questionnaire.

The QUEST 2.0 was administered at the end of each phase, after the participant had completed several runs with the powered wheelchair. This outcome is a subject measure related to the satisfaction of the powered wheelchair, with and without the IWS. Also, specific items within the QUEST 2.0 are related to a subjective view of safety, and usability (ease of use item). Satisfaction of assistive technology is an important measure because users with low satisfaction tend to abandon using their technology.

QUEST 2.0 has been validated for test re-test reliability, interrater reproducibility [51], and content validity [52]. Reliability was also validated with adults with multiple sclerosis [53]. The QUEST 2.0 has been used in a satisfaction survey related to wheelchairs for older adults in nursing homes and community dwelling settings [54].
5.4.6 System Measures

5.4.6.1 Adherence to Audio Prompting

To measure the effectiveness of audio prompting with users, the correctness of the audio prompt was first noted (i.e. did the prompt play when it was supposed to play, and was the correct direction prompted). If the prompt was correct, then the adherence to the prompt was noted. This was measured by looking at the first three joystick motions after the correct prompt was given. If the user committed the joystick into the prompted direction within these first three joystick motions, then they adhered to the audio prompting.

5.4.6.2 Incorrect Collision Detections

Errors with the anti-collision subsystem were noted (i.e. false positives, or missed detections). The reason for the error was then investigated.


5.4.7 Summary

Table 5-1 summarizes the outcome measures as they relate to the research questions.

<table>
<thead>
<tr>
<th>Safety</th>
<th>Usability</th>
<th>Satisfaction</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective Measures</strong></td>
<td><strong>Objective Measure</strong></td>
<td><strong>Subjective Measure</strong></td>
</tr>
<tr>
<td>• Number of collisions.</td>
<td>• Time to completion.</td>
<td>• QUEST 2.0: total device score.</td>
</tr>
<tr>
<td>• Area of collision.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Pass of movement task (no collision during task).</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Subjective Measure</strong></td>
<td><strong>Subjective Measures</strong></td>
<td></td>
</tr>
<tr>
<td>• QUEST 2.0: safety item.</td>
<td>• NASA-TLX.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• QUEST 2.0: ease of use item.</td>
<td></td>
</tr>
</tbody>
</table>

**System Measures**

- Correctness of audio prompting.
- Adherence to correct audio prompting.
- Number of incorrect anti-collision detections.
- Reason for incorrect anti-collision detection.

5.5 Data Collection Method

Collision and movement task pass data were collected on site (see Appendix F for data collection sheet). Subjective tests (NASA-TLX and QUEST 2.0) were also administered by the same researcher on site. Questions from the subjective tests were reiterated and described with common language that the participants could relate to (e.g. mental demand, “how much did you have to think during the task?”), and answers picked by the participants were reconfirmed for more validity (e.g. “so you did not have to think a lot during this task?”). Time to completion and system measures were analyzed through video recordings of the trials. Collision and movement pass data was re-checked and confirmed through video recordings of the trials.
5.6 Inclusion & Exclusion Criteria

To be included in this study, participants were to:

- be over the age of 65;
- have a mild-to-moderate cognitive impairment (between 15-24/30 on the Mini Mental State Exam (MMSE) [55]);
- be a resident at Harold and Grace Baker Centre in Toronto;
- have written consent given by their substitute decision maker (SDM);
- be able to sit in a powered wheelchair for at most an hour a day;
- be able to speak/understand English and respond to questionnaires; and
- be able to identify joystick directions.

Criteria for exclusion were:

- history of aggression;
- significant prior experience with a powered wheelchair.

5.7 Ethics

Ethics for this study was approved by the University of Toronto Research Ethics Board in February 2010. The collaborating institution (Harold and Grace Baker Centre) that allowed the study to be conducted on their premises, acknowledged the ethics approval process from the University of Toronto and a letter of support from the institution was given for this study.

5.8 Recruitment

Recruitment was conducted through Shirley Neff, the staff educator at Harold and Grace Baker Centre. The substitute decision makers (SDMs) of potential participants were contacted for informed consent before any screening of participants occurred. Participation was on a voluntary basis and no compensation was given for this study. Residents were informed of their right to
withdraw from the study at any time and that the study had no effect on their level of care at Harold and Grace Baker Center.

Informed consent was given by seven SDMs on behalf of long term care residents at the institution. From screening, two of these residents were rejected from the study because of: 1) a MMSE score that was too low, and 2) the participant was not willing to commit time to the study. The age for inclusion was lowered to 60 to allow for more participants to be accepted into the study.

The study began with five participants. Of those five, two withdrew because of: 1) leg pain, and 2) disinterest in the study. The remaining three participants completed both phases of the study. However, one of the remaining participants has a lower number of run data because of their lack of availability on some days of testing. Table 5-2 summarizes the information on the three participants that completed the study.

<table>
<thead>
<tr>
<th>Table 5-2: Participant Information</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Participant 1</strong></td>
</tr>
<tr>
<td>Age</td>
</tr>
<tr>
<td>MMSE Score</td>
</tr>
<tr>
<td>Dominant Hand</td>
</tr>
<tr>
<td>Prior Wheelchair Experience</td>
</tr>
<tr>
<td>Other Information</td>
</tr>
<tr>
<td>Phase Order</td>
</tr>
<tr>
<td>Runs Completed per Phase</td>
</tr>
<tr>
<td><strong>Participant 2</strong></td>
</tr>
<tr>
<td>Age</td>
</tr>
<tr>
<td>MMSE Score</td>
</tr>
<tr>
<td>Dominant Hand</td>
</tr>
<tr>
<td>Prior Wheelchair Experience</td>
</tr>
<tr>
<td>Other Information</td>
</tr>
<tr>
<td>Phase Order</td>
</tr>
<tr>
<td>Runs Completed per Phase</td>
</tr>
<tr>
<td><strong>Participant 5</strong></td>
</tr>
<tr>
<td>Age</td>
</tr>
<tr>
<td>MMSE Score</td>
</tr>
<tr>
<td>Dominant Hand</td>
</tr>
<tr>
<td>Prior Wheelchair Experience</td>
</tr>
<tr>
<td>Other Information</td>
</tr>
<tr>
<td>Phase Order</td>
</tr>
<tr>
<td>Runs Completed per Phase</td>
</tr>
</tbody>
</table>
5.9 Trial Issues

At first, the IWS was implemented using the occupancy grid method of collision detection (see section 3.6.1.1). However due to a number of false positives, and the anti-collision’s susceptibility to noise on sunny days, the decision was taken to implement the blob detection algorithm for collision detection (see section 3.6.1.2). This algorithm was still in development at the time, but was finished in time to implement for the intervention phase of participant 2 and 5. Overall, the functionality of the wheelchair with the IWS does not change between each method of collision detection. However, as noted before (section 3.6.1.2), the blob detection algorithm is less susceptible to noise and false positives. When evaluating the data, the difference between participant 1’s system, and participant 2 & 5’s system were considered.

Table 5-3: Change in IWS for Intervention Phase

<table>
<thead>
<tr>
<th></th>
<th>Participant 1</th>
<th>Participant 2</th>
<th>Participant 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collision</td>
<td>Occupancy Grid Method</td>
<td>Blob Detection</td>
<td>Blob Detection</td>
</tr>
<tr>
<td>Detection</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.10 Data Analysis Procedure

Analysis was separated by participant as is typically done in single-subject research designs.

All run data was checked for serial dependency before any further analysis was done. This is because serial dependency has been known to cause errors in visual analysis, and data must be independent for t-test statistical analysis [56]. To check for serial dependency, the lag-1 autocorrelation coefficients were calculated for each data set. These values were then evaluated with Bartlett’s test of serial dependency: where an autocorrelation coefficient greater than $2/\sqrt{n}$ (n is the number of points in the data set) represents a statistically significant degree of autocorrelation. Appendix G shows the autocorrelation values, none of the data was found to have serial dependency, and therefore were acceptable for further analysis. Statistical analysis of the lag-1 autocorrelation coefficients was done using SPSS version 19.

Frontal FOV collision, total collisions, and time data were analyzed visually through comparison of the sample mean ($\mu$), standard deviation ($\sigma$), and trend. Frontal FOV collisions are used for analysis instead of frontal collisions because these are the collisions that are detected by the IWS
and are expected to change with the anti-collision subsystem. The C-statistic and the celeration line method for single-subject statistical analysis could not be applied to the single-subject data because the minimum number of data points per phase (eight) was not met [57] [58]. The two standard deviation band method of single-subject statistical analysis was not used because of instability in the baseline phase (participant 2 and 5), or due to a low number of data points (participant 1 – at least two points outside of the deviation band is needed for statistical significance) [59]. The t-test was used to evaluate statistical difference in the mean between the phases [60]. Statistical analysis of t-test was done using SPSS version 19.

Movement pass data was totaled for each phase, and the pass rate of each movement task was calculated per phase (# of times passed for the movement / total # of movements driven through in the phase).

Subjective values of the NASA-TLX were averaged per phase, and the t-test was used to identify if any statistical difference existed between the means of the scores between each phase. QUEST 2.0 values are stated for each phase.

Hardware data were totaled for participant 1, and participants 2 & 5 separately because of the change in the IWS system.
For each participant the data has been divided into safety, usability and satisfaction sub-headings. These sections correspond to the research focus of the clinical trials (see section 0). For designation: phase A is the baseline phase, and phase B is the intervention phase.

5.11 Participant 1 Results

5.11.1 Safety

This section presents the objective (# of collisions, movement task pass rate) and subjective (QUEST 2.0) safety results for participant 1.

The graph below shows the number of frontal FOV collisions for participant 1:

![Participant 1: Frontal FOV Collisions](image)

**Figure 5-2: Frontal FOV collisions for participant 1.**

With IWS (μ=0.333; σ=0.577), without IWS (μ=1.0; σ=0.0).

Visually, there was no large discontinuity in performance between the last intervention run and the start of the baseline phase (which is a criterion for acknowledging that a mean changed occurred because of the intervention [56]). As well, the magnitude of the number of collisions remains low (0,1) in both phases. From inspection it appears that the intervention (IWS) had no significant impact on the number of frontal FOV collisions for participant 1. No statistically significant mean difference was found with the t-test (α=0.05, p=0.092).
The graph below shows the number of total collisions for participant 1:

![Participant 1: Total Collisions](image)

**Figure 5-3: Total collisions for participant 1.**
*With IWS (µ=1.0; σ=1.732), without IWS (µ=3.0; σ=1.0).*

Similarly, with the total collisions, there is no large change with the removal of the intervention. The magnitude of the collision values appear to increase with the number of runs. However this is likely due to variability in performance from the participant because the number of collisions is still quite low. From inspection it appears that the intervention (IWS) had no significant impact on the number of total collisions for participant 1. No statistically significant mean difference was found with the t-test ($\alpha=0.05$, $p=0.079$).
The following graph shows the movement task pass rates of each phase for participant 1:

![Graph showing movement task pass rates for participant 1](image)

**Figure 5-4: Movement pass rate for participant 1**  
*(n=3 for turn spot task per phase, n=6 for all other tasks per phase).*

Pass rate increased for the left turn, stopping block, and obstacles movement tasks with the IWS.

Subjective safety ratings from the QUEST 2.0 survey are shown in Table 5-4 for participant 1.

**Table 5-4: Participant 1, QUEST 2.0 - Safety Item**

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>(quite satisfied)</td>
<td>(very satisfied)</td>
<td></td>
</tr>
</tbody>
</table>

Satisfaction for the safety of the powered wheelchair increased with the IWS.
5.11.2 Usability

This section presents the objective (time to complete course) and subjective (NASA-TLX, QUEST 2.0) usability results for participant 1.

The graph below shows the time to course completion for participant 1:

![Graph showing time of run for participant 1 with and without IWS](image)

**Figure 5-5: Time to complete obstacle course for participant 1.**

With IWS ($\mu=216.67s; \sigma=37.54s$), without IWS ($\mu=165.67s; \sigma=10.69s$).

There appears to be a discontinuity in time performance between the end of the intervention and the start of the baseline phase. As well, the variance of values with each phase appears to be around different means; with the baseline phase having a lower mean. From inspection it appears that the intervention (IWS) increases the time taken to complete the obstacle course for participant 1. A statistically significant difference between the phase means was found with the t-test ($\alpha=0.05$, $p=0.043$).
The graph below shows the average NASA-TLX scores for participant 1:

![Participant 1: NASA Task Load Index](image)

**Figure 5-6: Average NASA-TLX scores for participant 1.**

Mental demand, perceived performance, perceived effort, perceived frustration, and the total task load demand was lowered with the IWS. Physical demand and temporal demand have increased with the IWS. Only the change in effort was found to be statistically significant by t-test ($\alpha=0.05$, $p=0.0005$). See Appendix F for remaining p-values.

Subjective ease of use ratings from the QUEST 2.0 survey are shown in Table 5-5 for participant 1.

**Table 5-5: Participant 1, QUEST 2.0 - Ease of Use Item**

<table>
<thead>
<tr>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (quite satisfied)</td>
<td>4 (quite satisfied)</td>
</tr>
</tbody>
</table>

Satisfaction for the ease of use of the powered wheelchair is unchanged with the IWS.
5.11.3 Device Satisfaction

This section presents the results for overall device satisfaction for participant 1 (Table 5-6).

<table>
<thead>
<tr>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.625 (more or less satisfied)</td>
<td>4.143 (quite satisfied)</td>
</tr>
</tbody>
</table>

Overall device satisfaction of the powered wheelchair has increased with the IWS.

5.11.4 Participant 1 Discussion

Does the IWS positively impact the safety of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?

The results suggest that the IWS had minimal impact on the objective safety of the powered wheelchair when driven by participant 1. Most likely, this is because participant 1 had an adequate level of skills required for driving a powered wheelchair safely without the aid of the IWS (as can be seen by the scores in the baseline phase). It could be argued that the IWS had an impact to lower or limit the number of collisions that occurred during driving (since the mean collision scores are lower during the intervention phase). However the evidence for this is not conclusive, as variability in driving ability could also be the cause of the change in collision values. Driving ability is affected by the participant’s alertness and focus during the trials. Participant 1 also had no frontal collisions outside of the camera FOV.

Although the pass rate of some movement tasks (left turn, right turn, obstacles) increased slightly with the IWS, the participant still had trouble completing the obstacle task without a collision. This is due to the fact that side and rear collisions are still not preventable by the IWS. It is difficult to conclusively say that the IWS caused the changes in movement pass rate, as variability in participant 1’s daily driving ability could also account for these changes.

Participant 1 felt more satisfied with the safety of the powered wheelchair when the IWS was enabled. This is a positive remark for the IWS, and shows that even though there was no
statistically significant change with objective safety, that the participant still felt reassurance in having the IWS.

**Does the IWS positively impact the usability of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?**

Objective usability was shown to decrease when the IWS was enabled. The time of trials were found to be significantly higher with the IWS, than without. This conclusion is supported by observations from the trials: that forward motion was blocked a number of times (by the IWS) when the participant wished to move forward. Several of these stops were false detections caused by noise detected by the occupancy grid method of collision detection. The prevention of motion when there is no obstacle caused confusion and delays.

In terms of usability from a task load perspective, the effort of driving the powered wheelchair decreased statistically significantly when the IWS was enabled. This is a positive statement for the IWS, as the system should not be perceived harder to use than a normal powered wheelchair.

Satisfaction with ease of use remained unchanged with the IWS.

**Does overall user satisfaction of a powered wheelchair change if the IWS is enabled?**

Overall device satisfaction increased when the IWS was enabled, suggesting that the participant would not readily abandon this device if he/she were dependent on it. However as part of the QUEST 2.0 survey, participant 1 mentioned that they would not consider the powered wheelchair with the IWS as an effective means of mobility because it was too slow. It is noted that the QUEST 2.0 satisfaction scores for this participant may not be an accurate reflection of the entire phase data because the participant suffered from severe memory loss. This memory impairment prevented the participant from recalling previous trial days.

All subjective scores for this participant were supported by descriptive statements that the participant used to reiterate their position on the subjective scales (e.g. “No, I didn’t have to think too much, but you have to have at least have some level concentration to be able to drive with this”; when picking a low score for the NASA-TLX mental demand). These descriptions helped to validate the subjective scores.
5.12 Participant 2 Results

5.12.1 Safety

This section presents the objective (# of collisions, movement task pass rate) and subjective (QUEST 2.0) safety results for participant 2.

The graph below shows the number of frontal FOV collisions for participant 2:

![Graph showing Participant 2: Frontal FOV Collisions](image)

**Figure 5-7: Frontal FOV collisions for participant 2.**

Without IWS ($\mu=6.8; \sigma=3.493$), with IWS ($\mu=1.2; \sigma=0.837$).

Visually, there is a discontinuity in performance between the last baseline run and the start of the intervention phase. As well, the magnitude of the number of collisions remains higher in the baseline phase than in the intervention phase. From inspection it appears that the intervention (IWS) had a significant impact in reducing the number of frontal FOV collisions for participant 2. The change in frontal FOV collision mean between phases was statistically significant with the t-test ($\alpha=0.05$, $p=0.0105$).
The graph below shows the number of total collisions for participant 2:

![Graph showing total collisions for participant 2]

**Participant 2: Total Collisions**

*Figure 5-8: Total collisions for participant 2. Without IWS (μ=12.2; σ=3.271), with IWS (μ=6.2; σ=1.924).*

There is a discontinuity in performance between the end of the baseline phase and the start of the intervention phase. As well, the magnitude of total collisions is lower in the intervention phase, than in the baseline phase. From inspection it appears that the intervention (IWS) had a significant impact in reducing the number of total collisions for participant 2. Change in total collision mean was statistically significant with t-test (α=0.05, p=0.004).
The following graph shows the movement task pass rates of each phase for participant 2:

**Figure 5-9: Movement pass rate for participant 2**
(n=5 for turn spot task per phase, n=10 for all other tasks per phase).

Pass rate decreased for the left turn; and increased for the right turn (quite significantly, 10% to 100%), straight path, and stopping block movements with IWS. Obstacles in both phases had a 0% pass rate.

Subjective safety ratings from the QUEST 2.0 survey are shown in Table 5-7 for participant 2.

**Table 5-7: Participant 2, QUEST 2.0 – Safety Item**

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (not very satisfied)</td>
<td></td>
<td>4 (quite satisfied)</td>
</tr>
</tbody>
</table>

Satisfaction for the safety of the powered wheelchair increased with the IWS.
5.12.2 Usability

This section presents the objective (time to complete course) and subjective (NASA-TLX, QUEST 2.0) usability results for participant 2.

The graph below shows the time to course completion for participant 2:

![Participant 2: Time of Run](image)

**Figure 5-10: Time to complete obstacle course for participant 2. Without IWS (μ=337.6s; σ=60.343s), with IWS (μ=353.2s; σ=29.525s).**

There is not a large discontinuity in performance between the phases. Additionally, the magnitude for time to completion is similar in each phase. From inspection it appears that the intervention (IWS) had no significant impact in changing the time taken to complete the obstacle course for participant 2. No statistically significant mean difference was found with the t-test ($\alpha=0.05$, $p=0.309$).
The graph below shows the average NASA-TLX scores for participant 2:

![Participant 2: Nasa Task Load Index](image)

**Figure 5-11: Average NASA-TLX scores for participant 2.**

All dimensions of the NASA-TLX were lowered with the IWS. The change in the physical demand ($\alpha=0.05$, $p=0.031$), effort ($\alpha=0.05$, $p=0.098$), and total score ($\alpha=0.05$, $p=0.0245$) were found to be statistically significant by the t-test. All NASA-TLX values were lower with the IWS. See Appendix F for remaining p-values.

Subjective ease of use ratings from the QUEST 2.0 survey are shown in Table 5-8 for participant 2.

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satisfaction</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>(not very satisfied at all)</td>
<td></td>
<td>(more or less satisfied)</td>
</tr>
</tbody>
</table>

Satisfaction for the ease of use of the powered wheelchair increased with the IWS.
5.12.3 Device Satisfaction

This section presents the results for overall device satisfaction for participant 2 (Table 5-9).

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Overall device satisfied</td>
<td>(not very satisfied)</td>
<td>(more or less satisfied)</td>
</tr>
</tbody>
</table>

Overall device satisfaction of the powered wheelchair has increased with the IWS.

5.12.4 Participant 2 Discussion

**Does the IWS positively impact the safety of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?**

The results show that the IWS had a significant impact on the objective safety of the powered wheelchair, when driven by participant 2. Frontal FOV collisions, and overall collisions were reduced when the IWS was enabled. This is supported by observations from the trials, in which the IWS helped to prevent several frontal collisions before they occurred. One thing to note is that there was a large variability in this participant’s baseline for the number of collisions per run. This suggests that the participant had worst driving days than others, which can be attributed to variability in the participant’s alertness and focus during different runs.

There were slight changes in movement pass rate when the IWS was enabled: left turn (decrease), straight path (increase), and stopping block (increase). It is difficult to conclusively say that the IWS had an impact on these pass rates because they could also be attributed to variation in daily driving ability. However, there was a large increase in the pass rate for the right turn task (10% to 100%) and this is likely due to the intervention of the IWS. This is a positive finding for the IWS, and shows that the system has the ability to improve safety of essential movements. Participant 2 continued to have difficulties with the obstacle task in both phases. Again the IWS could not prevent side and rear collisions, which is likely why there is no change for this pass rate. Movement pass rate was also not 100% for left turn, straight path and 180° turning tasks, with the IWS.
The participant felt more satisfied with safety of the powered wheelchair when the IWS was enabled. This is a positive remark for the IWS.

Participant 2 had one frontal collision outside of the camera FOV during the intervention phase. This collision occurred on the far-right of the camera mount and has minimal impact on the above conclusions for safety.

**Does the IWS positively impact the usability of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?**

Objective usability remained the same between the IWS and the normal powered wheelchair. The average time of the trials with and without IWS was not found to be statistically significant. It is noted that there was a slight increase in the average time for the intervention phase. This is likely due to delays when the participant was stopped to prevent a collision; however these delays were not significant enough to cause a large impact on objective usability.

For usability from a task load perspective, only the total workload score was found to be significantly lower with the t-test, when the IWS was enabled. There was large variability in the participant’s NASA-TLX scores during the baseline phase, which may be attributed to the variation in the participant’s daily driving ability and performance.

The participant felt more satisfied ease of use of the powered wheelchair when the IWS was enabled.

**Does overall user satisfaction of a powered wheelchair change if the IWS is enabled?**

Overall device satisfaction also increased when the IWS was enabled. Although satisfaction increased with the IWS, it is important to note that the participant’s ease of use score and overall device satisfaction score with the IWS are considered a moderate level on the QUEST 2.0 scale (3 – more or less satisfied). It is inferred that although participant 2 felt more satisfied with the IWS, this mode of transportation was less satisfactory than the participant’s ordinary mode of transportation (i.e. a manual wheelchair).
5.13 Participant 5 Results

5.13.1 Safety

This section presents the objective (\# of collisions, movement task pass rate) and subjective (QUEST 2.0) safety results for participant 5.

The graph below shows the number of frontal FOV collisions for participant 5:

![Participant 5: Frontal FOV Collisions](image)

**Figure 5-12: Frontal FOV collisions for participant 5.**
Without IWS ($\mu=2.0; \sigma=1.732$), with IWS ($\mu=0.6; \sigma=0.548$).

There appears to be no large discontinuity between the phase data. However, there is one run with a large number of frontal FOV collisions during the baseline (perhaps a bad driving day); the data in the intervention phase never reaches the magnitude of this run. From inspection it appears that the intervention (IWS) had an impact in maintaining a lower magnitude of frontal FOV collisions for participant 5. No statistically significant difference between means was found with the t-test ($\alpha=0.05$, $p=0.0615$).
The graph below shows the number of frontal FOV collisions for participant 5:

![Participant 5: Total Collisions](image)

Figure 5-13: Total collisions for participant 5. Without IWS ($\mu=4.4; \sigma=2.51$), with IWS ($\mu=3.6; \sigma=1.342$).

There is a discontinuity between the phase data. However, the variation of values between each phase appears to be similar and around the same means. From inspection it appears that the intervention (IWS) has no impact in reducing the total collisions for participant 5. No statistically significant difference was found with the t-test ($\alpha=0.05$, $p=0.2735$).
The following graph shows the movement task pass rates of each phase for participant 5:

![Participant 5: Movement Task Pass %](image)

**Figure 5-14: Movement pass rate for participant 5.**
*(n=5 for turn spot task per phase, n=10 for all other tasks per phase).*

Pass rate increased for the left turn and straight path movements with the IWS.

Subjective safety ratings from the QUEST 2.0 survey are shown in Table 5-10 for participant 5.

**Table 5-10: Participant 5, QUEST 2.0 – Safety Item**

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (quite satisfied)</td>
<td>5 (very satisfied)</td>
<td></td>
</tr>
</tbody>
</table>

Satisfaction for safety of the powered wheelchair increased with the IWS.
5.13.2 Usability

This section presents the objective (time to complete course) and subjective (NASA-TLX, QUEST 2.0) usability results for participant 5.

The graph below shows the time to course completion for participant 5:

![Participant 5: Time of Run](image)

**Figure 5-15: Time to complete obstacle course for participant 5. Without IWS (μ=275s; σ=77.691s), with IWS (μ=329.2s; σ=42.352s).**

There is a discontinuity in performance between the phases, with the intervention having a slightly higher mean. Additionally, the slope appears to be similar for the data in each phase. From inspection it appears that the intervention (IWS) caused an increase in the time taken to complete the obstacle course for participant 2. The downward trends in both phases suggest that the participant is learning and getting better at using the system. No statistically significant mean difference was found with the t-test (α=0.05, p=0.104).
The graph below shows the average NASA-TLX scores for participant 5:

![Participant 5: NASA Task Load Index](image)

**Figure 5-16: Average NASA-TLX scores for participant 5.**

Change in total score was found to be statistically significant by t-test ($\alpha=0.05$, $p=0.0475$). All workload values were lower with the IWS. See Appendix F for remaining p-values.

Subjective ease of use ratings from the QUEST 2.0 survey are shown in Table 5-11 for participant 5.

**Table 5-11: Participant 5, QUEST 2.0 - Ease of Use Item**

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 (very satisfied)</td>
<td>5 (very satisfied)</td>
<td></td>
</tr>
</tbody>
</table>

Satisfaction for the ease of use of the powered wheelchair is unchanged with the IWS.
5.13.3 Device Satisfaction

This section presents the results for overall device satisfaction for participant 5 (Table 5-12).

Table 5-12: Participant 5, Total Device Score (0 to 5)

<table>
<thead>
<tr>
<th></th>
<th>Phase A</th>
<th>Phase B (Anti-Collision)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.875</td>
<td>4.875</td>
</tr>
<tr>
<td>(quite satisfied)</td>
<td>(quite satisfied)</td>
<td></td>
</tr>
</tbody>
</table>

Overall device satisfaction for the powered wheelchair is unchanged with the IWS.

5.13.4 Participant 5 Discussion

Does the IWS positively impact the safety of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?

Observations from visual analysis show that the IWS had an impact on the objective safety of the powered wheelchair, when driven by participant 5. Frontal FOV collisions were maintained at a lower magnitude with the IWS, than without the system. The sharp spike on run four of the baseline phase, supports that this participant had a day that was more at risk of collisions than others (bad driving day). Total collisions however, were not found to be significantly different with the intervention. This can be explained by the fact that the IWS does not prevent side or rear collisions. So even though frontal collisions were limited, side and rear collisions were still occurring for this participant.

There were slight changes in movement pass rates when the IWS was enabled: left turn (increase) and straight path (increase). Although it is not conclusive that the left turn pass rate improved with IWS (due to variations in daily driving ability), it is supported that the straight path pass rate has improved with the IWS due to observations from the trials, where the IWS prevented possible collisions during this task. Participant 5 continued to have difficulties with the obstacle task in both phases, and right turn pass rate was not at 100% with the IWS.

Participant 5 felt more satisfied with the safety of the powered wheelchair when the IWS was enabled. This is a positive remark for the IWS.
Participant 5 had five frontal collisions outside of the camera FOV during the intervention phase. All of these collisions occurred on the far-right of the camera mount. The conclusion that the IWS can limit the magnitude of frontal collisions that occur during bad driving days is still valid even if these collisions were included in the run data.

**Does the IWS positively impact the usability of a powered wheelchair when driven by an older adult with mild-to-moderate dementia?**

Objective usability (time of trials) was decreased with the IWS than without, due to a higher mean time in the intervention phase. However, this difference was not found to be statistically significant. The discontinuity of the time values between the phases can be explained by unfamiliarity with the intervention system. Participant 5 showed promising trends in both phases, by lowering the time to complete the course after several runs. This supports that the participant had the ability to learn and improve their use of powered wheelchairs.

For usability from a task load perspective, the effort and total workload score was found to be statistically lower when the IWS was enabled. There was also large variability in the participant’s NASA-TLX scores during the baseline phase, which may be attributed to the variation in the participant’s daily driving ability.

Satisfaction for the ease of use of the powered wheelchair remained unchanged with and without the IWS.

**Does overall user satisfaction of a powered wheelchair change if the IWS is enabled?**

Satisfaction for the overall device remained unchanged with and without the IWS. It is noted that this participant was fairly enthusiastic with using any powered wheelchair, which may be why there is no difference for these satisfaction scores between phases.
5.14 System Results

The following results are a compilation of all hardware data in the phases. Participant 1 and participants 2 & 5 data are treated separately because of the change in the IWS’s anti-collision system between these participants (see section 5.9).

5.14.1 Participant 1: IWS with Occupancy Grid Method

Below, figure 5-17, is a summary of the prompting situations that occurred during the trials for participant 1.

![Participant 1: Correctness of Audio Prompting (n=12)](image)

**Figure 5-17: Correctness of Audio Prompting for IWS with Occupancy Grid Method.**

When an audio prompt was played, five different situations could occur during the trials:

1) **Correct free space & path** – the navigation subsystem correctly identified the area of greatest free space in the environment, and the prompting coincided with the user’s desired path plan to maneuver through the obstacle course. This is the ideal prompting situation.

2) **Correct free space, incorrect path** – as above, however the prompting was different than the user’s desired path plan. In this situation the user navigates against the prompt.

3) **Delayed prompt, object cleared** – the prompt was played too late because the participant had already maneuvered around the obstacle. The user would have to ignore the prompt in this scenario.
4) **Incorrect free space** – the prompting system does not correctly identify the area of greatest free space in the environment due to a limited FOV. It gives an erroneous prompt to suggest movement into an object. This user must ignore the prompt in this case.

5) **False detection** – an error in the anti-collision subsystem causes the navigation subsystem to detect a false object and give an erroneous prompt. The user will have to ignore the prompt in this scenario.

In total, five false detections occurred, these were due to natural light that caused noise in the image.

Because there were no “correct free space & path” prompts, the adherence to the prompting commands for participant 1 could not be calculated.
5.14.2 Participant 2 & 5: IWS with Blob Detection Algorithm

Below, figure 5-18, is a summary of the prompting situations that occurred during the trials for participant 2 & 5.

**Figure 5-18: Correctness of Prompting for IWS with Blob Detection Algorithm**

There were no false detections when the IWS used the blob detection algorithm.

Figure 5-19 summarizes participants 2 and 5’s adherence to the ideal prompting scenario: “correct free space & path”.

**Figure 5-19: Adherence to “correct space & free path” prompting for participant 2 & 5.**

Participant 2 had a higher level of adherence to the audio prompts than participant 5.
5.14.3 Discussion on System Results

What is the effectiveness of navigation subsystem’s audio prompting on producing a correct joystick response?

The effectiveness of navigation audio prompting is dependent on the participant’s adherence to the audio prompt. Since the adherence for participant 1 could not be calculated, the effectiveness of prompting on this participant is unknown. For participant 2, prompting was successful in producing a correct response for approximately 40% of the prompts (76.5% adherence of 51.7% correct prompts). For participant 5, prompting was successful in producing a correct response for approximately 29% of the prompts (56.4% adherence of 51.7% correct prompts).

The low effectiveness is partly due to the number of erroneous prompts that were given for delayed situations, incorrect path situations, and incorrect free space situations. And is partly due to the participants’ adherence of whether they acknowledge the prompt (i.e. responded correctly to it), or whether they ignore it or were confused by it. To improve prompting effectiveness both these areas must be addressed.

Are there any errors with the anti-collision subsystem in identifying objects or imminent collisions?

When the IWS was used with the occupancy grid method there were five false detection errors within the anti-collision subsystem, and one missed detection that caused a collision. False detection was caused by noise from natural lighting. The one missed detection was due to an error in the system that caused the system to shut down prematurely.

When the blob detection algorithm was used with the IWS, there were no errors due to false detections, and nine missed detections that caused a collision. Four of the missed detections were due the participant turning in a hard left/right direction into the object. The other five were after the system detected the obstacle and stopped the wheelchair, but still allowed movement in one of the forward-left/right direction, which the participant moved towards and hit the obstacle.

The values between the different anti-collision methods should not be compared by magnitude, as the blob detection algorithm was used more than the occupancy grid method. The purpose of this question is not to identify effectiveness, but to identify errors and areas of improvement.
Chapter 6
Clinical Trials Discussion

6.1 Overview

This chapter will discuss the findings from the clinical trials as relate to the second and third main research questions of the project (see section 1.3).

6.2 Safety & Usability for Cognitively Impaired Older Adults

Does the design of the IATSL-IWS improve the safety and usability of powered wheelchairs for older adults with cognitively impairments?

It is difficult to generalize single-subject results to the entire population of cognitively impaired older adults [61]. However, the single-subject results do give insight as to how the IATSL-IWS would affect individuals within that large population. Particularly, the results show how the IWS affected the safety and usability of a powered wheelchair when driven by an older adult with mild-to-moderate dementia.

From the discussions of participant 1 (section 5.11.4), participant 2 (section 5.12.4), and participant 5 (section 5.13.4), certain key concepts as to how the IWS affected safety and usability of a powered wheelchair for the individual have been found:

1) The IWS has the potential to improve powered wheelchair safety by limiting the number of frontal FOV collisions. From the collision results it can be inferred that each participant had a different level of driving ability. As driving ability decreased (i.e. more collisions seen) the system’s impact on the individual’s safety increased. Participant 1 had an adequate driving ability, and there was little difference between the frontal FOV collision with and without the IWS. However, participant 2 and 5 showed that with the IWS the magnitude of frontal FOV collisions per run was lowered and never above two. These observations show that the IWS’s anti-collision subsystem could prevent the occurrence of collisions and therefore increase safety. It also highlights that not everyone has the same reliance on the anti-collision subsystem.
2) **The IWS has the potential to improve powered wheelchair safety by helping the individual complete essential movements without a collision.** Although improvements upon movement pass rate were seen only for participant 2 (right turn) and participant 5 (straight-line path), these improvements still highlight the IWS’s potential to increase safety of essential movements for the individual. The difference in how much the IWS impacts movement pass rate is related to each individual’s driving style (e.g. participant 2 was more prone to frontal collisions when performing a right turn, therefore the IWS had a large impact on this movement task). Ideally with the IWS, the powered wheelchair would have a 100% pass rate for every essential movement. This ensures that the driver is safe and capable of navigating in their environment.

3) **Usability of the powered wheelchair may be hampered by the IWS anti-collision subsystem.** Participant 1 and participant 5 were shown to be negatively impacted in terms of usability when the IWS was equipped (i.e. longer course times). This observation highlights how stopping to prevent a collision could actually increase the difficulty of using a powered wheelchair for the individual. Safety is increased, but at the expense of usability. From trial observations, there were times where participants were stuck in a position because their joystick direction was blocked and they did not know how to navigate away from the obstacle quickly. Ideally, the IWS’s audio prompting is supposed to help in this situation, but adherence to the prompting is also an issue.

4) **Usability of the powered wheelchair with the IWS may be improved by individual adherence to prompting.** For participant 2 the usability of the powered wheelchair was not found to be significantly difference with and without the IWS. Also this participant had a higher level of adherence (76.5%) to the correct prompts. One inference that can be made is that with increase adherence, there is increase usability. For example it was observed that in similar situations of where participant 5 was stuck, participant 2 would listen to the audio prompt and then navigate away from the obstacle.

To summarize the IATSL-IWS has the potential to increase the safety of powered wheelchairs for cognitively impaired older adults. However usability of a powered wheelchair for this population may be decreased when the IWS is enabled, or at best be on a similar level as a normal powered wheelchair. Each individual is affected differently.
6.3 Future Improvements

What future improvements are needed for the IWS?

Several problems were identified from the trials that need improvement:

1) **Missed detection of obstacles** – although the IWS was able to lower the number of frontal FOV collisions, it did not prevent all collisions from occurring within the camera’s FOV. This missed detection of obstacles is a critical issue that must be solved to ensure driver safety. There were three reasons why missed detections occurred: 1) a system error that caused the IWS to shutdown; 2) hard-left/right turns into obstacles; and 3) allowance of forward-left/right movement when the clearance from the powered wheelchair to the obstacles was too close. The second and third errors could possibly be fixed by having a detection FOV that encompasses all areas around the wheelchair so that collisions can be detected before turning into them. As well, improving the calibration of when joystick zones should be block should fix the third error. There was not enough logging data to identify the cause of the system shutdown.

2) **Essential movements pass rates are not high** – the main goal of the IWS is to enable safe and intuitive mobility for cognitively impaired older adults, however before that can be achieved, mastery of essential movements must be shown. The fact that none of the participants were able to obtain high pass rates (i.e. no collisions) for all the essential movements with the IWS shows that the anti-collision subsystem still needs improvement. To correct this issue the detection FOV should encompasses all areas around the wheelchair so that all possible collisions can be detected and prevented. However, adding multiple stereovision cameras to widen the FOV may also be a problem because of the camera’s minimum detection distance (i.e. users will not be able to move within ~56cm of all obstacles). Careful design must be done to ensure accurate detection of obstacles, while ensuring that users of the wheelchair are not too limited in their movements. This may involve using other sensors for detection.

3) **Navigation effectiveness was low** – as identified in section 5.14.3 the effectiveness of the navigation prompts was low due to incorrect prompts and low adherence to the prompting. Prompting should be an accurate depiction of the local environment and
should not occur after the obstacle has been cleared. An increased FOV will help the IWS give more accurate readings of the local environment, and wheel encoders to know when the powered wheelchair is stopped (stuck) would avoid the issue of delayed prompting (i.e. prompt when the wheelchair is not moving). In order to increase user adherence, more research has to be done into what user interface(s) (e.g. visual, tactile, audio) would provide cognitively impaired individuals with high levels of adherence. This may also include re-examining if the suggestive prompting method is the best method of communication to these individuals. Perhaps receiving information on which directions are blocked could help as well.

4) **Is the control scheme acceptable?** – another issue is whether the control scheme of preventing joystick motion in the direction of obstacles is an acceptable method of anti-collision. Results from the trials showed that some individuals had greater difficulty with the IWS’s control scheme (usability issues – more time to complete trials) than with a normal powered wheelchair controls. Although safety was increased, usability suffered. Could there be a better method of preventing collisions, while still enabling high usability? This can be investigated further. Perhaps joystick motions do not have to be blocked entirely and the control scheme would be intelligent enough to “slide” pass obstacles if the joystick is pushed in the direction of the obstacle.

In summary, future improvements are needed to increase the IWS’s safety and usability.

### 6.4 Limitations of Clinical Study

Having five or three data points per phase has limited this study’s ability to perform analysis on the data collected. For scheduling reasons, more data points were difficult to add in this study. As such, the results from the trials are not as conclusive as single-subject designs that have been supported by stronger semi-statistical analysis. Also with more data points, additional phases could have been added to more strongly support if the intervention was causing the changes seen in the outcome measures (e.g A-B-A – expected to see a reversal effect, of more frontal FOV collision and perhaps less time to complete the course in the last baseline phase).

Low data points per phase also negatively affected the power of the t-test as a statistical analysis tool. Appendix I shows the post-hoc power values calculated on data sets used with the t-test.
Only participant 2’s frontal and total collisions; and participant 1’s NASA-TLX effort score were above 80% power. This means that in other data there is high likelihood of stating that there was no statistical significant difference between the phases, when in actuality there was one (type-II error). Still, it is noted that all of the participants’ time and collision data were primarily analyzed with visual analysis, and that the t-test was a supportive tool. As such, the main conclusions about safety and usability from this research do not change. However, the t-test was the only tool that was used to investigate the NASA-TLX scores. Therefore, there is a likelihood of type-II errors within the NASA-TLX analysis.

Another drawback of this study was the limited amount of participants. Although there were relevant findings from this research, three participants do not cover all the possible scenarios of interaction between the IWS and cognitively impaired older adults. By further limiting the testing population to older adults who suffered from mild-to-moderate dementia, the evaluation became more difficult to generalize to the larger population. At best, the results are possible responses of individuals within the cognitively impaired older adult population, but the percentage of how many individuals in the population would respond in the ways found in the study is unknown at the moment. This is a limitation of single-subject design and the inclusion criteria of the study. With more participants it is likely that more issues with the IWS would be found.

The validity of the NASA-TLX is also under question as no formal validation studies have been done to support its use with a cognitively impaired older adult population. Subjective outcomes are difficult to support formally within this study; they are only supported through observations (e.g. participant 1 supported each score with explanations that demonstrated understanding of the question) or correlations with other data that suggest the participants understood the survey (e.g. participant 2 and 5’s performance scores in the NASA-TLX have some correlation with their total collisions per run).

It can be argued that because the clinical population required substitute decision makers to consent for the study, that they do not have an adequate understanding of the subjective questions asked to them (from QUEST 2.0 or NASA-TLX). However, as mentioned above, observations within the trials showed that certain participants were able to support their answers or have correlations with other data. In future studies, recording the qualitative answers from
participants, as well as, using multiple subjective tests (for convergent validity) would increase the validity of the subjective results. Observations from care takers could also be used to support the validity of subjective answers.

Lastly, a short study does not allow participants much time to familiarize themselves with the powered wheelchair or form more concrete opinions about its use in their lives. As such, the satisfaction ratings may not be a very accurate depiction of real use.

6.5 Challenges Ahead

There are many challenges ahead in designing an intelligent wheelchair system for cognitively impaired older adults. Literature shows that within institutions it is not just a simple solution of reducing barriers to powered wheelchairs with technology. There are complexities in people’s attitude to the technology and other stakeholder’s use of the environment.

For example, an issue that may arise is that the stereovision camera may cause stigmatization for the driver, and this could cause them to abandon the technology. Or there could be an issue with the slow speed of powered wheelchair, which may cause annoyances with other residences in institutional settings who do not want to be delayed by a slow driver. Issues that fit these descriptions have already been highlighted in literature [18]. Other issues include the cost of the system, and its acceptance with clinicians who would refer this device to their patients.
Chapter 7
Conclusion

7.1 Summary

Results from the hardware and clinical evaluation have given insight into the main research questions:

1) Does the new intelligent wheelchair system provide an improvement, in terms of system performance, as compared to the previous IWS?

Hardware results showed that the newest iteration of the system considerably improved upon the computational speed of the previous IWS (approximately 1000% increase). As well the new system is more accurate in its stopping distances. However, one fault in the new IWS is that it may have difficulty identifying objects close to the minimum detection distance of the stereovision camera.

2) Does the design of the IATSL-IWS improve the safety and usability of powered wheelchairs for older adults with cognitively impairments?

Clinical results showed that the IWS was capable of limiting the number of frontal collisions that could occur when driving a powered wheelchair. As well, the IWS showed promise in its ability to help some individual pass movement tasks without a collision. This shows the systems potential to allow safe independent mobility for cognitively impaired older adult. One concern that was raised was that the IWS may increase the difficulty of using a powered wheelchair. Although safety was improved, usability was an issue when some adults were ‘stuck’ because of the anti-collision system.

3) What future improvements are needed for the IWS?

An increase in sensor coverage is needed in order to improve the safety of the system. As well, to resolve usability issues a better control scheme (i.e. other than preventing joystick
motion) and ways to improve the effectiveness of the navigation subsystem should be investigated.

This study has given a better understanding of the growing population of cognitively impaired older adults that may benefit from intelligent wheelchairs. Results from the study highlight how this population is diverse, and has different needs and abilities. Although the IWS’s anti-collision function showed promise in enabling safe mobility, the navigation function was found to be lacking for some individuals. In future intelligent wheelchairs for this population, this study suggest that it is better to have a higher degree of customizability to the user. Information to the user should be sent in a way that is easiest for them to understand.
References


1998.


http://www.focusrobotics.com/technology/benefits.html

http://www.pc104.org/pc104_specs.php


Appendix A: Joystick DCLM Schematic
Appendix B: Obstacle Course Spacing

Appendix Figure 1: Left/Right turn block (110 cm spacing to driver through).
Appendix Figure 2: Obstacle Blocks (80 cm between blocks lengthwise, 40 cm between blocks widthwise).
Appendix Figure 3: Stop Block must get within 50cm and stop.
Appendix Figure 4: Straight Path Block (1m in between walls).
Appendix C: Obstacle Course Layouts

1. Start/End location
2. Turnaround location
3. 180° turn spot
4. 90° left/right turn
5. Maneuverability obstacles
6. Stopping block obstacle (will be removed when participant stops within 0.5m of block)
7. Narrow straight line path
8. Ideal pathway for participant
Course 2

Course 3
and annoyed were you?

Very High

Frustration

Very Low

Very High

How insecure, discouraged, irritated, stressed?

How hard did you have to work to accomplish?

Effort

Very High

Very Low
Appendix E: QUEST 2.0 Questionnaire

QUEST 2.0, has a total of 12 questions, all are administered in the Likert format below. Only the 8 device related questions were asked in the clinical trials.

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td></td>
<td>not satisfied at all</td>
<td>not very satisfied</td>
<td>more or less satisfied</td>
<td>quite satisfied</td>
<td>very satisfied</td>
</tr>
</tbody>
</table>

**ASSISTIVE DEVICE**

1. How satisfied are you with the **dimensions** (size, height, length, width) of your assistive device?
   
   _Comments:_
   
   1 2 3 4 5

2. How satisfied are you with the **weight** of your assistive device?
   
   _Comments:_
   
   1 2 3 4 5

3. How satisfied are you with the **ease in adjusting** (fixing, fastening) the parts of your assistive device?
   
   _Comments:_
   
   1 2 3 4 5

4. How satisfied are you with the **safe and secure** your assistive device is?
   
   _Comments:_
   
   1 2 3 4 5

**SERVICES**

9. How satisfied are you with the **service delivery** program (procedures, length of time) in which you obtained your assistive device?
   
   _Comments:_
   
   1 2 3 4 5

10. How satisfied are you with the **repairs and servicing** (maintenance) provided for your assistive device?
    
    _Comments:_
    
    1 2 3 4 5

Sample questions from QUEST 2.0 Survey
Appendix F: Data Collection Sheets

Run Data Logging:

Participant #:  Anti-collision on?:  Date:
Run:  Phase:

Collision Logging (number collisions in order of occurrence):

Frontal Collision:

Left-Side Collision:  Right-Side Collision:

Rear Collision:

Task Completion (fill in tasks, checkmark if completed without collision):

Task:  
Forward  
Return  

Time to Complete Run (seconds):
### Subjective Test Scores:

#### Phase Order (A-B or B-A):

#### Pre-Phase:

<table>
<thead>
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<th>Tally (≥15)</th>
<th>Weight</th>
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<tbody>
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#### Phase 1 (Anti-collision: yes / no):

<table>
<thead>
<tr>
<th>Run</th>
<th>Mental Demand</th>
<th>Physical Demand</th>
<th>Temporal Demand</th>
<th>Performance</th>
<th>Effort</th>
<th>Frustration</th>
<th>Total</th>
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**QUEST 2.0 Device Scoring**

<table>
<thead>
<tr>
<th>Sum Total</th>
<th>Device Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</table>

#### Phase 2 (Anti-collision: yes / no):

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<th>Run</th>
<th>Mental Demand</th>
<th>Physical Demand</th>
<th>Temporal Demand</th>
<th>Performance</th>
<th>Effort</th>
<th>Frustration</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
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<td>3</td>
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</table>

**QUEST 2.0 Device Scoring**

<table>
<thead>
<tr>
<th>Sum Total</th>
<th>Device Score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix G: Serial Dependency Analysis

If the lag-1 autocorrelation coefficient is greater than the value from the Bartlett’s test, then the serial dependency in the data series is statistically significant.

Table: Serial Dependency of Clinical Data

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Lag-1 Autocorrelation Coefficient</th>
<th>Serially Dependent?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Participant 1</strong>: n=6, Bartlett’s test = 2/√n = 0.817</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal Collisions</td>
<td>0.417</td>
<td>No</td>
</tr>
<tr>
<td>Total Collisions</td>
<td>0.214</td>
<td>No</td>
</tr>
<tr>
<td>Time to Completion</td>
<td>0.257</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>0.217</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>0.440</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>0.233</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>0.308</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Effort</td>
<td>0.469</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>0.320</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>0.017</td>
<td>No</td>
</tr>
<tr>
<td><strong>Participant 2</strong>: n=10, Bartlett’s test = 2/√n = 0.633</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal Collisions</td>
<td>0.469</td>
<td>No</td>
</tr>
<tr>
<td>Total Collisions</td>
<td>0.382</td>
<td>No</td>
</tr>
<tr>
<td>Time to Completion</td>
<td>0.319</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>0.111</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>0.033</td>
<td>No</td>
</tr>
<tr>
<td>--------------------------</td>
<td>-------</td>
<td>----</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>0.348</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>0.064</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Effort</td>
<td>0.020</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>0.131</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>0.062</td>
<td>No</td>
</tr>
<tr>
<td><strong>Participant 5</strong>: n=10, Bartlett’s test = 2/√n = 0.633</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frontal Collisions</td>
<td>0.166</td>
<td>No</td>
</tr>
<tr>
<td>Total Collisions</td>
<td>0.059</td>
<td>No</td>
</tr>
<tr>
<td>Time to Completion</td>
<td>0.192</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>0.027</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>0.384</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>0.283</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>0.451</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Effort</td>
<td>0.236</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>0.143</td>
<td>No</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>0.156</td>
<td>No</td>
</tr>
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</table>
Appendix H: Statistical Significance of NASA-TLX

Listed are the p-values of non-statistically significant NASA-TLX data.

**Table: P-Value of Non-Statistically Significant NASA-TLX Data**

<table>
<thead>
<tr>
<th>NASA-TLX Dimension</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Participant 1</strong></td>
<td></td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>0.187</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>0.392</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>0.187</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>0.199</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>0.3375</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>0.165</td>
</tr>
<tr>
<td><strong>Participant 2</strong></td>
<td></td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>0.0505</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>0.304</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>0.122</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>0.101</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>0.0245</td>
</tr>
<tr>
<td><strong>Participant 5</strong></td>
<td></td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>0.100</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>0.0915</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>0.167</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>0.424</td>
</tr>
<tr>
<td>NASA-TLX: Effort</td>
<td>0.0575</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>0.3205</td>
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Appendix I: Power Analysis

Below is the post-hoc power analysis on data that was used with t-test statistical analysis.

**Table: Power of Data used with T-test**

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Power</th>
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</thead>
<tbody>
<tr>
<td><strong>Participant 1</strong></td>
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</tr>
<tr>
<td>Frontal Collisions</td>
<td>63.88%</td>
</tr>
<tr>
<td>Total Collisions</td>
<td>53.474%</td>
</tr>
<tr>
<td>Time to Completion</td>
<td>73.176%</td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>25.95%</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>2.62%</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>0.409%</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>24.199%</td>
</tr>
<tr>
<td>NASA-TLX: Effort</td>
<td>100%</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>11.652%</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>29.562%</td>
</tr>
<tr>
<td><strong>Participant 2</strong></td>
<td></td>
</tr>
<tr>
<td>Frontal Collisions</td>
<td>96.723%</td>
</tr>
<tr>
<td>Total Collisions</td>
<td>97.067%</td>
</tr>
<tr>
<td>Time to Completion</td>
<td>13.017%</td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>58.26%</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>70.0041%</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>13.343%</td>
</tr>
<tr>
<td>NASA-TLX: Performance</td>
<td>34.921%</td>
</tr>
<tr>
<td>NASA-TLX: Effort</td>
<td>40.69%</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>42.921%</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>75.006%</td>
</tr>
</tbody>
</table>

**Participant 5**

<table>
<thead>
<tr>
<th>Frontal Collisions</th>
<th>53.126%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Collisions</td>
<td>15.474%</td>
</tr>
<tr>
<td>Time to Completion</td>
<td>39.158%</td>
</tr>
<tr>
<td>NASA-TLX: Mental</td>
<td>40.141%</td>
</tr>
<tr>
<td>NASA-TLX: Physical</td>
<td>47.971%</td>
</tr>
<tr>
<td>NASA-TLX: Temporal</td>
<td>26.849%</td>
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<tr>
<td>NASA-TLX: Performance</td>
<td>7.397%</td>
</tr>
<tr>
<td>NASA-TLX: Effort</td>
<td>59.896%</td>
</tr>
<tr>
<td>NASA-TLX: Frustration</td>
<td>12.307%</td>
</tr>
<tr>
<td>NASA-TLX: Total</td>
<td>61.537%</td>
</tr>
</tbody>
</table>