DESIGN AND DEVELOPMENT OF ASSISTIVE ROBOTS FOR CLOSE INTERACTION WITH PEOPLE WITH DISABILITES

by

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People with mobility and manipulation impairments wish to live and perform tasks as independently as possible; however, for many tasks, compensatory technology does not exist, to do so. Assistive robots have the potential to address this need. This work describes various aspects of the development of three novel assistive robots: the Personal Mobility and Manipulation Appliance (PerMMA), the Robotic Assisted Transfer Device (RATD), and the Mobility Enhancement Robotic Wheelchair (MEBot). PerMMA integrates mobility with advanced bi-manual manipulation to assist people with both upper and lower extremity impairments. The RATD is a wheelchair mounted robotic arm that can lift higher payloads and its primary aim is to assist caregivers of people who cannot independently transfer from their electric powered wheelchair to other surfaces such as a shower bench or toilet. MEBot is a wheeled robot that has highly reconfigurable kinematics, which allow it to negotiate challenging terrain, such as steep ramps, gravel, or stairs. A risk analysis was performed on all three robots which included a Fault Tree Analysis (FTA) and a Failure Mode Effect Analysis (FMEA) to identify potential risks and inform strategies to mitigate them. Identified risks or PerMMA include dropping sharp or hot objects. Critical risks identified for RATD included tip over, crush hazard, and getting stranded mid-transfer, and risks for MEBot include getting stranded on obstacles and tip over. Lastly, several critical factors, such as early involvement of people with disabilities, to guide future assistive robot design are presented.

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1.0 INTRODUCTION

People with mobility and manipulation impairments wish to live and perform tasks as independently as possible; however, for many tasks, compensatory technology does not exist, to do so. Assistive robots have the potential to address this need. While assistive robots have existed for over 3 decades, recent advances in computing power density, sensors, and algorithms, combined with dramatic reduction in cost and size of these components have made the development and use of these devices more practical. This work will describe various aspects of the development of three novel assistive robots: the Personal Mobility and Manipulation Appliance (PerMMA), the Robotic Assisted Transfer Device (RATD), and the Mobility Enhancement Robotic Wheelchair (MEBot). PerMMA integrates mobility with advanced bi-manual manipulation to assist people with both upper and lower extremity impairments. For PerMMA, this will describe the robot architecture, the physical design, and introduce a framework for user/caregiver/computer shared control. The RATD is a wheelchair mounter robotic arm that can lift higher payloads and its primary aim is to assist caregivers of people who cannot independently transfer from their electric powered wheelchair to other surfaces such as a shower bench or toilet. The RATD architecture, physical design, and an initial focus groups with potential end users will be described. MEBot is a wheeled robot has highly reconfigurable kinematics, which allow it to negotiate challenging terrain, such as steep ramps, gravel, or stairs.

This work describes and comments on the innovations and strategies that were employed to allow MEBot to negotiate the six obstacles of the 2016 Cybathalon in Zurich, Switzerland. Lastly, a risk analysis has been performed on all three robots which will include a Fault Tree Analysis (FTA) and a Failure Mode Effect Analysis (FMEA) to identify potential risks and inform strategies to mitigate them. FTA is top down approach, which starts with high level adverse events, using deductive logic to arrive at basic causes. FMEA is a bottom up approach, starting with system components, using inductive logic to arrive at high level adverse events. The purpose of this analysis is to introduce systematic safety and reliability strategies to be better prepare these robots for more advanced user evaluation.

1.1 SIGNIFICANCE

1.1.1 Wheeled Mobility

Electric Powered Wheelchairs (EPW) have played a key role in providing mobility, independence[1], access to communities, satisfaction[2], and improving quality of life[3] in people with disabilities. Currently, 3.3 million adults benefit from using wheeled mobility devices, with an increase rate of 4.3% every year[4]. As of 2010, an estimated 400,000 people benefitted from EPWs[5]. This number is expected to continue to increase as the baby boom generation continues to grow older[5]. However, only minor improvements have been shown in EPWs in the past 20 years[6], including reliability[7], better suspension to minimize vibration exposure[8], and expanded user interfaces[6]. Despite some improvements, current EPW design limits most users to drive in indoor environments, and outdoors with firm and mostly flat, Americans with Disabilities Act (ADA) compliant environments. Furthermore, People with disabilities using EPW have difficulties, and thus often avoid, driving over uneven terrain or overcoming architectural barriers such as curbs, curb-cuts, and terrains non-compliant with ADA standards[9]. Studies[10, 11] have demonstrated that users adapted their behavior by choosing routes without physical barriers or by going to accessible places rather than to places they may really wish to go[12]. Research has shown that most common wheelchair-related accidents in such environments were tips and falls[13-16]. In addition, Salatin et al. showed that these accidents were often due to loss of traction, getting stuck, or loss of stability in the EPW[17]. As result of these accidents, more than 100,000 wheelchair related injuries are treated in emergency departments in the US every year[16]. In terms of cost, the treatment for wheelchair-related falls, including rehabilitation, can range between $25,000 and $75,000 per incidence[18].

1.1.2 Manipulation.

The need for assistive technology aimed at people with significant disabilities is great. Simpson et al[19] suggest that 1.4 to 2.1 million wheelchair users, in the U.S., could benefit from a smart wheelchair technology at least some of the time. Fehr et al[20] reported that from a survey of clinicians that 32% reported seeing as many clients that could be fitted for electric powered wheelchairs (EPW) but could not because the appropriate technology does not exist. Cooper et al[21] states in a recent review of trends in wheelchair technology that the incorporation of robotic technologies as an important area for development.

1.1.3 Transfers

The ability of people with mobility impairments to live in their homes and communities with maximal independence often hinges, in part, on their ability to transfer or to be transferred by an assistant. In order to help people with mobility that cannot independently transfer live at home and participate in life's activities, insurance or government agencies may provide for personal attendant care services and in some cases provide stipends for family members providing these services. Further, independent transfers are a common source of upper extremity injuries and joint degeneration that often leads to the need for assistance with transfers over time[22]. Recent research has also shown that many people who can perform independent transfers need assistance when the height differential between transfer surfaces is greater than 75 mm or the gap between surfaces is greater than 150 mm[23]. For people with mobility impairments who need human and/or mechanical assistance with transfers to and from wheelchairs, the options are limited. During dependent transfers with a human assistant, there is a high risk of injury (both acute and cumulative) to both the wheelchair user and the assistant, especially over the long-term[22].

Between 1973 and 1987, 770 wheelchair-related accidents that led to death were reported to the U.S. Consumer Products Safety Commission. 8.1% of these accidents were caused by falls during transfers[24]. Between 1986 and 1990, there were an estimated 36,000 wheelchair-related accidents in the U.S. that resulted in a visit to the emergency department. 17% of these accidents were due to falls during transfers[15]. In 2003, more than 100,000 wheelchair related injuries were treated in U.S. emergency departments, showing an upward trend in the number of injuries over time[16].

When caretakers assist in transferring wheelchair users, there is an additional risk of injury to the caretaker. In one study, of the 48 accidents reported by the 174 participants, 15.5% involved attendants[25]. There were more than 1,325,000 home care workers or clinicians in the United States in 2004. This group is expected to grow by 56% from 2004 to 2014[26]. Lower back injuries are a major risk for this group, and one estimate found that 10.5% of back injuries in the United States are associated with transferring patients. In one study investigating bed to chair transfers, it was found that healthcare workers experience up to 3500N of compressive forces during a single transfer[27]. In another study where lifts were implemented in a hospital to assist with patient transfers, it was found that over a 3 year period, there was a 70% decrease in claims cost at the intervention facility. The cost of compensation for injuries at this facility also decreased, with a 241% increase in the comparison facility[28].

There are approximately 1.5 million people in the United States who have disabilities that require them to use a wheelchair. One study found that 60% of people reported shoulder pain since beginning their wheelchair use. In comparison, only about 4.7% of the general population report regular shoulder pain[29]. Sitting pivot transfers (SPTs) are ranked among the most strenuous daily tasks of wheelchair users. Repetitions of this task over time can be detrimental to the shoulder and elbow joints of wheelchair users[30].

There are variations in wheelchair users' movements during transfers dependent on their level of injury. When a patient transfers him/herself from a wheelchair to another surface, most of their weight is initially supported by their trailing upper extremity. As they lose contact with the seat, weight is shifted to the leading arm[31]. During wheelchair transfers, large forces are placed on the shoulder and elbow joints. The leading shoulder encounters higher displacement and velocities than the trailing one[32]. This can cause damage in the leading arm to be accelerated and the onset of pain in this arm to occur sooner.

When wheelchair users are transferred by other people, the biomechanics of the transfer take on a different form. Strain is still placed on the wheelchair-users shoulder joints, although it is more evenly distributed across the sagittal plane. There is also an additional factor of strain placed on the lower back of the person assisting with the transfer. One study found that a pivot transfer puts 112 lbs of force onto the clinician assisting with the transfer and raises their risk of developing a lower back disorder to 38.8%.[26]

One technique that is used in many healthcare facilities is to move patients using ceiling-lifts. In one study where lifts were added to an extended care unit, 71.4% of care staff reported that it became their preferred method of transferring patients and 96% believed that the ceiling lifts made lifting residents easier[33]. While these lifts effectively transfer people without placing as much strain on the caretaker, they are often not used because they are time-consuming. In many cases, legislation concerning the implementation of lifts is focused on the caretakers' comfort and safety as opposed to the patients'. In rare cases, these lifts can even subject the patient to bruising or skin tearing. Another major concern when transferring patients using a lift system is that the patient may feel that being moved around in such a manner is undignified[34].

1.2 RELEVANT LITERATURE

1.2.1 Assistive Robots for Mobility

The RT-Mover robot[35-37] is a self-balancing robot wheelchair designed for uneven terrain. The RT-Mover is rather large and wide as well as having a slow response time for outdoor driving. The Viking Explorer wheelchair composed of four driving wheels and autonomous self-leveling through fore-aft seat tilt; requires a larger footprint and bigger wheels, which makes it impractical for indoor use. The TopChair is an advanced EPW with the addition of a track under the base to climb steps[38]. This feature, however, makes the wheelchair larger and heavier than standard EPWs. The iBOT3000, no longer on the market, provided outdoor terrain driving and step climbing[39]. Unfortunately, the user required good upper body range of motion and ability to shift his/her center of gravity in order to climb steps. Moreover, it could not accommodate power seating functions and alternative controls. Other advanced prototype designs of EPW have focused on overcoming architectural barriers such as curbs and steps to address accessibility; such as the wheelchair "q"[40-44], University of La Castilla-La Mancha[45] and Nagasaki University[46]. However, their designs required a large footprint and reduced their driving performance and maneuverability which should be taken in account for indoor and outdoor environments.

1.2.2 Assistive Robots for Manipulation

One of the earliest examples of an assistive robotic system in the literature is the Desktop Vocational Robotic Assistant (DeVAR) created at Stanford University[47, 48] to allow people with high spinal cord injuries to function more independently in a workplace setting. DeVAR consists of small robotic arm mounted on an overhead track system above a desk. It is controlled using discrete word voice commands that initiate preprogram routines to perform some functional task. DeVAR was followed by Professional Vocational Assistant (ProVAR), which incorporated force sensors and different interface modes. Input and output information was conveyed to and from the user using a PC based custom interface.[49-51]

One the most common assistive robots found in the literature is the Assistive Robot Manipulator (ARM) formerly known as Manus[52-70]. The ARM is anatomically based and has 6 degrees of freedom (DOF) plus a gripper and can be mounted to side of an electric powered wheelchair (EPW) for general manipulation. It can be operated in joint control mode or a Cartesian end effecter mode using either a standalone keypad or through programmable PC interface.[53, 61]

Commercial availability and the PC interface mode have allowed several research groups to leverage the ARM to create more complex assistive robotic systems. A group of researchers at Delft University of Technology and at TNO Science and Industry, Delft, The Netherlands, have developed a software framework for controlling the ARM which includes several novel control modes[55, 63-65]. They also have incorporated cameras into their system and developed computer vision algorithms for retrieving items using visual servoing[54, 59]. Another group at the Institut National des Telecommunications and University Pierre & Marie Curie in France have developed a graphical, software based, human environment interface for controlling the

ARM as well as other assistive technology[56, 57, 61]. In addition, they have placed the ARM on an unmanned mobile base equipped with cameras and ultrasound sensors to identify and locate objects and created path planning algorithms that allow the robot autonomously retrieve these objects[66, 67]. Another French group has appended the ARM to small mobile robot with goal of following the wheelchair user around, instead of having the ARM attached to the wheelchair[53, 69].

Another assistive robotic system is El-E, developed by Nguyen and Kemp at Georgia Tech, is designed to fetch items in the home environment for people with disabilities. It consists of a small mobile robotic base with a manipulator arm mounted on a vertical track. The user indicates the object they would like to fetch using a laser pointer and a combination of camera and laser range finder sensors help the robot identify, navigate to, grasp, and return the object to the user.[71-74]

The KAIST Rehabilitation Engineering Service system (KARES)[75] and KARES II[76-79] are assistive robotic systems aimed at providing general mobility manipulation for people with disabilities and older adults which were developed at the Korean Advanced Institute for Science and Technology (KAIST). KARES consists of a robot manipulator arm attached to the side of an EPW and server control system accepts inputs from the user and sensors. Much of the development has focused on autonomous control of the robot using visual servoing, specifically for use during feeding[76-78]. In addition to the robot, several user interfaces have been demonstrated including an eye mouse, an EMG interface, a head interface, and a shoulder interface[79].

Another EPW based system has been developed at the University of South Florida. The group has developed a 9 DOF assistive robotic system that provides both mobility and manipulation as well strategies for control of redundant DOF[79-91]. The system consists of custom built 6 DOF robotic arm and a custom gripper mounted and networked to an EPW[83-85, 87, 88]. Much work has focused on developing methods for controlling redundant degrees of freedom[80-82], including anthropomorphic control strategies[89]. Other work has focused on motion intent recognition[91] and a brain computer interface that uses P300 signals[90].

An assistive robotic system was developed at the Quality of Life Technology Center (QoLT) at Carnegie Mellon University[92]. The Home Exploring Robotic Butler (HERB) which features a robotic manipulator mounted on top of mobile base that will perform complex task around the home using environmental information from cameras that server as inputs to advance path planning algorithms[93]. The work focused on manipulating kitchen items, such as loading a dishwasher and retrieving specific items from a cluttered cabinet.

1.2.3 Assistive Robots for Transfers

Few high-tech devices for transfers are reported in the literature. One such device is the Home Lift, Position, and Rehabilitation chair (HLPR), which was developed to be able to lift wheelchair users, rotate them, and place them on a toilet, chair, or bed. However, this chair is meant for home use only and may tip over if inclined 10 degrees[94, 95].

2.0 PERSONAL MOBILITY AND MANIPULATION APPLIANCE[1]

2.1 INTRODUCTION

The purpose of the PerMMA project is to develop a robotic system with mechanical and electronic hardware, control algorithms, and user interfaces suitable for assisting people with disabilities in both mobility and manipulation with the practical aim of increasing their independence and reducing the need for caregiver assistance. This manuscript describes the design and development of the initial prototype and its evaluation by the design team in a realistic kitchen environment. The goals for this initial prototype include:

- Create a mechanical system the provides mobility and bi-manual manipulation
- Create electronics for controlling both mobility and bi-manual manipulation in highly integrated manner
- Demonstrate multiple methods of controlling the system
- Create a platform that is suitable for the testing of new user interfaces and advanced control algorithms

[1] This work was originally published as Grindle, G.G., et al., *Design and Development of the Personal Mobility and Manipulation Appliance.* Assistive Technology®, 2011. **23**(2): p. 81-92.

- Create a platform that is suitable for potential end user evaluation with respect to usability, safety, and aesthetics

This work builds on previous development at the Human Engineering Research Laboratories and Quality of Technology Engineering Research Center. A flexible input and output controller for EPW was described by Salatin et al[96], which contained amplifiers for actuating the drive wheels, numerous channels of I/O, and a single board computer for performing computation functions. Wang et al[97] used this same hardware to develop and compare open loop, PID, and model based traction control algorithms for EPW and concluded that the model based control performed the best. Coyle et al[98] used vibration data collected using this controller to develop a terrain classification algorithm for EPWs; and was able to distinguish between 8 different surfaces at 1m/s and 2m/s with a 90% success rate.

Diankov et al[99, 100] used as partially completed version of the PerMMA prototype as well as other robots to explore path planning algorithms for grasping with autonomous robots. PerMMA was used to successfully open a door autonomously. Other related autonomous research has been conducted on PerMMA's sister project, Home Exploring Robotic Butler (HERB), which has focused on using computer vision and OpenRAVE path planning tools to identify and manipulate kitchen items autonomously [100-105].

2.2 METHODOLOGY

2.2.1 Design

2.2.1.1 Integration

The PerMMA design integrates several commercially available and custom technologies to create a bi-manual, mobile robot with 22 degrees of freedom (DOF) that can transport a seated person. A Permobil C500 EPW with powered seat functions that allow the user to change their seating position was selected to provide the mobility feature. The included power seat functions are tilt-in-space, recline, seat elevator, and elevating leg rest. All the original electronics of C500 were remove to make space for custom electronics. Two ARMs were selected for performing the manipulation feature of the system due to their safety features, commercial availability, and suitability for being integrated with an EPW.

Table 2.1 Gives the component of PerMMA, their actuation features, and the number of degrees of freedom.

Components	Features	DOF
Mobile Base		2
Powered Seat Functions	Tilt-in-Space	1
	Recline	1
	Seat Elevation	1
	Elevating Leg Rest	1
Carriage	Along Track	1
	Swivel Arm	1
Right ARM	Arm	6
	Gripper	1
Left ARM	Arm	6
	Gripper	1
	Total	22

In order to integrate the ARMs with the mobile base a custom track and carriage system was designed and fabricated, as shown in figure 2.1. The track is attached to the seat frame, which allows it to move with the powered seat function, and consists of a single “U” shaped rail with a gear rack in the center of the outside face. The entire track is within the footprint of the mobile base, adding no extra width. Each carriage rolls along the track on 12 crowned roller bearings with the uneven spacing of the side rollers which allow it to traverse the bends in the track. Each carriage has two motors: one motor is attached to a pinion gear that pulls the carriage along the track and the other is connected to rotating mechanism that receives the ARM. Overall the track and carriages add 4 DOF to the system, allow the manipulators to move anywhere along three side of the mobile base, and greatly increasing the workspace of the system.

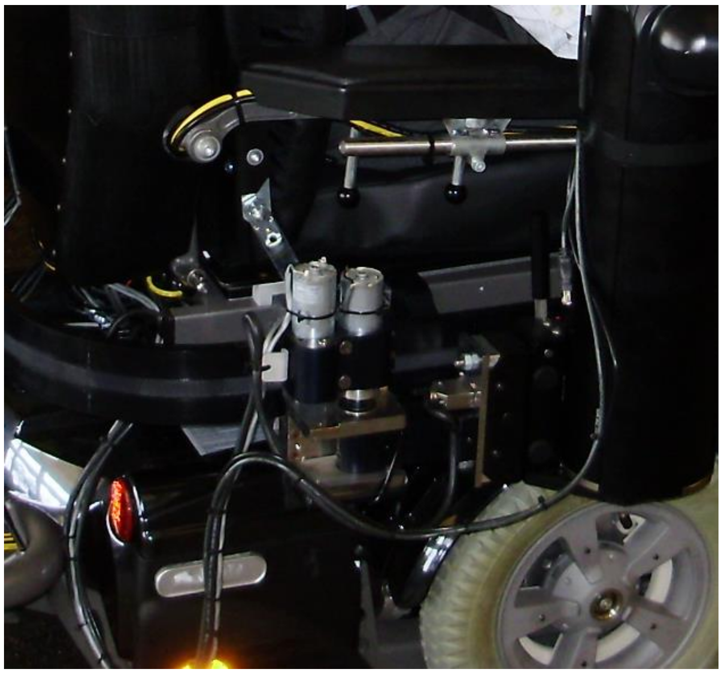

Figure 2.1 show a photograph of the track and carriage system

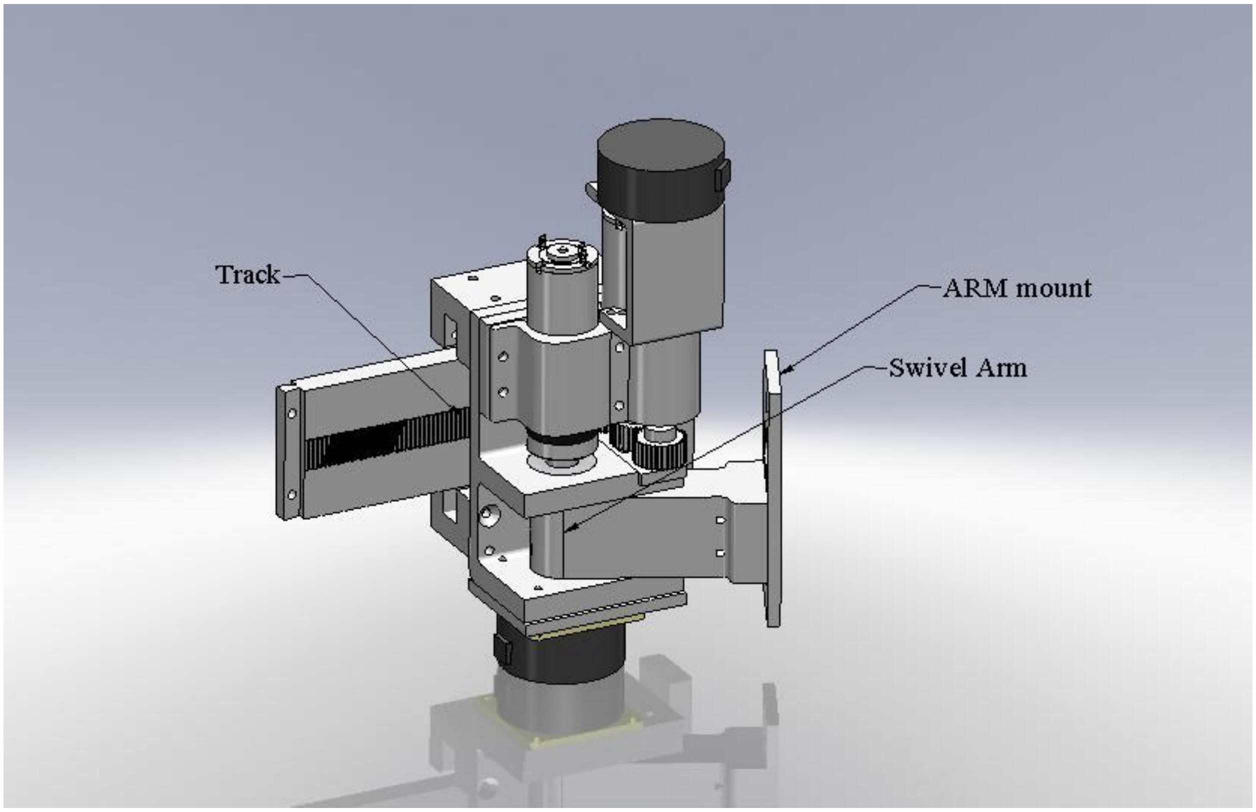

Figure 2.2 shows the carriage mechanism for PerMMA's track

In order to perform the control and computation features, a computer network was embedded in the base. The system consists of four computers: a server, an embedded mobile base controller, and an embedded controller for each ARM. The server is a PC laptop computer, located under the seat, which carries out high level computational functions. Its primary function is to interpret the signals from the manipulator input device(s), map the input device to the manipulator, and sends high level signals to the ARM computers; however, it also can send commands to the base controller, receive feedback from the base computer, and can be networked wirelessly to other computers or input devices using Wi-Fi or 3G.

The mobile base controller is a repackaged version of the controller described in Salatin et al[96], which consists of a single board computer, amplifiers for the drive wheel motors, and a circuit for controlling the brakes. A custom relay board was added to control the carriage and power seat functions. In addition to these hardware features this controllers executes the algorithms for translating the signals from the driving input device to the signal needed to drive the motors, as well as algorithms to read the sensors on the mobile base.

The ARM controller is an embedded computer that is provided with the commercially available ARM; it generates movements of the manipulator based on high level commands it receives from the server computer. In addition, it can provide feedback from the manipulator's regarding joint position to the server computer. A block diagram of the embedded control and computation system is given in figure 2. All the computer systems are run on battery power and PerMMA can operate completely un-tethered from external power for over 3 hours of continuous use.

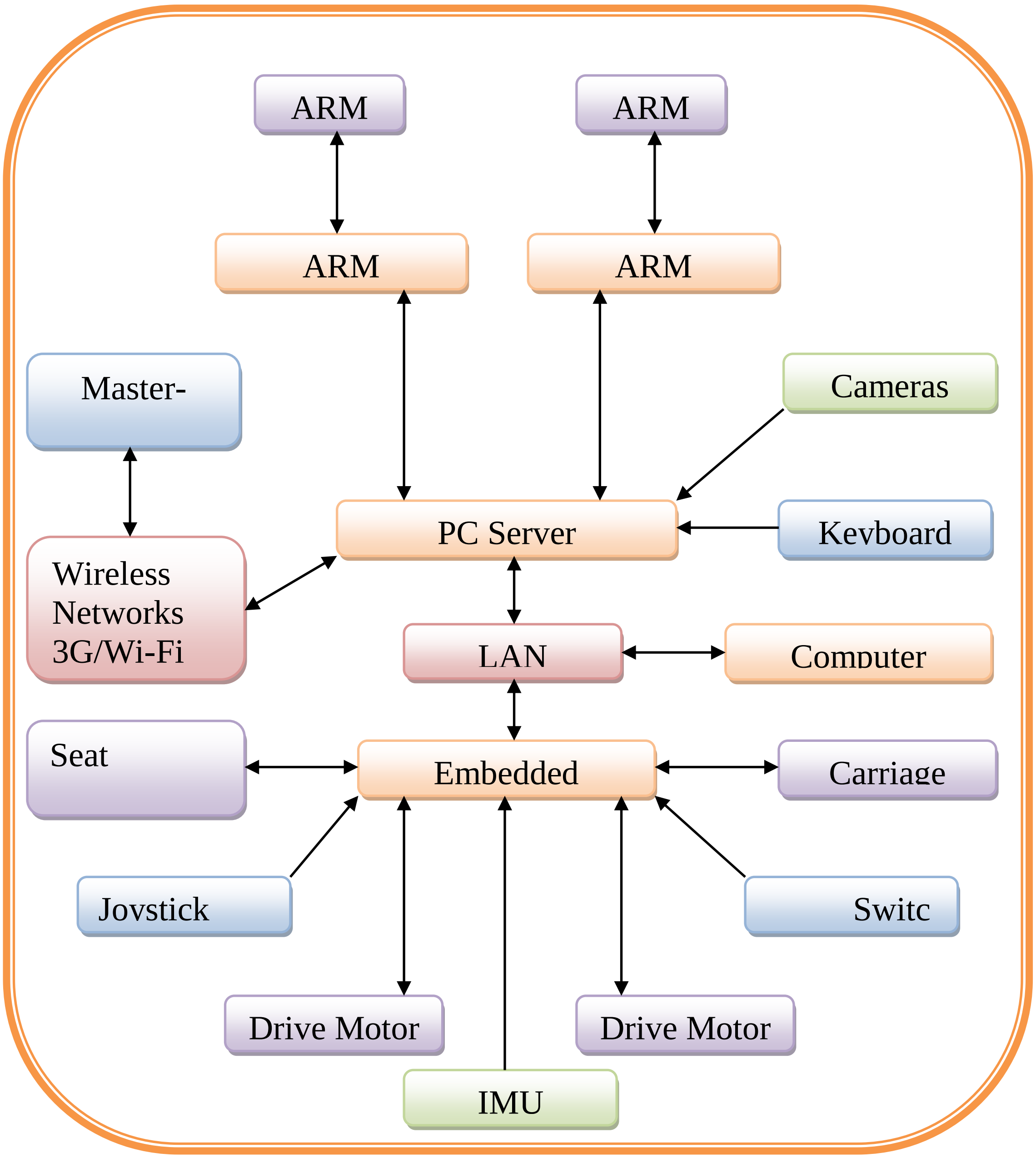

Figure 2.3 gives a block diagram of the embedded control and computation network

PerMMA is equipped with a variety of sensors that allows it to determine its own position, as well as obtain information regarding its environment. In order to obtain precise position information, each joint is equipped with an encoder. The drive wheels, powered seat functions, and the carriage were appended with custom design encoder packing, while the ARM has built in encoders. A six DOF inertial measurement unit was included to detect vibrations, roll rates, and in combination with the drive wheel encoders, wheel slip. For computer vision and remote operation cameras were mounted on the shoulder of each manipulator and a microphone was also included to allow for voice over IP communication between the user and a remote operator.

Overall the system is highly expandable. The system includes many common communication busses that allow for sensor expansion. The Wi-Fi and 3G wireless allow the system to communicate with commuters and devices in the environment, as well as other computers in remote location via the World Wide Web. An Ethernet switch allows for additional local computers to be added readily in the future.

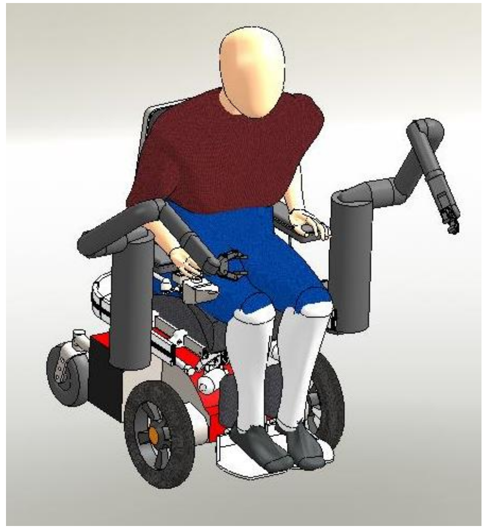

Figure 2.4 shows a solid model of PerMMA

2.2.1.2 Input Devices

Several different types of user interface devices have been incorporated into PerMMA, including a: joystick, keyboard, switch pad, and master-slave interface using two small robots. The joystick, similar to those found on commercially available EPW, was included as the primary interface for the mobile base and offers proportional control of the mobile base's two DOF. The secondary interface for the mobile base is the keyboard, which can also be used to control the manipulators in either a Cartesian or joint-by-joint mode. The small switch pad was incorporated to allow the user to manually move the carriage and access the powered seat functions in a manner similar to commercial EPW. In order for a person to control the 14 DOF of the manipulators simultaneously, a master-slave interface was created using two Phantom Omni haptic robots. The position of the small master robots were mapped in software to correspond with the movements of the larger ARM manipulators using joint-by joint mode. The system was mapped so the shoulder and elbow joint geometry of the haptic robots would be as similar as possible to the shoulder and elbow joint geometry of the ARMs. The small size and favorable geometry of the master robots allow for a user to manipulate both robots simultaneously as shown in figure 4. In addition to controlling position, haptic feedback is provided when the operator moves to the boundary of a keep out region that was programmed to keep the manipulators for crossing into the user's space. It should also be noted that system was designed to be flexible; it incorporates many common electronic interfaces, including USB, RS-232, Firewire, A/D, and general-purpose digital I/O, which allows for adoption of new interface device readily.

Figure 2.5 gives a photograph of a remote user using the master-slave interface

2.2.1.3 Control Methods

Due to the complexity of controlling 22 DOF, PerMMA has been designed to operate in several different modes, which include: local user, remote user, autonomous, and cooperative control. The simplest of these is local user mode, which utilizes no sensors and relies on the local user to close the feedback loop as show in figure 5. Currently, in this mode, the local user would use a joystick to control the mobile base, a switch pad to control powered seat functions and carriages, and a keyboard to control both manipulators.

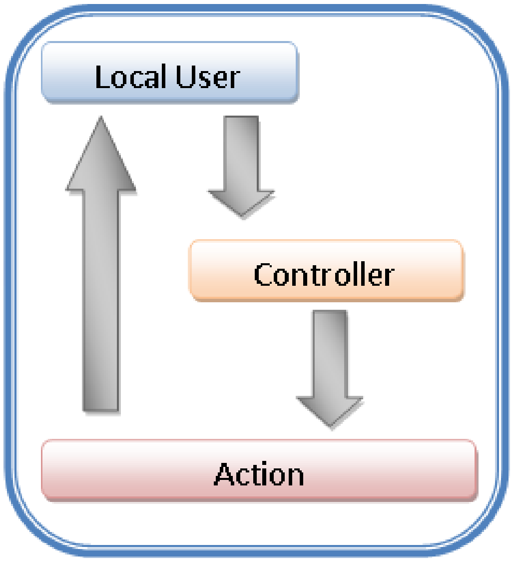

Figure 2.6 is a diagram demonstrating the flow of information in local user control mode

In remote user mode a person in different location connects to the system via the internet and assumes control of the device. The remote user receives a high level directive from the local user, attains feedback about the environment through the two web cameras, and then relays the desired commands to the controller, as summarized in figure 6. The web cameras implemented have 320x240 pixel resolution, and variable frame rate up to 30fps, typically around 22fps depending on bandwidth. The cameras are mounted on the shoulder of the ARM allowing them to pan with the shoulder movement. The cameras also have pan and tilt feature that also can be remotely controlled. In this situation, the remote user typically controls the manipulators using the master-slave interface and the other DOF using the keyboard.

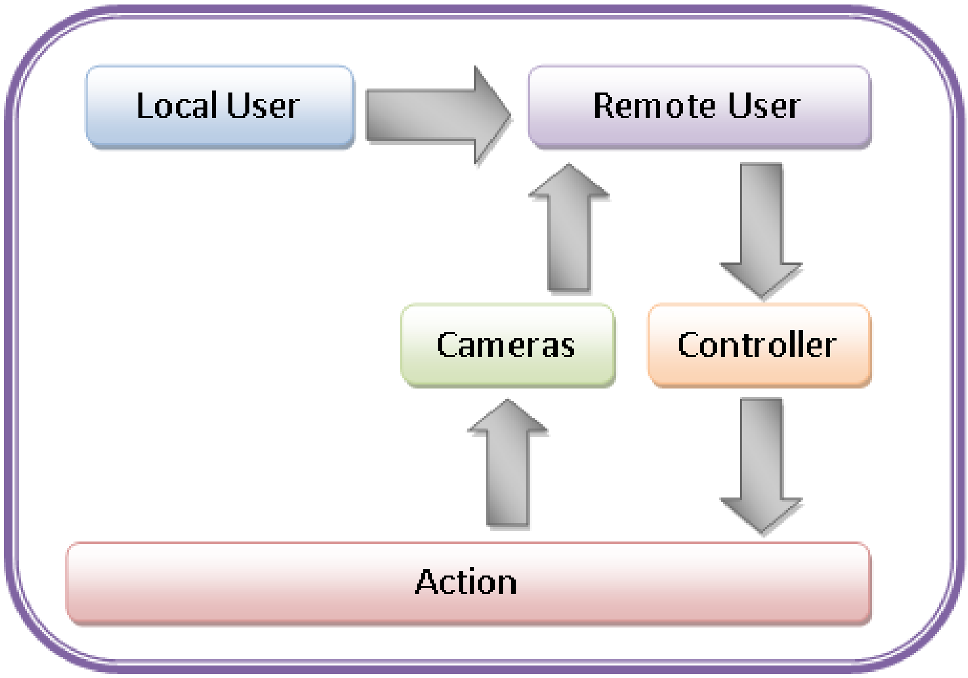

Figure 2.7 is a diagram demonstrating the flow of information in remote user control mode

In autonomous mode the local user gives a high level directive to the system and it uses information from its sensors and path planning algorithms to complete the action, as given in figure 7. Cameras and computer vision algorithms are used to detect the object of interest and OpenRAVE[99, 100] path planning tools are used to generate the manipulator's trajectory utilizing the ARM's joint-by-joint mode. OpenRAVE allows for

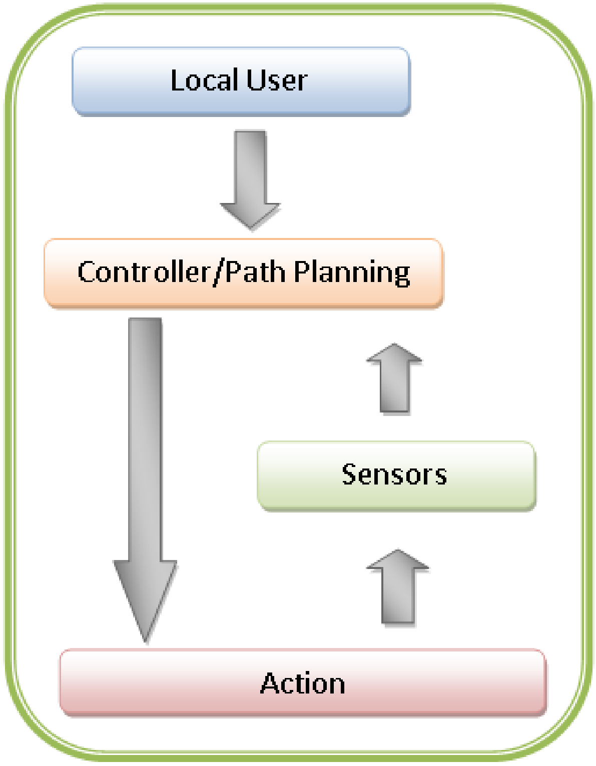

Figure 2. 8 is a diagram demonstrating the flow of information in autonomous control mode

Cooperative control mode is a method that blends the three previously described modes, so that complex tasks can be carried out by using two or more modes simultaneously or by seamlessly transitioning between individual modes. This mode also has the benefit of allowing information to flow between to the human users through each other and each can act on information in tandem. For the controller, if input signals from different sources are not in conflict they are permitted to be actuated simultaneously. If inputs signal from different sources are in conflict, a preconfigured hierarchy is followed. The flow of information in cooperative control mode is given in figure 8. Typically, in this mode, the remote user utilizes the master-slave interface to control the manipulators, while the local user generates additional movements of the mobile base and the carriage using a joystick and a switch pad, respectively. The local and remote users coordinate their movement using voice over IP.

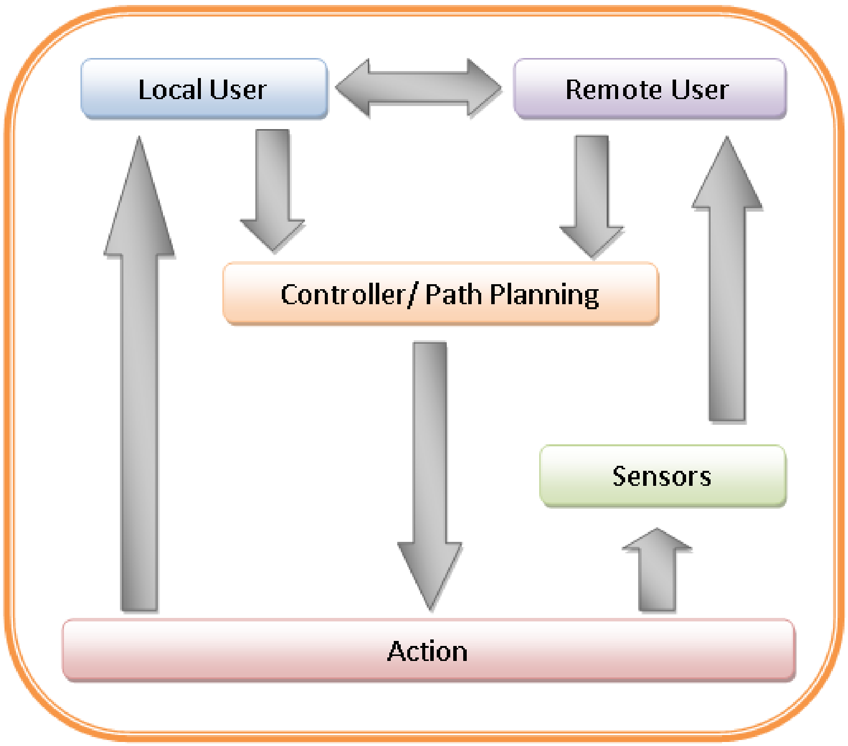

Figure 2.9 is a diagram demonstrating the flow of information in cooperative control mode

2.2.1.4 Power Consumption

In order to estimate the power consumption of PerMMA, power was calculated from measurements under three different conditions. The test conditions consisted of: the system idling; the ARMs stretch horizontally out in front of base while statically holding 3.3kg in each arm, the ARMs reported maximum payload; and diving at constant max speed with a 113kg passenger, the reported max payload of the Permobil C500. Voltage was measure across the battery terminals with a Fluke 190C portable oscilloscope/meter while the current was measured using a clamp style ammeter adaptor attached to the oscilloscope/meter. The measurements were sampled at xxHz and Watt-Hours were calculated using the product of the voltage, current, and totally sampling time.

2.2.2 Demonstration Protocol

In order to evaluate the features of the system, a demonstration protocol was established. The purpose of the protocol was to determine if the system: performed as designed from a qualitative perspective, posed any significant risk to human users, and could be used to complete practical tasks from beginning to end. The protocol consists of three successive challenges carried out in a realistic setting with the design team acting as expert operators. The evaluation was completed in a model accessible home, which had a kitchen with an “L” shaped layout. The challenges were: to open the refrigerator and retrieve a food storage container; remove the lid from the food storage container, and microwave the food container and place it on a table. A simplified version of cooperative control was used. The local user could control the track translation and manipulator height with a button array, and move the mobile base with a joystick. The remote user could control the 14 DOF of the ARMs using the master-slave interface and the mobile base with a keyboard. The local and remote users could communicate using voice over IP to facilitate coordination during tasks. The autonomous mode was not utilized for this experiment.

In order to determine aim 1, the system was closely observed through the use of instruments such as multi-meter, though system indicators such as ARM error codes, and direct visual observation. Items of particular interest included: software applications failures, battery voltage levels, robustness of cable connections, and the system responding as expected to inputs.

All irregularities were recorded and probed further for failure mode. The criteria for evaluating aim 2 centered on direct observation of the local users physical interaction with the system. Interactions that could be considered safety issues include, but are not limited to: unintended/improper actuation of the system, rapid acceleration/deceleration of the base, electric shock, exposed pinch points, system failures that result in objects being manipulated striking the user, and motions that could compress the user. For aim 3, each sub-task was given a pass or fail status based on the system's ability to complete it.

2.3 RESULTS

The evaluation demonstrated that PerMMA has the ability to perform the three kitchen challenges. Coordinated control mode was used to accomplish the challenges. The remote user with the master-interface was relied on heavily by the local user; however, the local user was able to make fine adjustments to the manipulators position using the switch pad and could perform some gross movement task, like shutting the refrigerator door by using the mobile base. Depth perception for the remote user was poor; however, extensive use of voice communication between the local and remote users helped to compensate. A custom made food container lid opening tool was utilized and the food container was transported in a basket from the refrigerator to the microwave in order to simplify manipulation. PerMMA could run on battery power for over three hours. Overall hardware and software performed as expected; however, a minor problem was identified and corrected in carriage control circuit. No potential safety issues were identified.

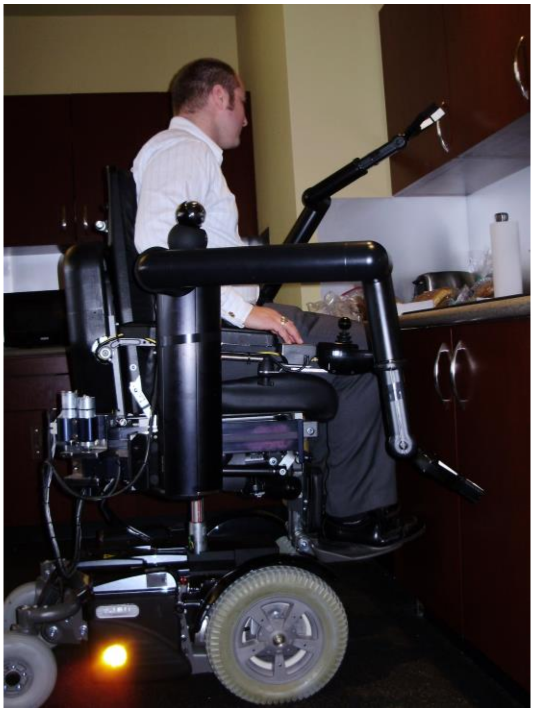

Figure 2.10 is a photograph of PerMMA opening up a high cabinet in a kitchen with the aid of the seat elevation powered seat function

Figure 2.11 is a photograph of PerMMA retrieving an eating utensil from a drawer in a kitchen

2.4 DISCUSSION

The evaluation in a realistic kitchen scenario demonstrated that the goals of the initial prototype have been meet to a high degree. Mechanically, the system is mobile, bi-manual and was able interact with objects over a wide workspace. Electronically, the hardware was able to handle input from multiple sensors and multiple input devices, while being able to translate this information into the expected motions. The remote user with the master-slave interface demonstrated that a person in a different location can assist another person with a robot in performing complex tasks. By allowing a few people in a call center, assist many people with disabilities in many locations, suggests this concept by itself could open up many new practical uses for assistive robots and warrants further investigation.

Three individual control modes were demonstrated successfully; however, of most interest is the cooperative control mode that blends them together. The evaluation demonstrated that with the remote user could perform gross motor functions, the local user could compensate for the remote user's poor depth perception through small adjustments and communicating position to the remote user, to accomplish the complex task of meal preparation. While inclusion of more automation will make the process even more efficient, the flexibility, the spontaneity, and robustness of including humans in the loop is likely to be superior to pure automation for assistive robotic applications. Human input, in whatever form they have the ability to do so, could greatly aid semi-autonomous robotics in cluttered and novel environments or in situations where sensor noise results in failure to find a solution. From an end user point of view, being in the loop, along with the functional benefits, may give them a greater sense of control; that they are in a symbiotic relationship with their robot, and not just dependent on another device.

Overall, PerMMA is a departure from previously developed robotic manipulation systems for several reasons: it has a high number of DOF, including bi-manual manipulation; its embedded control and computation system is powerful and expandable; and its design has focused on achieving the usability, safety, and aesthetics characteristics that are requisite for meaningful potential end user evaluation. The high number of DOF is significant from a rehabilitation perspective in that many everyday tasks can only be completed with bi-manual manipulation and many more are more quickly carried out using two manipulators. From a general robotics perspective, the high number of DOF makes PerMMA an interesting platform for developing and testing algorithms for complex control and path planning.

The power and expandability of the control and computation system also make PerMMA an interesting system for development. The number and variety of inputs to the controller allows for nearly any sensor to be readily adapted to the system for testing of a control algorithm or a novel user interface, such as a direct brain interface, to be plugged in and evaluated. The amount of processing power plus the ability to add more are what is necessary to execute complex computer vision and path planning strategies in real-time. Also, people with disabilities are not heterogeneous; for a large and varied population to use a complex assistive device, many interfaces must be available and the system allow for this.

The level of PerMMA's usability, safety, and aesthetics are significant because they allow the system to be evaluated by potential end users. Previously developed system do not incorporate powered seat function usage, a feature that a person with both upper and lower extremity impairment would need in order to safely sit for any reasonable length of time, without increasing the risk of pressure ulcers[106]. Great effort was made to conceal wires, shroud mechanisms, and make it look and function more like an end product rather than a prototype.

This is important because: it increases the safety level; it increases the study participant confidence that the system will work and is worth their time to evaluate; and it keeps the participant from being distracted by features that do not meet their expectations of what a wheeled mobility device should be. For example, one may be evaluating a new interface device; however, if the headrest does not adjust to a position the participant prefers, it may confound the results. PerMMA is also able to be completely un-tethered from external computer or power sources, which allows it to leave the laboratory and interact with potential end users in natural environments, leading to more contextually valid evaluations of the technology. End user involvement in the development process is essential to creating assistive robotic technology that will be adopted by the disability community.

Future work on PerMMA should focus on creating better user interfaces for both the local and remote users. An LCD display that provides either of these users with sensor, position, or composite data might make the system easier to use. The remote user might benefit from a 3-D display that provides some depth perception. More automated functions need to be explored to increase manipulation accuracy and decrease the time it takes to complete motions that are often repeated, and reduce cognitive load on human users. All control modalities could benefit from the addition of gripper haptics. Little effort was made to conserve power. In the future, power management strategies could be employed to maximize battery life. Lastly, evaluations with potential end users need to be performed to determine what features are useful, what features could be developed in the future, and how they wish to interact with the system.

3.0 ROBOTIC TRANSFER ASSIST DEVICE[2]

3.1 INTRODUCTION

The purpose of the Robotic Assist Transfer Device (RATD) is to aid in the transfers of people with disabilities to and from their EPW onto other surfaces. The RATD consists of a 4 DoF robotic arm that is connected to an EPW by a motorized track that allows the robot to move around the seat frame. The robot is controlled by a caregiver, who guides the speed and trajectory of the transfer, using a handle that senses the force applied by the caregiver. The device can be used for stand-pivot transfers or it can be used for fully dependent transfers, where the person being transferred is in a sling and the weight is fully carried by the robot. Since the RATD is attached to an EPW, transfers can be performed in community based settings.

A functional prototype of the RATD was designed and fabricated. To ascertain user attitudes toward the concept, a focus group was conducted. The prototype was presented to

[2] This work was originally published as Grindle, G.G., et al., *Design and user evaluation of a wheelchair mounted robotic assisted transfer device.* BioMed research international, 2015.

group of 16 end users and feedback on the device was obtained via a survey and group discussion.

3.2 METHODOLOGY

3.2.1 Design

The RATD's design allows for 5 powered degrees of freedom (DOF): two rotary joints, two prismatic joints, and track and carriage sub-system that allows the robot to translate around the seat frame of the wheelchair. When coupled to an EPW, the RATD has 7 overall DOF. The design of the track and carriage is adapted from previous work on the Personal Mobility and Manipulation Appliance (PerMMA)[107-109] robot and allows the RATD to be used on either side of the EPW seat, greatly increasing its workspace. It also allows the RATD to be stowed behind the seat without adding any width to the EPW when not in use. Proceeding from the carriage to the end effector, the first joint is the shoulder, which rotates internally toward the user or externally away from the user. The shoulder is connected to the proximal segment that contains a prismatic joint. This segment is along the axis of rotation of the shoulder and extends the robots workspace vertically. The proximal segment is connected to the distal segment by an elbow joint. The distal segment also contains a prismatic joint that allows the end effector to extend away from the elbow.

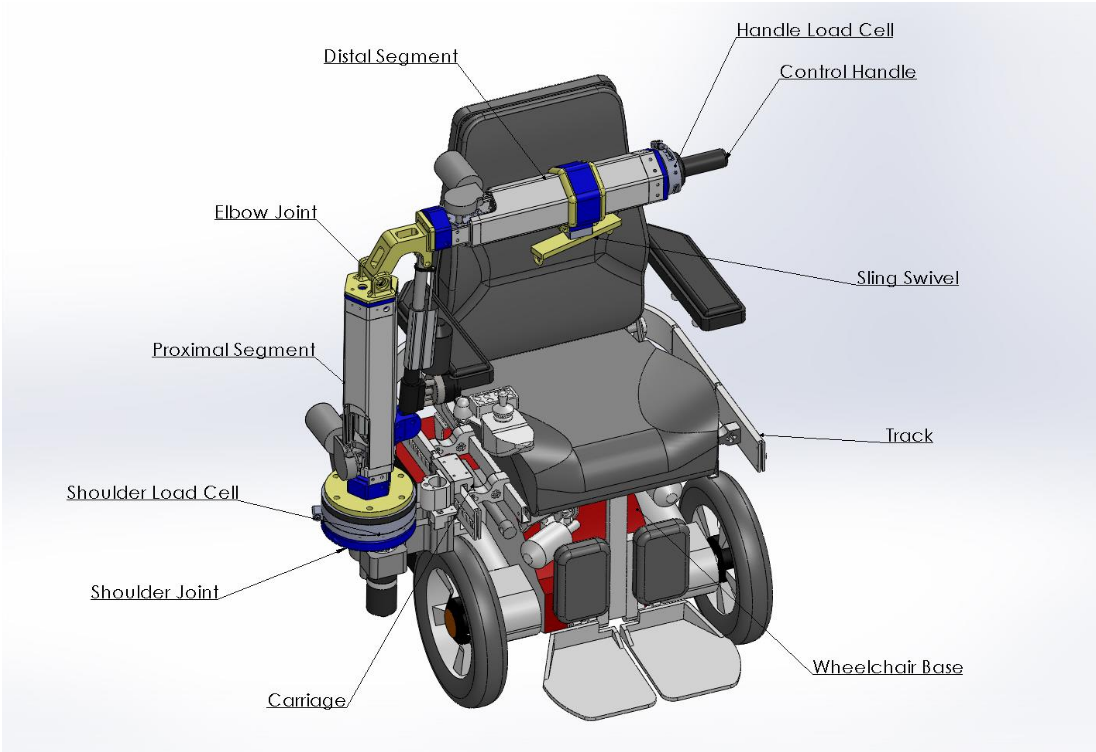

Figure 3.1 is an annotated solid model showing the key mechanical features of the RATD

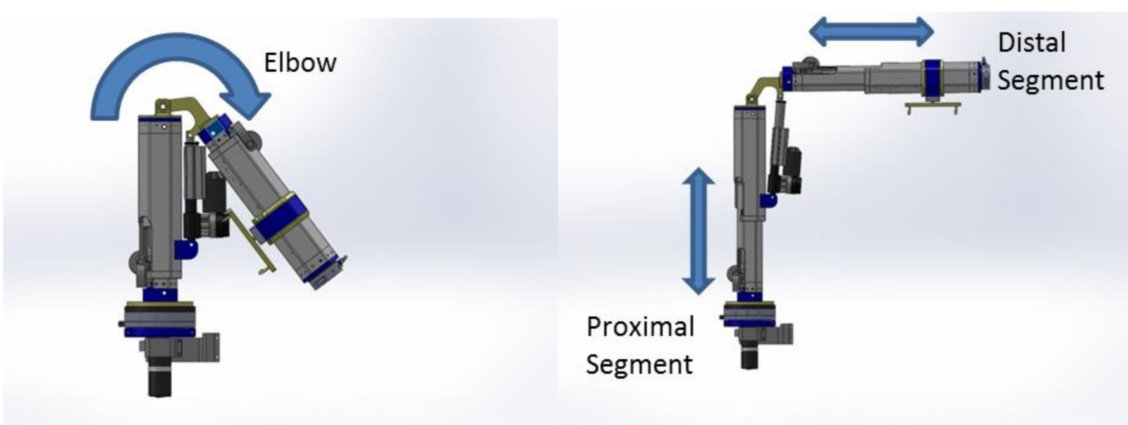

Figure 3.2 is a solid model showing the RATD's axis of motion for the shoulder, proximal segment, and distal segment joints

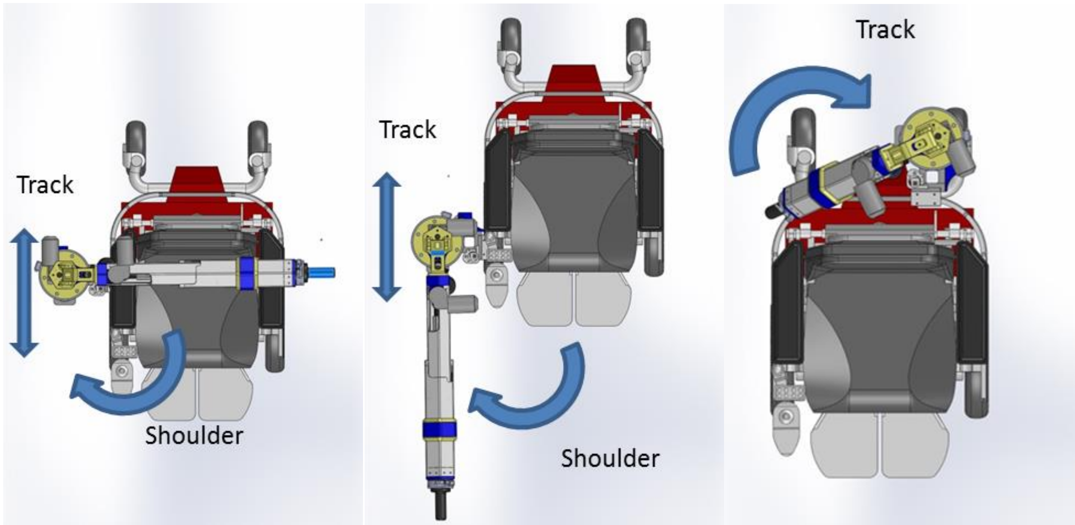

Figure 3.3 is a solid model showing the RATD's axis of motion for the shoulder and track joints

The robot is powered electromechanically by a combination of planetary gear motors and linear actuators. The carriage is moved around the track using a 24V, 0.52A planetary gear motor with a 100:1 gear ratio, which is connected to spur gear that propels it along a rack machined in the center of the face of the track. Mechanically, the shoulder joint is a 1.25 inch diameter steel shaft that is fixed to the proximal segment and connected to the carriage with a tapered bearing. It is actuated by a 24V, 2.2A planetary gear motor, with a 326:1 fixed to the carriage that has a spur gear that pushes another spur gear attached to proximal segment. Proximal and distal segments are identical in construction and are made up of two concentric hexagonal bodies that are able to slide past each other. The bodies are composed of nylon plastic shells created using Selective Laser Sintering (SLS), stainless steel threaded rods, and aluminum end plugs. The combination of elements provides the bodies with strength; the double walled nylon shells provide the compressive strength and the stainless steel threaded rods provide the tensile strength. The aluminum end caps allow threaded rods to be held and tensioned. The concentric bodies are coupled together with a 2500N linear actuator (Linak, L30) with 250mm stoke length. Pins inserted through the end plugs and through the clevis ends of the actuator hold the assembly together. An elbow joint connects the proximal and distal segment to each other. A linear actuator (Linak, L30) crosses the joint and powers the elbow to move from 35 degrees to 100 degrees from vertical. All three actuators have a spline and nut that prevents them from being back driven. Attached to the end of distal segment is a load cell and handle. Also, attached to the distal segment is a double hook on a swivel, which is used to hang the loops of a transfer sling.

The RATD is equipped with force and position sensors. The position of each joint is tracked using a microcontroller equipped, absolute encoder with digital output (Model A2, US Digital, Vancouver, WA). Two Absolute inclinometers with digital output (Model A2T, US digital, Vancouver, WA) are placed on the base of the wheelchair to determine the angle at which the wheelchair is sitting with respect to gravity. The encoders and inclinometers are able to be daisy chained to form a network called a Serial Encoder Interface (SEI) bus, which allows data from multiple devices to transmit data using only four lines. Force sensing is done in two places: at the base of the proximal segment, and at the handle. The 6 DOF load cell (Model Omega, ATI-IA, Apex, NC) at the base of the proximal segment can withstand high torque and serve as the primary measurement tool for load on the arm. The second 6 DOF load cell (Model Delta, ATI-IA, Apex, NC) is located between the end of distal segment and the handle. Its primary purpose is to serve as an input device for controlling the arm in conjunction with the handle.

The core electronic components that drive the arm consist of a single board computer (SBC) (Model Cobra, Versalogic, Tualatin, OR), an analog to digital converter board (Model

VCM-DAS-2, Versalogic, Tualatin, OR), a SEI Bus to USB converter (Model SEI-USB, US Digital, Vancouver, WA), and a custom designed relay board, as shown in figure 4. The SBC provides the programmability, memory storage, and data bus capability to the system. The relay board is used to translate low current digital logic signals from the SBC into high current switching needed to control the motors and linear actuators that power the robot's joints. In addition to receiving computer based signals, the relay board also capable of accepting inputs from a mechanical switch array to drive each joint. The analog to digital converter is used to digitize the signals from the load cells for use in the control algorithm. Similarly, the SEI to USB converter receives the signals from the encoder network and allows them to be read through a USB port on the SBC to be used in control algorithms. The electronics are powered via a DC-DC converter, which steps wheelchair batteries from 24v down to ±12v and 5v.

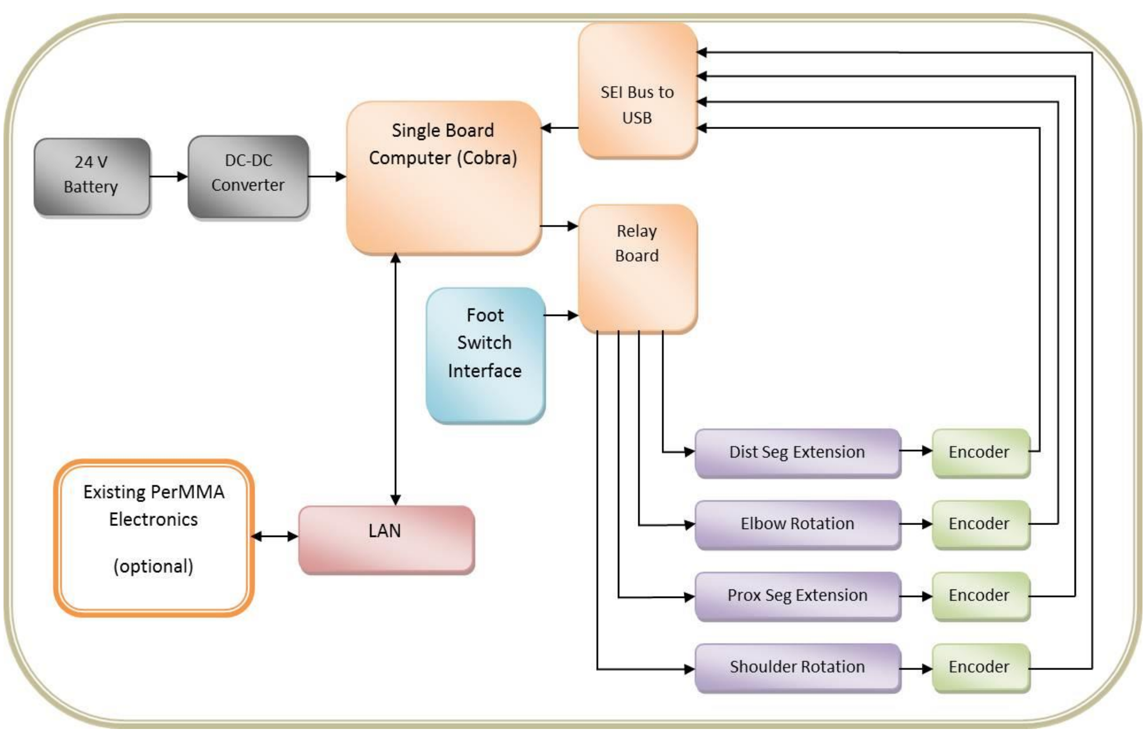

Figure 3.4 is a block diagram describing the RATD's motors, sensors, and associated electronics

The framework for conceptualizing the safety aspects of RATD is made up of 4 layers. The first of these layers consists of mechanical features, including shrouding of pinch points; rounded edges of metal and plastic surfaces; padding in strategic areas; and compliance, which allows the robot to elastically bend in under certain loading conditions. The second layer includes electronic features, including limit switches, hard force limits, hard speed limits, and user initiated emergency stops. The third layer is made up of software features, which allows for the programming of soft force limits, soft speed limits, keep-out zones, and the ability to limit the rate of loading. The fourth layer consists of the human caregiver, who has the ability to observe and make decisions regarding safety.

3.2.2 Focus Group Protocol

In order to obtain qualitative feedback regarding the concept for the RATD, a focus group was conducted. 18 participants were recruited at the 2011 National Veteran Wheelchair Games in Pittsburgh, PA. In order to participate, participants had to report that they used some type of wheeled mobility as primary means of mobility. After obtaining written informed consent, each person was asked to fill out a pre-survey that asked questions regarding their demographic information, types of assistive technology (AT) they used, and their satisfaction with that AT. Following the pre-survey, the participants were shown a live demonstration of the RATD and an explanation of the device by the design team. Participants were given the opportunity to ask the design team questions. A moderator, who was not involved with the design of the device, then led a group discussion of the device. The moderator probed the group as to what features of the device they like or disliked, what features they would the like to see added, and if they would use the device, in what context would they use the RATD. The conversation was recorded using a digital recorder. Following the group discussion, the participants were asked to fill out a post survey that asked questions related to the RATD and gave an additional opportunity to make general comments about the device. The post-survey contained a set of questions in which the participants were given a design feature related to the RATD and asked to rate on a 7-point Likert scale if the feature would make them less likely to want the device (1) or more likely to want the device (7). It also contained a second set of questions in which the participants were given a statement and asked to what extent they disagreed (1) or agreed (7) with the statement on a 7-point Likert scale.

For the purpose of analysis, the Likert scale responses were collapsed. For the question on product features, responses of 1 and 2 were categorized as 'less likely', 3, 4 and 5 as neutral, and 6 and 7 as 'more likely'. For the statement questions, responses of 1 and 2 were categorized as 'disagree', 3, 4 and 5 as 'neutral', and 6 and 7 as 'agree'. The responses were compiled using MS Excel and a descriptive analysis of the data was completed using SPSS.

3.3 RESULTS

3.3.1 Design Results

The design resulted in a prototype suitable for assisting with transfers, as shown in Figure 5. When attached to a C500 EPW the device has an overall work space height range of 20 to 40 inches. The elbow flexes from 33 to 100 degrees from vertical. The prismatic joints extend 9.84 inches from their contracted position. Mechanically, the shoulder can turn a full 360 degree, but cannot spin in a multi-turn fashion due to wires. Soft limits can be set in the software to prevent wire tangles depending on which side of the EPW the RATD is used.

Figure 3.5 shows a sequence of photographs of the RTD being used to transfer a person from an electric powered wheelchair to a mat table, by a caregiver

In the stowed position, the RATD fits within the footprint of the C500 and can fit through any doorway that a C500 without an RATD can fit through, as shown in Figure 6.

Figure 3.6 shows the RATD in its stowed position. On the left it is shown while passing through a doorway and on the right it is shown from above

3.3.2 Protocol Results

Of the 18 participants recruited, 16 finished the study and an analysis was performed using data from only the participants that finished the study. The group consisted of 11 males and 5 females, all of whom were Veterans. They were an average of 20±13 years since onset of disability. 8 participants used manual chairs and 8 participants used powered mobility. The types of disabilities represented in this study are given in Table 1.

Table 3.1 gives the disability and frequency of participants.

		Count
Disability	SCI	9
	Amputation	1
	MS	2
	TBI	1
	TBI & Amputation	1
	Back Injury	1
	Hemi-paralysis	1

When asked 'How much money out-of-pocket would you pay for the RATD?' the participants responded with an average of \$1407.69±2416.42 and a range of \$0-8,000. Three participants declined to answer this question. When asked if having a transfer device attached to a wheelchair would make them more or less likely to want it, 6% responded with less likely, 56% responded no difference, and 38% responded more likely. When asked if having a transfer device controlled by a caregiver would make them more or less likely to want it, 6% responded with less likely, 31% responded no difference, and 63% responded more likely. When asked if having a transfer device controlled by a computer program would make them more or less likely to want it, 7% responded with less likely, 43% responded no difference, and 47% responded more likely, with two participants declining to answer the question. When asked if having a transfer device controlled by the user would make them more or less likely to want it, 6% responded with less likely, 31% responded no difference, and 63% responded more likely. A summary of these responses is given in Table 2.

Table 3.2 gives the responses to the survey questions related to product features

	In percentages		
Product feature	Less Likely to want it	No difference	More likely to want it
A1.) A transfer device attached to a power wheelchair.	6	56	38
A2.) A transfer that can be controlled by a caregiver.	6	31	63
A3.) A transfer device that can be controlled by a computer program.	7	43	50
A4.) A transfer device that can be controlled by the user.	6	31	63

The results of the survey pertaining to agreement with a particular statement are summarized below in table 3.

Table 3.3 gives the responses to the survey questions related to agreement or disagreement with a statement

	In Percentages		
Statement	**Disagree**	**Neutral**	**Agree**
B1.) I would choose to use the RATD.	25	56	19
B2.) Using the RATD would make my life easier.	19	56	25
B3.) Leaning to use the RATD would be easy for me.	6	38	56
B4.) I would be anxious about using the RATD.	38	50	13
B5.) It would be embarrassing to be seen using the RATD.	73	20	7
B6.) It would be easier to just get another person to help rather than use the RATD.	38	31	31
B7.) It is important that we develop technology that can do this.	0	19	81

Three notable themes were brought up during the group discussion. The first was that the device would be especially good for travel. The RATD would minimize the amount of equipment that would need to be transported and that it would be easier to adapt to bathrooms that have less than ideal accessibility. The second is that the device should also be available with a user interface, so that the person with a disability could transfer themselves without a caregiver. It was noted in the discussion that the RATD could provide a range of transfer assistance from dynamically adjustable grab bars, through stand-pivot transfers, to fully dependent sling transfers. The participants suggested that those needing less assistance would like want to control the RATD themselves. Lastly, the participants indicated dissatisfaction with current sling technology for dependent transfers and that the RATD might open up new possibilities for improved slings or harnesses for both dependent and stand-pivot transfers.

3.4 DISCUSSION

The responses to the survey yielded some notable results. In regards to product feature A1, the majority of the participants were either neutral or supportive of the idea of having a transfer device attached to a power wheelchair, with only small minority objecting to this idea. This suggests that there is not a categorical bias against having a combination mobility and transfer device. Product features A2, A3, and A4 were aimed at determining what types of controls the participants were comfortable with, especially contrasting computer/robotic control of the device versus the more traditional user or caregiver control that is used on typical assistive devices. Given that the responses to all three types of controls were similar, this suggests that people are not categorically biased against computer programs controlling their device, and that several control methods are likely necessary to accommodate different people and the different contexts for which they might use a transfer device.

The responses to statements B3, B4, and B5 also suggest that the participants would be accepting of this robot technology. With statement B3, the majority of the participants agreed that they would be able to learn the how to use the RATD, which is contrary to the common perception of robots as complicated. Possible explanations for this might be that people are growing more comfortable with high tech devices or that the limited number of inputs and prismatic joints make the RATD more manageable to operate. With statement B4, the majority of participants suggested that they would not be anxious when using the RATD, which again may be contrary to common perceptions of robots. This may reflect that participants have already accepted other transfer devices and perceive the RATD as being able to perform comparably or better than other transfer devices. With statement B5, a strong majority of participants indicated that they would not be embarrassed to use the RATD, suggesting that the participants do not perceive any negative social bias toward the device.

The response to statement B6 suggests a possible weakness of the RATD. The group was split on whether seeking additional caregiver help would be easier than using the device. While evidence strongly indicates that transferring without properly used equipment is dangerous, this response suggests that humans are still considered an alternative to transfer technology by people with disabilities. Until transfer technology overcomes the speed and adaptability of humans, this perception will likely persist and is a key challenge for developers of transfer devices.

In order to better interpret the results, some discussion of the participants is warranted. While all the participants used wheeled mobility, some had the ability to independently transfer, some needed partial assistance, and others were completely dependent on caregivers for transfers. For survey questions such as B1, the participant's ability to transfer likely influenced their response. Future work should focus specifically on people who need some sort of assistance for transfers and in what context they would use the device. However, a strong majority agreed with statement B7, that a transfer device with RATD capabilities was important to develop. Suggests that while some the participants might not have a current need for the device, they could see that others might be able to benefit from it or that they might be able to benefit from it as their abilities change in the future. In regard to how much the user would be willing to pay out-of-pocket, most of the participants indicated would pay little or no money out of pocket for the device. This suggests that the participant expect 3rd party payers to fund the device.

It should be noted that this study has several limitations including small sample size, a relatively homogenous population, and the inherent limitations of qualitative data. Future design development should focus on improving controls for caregivers; user controls; further implementation of algorithms for tip over stability; and optimizing the device for cost, size, aesthetics, and reliability. Future experimental studies should focus on comparing the device to existing technology and the role of caregivers.

4.0 CHARACTERIZATION OF MEBOT PERFORMANCE AT THE 2016 CYBATHALON

4.1 INTRODUCTION

The purpose of this work is to describe the improvements, strategies, and performance of MEBot for and during the Cybathalon and document several general lessons learned that may be applied to other devices. The Cybathalon was a first of its kind athlete-robot competition held October 8th, 2016 in Zurich, Switzerland, in which athletes with disabilities competed while using different classes of assistive robots. An athlete piloting MEBot competed in the “powered wheelchair race” against 12 other competitors. Not just a simple race, the Cybathalon organizers billed the event as a way to: facilitate discussion between industry, academia, and people with disabilities, encourage the use and development of robotic assistive technology, and spur innovation in the field.

This work builds on previous development on MEBot at the Human Engineering Research Laboratories[110-114]. Two iterations of MEBot were designed and fabricated prior to the version used at the Cybathalon. Wang et. al.[110] described the initial iteration of MEBot mechanically, created a mathematical model of the system, and first proposed methods for using it to traverse uneven terrain and climb stairs. This version was used to further develop algorithms for curb climbing[115], and self-leveling[112, 113]. The next iteration was first described by Daveler et. al.[114] and included kinematics better optimized for self-leveling, curb climbing, variable drive wheel positioning, and a two wheeled balance mode. It also featured dimensions that made it better suited for indoor maneuverability.

Figure 4.1 shows the second iteration of MEBot

Following the release of the Cybathlon power wheelchair race course, the obstacles were constructed and the second iteration of the MEBot was evaluated for suitability. While conceptually promising, it was deemed that the kinematics of the second iteration of MEBot were not suitable for accomplishing the course, especially stair climbing, and that a third iteration would to be need to be designed and fabricated. The following describes the rational, designs, and results of the third iteration of MEBot.

4.2 METHODOLOGY

4.2.1 General Description

MEBot is a 10 DoF mobile robot capable of transporting a person with a disability. MEBot has 6 wheels: two drive wheels in the center and a set a of supporting caster wheels in both the front and rear of the robot. The rotation of the drive wheels is provided by electric motors and each drive wheel can be rotated up and down independently by a linear pneumatic actuator pushing a pivot arm. Additionally, the drive wheels can be moved independently fore-aft by electric motors, allowing MEBot to have characteristics of a front wheel, mid-wheel, or rear wheel drive wheelchair depending on the selected configuration. The front and rear casters are rotated up and down independently by linear pneumatic actuators attached to a linkage. The front wheels are "roller blade" style wheels, are attached to manually controlled ratchet mechanism, and do not swivel. The wheels on the rear casters are omni-wheels, which allow for turning while occupying less vertical space than traditional swivel style casters. The electric motors are powered by two 35AH, 12v gel cell batteries wired in series and the pneumatic actuators are powered by a 18 ft^3 (at standard pressure), carbon fiber, high pressure air (HPA) compressed air tank, filled to 4500 psi for storage, and down regulated to 110 PSI for use in the actuators. The seat has a locking manual tilt mechanism to allow the athlete to change their seat pitch. For consistency, all references for relative terms, such as up, down, fore, or, aft, are in relation to frame of the robot, not the ground.

4.2.2 Strategy

The table task represents indoor mobility, and centers around maneuverability and having a practical seat to floor height. The challenge is preserving this while also being able to effectively negotiate outdoor obstacles that are better suited for robots with a higher ground clearance. To address this challenge, Mebot's variable kinematics were employed. The first the drive wheels were raised their highest possible configuration and moved to most aft position. Once close to the table the pilot would raise the front caster arms setting the frame on the floor. The front bottom of the frame is designed to slide and the pilot could maneuver under the table.

Figure 4.2 shows the kinematics of Mebot with a pilot's legs under a table

The slalom task tests indoor maneuverability and the robot's ability to be controlled accurately and quickly. Generally, short wheelbase robots should be at an advantage for this task. The challenge; however, is balancing this with performance on the outdoor obstacles in the course, where a short wheelbase could be a disadvantage. The athlete negotiated this situation by configuring MEBot like a front wheel drive wheelchair and keeping the ground clearance low. With the front caster linkage raised, the wheel base is reduced to 30 in, making it easier turn about the pylons.

Figure 4.3 show MEBot being navigated by a pilot through the slalom

The ramp and door represents the transition from indoor to outdoor tasks and is a test of the athlete's functional workspace, while piloting the robot. This task combines three distinct challenges: ascending a steep ramp, providing the athlete enough functional workspace to open and close the door, and safely descending a steep ramp. The athlete and robot meet this challenge by using the variable kinematics to keep the athlete at an optimal attitude throughout this task. When ascending the ramp, the rear casters are lowered and the drive wheels raised to keep the athlete level. When approaching the door, the rear casters are lowered slightly to pitch the athlete forward making it easier to reach the door handle. After passing through the door the rear casters are raised and the drive wheels are lowered to pitch the athlete backward to make it easier to close the door. This configuration also prepares MEBot to descend the ramp.

Figure 4.4 shows the configuration of MEBot for ascending the steep ramp (left) and descending the steep ramp (right)

The “stones” simulate outdoor environment such as wooded areas, trails, or cobblestone surfaces. The challenge is to maintain traction and keep a straight drive path over the individual obstacle patterns. The strategy employed to negotiate this obstacle was to configure Mebot in a front wheel drive mode and raise the ground clearance by lowering the drive wheels and the rear casters slightly, effectively placing the fame on air springs. The athlete then drives at a high speed over the obstacles and allowing the air in the pneumatic cylinders to compress and expand with the intent of damping effects of the individual bumps.

The tilted ramp represents a more extreme outdoor environment. The primary challenge is to maintain traction, power, and ground clearance to negotiate the series of opposing ramps, while allowing the athlete to be able to maintain precise control of the robot's direction. The strategy for this obstacle is to leverage MEBot's ability to have laterally asymmetric kinematics to keep the athlete level and the drive wheels in contact with the ground. For the ascending and descending slopes, a similar technique was employed as in the ramp and door obstacle. For the cross slope, the drive wheel and rear caster where lowered down on downhill side of MEBOT while the drive wheel and the rear caster on the uphill side was lifted up, as shown in figure 4.5.

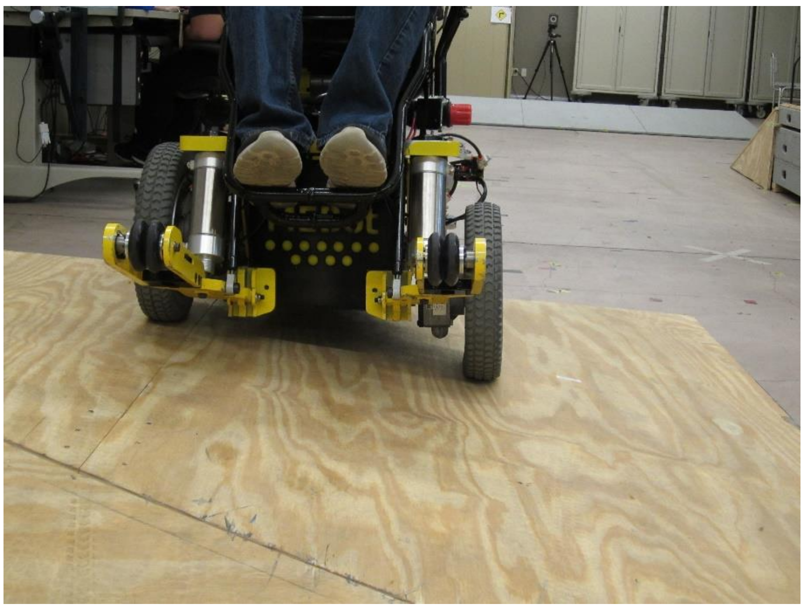

Figure 4.5 shows MEBot traversing the cross slope portion of the "tilted ramp". The drive wheel on the downhill side is lowered while the drive wheel of the uphill side is raise.

The stairs represent a common and most often, insurmountable barrier for most wheeled mobility devices. Ascending and descending stairs presents numerous challenges, including: the robot possessing sufficient power to lift itself, the ability to interface with the geometry of the steps, keeping the athlete in an orientation to allow them to reliably maintain posture, and maintaining directional control through the entire trajectory. The general strategy for MEBot to accomplish this task is to have it move like a walking robot to climb the steps. To execute this strategy, additional mechanical modifications were made to MEBot. First, the front caster linkage had to be lengthened and an anti-rollback, ratcheting caster wheel was added. A manually controlled tilt mechanism was added to the seat to allow the athlete to move their center of mass closer to the rear of the chair and to position the athlete in a more level position while on the stairs. The stair climbing is performed by approaching the stairs backward with the front and rear casters raised and the drive wheels back and lowered. This pose positions the frame of the chair at an angle matching that of the stairs. The drive wheels are then moved horizontally, moving the frame up the steps. Next the rear casters are lowered onto the second step until the drive wheels are lifted. While suspended in the air, the drive wheels are moved aft and are lowered onto the first step. Then the rear casters are lifted, the drive wheels are lowered further, and drive wheels are moved horizontally, pushing the frame further up the steps. The process is repeated to move the drive wheels to the second and third steps.

Figure 4.6 shows MEBot climbing a set of stairs

4.2.3 Performance Analysis

Visual inspection of the official Cybathlon competition video was used to determine split times. It was also used to determine completion or failure of each task. The video was as used to determine mode of failure for incomplete tasks. Qualitative feedback was obtained from the pilot and from field notes taken by team member before and during the competition. The official competition video and additional media available online was used to determine the general type of mechanism each of the robots in the competition employed to move through the course.

4.3 RESULTS

MEBot and its pilot competed in the both the preliminary and final rounds of competition at the 2016 Cybathlon. On both runs, all tasks except the stairs were completed. The split times for each of the six tasks for the both rounds are given in table 4.1.

Table 4.1 shows MEBot's split times for the six individual tasks for both the preliminary and final rounds

Obstacle	Round	Time Remaining (min:s)	Obstacle Time (s)
Table	Preliminary	7:29	31
	Final	7:20	40
Slalom	Preliminary	7:12	17
	Final	7:06	14
Ramp and Door	Preliminary	6:02	70
	Final	5:53	73
Stones	Preliminary	5:48	14
	Final	5:40	13
Tilted Ramp	Preliminary	5:21	27
	Final	4:59	41
Steps	Preliminary	0:00	NC
	Final	0:00	NC

MEBot and the athlete could complete all the tasks in the allotted time with the exception of stair climbing for both rounds. Mode of failure for the stair climbing task was mispositioning of the robot for both rounds. In the preliminary round, the drive wheels were not positioned high enough to clear the corner of the second step, pushing the robot forward and preventing the drive wheels from landing in the idea position on the second step. In the final round, the front caster needed to be lowered to further to have been able to move them to the first step, while the drive wheels pushed off the third step

Qualitative feedback from the pilot indicated that the interface was likely too complicated for most users and that the switch array lacked proper labeling. The pilot also commented that improvements could be made to combine DoF for functional tasks. The pilot expressed that the robot provides little to no feedback on the position each DoF and visual confirmation is not possible in many situations. Lastly, the pilot indicated that sequence for climbing stairs was too long and needed to be performed too precisely to be practical.

Twelve teams participated with 2016 Cybathlon with one team experiencing robot failure prior to completing any obstacles in the preliminary round. Of the 12 teams, 4 teams used wheels, 4 teams used wheels with deployable treads, 3 teams used wheels with walking actuation, and 1 team used treads as their means of moving the robot along the course. Six teams completed the course, with the details of rank, points, time remaining, and robot style for each team given in table 4.2.

Table 4.2 gives the final team ranking, points earned, time remaining and robot style for wheelchair competition at the 2016 Cybathlon

Rank	Team name	Points	Time Remaining (s)	Robot style
1	HSR Enhanced	660	214	Wheels/walking
2	HKUS Twheels	660	219	Treads
3	Avalanche	660	267	Wheels/treads
4	RT-Movers	660	312	Wheels/walk
5	B-Free in City	660	358	Wheels/treads
6	CaterWil	660	399	Wheels/treads
7	HERL	530	181	Wheels/walking
8	Team Imperial	530	266	Wheels
9	Enable	426	94	Wheels
10	laddroller	426	246	Wheels
11	Team Imperial	307	102	Wheels
12	Scewo	0	0	Wheels/treads

4.4 DISCUSSION

With the exception of the stairs, design modifications and strategies used to negotiate the course were successful in competition. The ability to change the kinematics of the MEBot were a key factor in this success. In the table task, the ability to set the frame on the ground allows for completion without repositioning the athlete. In the ramp and door and tilted table tasks, changing the kinematics to keeps the athlete in a comfortable position to operate the robot and to preform functional tasks, while maintaining weight on the drive wheels, improving traction. These advantages are not possible for each of these opposing scenarios with a robot with fixed kinematics.

One task that MEBot did especially well was the "stones" obstacle, completing this task in less time than all the others. The raised ground clearance, air suspension, and momentum are critical variables that contributed to this task. The raised ground clearance allows the frame to be higher than the obstacles and the air compressing and expanding in the pneumatics actuators allows the wheels to passively contour over the individual bumps, while the momentum of the frame carries it forward through the obstacle.

MEBot was unable to complete the stair climb task it the allotted amount of time during both rounds of the competition. While physically possible, a lack of automation in this area made successful completion in a competition setting unlikely. The athlete is tasked with executing a long series of steps with little to no visual feedback and small errors can lead to sequence failure. At the competition, the team attempted to overcome these barriers with a script sheet and verbal feedback from the course-side team mate; however, this approach is error prone and slow. Future work to improve MEBot at this task should center around ways to integrate sensors such as LiDAR, computer vision, path planning, and enhanced user feedback into the process.

During the competition and in training prior to, it was evident to the team that communicating the proper movement of the robot by a coach or trainer was difficult. Questions such as “What do you mean by up?” were regularly asked at these times and greatly slowed progress. If advanced mobility robots, such as the one competing at that Cybathlon, are to be become commercially available for everyday use, clear nomenclature protocols will need to be established to train users in a practical way to be successful. The protocols will need to concise, unambiguous, and jargon free.

While MEBot was not successful at negotiating the stairs in competition, the concept of having the speed and efficiency of wheeled mobility in most situations and walking robot capability when needed, still has potential to be a generalized mobility solution for people with disabilities in the community. The winning team employed a wheeled/walking strategy. Many competitors used “tank tread” technology, to negotiate the stairs and several were successful on the Cybathlon course. However, even when treads are used in conjunction with wheels, treads are not practical to use for indoor mobility, due to size and damage they do to many surfaces, and likely would be a poor solution for generalized mobility needs. Further work in needed to improve the speed and ease of use of walking modes.

In response to the pilot’s feedback on the human interface, a new interface was designed and fabricated. The new interface replaces spring centering toggle switches with slider bars. The extents of the slider bar’s range are set proportionally to the range of the DoF it controls and gives the pilot a sense of the DoF’s position. Additionally, selectable modes allow one slide to control multiple DoF simultaneously to perform a functional move, such as lowering all six wheels to elevate the seat, or a feature that moves the joint pairs symmetrically if either of the left or right slider moved. Labeled and color-coded buttons are added to improve usability. This improved interface was subsequently used successfully to carry out a user trial with MEBot.

In the case of the pilot feedback regarding MEBot's interface, the Cybathlon model proved useful. The interaction of the design team and the pilot while trying to accomplish difficult challenges led to innovation that likely would not have occurred or occurred as quickly. The Cybathlon model also likely led to attempting more challenging obstacles with people with disabilities piloting MEBot earlier in development than would have occurred in more controlled research protocol. While mostly qualitative, addressing these challenges earlier in the development process yielded valuable results information that was used to improve MEBot and better prepared it for more controlled research protocols on less challenging tasks.

It should be noted that in the area of advanced seated mobility robots for negotiating challenging terrain and obstacles, few works report evaluation of their device with more than a few participants with disabilities. Most studies or demonstration are carried out in laboratories or in highly contrived scenarios. Even fewer report the use of more rigorous methodology in less contrived scenarios to determine their usefulness.[36-46, 96-98, 110-113, 116-132] There are likely several reasons for this including: cost, study logistics, reliability, safety, and that the number of any given device is limited. However, if advanced seated mobility robots are ever to be become widely available to people with disabilities, more rigorous studies will need to be conducted to demonstrate generalized feasibility, safety, and efficacy. Competitions, such as the Cybathlon, that encourage robot developers to integrate people with disabilities into their teams, present realistic challenges, and promote exchange of information may help further this area of robotics from its current state of contrived demonstrations to more rigorous evaluation in realistic environments.

5.0 RISK ANALYSIS

5.1 INTRODUCTION

5.1.1 Problem Statement

There is a paucity in the literature of rigorous user trials related to assistive robots. Numerous designs have been described, but few report evaluation beyond a few participants in highly controlled and contrived scenarios, and few have become commercially available. Seventy manuscripts[60, 82, 85, 88, 90, 117, 133-197] in this area were reviewed and documented for: the number of participants with disabilities, the number of able body participants, were controls used, and if the studies were carried out in a computer simulation, laboratory, or community setting. This review focused on project that involved wheelchair mounted robotic arms. The search was performed using the search terms "wheelchair and robot", and "wheelchair mounted robotic arm" and "Assistive Robotic Arm". Additional manuscripts were found based on the authors knowledge of the groups working in the field and from cited literature in work found using the search terms. Only manuscripts available in English were included. The details of the review are given in Appendix C. While this review is not exhaustive or systematic, it does suggest that the state of the field is driven by engineering development, not end user needs or participation. In support of this claim: only 3 of these studies had more than 12 participants with disabilities, only 2 studies were carried out in a community setting, and only 3 utilized any sort of control. Over half the manuscripts did not report the use of human participants and numerous others reported only able body test pilots. Application engineering driven manuscripts are valuable, necessary, and likely to be plentiful in times of rapid basic technological advancements. However, technical feasibility and use with participants of these types of devices was documented at least as early as 1974[183] and the rigor with which these devices are tested for usefulness has progressed little from the first studies[147, 185] in assistive robots. Factors such as cost, study logistics, and limited resources for short production runs likely explain some of this paucity; however, the ability to create robots safe and robust enough to perform rigorous user trials is likely a critical factor and a critical step in allowing more participation by people with disabilities in experiments with assistive robots.

5.1.2 Aim

The goal of this work is to introduce a framework to help assistive robot developers move from technology demonstration studies to more rigorous studies that include larger number of people with disabilities, in less contrived settings. Two common methods for early stage systematic risk analysis will be presented in the context assistive robots. The Personal Mobility and Manipulation Appliance (PerMMA), Robot Assisted Transfer Device (RATD), and Mobility Enhancement Robot (MEBot) will be used as examples of how these methods can be applied and how they can prepare robots for use by people with disabilities. Lastly, generalized lessons learned from designing, bench testing, demonstrating, and participant testing with PerMMA, RATD, and MEBot will be presented.

5.1.3 Relevant Background

Two common tools used to assess risk in complex systems are Fault Tree Analysis (FTA) and Failure Modes and Effects Analysis (FMEA). FTA is a deductive tool for analyzing potential failure modes where high level events are identified and traced backward to find the root cause or combination of causes[198], and has been employed in nuclear[199] and Aerospace[200] fields for evaluating safety critical designs and processes for decades. FMEA is an inductive tool for analyzing risk where adverse events to individual components or subsystems are assumed and the system is analyzed to understand how the events propagate in relation to the devices intended function[201-203].

While risk analysis is often performed on medical devices by manufacturers and is in some cases required, in the United States, by the Food and Drug Administration for marketing approval, they are rarely reported in academic literature for medical devices.

5.2 METHODOLOGY

5.2.1 Risk analysis

5.2.1.1 Fault Tree Analysis

A review of the function of the existing design and prototype and was performed by a single analyst as described by Ericson [198]. Assumptions and boundaries of what constitutes the robotic system was defined for each robot with a block diagram. Next, the critical top-down adverse events were identified. In order to systematically identify adverse events, the analyst used a chronologic story board of the robot's actions while completing a specific task scenario that robot is designed to perform. The number of task scenarios varied with the robot depending on how many tasks it is designed to perform.

Once the adverse events had been identified, the analyst worked deductively to identify the potential intermediate and/or basic cause or causes. and create a tree for each adverse event using widely accepted symbols and methods[199, 200, 204].

5.2.1.2 Failure Mode Effects Analysis

The FMEA began with a meeting of key development team members and subject matter experts[201-203]. The team included people from various engineering background, people with disabilities, ATPs, and an occupational therapist. The team members first reviewed the existing design and prototypes. Assumptions and boundaries of what is included in robotic systems was defined with a block diagram. Second, team members identified failure modes through interactive dialog and a systematic, bottom up review of the robot's sub-systems, using its block diagram. Once all failures modes were recorded, the team assigned each failure mode a ranking in three categories: severity, frequency, and detection. For severity, rankings were assigned based on the criteria given in table 5.1.

Table 5.1 - presents the criteria for rating the severity of each failure

Rating	Evaluation Criteria
1	No health hazard – no physical effects
2	Limited health hazard – temporary minor physical effects or complaints
3	Moderate health hazard – permanent minor physical effects or temporary significant physical effects
4	Severe health hazard – Permanent significant physical effects
5	Catastrophic – Life threatening

The group then assigned a frequency rating for each failure based on the criteria given in table 5.2.

Table 5.2 - presents the criteria for rating frequency of occurrence for a give failure

Rating	Evaluation Criteria
1	Remote – failure unlikely
2	Low - relatively few
3	Moderate – occasionally
4	High – repeated failures
5	Extreme – almost inevitable

Lastly, the group assigned a detection rating for each failure base on the criteria given in table 5.3.

Table 5.3 presents the criteria for rating the ability to detect each failure

Rating	Evaluation Criteria
1	Bench testing
2	Simulated use testing
3	In-lab controlled participant testing
4	Supervised community based user testing
5	Unsupervised community based usage

5.2.2 Interpretation

The analysis focused on using both the FTA and FMEA to identify the adverse events most likely to occur and most like to do the most harm to humans. Logic diagrams or tables were created for both the FTA and FMEA and for each event, per established convention. Those that rank high in both severity and frequency were prioritized for risk mitigation. Following identification and analysis, mitigation strategies were developed for prioritized events.

The final analysis compared these three robots and identified several themes or lessons that may be generalizable to assistive robot development. This subjective analysis was based on extensive experience with designing, fabricating, operating, bench testing, publicly demonstrating, and participant testing with PerMMA, RATD, and MEBot. The FMEA was compiled for presentation using Excel (Microsoft, Redmond, WA) and the trees for presentation of the FTA were created using SmartDraw (SmartDraw, San Diego, CA).

5.3 RESULTS

5.3.1 RATD

5.3.1.1 FTA

The most critical high-level adverse events identified for the RATD are: a joint or joints failing to move, the robot moves the payload to an area of the workspace where it will tip the wheelchair over, and the robot moves into the user's space and crushes the person between the robot and the backrest. If a joint fails to move it was determined it could have been caused by 7 different basic component failures as shown in figure 5.1. There are primary potential causes of harm to the user for this failure, which includes the person being transferred going into tone and falling out the sling, or the person sliding out of the sling and being strangled as they fall.

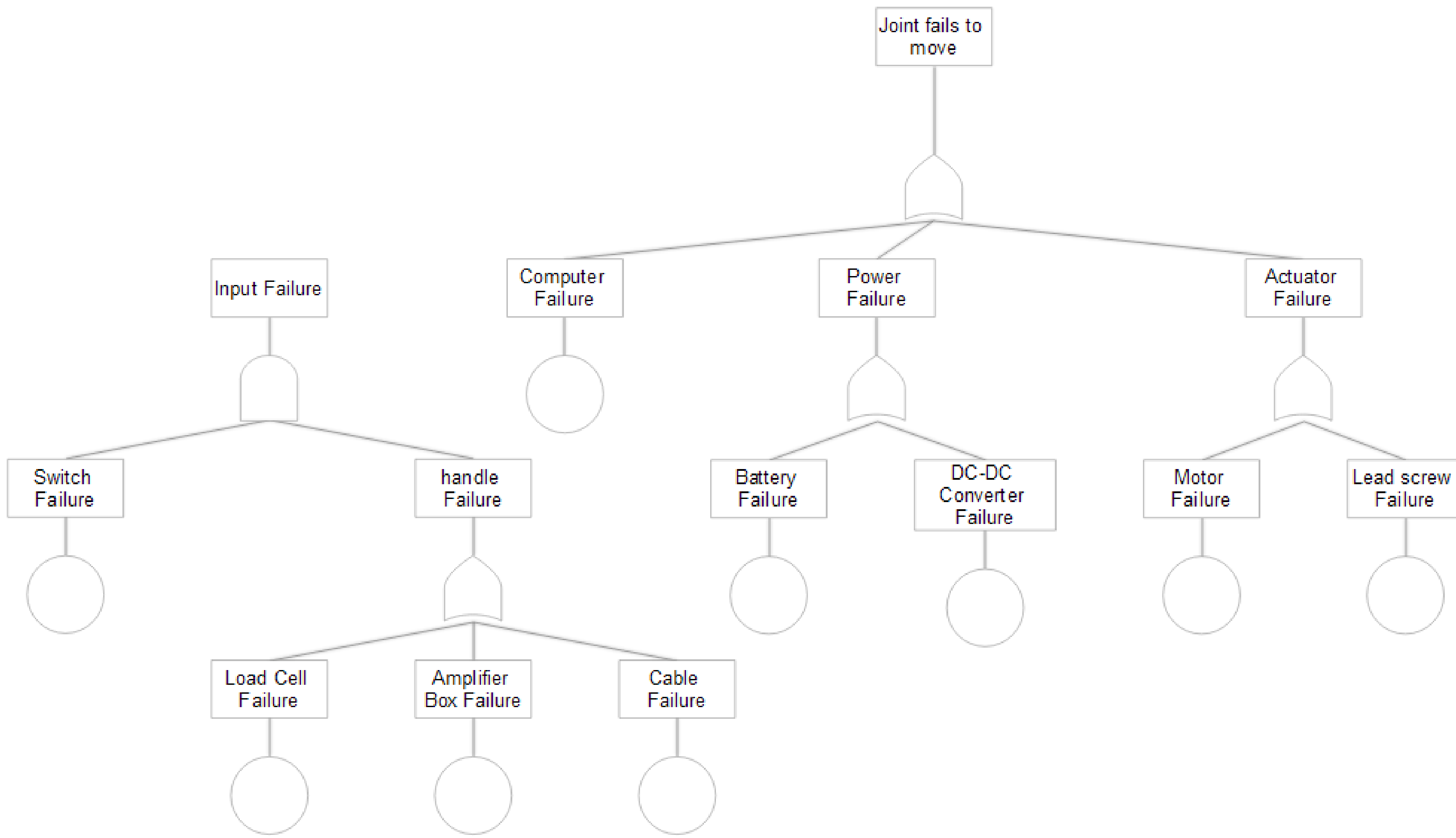

Figure 5.1 is the fault tree representing the cascading event for a joint failing to move on the RATD

Another identified critical event for the RADT is if the robot with a payload travels to an area of the workspace that would cause the wheelchair to tip over. For this to happen, the person would need to be in the process of being transferred, the safety zone algorithm would have to fail, and the payload, the person being transferred, would need to be moved into an area of the workspace that would cause wheelchair tip-over. The danger to the person would be falling and hitting the floor or other objects, such a bed or bathtub, with additional injury caused from the wheelchair and RATD falling on top of them.

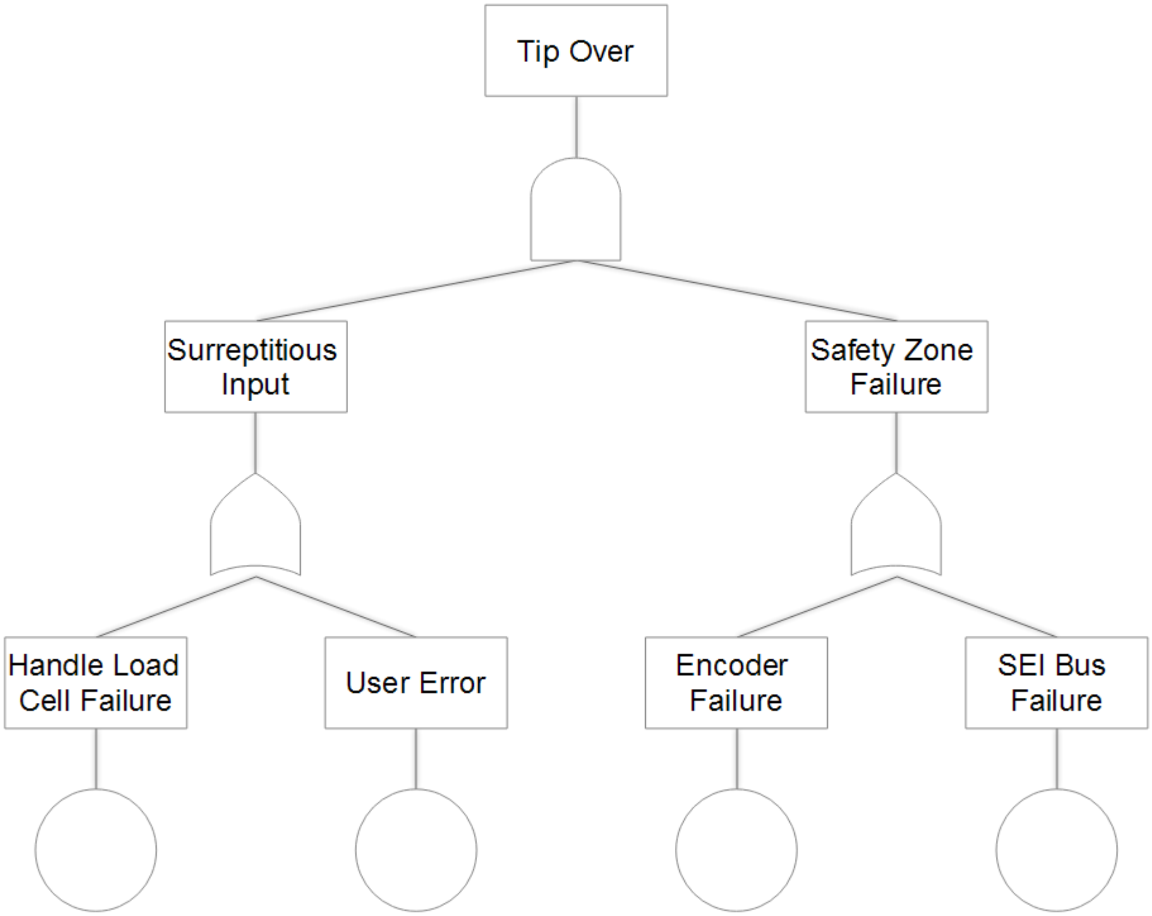

Figure 5.2 is the fault tree representing the cascading event for a tip-over to of the RATD and wheelchair

The third identified critical event for the RATD is the arm moving into the person in the wheelchairs workspace and crushing them between the robot and backrest. For this to happen, the person would need to be seated in the wheelchair, the safety zone algorithm would need to fail, and the robot would be moving unabated into the person. The harm to the person would be caused by the forces exerted by the arm to the face, neck, or torso.

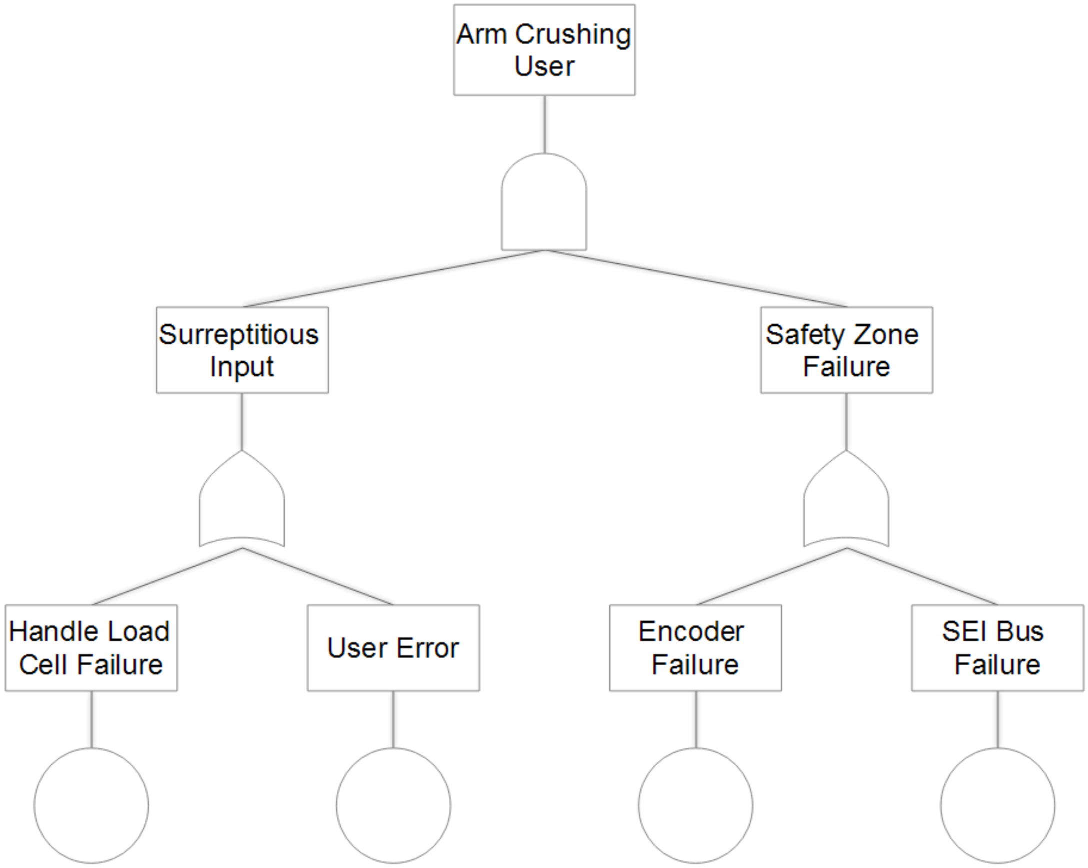

Figure 5.3 is the fault tree representing the cascading event for the RATD crushing a person between the robot the wheelchair backrest

5.3.1.2 FMEA

The FMEA for the RATD identified 21 different failure modes with 9 of them ranked a 4 or 5 on the severity scale, as given in table 5.4. Most of the failure modes that ranked high on the severity scale have an effect of stranding the person being transferred. The highest danger in this state is if the person goes into tone and falls out of the sling. If the person gets their head tangled in the sling while falling, there is the potential for strangulation. The other common effect of failure of consequence is failure of the safety zone algorithm. If this algorithm fails, there is a potential for the RATD to crush the user between the backrest and robot, or tip the whole system over.

Table 5.4 gives the results of the FMEA for the RATD

FMEA for Robotic Arm Transfer Assist Device					
Component	**Failure Mode**	**Effect of Failure**	**Severity**	**Occurrence**	**Detection**
Battery	Low charge	Robot stop/stranding	4	1	2
	Internal short	Fire	5	1	4
	Low capacity	Robot stop/stranding	4	2	1
	Incorrect size	Low current/stranding	4	1	2
DC-DC converter	Defect (V=0)	Robot stop/stranding	4	2	4
Handle	Mechanical break	Robot stop/stranding	4	3	2
		Surreptitious movement	5	2	2
	Deflection in sensor	Robot stop/stranding	4	3	2
		Surreptitious movement	5	2	2
	Button failure	Can't change mode	1	1	2
Computer	Brown out	No safety zones	3	5	1
Switches	Mechanical failure	No backup control	1	1	2
Relay board	Burned relay	Partial stop	2	2	3
Actuator	Motor failure	Loss of DoF	3	1	2
	Wire break	Loss of DoF	3	1	2
	Bent lead screw	Loss of DoF	3	1	2
Encoder	Zero output	No safety zones	3	2	5
	Incorrect output	Safety zone error	3	1	5
SEI bus	Zero output	Software stop	3	2	4
	Incorrect output	Safety zone error	3	1	5

5.3.2 PerMMA

5.3.2.1 FTA

The FTA of PerMMA identified two high-level adverse events for PerMMA: spilling hot liquids placed in a vessel with no lid and dropping a sharp object. The adverse events for PerMMA are limited due to the restricted payload of the Manus Arm, which is less the 5 pounds. This eliminates user crush hazards and the danger associated with dropping heavy things. For liquid the primary harm to the user is burns. Ten root causes were identified through the FTA and the pathways are shown in the figure 5.4.

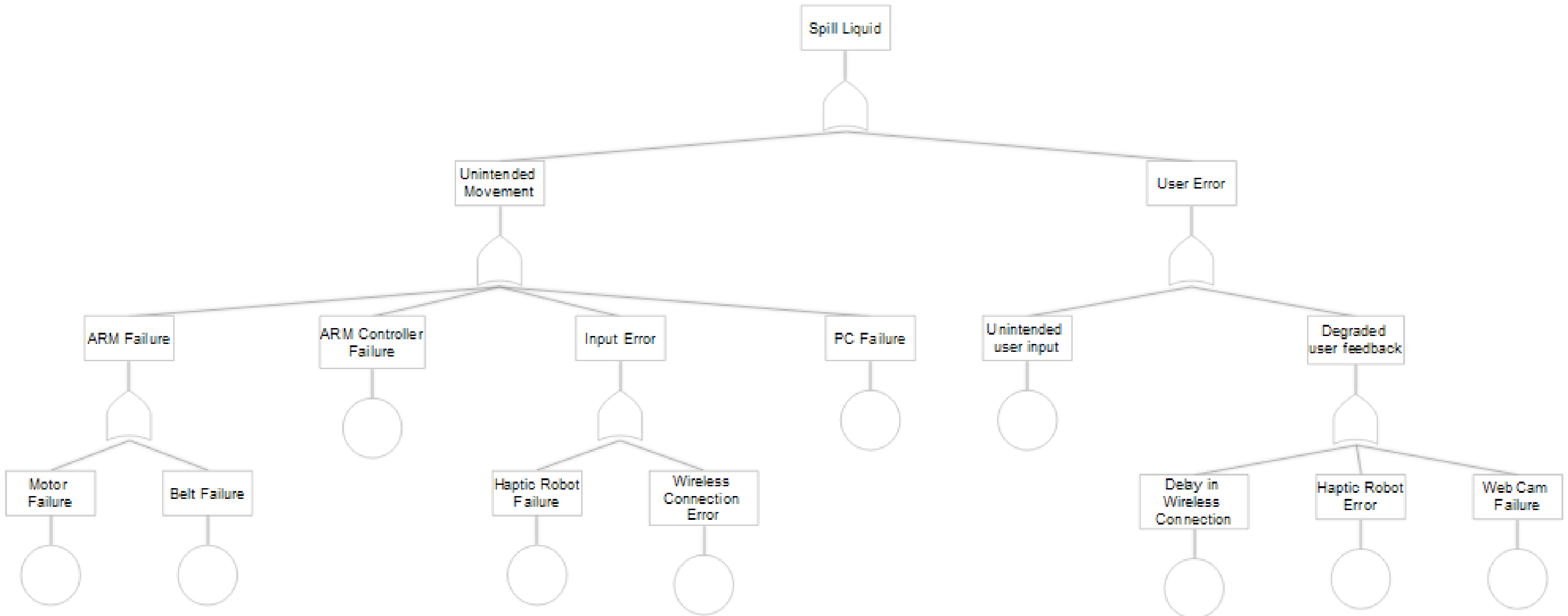

Figure 5.4 is the fault tree representing the cascading events for a spill condition to occur with PerMMA

The second adverse event is dropping a sharp object. For this to occur, the robot would have to be moving a sharp object, experience the failures in the tree shown in figure 5.5, and land on the user to cause harm.

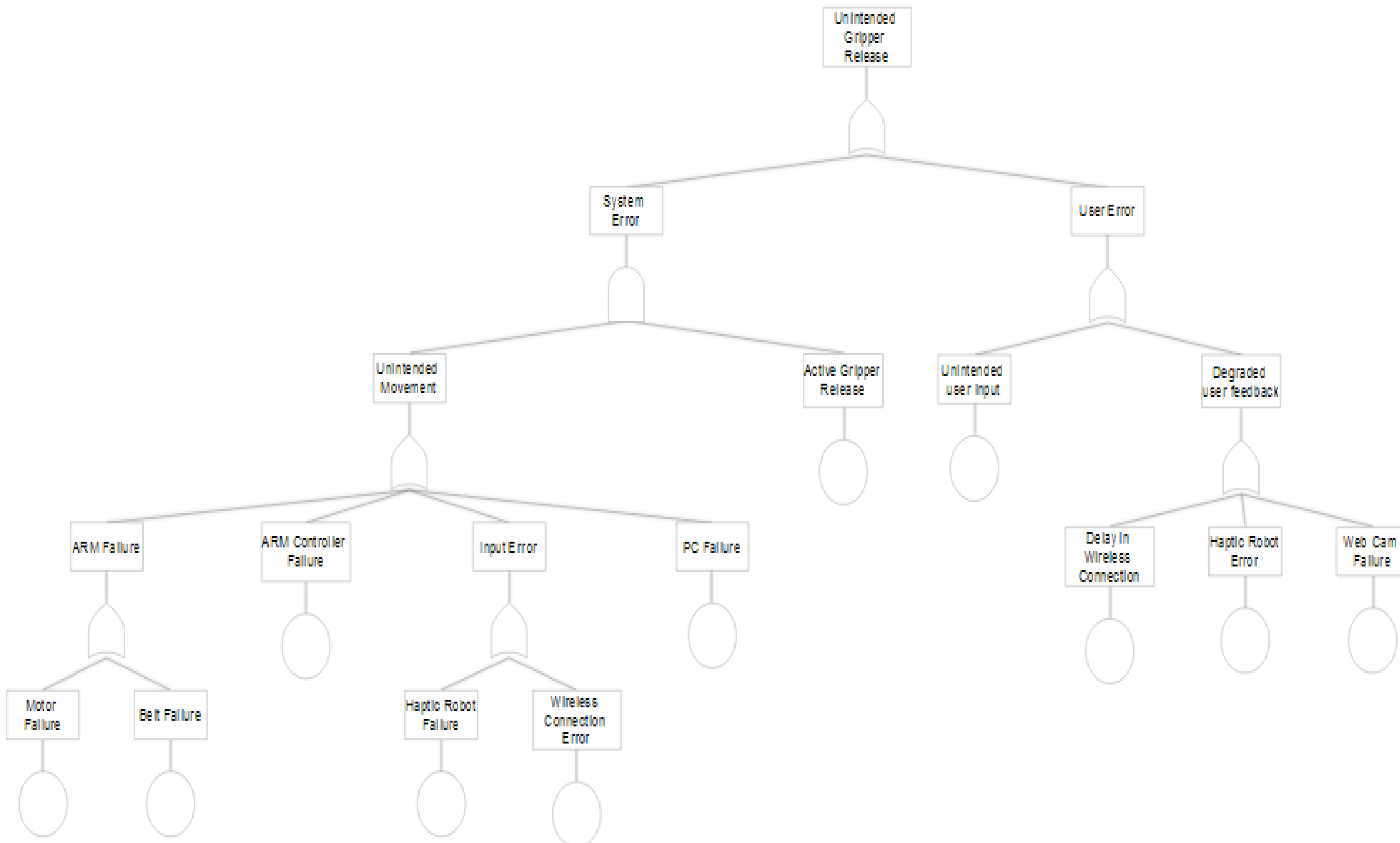

Figure 5.5 is the fault tree representing the cascading event for a tip-over to of the RATD and wheelchair

5.3.2.2 FMEA

The FMEA of PerMMA identified 29 unique failure modes, with 2 modes having an effect identified as high on the severity scale. These modes are: incorrect output of the embedded controller, which could cause the wheelchair base to move surreptitiously and the loss of seat functions due to mechanical failure. Due to design and safety check in the hardware and software, both modes are very unlikely to occur. Ten of the failure modes could lead to a spill or drop of the payload. While not likely to cause grave harm, the likelihood of this type of failure is high.

Table 5.5 gives the results of the FMEA for PerMMA

FMEA for PerMMA					
Component	**Failure Mode**	**Effect of Failure**	**Severity**	**Occurrence**	**Detection**
ARMS	Belt slip	Decrease RoM	1	5	3
	Motor Failure	ARM shut down/spill	2	1	1
	Belt Failure	ARM shut down/spill	2	2	1
ARMS Controller	Reset	ARM shut down/spill	2	1	1
	Brown out	ARM shut down/spill	2	1	1
Cameras	Mechanical damage	Loss of video/no remote mode	1	2	3
	Software failure	Loss of video/no remote mode	1	2	1
Carriage motors	Mechanical failure	Loss of track	3	2	1
Drive motors	Mechanical failure	Stranding of chair	3	1	2
Joystick	Mechanical failure	Stranding of chair	3	1	4
	Surreptitiously unplugged	Stranding of chair	3	2	4
Seat functions	Mechanical failure	Loss of RoM	1	1	2
		Inability to perform pressure relief	4	1	2
Wireless networks	Loss of signal	No Remote mode/spill	2	3	1
	Hardware failure	No Remote mode/spill	2	2	2
Haptic robots	Software failure	No Remote mode/spill	2	2	1
	mechanical failure	No Remote mode/spill	2	1	3
PC server	Brown out	Loss of use of ARMs/spill	2	2	2
	Reset	Temp. loss of use of ARMs/spill	2	2	2
LAN switch	Connection error	Loss of base/ARM integration	1	1	3
	No connection	Loss of base/ARM integration	1	1	3
Embedded controller	Brown out	Loss of mobile base/stranding	3	2	3
	Incorrect output	Surreptitious mobile base movement	5	1	3
Battery	Low charge	Loss of system function/Stranding	3	1	2
	Internal short	Fire	5	1	4
	Low capacity	Loss of system function/stranding	3	1	4
	Incorrect size	System will not boot properly	1	1	2
DC-DC converter	Defect (V=0)	Loss of system function/stranding	3	2	4

5.3.3 MEBot

5.3.3.1 FTA

Two critical high-level adverse events were identified for MEBot: Tipping over and getting stranded while traversing an obstacle. In the case of a tip over, the primary harm to the user could occur if the user fell out of MEBot or MEBot landed on top of them after the tip-over causing the person to be crushed between robot and ground. The FTA revealed 7 basic events that could cause a tip-over with 3 intermediate causes: rapid deflation of some actuators, surreptitious movement of the drive caused by the controller, and user error. The tree for these pathways is given in figure 5.6.

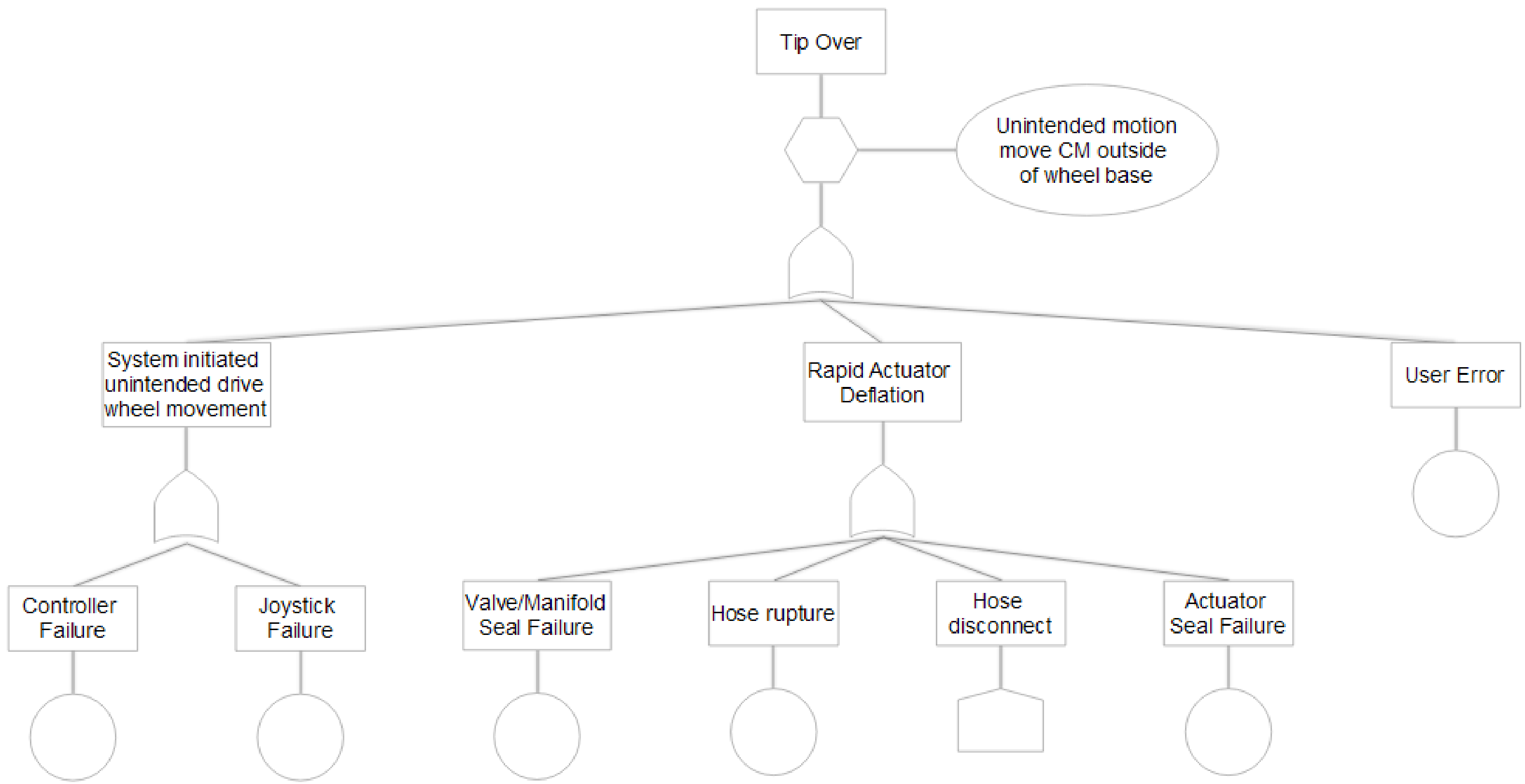

Figure 5.6 is the fault tree representing the cascading events for a tip-over of MEBot

The users being stranded in MEBot on an obstacle, such as stairs, is the other critical adverse event identified. The primary harm to the user in the scenario is that the user is stuck in MEBot until caregivers arrive and either move MEBot to a level surface through brute force or the caregivers transfer the user to new another mobility device. Help could take an extended period of time to arrive, allowing for secondary problems to arise that could be serious. These secondary problems could range from exposure to weather to interruption of bowl and bladder management. The FTA identified 15 different basic events that could cause the user to be stranded on an obstacle.

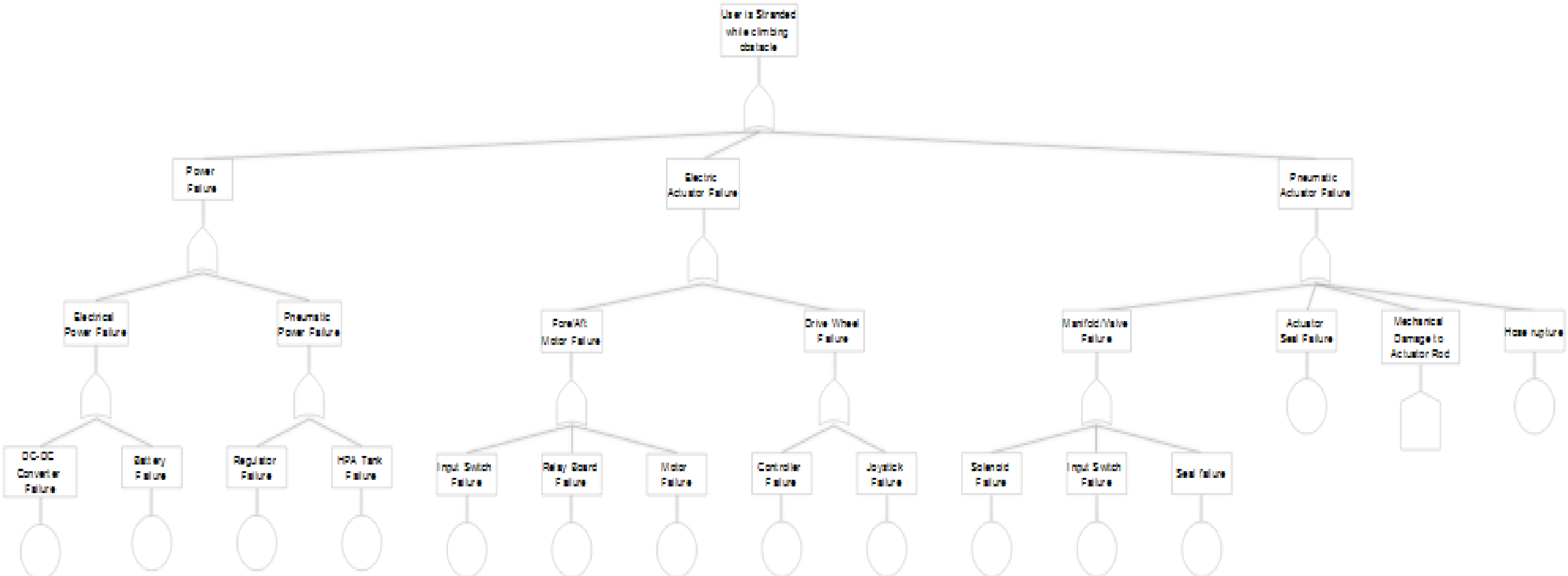

Figure 5.7 is the fault tree representing the cascading events for the user getting stranded in MEBot while on an obstacle

5.3.3.2 FMEA

The FMEA for MEBot identified 25 unique modes of failure with 19 of them rated as a four or five in severity. Of these modes that ranked high in severity, most involved the stranding of the user in MEBot while on an obstacle or the user tipping over in MEBot. Rupture of the high-pressure air (HPA) was identified as having potentially grave consequences; however, given the level of engineering in these tanks by the original equipment manufacturer (OEM) and the fact the they do not need to be removed from their secured location on the robot, this was deemed a very low likelihood of occurrence.

Table 5.6 gives the results of the FMEA for MEBot

FMEA for MEBot					
Component	**Failure Mode**	**Effect of Failure**	**Severity**	**Occurrence**	**Detection**
HPA air tank	Burst disk rupture	Loss of pneumatic power/stranding	4	1	2
	Stem rupture	Projectile	5	1	2
Regulator	Mechanical failure	Loss of pneumatic power/stranding	4	1	2
Switches (air)	Mechanical failure	Partial Loss of pneumatic control/stranding	4	1	2
	Cable failure	Loss of pneumatic control/stranding	4	1	2
Valve manifold	Electronic failure	Partial Loss of pneumatic control/stranding	4	1	2
	Solenoid failure	Partial Loss of pneumatic control/stranding	4	2	2
	Slow air leak	Difficulty of pneumatic control	2	2	4
	Rapid air lead	Rapid emptying of pneu. actuator/tip over	5	2	3
Pneumatic actuator	Piston seizing	Partial Loss of pneumatic control/stranding	4	1	3
	Rod bending	Partial Loss of pneumatic control/stranding	4	2	3
Low pressure hose	Rupture	Rapid emptying of pneu. actuator/tip over	5	2	3
	Disconnect	Rapid emptying of pneu. actuator/tip over	5	2	2
Joystick	Electronic failure	Loss of drive wheels/stranding	3	1	2
Controller	Electronic failure	Loss of drive wheels/stranding	3	1	2
Drive wheel motors	Mechanical failure	Loss of drive wheel/stranding	3	1	2
Fore/aft relay	Mechanical failure	Loss of fore/aft position control/stranding	4	2	3
Fore/aft motors	Mechanical failure	Loss of fore/aft position control/stranding	4	1	3
Fore/aft switches	Mechanical failure	Loss of fore/aft position control/stranding	4	1	3

Table 5.6 (Continued)

Battery	Low charge	Loss of system function/stranding	4	1	2
	Internal short	Fire	5	1	4
	Low capacity	Loss of system function/stranding	4	1	4
	Incorrect size	System will not boot properly	1	1	2
DC-DC converter	Defect (V=0)	Loss of system function/stranding	4	2	4

5.4 DISCUSSION

5.5 RISK ANALYSIS DISCUSSION

5.5.1 RATD

The risk analysis for the RATD identified two priority adverse events that need to be addressed to improve the robot's safety. The first is that damage could occur to the handle and cause the arm to move surreptitiously and either crush the user or tip the wheelchair over on top of the person being transferred. There were several failure modes that could cause this. This problem could be mitigated with the addition of a "dead man" switch. The switch would require the caregiver to depress it before the computer would recognize any of the signals coming from the handle. If the handle becomes damaged, the caregiver letting go of the switch would stop an errant motion.

The second priority adverse event that needs to be addressed is the case of a person being stranded mid-transfer. Currently, the only way to rescue a stranded person would be to have caregivers move the person from the sling to a stable surface. This would likely require the assistance of two or more caregivers, which may take time increasing the chance of fall or strangulation situation. A strategy for mitigating this situation would be to add a manually operated winch that could lower the sling to the ground or another stable surface. The mechanical advantage of the winch would allow a single caregiver to lower the person being transferred, quickly and without additional assistance. While this strategy has it limits, as a person on the floor is still a problem, it does limit the chances of the gravest scenarios.

5.5.2 PerMMA

The two priority adverse events identified for PerMMA, spilling hot liquids and dropping sharp object, are less consequential in relation to the adverse events identified for the other robots; however, they likely need to be addressed to allow people to fully use the device. A key point with hot liquids is identifying it as hot. A conductive temperature sensor could be added to the gripper or an infrared sensor could be added near the gripper with a digital readout that could let the user know the temperature of the liquid and avoid it, if necessary. For sharp objects, changing the object by covering the tip or protecting the person's lap with a thick towel, blanket or lap tray is likely more practical than making additional safety modifications to the robot. It should be note that any strategies that require the user to actively take precautionary action will require training and the cognitive ability to carry out this action.

5.5.3 MEBot

It was clear from both the FTA and FMEA of MEBot that that tip overs and user getting stranded on obstacles represent the greatest risk. For tip-overs, an air hose rupturing or becoming disconnected and one or some of the actuators deflating rapidly represent the more likely failure modes. One mitigation strategy, would be to keep the actuators from deflating. Flow sensors and valves could be placed at the inlet/outlet of the have the values shut if excessive flow is sensed. In this scenario, MEBot may lean a bit, but would be unlikely to completely tip over. A second strategy would be to deflate all pneumatic cylinders and put MEBot it is lowest and un-energized position, which is also its most stable. The pressure sensors for each inlet/outlet would be monitored for unexpected drops in pressure. If an unexpected drop in pressure were detected the system would deflate all cylinders to counteract the surreptitiously deflating cylinder(s). However, both strategies would lead to MEBot's user becoming stranded.

In order to mitigate the stranding scenario, changes would need to be made to MEBots' pneumatic system that would allow it to be manually inflated and deflated without the use of its computers, battery power, and it's HPA source. To use this method to navigate MEBot off an obstacle, external assistance will be needed, as well as, the user knowing how the system is operated in this manner and being able to explain it to a bystander. This will require training and will limit the use of the device to those cognitively able to understand the training.

5.5.4 Broader Implications

This analysis has revealed risks, a means to identify them, and a given ways way to mitigate these risk for three specific robots. However, a few generalized themes may be derived from this exercise. First, the more force an assistive robot is able to produce, the more serious risk mitigation needs to be. With RATD and MEBot many more failure modes were rated a 4 or 5 in severity and this is directly related the force they can generate. Conversely, PerMMA, which does not generate much force, had failure modes rated lower in severity, but is not capable of lifting much; therefore, its usefulness is limited. Good assistive robot design provides safety through systematic mitigation of risk, not by limiting the usefulness of the device. Additionally, even for relatively minor events, such as in the case of PerMMA spilling or dropping items, better assistive robot design will find mitigation strategies that allow the user to achieve tasks, rather than limit the scenarios that the device can be used.

A second point of note is that for assistive robots risk mitigation can be done with strategies that are automatically applied or ones that require user intervention. Both are useful. Solutions that require user intervention are likely to require training and possibly supervision by someone else who can intervene if a mitigation strategy fails. While training and supervision are not ideal, it may allow the person to perform tasks with the device beyond what is practical for the device's current state of development, thus enabling them. However, in the long term, better assistive robot design has risk mitigation strategies that are automatically applied and do not rely on training that may not be remembered or caregivers that may not be available.

It should be noted that in many cases, both the FTA and the FMEA identified the same failure, however, in a few cases the failures identified were unique. This is to be expected and supports the use both analyses to help identify risk. FMEA is a bottom up technique, starting with basic components, and can often can find adverse end results that are not obvious outcomes. FTA is a top down approach, starting with an adverse event, and is useful in identifying evens that are caused by two or more component failures. It should also be noted that FTA and FMEA can be applied can applied at any point during development or while a product is in use in the field. FTA is often used to determine the root cause of a failure observed in the field[198].

Lastly, if a failure cannot be avoided, the assistive robot should let the user know what is wrong. With the RATD, detection ranking increased with several failure modes due to being impossible to detect by the user. The inability of a failure to be detected by the user can exacerbate a failure. Often, users can avoid risky situations if they know a subcomponent has already failed. While error handling may seem only necessary in commercially available devices, a lack of error feedback may prevent a robot from being tested in a community based environment.

5.6 LESSONS LEARNED

In the course of designing, fabricating, demonstrating and testing these robots, several key points that may be helpful in the design of future robots were observed. The following documents these points and offers commentary about how their consideration in future robots could help move the field of assistive robots forward.

In reviewing assistive robot literature, the consideration of the human is often minimized in problem statements, background literature, design priorities, and testing methods. This lack of emphasis on the person who needs assistance is likely one of the reasons why few works report rigorous experimentation methods. The person and their needs should to be central to the entire process. The problem to be solved should be stated in terms of a functional gap the end user experiences, not in terms of a technology that can be applied. The background literature should include references from a variety of fields and provide evidence the problem is real and important to the population that the robot intends to help. Designs need to include people with disabilities starting at the conceptual phase. Block diagrams are a typical starting point for design and are often reported in literature, but often the human is omitted or given token reference in these diagrams. A typical paradigm often described in scientific and engineering literature is the person with a disability "pushes play" to initiate the action and is irrelevant to the rest of the process. Good designs will include the person with a disability, describe the precise inputs and outputs they can provide, and integrate them with other data that sensors provide to create a concept that will facilitate human-robot cooperation. Good designs also consider that people with disabilities will likely use a variety of devices to meet their medical and functional needs, such as cushions, power seat functions, ventilators, orthosis, or augmentative and alternative communication devices. Often, integration of these devices is not trivial and should be considered in the design requirements phase, not ad hoc. Lastly, people with disabilities need to be included in the testing of assistive robots. While it is acknowledged that engineering bench tests are an important step in verifying, function, safety, and reliability, they cannot be used to determine efficacy. Efficacy is the standard that medical devices are held to and if rigorous studies with people with disabilities are not conducted, assistive robots are not likely to be successful in the market place.

Assistive robots, whether for manipulation or advanced mobility, are likely to have a high number of DoF to be able to accomplish useful tasks. Even the most skilled humans are not naturally able to control devices with high number of DoF in an efficient and reliable manner. A key challenge for assistive robot designers will be to use interface design and automation to reduce the amount of input the person with a disability needs to contribute, to perform a task. While this may seem to suggest that the end goal is completely autonomous operation, previous work suggests that users want to retain some level of control[205]. Good designs will use automation to present the user with a manageable set inputs to control, rather than take over the task. There is strong potential to use computer vision, path planning algorithms, and artificial intelligence methods to adaptively present the user with different, limited sets of control inputs, based on the situation the robot detects it is in. It is also likely that user training will play a key role in allowing the person with a disability to control assistive robots with high DoF. Currently mobility and manipulation training methods are likely insufficient and new models, including business models, will need to be invented along with the technology. Related fields, such as computer access training and adaptive driving could help inform this development.

It is critical that potential end users evaluate assistive robots early in the design process. Assistive robot development is resource intensive and often design decisions are not easily modified, especially in the hardware development phase. Robot projects that do not involve end users early, run the risk of creating technology that is not useful and/or not usable. Surveys, focus groups, structured interviews, and “Wizard of Oz”[206] experiments are methods to help get user feedback early in the design process without needing a complete device. Experiments that allow people with disabilities to use the robot are preferred, but considerations for completeness, safety, and reliability must be met.

A key design consideration is that an assistive robot is designed for the environment that it is likely to be used in by the end user. For wheelchair mounted robotic arms and advanced mobility devices, this means that they must be able to operate untethered from external, power, sensory, or computational devices. They must also be able to move through doorways and be transported in vehicles. They will need to work in a variety of lighting conditions, cluttered environments, and be able to go outdoors in at least fair conditions. While many of these factors may seem like considerations to be left for a commercialization phase of development, good designs incorporate these factors early in the process, potentially allowing for more rigorous participant testing, in less contrived environments, earlier in development.

Assistive robots are complex devices and are resource intensive to develop. Computer simulations are great tools to rapidly experiment with different design choices without the time and cost associated with physically implementing those design choices. No assistive robot is likely to be successfully developed without the use of some type of computer simulation or modeling. However, simulations need to be verified by physical testing on a completed prototype. Numerous works report the use of simulations, but few compare to physical engineering bench test, and even fewer compare to experiments with human participants. Simulations are often highly simplified approximations of real items in specific situations, and may be prone to error and have limited generalizability. Maturity of the field of assistive robots will likely to remain stagnant unless more experiments can report confirmed results from simulations.

Lastly, people are not afraid of assistive robots and careful consideration needs to be given to the implications. This is in contrast with industrial robots, which traditionally are cordoned off via physical fences or light curtains and people are kept at a distance. On the more scientific side participants in the RATD focus group reported that they would not be anxious to use a robot, would not be embarrassed to use in it in public, and were ok with letting a computer control their transfer[205]. On the anecdotal side, PerMMA, RATD, and MEBot have collectively been demonstrated hundreds of time to thousands of members of the general public in the past 10 years with little to no reaction from the public in regard to safety. It is not uncommon for people to touch or lean on the robots, interact with their motions, or operate them out with little to no knowledge of how to use them. This suggests that people put a high amount of trust that the developers of these systems have ensured that they are safe. People with disabilities and the people around them will not likely self-regulate in terms of safety. It is therefore paramount that developers systematically mitigate safety risks to ensure this trust is not misplaced and prevent injury.

5.7 FUTURE WORK

Future work for PerMMA should include continued use of it as platform for developing user interfaces for wheelchair mounted robotic arms, remote operated assistive robots, and other high DoF systems for people with disabilities. While PerMMA is not likely to be commercialized in the near future in its current form, the control strategies and interfaces developed for it could be applied to less sophisticated devices already on the market to improve their function.

Additionally, more work could be performed on PerMMA's mechanical track to make it generalizable to more wheelchair mounted robotic arms and power wheelchairs.

Future work on the RATD should include mechanical improvements and simplification of the overall mechanism. A key issue is improving the robotic arm and the wheelchair base's rigidity in the vertical direction, while allowing some compliance in the horizontal plane for safety. Simplifications, such as a passive elbow joint, could be used to make the robot smaller, lighter, easier to stow, and lower cost. The RATD's electronics are based on aging designs. The latest single board computer and system on chip technologies could be used lower cost, increase performance, reduce power consumption, and reduce size. Weaknesses identified by the risk analysis should be implemented with an emphasis on more information being passed on the user about the robot's state and having redundancy in the interface to prevent unintended movement in the event of failure. Long term, replacements for the sling should be explored. Inflatable robotics have a strong potential to solve this problem for the RATD and other transfer devices. Automation of the mechanical interface between the person and the robot could allow people to transfer themselves, which would provide people with disabilities a higher level of independence. Rigorous experiments to help determine efficacy are critical at the current stage of development and in the future.

Future work for MEBot should include interface development, inclusion of advanced sensors such as LiDAR, and algorithms to reduce the amount of input the user needs to provide in a context. Evaluation with people with disabilities would likely inform developers about how much information a person can practically utilized and how many DoF are practical to control. The inclusion of advanced sensors, such as LiDAR would provide the robot with more information about the scene ahead. Advanced algorithms could prepare the robot's kinematics and decide what combination DoF the user would like to control for that scene. Additional work should focus on solutions for overcoming the device stranding and tip over problems identified by the risk analysis, which would allow for unsupervised community based evaluation.

Systematic risk analysis could be applied to other emerging assistive technologies to help identify problems before devices are deployed in the field. In addition to assistive robots, consumer technologies, such as the internet of things, apps, and high processing power, highly portable devices, such as tablets and smartphones are rapidly changing the assistive technology market. Many of these products are not regulated as medical devices and receive less scrutiny in terms of safety, reliability, and robustness. Additionally, it often takes integration of two or more of these devices or software packages to do something useful. They may or may not: be from the same manufacturer, tested for compatibility, be designed to be used in a particular manner, and/or be designed to be used by people with disabilities. FTA and FMEA are tools that may be able to help rehabilitation engineers who are developing systems through integration or clinical rehabilitation engineers who are solving a problem for a specific client to systematically assess the risk of a solution and better understand how to mitigate identified risk. Future work should focus on determining if these tools are suitable for this application, how they can best be applied, when they should be used, and how to train assistive technology professional on how to use them.

APPENDIX A

PERMMA KINEMATICS DEFINITION

The following gives the kinematic definition of PerMMA. The definition includes: the zero position, the placement local origins, their axis of rotation(s), and the distance between local origins in the standard position. This definition was created to aid in the writing of kinematic modes for analysis of workspace[207] and for implementation of path planning algorithms[99, 100].

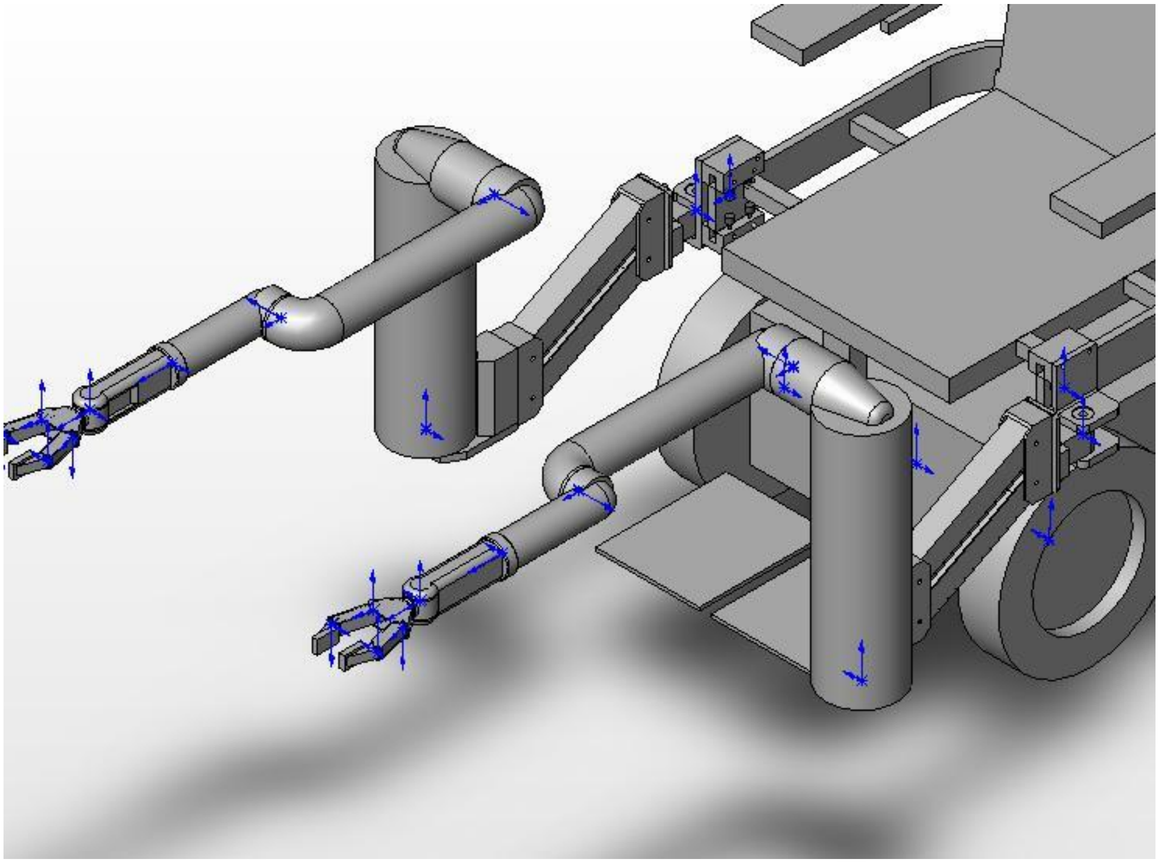

Figure A.1 Shows an overview of all local coordinate systems for PerMMA joint segments

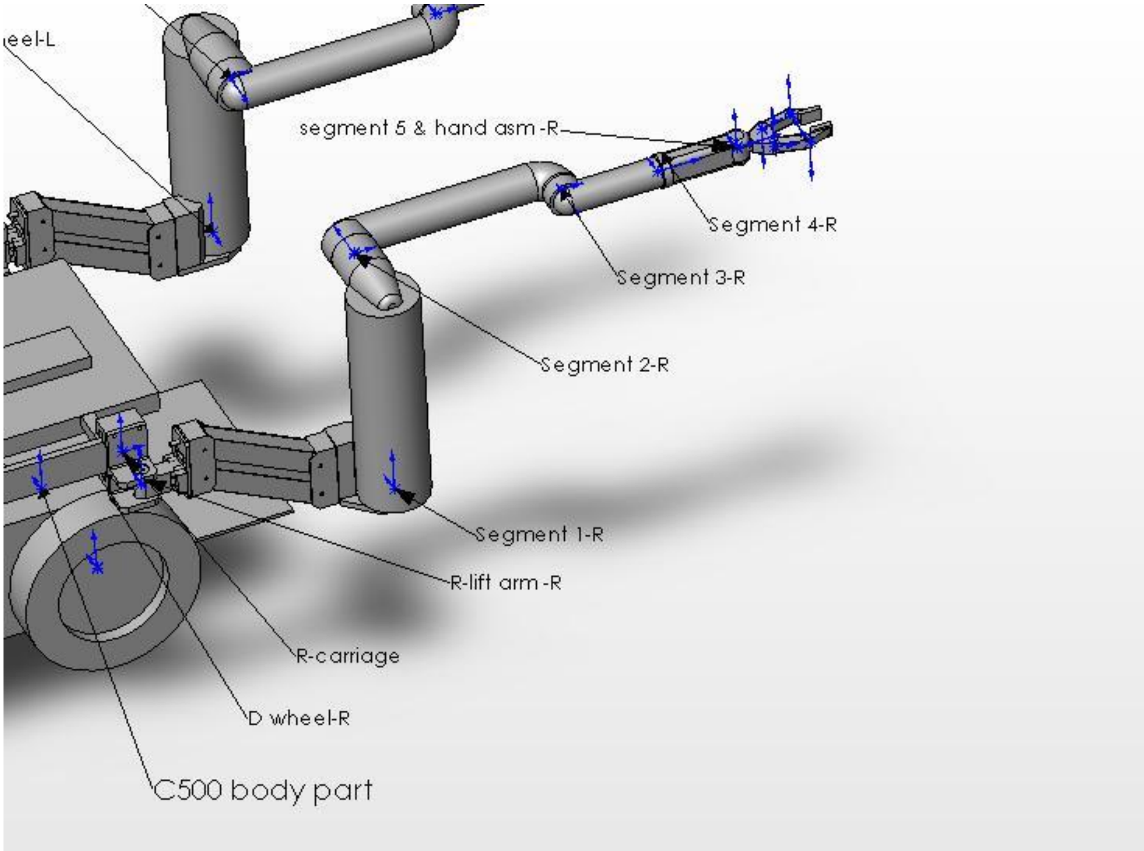

Figure A.2 Shows a detailed view of the right side coordinate systems for PerMMA joint segments

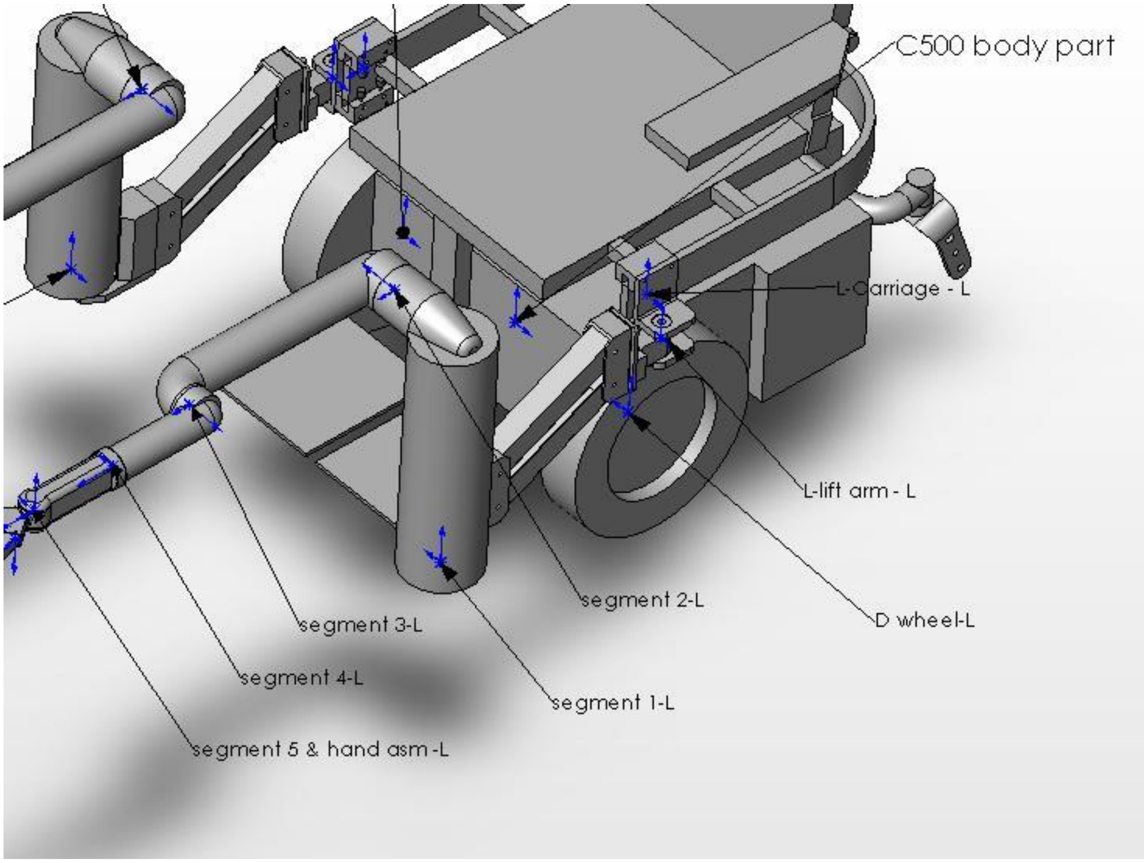

Figure A.3 Shows a detailed view of the left side coordinate systems for PerMMA joint segments

Global Axis

+Y is in the vertical direction

+X points to the Left of the chair

+Z points in the forward direction

Local Axis

For local axis Y was define as the axis of rotation if applicable. All coordinates (x,y,z) are in millimeters are the corresponding VRML files. Line 1 is the local coordinate origin with respect to the global. Line 2 is the rotation of the local axis from the global and line three is the range of rotation of the joint.

Table A.1 gives the cartesian distance between local coordinate systems in millimeters

FILE	Left/Right	X	Y	Z
C500 body Part	NA	0	0	0
D Wheel	R	-250.825	0	0
R-carriage	R	-317.5	301.498	35.56
R-lift arm	R	-366.6617	256.8304	50.8
segment 1	R	-412.0775	109.238	517.8517
segment 2	R	-281.9275	559.238	517.8517
segment 3	R	-281.9275	559.238	922.8517
segment 4	R	-311.9275	559.238	1098.8517
segment 5	R	-311.9275	559.238	1253.8517
hand asm	R	-311.9275	559.238	1253.8517
D Wheel	L	250.825	0	0
L-Carriage	L	317.5	301.498	35.56
L-lift arm	L	366.6617	256.8304	50.8
segment 1	L	412.0775	109.238	517.8517
segment 2	L	281.9275	559.238	517.8517
segment 3	L	281.9275	559.238	922.8517
segment 4	L	281.9275	559.238	1098.8517
segment 5	L	311.9275	559.238	1253.8517
hand asm	L	311.9275	559.238	1253.8517

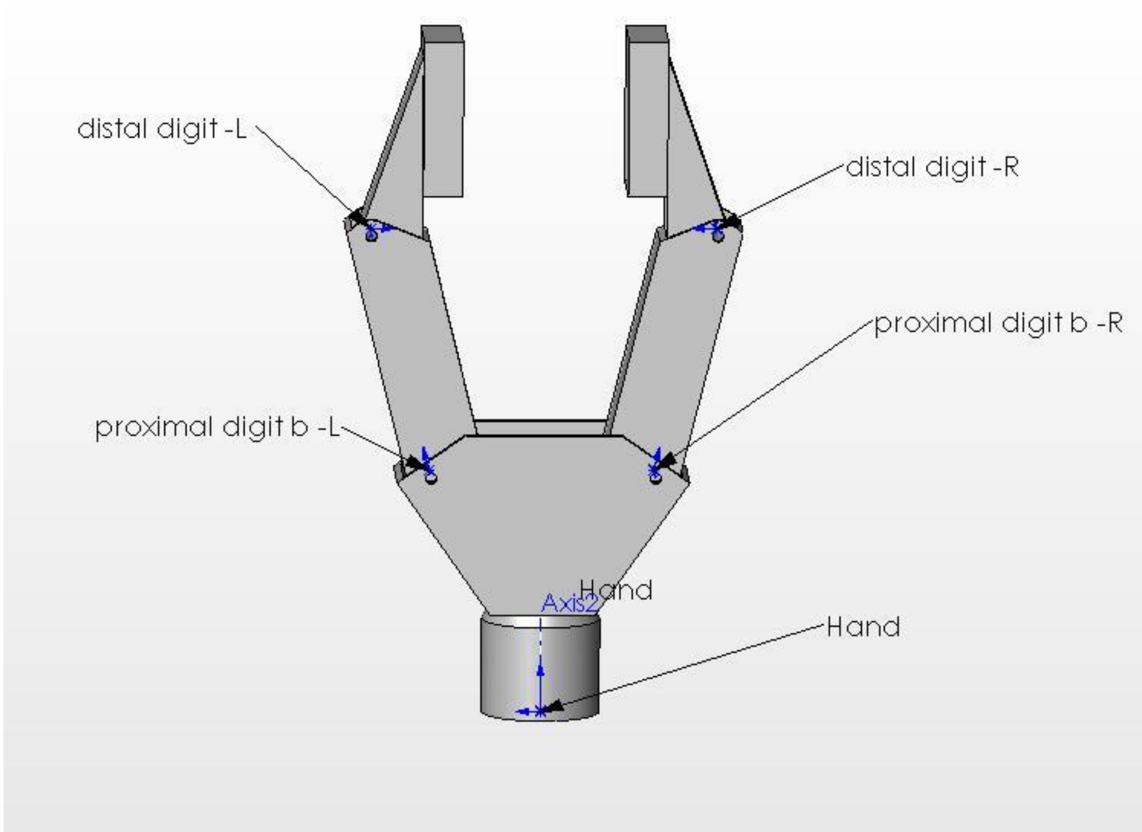

Figure A.4 Shows a detailed view of the local coordinate systems for the PerMMA gripper joint segments

There are three constraints in the gripper that are not implied by the joint rotations: symmetry of the proximal digit, symmetry of the distal digit, and the gripping surfaces of the distal digit must remain parallel.

Table A.2 gives the cartesian distance between local coordinate systems in millimeters

File	X	Y	Z
hand	0	0	0
proximal digit - R	-28.5686	62.1171	0
proximal digit - L	28.5686	62.1171	0
distal digit - R	-44.0511	124.2161	0
distal digit - L	44.0511	124.2161	0

APPENDIX B

MANUS ARM TRANSFER FUNCTION

The following describes the transformation matrix definition of the Manus Arm. The transfer function was used as a kinematic model for creating path planning trajectories in PerMMA autonomous mode.

$$Transformation\_Matrix = [L1]*[R1(z_1)]*[L2]*[R2(y_2)]*[L3]*[R3(y_3)]*[L4]*[R4(y_4)]*[R5(y_5)]$$

Figure B.1 gives the symbolic transformation matrix equation for a left-handed Manus Arm

$$Transformation\_matrix = \begin{bmatrix} 1 \\ 75 \\ 99 \\ 13 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_1 & -\sin\theta_1 & 0 \\ 0 & \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 \\ 0 \\ 175 \\ 501 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_2 & 0 & \sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\theta_2 & 0 & \cos\theta_2 \end{bmatrix} *$$

$$\begin{bmatrix} 1 \\ 0 \\ -75 \\ 400 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_3 & 0 & \sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\theta_3 & 0 & \cos\theta_3 \end{bmatrix} * \begin{bmatrix} 1 \\ 0 \\ 0 \\ 320 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_4 & -\sin\theta_4 & 0 \\ 0 & \sin\theta_4 & \cos\theta_4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_5 & 0 & \sin\theta_5 \\ 0 & 0 & 1 & 0 \\ 0 & -\sin\theta_5 & 0 & \cos\theta_5 \end{bmatrix}$$

Figure B.2 gives the transformation matrix equation for a left-handed Manus Arm.

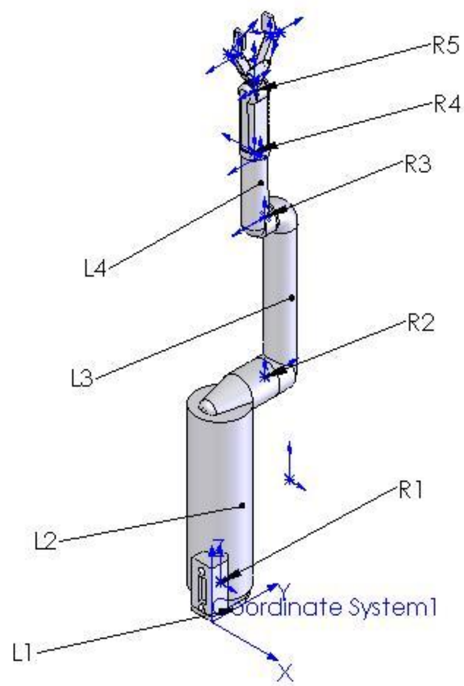

Figure B.3 shows the rotation definition for a left handed Manus Arm

APPENDIX C

RATD STANDARDIZED TESTING RESULTS

The RATD was tested for static and dynamic stability in accordance with ANSI/RESNA WC Standards January 2009. The goal was to determine how the RATD in its stowed position would affect the stability of the Permobil C500 Base. For WC-01: Determination of Static Stability, the tested “most stable” position was the standard stow configuration for the RATD and an alternative configuration was set to for the “least stable” configuration. These configurations are illustrated in figure C.1.

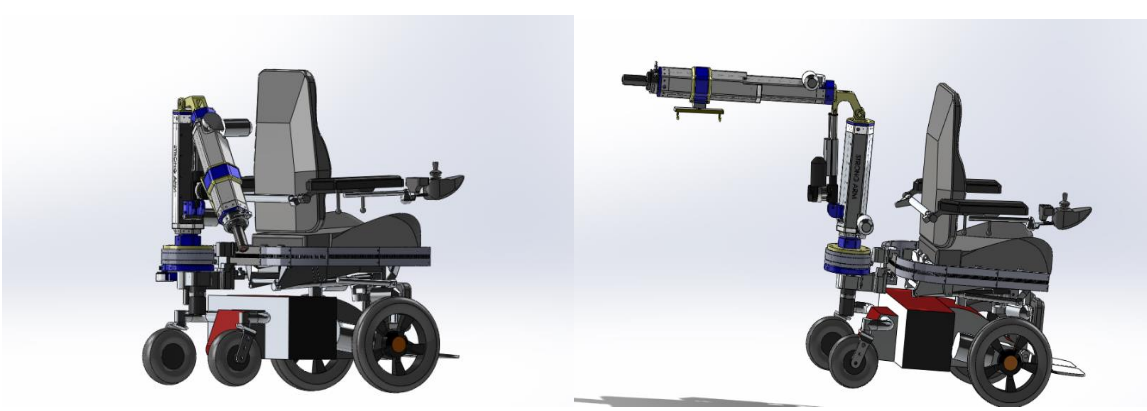

Figure C.1 illustrates the most stable configure of the RATD (left) and the least stable configuration (right) for the determination of static stability

The results of the static stability are given in table C.1. It is of noted that the left and right lateral tilting condition are asymmetric which is an atypical result and due to the asymmetry of the robot in the stowed configuration.

Table C.1 gives the results for the static stability testing for the RATD

Stability direction	Condition	Tipping angle (degrees)	
		Least stable	Most stable
Forward	Front wheels locked	14.1	28.6
	Front wheels unlocked	20.0	38.2
Rearward	Rear wheels unlocked	32.5	36.2
Lateral	Left	16.3	31.0
	Right	13.1	18.7

The results of the RATD being tested to WC-02: Determination of Dynamic Stability are given in table C.2. A “3” indicates that all wheels remained in contract with the ground during the test.

Table C.2 gives the results for the dynamic stability testing for the RATD

Test	Anti-Tip Devices	Method of Retardation	Stability score Ramp angle (º)			
			0	3	6	10
Rearward Dynamic Stability						
8.2 Starting Forwards	With anti-tip devices		N/A	N/A	N/A	N/A
	Without anti-tip devices		3	3	3	3
8.3 Stopping after traveling forwards	With anti-tip devices	R Release	N/A	N/A	N/A	N/A
		P Power off	N/A	N/A	N/A	N/A
		A Applying Reverse	N/A	N/A	N/A	N/A
	Without anti-tip devices	R Release	3	3	3	3
		P Power off	3	3	3	3
		A Applying Reverse	3	3	3	3
8.4 Braking when traveling backwards	With anti-tip devices	R Release	N/A	N/A	N/A	N/A
		P Power off	N/A	N/A	N/A	N/A
		A Applying Reverse	N/A	N/A	N/A	N/A
	Without anti-tip devices	R Release	3	3	3	3
		P Power off	3	3	3	3
		A Applying Reverse	3	3	3	3
Forward Dynamic Stability						
9.2 Braking when traveling forwards	N/A	R Release	3	3	3	3
		P Power off	3	3	3	3
		A Applying Reverse	3	3	3	3
9.3 Traveling forward down a slope onto a horizintal surface	N/A	N/A	N/A	3	3	N/T

Table C.2 (Continued)

Dynamic Stability in Lateral Directions						
10.2 Turning on a Slope	N/A	N/A	3	3	3	3
10.3 Turing in a circle at maximum speed (minimum diameter, in meters)	N/A	N/A	3	N/A	N/A	N/A
10.4 Turning suddenly at maximum speed	N/A	N/A	3	N/A	N/A	N/A

APPENDIX D

REVIEW OF ASSISTIVE ROBOT STUDIES

A thorough, but not systematic review of literature related to assistive robots was conducted to help determine the state of the art. This review focused on project that involved wheelchair mounted robotic arms. Wheelchairs strictly for advanced mobility or autonomous navigation were not included. The search was performed using the search terms “wheelchair and robot”, and “wheelchair mounted robotic arm”. Additional manuscripts were found based on the authors knowledge of the groups working in the field and from cited literature in work found using the search terms. Only manuscripts available in English were included.

The results of the review are summarized in table D.1. Information included in this table are: the first author, title, year of publication, general category of robot, name(s) of robot, number of able bodied participants, number of participants with disabilities, if controls were included (no = 0, yes =1), if simulations were used (no = 0, yes =1), if the study was conducted in a laboratory or clinical setting (no = 0, yes =1), if the study was conducted in a community setting (no = 0, yes =1), and the number of participants is the study was survey or focus group based. For a given manuscript, it listed as have multiple yes answers for simulation, laboratory, and community settings. A study was considered survey or focus group based, if it had human participants who did not actually use a robot as part of the study protocol. The manuscripts are not listed in any particular order.

Table D.1 gives the results of the review of assistive robot studies

Author	Title	Year	Type	Device	Able	Disability	Control	Simulation	Lab	Community	Survey
Kim	Eye-in-hand stereo visual servoing of an assistive robot arm in unstructured environments	2009	Robotic Arm	Manus/ARM	0	0	0	1	0	0	0
Van der Loos	ProVAR assistive robot system architecture	1999	Robotic Arm	ProVAR/PUMA	0	0	0	0	0	0	0
Kim	An empirical study with simulated ADL tasks using a vision-guided assistive robot arm	2009	Robotic Arm	Manus/ARM	0	0	0	0	1	0	0
Hockberg	Reach and grasp by people with tetraplegia using a neurally controlled robotic arm	2012	Robotic Arm/BCI	DEKA Arm	0	2	0	0	1	0	0
Kargov	Development of an Anthropomorphic Hand for a Mobile Assistive Robot	2005	Robotic Arm	FRIEND	0	0	0	0	1	0	0
Hillman	The Weston Wheelchair Mounted Assistive Robot - The Design Story	2002	Robotic Arm	Weston	0	1	0	0	0	1	0

Table D.1 (Continued)

Nguyen	El-E: An Assistive Robot that Fetches Objects from Flat Surfaces	2008	Robotic Arm/Mobile Base	EL-e	0	0	0	0	1	0	0
Kim	How autonomy impacts performance and satisfaction: Results from a study with spinal cord injured	2012	Robotic Arm	UCF-MANUS	0	10	0	0	1	0	0
King	Towards an Assistive Robot that Autonomously Performs Bed Baths for Patient Hygiene	2010	Robotic Arm	Cody	1	0	0	0	1	0	0
Ianez	Assistive robot application based on an RFID control architecture and a wireless EOG interface	2012	Robotic Arm/BCI	Fanuc LR Mate 200iB	5	0	0	0	1	0	0
Huete	Personal autonomy rehabilitation in home environments by portable assistive robot	2011	Robotic Arm	ASIBOT	0	5	0	0	1	0	0
Onose	On the feasibility of using motor imagery EEG-based brain–computer interface in chronic tetraplegics for	2012	Robotic Arm/BCI	Manus/ARM	0	9	0	0	1	0	0
Hillman	A wheelchair mounted assistive robot	1999	Robotic Arm	Weston	0	0	0	0	1	0	29
Jain	EL-E: an assistive mobile manipulator that autonomously fetches objects from flat surfaces	2010	Robotic Arm/Mobile Base	EL-e	0	0	0	0	1	0	25

Table D.1 (Continued)

Maheu	Evaluation of the JACO robotic arm	2011	Robotic Arm	Jaco	0	31	0	0	1	0	0
Tsui	Development and Evaluation of a Flexible Interface for a Wheelchair Mounted Robotic Arm	2008	Robotic Arm	Manus/ARM	0	8	0	0	1	0	0
Farahmand	An Intelligent Assistive Robotic Manipulator	2005	Robotic Arm	Custom Design	0	0	0	0	1	0	0
Matsumoto	A concept of needs-oriented design and evaluation of assistive robots based on ICF	2011	Robotic Arm	Manus/ARM, RAPUDA	0	0	0	1	0	0	0
Mokhtari	Toward a Human-Friendly User Interface to Control an Assistive Robot in the Context of Smart Homes	2004	Robotic Arm	Manus/ARM	0	0	0	0	1	0	0
Cunningham	Jamster: A mobile dual-arm assistive robot with Jamboxx control	2014	Robotic Arm	Baxter	1	0	0	0	1	0	0
Bassily	Intuitive and Adaptive Robotic Arm Manipulation using the Leap Motion Controller	2014	Robotic Arm	Jaco	0	0	0	1	1	0	0
Wagner	ProVAR assistive robot interface	1999	Robotic Arm	ProVAR/PUMA	0	0	0	1	0	0	0

Table D.1 (Continued)

Cook	School-Based Use of a Robotic Arm System by Children With Disabilities	2005	Robotic Arm	Rhino XR4	0	12	0	0	1	0	0
Tsui	“I want that”: Human-in-the-loop control of a wheelchair-mounted robotic arm	2011	Robotic Arm	Manus/ARM	0	12	0	0	1	0	0
Nguyen	Bio-inspired Assistive Robotics: Service Dogs as a Model for Human-Robot Interaction and Mobile	2008	Robotic Arm	EL-e	0	0	0	0	1	0	0
Balaguer	The MATS robot: service climbing robot for personal assistance	2006	Robotic Arm	MATS	0	0	0	0	1	0	0
Ciocarlie	Mobile Manipulation Through An Assistive Home Robot	2012	Robotic Arm/Mobile Base	PR2	0	1	0	0	0	1	0
Alqasemi	Analysis, Evaluation and Development of Wheelchair-Mounted Robotic Arms	2005	Robotic Arm	Alqasemi-Dubey	0	0	0	0	1	0	0
Tsui	Simplifying Wheelchair Mounted Robotic Arm Control with a Visual Interface	2007	Robotic Arm	Manus/Arm	0	12	0	0	1	0	0
Srinivasa	HERB: a home exploring robotic butler	2010	Robotic Arm/Mobile Base	WAM/Segway	0	0	0	0	1	0	0

Table D.1 (Continued)

Prior	An Electric Wheelchair Mounted Robotic Arm—A Survey of Potential Users	1990	Robotic Arm	non-specific	0	0	0	0	0	0	5 0
Palankar	Control of a 9-DoF Wheelchair-mounted robotic arm system using a P300 Brain Computer Interface:	2008	Robotic Arm/Wheelchair	Custom Design	6	0	0	0	1	0	0
Min	Human-Friendly Interfaces of Wheelchair Robotic System for Handicapped Persons	2002	Robotic Arm/ Wheelchair	KARES II	0	6	0	1	0	0	0
Song	KARES: Intelligent wheelchair-mounted robotic arm system using vision and force sensor	1999	Robotic Arm/ Wheelchair	KARES	0	0	0	0	1	0	0
Alqasemi	Maximizing Manipulation Capabilities for People with Disabilities Using a 9-DoF Wheelchair-	2007	Robotic Arm/ Wheelchair	Alqasemi-Dubey	0	0	0	1	0	0	0
Alqasemi	Analysis, Evaluation and Development of Wheelchair-Mounted Robotic Arms	2005	Robotic Arm/ Wheelchair	Alqasemi-Dubey	0	0	0	1	0	0	0
Schrock	Design, Simulation and Testing of a New Modular Wheelchair Mounted Robotic Arm to Perform	2009	Robotic Arm/ Wheelchair	Alqasemi-Dubey	0	0	0	1	1	0	0
Song	Visual Servoing for a User's Mouth with E ective Intention Reading in a Wheelchair-based Robotic Arm	2001	Robotic Arm/Wheelchair	KARES II	1	0	0	1	0	0	0

Table D.1 (Continued)

Bien	Development of a wheelchair-based rehabilitation robotic system (KARES II) with various human-robot interaction interfaces	2003	Robotic Arm/Wheelchair	KARES II	na	na	na	na	na	na	na
Edwards	Design, construction and testing of a wheelchair-mounted robotic arm	2006	Robotic Arm/Wheelchair	Alqasemi-Dubey	0	0	0	0	1	0	0
Alqasemi	Kinematics. Control and Redundancy Resolution ofa 9-DoF Wheelchair-Mounted Robotic Arm System for ADL tasks	2009	Robotic Arm/ Wheelchair	Alqasemi-Dubey	0	0	0	1	0	0	0
Mukai	Development of a Nursing-Care Assistant Robot RIBA That Can Lift a Human in Its Arms	2010	Transfer Robot	RIBA	10	0	0	0	1	0	0
Seamone	Early clinical evaluation of a robot arm/worktable system for spinal-cord-injured persons.	1985	Robotic Arm	APL/JHMI Robotic Arm/Worktable Systems	0	16	0	0	1	0	0
Song	KARES: intelligent rehabilitation robotic system for the disabled and the elderly	1998	Robotic Arm/ Wheelchair	KARES	0	0	0	0	1	0	0
Han	New EMG Pattern Recognition based on Soft Computing Techniques and Its Application to Control of a Rehabilitation	2000	Robotic Arm/Wheelchair	KARES	8	0	1	0	1	0	0

Table D.1 (Continued)

Buhler	Autonomous robot technology for advanced wheelchair and robotic aids for people with	1995	Robotic Arm	Manus/ARM	8	0	0	0	1	0	0
Jung	A study on the enhancement of manipulation performance of wheelchair-mounted	1999	Robotic Arm/Wheelchair	KARES	0	0	0	0	1	0	0
Uehara	A Mobile Robotic Arm for People with Severe Disabilities	2010	Robotic Arm	Custom Design	1	0	0	0	1	0	0
Pathirage	A vision based P300 Brain Computer Interface for grasping using a wheelchair-mounted robotic	2013	Robotic Arm/Wheelchair	Alqasemi-Dubey	6	0	0	0	1	0	0
Bach	Wheelchair-Mounted Robot Manipulators: Long Term Use by Patients with Duchenne Muscular	1990	Robotic Arm	Cobra RS2, Microbot 453-H	0	4	0	0	1	0	0
Chang	Development of a Robotic Arm for Handicapped People: A Task-Oriented Design Approach	2003	Robotic Arm	WAM	0	0	0	0	1	0	0
Jiang	ntegrated Vision-Based Robotic Arm Interface for Operators with Upper Limb Mobility	2013	Robotic Arm	Jaco	3	0	0	0	1	0	0
Driessen	MANUS—a wheelchair-mounted rehabilitation robot	2001	Robotic Arm	Manus/ARM	0	0	0	1	0	0	0

Table D.1 (Continued)

Martens	A FRIEND for Assisting Handicapped People	2001	Robotic Arm	FRIEND	0	0	0	1	1	0	0
Dune	Intuitive human interaction with an arm robot for severely handicapped people - A One Click	2007	Robotic Arm	Manus/ARM	0	0	0	0	1	0	0
Laffont	Evaluation of a Graphic Interface to Control A Robotic Grasping Arm: A Multicenter Study	2009	Robotic Arm	Manus/ARM	24	20	1	0	1	0	0
Stanger	Devices for Assisting Manipulation: A Summary of User Task Priorities	1994	Robotic Arm	non-specific	0	0	0	0	0	0	205
Bien	ntegration of a Rehabilitation Robotic System (KARES II) with Human-Friendly Man-Machine	2004	Robotic Arm/ Wheelchair	KARES II	0	6	0	0	1	0	0
Volosyak	Rehabilitation Robot FRIEND II - The General Concept and Current Implementation	2005	Robotic Arm/ Wheelchair	FRIEND II	0	0	0	0	1	0	0
Wang	The Personal Mobility and Manipulation Appliance (PerMMA): a Robotic Wheelchair	2012	Robotic Arm/ Wheelchair	PerMMA	0	0	0	0	1	0	0
Routhier	Benefits of JACO robotic arm on independent living and social participation: an exploratory study	2014	Robotic Arm	Jaco	7	0	0	0	1	0	0

Table D.1 (Continued)

Campeau-Lecours	JACO Assistive Robotic Device: Empowering People With Disabilities Through Innovative Algorithms	2014	Robotic Arm	Jaco	0	0	0	0	1	0	0
Jiang	Autonomous Performance of Multistep Activities with a Wheelchair Mounted Robotic Manipulator Using	2014	Robotic Arm	Jaco	4	0	0	0	1	0	0
Abolghasemi	AReal-TimeTechniqueforPositioningaWheelchair-MountedRoboticArmfor	2016	Robotic Arm	Jaco	0	0	0	1	0	0	0
Borboni	Kinematic performance enhancement of wheelchairmounted robotic arm by adding a linear drive	2016	Robotic Arm	Raptor	0	0	0	0	1	0	0
Abolghasemi	Real-time placement of a wheelchair-mounted robotic arm	2016	Robotic Arm	Jaco	0	0	0	1	0	0	0
Chung	FEASIBILITY ANALYSIS OF DAILY ACTIVITIES USING ASSISTIVE ROBOTIC MANIPULATORS		Robotic Arm	Manus/ARM, Jaco	1	0	0	0	1	0	0
Chung	Performance Evaluation of a Mobile Touchscreen Interface for Assistive Robotic Manipulators: A	2017	Robotic Arm	Manus/ARM	4	0	0	0	1	0	0
Chung	Task-Oriented Performance Evaluation for Assistive Robotic Manipulators: A Pilot Study	2017	Robotic Arm	Manus/ARM, Jaco	10	0	0	0	1	0	0

Table D.1 (Continued)

Ka	Assistive Robotic Manipulation Performance Evaluation between Manual and Semi-Autonomous	2016	Robotic Arm	Jaco	0	5	0	0	1	0	0
Ka	Performance evaluation of 3D vision-based semi-autonomous control method for assistive robotic	2017	Robotic Arm	Jaco	1 5	8	1	0	1	0	0
Jiang	Integrated vision-based system for efficient, semi-automated control of a robotic manipulator	2014	Robotic Arm	Jaco	3	0	0	0	1	0	0
Langdon	Analysis of Assistive Robotic Manipulator (ARM) Performance Based on a Task Taxonomy		Robotic Arm	Jaco	2	0	0	0	1	0	0
Jiang	Enhanced control of a wheelchair-mounted robotic manipulator using 3-D vision and multimodal	2016	Robotic Arm	Jaco	5	0	0	0	1	0	0
Ka	Three Dimentional Computer Vision-Based Alternative Control Method for Assistive Robotic Manipulator	2016	Robotic Arm	Jaco	0	0	0	0	1	0	0
Al-Halimi	Performing Complex Tasks by Users With Upper-Extremity Disabilities Using a 6-DOF Robotic Arm:	2017	Robotic Arm	Jaco	0	3	0	0	1	0	0

Table D.1 (Continued)

Grindle	Design and development of the personal mobility and manipulation appliance	2011	Robotic Arm	PerMMA	0	0	0	0	1	0	0
Schneider	A computer-aided robotic arm/worktable system for the high-level quadriplegic	1981	Robotic Arm	APL/JHMI Robotic Arm/Worktable Systems	1	0	0	0	1	0	0
Xu	Enhanced bimanual manipulation assistance with the Personal Mobility and Manipulation Appliance	2010	Robotic Arm	PerMMA	0	0	0	1	0	0	0

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