DESIGN AND EVALUATION OF A VISUAL CONTROL INTERFACE OF A WHEELCHAIR MOUNTED ROBOTIC ARM FOR USERS WITH COGNITIVE IMPAIRMENTS

BY

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B.S. UNIVERSITY OF MASSACHUSETTS LOWELL (2004)

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
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Wheelchair mounted robotic arms have been commercially available for the last decade. They provide independence to people with disabilities. However, a user must have a high level of cognitive load to operate these robot arms. Our target audience includes people who use power wheelchairs and have cognitive impairments as well. Thus, we must reduce the cognitive load.

Our research focuses on replacing the standard menu-based interface with a vision-based system while adding autonomy to the robot arm to execute a "pick-and-place" activity of daily living. Instead of manual task decomposition and execution, the user explicitly designates the end goal and the system then autonomously reaches towards the object.

We designed and implemented human-robot interfaces compatible with indirect (e.g., single switch scanning) and direct (e.g., touch screen and joystick) selection. We implemented an autonomous system to reach towards an object. We evaluated the interfaces and system first with able-bodied participants and then end-users from the target population. Based upon this work, we developed guidelines for interface design and experimental design for human-robot interaction with assistive technology.

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Thanks to all the members of the Robotics Lab, particularly Philip Thoren, Mark Micire, Munjal Desai, Harold Bufford, Adam Norton, and Jeremy Badessa. Thank you to Linda Beliveau and Tae-Young Park of Crotched Mountain Rehabilitation Center. Although I cannot explicitly states names, I would like to give a special thank you to all the participants from Crotched Mountain Rehabilitation Center for providing inspiration and passion to continue with my research in assistive technology. I dedicate this work to Andy Munroe.

Thank you to my friends for their support and patience. I would like to thank my parents for encouraging me with my schooling and supporting me throughout the process, especially in the pursuit of my higher education. Thanks to my brother Nick and sister Kim, who spent many late nights with me in the lab. Thank you to my better half, Mark Micire, for always being there for me, keeping me focused, and continuously inspiring me.

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CHAPTER 1
INTRODUCTION

1.1 Motivation

Activities of daily life (ADLs), such as picking up a telephone or drinking a cup of coffee, are taken for granted by most people. Humans have an innate ability to move through and manipulate environments. Moving from one location to another, acquiring an object, and manipulating an object is something most of us do without much effort. We are so adept at these tasks that we almost forget how complex they can be.

People with neuromuscular impairments, such as spinal cord injury and cerebral palsy, may require wheelchairs for mobility and rely on others for assistance. For this population, executing an ADL is anything but trivial. Often, a dedicated caregiver is needed. The person with disabilities cannot control when an ADL is aided or performed for them. Prior research has shown that users are very interested in tasks that occur regularly in unstructured environments, including “pick-and-place” tasks such as lifting miscellaneous objects from the floor, a shelf, or table (Stranger et al. 1994).

Workstations, such as feeding devices or door openers, may provide greater independence to a person with disabilities. Vocational workstations may allow a person to find employment. However, by definition, workstations can only manipulate in a fixed area, which limits when and where the user is able to operate the robot.

Alternatively, robot arms can be mounted on power wheelchairs to allow for greater mobility.

The Manus Assistive Robotic Manipulator (ARM) is a commercially available wheelchair mounted robot arm developed by Exact Dynamics (2008). It is designed to assist with general ADLs and can function in unstructured environments. The Manus ARM can be operated using a keypad, joystick, or single switch using hierarchical menus. Learning the menus and operating the robot arm is cognitively intensive. Training to use the Manus ARM typically takes twelve hours – two hours to master the controls and ten hours to use the robot arm as part of daily life (Exact Dynamics 2008). Additionally, the input devices may not correlate well to a user's physical capabilities.

1.2 Research Question

How can a person who uses a power wheelchair and may also have a cognitive impairment easily control a wheelchair mounted robotic arm to retrieve an object?

The Manus ARM menu hierarchy can be frustrating for people with physical disabilities who also have cognitive impairments. They may not be able to independently perform the multi-stepped processes needed for task decomposition. They may also have difficulties with varying levels of abstraction needed to navigate the menu hierarchy. Thus, we are investigating alternative user interfaces for the Manus ARM.

The trajectory of a human arm picking up an object is two separate events: gross reaching motion to the intended location, followed by fine adjustment of the hand (Woodworth 1899). We decompose object retrieval by a robot arm into three parts: reaching for the object, grasping the object, and returning the object to the user. The research in this thesis addresses the human-robot interaction and the gross manipulation.[1]

The most frequent activity of daily living is object retrieval (Stranger et al. 1994). Thus, our goal is to simplify the "pick-and-place" ADL by creating an interface which is used to specify the desired object and automate the reaching and grasping of the robot arm. Our alternate interfaces for the Manus ARM allow the user to select the desired object from a live video feed that approximates the view of the wheelchair occupant. The robot arm then moves towards the object without further input from the user.

1.3 Contributions

The contributions of this thesis are as follows:

- We designed and implemented human-robot interfaces compatible with indirect[2] (e.g., single switch scanning) and direct[2] (e.g., touch screen and joystick) selection.
- We implemented an autonomous system for the Manus ARM to reach towards a desired object.
- We evaluated the indirect selection interface and system with able-bodied participants. Evaluation with able-bodied participants provided a baseline because these subjects are able to quickly voice any concerns or discomforts and stop

[1] Our team is a multi-disciplinary collaboration with three main components: computer scientists and robotics researchers from UMass Lowell, occupational therapists and assistive technologists from Crotched Mountain Rehabilitation Center, and mechanical engineers from the University of Central Florida. Our mechanical engineering collaborators (Dr. Aman Behal and team) are researching the grasping of novel objects and the object return.

[2] We use the Louisiana Assistive Technology Access Network's definitions of direct and indirect selection (LATAN 2008). Direct selection is "a method of access that enables the person to use a body part or an extension of the body to directly identify a selection on a device in order to control or operate the device." Indirect selection is "a control or choice-making method that uses intermediary steps in making a selection."

a trial. Also, these subjects provide an upper bound of physical dexterity and cognition expected in the target population.

- We evaluated the direct selection interface with eight end-users at Crotched Mountain Rehabilitation Center who were representative of the target population. Evaluation with the end-users showed the viability of the interface.

Two broader contributions have resulted from this work that will impact the field of human-robot interaction with assistive technology (HRI-AT). First, we developed guidelines for designing interfaces for HRI-AT based on existing guidelines addressing usability, human computer interaction, and adaptive user interfaces. Second, based on our user testing and a survey of HRI-AT experiments, we developed guidelines for experimental design in HRI-AT.

1.4 Thesis Organization

The remainder of this document is organized as follows. Chapter 2 surveys assistive robot arm used in workstations or mounted to wheelchairs. Chapter 3 surveys experiments conducted with able-bodied and end-user participants in human-robot interaction for assistive technology. Chapter 4 documents the hardware and software of our system. Chapter 5 details the indirect selection system developed which used single switch scanning as the user interface. The chapter also details an able-bodied experiments of this system, which provides an upper bound of expected performance with the target population. Chapter 6 details the direct selection interface system which leverages popular assistive devices as user input. The chapter also details an end-user evaluation of the system run with eight participants from Crotched Mountain Rehabilitation Center for eight weeks. Chapter 7 enumerates our guidelines for human-robot interaction for assistive technology interface design and experimental design. Chapter 8 details future work for this research.

CHAPTER 2
RELATED LITERATURE ON ASSISTIVE ROBOT ARMS

Robot arms originated in industry to accomplish high precision, pre-programmed specific tasks (Marsh 2004). The automobile industry has used the Programmable Universal Machine for Assembly (PUMA) on the assembly line since 1961 (Marsh 2004). Robot arms have also been used for non-assembly tasks, such as the Telegarden (Kahn et al. 2005) and in assistive technologies, where robot arms have been used in fixed point workstations and on wheelchairs.

Haigh and Yanco (2002) provide a survey of assistive robot technologies. A historical survey of rehabilitation robotics through 2003 can be found in Hillman (2003).

2.1 Workstations

Robot arms may be mounted in a fixed location, thus creating a workstation for a user. Robotic workstations can be used for "fetch and carry" ADLs. Vocational workstations provide a wide range of "fetch and carry" ADLs (such as retrieving books, page turning, and operating a telephone), whereas a feeding device, for example, provides a single task.

Stanford University's DeVAR (Desktop Vocational Assistive Robot) was a vocational manipulation system (Van der Loos et al. 1999). It was controlled with voice recognition (of simple words trained to a specific user). DeVAR III was evaluated by twenty-four high functioning quadriplegics over eighteen months; participants used

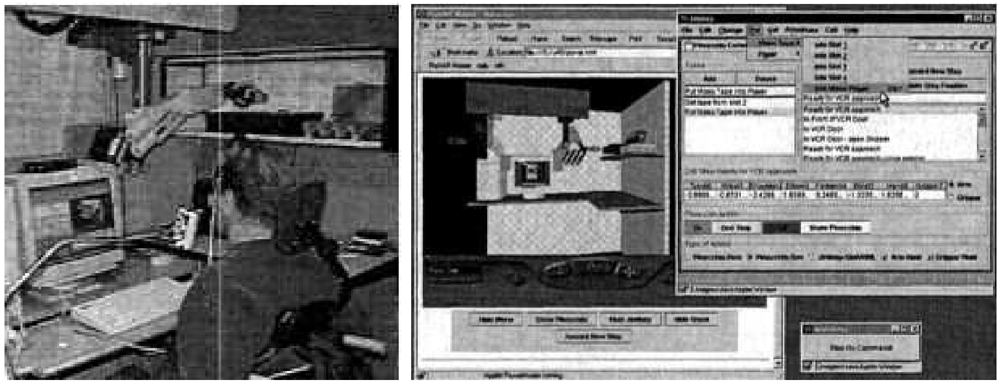

Figure 1. ProVAR and its GUI (from Wagner et al. 1999)

the robot to "brush their teeth, prepare meals, wash their faces, and shave" (Stranger et al. 1994) (Hammel et al. 1989). ProVAR (Professional Vocational Assistant Robot), shown in Figure 1, was the successor of DeVAR. It featured a PUMA-260 robot arm and a human prosthesis end-effector mounted on an overhead track that provided an open range of access for object retrieval and placement near the user (Van der Loos et al. 1999). ProVar used commercially available assistive technology as input, including a voice recognition program and a chin joystick (Van der Loos et al. 1999) (Wagner et al. 1999). The ProVAR user population included spinal cord injury (C2 to C6) and quadriplegia (Wagner et al. 1999).

The European Community Technology for the Socio-Economic Integration of Disabled and Elderly people (TIDE) also created a vocational workstation, shown in Figure 2 (Dallaway and Jackson 1992). The Robot Assisting Integration of the Disabled (RAID) project used an RTX robot arm (Universal Machine Intelligence Limited 1987) to manipulate a computer, computer peripherals (e.g., scanner, printer, disks, manuals, paper, CDs), reader board, and telephone. A power wheelchair user controlled RAID through their drive joystick which emulated a mouse to access a Windows graphical user interface. The user population of the RAID project included

Figure 2. RAID workstation (from Jones 1999)

spinal cord injury (C3 to C8), Duchenne's syndrome, multiple sclerosis, and traumatic brain injury (Jones 1999).

The Kanagawa Institute of Technology in Japan mounted a robot arm on a ceiling track above a hospital-style bed (Takahashi et al. 2002). Similar to the aforementioned vocational workstations, the robot arm was used to retrieve and manipulate objects around a patient's bed. A joystick was used to control a laser pointer mounted to the wall. The laser dot indicated the object of interest.

Some workstations focus on single tasks, such as feeding. Handy 1 was initially developed at Kale University for a twelve-year-old cerebral palsy patient as an independent eating device (Hegarty and Topping 1991) (Topping 1995). Handy 1, shown in Figure 3, used the Cyber 310 robot (Fazakerley 2006). A single switch was also used to accommodate the user population including people with multiple sclerosis, with muscular dystrophy, and who have had a stroke.

My Spoon was a commercially available product from SECOM, shown in Figure 4 (SECOM 2008). My Spoon was controlled with a joystick and button. The user was fed manually, semi-automatically (where the user only specifies the compartment), and automatically.

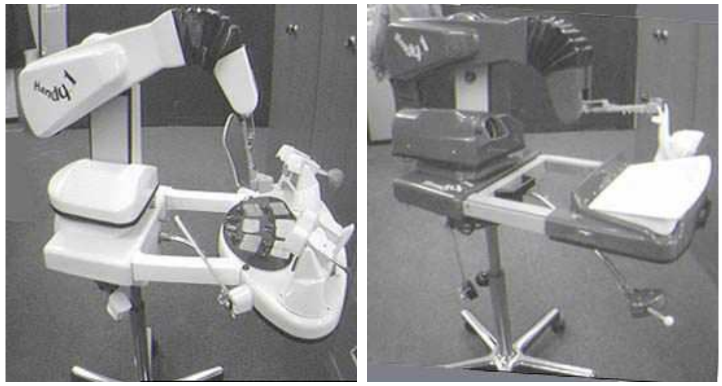

Figure 3. Kale University's Handy 1 feeding aid features a Cyber 310 robot arm (from Fazakerley 2006).

Figure 4. My Spoon, feeding aid (from SECOM 2008)

2.2 Wheelchair Mounted Robotic Arms

Workstations have had some successes. Schuyler and Mahoney found that 45% of 12,400 severely disabled individuals were employable with vocational assistance (Schuyler and Mahoney 1995). However, by definition, workstations can only manipulate in a fixed area, which limits when and where the user is able to operate the robot. Alternatively, robot arms can be mounted on power wheelchairs. Wheelchair mounted robotic arms have been under development since the early 1980's by both research institutions and industry.

The University of South Florida evaluated the range of motion of both the Raptor and the Manus ARM, which are discussed later in this section (McCaffrey

Figure 5. University of South Florida's 7 degree of freedom robot arm (from Higgins 2007)

2003). A Solid Works (SolidWorks Corporation 2008) model was developed for each arm and the ease of reaching a set of three hundred ninety six points in XYZ was then determined. Based on their findings, they have designed and built a new seven degree of freedom wheelchair mounted robotic arm with custom end effector, shown in Figure 5 (Alqasemi et al. 2005) (Alqasemi et al. 2007) (Higgins 2007). The robot arm was controlled in Cartesian space using both standard and novel input devices, including joystick, keypad, switches, hand tracking devices, and haptic devices (Alqasemi et al. 2005).

The Institute of Automation at the University of Bremen in Germany has created also created a custom seven degree of freedom wheelchair mounted robotic arm, FRIEND II (Valbuena et al. 2007). FRIEND II, shown in Figure 6, was the successor of FRIEND I, which used a Manus ARM for manipulation (discussed later in this section). Like FRIEND I, it was controlled with speech recognition and a pressure sensitive lap tray (Volosyak et al. 2005). FRIEND II was also controlled with a Brain-Computer Interface which read the user's electroencephalography (EEG) signals (Valbuena et al. 2007). The EEG signals were used to traverse a topological graphical user interface (i.e. "right" or "next," "left" or "previous," "select" or "open" or "start," and "cancel" or "back") (Valbuena et al. 2007). Users would navigate to

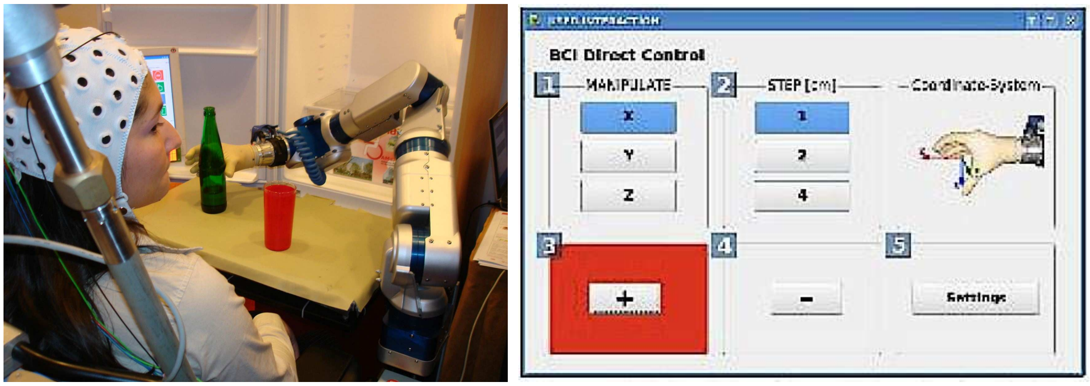

Figure 6. The University of Bremen's FRIEND II exhibited at ICORR'07 (Courtesy of Michelle Johnson). The manual control graphical user interface is shown on the right (from Lüth et al. 2007).

their desired semi-autonomous task, such as "pour in beverage" and "serve beverage." For manual control, another graphical user interface was provided. The user could translate or rotate the end-effector in Cartesian space by ± 1 cm, 2 cm, or 4 cm with respect to world or gripper coordinates (Lüth et al. 2007).

The Bath Institute of Medical Engineering in the United Kingdom created a custom wheelchair mounted robotic arm, Weston (Hillman et al. 2002). Weston was the successor of Wolfson, a workstation, and Wessex, a mobile manipulator. Weston was designed to maximize the range of manipulation on a horizontal plane. The robot arm, shown in Figure 7 (left), had five motors on its upper arm, one motor for vertical adjustment, and one motor for the gripper (Bath Institute of Medical Engineering 2008). Weston was controlled using a joystick, which could be a power wheelchair user's drive joystick in an integrated system (Hillman et al. 2002). The graphical user interface was menu based and displayed on a monochrome LCD. The gross movements of the robot arm was controlled in one menu (shown in Figure 7 on the right) and the fine gripper movements in another, but similar, one. Weston moved in Cartesian space and polar coordinates and could be preprogrammed with six tasks. Weston was evaluated with four end-users. Two participants were spinal cord injury patients, and

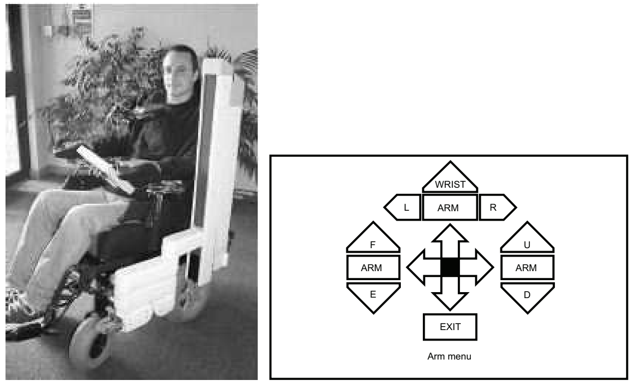

Figure 7. The Bath Institute of Medical Engineering's Weston robot arm is shown on the left, and graphical user interface shown on the right. (from Hillman et al. 2002)

Figure 8. The Flexator pneumatic air muscle robot arm by Inventaid (from Valiant Technology 2008)

two were diagnosed with spinal muscular atrophy. Due to mounting issues, only one participant was able to have Weston mounted to his power wheelchair and the other three participants used Weston mounted to a mobile platform.

The Flexator was developed by Inventaid (Henniquin 1992). The pneumatic air muscle robot arm was composed of eight joints, as shown in Figure 8 (Prior et al. 1993) (Valient Technology 2008). Middlesex University investigated the feasibility of using the Flexator as an assitive arm (Prior and Warner 1991) (Prior et al. 1993). A kinematic model for a sip-puff interface had been developed for training purposes (Prior 1999).

Although the Flexator was low cost and easy enough to use, precise control was difficult due to the nature of the pneumatic actuators. Middlesex University subsequently created an electrically actuated five degree of freedom wheelchair robot

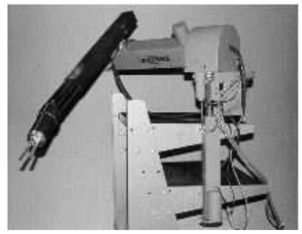

Figure 9. The Middlesex Manipulator (from Parsons et al. 2005)

Figure 10. The Polytechnic University of Catalunya's Tou is shown on the left (from Casals 1999). Tou's adapted keyboard is shown on the right (from Casals et al. 1993).

arm, the Middlesex Manipulator (Parsons et al. 2005). The robot arm, shown in Figure 9, could be operated in joint and Cartesian space, be preprogrammed with trajectories and absolute positions, and execute a preset task. The Middlesex Manipulator was controlled using speech recognition, head gestures, and biological signals, such as electromyogram (EMG). A case study evaluation was completed with a spinal cord injury (C4) patient.

The Polytechnic University of Catalunya in Spain created a modular, snake-like wheelchair mounted robotic arm (Casals 1999). Tou, shown in Figure 10 (left), was a "soft arm" which was designed to guarantee the safety of its user. Each link was a foam cylinder. Tou was controlled using voice recognition, adapted keyboard (shown in Figure 10 on the right), and joystick. Tou moved in Cartesian space ("up-down," "approach-go," and "right-left") and was able to be preprogrammed with tasks (Casals et al. 1993). Two case study evaluations were completed by tetraplegic patients.

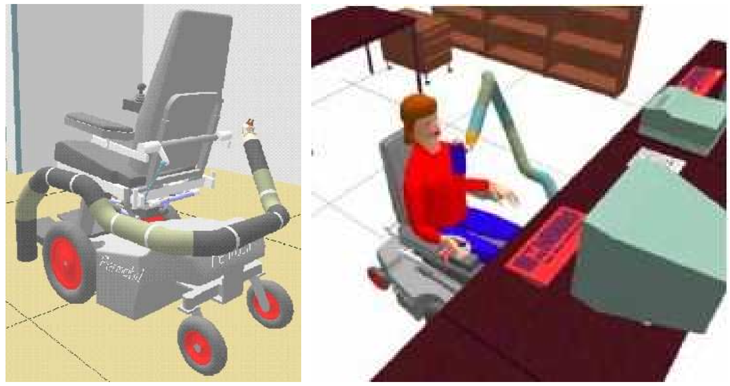

Figure 11. Simulation of Lund University's ASIMOV robot arm (from Fridenfalk et al. 1999)

At Lund University in Sweden, the Asimov project also created a modular, snake-like arm, shown in Figure 11 (Fridenfalk et al. 1999). Asimov was initially designed to have eight degrees of freedom to maximize the range of manipulation. It could be manually controlled from a power wheelchair user's drive joystick. The concept of Asimov was first tested in simulation and then a prototype was then built.

At KAIST in Korea, the KAIST Rehabilitation Engineering Service System (KARES) project created two custom six degree of freedom robot arms, KARES I (Song et al. 1998) and KARES II (Bien et al. 2003) (KAIST 2008). KARES I, shown in Figure 12 (left), was a six degree of freedom wheelchair mounted robotic arm (Song et al. 1998). It was controlled manually using a ten key keypad and voice recognition. KARES I was also designed to complete four autonomous tasks (picking up and drinking from a coffee cup, picking up a pen from the floor, feeding, and operating a switch on the wall). KARES II, shown in Figure 12 (right), was the successor of KARES I. It was also a six degree of freedom mobile manipulator and was controlled using an "eye-mouse," a haptic suit, and electromyogram (EMG) signals (Bien et al. 2003). KARES II also had the capacity for "intention reading," such as the intention to drink which was gauged by the openness of the user's mouth.

Figure 12. KAIST Rehabilitation Engineering Service System I (left) (from Song et al. 1998) and II (right) (from KAIST 2008)

Figure 13. The Raptor Wheelchair Mounted Robotic Arm (from Phybotics 2008). The Raptor exhibited at ICORR'07 (Courtesy of Michelle Johnson).

The intentions could then be interpreted for semi-autonomous manipulation of the robot arm.

The Raptor was a commercially available wheelchair mounted robot arm manufactured by Phybotics (2008). It had four degrees of freedom and a two-fingered gripper for manipulation, shown in Figure 13. The Raptor was approved by the U.S. Food and Drug Administration as an assistive robot (Phybotics 2008). The Raptor was controlled using a joystick, keypad, or a sip-puff interface (Parsons et al. 2005) The Raptor moved by joint reconfiguration, did not have joint encoders, and could not be preprogrammed in the fashion of industrial robotic arms (Alqasemi et al. 2005).

The University of Pittsburgh's Human Engineering Research Laboratories evaluated the effects of a Raptor arm on the independence of eleven spinal cord injury patients (Chaves et al. 2003a). Participants first completed sixteen ADLs without the Raptor arm, then again after initial training, and once more after thirteen hours of use. At each session, the participants were timed to task completion and classified as *dependent*, *needs assistance*, or *independent*. Significant ($p < 0.05$) improvements were found in seven of the sixteen ADLs, included pouring or drinking liquids, picking up straws or keys, accessing the refrigerator and telephone, and placing a can on a low surface (Chaves et al. 2003b). However, there were nine ADLs, including making toast, which showed no significant improvement, which the researchers ascribed to several factors. One possibility was the task complexity in the number of steps to completion and/or the advanced motor planning skills required. The researchers also believed the joystick input device for manual control did not correlate well to the users' motor skills (Chaves et al. 2003b).

Clarkson University evaluated eight multiple sclerosis patients over five ADLs with and without the Raptor arm (Fulk et al. 2005). The participants in this study all required assistance with self-care ADLs. Participants were evaluated before and after training on the Raptor arm. At each session, the participants were timed to task completion and interviewed. They also rated the level of difficulty of task performance and the Psycholosocial Impact of Assistive Devices Scale (Day et al. 2002). There was no statistical significance in task completion time and perceived level of difficulty in the five ADLs after training (Fulk et al. 2005). However, two users who were able to complete some of the ADLs manually were better able to complete the ADLs with the Raptor in a more functional and safe manner.

The Manus Assisive Robotic Manipulator (ARM) was a wheelchair mounted robot arm, developed and sold by Exact Dynamics (Exact Dynamics 2008). It was a six plus two degree of freedom robot arm, shown in Figure 14. The Manus ARM was controlled using a joystick, single switch, or alpha-numeric keypad. Each device had a corresponding menu of operation, as shown in Figures 23, 24, and 25 in Chapter

Figure 14. The Manus Assistive Robotic Manipulator can assist in activities of daily living, such as operating door handles and putting on glasses (from Exact Dynamics 2008).

4. The Manus ARM moved by joint reconfiguration, like the Raptor, or in Cartesian space. The Manus ARM had joint encoders, which provide readings as to its configuration.

Long-term end-user evaluations on the effect of the Manus ARM on ADLs have been conducted by Exact Dynamics and other institutions. In 1998, the Siza Village Group, a collaboration of facilities for individuals with physical and cognitive disabilities in the Netherlands, conducted an end-user evaluation of the Manus ARM with eight participants over the course of one year (Siza Dorp Groep 2008) (Brand and Ven 2000) (Römer et al. 2005). The eight participants had no prior experience with the Manus ARM and so received training with the robot arm (Römer et al. 2005). Week-long observations occurred every twelve weeks during which the amount and duration of the Manus ARM usage was recorded. The study estimated that, despite a range of physical and cognitive ability, 0.7 to 1.8 hours of caregiver costs could be saved each day.

In 1999, the Institute for Rehabilitation Research in the Netherlands conducted a study of the Manus ARM with respect to quality of life and usage (Gelderblom et al. 2001) (Römer et al. 2005). The study compared twenty one participants who did not use the Manus ARM versus thirteen participants who did.[1] The participants' independence (and, conversely, required assistance) and perceived quality of life was recorded over the course of four years. The ADLs were not constrained and included "eating, drinking, self-care activities like washing and brushing teeth, removing objects from the floor or out of the cupboard, feeding pets, and operating typical devices such as a VCR" (Römer et al. 2005). The study reported that participants with the Manus ARM were able to complete 40% more ADLs independently.

Two of the requirements of a potential Manus users were that a user has "very limited or non-existent arm and/or hand function, and cannot independently (without help of another aid) carry out ADL-tasks" and "have cognitive skills sufficient to learn how to operate and control the ARM" (Römer et al. 2004). Thus, the Manus ARM was largely suited to users who had limited motor dexterity and typical cognition. For example, Eva Almberg, a Swedish Manus ARM user since 1998, had congenital spinal muscular atrophy and limited mobility in her right arm and hand (Neveryd et al. 1999). Almberg reported, "When I thought about having a robotic arm I imagined it would bring a great deal of independence. I thought I would be able to manage on my own to a much greater extent than I am... I can spend more time on my own with the aid of the Manus, but not as spontaneously or as long as I thought I would."

Because of the high level of cognitive awareness required to operate the Manus ARM for long periods of time, several research institutions have investigated alternative interfaces. At the New Jersey Institute of Technology, Athanasiou et al. (2006) proposed three alternative interfaces for the Manus ARM: an infrared sensory box, a stylus with joints mimicking the robot arm, and a computer mouse.

[1] The thirteen participants with the robot arms also had full time caregivers and were not required to use the Manus ARM.

At TNO Science & Industry and the Delft University of Technology, the Manus ARM was augmented with cameras, force torque sensors, and infrared distance sensors. Their alternative interface, shown in Figure 15, was operated by a wheelchair joystick and a switch in "pilot mode" shared autonomy between the robot arm and the user (Driessen et al. 2005).

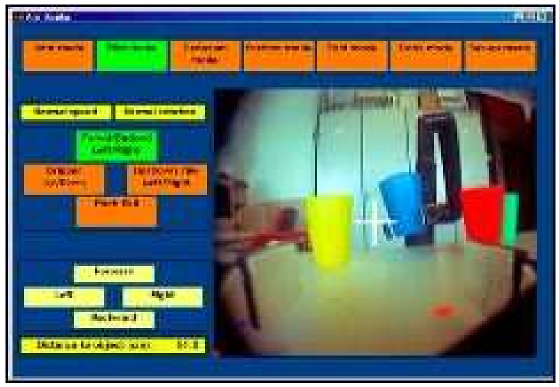

Figure 15. TNO Science & Industry and Delft University's alternative Manus ARM interface (from Driessen et al. 2005)

At the Institute of Automation at the University of Bremen in Germany, FRIEND I used a Manus ARM with uncalibrated stereo cameras and a pressure sensitive lap tray (Volosyak et al. 2005). The gripper was outfitted with an LED for localization purposes. Speech recognition was used to direct the robot arm in open-loop control.

At INRIA (Institut National de Recherche en Informatique et en Automatique), Dune et al. (2007) explored a "one click" computer vision approach. The robot arm was equipped with two cameras. The "eye-in-hand" camera provided a fixed overview of the workspace and the "eye-to-hand" camera offered a detailed view of the scene. The user clicked on the desired object (Leroux et al. 2004). Then the robot arm moved toward the object using a visual servoing scheme along the corresponding epipolar line (Dune et al. 2007).

2.3 Discussion

The research conducted at INRIA and TNO Science & Industry is the most similar to our research. INRIA has explored a "one click" single input approach for use with the Manus ARM. However, they largely focused on a geometrical means of approaching an object based on computer vision. To our knowledge, INRIA has not yet addressed the user interface aspect of their "one click approach."

TNO has focused on the user interface of the Manus ARM. Figure 15 depicts TNO's alternative interface to the menu hierarchy. Improvements, such as the gripper camera view and the display of estimated distance to object, have been made. However, the hierarchy for operation existed as modes shown as six buttons across the top of the interface (left to right: Joint mode, Pilot mode, Cartesian mode, Position mode, Fold mode, and Drink mode) (Driessen et al. 2005). The functionality to move the Manus ARM has been mapped to two groups of four buttons shown to the left of the video window (gripper controls clockwise from top: Forward/Backward and Left/Right, Up/Down Yaw and Left/Right, Pitch Roll, and Gripper Up/Down; arm controls clockwise from top: Forward, Right, Backward, Left) (Driessen et al. 2005). We believe this interface design is too complicated for user with cognitive impairments.

Our research focuses on creating better human-robot interaction with the Manus ARM. Our goal is to manipulate objects in an unstructured environment with a coordinate system centered around the user. We constrain our task to the "pick-and-place" ADL. We use a simple approach of allowing the user to specify the desired object from a live video feed. Our Manus ARM then autonomously reaches towards the specified object without further control from the user.

Further, our team is a multi-disciplinary collaboration with three main components: computer scientists and robotics researchers from UMass Lowell, occupational therapists and assistive technologists from Crotched Mountain Rehabilitation Center, and mechanical engineers from the University of Central Florida. As such, our occupational therapy and assistive technology team members have played an essential role in grounding our research in reality. We have taken an iterative prototyping approach to our interface research.

Most importantly, we have identified a unique end-user profile. Our target audience is people who use wheelchairs and may additionally have cognitive impairments. A subset of the assistive robot arm projects detailed in this chapter have stated their end-user profile. Of those, a subset have conducted experiments with end-users. The participants in these experiments largely included people with spinal cord injury and multiple sclerosis.

For example, TNO Science & Industry evaluated their interface with both able-bodied participants and end-users (further discussed in the next chapter). However, the end-user experiment lacked statistical significance due to the small data sample, thus their results were anecdotal. We have also conducted able-bodied and end-user evaluations, which ran with eight user for a period of eight weeks. In both experiments, we analyzed the data quantitatively and qualitatively.

CHAPTER 3

EVALUATION OF HUMAN-ROBOT INTERACTION WITH ASSISTIVE TECHNOLOGY

As a part of this research, we must evaluate our systems with the intended user groups. Experimental design for any human subject research has many facets to consider. There are a number of experiment types including controlled experiments, observational studies, and surveys. The type of participants in studies vary largely; for example, undergraduate college students, emergency responders, or pre-school children with developmental disabilities. The duration of a study can be a few minutes, hours, weeks, months, or years. Data collection can be both direct and indirect. For example, direct methods include pre- and post-experiment questionnaires, task completion time, measurement of cognitive workload. Indirect methods include post-hoc analysis and coding from video recordings.

Experimental design in assistive technology borrows heavily from clinical trials for medical devices, as they have an established protocol. The Good Clinical Practice Protocol requires clearly stated objectives, checkpoints, and types and frequency of measurement (US Food and Drug Administration 1997). It requires a detailed description of the proposed study and preventative biasing measures. The expected duration of the trial and treatment regiment and record keeping strategies must also be detailed. Further, “discontinuation criteria” for subjects or the partial/whole trial must be clearly defined.

Experimental design in human-robot interaction (HRI) is not quite as well established as clinical trials. However, it borrows from more established domains such as human-computer interaction (HCI), computer supported cooperative work (CSCW), human factors, and psychology. Drury, Scholtz, and Kieras (2007) applied GOMS (goals, operators, methods, selection rules) analysis (Card et al. 1983) from HCI to human-robot interaction. Drury, Scholtz, and Yanco (2004) employed the "think aloud" protocol (Ericcson and Simon 1980) from HCI and coding from psychology. Humphrey et al. (2007) used the NASA-Task Load Index (Hart and Staveland 1988) from human factors.

Experimental design at the intersection of human-robot interaction and assistive technology[1] is more complex due to the unique abilities of the people, thus generalizations cannot be easily made. Experimental design must consider a person's physical, cognitive, and behavioral ability. When executing a testing session, the quality of the data and length of the session is dependent upon the patient's mood, attentiveness, and endurance on a given day. The types of experiments conducted largely inherits from HRI (controlled experiments and observational studies as opposed to clinical evaluations). However, as with assistive technology, end-user evaluation is more prevalent; able-bodied subjects provide an upper bound of expected performance. A number of human-robot interaction for assistive technology (HRI-AT) studies have been conducted in areas such as autism therapy, stroke therapy, and eldercare. Some of the workstations and wheelchair mounted robotic arms described in Chapter 2 were also evaluated with their intended end-user. Six studies are detailed below, which represent the spectrum of methodologies, number of end-users, data collected, and statistical analysis.

[1] Assistive technology is any device or process that helps a person accomplish a task that they were not previously able to complete or had great difficulty completing (Wikipedia.org 2008c). An assistive device may be a high tech solution, such as a mouse emulating joystick or text-to-speech software. An assistive device may also be a low tech solution, such as a writing brace or door knob gripping cover.

3.1 Definitions

An experiment is defined as "a test or procedure carried out under controlled conditions to determine the validity of a hypothesis or make a discovery" (Dictionary.com 2007b). Controlled experiments are used to compare number of conditions. For example, two conditions are compared in an *AB*-style experiment. Users participate in all conditions in a within subjects study. In a between subjects study, users participate in only one condition as a new group of users is needed for each variable tested. Hypotheses answered with a controlled experiment require quantitative data for statistical significance, such as time to task completion. Controlled experiments are widely used in human subject research.

The term "observational study" is borrowed from psychology and social sciences. Derived from Wikipedia (Wikipedia.org 2008c) definition of longitudinal study, we define "observational study" as "a correlational research study that involves repeated observations over a long period of time, often months or years." A single condition per participant is tested for the duration of the study. Observational studies are also widely used in human subject research.

3.2 Controlled Experiments

Tijsma et al. (2005) conducted experiments of human-robot interaction with the Manus ARM in both a lab setting and field evaluation. In the lab evaluation, sixteen able-bodied subjects participated in a 2×2 experiment[2] (conventional mode switching versus their new mode and Cartesian mode versus "pilot" mode). The participants executed two tasks: picking up an upside-down cup and placing it right-side-up into

[2]Previously we described controlled experiments in terms of alphabetical characters. An *AB*-style experiment tests two conditions. A 2×2 experiment tests four conditions and may also be called an *ABCD*-style experiment. In this case, Latin squares were used to counter balance the start conditions (e.g., *ABCD*, *BCDA*, *CDAB*, and *DABC*).

another; and picking up a pen and placing it in the same cup. The experimental conditions were balanced using two Latin squares[2] (Bradley 1958). A third task, placing a block into a box of blocks, was used to investigate the center of rotation of the gripper (conventional versus alternative). Data collected included the number of mode switches, task time, and Rating Scale of Mental Effort (Zijlstra 1993). Factorial ANOVA (Langley 1971) was applied for statistical significance for the first two tasks, and standard ANOVA on the third task.

In Tijsma et al.'s field trial, four end-user participants were recruited; however, the interface was successfully integrated with the wheelchair joysticks of only two participants. The participants executed three tasks: picking up an upside-down cup and placing it right-side-up in another and picking up a pen and placing it in the same cup (the first two tasks of Tijsma et al.'s able-bodied experiments); putting two square blocks in a box of blocks (the third task of Tijsma et al.'s able-bodied experiments); and retrieving two pens out of sight. A baseline experiment was comprised of the first task in Cartesian mode and the second task in the conventional center of rotation; the third task was not part of the baseline evaluation. Due to fatigue, the participants were only able to perform one trial per experimental condition. Data collected included the number of mode switches, task time, Rating Scale of Mental Effort (at 5, 10, 20, and 40 minutes), and survey responses. Field study results were anecdotal due to the small sample size and insufficient data.

3.3 Observational Studies

Wada et al. (2004) conducted a longitudinal study of the therapeutic effects of Paro at an elderly day service center. Paro was a therapeutic robot seal shown in Figure 16 (National Institute of Advanced Industrial Science and Technology 2008). Twenty three elderly women, age seventy three to ninety three, volunteered or were selected

Figure 16. Paro, the theraputic robot seal (from National Institute of Advanced Industrial Science and Technology 2008)

to participate. The women interacted with Paro for twenty minute blocks for five weeks, one to three times per week, in groups of eight or less. Data collected included a self assessment of the participant's mood (pictorial Likert scale of 1 (happy) to 20 (sad)) before and after the interaction with Paro; questions from the Profile of Mood States questionnaire (McNair et al. 1992) to evaluate anxiety, depression, and vigor (Likert scale of 0 (none) to 4 (extremely)); urinary specimens; and comments from the nursing staff. Wilcoxson's sign rank sum test (Langley 1971) was applied to the mood scores to determine significance.

Wada et al. (2004) also examined the effects of Paro on the nursing staff with respect to burnout. Over a period of six weeks, four female and two male staff members participated in the burnout scale questionnaire once per week. Friedman's test (Langley 1971) was used to determine statistical significance on the total average score of the burnout scale.

Kozima et al. (2005) have used Keepon to studied social interactions in children with developmental disorders. Keepon was a four degree of freedom, minimally expressive social robot shown in Figure 17 (Kozima et al. 2007). A longitudinal study was conducted for over eighteen months with a group of children, ages two to four, at a day-care center in Japan (Kozima et al. 2005). Keepon was placed in the playroom. In a three-hour session, the children could play with Keepon during free play. During group activities, Keepon was moved to the corner. The paper detailed

Figure 17. National Institute of Information and Communications Technology's Keepon (from Kozima et al. 2007)

a case study of two autistic children in an anecdotal fashion. The first case described the emergence of a dyadic relationship of a girl with Kanner-type autism over five months with Keepon. The second case described the emergence of a interpersonal relationship between a three-year old girl, also with Kanner-type autism, her mother or nurse, and Keepon over eighteen months.

Robins et al. (2004) studied the effect of exposure to a robot doll, Robota (shown in Figure 18), over a long period of time on social interaction skills of autistic children. Four children, ages five through ten, were selected by their teacher to participate in this longitudinal study. Over a period of several months, the child interacted with the robot doll as many times as possible in an unconstrained environment. Trials lasted as long as the child was comfortable and ended when the child wanted to leave or was bored. In the familiarization phase, the robot doll danced to pre-recoded music. In the learning phase, the teacher showed the child that the robot doll would imitate his or her movements. Free interaction was similar to the learning phase without the teacher. A post-hoc analysis of video footage of interaction sessions yielded eye gaze, touch, imitation, and proximity categories. All video data

Figure 18. Robota, robot doll (from Robins et al. 2004)

Figure 19. ESRA, robot face (from Scassellati 2005)

was coded[3] on one second intervals using these four categories. An extension study investigated the preference of robot doll appearance (pretty versus plain).

Scassellati has also investigated human-robot interaction children with autism spectrum disorder (Scassellati 2005). In a pilot experiment, seven children with autism and six typically-developing children watched ESRA, a robot face shown in Figure 19, change shape and make sounds. The robot functioned in two modes: scripted and teleoperated. The session began with the script where the robot face "woke up," asked some questions, then "fell asleep." Then the operator manually controlled the robot face. Data collected included social cues such as gaze direction. Eye gaze was analyzed in each frame to determine the primary location of focus. The focal points were used train a linear classifier used to generate predictive models.

[3]One common scoring process involves content analysis (Robins et al. 2007). Units may range from keywords, phrases, or categories. Categories and definitions are defined from these units. The data, such as open ended responses to questions or recorded, can be annotated with the categories. Unit and definitions may need to be iteratively tuned. To ensure reliability, multiple coders are trained on the units and definitions. The scores must be correlated and Cohen's (1960) kappa is frequently used.

Figure 20. Université de Sherbrooke's Tito (from Michaud et al. 2005)

Michaud et al. (2007) conducted an exploratory study of low-functioning autistic children with a sixty centimeter tall humanoid robot, Tito (shown in Figure 20). Four autistic children, all age five, participated in a seven week study. Each child played with Tito three times per week for five minutes. In a session, the robot asked the child to imitate actions including smiling, saying hello, pointing to an object, moving their arms, and moving forwards and backwards. The child's favorite toy was also placed in the room with the robot. Data collected included video and automated interaction logs. The interactions were categorized into shared attention, shared conventions, and absence of shared attention or conventions; all video data was coded using twelve second windows. The coding was completed by two evaluators with a confidence[3] of 95%.

3.4 Discussion

In HRI-AT, the results tend to generally be more qualitative due to the uniqueness of the patients within a population. The data from a session may be skewed due to the patient's mood, their anxiety level, pain, sleepiness, etc. The Profile of Mood States questionnaire (McNair et al. 1992) can be used in self evaluation, but, largely, it is the subjective notes of an observer that capture the patient's unusual behaviors and feelings. However, quantitative analysis is still possible using measures such as interaction time and instances of classifications from coding.

We conducted a controlled experiment using able-bodied subjects as an evaluation baseline in August 2006. We collected both quantitative (e.g., time to task completion, distance to object, number of clicks, Likert scale rating) and qualitative (e.g., pre- and post-experiment surveys, observer notes) data. We conducted field trials with cognitively impaired wheelchair users in August and September 2007. To lend power to our evaluation with our target population, we conducted a hybrid observational evaluation; that is, we conducted a controlled experiment with four conditions, and ran the experiment for eight weeks. The subjects participated as frequently as possible, ranging from one session to eight. Again, we collected both quantitative (e.g., time to object selection, attentiveness rating, and prompting level) and qualitative (e.g., post-experiment questionnaire and experimenter notes) data.

CHAPTER 4

ROBOT HARDWARE AND SOFTWARE

The Manus ARM has been in development since 1984 (Parsons et al. 2005). Over 225 units have been in use by end users and research institutions (Römer et al. 2005). We selected this platform because of its success in the assistive technology market and also because of two key mechanical components – the joint encoders and slip couplings which added safety features. It was a well supported platform both as an end product and as a research platform.

In order to create better human-robot interaction, we needed to augment our Manus ARM with sensors and rework the control system. We added a vision system comprised of a shoulder camera and a gripper camera. We replaced the standard access methods with a touch screen, joystick, and switch. We created a multi-threaded control system to receive and decode packets sent from the Manus ARM. We developed vision algorithms for motion control.

4.1 Manus Assistive Robotic Manipulator

The Manus ARM, shown in Figure 21, weighed 31.5 pounds (14.3 kilograms) and had a reach of 31.5 inches (80 centimeters) from the shoulder (Exact Dynamics 2008). The gripper maximally opened to 3.5 inches (9 centimeters) and had clamping force of 4 pounds force (20 Newtons). The payload capacity at maximum stretch was 3.3 pounds (1.5 kilograms).

Figure 21. UMass Lowell's Manus ARM, Halo meaning "happy robot" in Japanese.

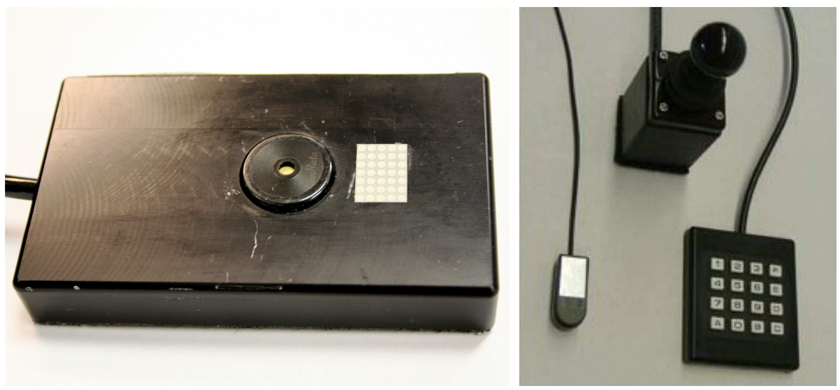

Figure 22. (Left) Feedback of the robot arm's current status was shown in a 5 × 7 LED matrix and piezo buzzer. (Right) The Manus ARM was controlled manually with a keypad, joystick, or single switch.

A user manually controlled the Manus ARM by accessing menus via standard access devices, such as a keypad, a joystick, or a single switch, as shown in Figure 22 (left). Feedback of the robot arm's current state was depicted on a small LED matrix and piezo buzzer, as shown in Figure 22 (right). Figures 23, 24, and 25 show the hierarchical menus corresponding to the keypad, joystick, and single switch inputs, respectively.

The Manus ARM was produced in two styles (a left and a right version) to accommodate the user's preference and available space on either side of the user's power wheelchair (Exact Dynamics 2008). Our Manus ARM is a right-mounted robot arm. The Manus ARM was typically mounted on a power wheelchair over the

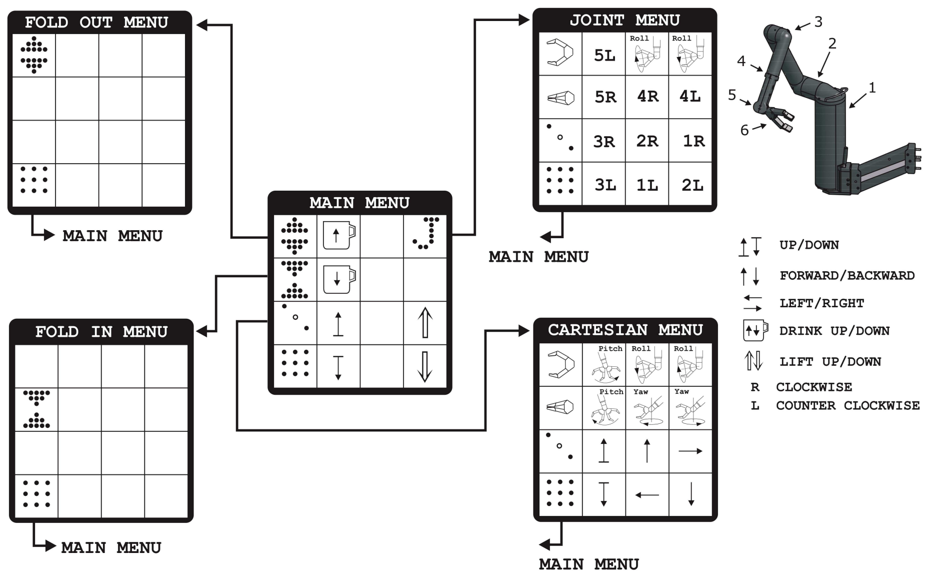

Figure 23. The Manus ARM's keypad menu was two layers deep for all functionality. The menus corresponded directly to the 4 × 4 alpha-numeric keypad. (Courtesy of Exact Dynamics)

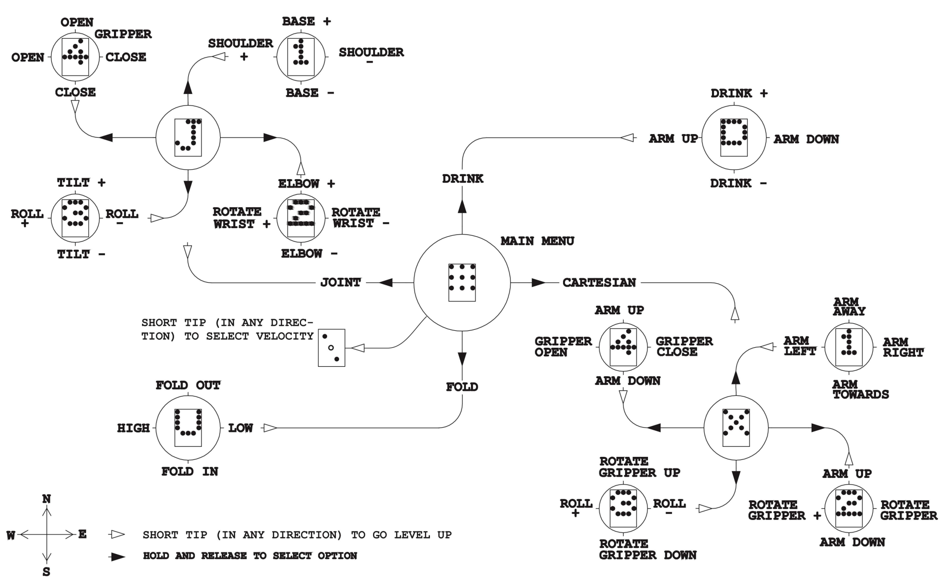

Figure 24. The Manus ARM's joystick menu was three layers deep to move in joint or Cartesian mode. To access a submenu, the user quickly tapped the joystick in the corresponding direction. (Courtesy of Exact Dynamics)

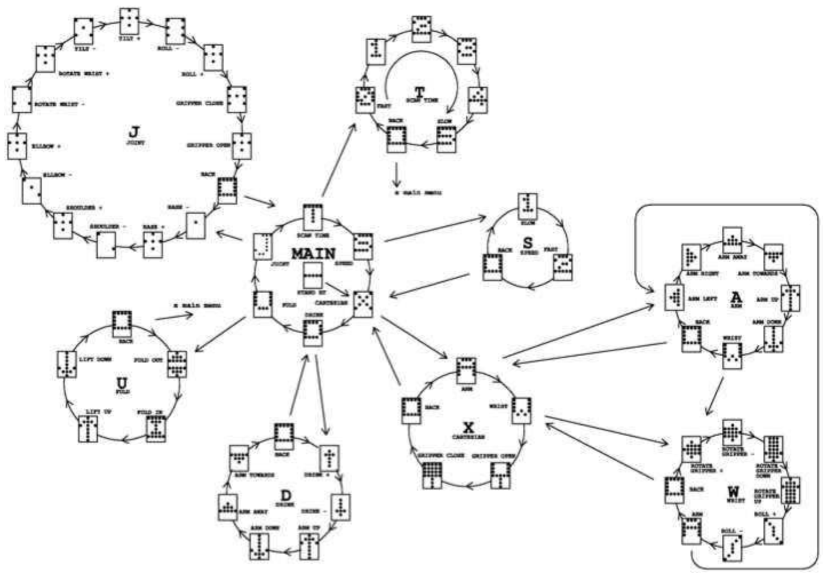

Figure 25. The Manus ARM's single switch menu was two or three layers deep depending upon the desired functionality and may interconnect between submenus. The timing component inherent to single switch applications was indicated as a clockwise cycle. (Courtesy of Exact Dynamics)

front wheels, as shown in Figure 26. The Manus ARM should be folded when not in use and during transport. During each usage, the user opened the robot arm with a sustained press while the Manus ARM unfolded along a preprogrammed trajectory. Then the user controlled the Manus ARM to perform an ADL. When complete, the user closed the robot arm again with a sustained press while the Manus ARM folded along a preprogrammed trajectory.

The joint mode, shown in Figure 27 (right), allowed the user to control the Manus ARM by moving its joints individually. The Cartesian mode, shown in Figure 27 (left), allowed the user to move the gripper of the Manus ARM linearly through the 3D *xyz* plane. In Cartesian mode, because the forward kinematics are computed onboard the Manus ARM, multiple joints could move simultaneously, unlike in joint mode.

The Manus ARM was programmable. The encoders values could be used for computer control. It communicates through controller area network (CAN) packets,

Figure 26. The Manus ARM was typically mounted over the front wheels of a power wheelchair. Left and right Manus ARMs are shown left and right, respectively. (from Exact Dynamics 2008)

Figure 27. The Manus ARM was controlled by moving its joints independently or by moving the gripper linearly through Cartesian space. (from Exact Dynamics 2008)

sending status packets at a rate of 50Hz to a CAN receiver. As with manual control, the Manus ARM could be operated in either joint or Cartesian mode.

4.2 Manus Augmentation

We added a vision system with two cameras to improve user interaction with the Manus ARM. A Canon VC-C50i pan-tilt-zoom camera at the shoulder provided the perspective of the wheelchair occupant for the interface (Canon 2003). The shoulder camera had 460 lines horizontally and 350 vertically. The viewing angle was approximately 45° and the capture mode was NTSC with 340,000 effective pixels. The

Figure 28. (Left) A Canon VC-C50i on the "shoulder" of the Manus ARM approximated the wheelchair occupant's view. (Right) A camera mounted within the gripper provided an up close view of the object to be grasped.

pan, tilt, and zoom functionality was controlled through a serial (RS-232) port. The Canon camera was able to pan $\pm 100^\circ$ and tilt -30° to $+90^\circ$. It featured a twenty six level zoom.

A small PC229XP CCD Snake Camera that we mounted within the gripper provided a close up view for the computer control, shown in Figure 28 (left) (Super Circuits 2008). The gripper camera lens measured 0.25 inches (11 millimeters) by 0.25 inches (11 millimeters) by 0.75 inches (18 millimeters). There was 6 inches (25 centimeters) of cable between the computational board which was mounted to the outside of the gripper. The gripper camera had 470 lines horizontally. Its viewing angle was approximately 50° and the capture mode was NTSC with 379,392 effective pixels. We empirically tuned the gripper camera to similar color, hue, contrast, and brightness as the shoulder camera using *xawtv*, a Linux TV application (Knorr 2008).

We replaced the Manus ARM's standard access methods with a touch screen and assistive computer input device. The touch screen was a 15 inch Advantech resistive LCD, shown in Figure 29 (left). The assistive computer input device was a USB Roller II Joystick which emulated a mouse, shown in Figure 29 (right). The computer that interfaces with the Manus ARM was a Pentium 4 2.8GHz Mini-ITX running Linux (2.6.15 kernel). The PC had a four-channel frame-grabber to accommodate the vision system. It also used a SerialSense (Chanler 2004) to poll the value of a red 3 inch jellybean switch, shown in Figure 29 (right), which was used as a supplementary access method. We replaced the Exact Dynamics proprietary ISA-CAN card with a GridConnect USB CAN adapter (Grid Connect Networking Products 2008).

Figure 29. Our visual interface utilizes commonly used assistive technology devices such as a touch screen (left), joystick (right), and jellybean switch (far right).

4.3 Control

Our computer control over the Manus ARM was multi-threaded to ensure timely response. The system data flow is shown in Figure 30. A communication thread stored and sent data to the Manus ARM. A decoding thread read the packets which contain the status and configuration of the Manus ARM, as well as generated a packet containing movement direction to be sent. The main thread from the interface computed the velocity inputs needed to move the Manus ARM.

4.3.1 Communication and Decoding Packets

The Manus ARM sent packets to the computer through the CAN bus every 20 ms (Exact Dynamics 2005). There were three types of incoming packets. The packets

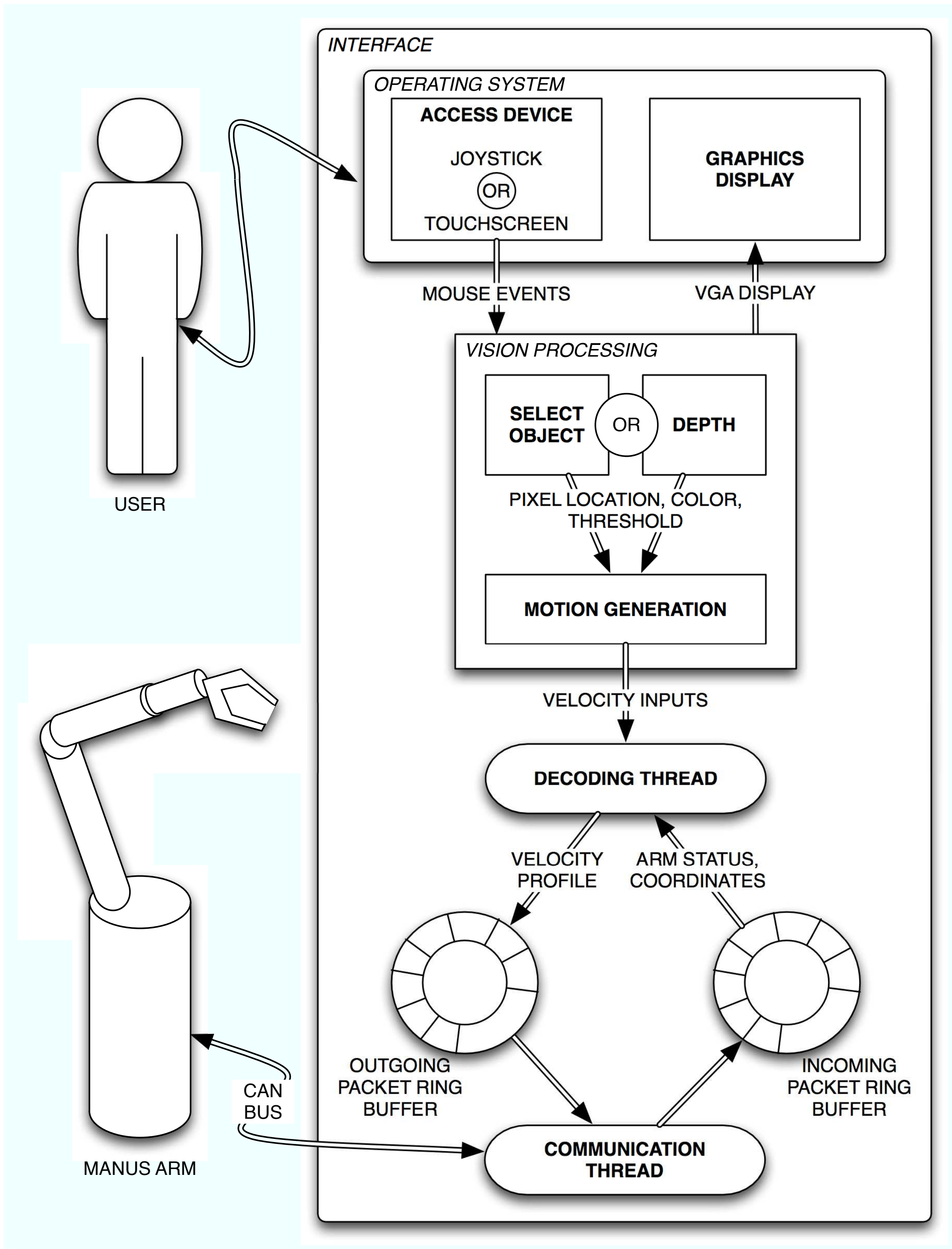

Figure 30. Data flow of our direct selection human-in-the-loop visual control system for the Manus ARM. The user provided input via touch screen or joystick mouse (top). The input was used in the vision processing (center) to position the robot arm (bottom).

cycled with IDs in the following manner: $0x350$, $0x360$, $0x37F$, $0x350$, $0x360$, and so on. $0x350$ packets and $0x360$ packets gave the status and configuration of the Manus ARM. $0x37F$ packets requested a packet in return.

To move the robot and interpret the encoder values, we created threads for communication with the Manus ARM and decoding its packets. The communication and decoding threads shared two semaphores as instances of the single producer/consumer problem (Tanenbaum 2001). The communication thread acted as the producer of the incoming packets semaphore. When a packet was received, the lock was acquired for the ring buffer. If there was space available, the new packet was inserted, the pointer for the next available slot was updated, and the message count was increased. The lock was released, and the decoding thread was signaled that there were packets waiting to be processed.

The decoding thread acted as the consumer for the incoming packet semaphore and as the producer for the outgoing packet semaphore. If there were incoming messages from the Manus ARM stored in the ring buffer, the lock was acquired. The packet was removed, the message count decremented, and pointer updated to the next status packet. The lock was released and the communication thread was signaled that there was space available for new incoming packets to be inserted.

The ID of the packet removed from the ring buffer was checked. $0x350$ packets updated the XYZ position of the Manus ARM's end effector (Exact Dynamics 2005). Additionally, warnings and errors were also read from the $0x350$ packets. $0x360$ packets updated the gripper's yaw, pitch, roll, and grasp. $0x37F$ packets indicated the the Manus ARM was waiting for a return packet with a movement information.

Four types of return packets were sent to Manus ARM (Exact Dynamics 2005). A $0x375$ packet unfolded the Manus ARM to its unfolded position along a preprogrammed trajectory. A $0x376$ packet curled the Manus ARM to its folded position along a preprogrammed trajectory. A $0x370$ packet halted all movement of the Manus ARM. A $0x371$ packet put the Manus ARM into Cartesian mode and specified how to move in XYZ, how to position the extended lift, and how to position the gripper using roll, pitch, yaw, and grasp. The velocity inputs were calculated from the arm movement controller function, which is further described in Section 4.3.3.

The decoding thread then acted as the producer of the outgoing packet semaphore. When a $0x37F$ packet was read from the incoming packet semaphore, a generated return packet was then inserted into the outgoing ring buffer. The communication thread acted as the consumer of the outgoing packet semaphore. When a $0x37F$ packet was received from the Manus ARM, a packet removed from the ring buffer was then written to the CAN bus for the Manus ARM to read.

4.3.2 Vision Processing Algorithms

Computer vision-based algorithms were used in both the indirect selection interface system and the direction selection interface system. In the indirect selection interface system, color tracking was used to control the movement of the Manus ARM. The indirect selection interface itself is further described in Chapter 5.

In the direct selection interface system, there were two Phission-based vision algorithms used to control the movement of the Manus ARM. The first algorithm used a custom Phission filter to decipher the color of an object and returned the largest instance of it within a given region. The second vision algorithm allowed the Manus ARM to move towards the desired object. The direct selection interface itself is further described in Chapter 6.

4.3.2.1 Phission Phission is a vision toolkit developed at the UMass Lowell Robotics Lab (Thoren 2007). It is a concurrent, cross-platform, multiple language vision software development kit. It constructs a processing sub-system of computer

Figure 31. The indirect selection interface system used color tracking to move the Manus ARM.

vision applications such as the interface presented in this paper. Phission abstracts the low-level image capture and display primitives. It supports multiple color spaces such as RGB (red, green, blue), YUV (luminance and chrominance), and HSV (hue, saturation, and value or brightness) (Wikipedia.org 2008b). We selected HSV for implementation of this interface due to its robustness in varying lighting conditions.

Phission includes several built-in vision algorithms. For example, color segmentation, or blob detection, finds all pixels in an image matching a particular color. Additional algorithms, such as region of interest (ROI) histogramming, can be easily integrated into Phission. Histogram analysis groups the pixel color values into bins; ROI histogramming shows the dominant color bin of a specified area.

4.3.2.2 Color Tracking in the Indirect Selection Interface System During the summer of 2006, a prototype system for the indirect selection interface was developed using color tracking. A fluorescent green bracelet was wrapped around the Manus ARM's "wrist," as shown in Figure 31. Prior to moving the robot, we color calibrated the value of the fluorescent green using histogram analysis to further reduce any lighting issues. The bracelet was tracked in pixel space from the shoulder camera view using a blob filter to control the movement of the robot arm.

Figure 32. Histogram analysis was performed on the 10×10 pixel region around the mouse click event. If a color was deciphered, then a bold, red rectangle surrounded the largest blob of that color within a 55×55 pixel region surrounding the mouse click.

4.3.2.3 Selecting an Object in the Direct Selection Interface When a user selected an object, a mouse click event was generated. Histogram analysis was performed in a 10×10 pixel area surrounding the click location. This color training returned the dominant color and threshold values. The color and histogram were used as input to Phission's blob filter. No adjustments to the hue, saturation, or brightness were needed because we immediately used the parameters.

In a 55×55 pixel region surrounding the click location, the blob filter looked for segments of the trained color. If the center of a non-trivial blob existed in the 55×55 pixel region, then a bold, red rectangle was drawn around the largest blob, as shown in Figure 30. This feedback indicated a positive object identification. Otherwise, no object was able to be discerned by the object selection algorithm. The center of the largest blob provided the destination to where the Manus ARM would open.

4.3.2.4 Deciphering Depth in the Direct Selection Interface System We required that the object must be in the gripper's view within twelve inches.[1] The

[1]For the purposes of integration, the team members at UMass Lowell and the University of Central Florida have decided that in the gross motion, the gripper should be at most twelve inches from the object. To proceed with the fine motion tracking and grasping, the object must be in the view of the gripper camera.

Figure 33. A view from the gripper camera after "dropping in" for depth Z. The gripper was well within twelve inches from the object.

color and threshold determined by the histogram was used to determine depth. The hue was widened slightly to accommodate minor color variation between the shoulder and gripper cameras. The saturation and value were liberally opened to accommodate for intensity and brightness variation which may have occurred due to environmental lighting or the texture of the object.

The object was segmented from the scene using a blob filter. We ignored trivial blobs of less than five hundred pixels. In the case of fragmentation, we interpreted blobs fragmented into less than ten pieces as one. The single larger blob was defined as the left-most, upper-most blob's upper-left (x_{pixel}, y_{pixel}) through the right-most, lower-most blob's lower-right (x_{pixel}, y_{pixel}). As the Manus ARM approached, the object increasingly filled the gripper camera's view. To keep the object in view, the gripper camera actively centered itself on the object. Figure 33 shows the gripper camera view after the Manus ARM "dropped in" for depth Z.

4.3.3 Generation of Velocity Inputs

We chose to program the Manus ARM to move in Cartesian mode because of the safety checks done by the math processor on the Manus ARM. To move the robot, Cartesian packets with velocity inputs were sent to the Manus ARM using computer control. In the Manus system, velocity v was given as

$$v = p/20 * 10^{-3} \tag{1}$$

where p was the position in millimeters, (Exact Dynamics 2005).

Our indirect selection interface system moved only in the XY plane towards the center of the selected location, emulating human motion control. The gripper of the Manus ARM centered on the shoulder camera view's XY position $\pm 3\%$ in pixel space. When the gripper was far from the desired location, the Manus ARM moved towards the location at a rate of 7 cm/s. As the gripper more closely approached the location, the velocity proportionally decreased using the following equations:

$$V_x = \begin{cases} 0 \text{ cm/s if within } \pm\ 3\% \text{ of location} \\ (1.0 - C_x) \times (7 \text{ cm/s}) \text{ if left of location} \\ \max(C_x - 1.0) \times (7 \text{ cm/s}), 7\text{cm/s}) \text{ if right of location} \end{cases}$$

$$V_y = \begin{cases} 0 \text{ cm/s if within } \pm\ 3\% \text{ of location} \\ (1.0 - C_y) \times (7 \text{ cm/s}) \text{ if above location} \\ \max(C_y - 1.0) \times (7 \text{ cm/s}), 7\text{cm/s}) \text{ if below location} \end{cases} \tag{2}$$

where C_x and C_y were the pixel locations of the center point of the current blob with respect to the size of the shoulder camera's capture size. For the purposes of indirect selection interface system, the depth Z was fixed.

In the direct selection interface system, we removed the color tracking of the fluorescent green bracelet.[2] The encoders provided the Manus ARM "wrist" coordi-

[2] We removed the color tracking of the fluorescent green bracelet for several reasons. First, the color tracking was not as reliable as anticipated. As the end effector moved away from the user (and into the scene), the blobbing was not able to find the green from the shoulder camera view, even when using the HSV color space. Second, when reaching for a target on the right side of the shoulder camera view, the bracelet was occluded by the "upper" arm, corresponding to axis 2. Third, the precision of the movement was directly related to the size of the capture window.

nates in Cartesian space. We correlated the coordinate space of the shoulder camera to the coordinate space of the Manus ARM using the following linear equations:

$$
\begin{aligned}
X_{arm} &= 42.1546875 \times X_{pixel\_point} + 17632 \\
Y_{arm} &= 40.2479167 \times Y_{pixel\_point} + 13458
\end{aligned} \tag{3}
$$

After the X_{pixel}, Y_{pixel} output from the object selection was translated into X_{arm}, Y_{arm} coordinates, the Manus ARM unfolded. It then moved towards the selected object in XY. The following equations determined the velocities for movement in XY:

$$
V_x = \begin{cases} 0 \text{ cm/s if within} \pm 3\% \text{ of } X_{arm} \\ 7 \text{ cm/s if left of } X_{arm} \\ -7 \text{ cm/s if right of } X_{arm} \end{cases}
$$

$$
V_y = \begin{cases} 0 \text{ cm/s if within} \pm 3\% \text{ of } Y_{arm} \\ 7 \text{ cm/s if above } Y_{arm} \\ -7 \text{ cm/s if below } Y_{arm} \end{cases}
$$

$$
V_z = 0 \text{ cm/s} \tag{4}
$$

Once the Manus ARM roughly moved to the calculated X_{arm}, Y_{arm} position, it then approached the object in the Z plane either dynamically or passing through a fixed plane[3] at a rate of 3.5 cm/s. If the gripper camera was able to detect color blobs based on the given parameters, the Manus ARM reached for the object until at least 30% of the object is in its gripper view while centering on the object. Otherwise, it simply reached forward.

[3]We wanted to ensure that the robot did not overextend itself. The plane $Z = 23000$ was empirically determined based on the eighty centimeter grasp of the Manus ARM.

$$V_x = \begin{cases} 0 \text{ cm/s if within } \pm\ 3\% \text{ of gripper view or no color blob in gripper view} \\ (1.0 - C_x) \times (7 \text{ cm/s}) \text{ if left of center of gripper view} \\ \max(C_x - 1.0) \times (7 \text{ cm/s}), 7\text{cm/s}) \text{ if right of center of gripper view} \end{cases}$$

$$V_y = \begin{cases} 0 \text{ cm/s if within } \pm\ 3\% \text{ of gripper view or no color blob in gripper view} \\ (1.0 - C_y) \times (7 \text{ cm/s}) \text{ if above center of gripper view} \\ \max(C_y - 1.0) \times (7 \text{ cm/s}), 7\text{cm/s}) \text{ if below center of gripper view} \end{cases}$$

$$V_z = \begin{cases} 0 \text{ cm/s if greater than 30\% in gripper view or penetrated plane } Z = 23000 \\ 3.5 \text{ cm/s otherwise} \end{cases} \tag{5}$$

where C_x and C_y were the relative locations of center point of the current blob with respect to the size of the gripper camera capture size.

CHAPTER 5
INDIRECT SELECTION INTERFACE

During the summer of 2006, we developed a prototype system using single switch scanning as the user input device and color tracking for movement. We hypothesized that users would prefer a visual interface (our computer control interface) over the default interface provided by the manufacturer. Additionally, we hypothesized that with greater levels of autonomy, less user input would be necessary for control. We conducted an AB-style evaluation of this system with able-bodied participants.

5.1 Interface Design

We assumed that single switch scanning[1] was the lowest common denominator for all patients in our target audience as there are many options for switch sites, including hands, head, mouth, feet, upper extremities, lower extremities, and mind (Lange 2006). Thus, we created a visual interface with text-based prompts which used the single switch as input to control a Manus ARM (Tsui and Yanco 2007). A conceptual flow diagram is shown in Figure 34.

In single switch scanning for object selection, the shoulder camera view was divided into quadrants. A red box cycles counter-clockwise[2] through the quadrants.

[1]Single switch scanning is switch access method where $n \times m$ number of options are presented. The individual options are highlighted at a set rate. The cycle frequency can be adjusted for an individual user. When the desired option is highlighted, the user presses the switch to choose the option. Single switch scanning can be used to control a general purpose computer or communication device (Better Living Through Technology 2008).

[2]There are four quadrants in the two dimensional Cartesian coordinate system. Quadrant I contains points with values (x, y). Quadrant II contains points with values $(-x, y)$. Quadrant III contains points with values $(-x, -y)$. Quadrant IV contains points with values $(x, -y)$.

Figure 34. The user "zooms in" on the doorknob using progressive quartering. The red box indicates the selected region which contains the desired object.

The cycle frequency was 1Hz, however it was adjustable to allow for reaction time. A second view opened to show an enlarged view of the highlighted region. The user was prompted to select the "major quadrant" by pressing the single switch when the red box contained the desired object.

The user repeated the process to select a smaller region. The selected region was again divided into quadrants; the view was one-sixteenth of the original image. On the shoulder camera view, the red box cycled within the "minor quadrant." The user was again prompted to press the single switch when the object desired was highlighted by the red box.

Once the "minor quadrant" was selected, the robot arm autonomously unfolded and reached towards the center selected region in XY, emulating human motion control. While reaching, the gripper opened. When the robot arm arrived at the location, a third window opened to show the live gripper camera view.

5.2 Hypotheses

We designed an experiment to investigate several of our hypotheses about this initial system. These hypotheses addressed the appropriateness of vision-based input and the complexity of the menu hierarchy.

- **Hypothesis 1: Users will prefer a visual interface versus the standard interface.**

From our own interaction with the Manus ARM using direct control, we found the standard menu-based system to be difficult to remember and frustrating to use. After the initial learning phase, simple retrieval of an object still took minutes to complete. More complex tasks and manipulation took proportionally longer time. Also, while directly controlling the Manus ARM, it was necessary to keep track of the end goal, how to move the end-effector towards the goal, the current menu, the menu hierarchy, and how to correct an unsafe situation. These requirements could cause sensory overload.

- **Hypothesis 2: With greater levels of autonomy, less user input is necessary for control.**

  As discussed in the previous hypothesis, there was a lot to keep track of while manually controlling the Manus ARM. Under manual control, the operator must be cognitively capable of remembering the end goal, determining intermediate goals if necessary, and determining alternate means to the end goal if necessary. By having the user simply and explicitly indicate the desired end goal, the cognitive load can be reduced.

- **Hypothesis 3: It should be faster to move to the target in computer control than in manual control.**[3]

  We expected that participants would be able to get closer to the target with direct control since they have the ability to move in the Z plane, but predicted that it will take them longer, even after the learning effect has diminished. However, we hypothesized that the ratio of distance to time, or overall arm movement speed, in manual control would be slower than computer control.

[3] The Manus ARM moved at 9 cm/s during manual control trials; its velocity was only 7 cm/s during computer control trials. Despite the Manus ARM moving faster in manual trials, we still hypothesized that computer control will allow the task to be completed more quickly.

5.3 Experiment

Evaluation with able-bodied participants provided a baseline because these subjects were able to quickly voice any concerns or discomforts and stop a trial. Also, these subjects provided an upper bound of physical dexterity and cognition expected in the target population. Twelve participants were recruited for an AB-style alternating condition experiment. Participants were asked demographic information in the pre-experiment questionnaire[4] which would serve to help uncover skill biases. In the post-experiment questionnaire[4], participants were asked about their experiences in an open-ended fashion and in Likert scale ratings.

5.3.1 Methodology

In each experiment, the participant was instructed to move the Manus ARM from its folded position towards a specified target. This positioning task was repeated six times. The entire process took approximately ninety minutes per participant, including pre- and post-experiment questionnaires.

Two conditions were tested: menu control and computer control. We defined menu control as the commercial, end-user configuration using menus. An equal number of start conditions were generated prior to all user testing and the control condition was alternated for each of the remaining runs. The user participated in three runs per condition to counteract any learning effect.

The input device was kept constant across conditions. The single switch menu (see Figure 25) was used for menu control. For computer control, the user pressed the switch to indicate the "major" and "minor" quadrants, as described in Section 5.1. Six of eight possible targets (shown in Figure 35) were chosen at random prior to all experiments for all twelve sequences.

[4]The questionnaires are available in Appendix A.

Figure 35. Representation of approximate centers of single switch scanning quadrants.

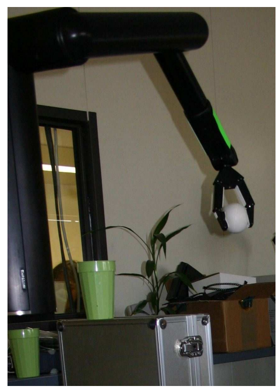

Figure 36. Training on the manual single switch interface was to “put the ball inside the cup.”

Participants first signed an informed consent statement and filled out a pre-experiment survey detailing background information about computer use and previous robot experience. The participants were then trained on each interface until they were comfortable using the interface. Training was necessary to minimize the learning effect. Training for manual control was the ball-and-cup challenge. An upside-down cup and ball were placed on a table. Users were asked to “put the ball in the cup,” meaning that they were to flip over the cup and then put the ball in it, as shown in Figure 36.

Training for computer control was an execution of the process on a randomly selected target, walked through and explained at each step. Text prompts were provided to guide the user. First, the user turned the Manus ARM on. Single switch scanning of the "major quadrants" began in the upper right and cycled counterclockwise. The user pressed the switch when the appropriate quadrant was highlighted. Then scanning of the "minor quadrants" began, and the user pressed the switch when the appropriate "minor quadrant" was highlighted. The Manus ARM unfolded. When the Manus ARM completed the unfolding, the user then color-trained the system. The Manus ARM then moved to the center of the selection by tracking color blobs, as described in Equation 2 in Section 4.3.3.

For each run, the desired object was appropriately placed at the predetermined target. The Manus ARM's initial starting configuration was folded. Time began when the user indicated, and ended for manual control when the user indicated "sufficient closeness"[5] to the target or for computer control upon prompt indication. Distance between the gripper camera and the center of the desired object was recorded. The Manus ARM was refolded for the next experiment, and the object was moved to the next predetermined target. The total changeover time took approximately two minutes. At the completion of each trial, a short survey was administered. At the conclusion of the experiment, we administered an exit survey and debriefed the participant.

5.3.2 Participants

Twelve physically and cognitively intact people (ten men and two women) participated in the experiment. Participants' ages ranged from eighteen to fifty two. With respect to occupation, eight were either employees of technology companies or sci-

[5]In our manual control runs (control experiments), we asked the participant to maneuver "sufficiently close" to the desired object with the gripper open. While this does add user subjectivity, the researcher verified the arms closeness to the object, thus allowing for consistency across subjects. Since we have only developed the gross motion portion of the pick up task for computer control, we needed to design a use of the manual control that would be similar to the task that could be completed by computer control.

ence and engineering students. All participants had prior experience with computers, including both job related and personal use. Eight participants reported spending over twenty hours per week using computers, three reported spending between ten and twenty hours per week, and the remaining one reported spending between three and ten hours per week. Four of the participants had prior experience with robots. Of these, one worked at a robot company, but not with robot arms. Three, including the aforementioned participant, had taken university robotics courses. The remaining participant had used "toy" robots, though none were specifically mentioned.

5.3.3 Data Collection

We collected data from questionnaires (pre- and post-experiment), video, and observer notes. Post-experiment surveys asked both open ended and Likert scale rating questions, and solicited for interface improvement suggestions.

Video was filmed from two locations: capturing the Manus ARM movement towards the desired object, and capturing the interface display from over the participant's shoulder during use of computer control. An observer timed the runs and noted distance, failures, technique, and number of clicks executed. Distance between the gripper camera and the center of the desired object was recorded.

Pre- and post-experiment questionnaires are provided in Section A.1. The run time and distance data are given in Tables 1 and 2. The number of clicks executed in the manual runs during the experiment are given in Table 3.

5.4 Results

We used MATLAB (MathWorks 2008) with the Statistics Toolbox to compute the statistical significance of the data using paired t-tests with $\alpha = 0.05$. MATLAB's *ttest* treats NaN values (here denoted as "-") as missing values and ignores them in

Table 1. Time to complete runs in seconds and distance from goal in centimeters in single switch menu (manual) control of the Manus ARM.

Participant	**Run 1**		**Run 2**		**Run 3**	
	Time (s)	**Distance** (cm)	**Time** (s)	**Distance** (cm)	**Time** (s)	**Distance** (cm)
P1	422.7	13	160.3	10	279.3	9
P2	213.1	15	218.8	5	122.8	5
P3	286.9	5	217.4	4.5	184.6	3
P4	171.6	5	148.1	4.5	111.8	3
P5	259.7	5	135.4	8	157.0	3
P6	261.2	5	207.0	7	202.0	3
P7	146.7	16	39.8	12	121.8	8
P8	346.3	4	125.3	3	177.3	5
P9	185.3	3	128.0	7	130.0	5
P10	222.8	4	395.6	14	218.5	5
P11	208.8	4	196.9	3	90.7	5
P12	748.0	3	275.5	3	290.5	5
Average	289.4	7.5	187.3	6.8	179.6	4.9
Std Dev	47.4	1.4	25.8	1.1	18.3	28.7

the calculation (MathWorks 2008). We analyzed the time to target, the Likert scale ratings of the manual and computer control interfaces, the average clicks per second, and the distance to time ratio. We verified that less user input is necessary for control when the autonomy is increased. Also, we verified that the Manus ARM was able to move faster in computer control than manual control. We qualitatively found a preference for manual control, which however was not supported by the quantitative analysis. We further discussed this mixed result and the overall effects of learning on the system.

5.4.1 Hypothesis 1: Preference for Visual Interface

We hypothesized that a visual interface of computer control would be preferred over the menu-based system of manual control. Referring to manual control, one participant stated that it was “hard to learn the menus.” In the users’ exit interviews, ten

Table 2. Time to complete runs in seconds and distance from goal in centimeters in single switch computer control of the Manus ARM.

Participant	Run 1		Run 2		Run 3	
	Time (s)	**Distance** (cm)	**Time** (s)	**Distance** (cm)	**Time** (s)	**Distance** (cm)
P1	72.7	15	65.0	10.5	96.9	23
P2	127.3	18	66.3	17	77.6	11
P3	114.6	20	75.7	10	74.7	16
P4	60.2	21	77.8	9	70.0	38
P5	56.8	18	50.1	16	51.6	10
P6	132.2	18	83.5	16	70.9	18
P7	52.7	-	58.3	-	54.0	-
P8	90.9	-	60.4	20	61.9	19.5
P9	104.4	-	101.3	10	60.8	-
P10	114.0	-	136.8	21	65.9	14
P11	70.2	34	65.9	16	66.1	17
P12	112.3	-	128.6	-	110.9	-
Average	92.4	20.6	80.8	14.6	71.8	18.5
Std Dev	28.7	6.2	27.7	4.4	17.1	8.4

participants stated an explicit preference for manual control. Four of these ten offered that the computer control was simpler to use than the manual control. The remaining two participants preferred computer control. They felt it was a fair exchange to trade the manual control for the simplicity and speed of computer control.

Participants were asked to rate their experience with each interface using a Likert scale from 1 to 5, where 1 indicated most positive. Computer control averaged 2.5 (standard deviation (SD) 0.8) and manual control averaged 2.8 (SD 0.9). This suggested that participants had relatively better experiences with computer control despite their stated preference for manual control, although the differences are not significant. With the Likert scale, half rated computer control higher than manual control, three ranked them equally and three ranked manual control above computer control. Thus, this hypothesis (preference for visual interface) was unconfirmed.

Table 3. Number of clicks executed by participants per manual control trial. The time to task completion is repeated from Table1. The average clicks per second (CPS) is shown in a third column.

	Run1			Run 2			Run 3		
Partici-pant	**Clicks**	**Time** (s)	**CPS**	**Clicks**	**Time** (s)	**CPS**	**Clicks**	**Time** (s)	**CPS**
P1	18	422.7	0.04	9	160.3	0.06	17	279.3	0.06
P2	11	213.1	0.05	32	218.8	0.15	17	122.8	0.14
P3	17	286.9	0.06	20	217.4	0.09	16	184.6	0.09
P4	55	171.6	0.32	20	148.1	0.14	23	111.8	0.21
P5	8	259.7	<0.00	6	135.4	<0.00	11	157.0	0.07
P6	37	261.2	0.14	23	207.0	0.11	15	202.0	0.07
P7	31	146.7	0.21	24	39.8	0.60	25	121.8	0.20
P8	25	346.3	0.07	20	125.3	0.16	24	177.3	0.14
P9	38	185.3	0.20	20	128.0	0.16	35	130.0	0.27
P10	23	222.8	0.10	38	395.6	0.10	29	218.5	0.13
P11	23	208.8	0.11	30	196.9	0.15	12	90.7	0.13
P12	97	748.0	0.13	65	275.5	0.24	60	290.5	0.21
Average	31.9	289.4	0.12	25.6	187.3	0.16	23.7	179.6	0.20
Std Dev	24.2	47.4	0.09	15.3	25.8	0.15	13.5	18.3	0.17

5.4.2 Hypothesis 2: Input and Autonomy

We hypothesized that with greater levels of autonomy, less user input would be necessary for control. The number of clicks executed by participants per manual control trial was recorded (shown in Table 3). The number of clicks in computer control was fixed by design ($n = 3$). Run workload was the number of clicks during the run divided by the run time, which was the average clicks per second. This hypothesis was quantitatively confirmed using a pair of t-tests on the average normalized workload of manual control and computer control trials per user ($p < 0.01$). Qualitatively, eight of the twelve participants stated that manual control was "frustrating" or "confusing," which was indicative of the sensory overload the user was anticipated to feel.

5.4.3 Hypothesis 3: Speed Moving to Target

We hypothesized that it would be faster to move to the target using computer control than manual control. The distance to time ratio was used as a means of cost analysis: moving X distance takes Y time. All distance to time ratios (for complete runs) quantitatively validated this hypothesis ($p < 0.001$). Three users stated that computer control was "quick" or "fast." Despite the bias, the Manus ARM was able to move farther in less time, and this hypothesis was confirmed.

5.5 Discussion

5.5.1 Learning Effects

The controlled experiment was designed to minimize the effects of learning. Participants were allowed to train on each interface until they felt comfortable. One participant (P12) trained on the manual interface for over an hour. The start conditions were also randomized and alternated. Even with training, we hypothesized that users would take the longest time during their first runs on each interface and that each subsequent run would take less time. Our time data showed this trend. In the first run, participants averaged 289.4 seconds (SD 47.4) with manual control and 92.4 seconds (SD 28.7) with computer control. In the second run, 187.3 seconds (SD 25.8) and 80.8 seconds (SD 27.7), respectively. Finally in the third run, 179.6 seconds (SD 18.3) and 71.8 seconds (SD 17.1), respectively.

Given a larger number of runs in a single session, the time to target would likely converge for both manual and computer control. In manual control, we noted techniques the participants would use to unfold the Manus ARM. Depending on which target was chosen, the participant may have used a different unfold technique. That is, if the target were on the lower region, a participant may have only partially unfolded (i.e. interrupt the preprogrammed trajectory) and then maneuver the Manus ARM to the target. If the target were towards the middle or upper region, the participants typically unfolded the Manus ARM completely. In computer control, the Manus ARM always fully unfolded.

Even with the unfolding shortcut, it is unlikely however that the manual control would be faster than computer control. When maneuvering the Manus ARM in manual mode, the participants had to continuously operate the controls. If they stopped, the robot stopped. The robot was stopped when the participants changed modes or waited while the menu cycled until their desired operation came up. In computer control, the participants made a fixed number of selections while the Manus ARM was unfolding. Often, the participants were finished selecting before the Manus ARM was finished unfolding. We hypothesize that the time savings will be most evident when the grasp and the return of the object are incorporated into the system because the user will not have to spend time manually adjusting the fine motion details.

5.5.2 Mixed Results of Hypothesis 1

The lack of significance of Hypothesis 1 (preference for visual interface) was likely due to a confounder – the color calibration step in the computer control process which did not exist in the menu control process. Six participants specifically mentioned having difficulties with the act of color calibration. Ten of thirty six runs failed because either the user forgot to or did not correctly color calibrate. Thus, the color calibration may have made computer control less preferable. Despite training, one user stated, “I felt confused about what I was actually doing. I didn’t understand why I was doing the steps I was trained to do in order to accomplish the task.”

We removed the color tracking for robot arm movement from the system. The current system, described in Chapter 6, relies solely on the joint encoder readings.

CHAPTER 6
DIRECT SELECTION INTERFACE

We needed to assess the viability of the indirect selection interface with our target population. The occupational therapist on our team assessed the system, which provided two related results. First, the single switch scanning access method is difficult for users with cognitive impairments. Some users may find the timing aspect of when to press the switch to be difficult. Other users may have difficulty with the multi-stepped process and remembering the abstraction of the red rectangle for selection. As such, single switch scanning is not a common access method used among our target population at Crotched Mountain Rehabilitation Center.

We replaced the single switch scanning with a means of direct selection. We leveraged the technology transfer of two well established access methods, a joystick and touch screen. We drew inspiration from how humans view a scene and focus on particular items to fix or move the shoulder camera. Based on the input device and camera view, we created four versions of a "flexible" interface (Tsui et al. 2008a). Our goal was to develop a flexible interface which could be tuned for individuals, instead of a custom-built solution for each which is typical.

To evaluate our current interface, we designed a modified recreation of the able-bodied experiment from Section 5.3 (Tsui et al. 2008b). We conducted the controlled experiment for eight weeks with eight participants from the Crotched Mountain Rehabilitation Center. The subjects participated as frequently as possible with a range of one session to eight. In this chapter, we present the data collected, the statistical and anecdotal analyses, and discussion of the results.

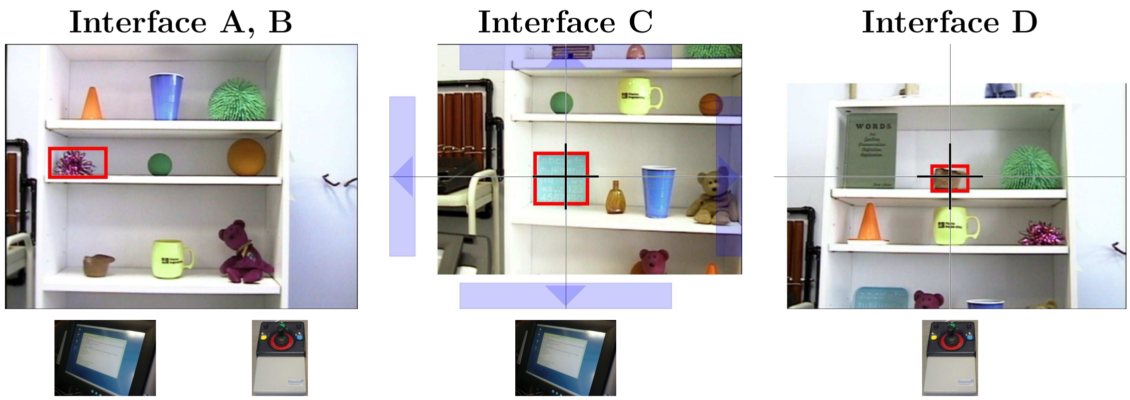

Figure 37. Object selection using our direct selection interface. The fixed camera view selection is shown on the left. The moving camera view is shown center and right, using touch screen and joystick, respectively.

6.1 Interface Design

According to (Stephanidis 2001) and (Gnanayutham et al. 2005), there are three types of user interface adapations. The first is adaptive which responds dynamically based on user performance. The second is adaptable which allows the end-user to select the presentation and built in interaction styles. The third is adapted which encompasses design with the end-user in mind. Our interface is both adapted and adaptable since it was both designed for a particular target audience and can be easily configured for an individual's best experience. We call our interface “flexible” since it can accommodate a number of users with their own tuned profiles, in addition to being both adapted and adaptable.

Four versions of the interface were created based on specific access methods and camera movement. Many users were already able to drive a powered wheelchair with a joystick or use a mouse-emulating joystick to control a computer. Touch screens have been commonly used as communication devices. Also, we drew inspiration from people's innate abilities to see and touch. The shoulder camera with a fixed view was similar to when an object is in the center of a person's view. The shoulder camera view with a moving view simulated when an object is in the periphery of a person's view. Typically, one would move their head to focus on the object.

The focus of the interface was largely the shoulder camera view, which was assumed to be similar to the wheelchair occupant's view. This assumption was consistent with the prototype interface. If the shoulder camera was stationary, then the interface was simply the video feed for both joystick and touch screen access methods (shown in Figure 6 on the left).

When the shoulder camera was moved, thin black cross hairs outlined in white were overlaid on the video. A bolder, black plus overlaid on the cross hairs emphasized the center of the screen. If the access method was touch screen with the moving camera view, the resulting interface was Figure 6 (center), which also had blue semi-transparent buttons at the top, bottom, left, and right with corresponding indicator arrows. If the access method was a joystick with the moving camera view, Figure 6 (right) was the resulting interface and the cursor was hidden. Also, as the shoulder camera was panned and tilted, unreachable regions for the robot arm were not displayed. Instead, the unreachable regions were covered with white rectangles.

The interface had tunable parameters for the user, as shown in Figure 38. Cursor size could be set to a small (32×32 pixels), medium (48×48 pixels), or large (64×64 pixels) cursor. The cursors were enhanced with a white outline to provide visibility against a dark background. Cursor speed could be set for interfaces where the joystick is the designated access method. Another tunable parameter was a dwell period for users who were not easily able to move between a joystick and a button. When the cursor remained stationary for a period greater than the set dwell length, the system interpreted a mouse click.

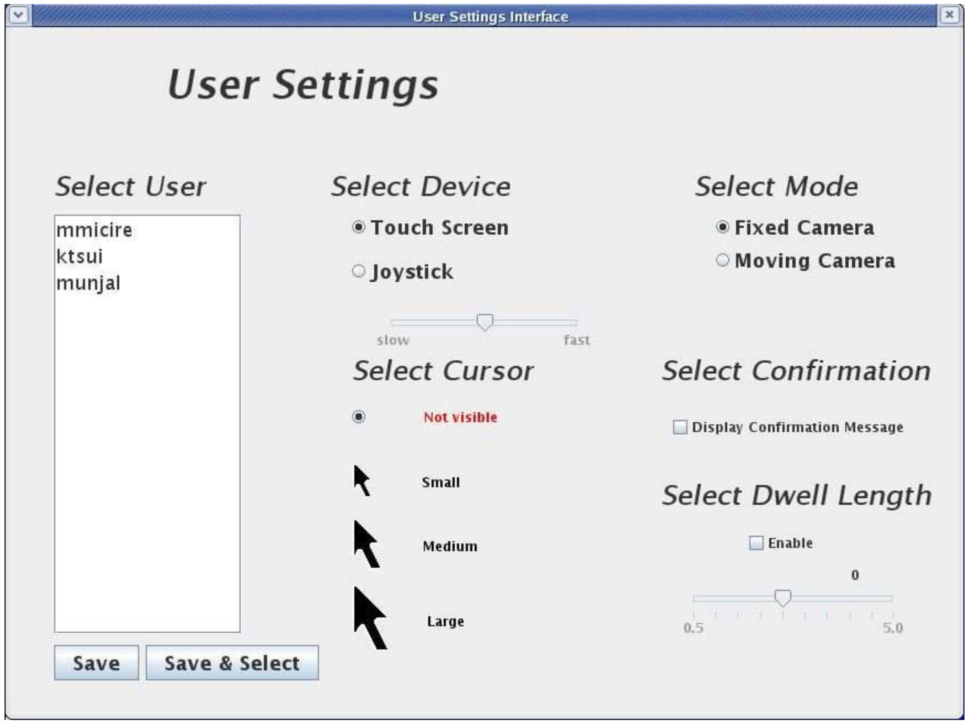

Figure 38. The direct selection interface's tunable parameters included cursor size, cursor speed, and dwell period.

6.2 Hypotheses

We designed an experiment to investigate several of our hypotheses about this direct selection interface. These hypotheses addressed the ease of use of the direct selection interface, the appropriateness of vision-based interface, and correlation of a person's abilities and his or her performance.

- **Hypothesis 1: The versions of the direct selection interface are easy to use.**

  The direct selection interface was a design collaboration between roboticists and occupational therapists. It was designed for a specific participant population which is representative of the overall end-user. It accommodated the multiple access devices (touch screen and joystick), used audio feed back in addition to visual, and had at most a two-step process for object selection. However, whether or not the interface was not frustrating and discouraging to use was subjective.

- **Hypothesis 2: It should be easier to select an object from a fixed camera view than a moving camera view.**

  Assuming that the user has finger isolation to use a touch screen or functional control of a joystick, the fixed camera interfaces should have faster object selection times. For the touch screen, the process was a single step. The user put their finger on top of the object representation on the display. The joystick emulated a mouse. Typical use of the joystick as a computer input method would be to move the mouse cursor with the joystick and press the yellow button (or an external switch connected to the yellow button input) to select. This selection can be viewed discretely as a two step process, but is generally viewed as a complete skill. Both access methods are considered direct selection methods in assistive technology.

  For the moving camera view, there was a layer of abstraction that did not exist with the fixed camera view. The user must have the ability to reason how to aim the camera towards the object, which may or may not have been within the current camera view. Physically, the process was always two steps: center the camera on the object and press the external button. To move the camera's view, the user pressed a button on the touch screen or use a joystick to the corresponding direction (up, down, left, and right). However, the user must have the ability to reason how to aim the camera towards the object.

- **Hypothesis 3: A correlation exists between physical and cognitive abilities and interface performance.**

One goal of this research was to understand which interface works well for a particular type of user. A participant profile included information on computer access method, visual ability, cognitive ability, and behavioral skills, as seen in Table 4 which was provided by our occupational therapy team member.[1] Based upon these traits, users with particular traits may be able to use one version of the interface better than another.

6.3 Experiment

With the help of our colleagues at Crotched Mountain Rehabilitation Center, we ran a controlled experiment in August and September 2007 to evaluate the effectiveness of the visual interface used to control the Manus ARM. The participants in this experiment were representative of the intended end-user.

6.3.1 Methodology

6.3.1.1 User Task Tasks should place appropriate demands on the user. That is, tasks should be interesting without being too easy or difficult for a given user. For this experiment, matching was decided to be an appropriate task by Crotched Mountain Rehabilitation Center educational staff. The participant was asked to match the flash card of an object with the object displayed on the screen in front of them.

The objects used in this experiment had real-world qualities so that the task was not deemed trivial by the participants and to satisfy educational requirements of the school. The set of objects consisted of a yellow mug, a blue cup, a teal stencil, a green book, a purple plush bear, a tan plush bear, a clay pot, an orange egg salt shaker, an orange bottle, a purple gift wrapping bow, and various colored and textured balls (Figure 39).

[1] The participant profiles were not stored directly in the system. However, a user's initial parameters were generated based on his or her profile. These details are described in Section 6.3.2.

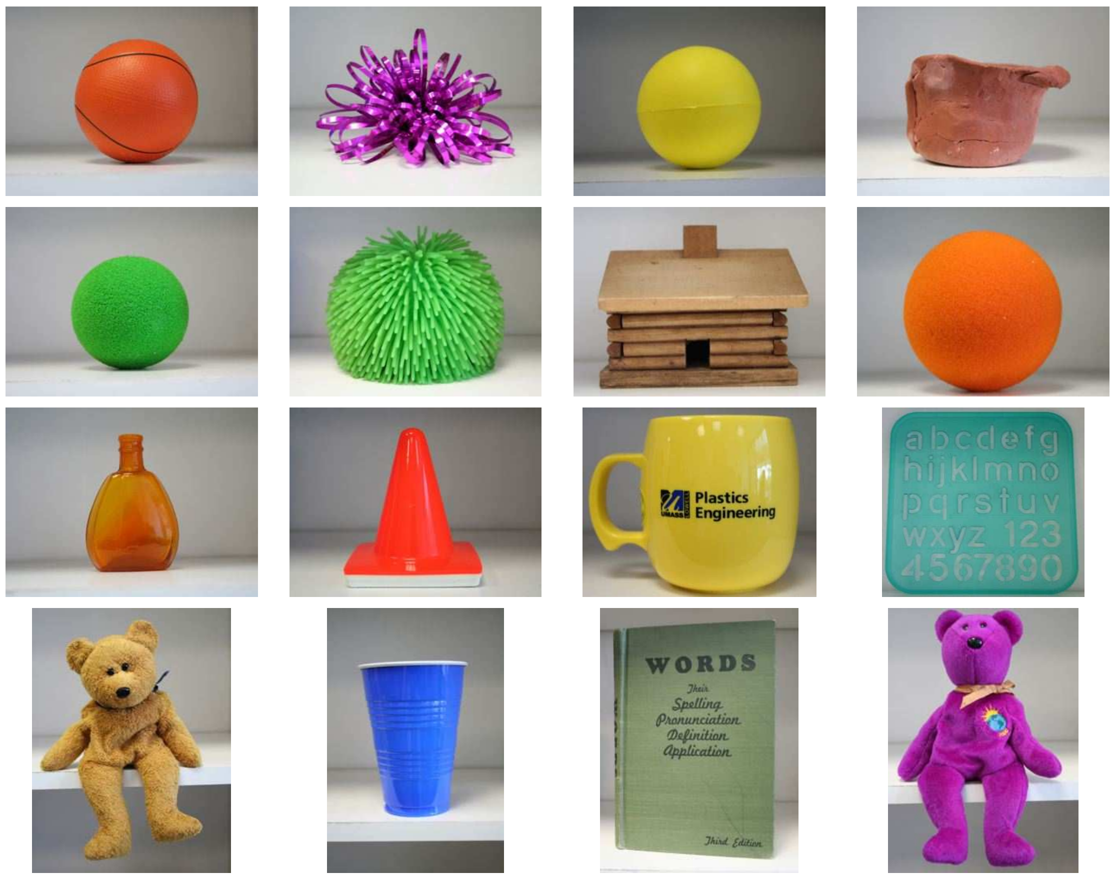

Figure 39. The set of objects used in the experiment. Note that the size is not to scale.

Abstraction is defined as "the act of considering something as a general quality or characteristic, apart from concrete realities, specific objects, or actual instances" (Dictionary.com 2007a). People with cognitive impairments who understand the physical instance of an object, such as an apple, may not be able to understand a picture of the apple. Further, those who understand the picture may not be able to understand the word "apple." Thus, abstraction can be a limiting factor. For this experiment, all participants were able to understand the actual object and also the photo of the object. To remove the possible confounding factor of semantics (e.g., "the purple bear"), an individual photograph of the object was used as a flash card. The flash card served as the primary prompt, and verbal semantics served as a secondary prompt.

According to Fitts' Law, time to move to a target area is the function of the distance to the target and the target size (Fitts and Deninger 1954). Thus, the size of the object directly affects the difficulty of the task. A smaller object would be more difficult to select, and conversely, a larger object would be easier to select. Choosing smaller or larger sized objects for each run allowed the experimenter to tune the difficulty in a session to engage the user without altering the user's interface parameters.

The objects from which the participants would select were placed on a three-shelved bookshelf in one of four scenarios, according to difficulty, as seen in figure 40. Size, color, and reflectivity of the objects were taken into account when designing the scenarios. The scenarios were generated by the experimenters prior to commencing user testing. The task level could be adjusted by prompting the participant to select larger or smaller objects, or the configuration could change entirely.

6.3.1.2 Trials The experiments were conducted by assistive technology technicians at Crotched Mountain. The initial profile was used during the participant's first session. The profile was iteratively adjusted as needed before each session.

Figure 40. Object configurations used for testing. The level of difficulty increased from left to right.

Figure 41. Experimental setup.

At the start of a session, the experimenter placed the robot arm on the participant's right-hand side and the touch screen in front, as shown in Figure 41. The previous session was briefly reviewed. The experimenter then described the interface to be used in the current session, the method for object selection, and arm movement. The participant was then trained on the interface. Training was necessary to minimize the learning effect.

Once the participant was comfortable, the trial began. The participant was shown a flash card of the desired object and prompted and encouraged as necessary by the experimenter.[2] The participant then used the interface to select the object. A correct selection would yield a red rectangle around or on the object and a "ding" played. Otherwise, a "Please, try again!" prompt sounded. The participant made

[2]The experimenter is a trained assistive technologist at Crotched Mountain Rehabilitation Center. Prompting administered by the experimenter was to remind and encourage only.

three object selections per session, which would maximize their attention to task and minimize exhaustion and behavioral issues. At the conclusion of a session, the experimenter administered a survey and removed the robot arm and touch screen. The experiment ran for eight weeks and the participants interacted with the robot arm as frequently as possible. Sessions ranged from one to eight per participant and totaled twenty nine sessions overall.

6.3.2 Participants

The assistive technology director of the Crotched Mountain Rehabilitation Center played the central role in recruitment of participants. The director evaluated the overall physical dexterity, cognitive ability, visual ability, and access method of the students[3] of the Crotched Mountain School and the residents[3] of the Crotched Mountain Brian Injury Center. Candidates were invited to participate in the experiment. Eight participants consented: three were their own guardians, and the remaining five required parental or guardian approval.

All participants had medium to high cognitively functional ability, minor vision impairment, and were able to operate a joystick or touch screen (finger isolation for pointing only). Eight people participated in the experiment: four men and four women. Participants' ages ranged from seventeen to sixty. Five of the participants are students of the Crotched Mountain School; three were diagnosed with cerebral palsy, one with spinal bifida, and one with osteogenesis imperfecta. The remaining three participants are patients of the Crotched Mountain Rehabilitation Brain Injury Center; all were diagnosed with traumatic brain injury. Three participants used a

[3]Crotched Mountain Rehabilitation Center is a community for people with disabilities (Crotched Mountain Rehabilitation Center 2008). There are several on-site components of the Crotched Mountain Rehabilitation Center including a school, brain injury center, and hospital. The day school teaches skills, such as self care, communication, and problem solving, to K-12 students with physical and developmental disabilities. The Brain Injury Center provides resident adults in-patient rehabilitation and also out-patient services. The Children's Specialty Hospital provides children and young adults to age thirty individualized therapy.

power wheelchair, four used a manual wheelchair, and one was able to use both. All participants were capable of operating a joystick as an access method, although to varying degrees. Table 4 describes the participants' visual abilities, cognitive abilities, behavioral abilities, and computer access devices.

Each participant was given an initial interface settings profile by an assistive technologist. A profile contained parameters for access method (joystick or touch screen) based upon the participant's accessibility and behavioral abilities; fixed camera view or moving based on their level of cognition; cursor size based upon their visual acuity; cursor speed (if applicable) based on their physical dexterity; and dwell length (if applicable) also based in their physical dexterity. For example, one user who might strike the touch screen was assigned the joystick as her access method to prevent injury to the patient and equipment.

6.3.3 Data Collection

Data was collected from manual logs, post-session questionnaires, and computer generated log files. Each session was video recorded. Qualitative data included the post-experiment questionnaire administered at the end of each user session and the observer notes. The questionnaire posed open ended questions about which interface the user liked most, which interface they liked least, and suggestions for improving the interface. Observer notes contained relevant information about the session, including length of reorientation[5].

[4]Our occupational therapist team member further described "inattention" as "a condition in which the individual (who has experienced a stroke, head injury or other neurological insult) does not notice or understand objects on one side of a visual field. This is not the result of direct problems with the eye, but it involves the part of the brain that processes information."

[5]Reorientation included a description of the Manus ARM, a description of the task, a review of the previous session (specifically which interface had been used), training on operating the interface, and training on the process of using the interface.

Table 4. Participant profiles for the August and September 2007 end-user evaluations.

	Age	Diagnosis	Cognition	Behavior	Vision	Chair	Computer
P1	26	Spinal cord injury, traumatic brain injury	Not significantly impaired	No impairments	Typical	Manual	Standard
P2	60	Traumatic brain injury	Distractible	Very sociable; follows prompts well	Left inattention[4]; right visual processing disorder	Manual	Standard
P3	17	Spinal bifida	Good memory and receptive/expressive language	Low frustration tolerance; needs encouragement	Reduced acuity	Manual	Standard (limited dexterity)
P4	20	Cerebral palsy	Good receptive language and expression with communication device; able to learn new skills; mild limitation with problem solving	Aggressive when frustrated; can express need for break	Functional	Manual, Power	Communication device; touch screen with keyguard
P5	20	Cerebral palsy	Below age level; moderate decision making ability	Needs encouragement	Functional	Power	Standard (limited dexterity)
P6	37	Traumatic brain injury	Challenged by multi-step process; short term memory impairment	No impairments	Functional	Manual	Standard
P7	20	Osteogenesis imperfecta	Mild deficits; slight prompting needed due to vision	Cooperative	Mild perceptual impairment	Power	Standard
P8	18	Cerebral palsy	Mild deficits; slightly below age level; slight prompting needed	No impairments	Functional	Power	Standard (limited dexterity)

Quantitive data included trial run time, attentiveness rating, prompting level, close up photos of the object selected, and computer generated log files. For each trial, the run time was recorded, specifically the time from object prompt to participant selection, the time from the Manus ARM movement to displaying the close up photo of the object on the screen, and the time for the Manus ARM to complete folding. The experimenter, who is an assistive technologist professional, rated the user's prompting level per trial based on the FIM scale[6], where 0 indicated "no prompting needed" and 5 indicated "heavy prompting needed" (MedFriendly.com 2007). The experimenter also rated the user's attentiveness to the task on a Likert scale, where 0 indicated "no attention" and 10 indicated "complete attention." Two separate scales were used because it is not necessarily the case that a person who requires high levels of prompting is unmotivated to complete the task.

The post-experiment questionnaire and manual logs are available in Section A.2. The user selection time, attentiveness level, and prompting level data are available in Tables 5, 6, and 7.

6.4 Results

We used Excel (Microsoft 2008) to compute the statistical analysis of the data using paired t-tests assuming unequal variance with $\alpha = 0.05$. We analyzed the time to object selection, the participants' attentiveness, the participants' prompting levels, and positive and negative comments about each of the four versions of the direct selection interface.

We found that participants performed similarly between Interfaces A and B (fixed camera view with touch screen and joystick, respectively) with respect to time to selection and attentiveness. We found that participants performed better on Interface A than C (fixed camera view and moving camera view with touch screen, respectively) with respect to time to attentiveness and prompting levels. The participants reported that they most liked Interface A (fixed camera view with touch screen) and least liked Interface D (moving camera view with joystick).

[6]The FIM scale measures "one's ability to function with independence" (MedFriendly.com 2007). The score ranges from 1 (total assistance) to 7 (complete independence). The FIM score applies to ADLs (such as eating, dressing, transferring, and locomotion) and cognitive areas (such as problem solving and relationships).

Table 5. Participant time to object selection (in seconds). Sessions are grouped into tuples; for example, Sx: $(t_1, t_2, ..., t_n)$ translates to "session x, where run one took t_1 seconds, run two t_2 seconds, ..., run n took t_n seconds."

	Interface A Fixed camera, touch screen	**Interface B** Fixed camera, joystick	**Interface C** Moving camera, touch screen	**Interface D** Moving camera, joystick
P1				S1: (94.72, 46.8, 4.43) S2: (1.67, 2.58, 2.26, 17.03)
P2	S1: (6.22, 69.33, 4.18) S2: (0, 0, 0)	S6: (5, 4, 6)	S3: (12.93, 38.2, 0) S4: (1.94, 6, 6) S7: (1, 4, 2) S8: (2, 4, 4, 3)	S5: (2, 88, 92, 3) S6: (4)
P3	S3: (3.28, 2, 7)	S4: (2, 4, 1)	S2: (57.7, 5, 4.11)	S1: (3, 2, 2) S5: (0, 5, 2)
P4	S1: (175, 0, 5) S4: (2, 1)	S2: (10, 9, 7) S3: (2, 5, 5) S6: (1.01, 0.4, 0.49, 1.1, 0.06)	S4: (2, 3) S5: (0.98, 0.43, 1.04)	
P5	S2: (3.88, 4, 4.2) S3: (0, 0, 3, 2, 4, 3)	S1: (12, 53, 5.39)		
P6		S1: (7, 5, 8)	S2: (4, 6, 1)	
P7		S1: (2, 2)		S1: (35.8)
P8	S1: (2, 2, 2, 0)		S1: (3)	S2: (1, 4, 2, 2)

6.4.1 Hypothesis 1: Ease of Use

Although difficult to quantify, object selection time can be viewed as a measure of ease of use of the interface. The overall participants' mean time from prompt to object selection ranged from 5.87 seconds to 18.14 seconds; however, the median selection time was much more consistent with each other (2 (SD 35.21), 4 (SD 9.75), 3.5 (SD 13.71), and 3 (SD 31.27) seconds respectively). Paired t-tests assuming unequal variance were used for statistical analysis. Participants were found to perform better in Interface C (moving camera view with touch screen) than Interface D (moving

Table 6. Participant attentiveness (0 low to 10 high). Sessions are grouped into tuples; for example, Sx: $(a_1, a_2, ..., a_n)$ translates to "session x, where in run one, the participant had level a_1 attention, run two level a_2, ..., run n level a_n."

	Interface A Fixed camera, touch screen	**Interface B** Fixed camera, joystick	**Interface C** Moving camera, touch screen	**Interface D** Moving camera, joystick
P1				S1: (8, 10, 10) S2: (10, -, -, 10)
P2	S1: (-, 0, 4) S2: (6, 5, 3)	S6: (10, -, 10)	S3: (10, 7, 6) S4: (10, 5, 10) S7: (4, 2, 10) S8: (10, 10, 6.5, 10)	S5: (4, 10, 6, 3) S6: (10)
P3	S3: (10, 10, 10)	S4: (10, 10, 10)	S2: (10, 9, 9)	S1: (10, 10, 10) S5: (10, 10, 10)
P4	S1: (5, 5, 3) S4: (3, 3)	S2: (3, 2.5, 8) S3: (3, 4, 2) S6: (2, 3, 2)	S4: (2, 3) S5: (4, 10, -)	
P5	S2: (10, 10, 10) S3: (10, 6, 10, 9, -, 10)	S1: (9, 10, 10)		
P6		S1: (10, 10, 10)	S2: (10, 10, 10)	
P7		S1: (10, 10)		S1: (10)
P8	S1: (10, 10, 10, 10)		S1: (10)	S2: (10, 10, 10, 10)

camera view with joystick), with $p < 0.01$ given $\alpha = 0.05$. Also, participants were found to perform better in Interface B (fixed camera view with joystick) and Interface D (moving camera view with joystick), with $p < 0.01$ given $\alpha = 0.05$.

Other measures of ease of interface use were the participants' attentiveness and prompting levels. (Recall that it may not necessarily be the case that a person who requires high levels of prompting is unmotivated to complete the task.) Participants were found to have more attention in Interface A (fixed camera view with touch screen) than Interface C ($p < 0.01, \alpha = 0.05$), and Interface B than D ($p < 0.01, \alpha = 0.05$). Since we did not have any participants with short-term memory impairments, prompting levels may be inversely correlated to ease of use and moti-

Table 7. Participant prompting level (0 low to 5 high). Sessions are grouped into tuples; for example, Sx: $(p_1, p_2, ..., p_p)$ translates to "session x, where in run one, the participant required a level p_1 prompting, run two level p_2, ..., run n level p_n.

	Interface A Fixed camera, touch screen	**Interface B** Fixed camera, joystick	**Interface C** Moving camera, touch screen	**Interface D** Moving camera, joystick
P1				S1: (0, 0, 0) S2: (0, -, -, 0)
P2	S1: (0, 1, 3) S2: (0, 0, 0)	S6: (0, -, 0)	S3: (0, 2, 4) S4: (0, 2, 0) S7: (0, 2, 2) S8: (4, 5, 3.5, 0)	S1: (0, 3, 0, 1) S5: (2)
P3	S3: (2, 0, 0)	S4: (0, 0, 0)	S2: (1, 1, 0)	S1: (1, 0, 3) S5: (0, 0, 0)
P4	S1: (5, 0, 0) S4: (1, 0)	S2: (3, 3, 0) S3: (3, 3, 3) S6: (-, -, -)	S4: (2, 3) S5: (3, 5, 5)	
P5	S2: (3, 0, 0) S3: (0, 0, 0, 0, -, 0)	S1: (1, 2, 0)		
P6		S1: (2, 3, 0)	S2: (2, 2, 2)	
P7		S1: (1, 0)		S1: (0)
P8	S1: (0, 0, 0, 0)		S1: (1)	S2: (3, 4, 0, 0)

vation. Participants were also found to require less prompting in these cases (both $p < 0.01, \alpha = 0.05$), and for Interface A than Interface B.

In twenty of the post-experiment surveys[7], the participants specifically expressed their preference for particular interfaces in the first two open-ended questions ("Which interface did you like the best? Why?" and "Which interface did you like the least? Why?"). Interface B was the most liked with seven positive comments ($p < 0.02, \alpha = 0.05$). Interfaces A and C received mixed reviews with four positive/two negative and four positive/one negative respectively. Interface D received was the least liked interface with four negative remarks.

[7]The remaining nine of the twenty nine surveys had no response.

Table 8. Summary of statistical results for the August and September 2007 end-user evaluation.

Interface Comparison	**Statistical significance with** $\alpha = 0.05$
Fixed Camera View (Interface A vs. B)	*Time*: no significance ($p < 0.50$) *Attentiveness*: no significance ($p < 0.33$) *Prompting*: $p < 0.01$
Moving Camera View (Interface C vs. D)	*Time*: $p < 0.01$ *Attentiveness*: no significance ($p < 0.25$) *Prompting*: no significance ($p < 0.49$)
Touch screen (Interface A vs. C)	*Time*: no significance ($p < 0.50$) *Attentiveness*: $p < 0.01$ *Prompting*: $p < 0.01$
Joystick (Interface B vs. D)	*Time*: $p < 0.01$ *Attentiveness*: $p < 0.01$ *Prompting*: $p < 0.01$

6.4.2 Hypothesis 2: Preference for Fixed Camera View

In statistical analysis over selection time, attention, and prompting, the fixed camera view interfaces outperformed the moving camera view interfaces, except in the case of Interface B and D with respect to time. The users also selected interface D, a moving camera view, as their least favorite, and Interface A, a fixed camera view, as their most preferred.

6.4.3 Hypothesis 3: Correlation with Abilities

Due to the small sample size and sparsity of data of certain conditions in this experiment, we did not wish to make generic claims. In future experiments, the participant population will contain a larger variation in cognitive ability. However, interestingly, two diagnoses dominated the participant pool: traumatic brain injury (TBI) and cerebral palsy (CP). We conducted statistical analysis using paired t-tests with unequal variances on selection time. The participants were divided into TBI versus non-TBI and CP versus non-CP. The selection times of the TBI patients versus non-TBI patients were not statistically significant. However, the selection times of

CP patients were faster than non-CP patients for both moving camera conditions ($p < 0.01, \alpha = 0.05$).

6.5 Discussion

Evaluation of our system with the end-users provided valuable insight. We further discussed the participants' interface preferences with respect to input device and camera view. We noted the limited statistical power of paired t-tests. We also provided anecdotes about two particular participants' experiences.

6.5.1 Preference Analysis

We believed that the preference of Interface A (fixed camera view with touch screen) was due to two factors. The first was the "direction manipulation" enabled by the touch screen (1983). By Shneiderman's definition, a joystick was also a method of direct manipulation. However, McLaurin (1990) notes that a joystick was "far from ideal for many users" and that the user should only need to provide high-level control. In Interface B (fixed camera view with joystick), the participant used an assistive joystick to provide the high-level control for the Manus ARM. In general comments, P2 indicated her preference for both the touch screen and joystick. P2 stated that she preferred the touchscreen to the joystick in her second session and that she preferred the joystick to the touch screen in her eight session. P3 twice stated her preference for the touch screen (second and fifth sessions) and once stated her dislike of the joystick (first session).

The second factor was the fixed camera view. We had designed the moving camera view to emulate how a person views the world when focusing on an object that was initially on his or her periphery. However, the offset between the shoulder camera and the user view required the participant to translate between the two views, which likely added cognitive load to the user. The fixed camera view simplifies the translation between the video and reality because the frame of reference is fixed.

The participants stated that their least liked interface was Interface D (moving camera view with joystick). The additional cognitive load in translation between the video and the user's view was likely a factor in their stated preference. Interestingly, P8 commented that "[the] moving camera felt more real" and that "[the] fixed camera [was] too easy." On two separate occasions, she gave negative comments towards Interface A.

Also, in the post-experiment questionnaire, the third question solicited improvements to the system. The participants repeatedly mentioned the drift of the cross hairs over the object in the moving camera interfaces, especially the joystick version of the interface. There were three specific statements about this in the post-experiment surveys. One user remarked that "the joystick [would make the system easier to use] if there wasn't any drift." The drift could be minimized by slowing the cursor speed down.

6.5.2 Paired T-test Analysis

We quantitatively analyzed the time to object selection, attentiveness, and prompting level data with paired t-tests assuming unequal variance. We kept certain variables constant which performing the paired t-tests. For example, we compared Interface A and B (fixed camera view with touch screen and joystick, respectively) together which allowed us to analyze the performance based on input devices. We repeated this for the moving camera view, touch screen input device, and joystick input device.

We were able to find relative statistical significance, as shown in Section 6.4.1. However, we were unable to provide a total ordering of which version of the interface facilitated the best performance and which version supported the worst performance.

To find a total ordering, we would perform an ANOVA analysis to compare multiple conditions simultaneously. Our data unfortunately contained an uneven number of sessions per participant, ranging from one session to eight. In future experiments, we will strive to have an equal number of sessions per participant so that we can simultaneously compare multiple conditions.

6.5.3 Leveraging Technology Transfer

We intended to leverage the technology transfer of well established assistive technology devices, specifically a touch screen and joystick. We believed that this approach was largely successful in the fixed camera view interfaces. For example, one participant (P5) uses a communication device displayed on a touch screen with a keyguard on a daily basis. His finger isolation is quite good even when in an emotionally excited state. In one session, Interface C (moving camera view with touch screen) was selected by the experimenter. The participant understood the process for selection quickly and trained easily in one run. However, when the recorded run began, his finger isolations were not directly on the blue buttons. Each missed button pressed equated to an inadvertent object selection. The selections queued rapidly and the vision processing algorithm was not able to discern an object. The delayed response of "Please, try again!" caused frustration. He continued to try to move the camera, and the selections continued to queue. He pushed the touch screen away, indicating his frustration.

In the participant's previous session, three successful runs were executed with Interface B (fixed camera view with joystick); in the participant's following run another three successful runs and one system failure were executed with Interface A (fixed camera view with touch screen). In a post-experiment survey, he indicated that he like Interface A the best. This selection is consistent with his current access methods.

6.5.4 Principles of Universal Design

We asked participant (P1) to evaluate the original keypad menuing interface in addition to the direct selection interface. He successfully learned and executed three runs in the span of an hour. He commented that the keypad was "easier to use" while the joystick control in Interface C had "too much play" (drift). This participant had high cognitive ability and his preference for the original keypad echoes the findings of the August 2006 experiments with able-bodied participants (Tsui and Yanco 2007). The following week, he tried the remaining versions of the direct selection interface. When he used Interface A, he remarked that he liked it the best.

We viewed this session as an indicator that the principle of equitable use holds (The Center for Universal Design 2008). We found that participants with cognitive impairments (albeit of high cognition) stated a preference for Interface A. A user with typical cognition was able to use Interface A and stated that he liked it the best of all the previous interfaces he had tried, including the manual keypad. We believed that his preference is based upon the ease of use of the interface due to aspects of our design that leverage how humans manipulate the world (i.e. "I want that" as a person reaches or points towards an object).

The participant (P1) later noted that he still liked the original keypad interface. We realize that our interfaces are constrained to the "pick and place" ADL, whereas the original keypad interface allows for general manipulation. Our goal is not to provide a "one click" solution for all ADLs. The Manus ARM has six degrees of freedom. An occlusion may block the Manus ARM and our "one click" solution would fail. We realize that there will still be a need to move the Manus ARM manually in some cases. However, we believe that in many cases, the "one click" solution will be preferable because of the reduced cognitive load and increased autonomy.

CHAPTER 7
GUIDELINES AND RECOMMENDATIONS

The field of HRI has studied how a person would interact with a robot. A number of studies have been conducted in areas such as remote robot operation, robot appearance preference, and robot interaction as a teammate. In these studies, the participants were people with typical cognition and typical motor dexterity. Thus, certain assumptions or models could be made about how different people will interact with the same system. For example, we can correctly assume that the end-users (i.e. rescue personnel and fire fighters) will have good motor dexterity in their hands. Thus, a remote robot interface may have widgets (e.g., buttons, switches, levers, dials) that require manipulation.

A general assumption like that does not necessarily hold when applied to people with physical and/or cognitive disabilities. Differences such as motor dexterity, cognition, vision must be taken into account during design. We have developed guidelines for designing assistive technology interfaces which are consistent with HCI, adaptive user interfaces, and usability. Further, we have developed recommendations for evaluating assistive technology devices based on our user testing experience.

7.1 Guidelines for Designing Assistive Technology Interfaces

Design of assistive technology devices must take into account differences in cognitive ability, sensory impairments, motor dexterity, behavioral skills, and social skills (University of Texas Austin 2007). Often there is more than one way to successfully accomplish a given task. Each person is unique, and often has his or her own customized solution. Generalizations over populations cannot be easily made for HRI in assistive technology (AT). We must also take into account these differences when designing HRI for people with disabilities. We propose the following HRI-AT design guidelines, inspired by the research fields of usability, human computer interaction, and adaptive user interfaces (Shneiderman 2000) (Shneiderman 1998) (Card et al. 1983) (Oppermann 1994):

1. Interfaces should be easy to use.

2. Interfaces should have simple processes. A person with a cognitive impairment may not be able to perform a lengthy process with multiple steps.

3. Interfaces should adjust prompting levels. A person may require some form of prompting to perform a process.

4. Interfaces should leverage a person's sensory skills to augment their feedback.

5. Interfaces should accommodate multiple access devices. Slight variations in the interface may be required to support a variety of similarly purposed access devices.

Guideline 1 (ease of use[1]) is consistent with principles found in HCI and universal design. According to the third universal design principle (simple and intuitive), "use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level" and more importantly "be consistent with user expectations and intuitions" (The Center for Universal Design 2008).

[1]Ease of use is a subjective measure and relies on a user's desired ownership and control level, capabilities, and workload. In situations where the user's workload is low, he or she may wish to have a more engaging experience with the system. However, if the user's workload is high, he or she may wish to have a high level of transparency.

Guideline 2 (minimal length processes) is consistent with principles found in HCI specifically Nielsen's (1993) third heuristic (minimize the user's memory load). The third principle of universal design (simple and intuitive) also applies to process length. "Eliminate unnecessary complexity" (The Center for Universal Design 2008).

Guideline 3 (adaptive prompting) is consistent with principles found in HCI, specifically Shneiderman's (Shneiderman 1998) third golden rule of interface design (offer informative feedback). It is also consistent with the third principle of universal design (simple and intuitive) which states, "provide effective prompting and feedback during and after task completion" (The Center for Universal Design 2008).

Guideline 4 (augmented feedback) is consistent with principles found in HCI, specifically Nielsen's (1993) fifth heuristic, and universal design (Principle 4: Perceptible information). According to the fourth principle of universal design, "use different mode (pictorial, verbal, tactile) for redundant presentation of essential information" (The Center for Universal Design 2008).

Guideline 5 (multiple access devices) is consistent with principles found in HCI, specifically extensibility and adaptability. According to the second principle of universal design (flexibility in use), "the design accommodates a wide range of individual preferences and abilities" (The Center for Universal Design 2008).

7.1.1 Compliance of Our Direct Selection Interface

The flexible interface was a design collaboration between roboticists and occupational therapists. By design, it largely adheres to the HRI-AT guidelines.

Whether the flexible interface is not frustrating and discouraging to use is largely subjective (guideline 1). In the August and September 2007 user testing, it was shown that Interface A (fixed camera view with touch screen) was the easiest to use through analysis of object selection time, attentiveness level, and prompting level.

It should be noted that the participants overall had a positive experience, which is indicative that the flexible interface was not too frustrating to use.

The flexible interface has minimal stepped processes as it has at most a two-step process for object selection (guideline 2). For Interface A (fixed camera view with touch screen), the user touched the object to indicate selection. For Interface B (fixed camera view with joystick) and D (moving camera view with joystick), the user moved the joystick to the desired object and then pressed a button to indicate selection.

Adjustable prompting has not yet been incorporated (guideline 3). For the August and September 2007 user testing, the experimenter prompted and encouraged the user as necessary. The primary experimenter was a trained assistive technologist with many years of experience.

The flexible interface used audio feedback in addition to visual (guideline 4). When a selection occurred, a bold, red rectangle around or on the object and a "ding" played. Otherwise, a "Please, try again!" prompt sounded.

The flexible interface accommodated the multiple access devices (guideline 5). Many users are already able to drive a powered wheelchair with a joystick, access a computer with a joystick or touch screen, or both. Four versions of the interface were created and tuned for the specific access methods.

7.1.2 Compliance of Other HRI-AT Interfaces

A sampling of assistive robot arms and HRI-AT projects was presented in Chapter 2. We examine how aspects of these interfaces complied with our HRI-AT interface design guidelines.

The HRI-AT community has primarily focused on access devices (guideline 5). Many projects leverage standard access devices or are investigating novel input devices. Stanford University's DeVAR was controlled with a restricted voice recognition system (Van der Loos et al. 1999). Each user was trained with simple words in order to command the robot. Thus, ProVar was designed to interface with "any commercially available assistive technology... [thus] assuring a customized, optimized fit to each operator's individual needs."

Like Stanford University, the University of South Florida has investigated a number of access devices for controlling their seven degree of freedom wheelchair mounted robotic arm (Alqasemi et al. 2005). The robot arm can be controlled with standard access devices (such as joystick, keypad, and switches) in addition to novel input devices (such as hand tracking and haptic devices). Middlesex University has also investigated novel input devices (such as speech recognition, head gestures, and biological signals) for control of their robot arm (Parsons et al. 2005).

Joysticks are a popular input device as they can be typically found as a power wheelchair user's drive mechanism and also as an assistive computer mouse. RAID, Weston, Asimov were controlled through a user's wheelchair drive joystick (Dallaway and Jackson 1992) (Hillman et al. 2002) (Fridenfalk et al. 1999). Integrating into a user's drive joystick allows for transparency as the user does not have use a superfluous input device. Kanagawa Institute of Technology's robot arm was also controlled with a custom "joystick lever" (Takahashi et al. 2002). My Spoon, a feeding device, used a joystick to indicate food selection (SECOM 2008) (Soyama et al. 2003). In manual mode, the user moved the joystick to "position adjustment" to directly select the location of the food. In semi-automatic mode, the user moved the joystick to select which of the four compartments food should be retrieved. My Spoon provided the option of a "standard" or "reinforced" joystick (for users with tremors). Additionally, My Spoon provided guidelines for mode and device.

The HRI-AT community has somewhat addressed the ease of use of interfaces (guideline 1). For example, Stanford University's DeVAR was a rigid system with respect to changing or adding user tasks (Van der Loos et al. 1999). Also, DeVAR was strictly position-based and any offset of an object's position would cause DeVAR to fail. Both rigidities resulted in a frustrating user experience. Thus, ProVAR was designed to be a more flexible system with respect to user tasks and object manipulation.

The HRI-AT community has also partially addressed process length needed to operate an interface. The Polytechnic University of Catalunya's Tou used an adapted keyboard (Casals et al. 1993). The adapted keyboard allowed Tou to be moved in Cartesian space with the "up-down," "approach-go," and "right-left" on a single display (see Figure 10 on the right).

However, it is still common to use modes and menu hierarchies for control. Like ProVar and RAID, the Institute of Automation at the University of Bremen has a software application as the user interface (Valbuena et al. 2007). The user traversed a topological graphical user interface (i.e. "right" or "next," "left" or "previous," "select" or "open" or "start," and "cancel" or "back") to operate the robot arm. This traversal was similar to the commercially available Manus ARM's menu hierarchy. Weston was also controlled with a menu hierarchy (Parsons et al. 2005). Figure 7 (right) shows the "arm mode."

Interestingly, in the assistive robot arm survey from Chapter 2, the HRI-AT community has not yet addressed adjustable prompting (guideline 3) or augmented user feedback (guideline 4) specifically. It may be that the users are well trained on the systems and do not require supplementary prompting.

7.2 Experimental Design for Human-Robot Interaction with Assistive Technology

User trials at the intersection of human-robot interaction and assistive technology require careful experimental design. We have surveyed the HRI-AT field and noted the types of experiments conducted, numbers and types of participants, duration of studies, tasks, types of data collected, and analysis techniques, described in Chapter 3. In our research, we have conducted two experiments, described in Sections 5.3 and 6.3. The able-bodied experiment provided a baseline for our current work with cognitively impaired wheelchair users. We have shown the similarities in data collection and analysis and the differences in experimental design when testing with our target population versus an able-bodied population. Based on our user testing experiences (Tsui and Yanco 2007) (Tsui et al. 2008a) (Tsui et al. 2008b), we offer the following HRI-AT recommendations:

Involve the end-user. Involve the end-user as soon as possible in the design process. The interface style changed from the indirect selection (single switch scanning) to direct selection (using touch screen or joystick) due to an incorrect assumption. By involving the end-user and, in the case of assistive technology, their staff (caregiver, nurse, occupational therapist, physical therapist, etc.), a clear understanding of the users' desires and abilities grounds the project in reality.

Involving the end-user is a well-known principle in the HCI field (e.g., user centered design (Norman 2002)). Since HRI borrows techniques from HCI, we are not surprised that the principled of involving the end-user should apply to HRI-AT as well.

Define the user population. People with disabilities have a wide range of physical and cognitive impairments with wide range in severity. Generalizations cannot be made over this population, thus it is imperative to choose a well defined user population. In the case of this experiment, we chose users with mild cognitive impairments and minor vision problems which resulted in a participant population of eight. In future experiments, we will add users with lower cognitive capability to determine the bounds of usability of our robot arm system.

Additionally, consider the number of participants necessary for statistical significance in a controlled experiment. When evaluating with end-users, a smaller sample size may be acceptable. If the population is too small for statistical analysis, the experiment may need to be changed to an observational study. Even then, it is difficult to make generalizations because every person is unique.

As with the previous recommendation, defining the user population is another well-known HCI principle. Nielsen (1993) discussed both experiment type and user population in his "Usability Engineering" text. Again, since HRI borrows techniques from HCI, we are not surprised that the principled of defining the user population applies to HRI-AT.

Consider setup and mounting. Fast setup and break down time are essential to good user testing. Often a participant will lose motivation or feel frustrated if the setup time takes too long. Since the session length averaged thirty minutes, we wanted to mount as generically as possible.[2] Thus, the ARM was mounted to the wheelchair with casters and clamps. However, unforeseen issues did occur with the joystick and touch screen placement. The joystick was initially placed on a lap tray, instead of mounting the joystick to the participant's wheelchair. Some users had shallow laps and therefore could not use the lap tray easily. Eventually, a small, adjustable height side tray was used to hold the joystick. Still, some power wheelchair users had difficulty positioning the joystick because their wheelchair joystick was al-

[2]The duration of a session in future trials will be longer; we expect sessions to last multiple hours or days. At this point, we will interface with the patients' drive joysticks and fully mount the robot and touch screen to their wheelchairs.

ready placed in its optimal position on their dominant hand. This would result in having two abutting joysticks. Most users were able to reposition their arm and hand to operate the non-driving joystick. However, there was one person who was not able to participate in the user trials because he did not have adequate motor skills in his right arm to accommodate the awkwardly placed non-driving joystick.

Choose an appropriately challenging task. A task that is too easy will bore a user; one that is too difficult is frustrating. Either can cause the user to feel disdain towards the experiment or underlying system. For our system, it was determined that not all users would be able to use the original menu hierarchy to control the robot arm. Therefore, the baseline was removed as an interface option. Using the original menu hierarchy would likely cause frustration, and the users might dislike the robot arm system overall.

Understand the user's motivation and interest. It was imperative not to bore or overwhelm the participants with the task because we will be working with this patient population in the future. The matching task was suitable because it was game-like and the level of difficulty was customizable to the participant. If necessary, the generic objects could be replaced with personal items, thereby increasing their motivation.

The participants' reasons for being in the study differed. Some thought the robot arm was fun and were excited about using new technology. Others wanted to help with the on-going research. Many asked questions about the inner workings of the robot arm and about the system developers. It is imperative that the users not feel obligated to continue in the study. After each session, the participants were always asked if they would like to come again to use the robot arm.

Collect qualitative and quantitative data. When conducting experiments in HRI-AT, it is imperative to collect both qualitative and quantitative data. Qualitative data can be derived, for example, from interviews with the participant, observer notes about a trial, and caretaker observations of the participant. Quantitative data is more difficult to obtain. Ease of use and user workload may be derived from task completion time and commands issued. Coding of recorded video sessions may also provide quantitative data.

CHAPTER 8
SUMMARY AND FUTURE WORK

8.1 Future Work

Our system has several assumptions which will need to be addressed. The shoulder camera view is assumed to approximate that of the wheelchair occupant, which may not necessarily be true. Users may also bias their head position to one side to be comfortable. Thus, their periphery is skewed with respect to the shoulder camera, which is vertically oriented in the direction of gravity. Additionally, users may have vision impairments such as permanent vision loss and/or temporary blurring.

The touch screen serves as the display for the interface, which represents a layer of abstraction between the user and the objects in the real world. Some users may be able to understand a real apple but not a picture of it. This restricts the end-user population to those with higher cognitive capabilities. We plan to evaluate interfaces for our system which do not require the display.

Adjustable prompting (guideline 3) has not yet been incorporated in our system. This is a key component to a user's success with an assistive technology because automated prompting allows for the same delivery each time. The perception of the prompt by the user is likely to remain the same over time, unlike when a person prompts as the same prompt may be perceived differently given intonation, surroundings, etc.

We will also investigate the lower boundary for required cognition for our system and study the correlation of cognitive ability with interface profile recommendations. The able-bodied experiment from August 2006 provided an upper bound. The end-user evaluations from August and September 2007 featured high functioning individuals who were highly cognitively capable.

8.2 Summary

We have implemented an autonomous system for the Manus ARM to reach towards the desired object in a "pick-and-place" activity of daily living (ADL). We designed and implemented a prototype system which used indirect selection (e.g., single switch scanning) and evaluated with able-bodied participants in August 2006. We have designed and implemented a flexible interface compatible with direct selection (e.g., touch screen and joystick) in accordance with the human-robot interaction for assistive technology (HRI-AT) interface design guidelines. We designed and conducted an experiment that ran over the course of eight weeks (August and September 2007) with eight end-users who were representative of the intended user population.

Two broader contributions have resulted from this work that will impact the field of human-robot interaction with assistive technology (HRI-AT). First, we have developed guidelines for designing interfaces for HRI-AT based on existing guidelines in usability, human computer interaction, and adaptive user interfaces. Second, based on our user testing and a survey of HRI-AT experiments, we have developed guidelines for experimental design in HRI-AT.

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APPENDICES

Appendix A
Data Collection Questionnaires and Forms

A.1 Able-bodied Controlled Experiments

A.1.1 Pre-test Questionnaire

Gender: Female Male

Age: ____________________

Occupation: ____________________

1. What types of computer do you normally use? Check all that apply, and state the approximate number of years you've used each.

___ Macintosh Years: _______

___ PC Years: _______

___ Unix or Linux Years: _______

___ Others: _____________ Years: _______

2. Approximately how much time do you spend using computers?

___ 0 - 3 hours

___ 3 - 10 hours

___ 10 - 20 hours

___ over 20 hours

3. What applications (e.g., Microsoft Word) do you use on a regular basis?

4. How would you rate your level of computer expertise? Please choose the description that matches the closest match.

___ Casual: Primarily occasional e-mail and web-browsing

___ Moderate: I do a lot of regular work or leisure activities on a computer

___ Expert: I troubleshoot and upgrade applications or operating systems

___ Guru: Other come to me for solving their problems

5. Have you ever operated a robot before? Yes No

If yes, what type of robot and how?

6. How many hours a week do you play video games? ______

A.1.2 Post-experiment Questionnaire

Definitions:

Interface 1 is the standard interface, meaning the "out of the box" configuration. In the August 2006 experiment, the single switch using the cyclic menu was used.

Interface 2 is the alternative interface, meaning the visual "zoom, zoom, train color" text prompted configuration.

Rating scale : 1 (best/yes/intuitive/calm) to 5 (worst/no/unintuitive/frustrated); whole numbers only please, otherwise will be rounded down.

Questions:

1. Which interface did you prefer? Why?
2. Which feature did you like most about the first interface? The second?
3. Which feature did you like least about the first interface? The second?
4. Do you have suggestions for changing the interface that could make the task easier to complete?
5. Rate your overall experience with Interface 1.
6. At the end of the "put the ball in the cup" training, rate how comfortable you feel with Interface 1.
7. Define "sufficiently close."

8. What strategy, if any, did you have when approaching the ball when using Interface 1?

9. Rate your feelings about Interface 1 (ie. emotional status).

10. Rate your overall experience with Interface 1.

11. At the end of the alternative interface training, rate how comfortable did you feel with Interface 2.

12. Rate the intuitiveness of the text prompts used in Interface 2.

13. In Interface 2, did you follow the text prompts for the next step, or did you use memory recall? Did you miss a step or were confused as to where you were in the process?

14. Discuss the color calibration step in Interface 2.

15. In Interface 2, in the user selection view, when zooming in the second time, did you know where you were with respect to the larger/shoulder view?

16. Rate your feelings about Interface 2 (ie. emotional status).

17. Do you have any questions for me or other comments?

A.2 End-user Hybrid Observational Evaluation

A.2.1 Session Setup Form

Participant name: Date of session:

Start time:

Number of objects in scene: 3 4 5 6 7 8 9 10

Sketch of object placement: Easy Medium Difficult Variety

Cursor size:Small Medium Large

Dwell length:

Length of reorientation:

Notes about reorientation, changes to user set up, etc.:

A.2.2 Run Data Record

Participant name: Date:

Session number: 1 2 3 4 5 6 7 8 9 10

Fixed Camera	Moving Camera	Joystick w/ button	Joystick w/ dwell	Touch screen

Object to select: ____

Task Level: Easy 1 2 3 4 5 Hard

Start time for select	Finish time selection (Start arm movement)	Time object shown on screen	Time arm completed folding

Correct object selected? Yes No Selected, but arm went to wrong object

Amount of prompting (FIM scale): 0 1 2 3 4 5

Attentiveness: 0 1 2 3 4 5 6 7 8 9 10

Notes about this selection:

A.2.3 Post-experiment Questionnaire

1. Which interface did you like the most? Why? (If more than one used)

2. Which did you like the least? Why?

3. What would make the system easier to use?

Notes (other questions you may ask, thoughts on this particular testing session, comments made by teachers with the participant):

BIOGRAPHY

Kate Tsui is a second year Computer Science doctoral student at UMass Lowell. From 2001 through 2006, she worked for Sun Microsystems in several software engineering roles, including development and quality assurance. In 2004, she graduated from UMass Lowell with her BS in Computer Science.

Kate is a robotics researcher specializing in human-robot interaction and assistive technology at UMass Lowell's Robotics Lab. Her research has produced several peer-reviewed publications: *AAAI Spring Symposium Series on Multidisciplinary Collaboration for Socially Assistive Robotics* (2007), *International Conference on Rehabilitation Robotics* (2007), *AAAI workshop on Human Implications of Human-Robot Interaction* (2007), *Human-Robot Interaction* conference (2008), and *Human-Robot Interaction workshop on Robotic Helpers: User Interaction, Interfaces and Companions in Assistive and Therapy Robotics* (2008). Kate received the UMass Lowell College of Science's Outstanding Research Scholar Award in 2008.

Kate is a member of the Association for Computing Machinery (ACM), Rehabilitation Engineering & Assistive Technology Society of North America (RESNA), Institute of Electrical and Electronics Engineers (IEEE), IEEE Women in Engineering (WIE), IEEE Robotics and Automation Society (RAS), and Association for the Advancement of Articial Intelligence (AAAI).

Kate has served as the teaching assistant and guest lecturer for the Organization of Programming Languages class. She is also actively involved with increasing participation in STEM (science, technology, engineering, and math) fields through educational outreach to K-16 students. Additionally, Kate founded the Women in Computer Science group in September 2007. She received the Computer Science Department's Meritorious Service Award in 2007.