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Kinematic and Experimental Evaluation of Commercial Wheelchair-Mounted Robotic Arms

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by

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Dedication

I dedicate this work to my colleagues, friends, and family who constantly inspire me and give me the courage and drive to succeed.

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Abstract

Commercially available wheelchair-mounted robotic arms (WMRAs) are becoming more prevalent internationally but have yet to be largely developed and approved by the Food and Drug Administration in the United States. The purpose of this study was to experimentally evaluate commercially available WMRAs in a controlled test environment. The goal was to quantitatively compare each device through a standardized testing protocol. The study produced theoretical manipulability measurements as well as efficacy ratings of each device based on Denavit-Hartenberg kinematic parameters and physical testing, respectively. Both the manipulator and control devices of WMRA systems were evaluated. The iARM WMRA system was presented to be more effective than the JACO WMRA system based on kinematic analysis. Despite this, the JACO system was shown to be more effective than the iARM system in three of four experimental tasks. Effective design features were brought to light with these results. The study and its procedures may serve as a source of quantitative and qualitative data for the commercially available WMRAs.

Chapter 1 Introduction

1.1 Motivation

Assistive devices are meant to increase the quality of life of individuals with disabilities by reducing dependence on dedicated caregivers. Increased independence is available in the form of modifications to a dwelling, specialized electromechanical devices like automatic door openers, electric power wheelchairs, adapted communications devices, and automotive modifications.

The key point in a successful assistive device or system is to allow for easy performance of activities of daily living, or ADLs. The simplest ADLs are often the most necessary. The act of reaching outward to interact with the immediate environment is essential for independent living. This act not easily performed in an unstructured environment without extensive modification to the surroundings.

Robotic manipulators have been employed for reaching tasks in the industrial setting for decades (1). As technology shrinks it is feasible to create compact, lightweight robotic manipulators for personal use by those who suffer from a condition or illness resulting in degradation of mobility.

Commercial development of the assistive measures mentioned above has matured overall. In the United States however, growth of assistive manipulator products has been largely non-existent, with a few notable exceptions. In countries such as Canada, the Netherlands, and Scandinavia assistive manipulators in the form of wheelchair-mounted robotic arms, or WMRAs, are government approved and covered by medical insurance, in most cases by law. The degree to which WMRAs are used abroad gives evidence to the positive influence of the devices on the life of the user.

In the U.S., a study was conducted with a sample population consisting of 50 power wheelchair users with severe disabilities (2). The survey was used to determine the theoretical desirability of WMRAs for assistive purposes. Results of the 110 question survey are displayed in Table 1 below.

Table 1 - Results of desirability survey for WMRAs in the U.S. (2)

Average Age	40 Years
Marital Status	68% Single
Living	58% Home, 69% with Family Support
Employment	79% Unemployed
Disability	24% SCI, 16% MS, 60% Other
Purchase Desirability	84%

The purpose of this study is to experimentally evaluate wheelchair-mounted robotic arms. Those who take part in this study may find quality of life benefits as a result of becoming familiar with WMRA assistive devices. Participants may also find using a WMRA helpful in performing activities of daily living. The research study may help to increase local awareness of WMRAs.

1.2 Goals

The goal of the study is to quantitatively compare the two commercially available WMRAs; the iARM by Exact Dynamics and the JACO by Kinova. In order to compare each device, a sample of able bodied and wheelchair dependent individuals will be recruited. With each WMRA, participants will be asked to perform a series of four activities of daily living. Participants will be presented with a survey at the conclusion of each task. The survey is designed to quantitatively rank each WMRA's performance. The time to complete each task with each arm will also be recorded.

This study will experimentally evaluate the WMRAs by gauging feedback from participants operating the devices in a controlled test environment. There will be two groups of participants. One composed of able bodied individuals (n~=10) and a second composed of wheelchair dependent individuals who are confined to a power wheelchair (n~=10).

The outcomes of this study identified desirable design features of WMRAs and input devices so that future production systems may exhibit increased effectiveness in the tasks presented in this study. Furthermore, theoretical efficacies were calculated using kinematics to determine the manipulators' hypothetical effectiveness in key points of interest.

So, the goals of the project were to:

1. Determine WMRA system efficacies with physical arm operation
2. Determine theoretical manipulator efficacies with kinematic analysis
3. Identify positive and negative features of each device

The study and its procedures may serve as a source of quantitative and qualitative data for the commercially available WMRAs.

Chapter 2 Background

The following sections will introduce developments in assistive robotics which helped to bring viability to WMRA systems.

2.1 Rehabilitation Robotics

Rehabilitation robotics is a division of general robotics in which devices like robotic manipulators are created in order to help individuals with reduced mobility complete every day activities. Conditions in which rehabilitation or assistive robotics are applied range from rehabilitation in the traditional sense of physical therapy in which the user of the robotic device will eventually regain lost mobility to application for those who have permanently lost mobility, strength, or dexterity (3). When considering WMRAs, it is mostly assumed the condition is the latter and the user suffers from a debilitating disease or injury.

To appreciate the WMRA, one must be presented with the development lines which ultimately lead to the mobile manipulator, and thus, WMRA concept. The background of the assistive robotics is presented in the following sections.

2.1.1 Workstations

Workstation robots were the first iterations of the application of relatively small robotic manipulator arms for use of disabled individuals. These devices usually consist of extensive framing in a fixed location with robotic arm suspended from the frame. The arm could be moved across the frame manually or with powered actuation depending on the model.

Various models of workstation manipulators were developed. One could expect a workstation to be highly tailored to do specific tasks very well, or be designed for a broad range of tasks which can be performed in a fixed area. With these characteristics, workstations are highly effective in the workplace.

Affordable stationary assistive devices such as assistive feeders are a development from large complex systems such as the desktop vocational assistant robot (DeVAR) developed by Stanford University (4). These systems in addition to MASTER and RAID workstation robots assisted the user in a wide variety of stationary tasks by utilizing a rail-mounted robotic manipulator. Though a large quantity of tasks could be completed, large workstation systems offered no aid to the user outside of the workspace.

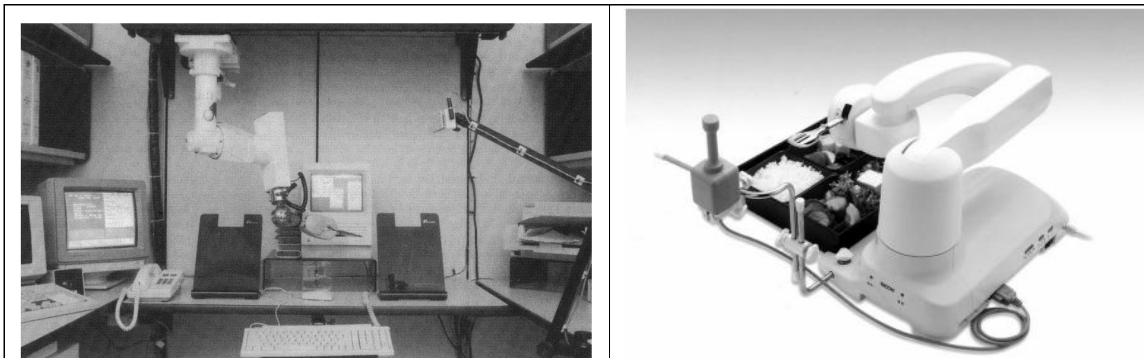


Figure 1 – From left: DeVAR workstation, MySpoon assistive feeder (4), (5)

Problems with desk-mounted robotic systems stem from being confined to one space. Assistive feeders though smaller than full scale workstations still require the help of a caregiver to position or transfer from place to place (5). Desk-mounted robots can be tailored to perform a narrow range of tasks exceedingly well, or designed to have a greater capacity to perform general activities. In either case, a desk-mounted or workstation robot or stationary assistive device confines the user to a single location within a room, building, etc. which removes the user from effectively interacting with people located throughout the space.

2.1.2 Rail-Mounted Manipulators

Trolley- or rail-mounted assistive manipulators achieve a level of mobility at a low cost when compared with free-range mobile robots. With this system, the manipulator may be continually relocated anywhere along a system of rails or tracks, thus expanding the volume in which the operator can be effective in independently performing certain tasks. A drawback in rail-mounted systems is that the manipulator base which is connected to the rail or track providing the means of translation is not powered in some systems. This means that the robot must be manually moved to a given workspace which may be difficult for a severely disabled operator to do.

This drawback can be easily remedied with the addition of a powered manipulator base which can be driven on the rail or track electronically with the push of a button. However, adding powered locomotion increases the cost of the overall system and still restricts the operator to being independent in a space which the frame is installed. An example of such an assistive device is the rail-mounted system and the professional vocational assistant robot (ProVAR) developed by Stanford University (6).

2.1.3 Mobile Robots and Mobile Manipulators

A powered platform which carries a robotic manipulator may be referred to as a mobile manipulator. The platform or base of the device is able to move about an environment freely and is not confined by a track, rail, or connections to a fixed object. In many cases, the base of a mobile manipulator is an autonomous or semi-autonomous sensor-infused robot capable of navigating or being navigated through and around an environment in order to present the attached robotic manipulator optimal positioning for a given task. The manipulator may be considered as a feature of a mobile robot.

Mobile robots may be designed to operate in the air, under water, or on the ground whether they feature a manipulator or not. Examples of mobile robots capable of operating in these environmental theaters include the Northrop Grumman Global Hawk, the Woods Hole Oceanographic Institution REMUS 100 AUV, and the Foster-Miller Talon AGV respectively (7).

Current research and commercial mobile robots can give care to elderly or sick, maintain surveillance over an area, or assist in a limited way in activities of daily living. Mobile service robots (MSRs) of the care-giving variety are designed to monitor the health and safety of a patient, elderly person, or child. Current MSRs are tall and slender which allows easy movement through interior household spaces (8).

These commercially available mobile robots provide around the clock over watch to the care receiver and can remind the care receiver of medication, appointments, provide critical information to emergency personnel in the event of an accident, alert the care receivers to visitors or intruders, and become a communications link to family members and physicians for virtual check-ups.

Figure 2 – Gecko Systems CareBot in working environment (8)

Interface between MSRs and users range from audio/visual communication to tactile and touch screen monitors and input devices. Voice recognition and command of the unit is commonly paired with audible response from the MSR to confirm a desired control input or to relay information. Autonomous navigation of the human environment is carried out through software augmented by bump, ultrasonic, and laser sensor batteries.

Versatility in design of systems with these features allow MSRs to fill a variety of applications such as additional service industries like sales, hospitality, and touring, as well as homeland security roles in facility monitoring and remote inspection, and military patrol and weapons detection.

Mobile autonomous robots like MSRs are designed to provide surveillance. However, the limited capacity of MSRs to physically interact with their environment reduces their effectiveness in ADL support. An appropriately designed MSR may be able to open a door for the care receiver but cannot retrieve an object of the user's interest located towards the center of a large table as MSRs are not commonly equipped with manipulators. Typical manipulation hardware mounted to select models of MSRs is one or two degree of freedom short-reach grippers. MSRs with more complex manipulators are under development and unavailable on the global scale. Increased cost associated with adding levels of autonomy also limits the number of MSR platforms with complex manipulators in the commercial environment.

2.1.3.1 WMRAs

Wheelchair-mounted robotic arms allow the user to be more independent no matter his or her location (assuming he or she is operating a power wheelchair equipped with a robotic manipulator). A WMRA is installed on a user's power wheelchair. The robotic arm uses the power wheelchair on-board power supply and may be controlled through a variety of input devices. Input devices range from numeric keypads to 3D joysticks to brain-computer interface (BCI) -based signals. Since a WMRA includes the user in the control loop, a high level of cognitive power is available without the added costs of robotic automation.

WMRAs differ from other types of robotic manipulators in that they are in intimate proximity to the operator. WMRAs are designed to be mounted as close the user as possible so that the end effector can interact with the user as well as the user's immediate environment. This facilitates manipulation of objects at a maximum distance as well as use in feeding, retrieving, and hygiene activities.

2.2 WMRA Design Considerations

Critical design considerations in robotic systems designed for personal use are in the areas of mobility and control. The following sections details how these considerations are addressed in WMRAs.

2.2.1 Mobility

As previously stated, the proximity of a WMRA to the user is relatively small and warrants special consideration. The range of motion of a WMRA must be greater than that of fixed or rail-mounted manipulators as the user will expect to use the WMRA as an extension of his or herself in a given environment. The expected vertical range of a WMRA is from very near or on the floor to standing height, approximately 5' from the floor. This range should allow for retrieving low lying objects to personal hygiene to overhead shelf access. The horizontal range is most affected by the position of the wheelchair as the distance from a target object or area can be increased or decreased by positioning the wheelchair, and therefore WMRA, further away from or closer to the target.

The addition of a WMRA to a wheelchair must not degrade wheelchair stability, steering, user control of the wheelchair, maneuverability, ability to move through ADA compliant doorways, or user vision. Furthermore, a WMRA must not degrade the comfort of the user which includes seat adjustment, pressure relief, and the ability to transfer into and out of the wheelchair. Finally, social considerations impact WMRAs more so than any other robotic manipulator. A WMRA may be used throughout the day and in any location to include public areas. The user should not suffer social discomfort from aesthetically undesirable WMRA design. The user should be able to interact freely. (9), (10), (11), (12), (13)

2.2.2 Control

Control devices range from conventional joystick control to invasive and noninvasive brain-computer interface (BCI) control of assistive manipulator systems (14), (15). Conventional joystick control uses joystick types typically used to control power wheelchairs providing control over the velocity of the drive wheels resulting in translation, rotation, or a combination of both in order to navigate the wheelchair in a given environment. Two-dimensional, or 2D, control indicates restriction to planar control of device. Combinations of control devices may serve to make assistive devices more accessible. The Easy Rider Company manufactures several modular control devices, interfaces, and processors which can be individually selected to give the user the most effective suite of input devices for wheelchair and wheelchair-mounted assistive device control.

2.3 Research WMRA Designs

Internationally, many academic studies center on WMRAs. Research is being done on many aspects of the WMRA concept. Many institutions have attempted to create proprietary manipulator designs while others use commercially available WMRAs to further the study of control interface, automation, and sensor infusion among other topics. Some of these projects are briefly reviewed in the following sections.

2.3.1 KARES-II

The KARES series of WMRA systems were developed in South Korea at the Korea Advanced Institute of Science and Technology (KAIST). KARES-II is the second iteration of the KAIST side-mounted WMRA and features 6 degrees of freedom. The construction of the KARES-II uses aluminum tubing for the structure of the arm. The drive system uses a cable transmission to drive the primary joints.

Figure 3 – KARES-II, the KAIST wheelchair-mounted robotic arm (11)

Control for the KARES-II system relies heavily on non-physical user input. Visual servoing and voice command interfaces have been specially developed for feeding tasks in which the manipulator performs a single task repetitively. The visual system is used to recognize the user and food source as targets for certain positions and orientations. Other control methods include eye tracking pointers, electromyography where sensors detect electrical activity in skeletal muscle mass, and head and shoulder interfaces (11).

2.3.2 PerMMA

The personal mobility and manipulation appliance, or PerMMA, is a joint development of the Quality of Life Technology Center at Carnegie Mellon University and the University of Pittsburgh. The PerMMA explores the usefulness of bimanual, or two-handed, robotic arm manipulation. The system consists of a single power wheelchair on which two Exact Dynamics ARM robotic manipulators are mounted. One ARM is mounted on both the left and right side of the wheelchair.

Figure 4 – The PerMMA manipulator appliance (16)

The PerMMA ARMs can be jointly operated by a user seated in the wheelchair, remotely (teleoperated), cooperatively, or autonomously. The remote or teleoperated mode allows the WMRA system to be controlled by an outside user. This may be useful if the wheelchair user is unsure or incapable of performing a complex task with the device. The autonomous mode may be useful for repetitive or complex tasks (16).

2.3.3 Weston

The initial concept of the Wesson WMRA began with mounting the rail-mounted Wessex manipulator on an unpowered wheelchair. The Wessex arm has 4+1 planar DoF in SCARA configuration. The wheelchair was modified to include a single vertical actuator for which the manipulator could be mounted to allow for vertical range of motion.

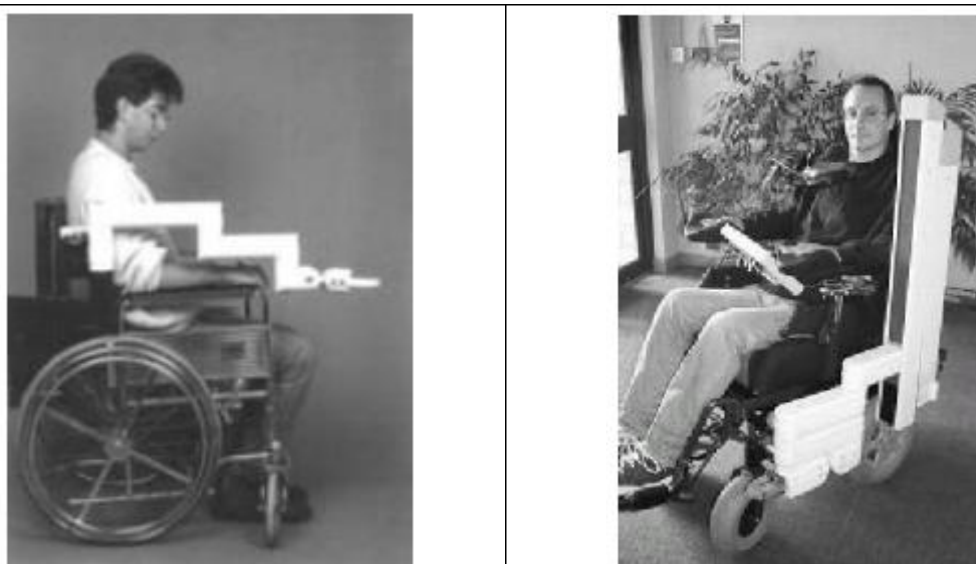


Figure 5 – From left: Weston concept design, operational Weston WMRA (10)

Evaluation of the initial design resulted in locating the vertical actuator on the side and towards the rear of a wheelchair, approximately at the vertex of seat back and seat bottom. This allowed the user to utilize desk and table space which required the wheelchair to go under the tabletop. The overall stowed height of the vertical actuator was reduced by implementing a telescoping feature.

The manipulator consists of three planar joints plus a gripper joint. Locomotion is generated by geared servomotors driving pulley mechanisms and a reverse differential in the gripper. The lower power motors and effective gearing increase safety to the user as well as increase electric power economy. The compact design increase aesthetic appeal. The gripper is a two parallel finger design. Features include single motor actuation, slim profile for maximum visibility, linkage compliance for durability, and non-backdrivable gearing.

For initial volunteer testing, the Weston was mounted on a passive mobile platform which was then temporarily attached to the wheelchair of the volunteer tester. The passive mobile platform simulated the end-user mounting position of the WMRA which gave a clear indication as to how the WMRA would function both statically and dynamically.

Control electronics were given consideration. All necessary electronics are mounted on the manipulator or vertical actuator architecture and have wiring internal to the manipulator links. The 24V source of the wheelchair is utilized to power the control electronics.

Control software displays the user interface on a small monitor mounted to the wheelchair and easily visible to the operator. The default input device is a 2D joystick which is a limiting factor in the system design. The joystick is used to make movement selections on the monitor. The manipulator arm operates in the horizontal plane and can be issued 2D Cartesian commands with respect to the base reference frame. The elevation of the arm can be adjusted by making the appropriate selections with the joystick (10).

Drawbacks to the Weston system include limited forward reach and small useful volume of manipulation, excessive wheelchair width increase as a result of the side mounted system, bulkiness of the display monitor, and having separate wheelchair and WMRA joysticks.

2.3.4 WMRA-I

The University of South Florida has developed a unique wheelchair-mounted robotic arm referred to simply as WMRA-I. The design centers on offering the user a control scheme in which the robotic manipulator and electric power wheelchair move cooperatively. Cooperative motion may be observed when the robot arm of WMRA-I reaches the extent of its workspace at which it can no longer extend.

Cooperative control commands the wheelchair to move in the desired direction in order to advance the workspace to an acceptable area. Coupling control of a 7-degree-of-freedom manipulator and the 2-degrees-of-freedom of the wheelchair creates a 9-degree-of-freedom system (8).

Figure 6 – University of South Florida developed WMRA-I with Barrett HAND

In order to achieve cooperative control of a wheelchair, the WMRA-I system requires that encoders be mounted on the powered wheels. Encoder signals are then passed to the WMRA-I control hardware where precise velocity measurements can be read. The control system, which includes a laptop computer then issues commands to the wheelchair control system to compensate for the rate at which the end effector is commanded to move beyond the workspace.

The robotic arm of WMRA-I is a 7-degree-of-freedom design which allows for a wide range of configurations and optimization techniques (14), (17).

2.3.5 WMRA-II

The second iteration of USF developed WMRAs is WMRA-II. It features the 9-degree-of-freedom cooperative movement design and uses similar construction. WMRA-II employs smaller and lighter high-torque motors than WMRA-I while maintaining the use of harmonic drive gear reduction.

WMRA-II is subject to the command of three possible user interfaces: A touch-screen tablet command input system, the Spaceball™ three-dimensional manipulation tool, or a brain-computer interface (BCI) which can be controlled by an individual completely devoid of personal motor function.

Initially, WMRA-II was designed with composite links in order to reduce the overall weight of the arm while maintaining excellent strength and rigidity. The composite material design consisted of two types of load bearing structures per link: A series of three carbon fiber rods to carry tensile loads, and a single large diameter polycarbonate cover to support bending and torsional loads.

The composite material design was found to be inadequate and a re-design was needed. It was decided through mutual efforts that WMRA-II would employ an aluminum link construction similar to that of WMRA-I. Motors and harmonic drives are mounted with modified aluminum brackets while the load bearing links are bolted radially to these fixtures. Refer to Figure 7 below for a display of the redesigned configuration (13).

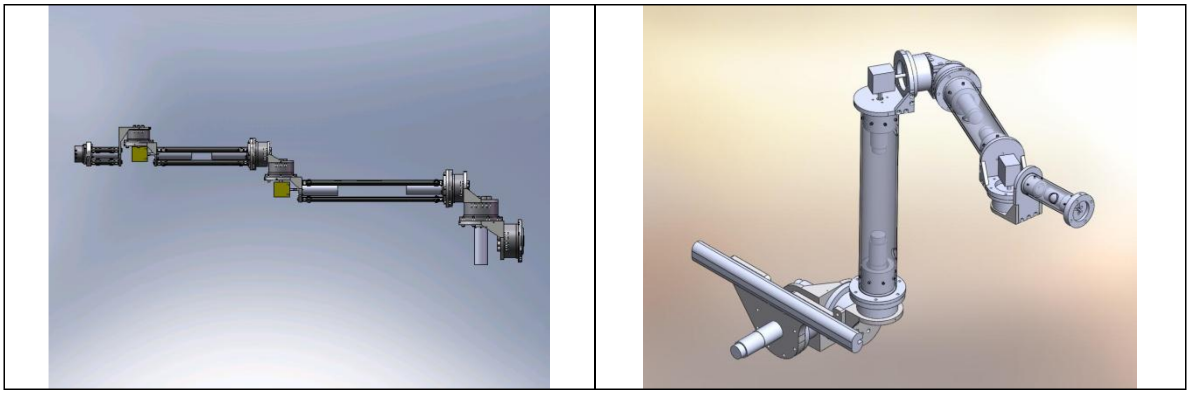


Figure 7 – From left: WMRA-II composite design concept, aluminum design with transparent links (13)

The benefits of the radially fastened aluminum link configuration include simpler design, manufacture, and maintenance over both WMRA-I and the composite link design.

The first of three user interfaces currently being employed by the WMRA project is a touch-screen laptop. This method of control is intended for those who are confined to a wheelchair but maintain a large enough capacity of strength and range of motion to manipulate a small stylus over a thirteen inch tablet PC computer screen. The screen displays a complete range of preprogrammed actions the WMRA can perform. With this control type this user simply selects the actions they desire and watch them be carried out.

The SpaceBall input device method of control is similar to the way a mouse is used to control a computer. The SpaceBall allows the user to manipulate objects in a 3D environment and was implemented as a WMRA control device for those with severely reduced upper limb strength and range of motion (18). The user simply grasps and applies pressure to the spherical control surface and drives the WMRA towards the desired objective.

The brain-computer interface (BCI) is a method of control accessible for those who lack any kind of motor function but who are conscious and maintain the ability to reason such as patients with Locked-In Syndrome (19). The BCI allows the user to select from the same preprogrammed actions provided in the touch-screen laptop control method, but does so by time-locking the user's P300 brain wave reactions. The P300 reactions are triggered by a flashing matrix composed of the fifteen preprogrammed WMRA actions. The desired actions are selected, queued, and performed in sequential order by the WMRA (20).

2.4 Commercial WMRA Designs

The international community has developed and is continuing to develop WMRAs for the assistive medical device market. In the United States however no WMRA has been FDA approved since the Raptor which is detailed in section 2.4.3. In countries like Canada, the Netherlands, Scandinavia, and others, WMRAs are government approved and covered under medical insurance depending on the user's disability. The commercially available WMRAs considered in this study are presented in the following sections.

2.4.1 iARM

A company of the Netherlands, Exact Dynamics is a veteran of several successful WMRAs. The original product, called MANUS, was a 6-degree of freedom wheelchair mounted manipulator with a 2-finger end effector. The overall design of MANUS has carried through subsequent generations of Exact Dynamics WMRAs, with the ARM, and later iARM, all of which are designed for general ADL tasks and light object manipulation. The latest model, the iARM, weighs 9 kg (20 lbs) and runs on battery power from the wheelchair.

Figure 8 – iARM by Exact Dynamics (tzechienchu.typepad.com)

The basic layout of these devices begins in the base link, link 1. The base link is the largest link and houses all of the drive components of the manipulator. The six joints are driven by six DC geared servomotors. The motors transmit power from the base of the arm via an extensive transmission system which runs throughout the remaining links and to the end effector. The end effector itself is driven by a single motor of decreased size and power.

The physical configuration of the arm and its links are intended to be a function of the instantaneous use of the device. When the arm is not being used, the operator may choose to stow the manipulator so that it is largely removed from the operator's space. In the stowed position, the links of the arm fold into a compact form, occupying the minimum volume dictated by physical dimension of the model (MANUS, ARM, iARM).

When the operator chooses to use the manipulator, the arm unfolds, or "unpacks". The end of the unpacking movement is the "ready" position. This is where the operator can begin to take useful control of the device. The ready position is constant; the arm will always unpack to this position.

The base link has also housed control electronics for each iteration of Exact Dynamics WMRA. Here, a central hub is connected to the manipulator within the base link. Power and input devices are plugged into the hub the configuration of which is then recognized by the control electronics of the arm. The hub may be mounted anywhere on the end-user's wheelchair. Input devices are readily adaptable to custom mounting, i.e. special brackets, OEM structural members or armrests, or Velcro surfaces. Input devices for the iARM range from 16 button keypads of varying dimension, 2D joystick, to single-button control.

The manipulator itself features a special interconnect and must receive custom mounting and modification to the wheelchair. Exact Dynamics manipulators are side-mounted devices and therefore a left-or right-handed bias must be disclosed by the end-user.

This bias may be the result of household access bias, wheelchair configuration, wheelchair use, or personal preference. In either left- or right-hand configuration, distributors work to achieve optimal mounting distances from the user based on specific information provided by Exact Dynamics.

Left or right bias preference determines the preprogrammed ready position. The optimal mounting location of the WMRA on the wheelchair ensures the user can operate the device as effectively as possible.

The option of a “z-lift” device often effects the final mounting position. The z-lift locates the manipulator base approximately 12" forward from the physical connection of the mount to the wheelchair, and allows the manipulator to be raised and lowered in what is considered the z, or vertical direction. The z-lift is designed to increase overhead reach without undesirably effecting compactness of the arm in “packed”, or stowed configuration when not in use.

Once the main connector is mounted, the manipulator may be easily applied or removed from the wheelchair by a caregiver or WMRA distributor for long-term storage, or service.

In addition to the variety of input devices, Exact Dynamics WMRAs can operate in several control modes. Cartesian mode moves the end effector in a straight line with respect to the base. Rotations of the end effector can also be performed in this mode. Pilot mode is similar to Cartesian mode but rotates the end effector so that it points in the direction of movement. Macro mode allows for on-the-fly storage of arbitrary 3D points which can then be recalled by pressing and holding a single button.

Exact Dynamics WMRAs also feature a drinking movement feature which simultaneously rotates and raises the end effector. This is designed to keep the rim of an open container at a single point so that the user may more easily intake directly from the container. Exact Dynamics products are available in Europe, Japan, and Canada and have been research tools and research topics of many universities around the world (21).

2.4.2 JACO

Kinova is based in Montreal, Canada and has recently released its first commercial product, the JACO WMRA. Several years of development have lead to the recent release of a 6-degree of freedom, 3-finger end effector manipulator. Also designed for a wide range of light ADL tasks, the use of composite materials cuts the weight of the arm giving it a total mass of 5 kg (11 lbs). JACO features a weather proof design and claims to consume less energy than a standard light bulb.

Figure 9 – JACO by Kinova (Kinova, Inc.)

The six joints of the JACO are individually driven by six DC geared servomotors located in each joint. Each motor module includes a planetary gearhead. Two types of motor modules are used depending on joint location in the kinematic chain. Joints 1 – 3, where joint 1 the nearest to the base, use large motor modules while joints 4 – 6 use small motor modules. Within a single manipulator, each motor module is interchangeable in terms of its position based on its class. That is to say, a small motor module can replace any motor module of joints 4 – 6 without any affect on the performance of the arm. The carbon-fiber links house the series of motor modules at the links while wiring is routed through the hollow members. Each finger in the end effector is driven by an individual motor bringing the sum of motors to 9.

The physical configuration of the arm and its links are intended to be a function of the instantaneous use of the device. When the arm is not being used, the operator may choose to stow the manipulator so that it is largely removed from the operator's space. In the stowed position, the links of the arm fold into a compact form. The packed configuration is programmable by the distributor. The angle of link 1 can be varied between 0° and 60° with the horizontal. This is meant as a customization feature for the end-user but the setting the angle to 0° maximizes compactness in the packed position. When the operator chooses to use the arm, the manipulator unfolds into the ready position. The ready position is constant.

The base of the JACO houses the digital signal processor (DSP) which sends information to each motor joint and finger motor based on user input. Power and input devices are plugged into the base of the arm, the configuration of which is then recognized by the control electronics. JACO comes standard with a 3-axis, or 3D joystick. The JACO joystick is readily adaptable to custom mounting, i.e. special brackets, OEM structural members or armrests, or Velcro surfaces. JACO is integrable with Easy Rider systems by HMC International; the company offers a variety of power wheelchair control components.

The manipulator itself features a cuff at the base designed to accept 40mm t-slot extrusion. A series, usually two, t-slot extrusion members are configured in a manner which best negotiates the geometry of the wheelchair, to include armrests and other add-ons, and provides a vertical member for the cuff of the JACO to fit over. The t-slot extrusions must be custom mounted to the wheelchair. The cuff is then secured to the vertical t-slot extrusion member via two orthogonal bolts on the horizontal plane. JACO is a side-mounted device and therefore a left- or right-handed bias must be disclosed by the end-user. Distributors work to achieve optimal mounting distances from the user based on specific information provided by Kinova. Left or right bias preference determines the preprogrammed ready position.

Once the t-slot extrusions have been mounted, the manipulator may be easily applied or removed from the wheelchair by a caregiver or WMRA distributor for long-term storage, or service.

JACO may be operated in several control modes. Cartesian mode moves the end effector in a straight line with respect to the base. Rotations of the end effector can also be performed in this mode though the reference of JACO rotations is from a fixed point located at the vertex of finger contact. JACO features Pilot mode which rotates the end effector so that it points in the direction of movement.

JACO can record a single end effector location on the fly and return to that position from a random position and orientation by holding a single button. JACO also features a drinking movement which simultaneously rotates and raises the end effector. This feature reduces the difficulty of drinking from an open container. The Kinova JACO is available in Europe and Canada (22).

2.4.3 Raptor

The Raptor WMRA was developed by the Rehabilitation Technologies Division of Applied Resources Corporation. The Raptor was the first and remains the only WMRA approved by the United States Food and Drug Administration. This means that Raptor was the only WMRA allowed to be purchased with the aid of insurance coverage as a medical device. Raptor was released in 2002 and has since been discontinued by Applied Resources along with the Rehabilitation Technologies Division (10).

The Raptor was developed under design specifications of the Department of Veterans' Affairs which were implemented with the intention of reducing cost and maintaining effectiveness. Raptor is a 4-degree of freedom manipulator with a 2-finger end effector. The arm is constructed using polymer links and has a mass of approximately 8 kg (17 lbs).

Figure 10 – Raptor by Applied Resources (9)

The four joints are driven by individual DC geared servomotors. Joint 3 utilizes a local transmission to achieve its range of motion. Joint 1 is a connection between the manipulator arm and motor 1 which serves as the base of the device with mounting features. Motor wiring is routed through the hollow links of the manipulator except at the elbow joint, joint 3.

The Raptor does not configure to a packed or ready position to the author's knowledge. Instead, the arm is held in whatever position the user leaves it in at the conclusion of each operation.

Control of the Raptor arm is achieved with a 2-axis joystick while the end effector is operated with a small 2-button keypad. The device functions on a joint-by-joint basis. This forces the user to move a single joint at a time while using the device. The Raptor was a product of the Rehabilitation Technologies Division (RTD) of Applied Resources headquartered in Fairfield, New Jersey (23), (24).

Chapter 3 Evaluation Procedures

This project is multi-faceted in that it considers both theoretical and experimental results when commenting on the effectiveness of WMRA systems. The following sections will detail how study procedures are derived and implemented.

For this and subsequent chapters, the U.S. Customary system of measurement and notation will be used where a single quotation mark will be used to indicate a measure in inches, i.e. 11.05" is equal to 11.05 inches. Also, numerical values in body text are truncated by a convention left to the discretion of the author to reduce characters but maintain enough significant figures for numerical values to be useful, i.e. 14.633" is truncated to 14.63", the normalized manipulability of 0.361703 was truncated to 0.361 and converted to the percentage 36.1%. Manipulability and normalized manipulability are first covered in sections 3.1.4 and 4.1.

3.1 Theoretical Kinematic Analysis

In addition to experimental data, the study applies the theoretical manipulability method of determining a WMRA's effectiveness. This method was first utilized at USF in the evaluation of the Raptor and MANUS WMRAs built by Applied Resources and Exact Dynamics respectively.

3.1.1 Previous Work

The work done by McCaffrey, (9), shows theoretical manipulability measures of MANUS and Raptor based on kinematic analysis. The method applied kinematics to find manipulability measures of the end effector at select points for each arm.

The manipulability measures were tabulated and normalized. These values were then compared between each arm showing, theoretically, if each arm could approach a select point and how well the arm could access the space if an approach was possible. The term "approach" describes reaching a point in space without regard for gripper orientation. This means that the end effector is capable of moving towards the target volume with ease.

The series of 131 points was developed by identifying desirable areas of operation of a WMRA. The user would expect a WMRA to operate in these areas or consider the device ineffective. The same series of points will be used for theoretical evaluation of both iARM and JACO in this study. These areas include low ground areas approximately 2 inches from the floor, table and door knob or latch heights of around 31 inches from the floor, and shelf heights at 56 inches, among others.

MATLAB was used to generate the theoretical results of MANUS and Raptor, and will also be utilized in the evaluation of iARM and JACO. An updated MATLAB code which utilizes the Robotics Toolbox (25) will be employed for this study and is based on the robotics concepts presented in this chapter.

3.1.2 Forward Kinematics

In order to effectively speak about robotic devices, it is important to adopt a universal convention for describing movement of the device in 3-dimensional space. This convention is based on Denavit – Hartenberg, or D-H kinematic parameters introduced in 1955 and describes the position and orientation of the links and joints that make up the robotic arm (26).

To describe the position and orientation of a robotic manipulator, 3-dimensional reference coordinate systems are coupled in a particular manner to each joint. These reference coordinate systems are referred to as reference frames, or simply, frames. Information about each joint can then be inferred from the interdependency of each frame as the arm moves through space. The overall kinematic objective is to precisely know the location and orientation of the end effector with respect to a useful reference point, usually the base of the manipulator, if given the joint angles, and vice versa.

The kinematics of a robotic manipulator contain information about the geometry of the arm links and joints by observing each link as a rigid connection between two joint axes as seen in Figure 11. Joint axes are defined by an infinite line in space around which a link rotates with respect to a neighboring link. The link length, a_{i-1}, is the fixed distance between joints i and $i-1$. The link length is a straight line and is mutually orthogonal to joint axes i and $i-1$.

Link twist further defines the geometric relationship between joint axes in a link. Link twist, α_{i-1}, is the angle between link axes measured on the plane normal to the link length. Link twist is taken with the Right-hand rule from axis *i-1* to axis *i* about a_{i-1}. For intersecting link axes, link twist is measured on the plane containing both axes.

Further link description is quantified by the link offset, d_i, and joint angle, $Ø_i$. Link offset is said to be the distance along the common joint axis between links while joint angle is the amount of rotation about the common joint axis between links (26).

These four kinematic values are tabulated as D-H parameters which consider the kinematic values as either joint variables or link parameters. Link parameters are observed to be fixed quantities which do not change as the manipulator moves in space while one of the joint variables is continuously varied based on the desired movement of the arm and end effector. The manipulators considered in this study utilize only revolute joints; therefore the only joint variables are the joint angles at each joint, $Ø_i$.

Since the objective of effectively speaking about robotic manipulators is to know the position and orientation of the end effector with respect to a useful reference frame, we must now use these kinematic principles and D-H parameters to allow us to consider the manipulator as a whole device rather than a collection of individual links.

Constructions of matrix transforms will define frame *i* with respect to frame *i-1* beginning with the base frame and ending with the end effector frame. The series of transformation matrices will then be multiplied together to generate a single matrix that contains position and orientation information of the end effector with respect to the base frame.

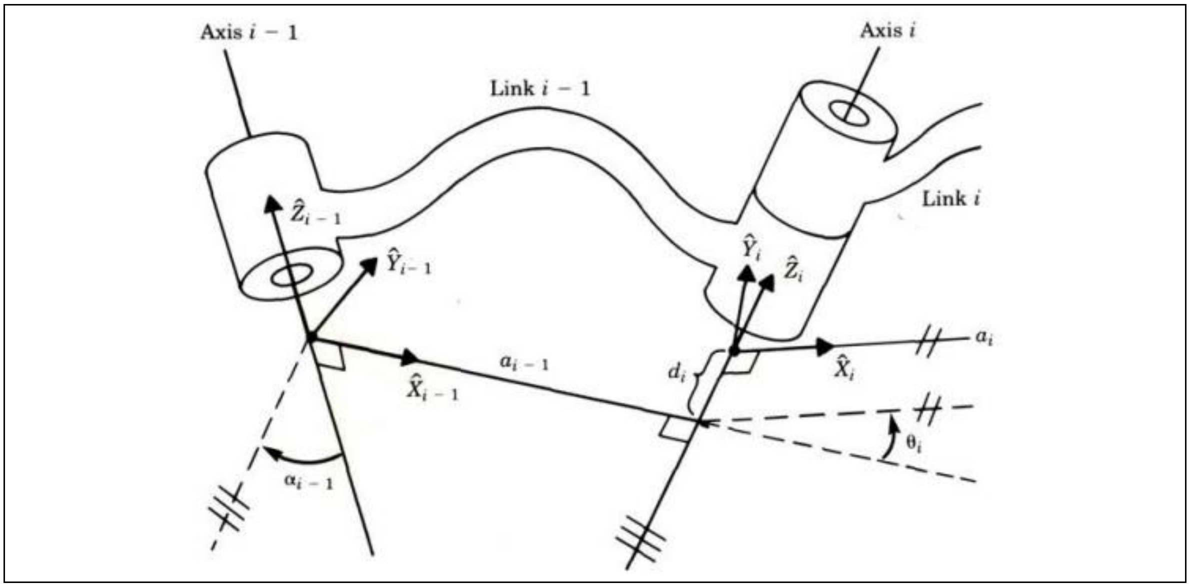


Figure 11 – D-H parameter definitions (26)

Transformation matrices are generated with the derivation of rotation and position submatrices. The rotation submatrix is a 3x3 matrix of direction cosines, or dot product of two unit vectors. Direction cosines describe the relative 3-dimensional angle of one reference frame with respect to another. Similarly, the position submatrix is a 3x1 vector indicating the relative magnitude of displacement of two frames.

3.1.3 Jacobians

A Jacobian is a multidimensional matrix that relates joint velocities to Cartesian velocities of the end effector, or tool frame (26). The Jacobian matrix dimensions indicate the number of degrees of freedom and the number of joints of a robotic arm. For instance, if we consider a simple two-link manipulator, the size of its Jacobian matrix would be a 2x2; one row for each degree of freedom, and one column for each joint.

To construct a Jacobian we must first examine the forward kinematics of our robotic arm. Here we consider a three degree of freedom manipulator with three independent equations and three independent variables governing the positional submatrix. Now, consider the equations and variables in the form of a set of functions where *y* indicates position and *x* indicates joint angles. The functions, f_i represents the positional submatrix of the transformation matrix of the end effector frame with respect to the manipulator base. Equations 1 through 9 were found in the work by Craig (26).

$$y_1 = f_1(x_1, x_2, x_3)$$
$$y_2 = f_2(x_1, x_2, x_3) \qquad \text{Equation 1}$$
$$y_3 = f_3(x_1, x_2, x_3)$$

This system written in vector notation is as follows:

$$Y = F(X) \qquad \text{Equation 2}$$

To attain velocities from position we must take a derivative. We apply the chain rule to the set of equations with respect to the variables, x_j.

$$\delta y_1 = \frac{\delta f_1}{\delta x_1}\delta x_1 + \frac{\delta f_1}{\delta x_2}\delta x_2 + \frac{\delta f_1}{\delta x_3}\delta x_3$$

$$\delta y_2 = \frac{\delta f_2}{\delta x_1}\delta x_1 + \frac{\delta f_2}{\delta x_2}\delta x_2 + \frac{\delta f_2}{\delta x_3}\delta x_3 \qquad \text{Equation 3}$$

$$\delta y_3 = \frac{\delta f_3}{\delta x_1}\delta x_1 + \frac{\delta f_3}{\delta x_2}\delta x_2 + \frac{\delta f_3}{\delta x_3}\delta x_3$$

This system written in vector notation is as follows:

$$\delta Y = \frac{\delta F}{\delta X}(\delta X) \qquad \text{Equation 4}$$

Here the 3x3 matrix of derivatives is called the Jacobian, *J*. With nonlinear functions f_1 through f_3 the partial derivatives are a function of x_i and can be written as follows:

$$\delta Y = J(X)\delta X \qquad \text{Equation 5}$$

Dividing both sides by the differential time element, the Jacobian transforms angular velocities in *X* to Cartesian velocities in *Y*. This is a mapping procedure which changes joint velocities to end effector velocity with respect to the base frame.

$$\dot{Y} = J(X)\dot{X} \qquad \text{Equation 6}$$

In robotics, the Jacobian of a manipulator must be invertible, or nonsingular, in order to function properly. This condition comes from the relationship of the inverted Jacobian.

$$\dot{\Theta} = J^{-1}(\Theta)v \qquad \text{Equation 7}$$

The inverted Jacobian transforms Cartesian end effector velocities to angular joint velocities. If the matrix is singular and the manipulator is said to be in a singular configuration, it loses one or more degrees of freedom resulting in the inability to move in at least one direction in space no matter how great the joint velocities are. Singular configurations, or singularities, always occur at the edge of the manipulator workspace but may also occur within the workspace when two or more joints are aligned.

3.1.4 Manipulability

A measure of how effective a robotic arm is in a given local area is called a manipulability measure, *w*, and is defined mathematically as the absolute value of the determinant of the Jacobian for nonredundant manipulators; those possessing the same amount of degrees of freedom necessary to execute a given task (26), (27).

$$w = |\det(J(\Theta))| \qquad \text{Equation 8}$$

As stated above, singular configurations reduce the effectiveness of a robotic arm by reducing the number of degrees of freedom which prevents the ability of the end effector to move in a given direction. The above equation considers the volume of the manipulability ellipsoid as the basis for manipulability measure (27). It may be seen that if the manipulator reaches a singularity, the determinant of the Jacobian forces the manipulability to zero because the determinant of a singular matrix is zero. This results in unreasonably large joint velocities when the Jacobian is inverted during the inverse kinematics process which will be detailed in later sections.

$$\det(J(\Theta)) = 0 \qquad \text{Equation 9}$$

A well designed manipulator will maximize manipulability in all configurations or employ computational features to avoid areas of low manipulability.

3.1.5 Determination of Workspace

A workspace has been chosen which reflects specific requirements of wheelchair-dependent individuals (9), (28), (29). The workspace axes were taken with respect to the base of the WMRA mount as the origin. Horizontal planes (xy) were defined in accordance with above cited work. These planes range from 2.00" above the floor to allow for end effector clearance to 56.00" above the floor to reach a low shelf above a kitchen counter top. These planes coincide with the ADL task pool which will be detailed in subsequent sections.

The following list gives the height (z-dimension) of common household items and surfaces on which many ADLs may be performed. The values in parenthesis are the z-axis height with respect to the origin at the base of the manipulator mount as shown in Figure 12. For the sake of time, a readily available WMRA figure will be used to indicate the location of the planes.

1. Small objects on the floor: 2.00" (-14.36")
2. Larger light objects on the floor: 9.00" (-7.3")
3. Height of electric socket: 18.00" (1.6")
4. Low coffee table: 26.00" (9.61")
5. Height of standard table and door knob: 31" (14.63")
6. Kitchen counter top: 38.00" (21.61")
7. Wall-mounted light switch: 50.00" (33.63")
8. Low shelf above kitchen counter top: 56.00" (39.61")

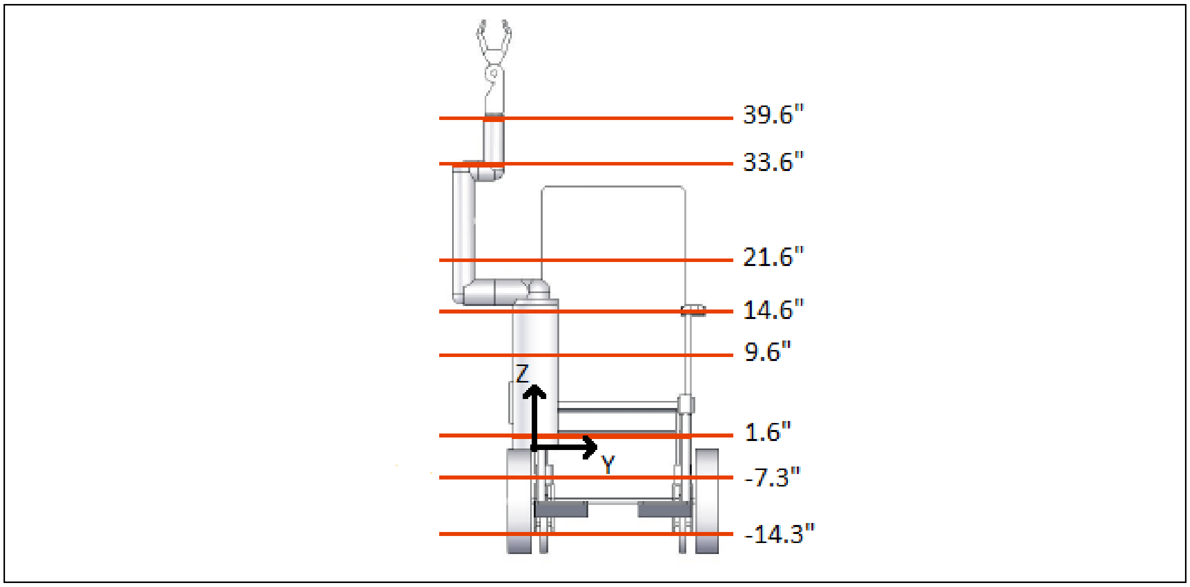


Figure 12 - Workspace horizontal planes (xy)

Intersecting each horizontal plane are vertical (yz) planes which indicate distances forward and backward of the origin as if the user were driving straight forward or backward. Figure 13 shows these forward and backward distances while the following list provides description of each plane with respect to the user. The values in parenthesis are the x-axis distances with respect to the origin.

1. 2.00" past standard footrest dimension: 27.50" (12.54")
2. 14.00" in front of user: (-1.00")
3. 6.75" in front of user: (-8.00")
4. 0.50" in front of user: (-14.00")
5. Intersecting user frame: (-15.00")
6. 4.00" behind the user frame representing the mouth of the user: (-19.00")

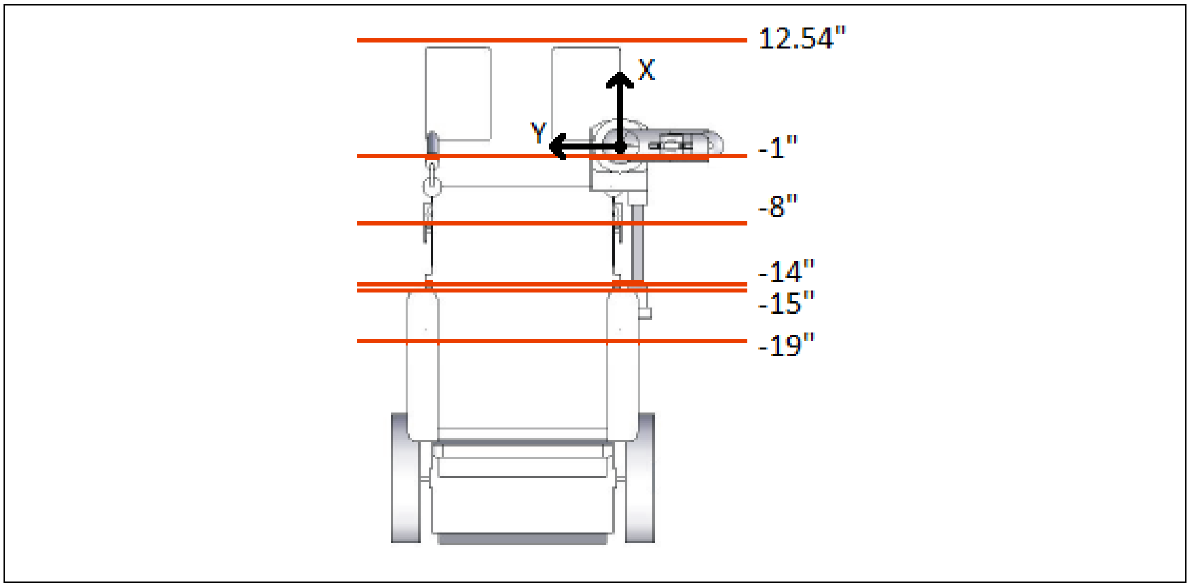


Figure 13 - Workspace vertical planes (yz)

Orthogonal vertical planes define 3-dimensional points of interest. The xy-planes separate the wheelchair into two lateral halves when considering typical wheelchair width dimension of approximately 27.00" including drive wheels.

The analysis takes the xz-plane dimensions with respect to the user as follows where the dimensions in parenthesis are the xz-plane dimensions with respect to the origin at the base of the manipulator. Refer to Figure 14 for these planes.

1. The plane intersecting the user frame: 0.00" (10.00")
2. 13.50" from the user toward the WMRA: (-3.50")
3. 23.50" from the user to the WMRA, or 10.00" from the outer edge of the wheels: (-13.50")

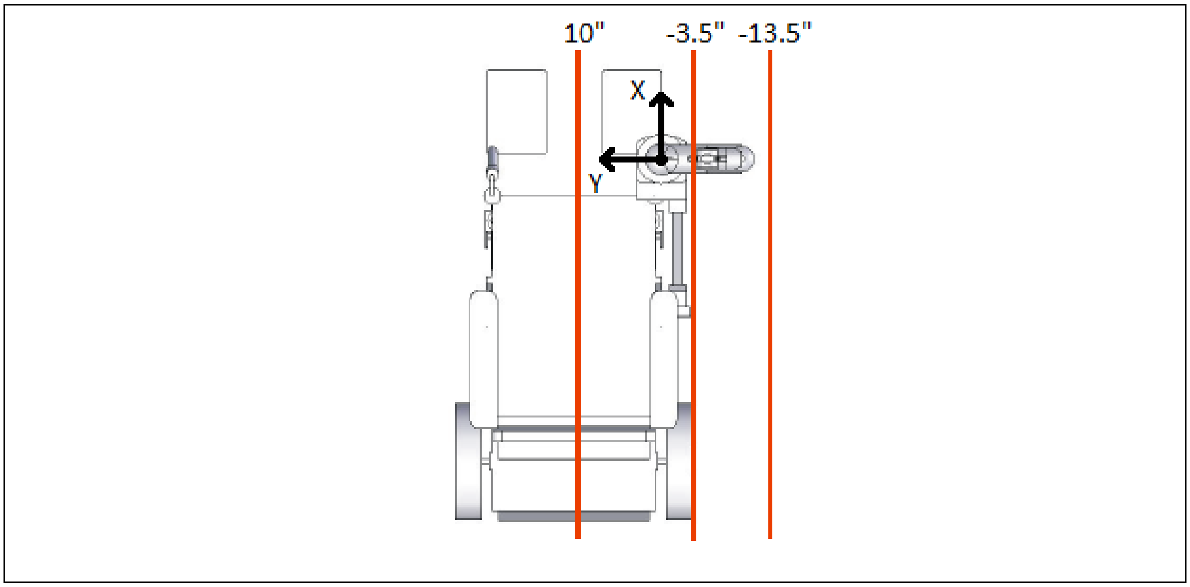


Figure 14 - Workspace vertical planes (xz)

3.1.6 MATLAB Kinematic Manipulability Program

Using the information contained in section 3.1, a MATLAB program was developed using functions from the Robotics Toolbox. The steps of the kinematic manipulability program are as follows:

1. Prompt the user to select which WMRA to evaluate
2. Construct links based on hardcoded D-H parameters
3. Construct robot
4. Read set of points of interest from file or hardcode
5. Generate straight line trajectory from initial position to final position
6. Generate manipulabilities

The MATLAB manipulability program code is presented in Appendix A.

3.2 Experimental Analysis

Previous work has shown the theoretical effectiveness of MANUS and Raptor WMRAs based on forward and inverse kinematics which generated manipulability values at points of interest (9). This study includes and expands on the theoretical method to a physical evaluation of iARM and JACO WMRAs.

There will be two groups of participants. One composed of able bodied individuals and a second composed of wheelchair-dependent individuals who are confined to a power wheelchair. Table 2 shows information pertaining to the gender, condition, and power wheelchair experience of wheelchair-dependent participants. For this table MS indicates Multiple Sclerosis, SCI indicates Spinal Cord Injury, and SMA indicates Spinal Muscular Atrophy.

Table 2 - Wheelchair-dependent participant information

Initials	Gender	Condition	Years in Power Wheelchair
CE	Female	MS	1
DS	Male	SCI - C5/C6 Incomplete	13
JM	Male	SMA	15
JMc	Male	SCI - C5/C6 Incomplete	9
JV	Male	SMA	19

When considering the test environment, it is important to simulate the physical world. Steps are taken to closely match the end-user mounting positions indicated by each respective WMRA manufacturer. A mounting frame was fixed to participant wheelchairs so simulated mounting positions could be achieved. Able bodied participants were also provided a test wheelchair so that each operator, able bodied or wheelchair dependent, shared the same perspective when attempting tasks.

This chapter details the development of the physical test environment and Passive Mobile Manipulator Platform, or PMMP, which was designed and employed for the project.

3.2.1 Simulation of Real Environment

The experimental nature of this study requires a physical test environment be developed so that WMRAs may be observed in operation under conditions close to the end-user perspective of an open world. This was achieved by creating mock representations of actual components of interest which a WMRA customer may come in contact with on a day-to-day basis.

For simplicity, the test environment is considered to be free of end-user modification. Actual WMRA customers have the option of tailoring their dwelling so that their WMRA can most easily access the common spaces. The study will negate these modifications as they may favor one WMRA or another.

Also, end-user modifications heighten WMRA effectiveness only in the modifiable space. In a work or social environment, modifications to the environment may not be possible. With this in mind, the test environment is kept to a standard unmodified form.

3.2.1.1 Tasks

A collection of everyday activities was generated based on the experience of research personnel. These tasks are considered essential to independent living. The task pool is separated into categories and displayed in Table 3:

Table 3 - Initial task pool

Opening Tasks	Operation Tasks	Reaching Tasks	Cognitive Tasks
Open/close cabinets at varying heights	Operate sink fixtures	Tabletop manipulation	Perform any task with additional cognitive load
Open/close drawers at varying heights	Operate light switches	High/low object retrieval	
Open/close personnel door	Operate telephone	Retrieve food or drink	

The task pool is highly expandable as future testing may be subject to any task given here or a variation in which a certain parameter of the activity is changed. The variability of tasks is needed to accurately simulate the physical world. The study does not consider modification to personal dwellings and therefore centers on WMRA effectiveness in a general setting away from any compensatory measures.

The four tasks selected for this study are:

1. Flip toggle light switch
2. Low cabinet door open and close
3. Tabletop drink retrieval
4. Personnel door open

3.2.1.2 PMMP

The Passive Mobile Manipulator Platform (PMMP) is a frame designed and used as a mounting platform during research and development of power wheelchair-mounted devices and secondary equipment. For this study, a PMMP was temporarily attached to a participant's power wheelchair during testing. This allowed participants to operate each arm as if it were properly mounted to the power wheelchair.

Figure 15 - PMMP supporting testing of Exact Dynamics ARM

The PMMP restricted the operator from moving through doorways, even those compliant with ADA standards. The advantages of the PMMP were necessary for effective testing, however. These advantages are detailed hereafter.

The PMMP used in this study was constructed of t-slotted aluminum extrusion. Each of the four sides of the frame consisted of two segments of t-slotted extrusion. The two extrusion segments were designed to slide in a telescoping fashion in order to provide large adjustments in length and width dimensions. A similar telescoping arrangement was designed for each corner of the frame allowing for vertical height adjustment of the mounting surfaces. Each corner also featured castor wheels so that the PMMP could match the movements of the participant wheelchair during testing.

The use of a PMMP allowed wheelchair-dependent participants to remain in their personal wheelchairs during the study, eliminating the need for participant transfer. The high level of adaptability of the PMMP design used in the study allowed it to accommodate the dedicated able-bodied test wheelchair and wheelchair-dependent wheelchairs without modification. Participant risk and discomfort was greatly reduced with the use of the PMMP.

In addition to reducing risk and discomfort, the PMMP used in the study had the capacity to mount each WMRA and supporting devices such as controllers and wiring. Since an entire WMRA system could be mounted to the PMMP, each participant could operate the WMRA system from the operating perspective of a wheelchair. The PMMP allowed participants to be completely mobile in the test environment. This mobility may be required for the experimental tasks to be detailed in later sections.

PMMP devices may be useful for any entity which deals with assistive devices for use with power wheelchairs. Table 4 shows selected entities with different products or technologies being developed and how the use of a PMMP device(s) may aid in their efforts (21), (22), (30), (31), (32).

Table 4 - Selected research and development entities and technologies

Company	Product/Technology	Description
Rhamdec	Desktop surface for power wheelchairs	PMMP supports research in desk surface location relative to the user independent of power wheelchair make/model
Univ. Mass.	Univ. developed Door Opening Robot (DORA)	DORA easily mounted on PMMP to facilitate experimental research with human operation
Univ. Ferrara	Application of powered prosthetic arm to power wheelchairs	Complex mounting of non-wheelchair intended arm simplified by PMMP
Kinova	Commercially available WMRA	PMMP used for product testing without modification to personal wheelchairs
Exact Dynamics	Commercially available WMRAs, arm support	PMMP used for product testing of many different products without modification to personal wheelchairs, PMMP allows for simultaneous testing of multiple products
Philips App. Tech.	Big business developed WMRA	Large volume of human testing of commercial WMRAs easily supported by multiple PMMPs

3.2.2 Quantitative Data

The experimental component of the study will rely on subjective opinion of study participants. In an effort to generate meaningful objective data, ease of use and time of performance data will be collected quantitatively with the study survey included in the Appendix. The quantitative data will be contrasted so that clear trends in WMRA rating will develop. These trends will indicate the relative effectiveness of each WMRA in a given task, thus exposing the key design features which drive task effectiveness.

3.2.2.1 Time of Performance

Time of performance will be recorded as the elapsed time from initial unpacking of the WMRA to the “task complete” condition in which the activity has been successfully executed. The "task complete" condition is disclosed to the participant prior to each series of task practice session. An example of a predefined "task complete" condition is when a light switch is toggled to the opposite position, or when a cabinet door is closed after being opened. Refer to the list below for "task complete" positions.

1. Light Switch - Toggled to alternate position
2. Tabletop Drink - Within the volume in front of the face of the participant
3. Low Cabinet Door - Returned to closed position after opening
4. Personnel Door - Opened to 90° or greater

Time of performance is recorded for each of three testing trials. The testing trials commence upon adequate practice at each task. Adequate practice is determined by a noted confidence level of the participant. This data is objective and may be used to determine the validity of ease of use task ratings. It is assumed that time of performance and ease of use are inversely related. So, as time of performance of a task decreases while using one WMRA, its ease of use rating will increase.

3.2.2.2 Ease of Use

Ease of use will be recorded quantitatively by asking each participant to rate how easy each task was to complete with each WMRA system. The rating scale is from the lowest rating of "1" to the highest rating of "5". In order to attach a physical meaning to the ease of use ratings, a convention was developed during testing. This rating scale was developed by research personnel.

For able bodied participants, a rating of 1.0 was meant to indicate that the task was virtually impossible to complete with the WMRA system while a rating of 5.0 was meant to indicate that completing the task with the WMRA system was similar to completing the task with a participant's own arm. It is noted that this rating convention limits the useful range of the 1.0 – 5.0 scale. It is not probable that a participant will rate a WMRA as easy to use as one's own arm so the scale may be effectively limited to a 1.0 – 4.0 scale. To offset this, fractional ratings were allowed, i.e. "4.5". This adjustment makes the 1.0 – 5.0 rating scale have an effective range of 1.0 – 9.0, allowing greater resolution on ease of use rating.

For wheelchair dependent participants, a rating of 1.0 was also meant to indicate the task was virtually impossible to complete with the WMRA system while a rating of 5.0 was meant to indicate that the WMRA system could complete the task with exceeding ease. A fractional scale was also offered.

3.2.3 Study Protocols

This section outlines the study protocol in step-by-step form. Note that for the iARM system, the procedure is altered slightly to take account of multiple input devices.

3.2.3.1 Pre Testing

1. Individuals freely willing to take part in the study will be instructed to arrive at the testing facility during a specified test time. A participant will be asked to review and sign a USF IRB approved Informed Consent form indicating he or she has reviewed and accepts all risks and benefits associated with the study. Any questions or concerns the participant has will be addressed by the Co-Investigator or appropriate Key Personnel.

2. After the Informed Consent form is reviewed and signed, the participant will be familiarized with the iARM and JACO WMRAs as well as support items, such as input devices, and the experimental environment. The PMMP will be temporarily attached to the participant's wheelchair. The PMMP will serve to locate and position input devices so the participant may operate the WMRA as comfortably as possible.

3. Key Personnel will then begin to showcase the experimental environment to the participant. The showcase will identify key features of the environment and briefly explain what types of tasks the participant will be asked to perform.

4. The first WMRA will be mounted to the PMMP. Input device(s) for the first WMRA will be positioned on the PMMP such that the participant may operate the devices comfortably. Key Personnel will assist the participant in becoming familiar with the first WMRA by giving detailed instructions on how to perform elementary tasks (i.e. basic Cartesian movement). The convention developed during testing was to test iARM first because of the alternate input device. Switching input devices requires additional downtime and is therefore thought to be best dealt with at the beginning of the testing session.

3.2.3.2 During Testing

5. Once the participant has become sufficiently familiar with the WMRA/input system, he or she will be asked to practice a specific task of interest (i.e. a task for which data will be recorded) by performing the task three times. It was assumed that with each practice trial, a participant would become more familiar with the WMRA system. It has been the experience of study personnel that small amounts of practice may largely increase proficiency in use of the device. At the end of each practice trial, the task was reset (i.e. objects and environment must be restored to original location, orientation, etc.).

6. At the conclusion of the final practice trial, the participant will be asked to perform the same task three additional times. These will be testing trials where time of performance will be recorded. The time of performance will begin when the participant initializes the task. The time of performance will stop when the task has been completed. At the end of each testing trial, the task must be reset.

7. In order to quantitatively evaluate the efficacy of each WMRA, a survey will be presented to the participant at the conclusion of the final testing trial of each task of interest. The participant will be asked to rate the ease of performing the given task with the given WMRA and input device on a number ranking scale. The survey should be completed at the conclusion of testing trials for each task (the participant will be asked to perform up to four individual tasks).

8. When the time of performance data and ease of performance survey has been recorded, Key Personnel will ask the participant to perform a new task. Steps 5 – 7 should be repeated for each of the subsequent tasks (up to four).

9. The iARM will be evaluated with two different input devices. In order to test the efficacy of multiple input devices, the participant will be asked to repeat one of the tasks of interest while operating the iARM with a different input device. In these cases, up to four tasks of interest will be completed by using the initial input device. At the conclusion of the testing trials, Key Personnel will remove the current input device and install the subsequent input device. A task of interest will then be chosen to be repeated.

The choice of repeated task will represent a moderate difficulty. Once the new input device is installed, steps 5 – 7 will be repeated. Note that only one repeated task will be recorded so that step 8 will not be repeated with the new input device. When testing JACO, this step is negated and the protocol continues to step 10.

10. In order to compare and contrast each WMRA, repeat steps 4 – 9 for each WMRA. In these steps Key Personnel will remove the first WMRA, mount the next WMRA to be tested, assist the participant in learning the new WMRA/input system, asks the participant to perform three practice trials with the new WMRA, asks the participant to perform three testing trials, record time of performance for each testing trial, and record ease of performance surveys for each task. This step should be repeated for each WMRA. The participant will have time for a break and refreshments as Key Personnel remove and install WMRAs.

11. At the conclusion of the final testing trial of the final WMRA, the participant will be asked for information pertaining to his or her overall experience with all the WMRAs. This survey will provide a general outlook of the participant on the use of WMRAs.

3.2.3.3 Post Testing

12. With the data and surveys collected, Key Personnel calculated statistical comparisons between each device including mean and standard deviation comparisons. Times of performance were compared. Ease of performance surveys were normalized and compared. The results indicated time of performance and efficacy of each WMRA.

13. Based on the results of the statistical analysis and ease of use surveys, the design of each WMRA and input device will be evaluated. Key design features will be noted and recommendations will be made for common desirable features which increase manipulator efficacy and ease of use.

Chapter 4 Outcomes

Physical and theoretical results are presented here. The theoretical results will attempt to determine each WMRA's effectiveness by measuring manipulability values at a series of 3D points located around the manipulator. These points represent areas which a WMRA end user would expect an effective WMRA to approach and access easily.

Physical results will show time of performance and ease of use ratings collected from 11 able-bodied and 5 wheelchair-dependent study participants. This data was collected for each task; tabletop drink, flip-toggle light switch, low cabinet door, and personnel door.

4.1 Theoretical Results

Kinematic parameters of the iARM and JACO were procured from the respective manufacturers and confirmed with physical measurement. These parameters along with approximated end effector initial positions were input into the kinematic MATLAB program.

The MATLAB program was used to graphically simulate each manipulator for analysis. The output was manipulability values of the end effector frame for 131 points of interest representing points in space which a WMRA end user would expect an effective manipulator to approach and access.

Manipulability values were normalized for graphical and tabular display. Normalized values were calculated by taking the ratio of manipulability value for each point with respect to the maximum manipulability for each WMRA. Normalized manipulability values are percentages of maximum manipulability for each WMRA. D-H parameters for each manipulator are presented below.

Table 5 - iARM and JACO D-H parameters

iARM				
i	α_{i-1} (rad)	a_{i-1} (inch)	θ_i (rad)	d_i (inch)
1	0.00	0.00	0.00	15.43
2	-pi/2	0.00	0.00	7.57
3	0.00	15.74	0.00	-3.93
4	-pi/2	0.00	0.00	12.99
5	pi/2	0.00	0.00	0.00
6	-pi/2	0.00	0.00	5.31

JACO				
i	α_{i-1} (rad)	a_{i-1} (inch)	θ_i (rad)	d_i (inch)
1	0.00	0.00	0.00	8.27
2	-pi/2	0.00	0.00	0.00
3	0.00	16.14	0.00	0.00
4	-pi/2	0.00	0.00	9.81
5	0.96	0.00	0.00	3.33
6	0.96	0.00	0.00	8.94

Normalized manipulability measures were given a classification of "excellent" to "undetermined" based on the information in Table 6.

Table 6 - Normalized manipulability classification

Manipulability Measure	Classification
81 - 100%	Excellent
61 - 80%	Very Good
41 - 60%	Good
21 - 40%	Limited
01 - 20%	Very Limited
> 1%	Undetermined

4.1.1 Vertical Planes

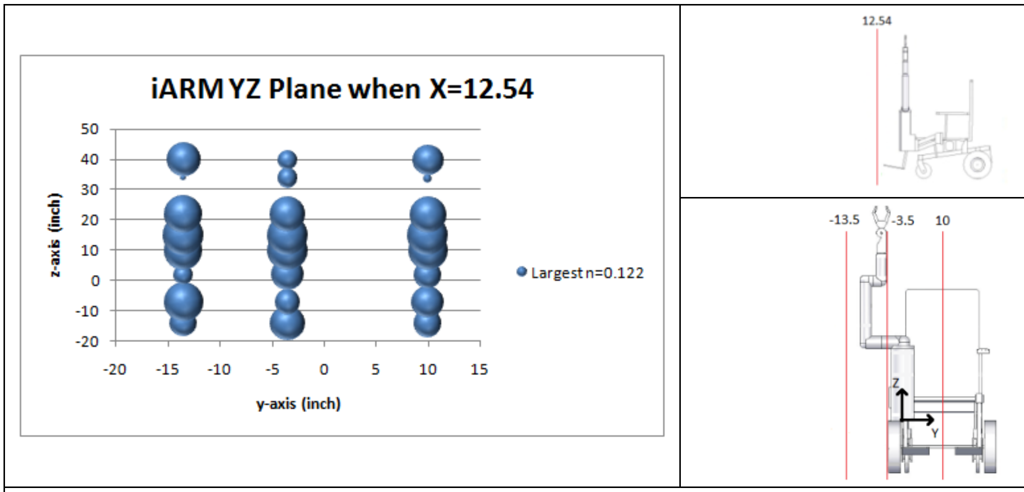
To represent the theoretical data effectively, bubble charts are used to show the coordinates of points of interest within a single 2D plane. The diameter of the bubble indicates the normalized manipulability measure at a point. The larger the bubble diameter, the larger the normalized manipulability value. Subsequent figures will show manipulability measures for both WMRAs in vertical planes within the defined workspace. For the sake of time, a readily available WMRA figure will be used to indicate the location of the planes.

Figure 16 and Figure 17 show manipulability data for iARM and JACO in the vertical yz-plane when the x-dimension is 12.54" forward of the origin at the base of each manipulator mount. For iARM, consistent manipulability is observed at mid-range elevations ranging from 9.61" to 21.61". This indicates ease when approaching coffee table, door knob, and counter top spaces. The greatest normalized manipulability value is 11.7%.

Less consistent manipulability zones occur at elevations of -14.36" to 1.63". This indicates ease when approaching low ground, high ground, and electric socket spaces. Relatively low manipulabilities are observed at points (12.54, -13.50, 33.63) and (12.54, 10.00, 33.63) as link 2 approaches a parallel configuration with link 1.

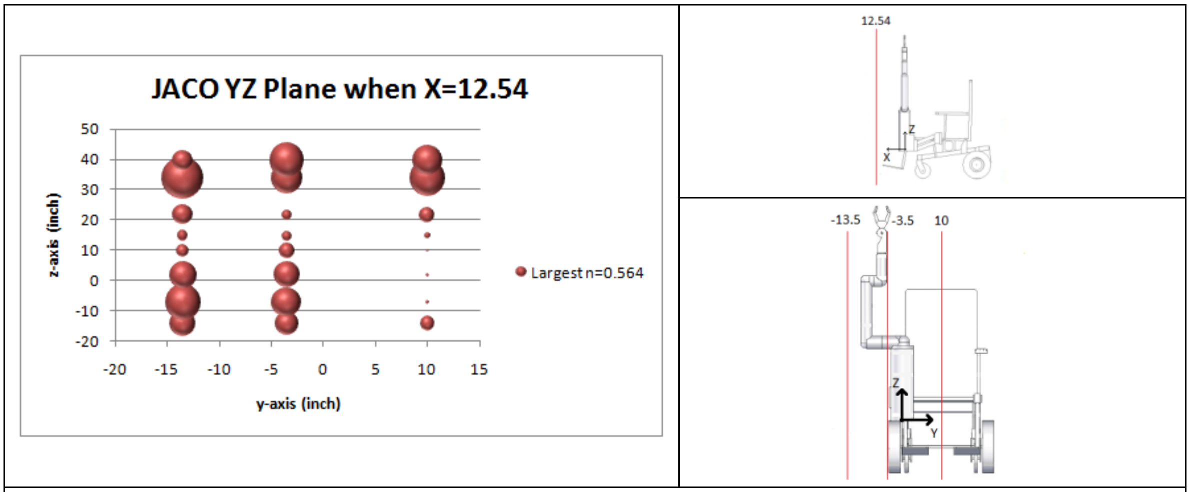
JACO is observed to perform most consistently in the 33.61" elevation, when y = -13.50", and when y = 3.50". Relatively high manipulabilities are shown in approach to wall-mounted light switch for all y-values, and floor spaces in the negative y-direction.

Relatively low manipulabilities occur in the positive y-direction as a result of link 3 nearing a parallel configuration with link 2. As these values go to zero, approach to the space should be considered unobtainable.



Point #	n	x	y	z	Flag
1	0.055275593	12.54	10	-14.367	0
2	0.085938649	12.54	-3.5	-14.367	0
3	0.049402161	12.54	-13.5	-14.367	0
4	0.074095993	12.54	10	-7.367	0
5	0.044779783	12.54	-3.5	-7.367	0
6	0.110826697	12.54	-13.5	-7.367	0
7	0.053201388	12.54	10	1.633	0
8	0.071277372	12.54	-3.5	1.633	0
9	0.026486488	12.54	-13.5	1.633	0
10	0.11258697	12.54	10	9.613	0
11	0.115165972	12.54	-3.5	9.613	0
12	0.106619586	12.54	-13.5	9.613	0
13	0.11775211	12.54	10	14.633	0
14	0.113736152	12.54	-3.5	14.633	0
15	0.122489185	12.54	-13.5	14.633	0
16	0.097245799	12.54	10	21.613	0
17	0.093275274	12.54	-3.5	21.613	0
18	0.107730469	12.54	-13.5	21.613	0
19	0.004518418	12.54	10	33.633	0
20	0.0282378	12.54	-3.5	33.633	0
21	0.001910317	12.54	-13.5	33.633	0
22	0.067526887	12.54	10	39.613	0
23	0.027375673	12.54	-3.5	39.613	0
24	0.082850336	12.54	-13.5	39.613	0

Figure 16 - Normalized iARM manipulabilities in the yz-plane when x = 12.54"



Point #	n	x	y	z	Flag
1	0.061744609	12.54	10	-14.367	0
2	0.188853956	12.54	-3.5	-14.367	0
3	0.207565225	12.54	-13.5	-14.367	0
4	0.003270493	12.54	10	-7.367	0
5	0.290981372	12.54	-3.5	-7.367	0
6	0.418142932	12.54	-13.5	-7.367	0
7	0.003190943	12.54	10	1.633	0
8	0.219381082	12.54	-3.5	1.633	0
9	0.244169992	12.54	-13.5	1.633	0
10	0.00146159	12.54	10	9.613	0
11	0.082188037	12.54	-3.5	9.613	0
12	0.045609963	12.54	-13.5	9.613	0
13	0.011807624	12.54	10	14.633	0
14	0.028324914	12.54	-3.5	14.633	0
15	0.033892392	12.54	-13.5	14.633	0
16	0.073800485	12.54	10	21.613	0
17	0.030523673	12.54	-3.5	21.613	0
18	0.129792456	12.54	-13.5	21.613	0
19	0.419018586	12.54	10	33.633	0
20	0.321526469	12.54	-3.5	33.633	0
21	0.564825701	12.54	-13.5	33.633	0
22	0.296865721	12.54	10	39.613	0
23	0.39963587	12.54	-3.5	39.613	0
24	0.12384544	12.54	-13.5	39.613	0

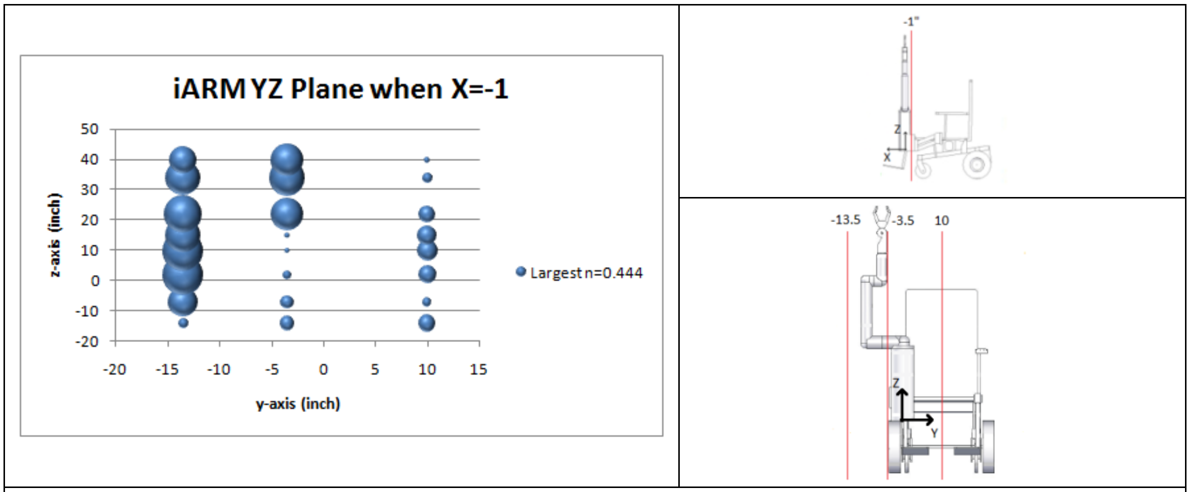
Figure 17 - Normalized JACO manipulabilities in the xy-plane when x = 12.54"

Figure 18 and Figure 19 show manipulability data in the yz-plane when x = -1.00". Consistent and relatively high manipulabilities are observed for most elevations when y = -13.50" for iARM. This indicates ease when approaching all spaces to the extreme right of the manipulator except spaces very low to the ground.

Relatively low manipulabilities occur when the end effector is commanded to approach link 1. This forces the arm to collapse creating multiple singular configurations. These points should be considered unobtainable despite exhibiting acceptable manipulability values as the end effector would collide with the wheelchair or the manipulator itself in a physical environment.

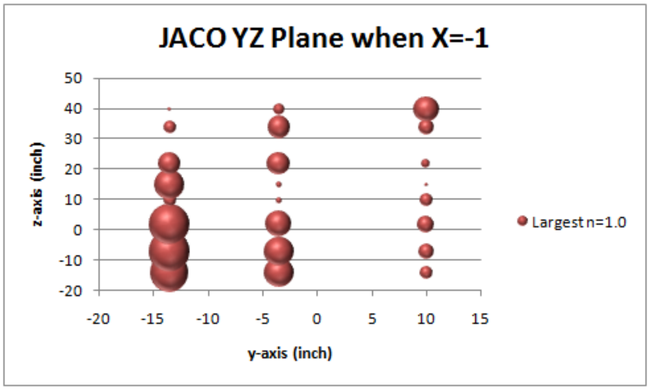
JACO shows relatively high manipulability values at mid to low elevations when y = -13.50" indicating high ease of approach to spaces from the low floor to the height of an electrical socket. Values tend to decrease for this y-value as the z-coordinate increases because the end effector approaches the extremity of its workspace.

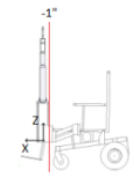
Relatively low values are observed when y = 10.00" as links 2 and 3 approach parallel configurations. Furthermore, these manipulability values for low elevations when y = -3.50" should be considered unobtainable in a physical system because of the risk of collision.

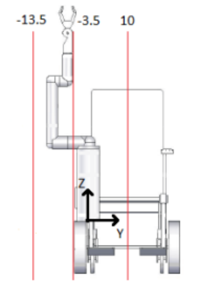


Point #	n	x	y	z	Flag
25	0.072787072	-1	10	-14.367	0
26	0.052828538	-1	-3.5	-14.367	0
27	0.024615075	-1	-13.5	-14.367	0
28	0.018964577	-1	10	-7.367	0
29	0.044078664	-1	-3.5	-7.367	0
30	0.231231261	-1	-13.5	-7.367	0
31	0.078196656	-1	10	1.633	0
32	0.019413565	-1	-3.5	1.633	0
33	0.444797873	-1	-13.5	1.633	0
34	0.103531036	-1	10	9.613	0
35	0.006075601	-1	-3.5	9.613	0
36	0.436159748	-1	-13.5	9.613	0
37	0.093947987	-1	10	14.633	0
38	0.005438778	-1	-3.5	14.633	0
39	0.310991086	-1	-13.5	14.633	0
40	0.069759334	-1	10	21.613	0
41	0.262203347	-1	-3.5	21.613	0
42	0.366173813	-1	-13.5	21.613	0
43	0.02652284	-1	10	33.633	0
44	0.334655494	-1	-3.5	33.633	0
45	0.313202184	-1	-13.5	33.633	0
46	0.007761552	-1	10	39.613	0
47	0.290870143	-1	-3.5	39.613	0
48	0.194439811	-1	-13.5	39.613	0

Figure 18 - Normalized iARM manipulabilities in the yz-plane when x = -1.00"







Point #	n	x	y	z	Flag
25	0.092361027	-1	10	-14.367	0
26	0.509388679	-1	-3.5	-14.367	0
27	0.850745961	-1	-13.5	-14.367	0
28	0.129525435	-1	10	-7.367	0
29	0.516689333	-1	-3.5	-7.367	0
30	1	-1	-13.5	-7.367	0
31	0.15967936	-1	10	1.633	0
32	0.38380573	-1	-3.5	1.633	0
33	0.954215257	-1	-13.5	1.633	0
34	0.098231476	-1	10	9.613	0
35	0.017715086	-1	-3.5	9.613	0
36	0.086534567	-1	-13.5	9.613	0
37	0.006362211	-1	10	14.633	0
38	0.016617981	-1	-3.5	14.633	0
39	0.505874413	-1	-13.5	14.633	1
40	0.038695304	-1	10	21.613	0
41	0.297801555	-1	-3.5	21.613	0
42	0.30057577	-1	-13.5	21.613	0
43	0.12940816	-1	10	33.633	0
44	0.283392181	-1	-3.5	33.633	0
45	0.083443459	-1	-13.5	33.633	0
46	0.373022162	-1	10	39.613	0
47	0.062876361	-1	-3.5	39.613	0
48	0.007420385	-1	-13.5	39.613	0

Figure 19 - Normalized JACO manipulabilities in the yz-plane when x = -1.00"

For JACO point #39, (-1 -13.5 14.6), the MATLAB simulation program returns a flag value of 1 indicating a discontinuity in the curve of manipulability with respect to the step in trajectory. The non-normalized manipulability versus trajectory step curve is shown in Figure 20 below. The trajectory has 100 steps.

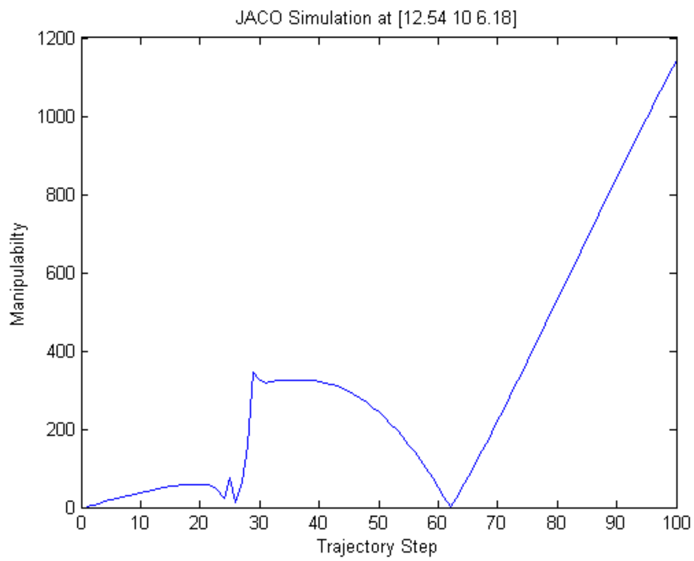


Figure 20 - Discontinuous JACO manipulability vs. trajectory step curve

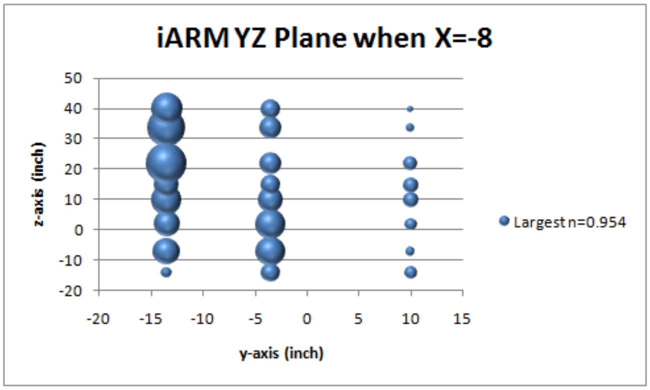
Discontinuity in the manipulability versus trajectory step curve and the resulting flag highlights a singular configuration which instantaneously changes joint "elbow up" or "elbow down" pose. Mathematically, at least one joint underwent a change in angle of considerable magnitude from one trajectory step to the next consecutive trajectory step, or instantaneously, resulting in infinite joint velocities. From the MATLAB program, nominal angle changes between trajectory steps was seen to be on the order of 10^{-2} radians or smaller.

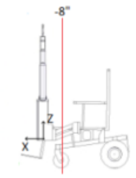
Instantaneous pose change may require a joint to rotate by as much as π/2 radians. A value called Δ-angles, or change in angles, was calculated by taking the magnitude of joint angle change between trajectory steps for each manipulator joint. Analysis of this value showed that if Δ-angles was greater than 1, an instantaneous pose change was exhibited. A trajectory in which a Δ-angle value of 1 or greater occurred was flagged for manipulability curve analysis. From Figure 20, the flag occurs towards the beginning of the trajectory but does not affect the confidence of the manipulability value for the end point.

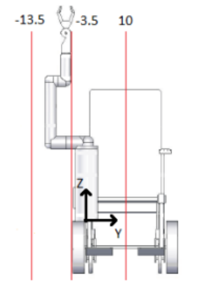
Figure 21 and Figure 22 show manipulability data for the yz-plane when x = -8.00". iARM is shown to exhibit relatively good effectiveness values when y = -3.50" and -13.50". However, as the x-coordinate decreases, the likelyhood of collision with the wheelchair or the manipulator itself when y = -3.50" increases. Thus, even though acceptable manipulability values are calculated, points that represent areas of physical collision with the wheelchair or manipulator may be taken as physically unobtainable.

Relatively low manipulability values for iARM occur when y = 10.00" as the end effector position passes sufficiently close to link 1, reducing the effectiveness of joint 1 when the Cartesian movement of the end effector decreases in the x-direction.

For the JACO manipulator, the highest manipulabilities are exhibited when y = -13.50", and in mid to high elevations when y = -3.50" and 10.00". When y = -3.50" and 10.00", relatively low manipulabilities are observed as a result of link 3 approaching a parallel configuration with link 2.

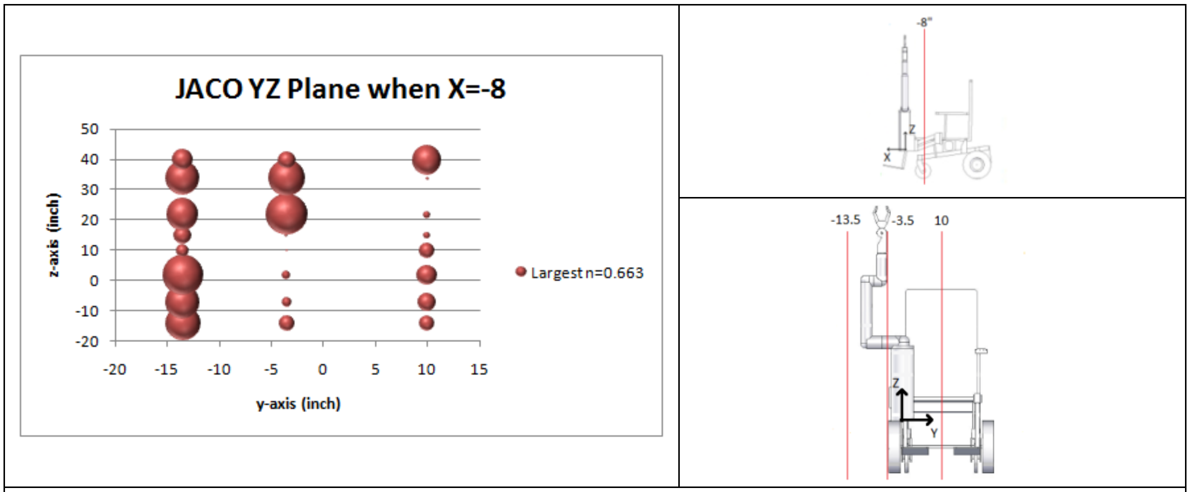






Point #	n	x	y	z	Flag
49	0.085739202	-8	10	-14.367	0
50	0.195597885	-8	-3.5	-14.367	0
51	0.057129814	-8	-13.5	-14.367	0
52	0.04053471	-8	10	-7.367	0
53	0.474867779	-8	-3.5	-7.367	0
54	0.409972925	-8	-13.5	-7.367	0
55	0.0778767	-8	10	1.633	0
56	0.517717093	-8	-3.5	1.633	0
57	0.363102957	-8	-13.5	1.633	0
58	0.12231688	-8	10	9.613	0
59	0.346933851	-8	-3.5	9.613	0
60	0.515538528	-8	-13.5	9.613	0
61	0.121976082	-8	10	14.633	0
62	0.211725858	-8	-3.5	14.633	0
63	0.329253468	-8	-13.5	14.633	0
64	0.102690136	-8	10	21.613	0
65	0.242367064	-8	-3.5	21.613	0
66	0.954254029	-8	-13.5	21.613	0
67	0.035429332	-8	10	33.633	0
68	0.261641508	-8	-3.5	33.633	0
69	0.805981658	-8	-13.5	33.633	0
70	0.020817679	-8	10	39.613	0
71	0.198922938	-8	-3.5	39.613	0
72	0.554740686	-8	-13.5	39.613	0

Figure 21 - Normalized iARM manipulabilities in the yz-plane when x = -8.00"



Point #	n	x	y	z	Flag
49	0.080392274	-8	10	-14.367	0
50	0.096478568	-8	-3.5	-14.367	0
51	0.479404602	-8	-13.5	-14.367	0
52	0.126518187	-8	10	-7.367	0
53	0.029382374	-8	-3.5	-7.367	0
54	0.473690813	-8	-13.5	-7.367	0
55	0.155034306	-8	10	1.633	0
56	0.024976912	-8	-3.5	1.633	0
57	0.640572	-8	-13.5	1.633	0
58	0.090852295	-8	10	9.613	0
59	0.001120183	-8	-3.5	9.613	0
60	0.054525461	-8	-13.5	9.613	0
61	0.016354199	-8	10	14.633	0
62	0.002794997	-8	-3.5	14.633	0
63	0.114846918	-8	-13.5	14.633	0
64	0.017001974	-8	10	21.613	0
65	0.663379931	-8	-3.5	21.613	0
66	0.40261054	-8	-13.5	21.613	0
67	0.00292769	-8	10	33.633	0
68	0.515258416	-8	-3.5	33.633	0
69	0.420783337	-8	-13.5	33.633	0
70	0.328436535	-8	10	39.613	0
71	0.10803708	-8	-3.5	39.613	0
72	0.162977984	-8	-13.5	39.613	0

Figure 22 - Normalized JACO manipulabilities in the yz-plane when x = -8.00"

Figure 24 and Figure 25 show manipulability data in the yz-plane when x = -14.00". The iARM is shown to exhibit relatively high manipulability values for most elevations when x = -13.50" and to lose manipulability steadily as the x-coordinate increases. Loss in manipulability is the result of approach of parallel configurations in the links which tends to increase as the x-coordinate increases.

For iARM point #75, (-14.00, -13.50, -14.36), the MATLAB simulation program returns a flag value of 1 indicating a discontinuity in the curve of manipulability with respect to the step in trajectory. The manipulability versus trajectory step curve is shown in Figure 23 below. The trajectory has 100 steps.

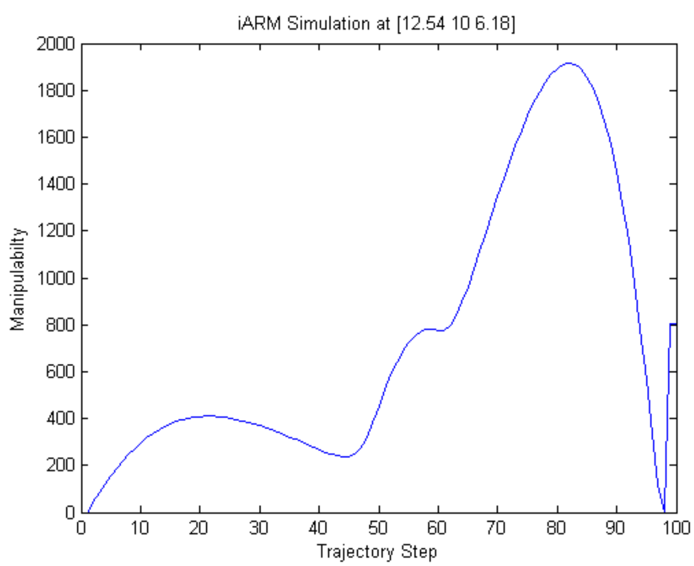
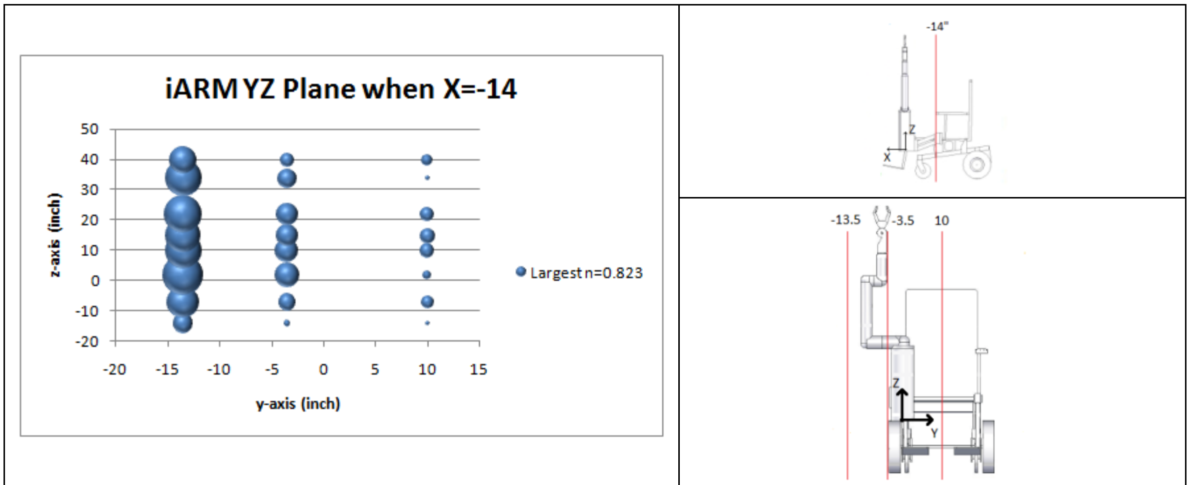


Figure 23 - Discontinuous iARM manipulability vs. trajectory step curve

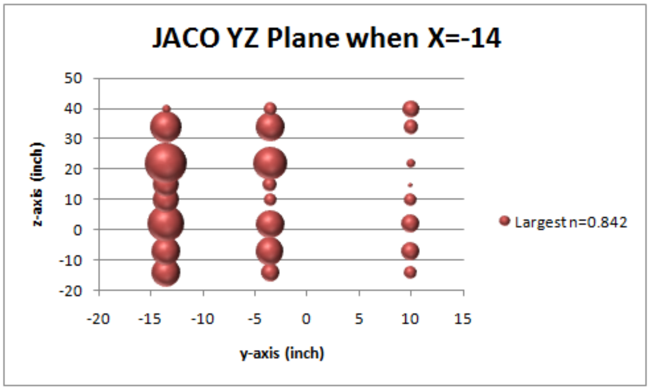
Discontinuity in the manipulability versus trajectory step curve and the resulting flag highlights a singular configuration which instantaneously changes joint "elbow up" or "elbow down" pose. Since this error occurs towards the end of the trajectory, the confidence of the manipulability value for this point is very low.

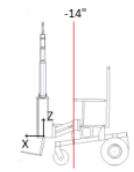
JACO also fits the trend of decreasing manipulability value for increasing y-coordinate in the yz-plane when x = -14.00". Consideration must be given to unobtainable physical end effector positions for low elevations when y = -3.50" and -10.00". Lower manipulability values when y = 10.00" is a result of links 2 and 3 approaching parallel configuration. Relatively low manipulability for point (-14.00, -13.50, 39.61) is the result of fully outstretched configuration at the extremity of the JACO workspace.

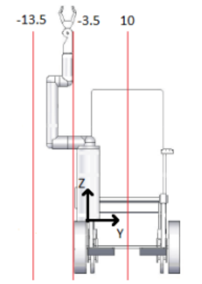


Point #	n	x	y	z	Flag
73	0.008212181	-14	10	-14.367	0
74	0.022041	-14	-3.5	-14.367	0
75	0.233765328	-14	-13.5	-14.367	1
76	0.096255456	-14	10	-7.367	0
77	0.175276	-14	-3.5	-7.367	0
78	0.601991208	-14	-13.5	-7.367	0
79	0.039950929	-14	10	1.633	0
80	0.342932694	-14	-3.5	1.633	0
81	1	-14	-13.5	1.633	0
82	0.113432495	-14	10	9.613	0
83	0.31168515	-14	-3.5	9.613	0
84	0.79353705	-14	-13.5	9.613	0
85	0.12701286	-14	10	14.633	0
86	0.289176472	-14	-3.5	14.633	0
87	0.750035337	-14	-13.5	14.633	0
88	0.112940213	-14	10	21.613	0
89	0.297994567	-14	-3.5	21.613	0
90	0.823120587	-14	-13.5	21.613	0
91	0.011498922	-14	10	33.633	0
92	0.21076605	-14	-3.5	33.633	0
93	0.793042653	-14	-13.5	33.633	0
94	0.067748088	-14	10	39.613	0
95	0.11006723	-14	-3.5	39.613	0
96	0.443902888	-14	-13.5	39.613	0

Figure 24 - Normalized iARM manipulabilities in the yz-plane when x = -14.00"







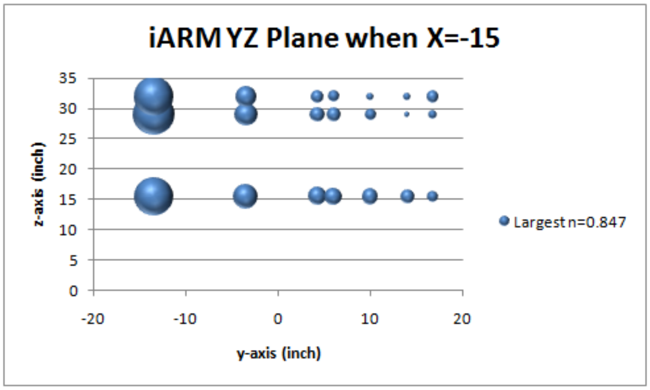
Point #	n	x	y	z	Flag
73	0.078127593	-14	10	-14.367	0
74	0.170357741	-14	-3.5	-14.367	0
75	0.395348944	-14	-13.5	-14.367	0
76	0.163025985	-14	10	-7.367	0
77	0.369910262	-14	-3.5	-7.367	0
78	0.395991992	-14	-13.5	-7.367	0
79	0.155014972	-14	10	1.633	0
80	0.38712849	-14	-3.5	1.633	0
81	0.664825603	-14	-13.5	1.633	0
82	0.068937966	-14	10	9.613	0
83	0.070983277	-14	-3.5	9.613	0
84	0.337434945	-14	-13.5	9.613	0
85	0.008203596	-14	10	14.633	0
86	0.089571244	-14	-3.5	14.633	0
87	0.308020236	-14	-13.5	14.633	0
88	0.03566496	-14	10	21.613	0
89	0.548020691	-14	-3.5	21.613	0
90	0.842826859	-14	-13.5	21.613	0
91	0.094696344	-14	10	33.633	0
92	0.418127068	-14	-3.5	33.633	0
93	0.496941971	-14	-13.5	33.633	0
94	0.140317324	-14	10	39.613	0
95	0.082168212	-14	-3.5	39.613	0
96	0.031022486	-14	-13.5	39.613	0

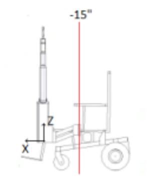
Figure 25 - Normalized JACO manipulabilities in the yz-plane when x = -14.00"

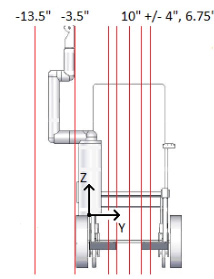
Figure 26 and Figure 27 show manipulability data for the yz-plane when x = -15.00". This x-coordinate brings the end effector within the space immediately in front of the user's face. Resolution is added to either side of the expected head space to better understand where the end effector is effective during possible hygiene tasks. Elevation, or z-coordinates have also been adjusted to focus on upper torso and head spaces.

For the iARM, manipulability is greatest when y = -13.50" and generally decreases as the y-coordinate increases. Manipulability is greater when z = 15.00" when compared with higher elevations within the y-component range of 4.25" to 16.75". Lower manipulabilities are exhibited when approaching the volume immediately in front of the user's face as link 2 approaches a parallel configuration with link 1 in addition to decreased effectiveness of joint 1 in imparting rearward motion during Cartesian end effector movement.

For JACO, manipulability value generally varies from higher to lower in the z-direction. Values are greatest in the highest elevations when y = -13.50", -3.50", 14.00", and 16.75". This shows high effectiveness when approaching the volume in front of the face at these points.

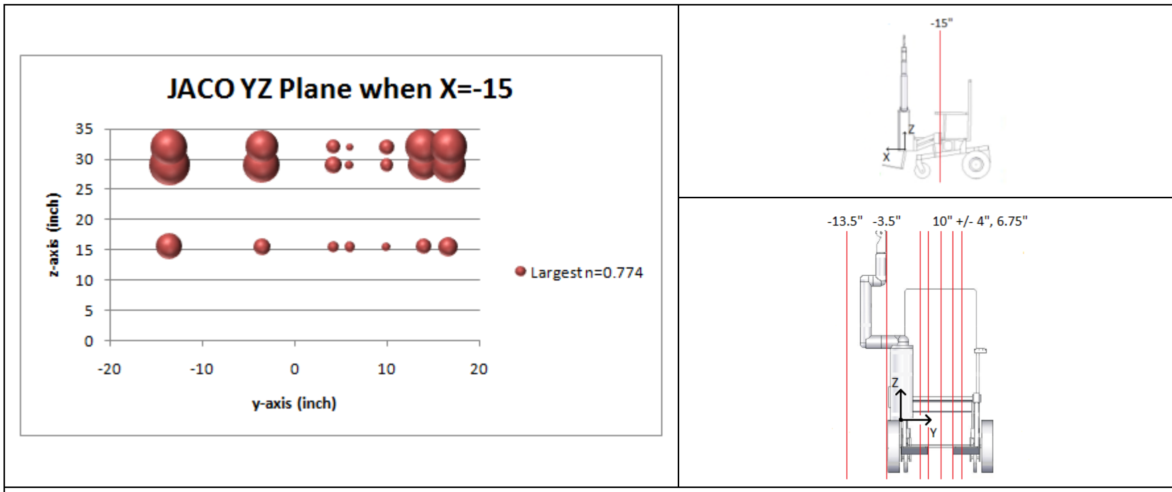






Point #	n	x	y	z	Flag
97	0.158356071	-15	4.25	15.4	0
98	0.146379704	-15	6	15.4	0
99	0.122395884	-15	10	15.4	0
100	0.087061171	-15	14	15.4	0
101	0.048362961	-15	16.75	15.4	0
102	0.286382097	-15	-3.5	15.4	0
103	0.748876087	-15	-13.5	15.4	0
104	0.10149531	-15	4.25	28.9	0
105	0.087186838	-15	6	28.9	0
106	0.056011982	-15	10	28.9	0
107	0.012108849	-15	14	28.9	0
108	0.03127322	-15	16.75	28.9	0
109	0.253675025	-15	-3.5	28.9	0
110	0.847938237	-15	-13.5	28.9	0
111	0.072889298	-15	4.25	31.9	0
112	0.057855522	-15	6	31.9	0
113	0.023238546	-15	10	31.9	0
114	0.024540051	-15	14	31.9	0
115	0.06884733	-15	16.75	31.9	0
116	0.219769587	-15	-3.5	31.9	0
117	0.800264559	-15	-13.5	31.9	0

Figure 26 - Normalized iARM manipulabilities in the yz-plane when x = -15.00"



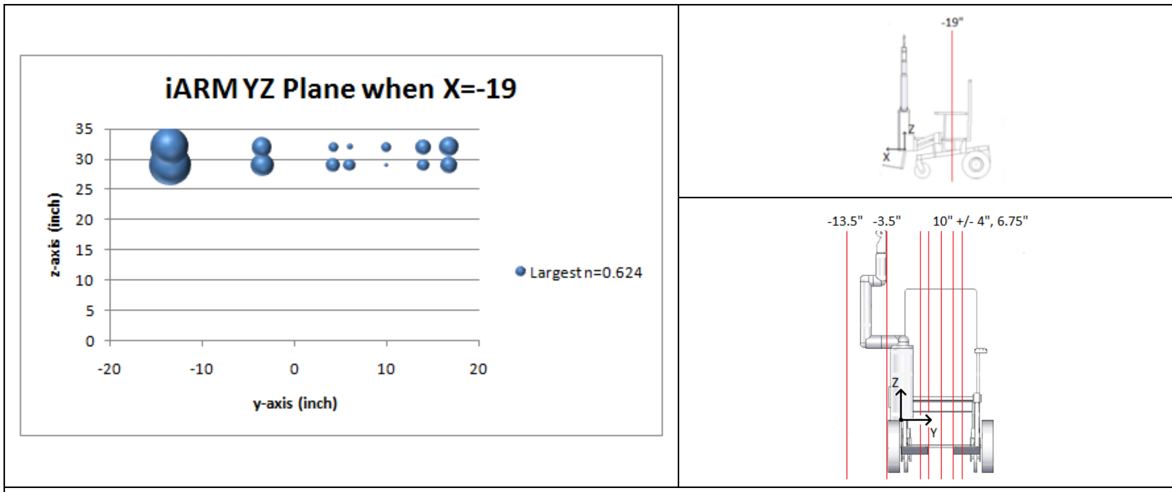
Point #	n	x	y	z	Flag
97	0.048422016	-15	4.25	15.4	0
98	0.044810482	-15	6	15.4	0
99	0.032199056	-15	10	15.4	0
100	0.103748569	-15	14	15.4	0
101	0.161039101	-15	16.75	15.4	0
102	0.127360617	-15	-3.5	15.4	0
103	0.297781849	-15	-13.5	15.4	0
104	0.138730233	-15	4.25	28.9	0
105	0.031549776	-15	6	28.9	0
106	0.071478164	-15	10	28.9	0
107	0.418240518	-15	14	28.9	0
108	0.543018728	-15	16.75	28.9	0
109	0.59534022	-15	-3.5	28.9	0
110	0.77468385	-15	-13.5	28.9	0
111	0.088275642	-15	4.25	31.9	0
112	0.022259628	-15	6	31.9	0
113	0.096843003	-15	10	31.9	0
114	0.563494754	-15	14	31.9	0
115	0.638156931	-15	16.75	31.9	0
116	0.476203524	-15	-3.5	31.9	0
117	0.609322814	-15	-13.5	31.9	0

Figure 27 - Normalized JACO manipulabilities in the yz-plane when x = -15.00"

Figure 28 and Figure 29 show manipulability data in the yz plane when x = -19.00". This x-value represents approach to the user's mouth. Resolution has been added to the head space and elevation has been restricted to 28.90" and 31.90" above the origin at the base of the manipulator, or the expected elevation of the user's head and mouth.

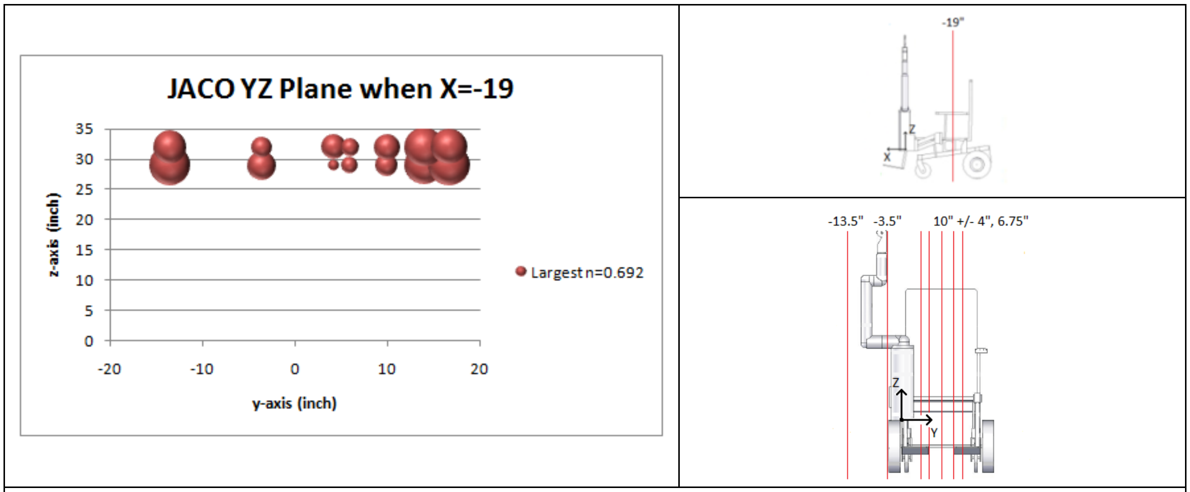
iARM manipulability values are greatest when y = -13.50". In the vicinity of the mouth, manipulability is greatest when y = 16.75" giving relatively high ease of approach to the left side of the head and face of the user.

The JACO arm shows higher manipulability values in regions given the x-value of -19.00". Increased manipulability is due to a more outstretched configuration when y = 14.00" and 16.75". This eliminates the approach of parallel link configuration. JACO exhibits the largest manipulabilities on the left side of the expected user's head and face.



Point #	n	x	y	z	Flag
118	0.066696454	-19	4.25	28.9	0
119	0.048899656	-19	6	28.9	0
120	0.004818067	-19	10	28.9	0
121	0.052465716	-19	14	28.9	0
122	0.100725431	-19	16.75	28.9	0
123	0.184628076	-19	-3.5	28.9	0
124	0.624510828	-19	-13.5	28.9	0
125	0.029544656	-19	4.25	31.9	0
126	0.011660843	-19	6	31.9	0
127	0.033211862	-19	10	31.9	0
128	0.089331818	-19	14	31.9	0
129	0.132064653	-19	16.75	31.9	0
130	0.141171813	-19	-3.5	31.9	0
131	0.53288402	-19	-13.5	31.9	0

Figure 28 - Normalized iARM manipulabilities in the yz-plane when x = -19.00"



Point #	n	x	y	z	Flag
118	0.038528446	-19	4.25	28.9	0
119	0.098194811	-19	6	28.9	0
120	0.205108826	-19	10	28.9	0
121	0.623794497	-19	14	28.9	0
122	0.687777379	-19	16.75	28.9	0
123	0.327361557	-19	-3.5	28.9	0
124	0.692765536	-19	-13.5	28.9	0
125	0.23339968	-19	4.25	31.9	0
126	0.123334025	-19	6	31.9	0
127	0.274566582	-19	10	31.9	0
128	0.631136184	-19	14	31.9	0
129	0.520159374	-19	16.75	31.9	0
130	0.171456367	-19	-3.5	31.9	0
131	0.447448763	-19	-13.5	31.9	0

Figure 29 - Normalized JACO manipulabilities in the yz-plane when x = -19.00"

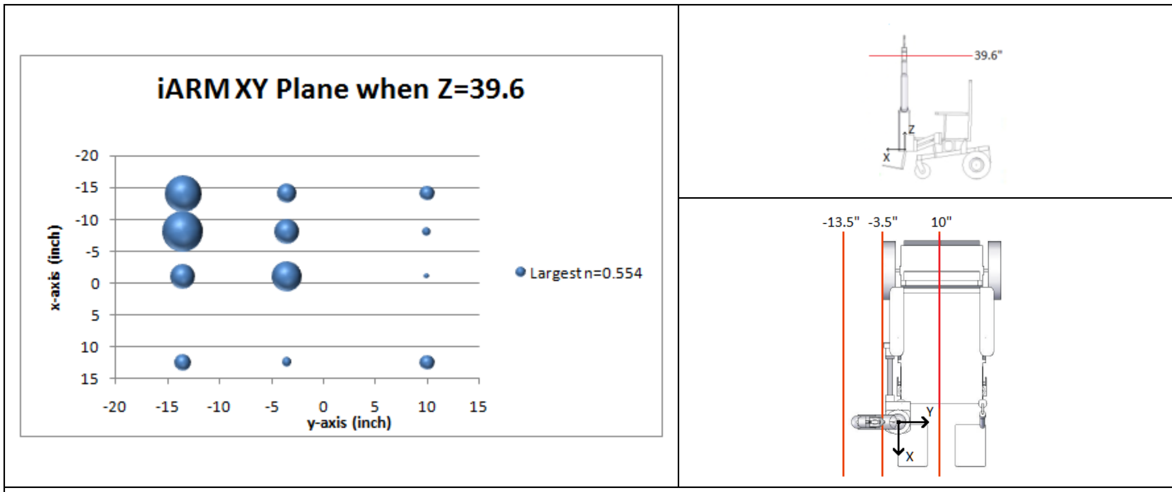
4.1.2 Horizontal Planes

Analyzing effectiveness in horizontal planes represents a different paradigm of useful WMRA design. Whereas observation of vertical plane kinematics may be physically related to retrieving objects from confined spaces where an overhead approach may be limited or impossible, horizontal plane analysis may be physically related to more common orientation constraints like those seen in object manipulation on a tabletop or counter.

Horizontal planes show the dependence of end effector orientation on manipulability value. Large disparity from manipulability from point to point may be the result of poor end effector orientation on approach to a target. In these instances, the user may be required to approach the target with a different end effector orientation in order to access a region in space. Horizontal plane analysis will also more easily show manipulability decrease as the end effector approaches joint 1/link 1.

Figure 30 and Figure 31 show manipulability data for the xy-plane when z = 39.61". This is the elevation for access to low shelves above a kitchen counter top. iARM is shown to exhibit higher manipulability to the rear and right of the determined workspace. Since these areas of high manipulability are to the rear of the user, it will be difficult to exploit this highly effective region of the workspace in a physical environment. The greatest normalized manipulability value is 55.4%.

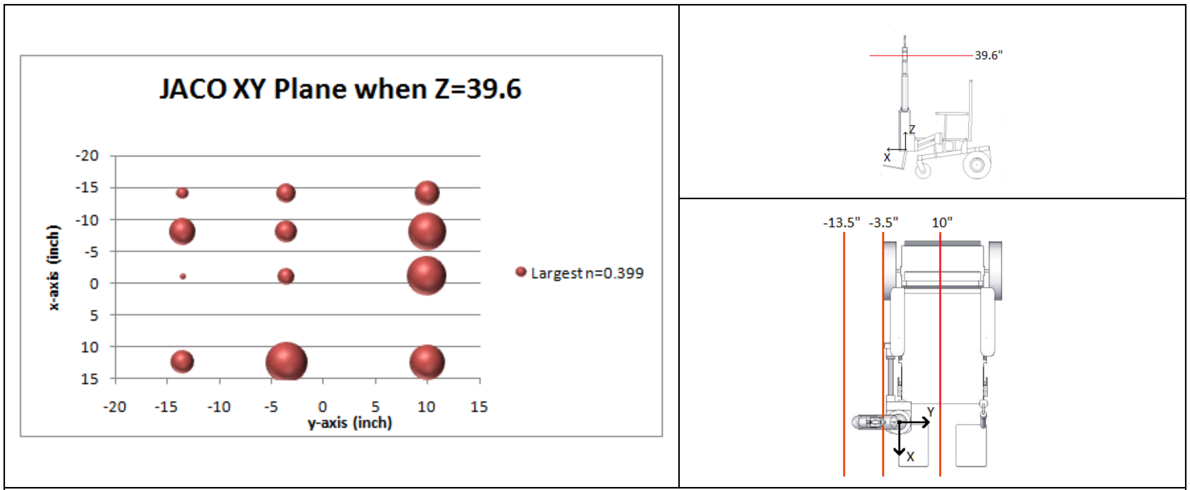
Low manipulabilities occur forward and the left of the determined workspace. These manipulabilities are diminished as a result of parallel configuration of links 1 and 2 as well as end effector proximity to joint 1 in the xy-plane.



Point #	n	x	y	z	Flag
22	0.067526887	12.54	10	39.613	0
23	0.027375673	12.54	-3.5	39.613	0
24	0.082850336	12.54	-13.5	39.613	0
46	0.007761552	-1	10	39.613	0
47	0.290870143	-1	-3.5	39.613	0
48	0.194439811	-1	-13.5	39.613	0
70	0.020817679	-8	10	39.613	0
71	0.198922938	-8	-3.5	39.613	0
72	0.554740686	-8	-13.5	39.613	0
94	0.067748088	-14	10	39.613	0
95	0.11006723	-14	-3.5	39.613	0
96	0.443902888	-14	-13.5	39.613	0

Figure 30 - Normalized iARM manipulabilities in the xy-plane when z = 39.61"

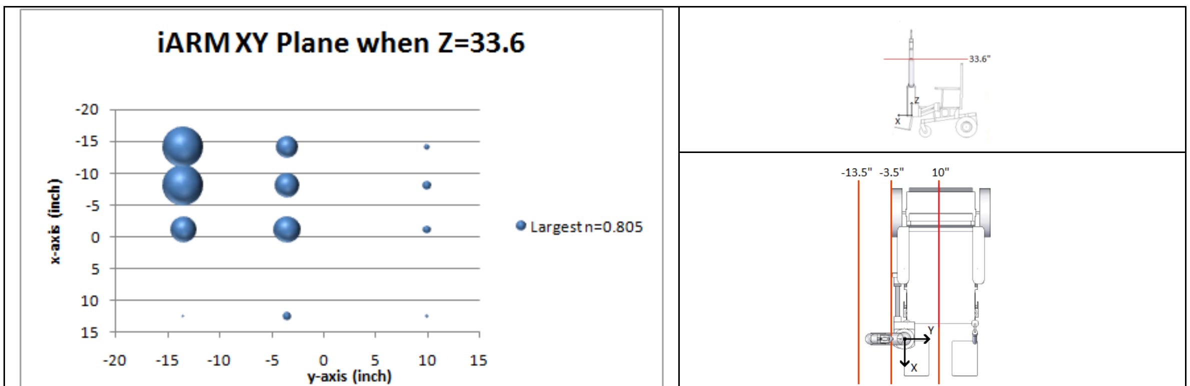
JACO is observed to have high manipulabilities towards the front and right of the workspace where these effective areas can be utilized in forward reaching tasks. One of the largest manipulability values occurs in the z = 39.61" plane at (12.50, -3.50). The greatest normalized manipulability value is 39.9%. Low manipulabilities occurring when y = -13.50" are the result of the arm becoming fully extended.



Point #	n	x	y	z	Flag
22	0.296865721	12.54	10	39.613	0
23	0.39963587	12.54	-3.5	39.613	0
24	0.12384544	12.54	-13.5	39.613	0
46	0.373022162	-1	10	39.613	0
47	0.062876361	-1	-3.5	39.613	0
48	0.007420385	-1	-13.5	39.613	0
70	0.328436535	-8	10	39.613	0
71	0.10803708	-8	-3.5	39.613	0
72	0.162977984	-8	-13.5	39.613	0
94	0.140317324	-14	10	39.613	0
95	0.082168212	-14	-3.5	39.613	0
96	0.031022486	-14	-13.5	39.613	0

Figure 31 - Normalized JACO manipulabilities in the xy-plane when z = 39.61"

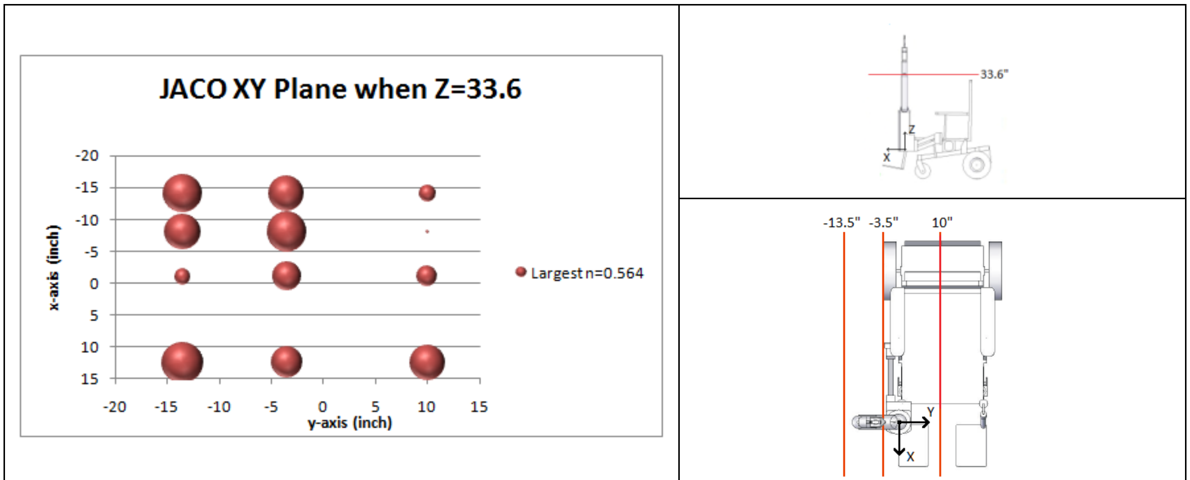
Figure 32 and Figure 33 show manipulability data in the xy-plane when z = 33.63". This horizontal plane represents the height of standard wall-mounted light switches. Again, the greatest manipulability values calculated for iARM are to the rear and left of the origin at the base of the manipulator and the user. Visual simulation shows that at the areas of greatest manipulability links 2 and 1 are moving out of parallel configuration, while the areas of low manipulability show the links approaching the parallel configuration. The distribution of manipulability values reduces the theoretical effectiveness of the end effector as it approaches targets forward of the user. The greatest normalized manipulability value is 80.5%.



Point #	n	x	y	z	Flag
19	0.004518418	12.54	10	33.633	0
20	0.0282378	12.54	-3.5	33.633	0
21	0.001910317	12.54	-13.5	33.633	0
43	0.02652284	-1	10	33.633	0
44	0.334655494	-1	-3.5	33.633	0
45	0.313202184	-1	-13.5	33.633	0
67	0.035429332	-8	10	33.633	0
68	0.261641508	-8	-3.5	33.633	0
69	0.805981658	-8	-13.5	33.633	0
91	0.011498922	-14	10	33.633	0
92	0.21076605	-14	-3.5	33.633	0
93	0.793042653	-14	-13.5	33.633	0

Figure 32 - Normalized iARM manipulabilities in the xy-plane when z = 33.63"

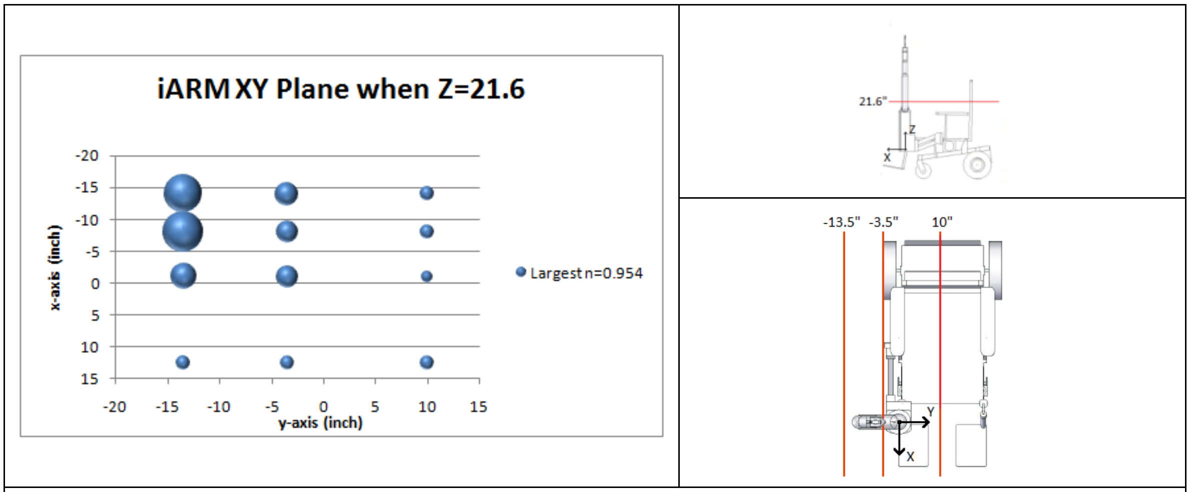
JACO shows a relatively even distribution of manipulability values. High manipulability is calculated for rearward end effector positions as well as forward making the theoretical approach to targets in front of the user at this elevation very easy. The maximum normalized manipulability value in this horizontal plane is 56.4% occurring at (12.54, -13.50, 33.630).



Point #	n	x	y	z	Flag
19	0.419018586	12.54	10	33.633	0
20	0.321526469	12.54	-3.5	33.633	0
21	0.564825701	12.54	-13.5	33.633	0
43	0.12940816	-1	10	33.633	0
44	0.283392181	-1	-3.5	33.633	0
45	0.083443459	-1	-13.5	33.633	0
67	0.00292769	-8	10	33.633	0
68	0.515258416	-8	-3.5	33.633	0
69	0.420783337	-8	-13.5	33.633	0
91	0.094696344	-14	10	33.633	0
92	0.418127068	-14	-3.5	33.633	0
93	0.496941971	-14	-13.5	33.633	0

Figure 33 - Normalized JACO manipulabilities in the xy-plane when z = 33.63"

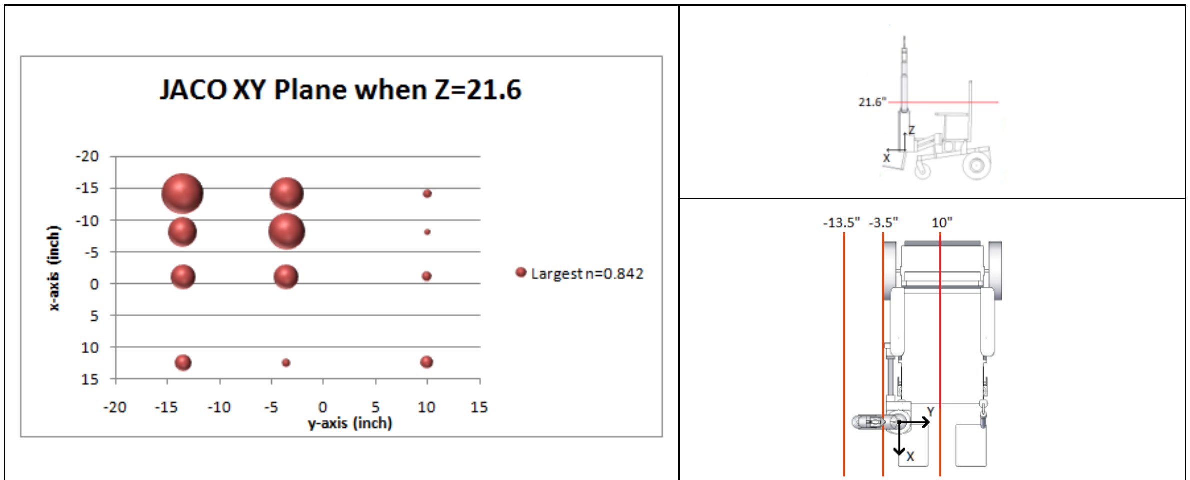
Figure 34 and Figure 35 show manipulability data in the xy-plane when z = 21.61". This elevation represents the height of standard kitchen countertop locations. The iARM has the greatest manipulability values towards the rear and right of the workspace. The greatest normalized manipulability values is 95.4%.



Point #	n	x	y	z	Flag
16	0.097245799	12.54	10	21.613	0
17	0.093275274	12.54	-3.5	21.613	0
18	0.107730469	12.54	-13.5	21.613	0
40	0.069759334	-1	10	21.613	0
41	0.262203347	-1	-3.5	21.613	0
42	0.366173813	-1	-13.5	21.613	0
64	0.102690136	-8	10	21.613	0
65	0.242367064	-8	-3.5	21.613	0
66	0.954254029	-8	-13.5	21.613	0
88	0.112940213	-14	10	21.613	0
89	0.297994567	-14	-3.5	21.613	0
90	0.823120587	-14	-13.5	21.613	0

Figure 34 - Normalized iARM manipulabilities in the xy-plane when z = 21.61"

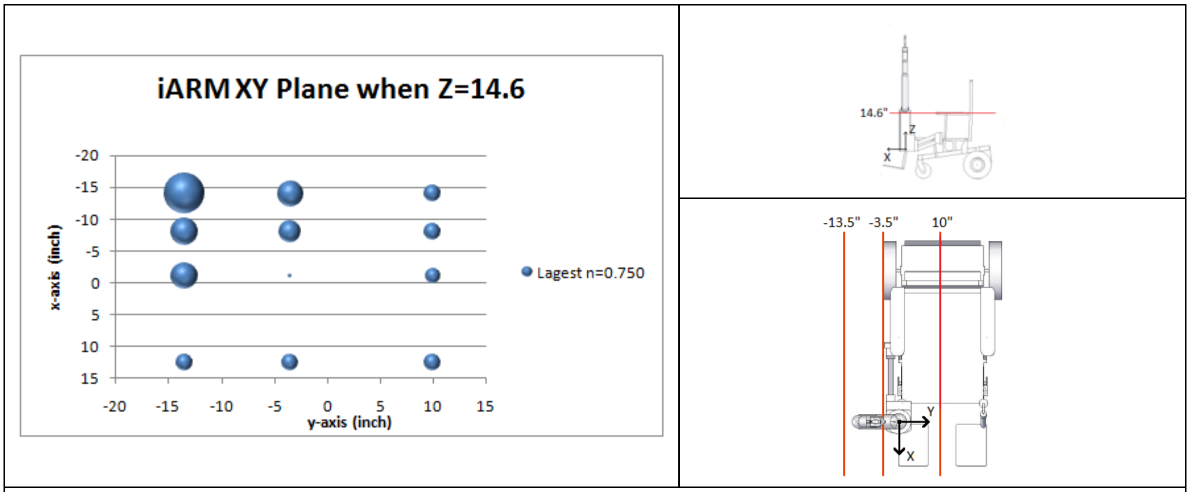
For the JACO, the highest manipulabilities are calculated for y-coordinate values of -13.50" and -3.50", and x-coordinate values of -1.00", -8.00", and -14.00". The greatest normalized manipulability value for this elevation is 66.3%. The position of these values in the workspace makes the approach of a door knob theoretically difficult. Lower manipulability values are calculated when y = 10.00" as the proximity of the end effector to joint 1 is sufficient to decrease theoretical effectiveness.



Point #	n	x	y	z	Flag
16	0.073800485	12.54	10	21.613	0
17	0.030523673	12.54	-3.5	21.613	0
18	0.129792456	12.54	-13.5	21.613	0
40	0.038695304	-1	10	21.613	0
41	0.297801555	-1	-3.5	21.613	0
42	0.30057577	-1	-13.5	21.613	0
64	0.017001974	-8	10	21.613	0
65	0.663379931	-8	-3.5	21.613	0
66	0.40261054	-8	-13.5	21.613	0
88	0.03566496	-14	10	21.613	0
89	0.548020691	-14	-3.5	21.613	0
90	0.842826859	-14	-13.5	21.613	0

Figure 35 - Normalized JACO manipulabilities in the xy-plane when z = 21.61"

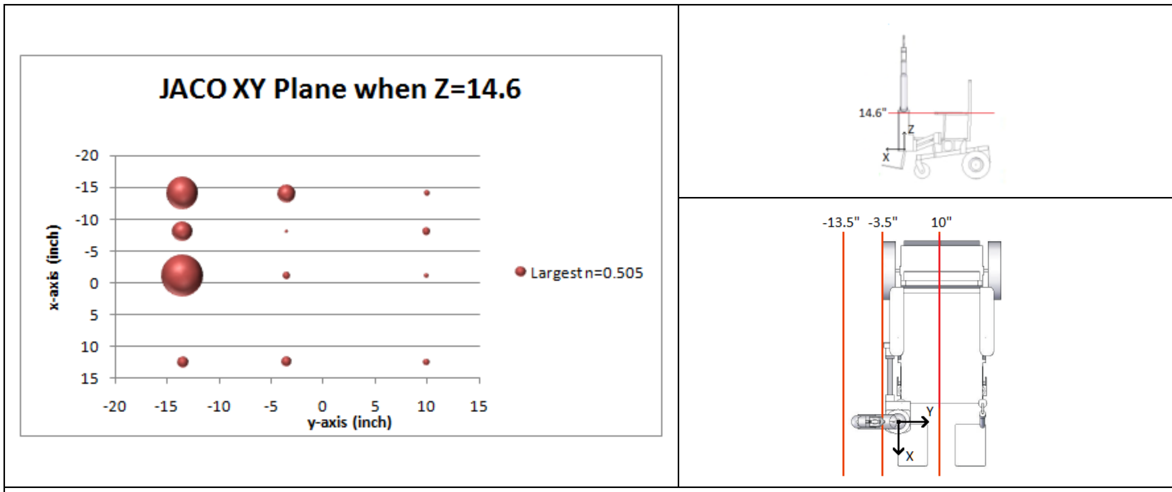
Figure 36 and Figure 37 show manipulability values in the xy-plane when z = 14.63". This elevation represents the standard height of a door knob or table. The iARM shows a peak normalized manipulability value of 75.0% for this elevation. This point occurs at the right, rear corner of the workspace out of line of sight for most WMRA users.



Point #	n	x	y	z	Flag
13	0.11775211	12.54	10	14.633	0
14	0.113736152	12.54	-3.5	14.633	0
15	0.122489185	12.54	-13.5	14.633	0
37	0.093947987	-1	10	14.633	0
38	0.005438778	-1	-3.5	14.633	0
39	0.310991086	-1	-13.5	14.633	0
61	0.121976082	-8	10	14.633	0
62	0.211725858	-8	-3.5	14.633	0
63	0.329253468	-8	-13.5	14.633	0
85	0.12701286	-14	10	14.633	0
86	0.289176472	-14	-3.5	14.633	0
87	0.750035337	-14	-13.5	14.633	0

Figure 36 - Normalized iARM manipulabilities in the xy-plane when z = 14.63"

JACO manipulability data for this elevation shows a greatest normalized manipulability value of 50.5% at (-100, -13.50, 14.63). Low manipulability values are the result of the approach parallel configuration of links 1 and 2.

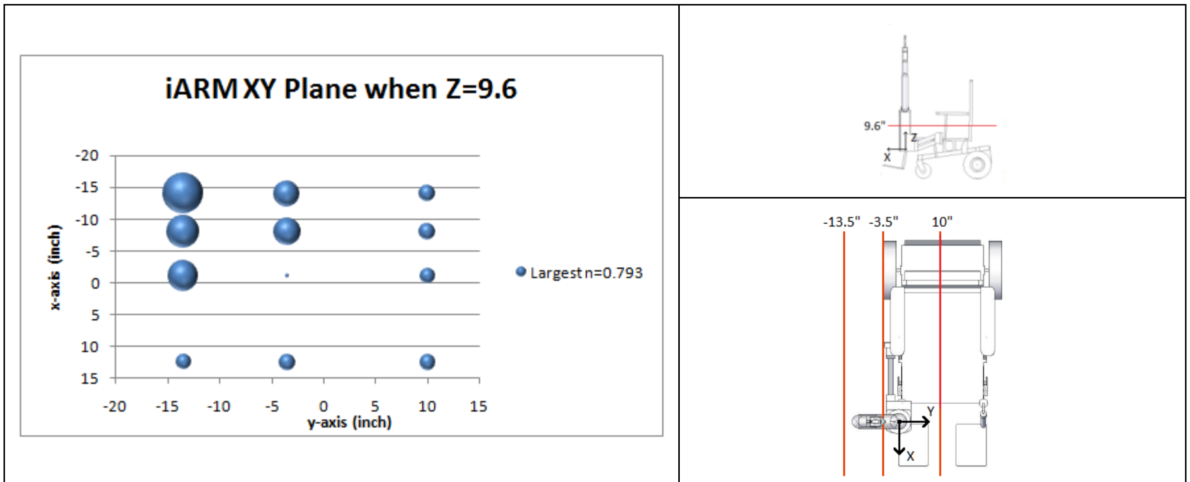


Point #	n	x	y	z	Flag
13	0.011807624	12.54	10	14.633	0
14	0.028324914	12.54	-3.5	14.633	0
15	0.033892392	12.54	-13.5	14.633	0
37	0.006362211	-1	10	14.633	0
38	0.016617981	-1	-3.5	14.633	0
39	0.505874413	-1	-13.5	14.633	1
61	0.016354199	-8	10	14.633	0
62	0.002794997	-8	-3.5	14.633	0
63	0.114846918	-8	-13.5	14.633	0
85	0.008203596	-14	10	14.633	0
86	0.089571244	-14	-3.5	14.633	0
87	0.308020236	-14	-13.5	14.633	0

Figure 37 - Normalized JACO manipulabilities in the xy-plane when z = 14.63"

Figure 38 and Figure 39 show manipulability data in the xy-plane when z = 9.61". As the workspace approaches that of a low coffee table, consideration must be given to collision with the wheelchair or the manipulator itself for both WMRA systems. Points to the rear and left of the origin at the base of the manipulator may be considered unobtainable as a result of collision.

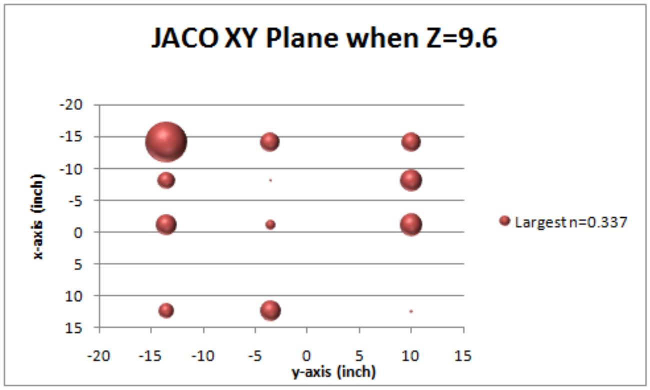
The highest normalized manipulability value for iARM for this elevation is calculated as 79.3% and occurs at the back, right of the determined workspace. Lower manipulabilities are calculated as a result of end effector proximity to joint 1.

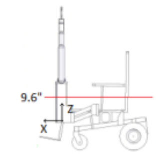


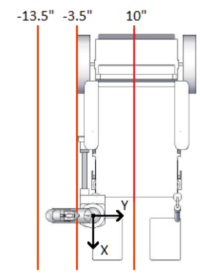
Point #	n	x	y	z	Flag
10	0.11258697	12.54	10	9.613	0
11	0.115165972	12.54	-3.5	9.613	0
12	0.106619586	12.54	-13.5	9.613	0
34	0.103531036	-1	10	9.613	0
35	0.006075601	-1	-3.5	9.613	0
36	0.436159748	-1	-13.5	9.613	0
58	0.12231688	-8	10	9.613	0
59	0.346933851	-8	-3.5	9.613	0
60	0.515538528	-8	-13.5	9.613	0
82	0.113432495	-14	10	9.613	0
83	0.31168515	-14	-3.5	9.613	0
84	0.79353705	-14	-13.5	9.613	0

Figure 38 - Normalized iARM manipulabilities in the xy-plane when z = 9.61"

The highest normalized manipulability value for JACO is 33.7% at this elevation. This point occurs at the back, right corner of the workspace. Lower manipulabilities are calculated as a result of singular configuration of links 1 and 2.





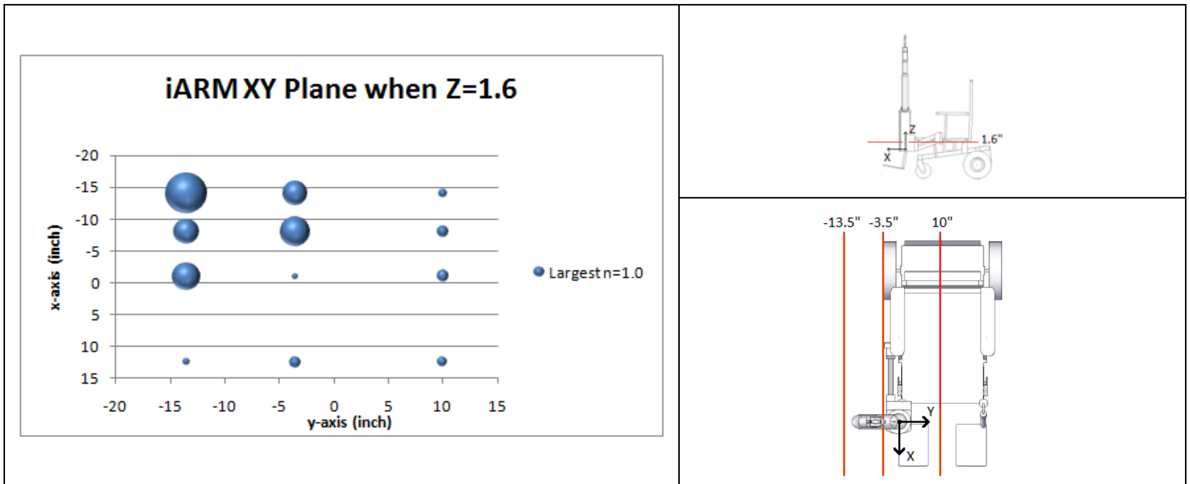


Point #	n	x	y	z	Flag
10	0.00146159	12.54	10	9.613	0
11	0.082188037	12.54	-3.5	9.613	0
12	0.045609963	12.54	-13.5	9.613	0
34	0.098231476	-1	10	9.613	0
35	0.017715086	-1	-3.5	9.613	0
36	0.086534567	-1	-13.5	9.613	0
58	0.090852295	-8	10	9.613	0
59	0.001120183	-8	-3.5	9.613	0
60	0.054525461	-8	-13.5	9.613	0
82	0.068937966	-14	10	9.613	0
83	0.070983277	-14	-3.5	9.613	0
84	0.337434945	-14	-13.5	9.613	0

Figure 39 - Normalized JACO manipulabilities in the xy-plane when z = 9.61"

Figure 40 and Figure 41 show manipulability data in the xy-plane when z = 1.63", or the standard height of an electrical outlet. Collision with the wheelchair must now be greatly considered as positions between y = -3.50", 10.00", and x = -1.00", -14.00" are physically unobtainable due to wheelchair collision despite acceptable manipulability values.

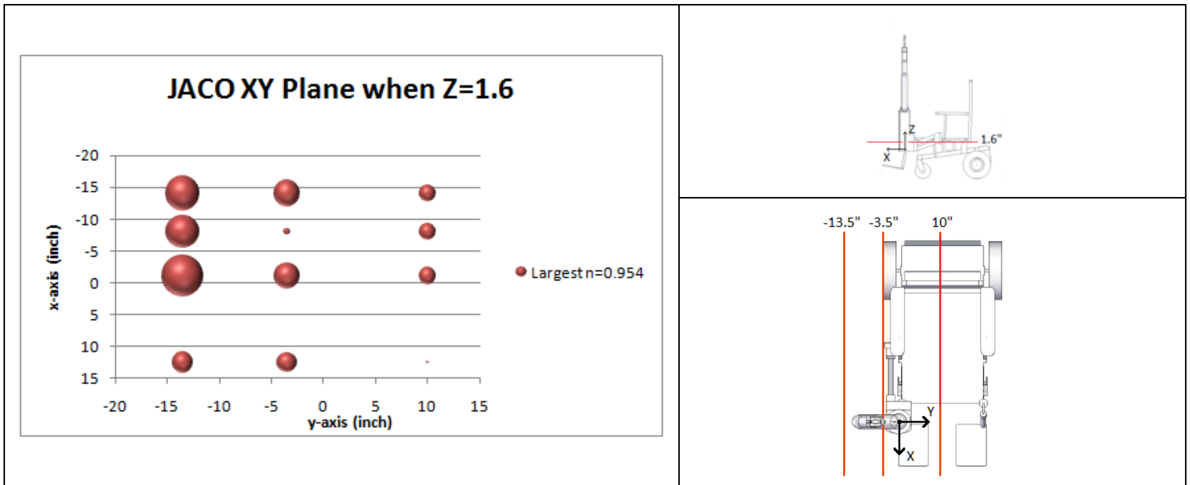
The greatest iARM normalized manipulability was calculated as 100%, meaning this was the highest iARM manipulability value for all points in all planes. The point is located to the rear and right of the user's line of sight.



Point #	n	x	y	z	Flag
7	0.053201388	12.54	10	1.633	0
8	0.071277372	12.54	-3.5	1.633	0
9	0.026486488	12.54	-13.5	1.633	0
31	0.078196656	-1	10	1.633	0
32	0.019413565	-1	-3.5	1.633	0
33	0.444797873	-1	-13.5	1.633	0
55	0.0778767	-8	10	1.633	0
56	0.517717093	-8	-3.5	1.633	0
57	0.363102957	-8	-13.5	1.633	0
79	0.039950929	-14	10	1.633	0
80	0.342932694	-14	-3.5	1.633	0
81	1	-14	-13.5	1.633	0

Figure 40 - Normalized iARM manipulabilities in the xy-plane when z = 1.63"

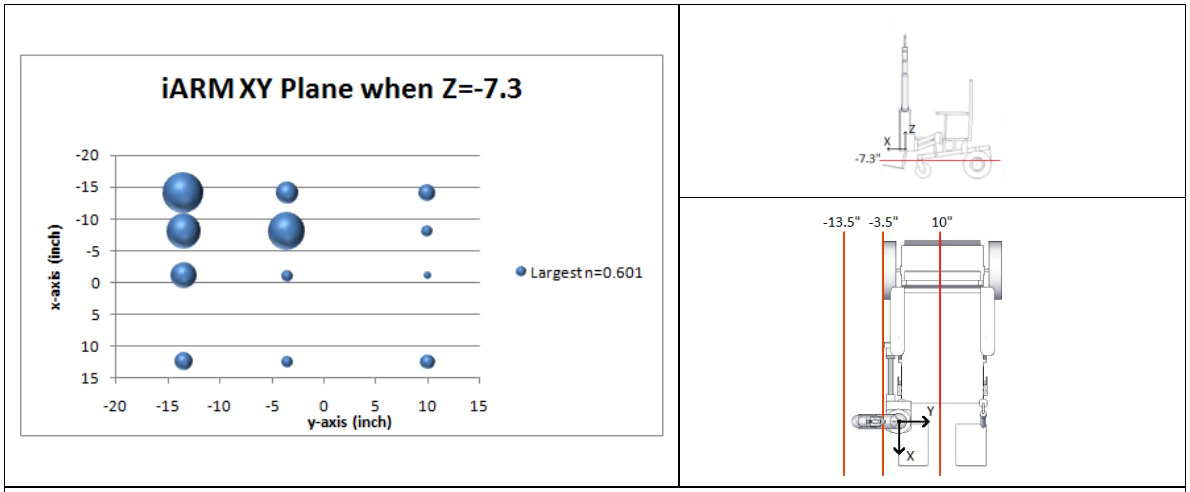
JACO manipulabilities are greatest to the rear and right of the origin, largely out of the line of sight of the user. The highest normalized manipulability value is calculated to be 95.4%.



Point #	n	x	y	z	Flag
7	0.003190943	12.54	10	1.633	0
8	0.219381082	12.54	-3.5	1.633	0
9	0.244169992	12.54	-13.5	1.633	0
31	0.15967936	-1	10	1.633	0
32	0.38380573	-1	-3.5	1.633	0
33	0.954215257	-1	-13.5	1.633	0
55	0.155034306	-8	10	1.633	0
56	0.024976912	-8	-3.5	1.633	0
57	0.640572	-8	-13.5	1.633	0
79	0.155014972	-14	10	1.633	0
80	0.38712849	-14	-3.5	1.633	0
81	0.664825603	-14	-13.5	1.633	0

Figure 41 - Normalized JACO manipulabilities in the xy-plane when z = 1.63"

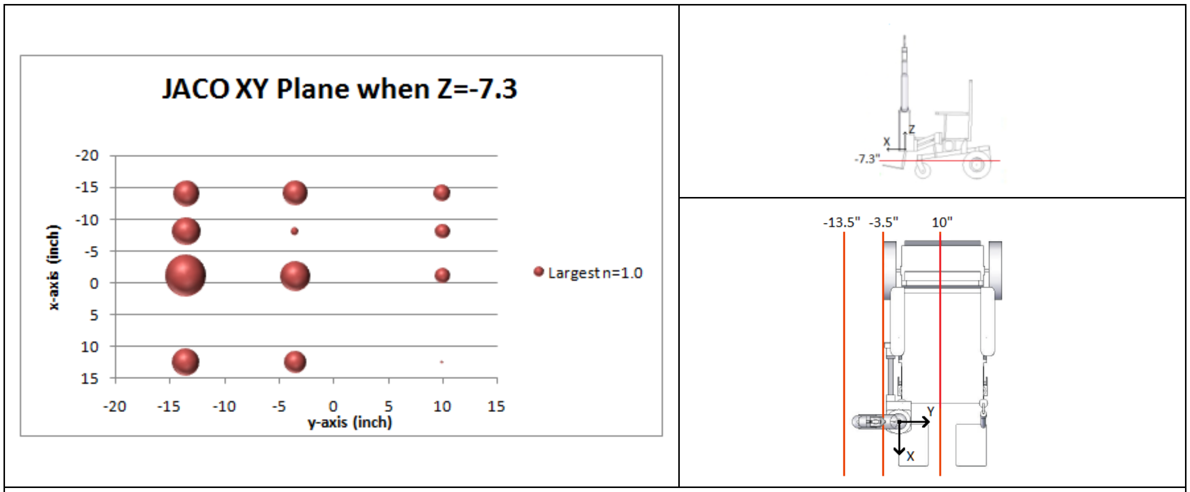
Figure 42 and Figure 43 show manipulability data for the xy-plane when z = -7.36". At this elevation, points in the first quadrant of the workspace are considered to be unobtainable. The highest obtainable normalized manipulability value for iARM is 60.1% and occurs at (-14.00, -13.50, -7.36). Lower manipulability values are the result of close end effector position with respect to joint 1.



Point #	n	x	y	z	Flag
4	0.074095993	12.54	10	-7.367	0
5	0.044779783	12.54	-3.5	-7.367	0
6	0.110826697	12.54	-13.5	-7.367	0
28	0.018964577	-1	10	-7.367	0
29	0.044078664	-1	-3.5	-7.367	0
30	0.231231261	-1	-13.5	-7.367	0
52	0.04053471	-8	10	-7.367	0
53	0.474867779	-8	-3.5	-7.367	0
54	0.409972925	-8	-13.5	-7.367	0
76	0.096255456	-14	10	-7.367	0
77	0.175276	-14	-3.5	-7.367	0
78	0.601991208	-14	-13.5	-7.367	0

Figure 42 - Normalized iARM manipulabilities in the xy-plane when z = -7.36"

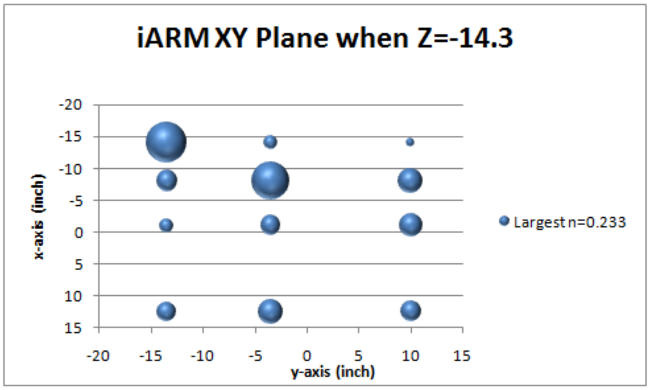
JACO shows a slightly higher distribution of manipulability values in the effective workspace in front of the user though the highest normalized value in this plane is 100% occurring at (-1.00, -13.50). Forward normalized values are 41.8% and 29.0% representing useful effectiveness when approaching high ground targets.

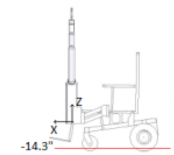


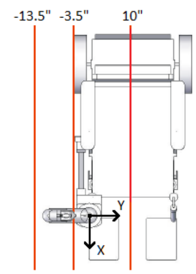
Point #	n	x	y	z	Flag
4	0.003270493	12.54	10	-7.367	0
5	0.290981372	12.54	-3.5	-7.367	0
6	0.418142932	12.54	-13.5	-7.367	0
28	0.129525435	-1	10	-7.367	0
29	0.516689333	-1	-3.5	-7.367	0
30	1	-1	-13.5	-7.367	0
52	0.126518187	-8	10	-7.367	0
53	0.029382374	-8	-3.5	-7.367	0
54	0.473690813	-8	-13.5	-7.367	0
76	0.163025985	-14	10	-7.367	0
77	0.369910262	-14	-3.5	-7.367	0
78	0.395991992	-14	-13.5	-7.367	0

Figure 43 - Normalized JACO manipulabilities in the xy-plane when z = -7.36"

Figure 44 and Figure 45 show manipulability data in the xy-plane when z = -14.36". The highest obtainable normalized manipulability value for iARM is 23.3% and occurs at (-14.00, -13.50, -14.36) though relatively acceptable normalized manipulabilities of 5.5%, 8.5%, and 4.9% occur forward of the user and well within line of expected line of sight. This allows for theoretically possible low ground object manipulation.



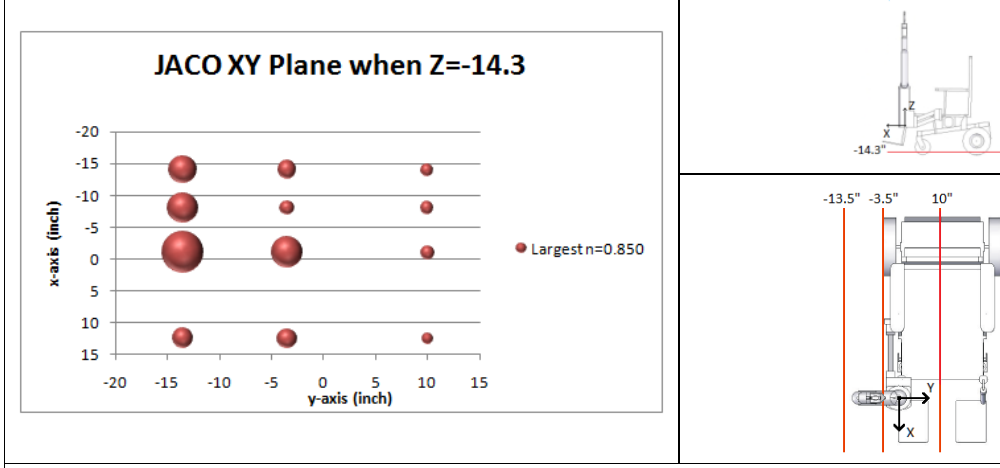




Point #	n	x	y	z	Flag
1	0.055275593	12.54	10	-14.367	0
2	0.085938649	12.54	-3.5	-14.367	0
3	0.049402161	12.54	-13.5	-14.367	0
25	0.072787072	-1	10	-14.367	0
26	0.052828538	-1	-3.5	-14.367	0
27	0.024615075	-1	-13.5	-14.367	0
49	0.085739202	-8	10	-14.367	0
50	0.195597885	-8	-3.5	-14.367	0
51	0.057129814	-8	-13.5	-14.367	0
73	0.008212181	-14	10	-14.367	0
74	0.022041	-14	-3.5	-14.367	0
75	0.233765328	-14	-13.5	-14.367	1

Figure 44 - Normalized iARM manipulabilities in the xy-plane when z = -14.36"

JACO shows a lower degree of relative manipulability in forward areas. The highest normalized manipulability is 39.5% while the greatest forward manipulability is 20.7%.



Point #	n	x	y	z	Flag
1	0.061744609	12.54	10	-14.367	0
2	0.188853956	12.54	-3.5	-14.367	0
3	0.207565225	12.54	-13.5	-14.367	0
25	0.092361027	-1	10	-14.367	0
26	0.509388679	-1	-3.5	-14.367	0
27	0.850745961	-1	-13.5	-14.367	0
49	0.080392274	-8	10	-14.367	0
50	0.096478568	-8	-3.5	-14.367	0
51	0.479404602	-8	-13.5	-14.367	0
73	0.078127593	-14	10	-14.367	0
74	0.170357741	-14	-3.5	-14.367	0
75	0.395348944	-14	-13.5	-14.367	0

Figure 45 - Normalized JACO manipulabilities in the xy-plane when z = -14.36"

Major theoretical kinematic outcomes may be observed in the following table which lists the highest obtainable normalized manipulability values at each elevation. The floor manipulation task averages high and low ground target manipulability measures.

Table 7 - Classification of manipulability measure for given tasks

Typical Task at Elevation	iARM		JACO	
Access to Mouth	62.4%	Very Good	69.2%	Very Good
Low Kitchen Shelf	55.4%	Good	39.9%	Limited
Light Switch	80.5%	Very Good	56.4%	Good
Kitchen Countertop	95.4%	Excellent	66.3%	Very Good
Door Knob	75.0%	Very Good	50.5%	Good
Coffee Table	79.3%	Very Good	33.7%	Limited
Floor Manipulation	41.7%	Good	45.5%	Good

From observation of the above table, iARM is shown to exhibit "very good" manipulability overall and reaches the greatest possible manipulability classification of "excellent" in the kitchen countertop work area. The average normalized manipulability value for iARM for all 7 theoretical task areas is 69.9% (very good). The lowest normalized manipulability value reported in Table 7 is 41.7% (good) and was calculated for floor manipulation tasks.

The average normalized manipulability value for JACO for all 7 task areas is 51.6% (good). The lowest normalized manipulability value reported in Table 7 is 33.7% (limited) and was calculated for coffee table tasks. Overall, JACO is shown to exhibit "good" manipulability.

4.2 Experimental Results

For experimental testing, it was predetermined that each test trial would start from the "parked" or most compact configuration of the WMRA. This determination stemmed from considering each task as newly identified as necessary.

That is to say that since WMRA end users do not leave the manipulators in the "ready" or deployed position throughout the day and only unpack the device when necessary. Therefore, it was considered that each task was newly discovered or necessary at the beginning of each test trial. The following sections show the outcomes of experimental testing.

4.2.1 Time of Performance

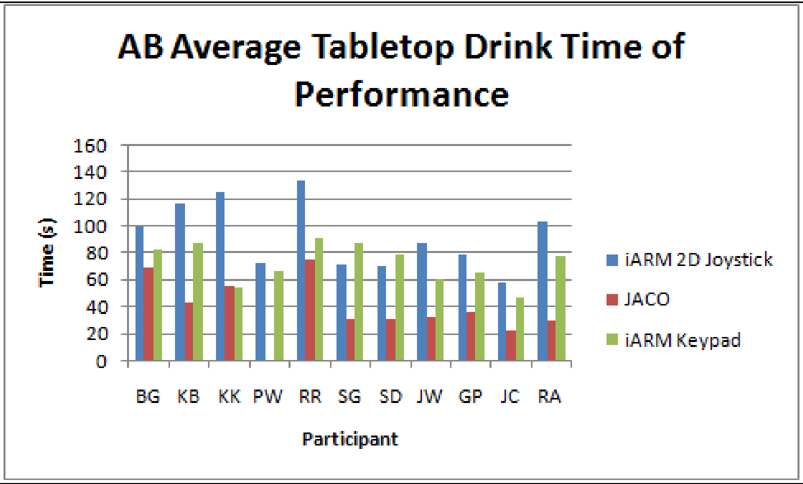
Time of performance data is presented here. Figure 46, Figure 48, Figure 49, and Figure 50 show the average time of performance for each participant for each of the 4 tasks. Average time of performance for a single participant is the mean of his or her 3 test trial times. The standard deviation of averages will be reported for each WMRA/input device system. Standard deviation of averages is the standard deviation of the averages of all participant times of performance given by the formula:

$$\sigma_{avg} = \sqrt{\frac{\sum_{i=1}^{n}(average_i - overall\ average)^2}{n-1}} \qquad \text{Equation 9}$$

In order to maintain overall testing time to 4 hours or less, a time-out time was predetermined. The time-out time of 500 seconds was the maximum amount of time a participant had to complete a testing trial.

4.2.1.1 Tabletop Drink

A convention was developed during testing to begin each participant with the tabletop drink task. This task, which requires the participant to reach and retrieve a 20 oz. bottle of water, was found to be the safest task to begin physical testing. The task is considered safe as the bottle is free to translate and rotate on the tabletop. This lack of constraint protects the WMRA from damage if accidental contact is made with the target object. The lack of constraint also eliminates manipulator overload as the participants learned the WMRA systems. The drink task was also chosen as the duplicate task for testing alternate iARM user interfaces for this reason.



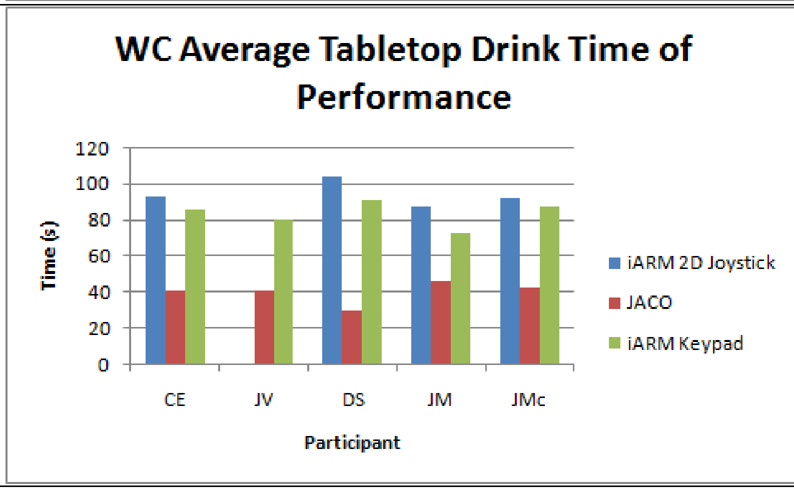


Figure 46 - Tabletop drink average time of performance

From Figure 46, it can be seen that the iARM with 2D joystick interface is generally slower than both iARM with keypad interface and JACO manipulator. The greatest average able bodied time of performance of iARM with 2D joystick interface is 134 seconds. Able-bodied participants show a standard deviation of averages of 25 seconds for the drink task with the iARM/2D joystick system.

For wheelchair-dependent participants, the greatest iARM/2D joystick average time of performance that was not a time-out value was 88 seconds while the average of standard deviations for the task is 7 seconds. This low average of standard deviations shows that wheelchair-dependent participants completed this task with 2D joystick control in time intervals very close to the average time of performance. One wheelchair-dependent participant was unable to use iARM 2D joystick control for lack of the ability to effectively use the "quick flip" control mode scheme.

The iARM "quick flip" control scheme for the 2D joystick recognizes small movements of the joystick executed over a fraction of a second as commands to change Cartesian and Pilot control modes of the manipulator. The time to register such a command was observed to be no greater than 0.5 seconds.

There are four Cartesian modes:

1. Translation in the xy-plane
2. Translation in the z-direction and end effector rotation about the gripper axis (roll)*
3. End effector rotation in the horizontal plane and vertical plane (yaw and pitch)
4. Translation in the z-direction and end effector open/close

There are also four Pilot mode selections:

1. Translation in the xy-plane
2. Translation in the z-direction and end effector rotation in the horizontal plane (yaw)*
3. End effector rotation in the vertical plane and rotation about the gripper axis (roll)
4. Translation in the z-direction and end effector open/close

Notice the change in modes 2 and 3 between Cartesian and Pilot methods of manipulator operation indicated by an asterisk (*).

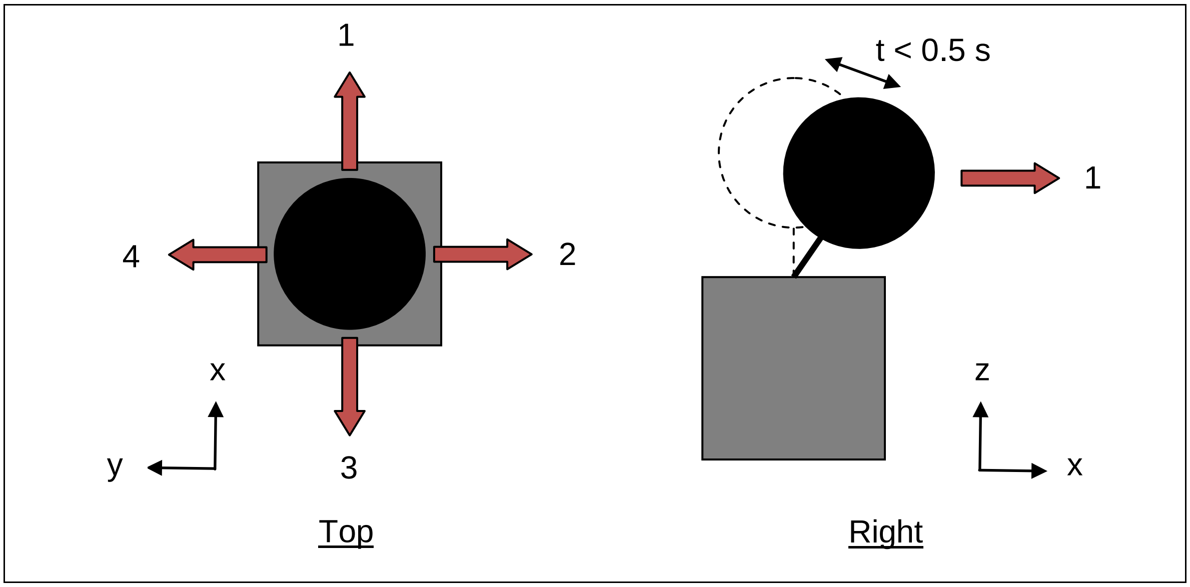


Figure 47 - iARM joystick "quick flip" mode change scheme

A representation of the "quick flip" mode change scheme can be seen in Figure 47. The top view shows the directions which select modes 1 through 4. The right view shows an example of selecting mode 1 by moving the joystick forward (positive x-direction) and returning to the neutral position in less than 0.5 seconds.

This, and all "quick flip" executions, required a level of hand dexterity, control, and strength that was not exhibited by all participants. Furthermore, accidental mode changes were prevalent during attempts at issuing fine end effector movement commands.

The high time of performance for the iARM/2D joystick system in both able-bodied and wheelchair-dependent participants is attributed to inaccuracies of the "quick flip" mode change scheme. "Quick flip" related inefficiencies also attributed to high standard deviation of averages. The "quick flip" joystick scheme made the task impossible to complete for one wheelchair-dependent participant. Impossibilities are displayed as time-out values of 500 seconds.

iARM with keypad interface is seen to be faster with a highest average time of performance of 91 seconds and an average of standard deviations of 14 seconds for able-bodied participants.

The highest wheelchair-dependent average time of performance for the iARM/keypad system was recorded as 90 seconds. Standard deviation of averages with keypad control is 14 seconds.

This decreased time of performance in both participant categories is attributed to having control of each manipulator axis without mode change with the keypad interface. The keypad interface has the lowest standard deviation of averages for the drink task as participants could more easily remember and input a set series of commands to complete the task.

JACO was mostly operated in 3D mode by able-bodied participants, though one able-bodied participant elected to use the JACO joystick in 2D mode in order to simulate restricted control dexterity; as seen in SCI C5/C6 participants. Regardless of axis mode, participants recorded the fastest tabletop drink times with the JACO system. Its highest average time of performance for able-bodied participants for the drink task was 75 seconds with an average of standard deviations of 18 seconds.

The missing JACO data entry is a result of a critical malfunction of the pre-release version of the manipulator originally supplied for testing. A motor in the end effector was observed to draw a large current and heat until power to the unit was turned off. This event took place during a participant testing time and resulted in permanent damage to the end effector, making it unable to properly grasp objects and thus, complete the drink task. An updated release version of JACO was provided.

Kinova maintains the heating issue was addressed in the release version. Testing of the release version of JACO with subsequent participants continued without incident. The end effector motor failure in the JACO system also lead to the missing data in some of the figures to follow.

For wheelchair-dependent participants, 2 of 5 participants were only capable of operating in 2D mode of the JACO joystick. These participants experienced incomplete cervical level spinal cord injuries and lacked the dexterity to perform the twisting motion allowed by the 3D mode of the JACO joystick. Regardless of axis mode, participants recorded the fasted task times with the JACO system with a highest average time of performance and average of standard deviations of 42 and 6 seconds, respectively.

4.2.1.2 Flip-Toggle Light Switch

The light switch task was executed secondly by convention. This task was deemed the next safest activity as it introduces rigid body interaction but requires no curvilinear motion of the WMRA systems.

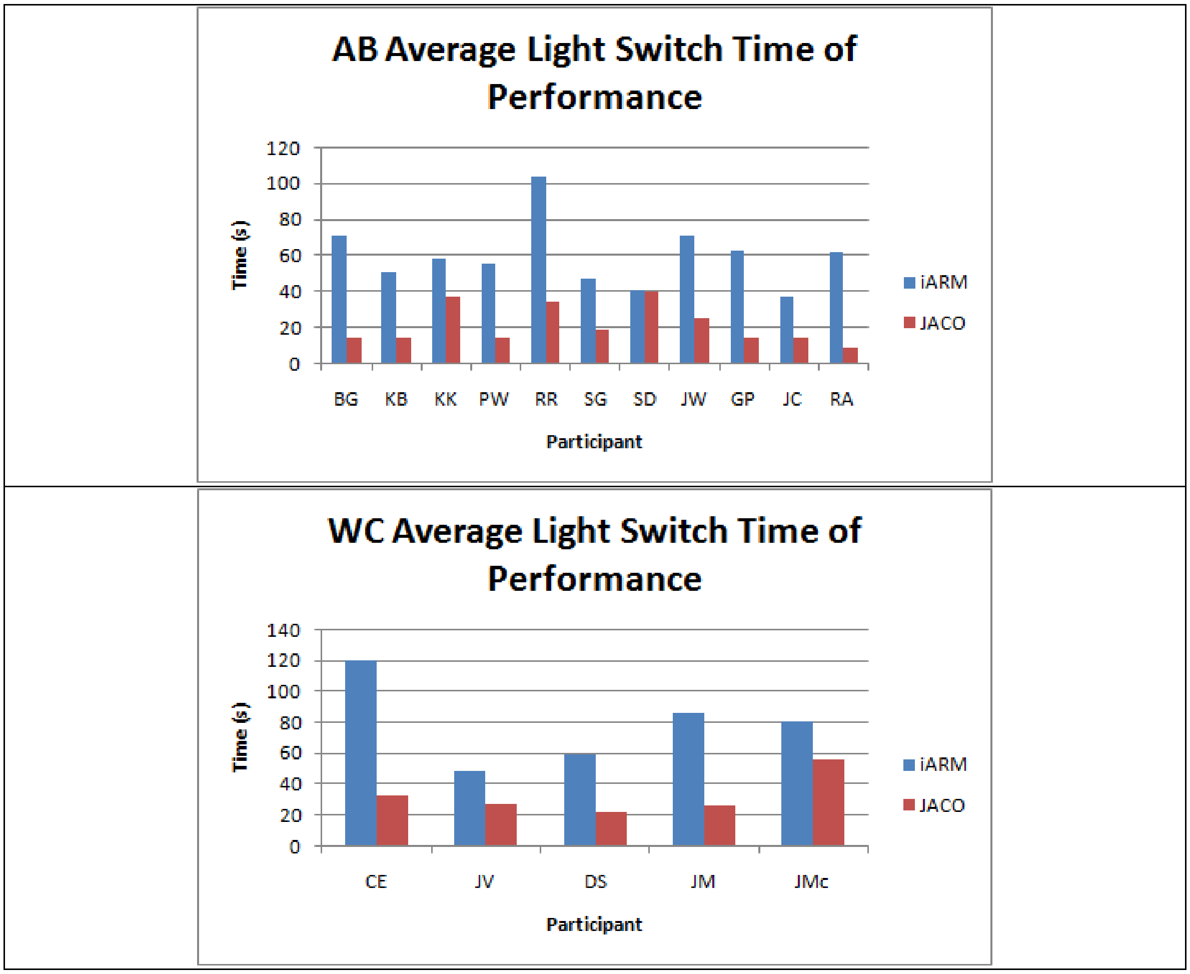


Figure 48 - Light switch average time of performance

The greatest average time of performance of able-bodied participants for iARM was recorded as 104 seconds with 2D joystick control. The greatest average time of performance of wheelchair-dependent participants for iARM was recorded as 120 seconds with 2D joystick control. Figure 48, Figure 49, Figure 50, and Figure 51 do not consider 2D joystick and keypad input devices separately.

The slower average times of iARM and its control devices is a result of numerous mode change requirements with accidental "quick flips" and hunt-and-peck guessing of keypad commands, respectively.

The standard deviation of averages of iARM trials for the light switch task is 18 and 27 seconds for able-bodied and wheelchair-dependent participants, respectively.

Participants operating the JACO system in either 2D or 3D control modes generally posted the fasted times of the study in the light switch task. The 3D control mode allowed for able-bodied participant average times of performance ranging from 39 to 9 seconds with a standard deviation of averages of 10 seconds, the narrowest margin of able-bodied recordings. A wheelchair-dependent participant completed the task with 2D JACO control with an average time of performance of just over 20 seconds. A large disparity of iARM and JACO light switch times can be seen in Figure 48.

4.2.1.3 Low Cabinet Door

The low cabinet became the third task by convention and introduced rigid body curvilinear motion to the participants. To allow the cabinet door to open successfully, participants were required to input orthogonal components of motion to each control device.

Two different end effector strategies were employed during this activity; achieving a firm grasp of the handle or inserting the vertex of the end effector tip between the handle and cabinet using friction instead of a grasp to apply the necessary components of motion. Most participants elected to grip the handle with iARM and use the second strategy of "flicking" the cabinet open with JACO.

The particular cabinet door considered in the study features a linkage mechanism which preloads the door in the closing direction. A considerably large force is required to overcome the preload and open the door. A considerably small force is required to close the door.

A change point position was identified between 30° to 45° of the range of motion of the door; the range of motion being approximately 90°. At the change position, the door would be held open by the preloading mechanism even if end effector contact with the handle or door surface was lost. If a change point position occurred, participants used whole-arm manipulation to open and close the door.

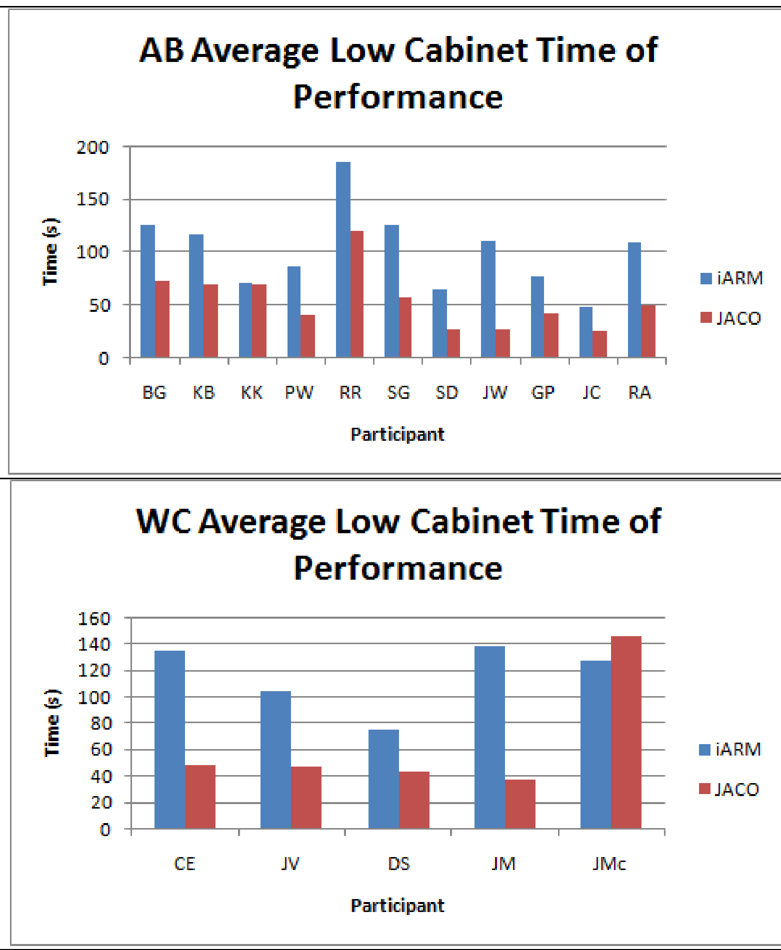


Figure 49 - Low cabinet average time of performance

The task was defined by opening and closing the low cabinet door. Thus, Figure 49 shows average times of performance for a complete open/close cycle. For able-bodied participants, the greatest average time of performance for iARM was recorded as 185 seconds with the 2D joystick. The average of standard deviations between participants using the iARM/control system is 38 seconds. For wheelchair-dependent participants, the greatest average time of performance for iARM was recorded as 134 seconds while average of standard deviations is 26 seconds.

The iARM was subject to large angular offsets of joint 1 as a result of transmission slippage from overloading during the cabinet door task. This offset causes straight line translation control issues in the xy-plane as these movements are directly affected by joint 1 rotation. For example, if the iARM is overloaded and causes slippage of joint 1 resulting in an angular offset of 45°, a user command to move the end effector forward now moves the end effector forward at a 45° angle.

A recalibration procedure is specified to correct each instance of offset in any joint but requires a technician to complete. The researchers of this study were given training in the recalibration procedure but to maintain a maximum testing time of 4 hours manual manipulation of joint 1 was used while the manipulator was powered off to correct the offset problem. This procedure was carried out each time the offset occurred and eliminated all control issues.

The highest average time of performance of able-bodied participants for JACO was recorded as 120 seconds in the 3D control mode. The standard deviation of averages for the JACO system is 29 seconds. Wheelchair-dependent participants recorded greatest average time of performance and average of standard deviations times of 146 and 45 seconds, respectively.

The pre-release version of JACO exhibited end effector assembly failures as a result of overloading when using the "flick" strategy of opening the door. The failure would manifest when hyperextension of the fingers was induced. The post-release version featured improved end effector assembly methods which eliminated the problem during subsequent testing.

4.2.1.4 Personnel Door with Knob

Participants were asked to open the standard interior personnel door (a door which people move through) with knob mechanism as the final task. Again, two different successful strategies were developed.

The first door knob strategy was to position the wheelchair directly in front of the door in a "heads-up" position in which the orientation of the wheelchair was square with the door. This position brought the target object, the door knob, within the workspace of the arms but blocked the door from being able to be opened completely.

Therefore, the heads-up strategy was executed with a manipulator operation to unlatch the knob mechanism, a wheelchair operation to remove the wheelchair from the curvilinear path of the door, followed by a second manipulator operation using whole-arm manipulation to push the door open to 90° or greater.

To eliminate multiple operations, the second door knob strategy allowed the participant to find an ideal wheelchair position and orientation during practice trials. The ideal position and orientation kept the door knob in the manipulator workspace and wheelchair out of the path of the door. With the second strategy, the task could be performed in one manipulator operation. The choice in strategy was left to the participant.

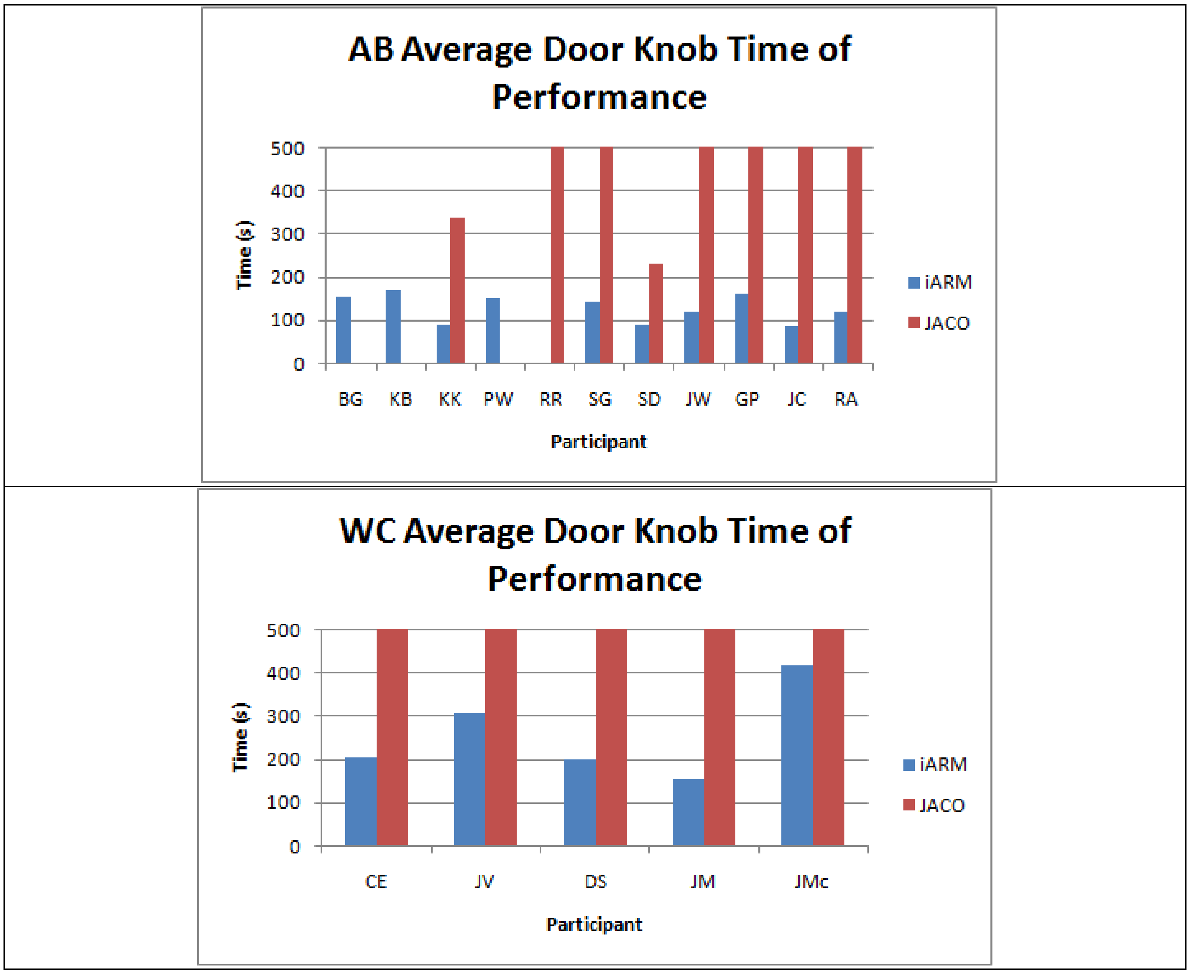


Figure 50 - Personnel door with knob average time of performance

Figure 50 shows the average time of performance for many of the participants using the JACO system reached the time-out limit of 500 seconds.

The Figure 50 also shows missing JACO data as a result of the pre-release version losing end effector gripping capability. This failure made it impossible to grasp the door knob. Therefore, this task was omitted for JACO until a replacement was received.

It can be seen that the JACO system, pre- or post-release was largely ineffective at this task as most its average times of performance met the time-out limit. Only two able-bodied participants were successful in completing this task with JACO. The greatest average time of performance that was not a time-out time was recorded as 337 seconds while operating in 3D mode. The average of standard deviations is calculated to be 97 seconds but this value lacks meaning as the majority, 6 of 11, of participants found the task to be impossible to perform within an acceptable time frame and 3 of 11 were unable to attempt the task as a result of system failure.

Similarly, the average time of performance for all wheelchair-dependent participants reached the time-out limit of 500 seconds thereby forcing the average of standard deviations to a value of zero.

The greatest average time of performance by able-bodied participants for the iARM system was recorded as 169 seconds while using the 2D joystick. An average of standard deviations of 31 seconds shows that the iARM system, regardless of input device, was able to complete this task with acceptable effectiveness.

Wheelchair-dependent participants posted greatest average time of performance of 417 seconds with 2D joystick control. This value is approaching the time-out limit but a high inter-system disparity and average of standard deviations shows the iARM system was capable of completing the task with acceptable effectiveness in most cases.

4.2.1.5 Cumulative Average Time of Performance

Cumulative average of all participant times of performance were calculated to show the overall speed at which each system was capable of completing each task. Figure 51 shows able-bodied and wheelchair-dependent average times of performance per task. The graphs omit the JACO door knob value as it approaches the time-out limit of 500 seconds.

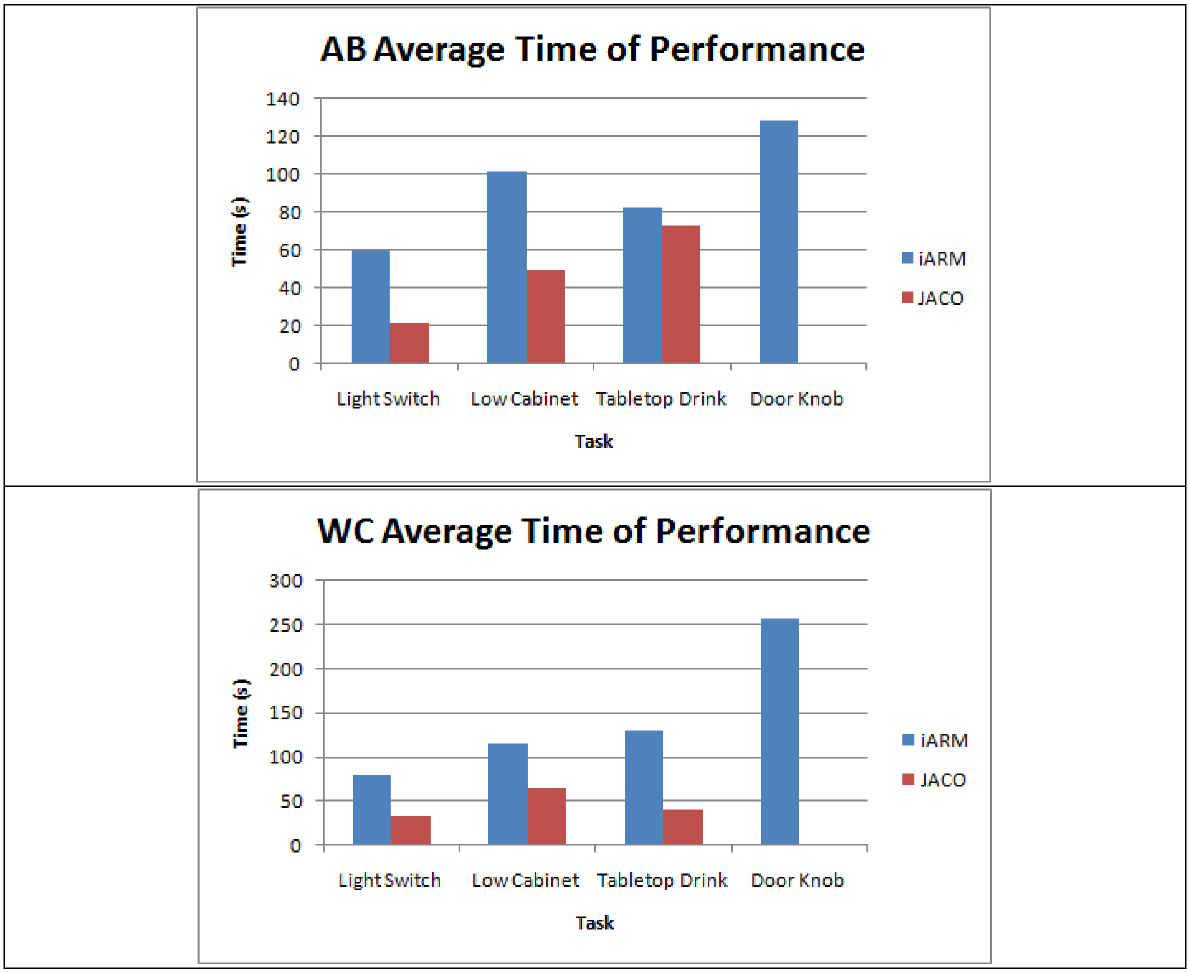


Figure 51 - Average time of performance per task

It was seen that the JACO system, regardless of axis control mode excels at each task when compared to iARM with the exception of the door knob task. For the first three tasks, the difference between average time of performance per task for able-bodied participants approximately ranges from 40 to 60 seconds. The difference for wheelchair-dependent participants approximately ranges from 25 to 100 seconds.

This disparity shows the JACO system completed these tasks in 35% and 40% of the iARM average time of performance for able-bodied and wheelchair-dependent participants, respectively. It is shown that JACO performance overall is hampered by its inability to perform the door knob task repeatably while iARM excels in the personnel door opening task.

4.2.2 Ease of Use

Participant ease of use ratings for each task are presented graphically in Figure 52 through Figure 55. Standard deviation of ease of use ratings are also reported to indicate the most selected ease of use rating on a scale of 1.0 - 5.0. Standard deviation of ease of use is calculated by the following formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(ease\ of\ use_i - average\ ease\ of\ use)^2}{n-1}} \qquad \text{Equation 10}$$

To help gauge the physical meaning of the 1.0 - 5.0 scale, a rating of 1.0 was said to represent a task which was impossible to complete with the given WMRA system while a rating of 5.0 was said to represent the ability to execute the task with exceeding ease. The upper end of the scale was said to be approaching one's own arm for able-bodied participants. Details on desirable features and shortcomings of the WMRA systems will be elaborated on in the following sections.

4.2.2.1 Tabletop Drink

Figure 52 shows ease of use ratings per participant for the tabletop drink task. Since this task was deemed the most suitable to evaluate all input devices, three series are displayed for the iARM 2D joystick, JACO, and iARM keypad. The able-bodied average ease of use ratings are 3.7, 4.5, and 3.7 for iARM 2D joystick, JACO, and iARM keypad, respectively. Wheelchair-dependent participants recorded average ease of use ratings of 3.6, 5.0, and 4.2 for each respective WMRA system.

It is interesting to note that some participants attempted to complete the drink task by opening the end effectors at a height over the target object and proceed to drop down over the bottle. This sequence of steps results in increased mode change and is not as efficient as grasping the object from the side. For these cases, recommendations were made on how to most efficiently execute the task.

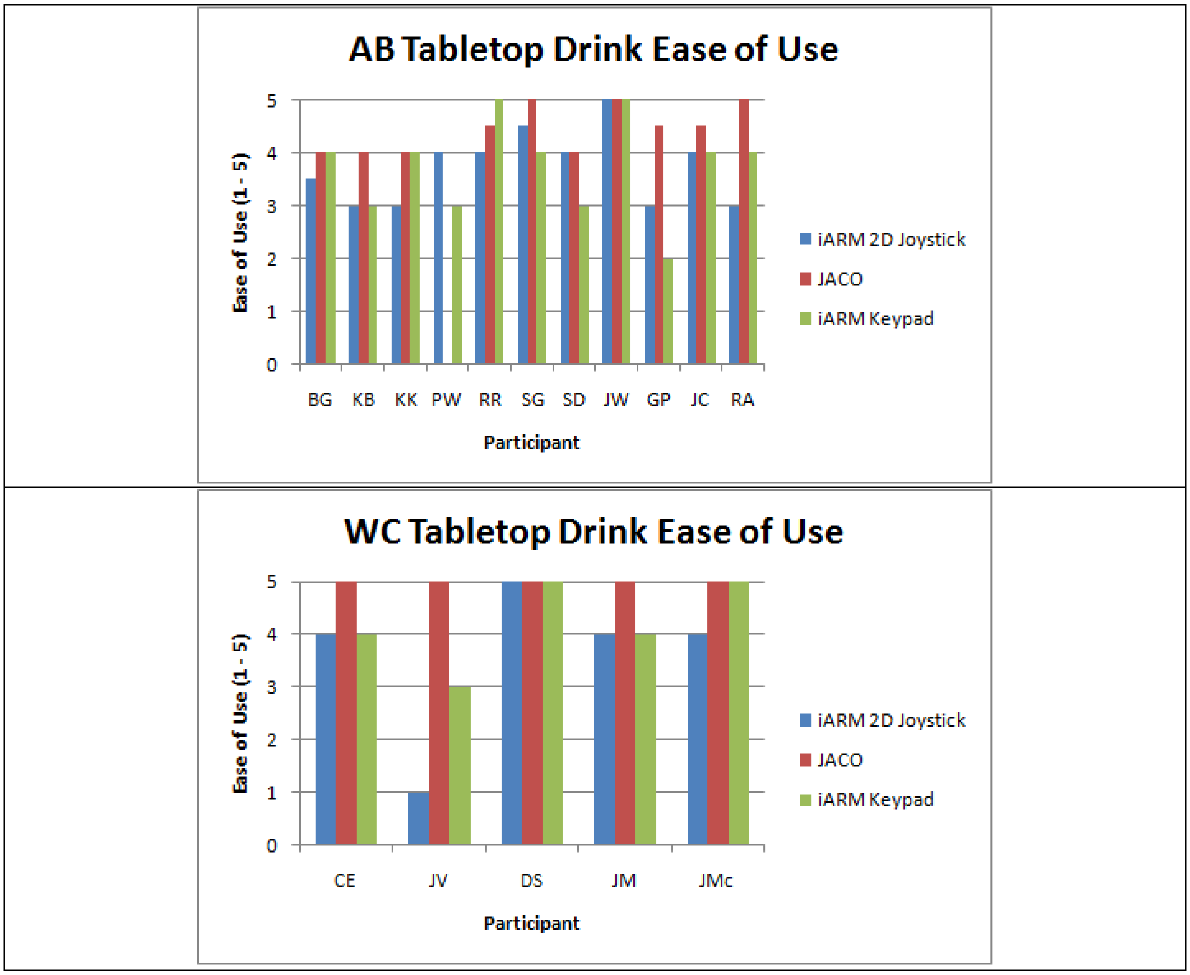


Figure 52 - Tabletop drink ease of use

As previously stated, input devices and control modes were selected by participants after ample training and familiarization time with all options. Along these lines, Pilot operation was made evident to all participants.

In Pilot mode, the end effector continuously reorients itself to point in the direction of straight line translation in the xy-plane. This mode was found especially useful for the drink task in particular as fewer mode changes were needed to orient the end effector in an acceptable pose to grasp the bottle and subsequently bring the bottle to an easily accessible area in very close proximity to the participant.

The JACO manipulator operates exclusively in Pilot mode while iARM control mode may be selected from several menus, included Cartesian and Pilot. Participants using iARM were allowed to explore both of these modes for each task. 6 of 11 able-bodied participants chose to operate iARM in Pilot mode with 2D joystick control for at least one time trial of the drink task. 2 of 5 wheelchair-dependent participants chose to do the same. No participant chose to operate in Pilot mode with the keypad input device.

The effectiveness of iARM Pilot mode is less than that of JACO. This is observed by examining Figure 46 and Figure 52. The differing feature of comparably operated iARM and JACO WMRAs is the rate at which the end effector continuously reorients to point in the direction of straight line translation in the xy-plane. The iARM end effector reorients at a much higher rate which tends to reduce precise control of gripper orientation in both gross and fine xy-translation. Reduction in fine control caused the end effector to push the target object farther away from the manipulator in some cases.

Six of sixteen total participants found the iARM/keypad system to be more effective than the manipulator with 2D joystick control. Though keypad control decreases time of performance and variation, 2D joystick control is still preferred in terms of ease of use.

Overall, participants found the JACO system to complete the drink task with great speed and ease stating that the system moved fluidly and felt more like a natural extension of their being than a robotic device. This theme will continue throughout the study.

4.2.2.2 Flip-Toggle Light Switch

The light switch task introduced interaction with a fixed rigid body. This task tested the effective compliance of each WMRA system. Since a flip-toggle switch was being considered, the point of contact which must be made to complete the task was very small. Maximizing end effector contact surface is a key strategy in successfully and repeatably executing this task.

It was recommended by study personnel that the end effectors of both WMRAs be oriented horizontally and tangent with the face of the wall which the light switch was installed. In this end effector orientation, finger surfaces could be used to contact the switch instead of attempting to contact the small switch with the tips of the fingers. Once a finger surface was properly aligned and within sufficient closeness to the wall face, a simple positive or negative translation could be made in the z-axis to toggle the switch.

Using the suggested method, able-bodied participants rated the ease of use of the task an average of 3.7 on a scale of 1.0 - 5.0 with a standard deviation of 0.5 for the iARM system. JACO received an average rating of 4.3 and a standard deviation of 0.7 from able-bodied participants. Wheelchair-dependent participants gave ratings of 4.2 and 4.8 with standard deviations of 0.8 and 0.4 to iARM and JACO, respectively.

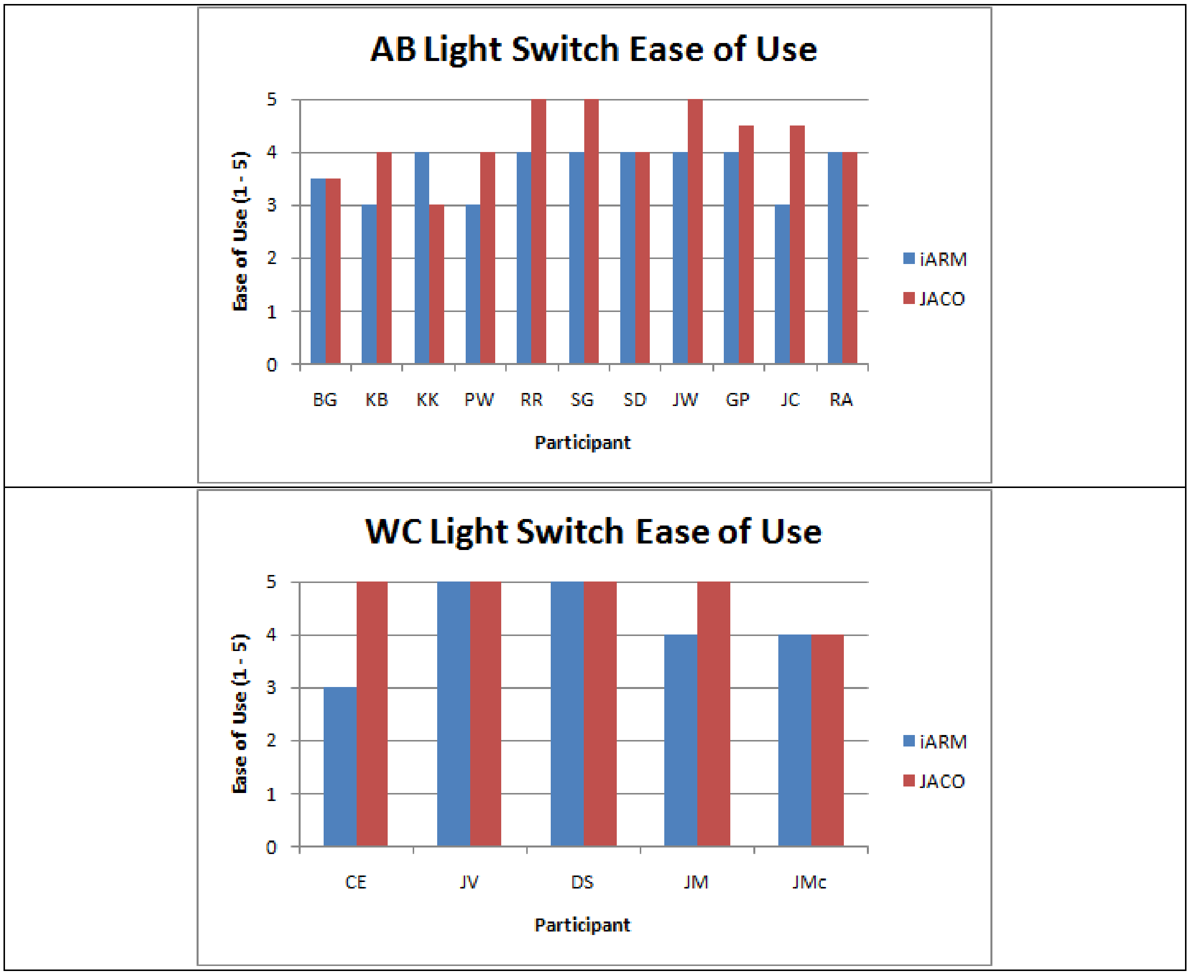


Figure 53 - Flip-toggle light switch ease of use

Problems encountered by the JACO system for this task stemmed from its 3-finger end effector design. Some participants found the bulk of the design to hinder line of sight to the target. Line of sight obstruction came from both the large shell of the end effector and the third finger.

The third finger was also observed to not contribute greatly to gripping power in subsequent tasks. The iARM end effector has a significantly reduced cross section with respect to JACO.

The compliance of the under-actuated fingers of the JACO end effector did allow for alignment and proximity errors. If the end effector was angled too far towards the wall or if the fingers were opened wider than needed the fingers exhibited a great enough compliance to bend over small obstacles and complete the task without repositioning. Finger compliance also compensated for uncontrollable fine end effector movements during gross z-axis movements. The rigidity of the iARM end effector created more instances of large spring force generation as a result of getting momentarily trapped on wall features.

Ultimately, the quicker unpack time and faster gross speed of the JACO manipulator coupled with the easier mode changes of the controller decreased the time of performance of JACO during the light switch task. However, in terms of ease of use, most wheelchair-dependent participants, 3.0 of 5.0, found both iARM and JACO equally effective though JACO received a higher average ease of use rating. Able-bodied participants found the JACO more effective overall.

4.2.2.3 Low Cabinet Door

The third task of the study further taxed participants by forcing an interaction with a rigid body with an angular range of motion. Special instructions were given to cope with the cabinet door task. These instructions lead to the development of the "grip" and "flick" strategies covered in section 4.2.1.3. The same section also detailed shortcomings of each WMRA system, including iARM angular offsets resulting in power cycles and manual manipulation by study personnel, and pre-release JACO finger/end effector separation issues.

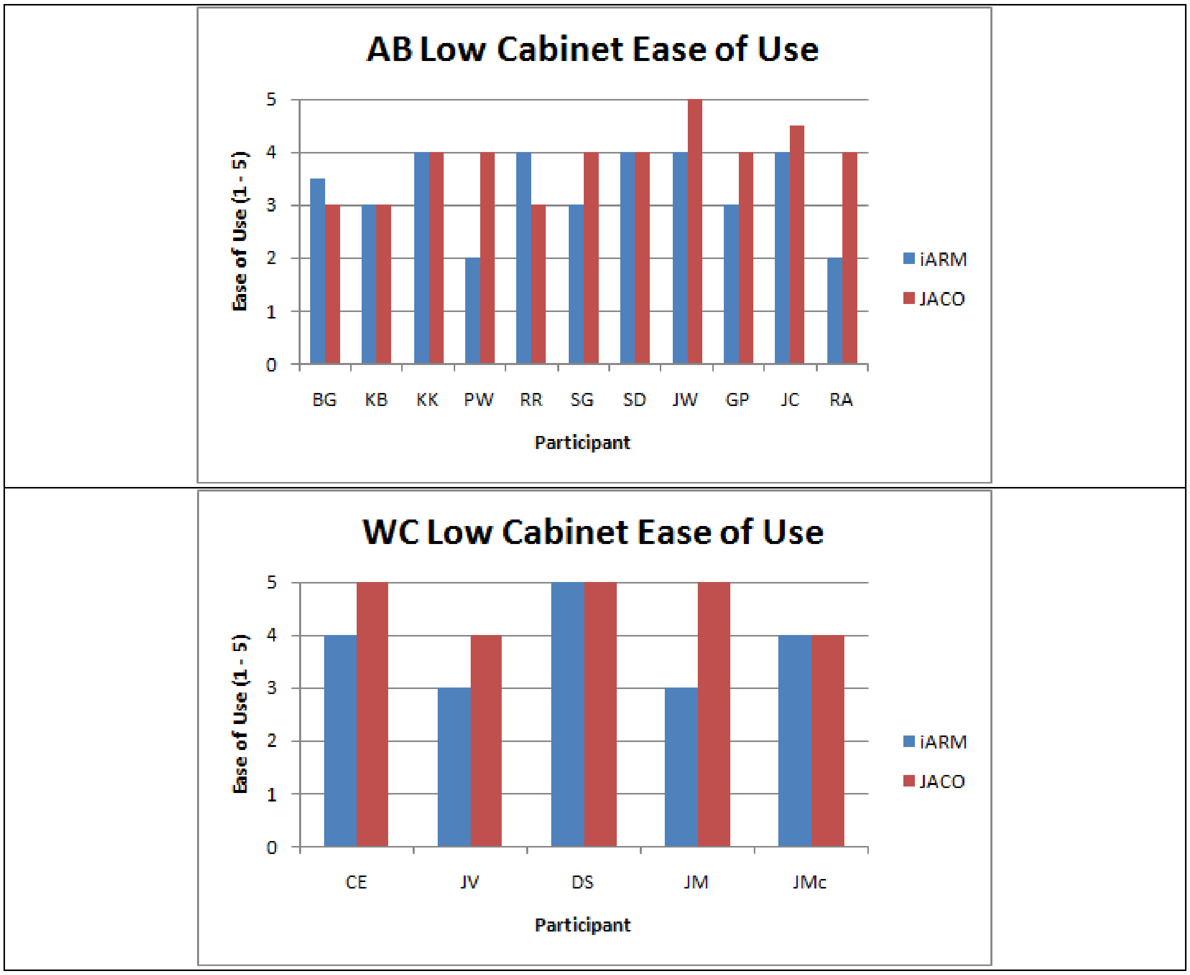


Figure 54 - Low cabinet door ease of use

Figure 54 displays ease of use data for the low cabinet task. Observation of the figure will show 6 of 11 able-bodied and 3 of 5 wheelchair-dependent participants rated the JACO system as easier to use for this task with respect to the iARM systems. Average ease of use ratings for iARM are 3.3 and 3.8 for able-bodied and wheelchair-dependent participants, respectively. JACO ratings are 3.9 and 4.6 in the same respect.

For this task, left or right handed WMRA mounting position is important. The low cabinet of the physical test environment opens counter-clockwise by the Right Hand Rule taking the positive z-direction as pointing upward.

With a right hand mounted WMRA system, the most effective methods for completing the cabinet task are the two previously detailed grip and flip strategies. All participants operated iARM and JACO in the right hand mounting position for study consistency.

Three of sixteen participants stated the low cabinet task may be completed with an alternative strategy, given a left hand mounted WMRA. This third strategy is to position the end effector joint towards the hinge of the cabinet and contacting the handle of the cabinet with the tip of the end effector. This is only possible when the cabinet door and end effector dimensions are agreeable. The end effector joint would then be rotated about the z-axis, thereby completing the task with a single gripper rotation in lieu of multi-component translation in the xy-plane. The third strategy could also be employed given a low cabinet with clockwise opening rotation and right hand mounted WMRA.

Participants generally found the low cabinet door task to be the second most difficult task based on subjective comments made during testing. JACO is again seen to be rated at higher effectiveness compared to the iARM system.

4.2.2.4 Personnel Door with Knob

The personnel door with knob opening task proved to be the lowest rated activity of the study. The low average effectiveness ratings stem from high end effector alignment accuracy requirements, and critical wheelchair position and orientation considerations. Average participant ease of use ratings can be seen in Figure 55. Overall average ratings for iARM and JACO are 3.0 and 1.1, and 3.0 and 1.0 for able-bodied and wheelchair participants, respectively.

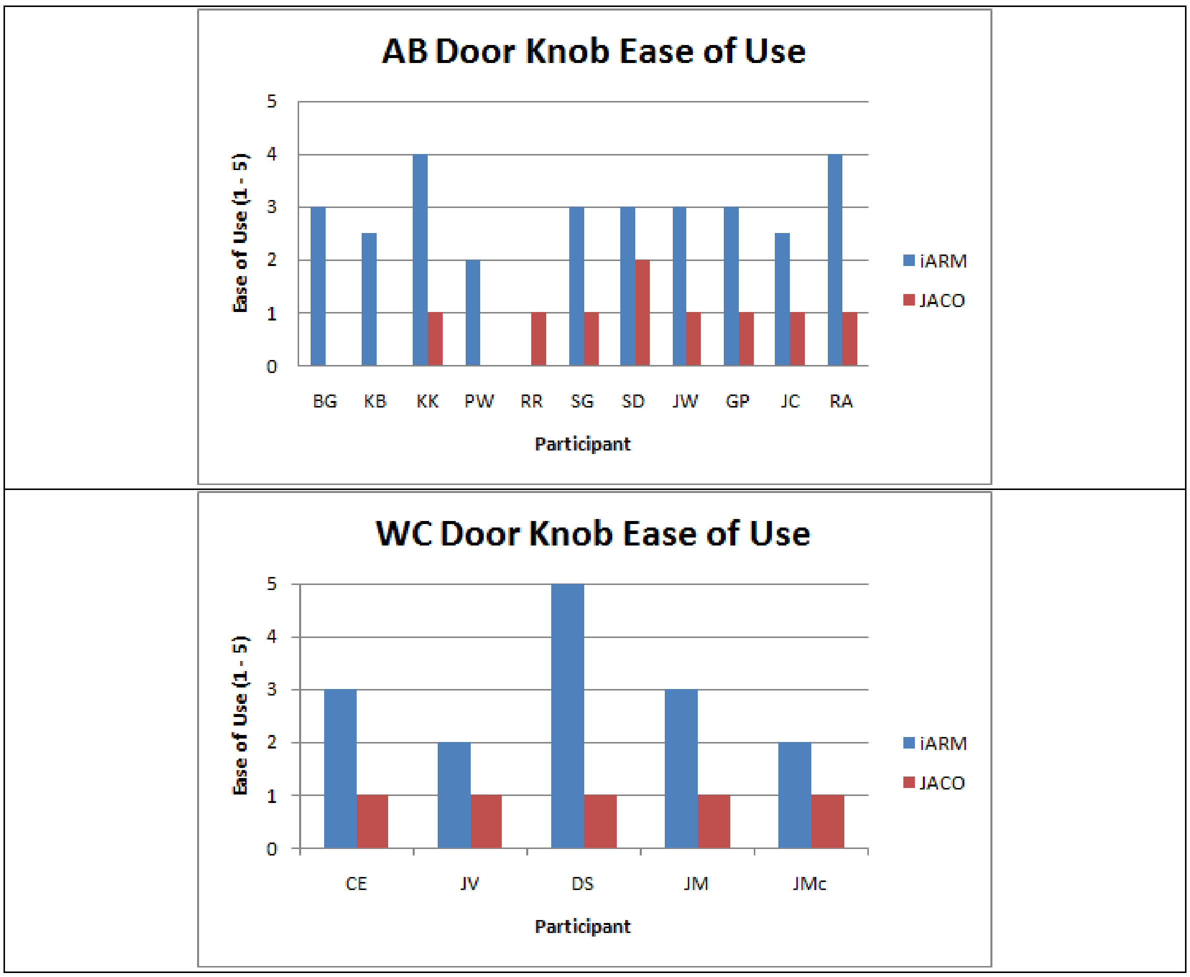


Figure 55 - Personnel door with knob ease of use

The driving factor of the success of the iARM system is the end effector design. The 2-finger gripper uses rigid link construction and a single ACME screw and nut to drive open/close motion. The rigid link construction supported load both in the open/close direction as well as transverse load oriented orthogonally to the open/close direction. iARM end effector rigid link construction provides comparatively superior gripping force capability.

Furthermore, the high friction pads of the iARM end effector provide finite circular areas of high friction coefficient with gaps in between each circular area. The circular high friction pads also feature a filleted edge. Both features provide increased friction characteristics over the JACO end effector.

For the final task, the under-actuated end effector fingers of the JACO system failed to apply the appropriate torque to unlatch the door knob mechanism which resulted in task ineffectiveness and virtual impossibility.

4.2.2.5 Cumulative Average Ease of Use

From Figure 56, it can be seen that the JACO system is rated with higher effectiveness in 3 of 4 common ADLs compared with the iARM system. The JACO manipulator exhibited higher speed and fluidity of movement while the control scheme of the JACO joystick in either 3D or 2D mode was more desirable.

However, the JACO system was given the lowest possible effectiveness rating of "virtually impossible" for the personnel door with knob task as a result of overly compliant end effector fingers. In this activity, the iARM system performed reliably with an effectiveness rating of 3.0.

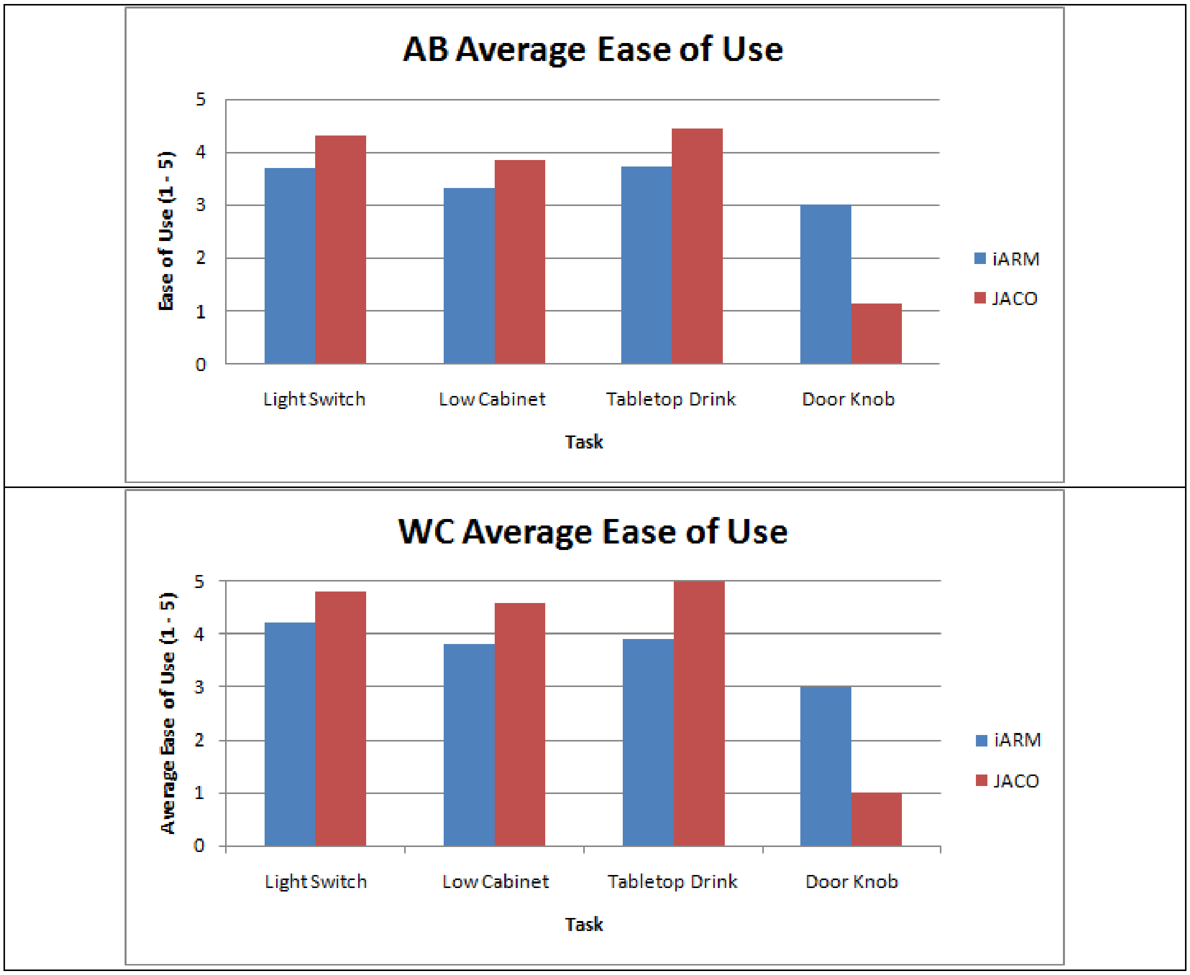


Figure 56 - Average ease of use per task

From the data recorded form this study, the assumption of the inverse relationship between ease of use and time of performance is validated as seen in Figure 57. Here, a linear trendline with a negative slope is used to show the correlation between a reduction in ease of use (effectiveness) as time of performance increases. The horizontal axis of Figure 57 is limited to 200 seconds and origin is taken at (0,1). The slope of the trendlines were calculated based on the complete data set which includes data points at 500 seconds with ease of use ratings of 1.

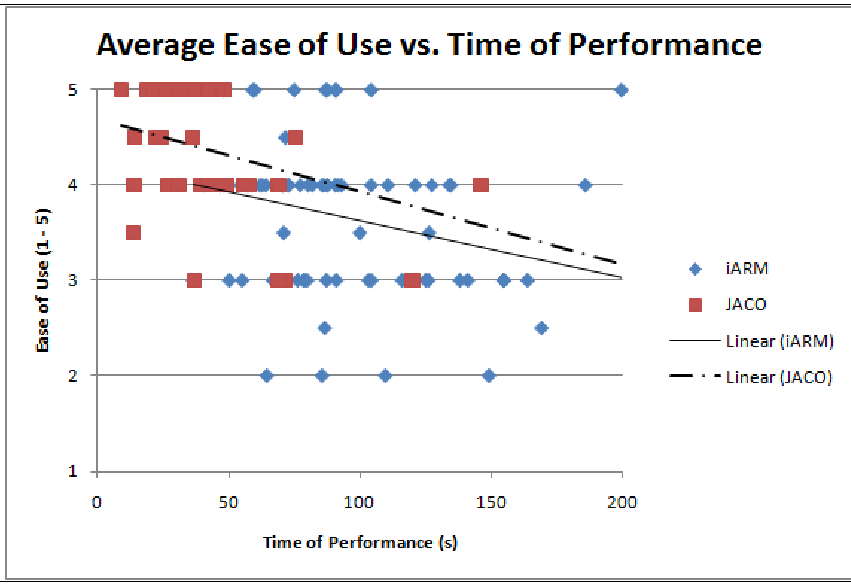


Figure 57 - Trend in ease of use versus time of performance

Table 8 shows qualitative information collected from wheelchair-dependent participants. This information includes preferred input devices and manipulators for each participant as well as the daily frequency of WMRA use each participant felt he or she would use a WMRA system if purchased.

Table 8 - Personal preferences of wheelchair-dependent participants

Participant Initials	Preferred Input Device	Preferred Manipulator	Hypothetical Daily WMRA Use
CE	JACO Joystick	JACO	Constantly
DS	JACO Joystick	JACO	Seldom
JM	JACO Joystick	JACO	Many
JMc	iARM Keypad	JACO	Many
JV	JACO Joystick	JACO	Constantly

From the information in this table, it was determined that despite the failure of the JACO system to complete the door knob task the JACO manipulator is preferred by all wheelchair-dependent participants. This determination is supported by ease of use data and further subjective perceptions of pleasing aesthetics and increased positive social impact of the JACO design. Comments from participants on aesthetics and social impact were recorded during testing on an informal basis.

Table 8 also shows the preference of the JACO joystick by 4 of 5 wheelchair-dependent participants. This was observed to develop from the ease in mode changing offered by the push-button mode change scheme of the JACO joystick. 1 of 5 wheelchair-dependent participants preferred the iARM keypad as he found both joysticks difficult to use. This case further shows the need for push-button operation.

Hypothetical daily WMRA use was given a range of "constantly" to "not at all" where "many" and "seldom" represent the second highest and second lowest frequency, respectively. 1 of 5 wheelchair-dependent participants determined that WMRA assistance would only be required "seldomly" as his condition allowed for acceptable personal mobility and interaction with his environment for purposes of ADLs. 4 of 5 wheelchair-dependent participants determined that WMRA assistance would be useful throughout the day, or at a high frequency, when performing the tasks of this study and other ADLs.

Chapter 5 Design Highlight and Recommendations

A host of key design features directly impacts the usefulness the iARM and JACO WMRA systems. These design features will now be brought to light based on data collected from participants during physical testing and theoretical kinematic analysis. Additional comments will be made on recommendations for each WMRA system and future designs.

5.1 iARM

The iARM demonstrates a large reach, durable construction, and a selection of input devices to be matched to a particular end user. The excellent reach of the manipulator, which is approximately 35.5 inches, produces high kinematic ratings for high elevation tasks as seen in section 4.1.2. For the experimental tasks considered by the study, the reach of the arm allowed participants to position the wheelchair at a farther distance from the target. A maximum distance from door opening tasks was useful as the low cabinet or personnel doors could be opened through full or partial range of motion without repositioning.

Participants considered the iARM to be of durable construction and felt that the manipulator could withstand the rigors of everyday use very well. This thinking was presented with the use of whole arm manipulation of both cabinet and personnel doors where whole arm manipulation refers to using the end effector in addition to link surfaces to interact with the environment. In the inevitable event of manipulator force overload, the transmission system of the iARM allows slippage of joint angles. This is intended to decrease the possibility of damage to the device, user wheelchair, or the user.

Durable, rigid end effector construction was highlighted by overwhelming iARM success in the personnel door with door knob task. The 2-finger, rigid link design of the end effector produced superior gripping power and the application of torque along the gripper axis (z-axis). This critical end effector design made users consistently capable of unlatching the door knob mechanism, hypothetically granting a large increase in independence to the end user.

The iARM system was provided with 2D joystick and 16-button keypad controllers. This selection of input devices was convenient when dedicated use of one device or the other was not suitable for participant disability.

An example of this may be observed in section 4.2.2.1 when one wheelchair-dependent participant was unable to operate the 2D joystick effectively and found the keypad controller acceptably easy to use. These and more control options are presented to end users as both WMRAs are integrable with modular control electronics.

The iARM was rated comparatively low in 3 of 4 experimental tasks as a result of 2D joystick control scheme, difficulty in easily achieving fine end effector movement, and internal collision and singularity issues.

The "quick flip" menu and mode cycling scheme of the 2D joystick proved to be especially difficult for participants to master. The "quick flip" scheme in which 2-dimensional Cartesian control axes are selected by making small movements of the joystick in one of four directions very quickly may be an attempt to maintain effective system operation by users with decreased hand dexterity. The scheme does allow individuals with no finger dexterity to change modes, but accidental mode changes were prevalent which lead to participant frustration and overall dislike of the system. Accidental "quick flips" occurred most often when attempting to perform fine end effector movement.

It was also observed that the iARM, while being operated with the 2D joystick, did not respond as quickly as expected to joystick input. This is thought to be the result of the control electronics attempting to detect a "quick flip" input, determining the input is not a "quick flip" mode change, and then finally carrying out the movement which the user is asking to the system to execute. This momentary lag between input and movement increases time of performance and consequently decreases ease of use ratings.

Fine movement was difficult to achieve both as a result of manipulator input/movement lag and the aforementioned accidental "quick flip" issue. Difficulty in precise positioning of the end effector in door tasks lead to loss of grip and increased time of performance.

The light switch task also requires a level of fine movement to obtain acceptable alignment and proximity of the end effector to the wall. The problem of fine movement control was observed to decrease over time, with practice, and with comments from study personnel, however accidental mode changes did not.

The iARM end effector is allowed to collapse through its range of motion onto link 3 in Cartesian movements, i.e. forward, rightward. When the collapse is sufficient to disallow further range of motion of joint 5, arm movement is forced to stop by the control electronics.

An image meant to represent the end effector is flashed on the small LED display at the top of the manipulator and the user is forced to find an alternative path to the target of interest or change modes (if operating with 2D joystick) to overcome the problem. End effector collapse and subsequent manipulator stoppage occurs in both Cartesian and Pilot modes with both 2D joystick and 16-button keypad control.

Social impact considerations were considered. The iARM was not held to be aesthetically pleasing by participants. The manipulator was said to appear "technical" while the input devices were said to appear "clunky" by one participant. The noise generated by the manipulator during operation was observed to be noticeably loud. Pack and unpack times were longer than expected (approximately 17 seconds) and a large volume is required to perform these functions. These issues are thought to draw negative attention during use in a social setting.

Overall, the iARM system excels in giving the user a sense of durability and performs reliably in the door knob task. The system proved to be an effective tool in the experimental tasks considered by the study and scored high in theoretical kinematic analysis. However, control scheme issues and aesthetic considerations tend to decrease comparative desirability.

It is recommended that standard control devices be designed to allow easier control of arm movement with easier mode changes for 2D control. Also, aesthetics should be improved and noise should be limited.

5.2 JACO

The JACO shows quick, responsive reaction to input, an effective control device, and an aesthetic appeal that may contribute to increased positive social impact. Control input from the standard 3-axis joystick controller is observed to be highly responsive giving the user great gross and fine end effector control. The speed at which the end effector translates in Cartesian movement is considered to be fast. The speed at which the JACO manipulator completed experimental tasks is due, in part, to the quick instantaneous response to control input higher overall speed. Times of performance for all experimental tasks may be observed in section 4.2.1. "Natural", "fluid" movement was said to be gained by the speed and response of the manipulator.

The 3-axis JACO joystick was considered greatly useful in either 3D or 2D mode. Most wheelchair-dependent participants did not possess sufficient hand dexterity to operate in the joystick in 3D mode, but found push-button mode changes easy to perform. Joystick movement was observed to be smooth while the grip and feel of the joystick was pleasing.

For those who could utilize the third axis of the joystick, time of performance was greatly decreased as a result of simultaneous control of all Cartesian straight line movement, or all end effector rotation axes. Ease of control also contributed to fluid movement of the manipulator.

Aesthetically, the JACO system was held in high regard. The link profiles are considered to have an organic style while the joystick, with easy to see push buttons, resembled wheelchair control devices already mounted to participant wheelchairs. Noise was notably soft during operation with the exception of intermittent vibration of one end effector motor in the release version of the JACO manipulator. This vibration is believed to be the result of improper PID gain tuning. Subjective comments such as aesthetics and noise levels were recorded as notes for each participant. The survey did not specifically ask for this information.

Furthermore, the manipulator requires no forward space for packing or unpacking while the pack/unpack operation takes only 5 seconds. Coupled with the fluid movement and appealing visual aesthetics, the act of initiating the arm for use may be more naturally accepted in social environments.

As a result of high end effector finger compliance, participants gained the impression of fragility when using the JACO for door opening tasks. This perception was confirmed in the pre-release version as finger assembly failures were commonly experienced when attempting to perform the low cabinet door task using the fingers to "flick" the door open. This perception may have been reduced with the release version as the finger assembly method was improved, but participant confidence in durability was not completely instilled.

Overly compliant finger design caused JACO to be rated with the lowest possible score of 1 in terms of ease of use by 15 of 16 participants for the door knob task. This task was successfully completed by 2 of 16 participants. The standard deviation of door knob testing trials of these two participants
was 147 and 230 seconds indicated timely repeatability of task execution was very low. This issue stemmed from the fingers not being capable of applying a great amount of torque on the axis of end effector rotation. It is understood that since the JACO manipulator is driven by geared servomotors at each joint, increasing rigidity in the fingers may bring overall compliance of the arm to critically low levels and cause damage to the device, a user's wheelchair, or the user.

Overall, the JACO system excels in speed, response, and user friendliness. The system was highly effective in 3 of 4 experimental tasks and posted excitingly low times of performance. However, completing the door knob task was virtually impossible with this system which maintains user reliance on other individuals for assistance in the real, unstructured world. It is recommended that the fingers be made to support force in the direction perpendicular to finger articulation in order to increase torque transmission along the end effector axis.

Chapter 6 Summary and Future Work

The introduction of Kinova and the JACO system to the WMRA market will again bring exciting competition to this useful application of robotics to assistive technologies that has not been seen since Applied Resources released the Raptor in 2002. This competition, along with advances in technology may help drive down the initial cost of WMRA systems that has been a prohibitive barrier for many years. The continuation of clinical evaluation of WMRAs will continue to generate quantitative data supporting the claim that assistive robotic devices increase the independence of severely disabled individuals. The following sections will present the final thoughts for each WMRA considered in this study and comment on future work.

6.1 Highlight and Recommendations

In summary, the iARM system is acceptably effective for all experimental tasks considered by the study. The iARM manipulator also shows great capability in theoretical kinematic analysis. The system is considered to increase independence of the end user as it is highly customizable to accommodate end user mobility level. It is suggested that the iARM receive updated aesthetic and ergonomic design treatments both for the manipulator and input devices.

The JACO system is highly effective in 3 of 4 experimental tasks considered by this study but its maximum reach and link configuration reduces expected capability in theoretical kinematic analysis. Aesthetics and perceived social impact were was said to be increased and the system is considered to increase independence of the end user as it is capable of performing many ADLs with great ease. It is recommended that the fingers of the end effector be made to apply higher torque along the gripper axis while not increasing rigidity of the manipulator to a level that would cause damage to the device, user, or user property.

6.2 Limitations

As it is shown, the current analysis of data does not present error analysis of standard deviations such as the use of the standard error formula. This and other statistical methods are useful in determining the variance of data a more useful level and will be employed during international publication.

Both WMRAs tended to be mounted on the right side of the participant. Though the experimental survey seen in Appendix C asked participants about mounting side preference, this study generally did not allow for mounting side to be a participant determined variable.

6.3 Future Work

This study has set the groundwork for a dedicated clinical evaluation program for assistive robotic devices at the University of South Florida. Developments of the program may immediately take place in the form of selecting new tasks from the ever-expanding task pool. Re-evaluation of the iARM and JACO systems with more complex tasks will lead to a greater clinical understanding of how end users find ways of increasing independence in their everyday lives.

In depth kinematic evaluation in which all 6 degrees of freedom of these manipulators can be analyzed will more accurately predict how the system will perform in the physical world. More accurate simulation may be utilized in training programs for new WMRA customers as well. A virtual reality trainer may allow future end users to practice using a WMRA before they make a purchase decision or take delivery of a WMRA system.

The USF developed WMRAs will be included in future studies with the methods detailed in this work. Repeating this standardized protocols will allow USF researchers to develop efficacy ratings for both current and future WMRA prototypes.

From this work, it can be seen that advances in compact computing and robust control must be made to further increase WMRA effectiveness. Commercial and research entities must work to find user friendly and cost effective means of driving assistive robotic devices making the devices more accessible to those with debilitating conditions.

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APPENDICES

Appendix A MATLAB Programs and Functions

MATLAB Manipulability Test Program

```
%  Manipulability Test Progam
%  John Capille
%  October 1, 2010

close all
clear all
clc

%  Have user select which arm to use
type=input('Specify iARM or JACO by selecting 1 or 2, respectively:
');

%  List D-H parameters for iARM and JACO with columns alphi(i-1), a(i-
1), theta(i),
%  d(i) to match the Robotics Toolbox 'mod' form
iARM_D-H=[0 0 0 15.433;
    -pi/2 0 0 7.574;
    0 15.748 0 -3.937;
    -pi/2 0 0 12.9921;
    pi/2 0 0 0;
    -pi/2 0 0 5.3149];

JACO_D-H=[0 0 0 8.2755;
    -pi/2 0 0 0;
    0 16.1417 0 0;
    -pi/2 0 0 9.8149;
    0.96 0 0 3.3307;
    0.96 0 0 8.9488];

%  Specifiy which list of D-H parameters to use based on the selection
of
%  manipulator from the user
if type==1
    D-H=iARM_D-H;
    IA=[-2*pi/3 -2*pi/3 -pi 0 0 0];
else
    D-H=JACO_D-H;
    IA=[0 -pi/3 pi/4 0 0 0];
end

%  Construct links
L{1}=link([D-H(1,1:4) 0], 'mod');
L{2}=link([D-H(2,1:4) 0], 'mod');
L{3}=link([D-H(3,1:4) 0], 'mod');
L{4}=link([D-H(4,1:4) 0], 'mod');
L{5}=link([D-H(5,1:4) 0], 'mod');
L{6}=link([D-H(6,1:4) 0], 'mod');

%  Specify robot name based on the selection of manipulator from the
user
```

```
if type==1
    Robot=robot(L, 'iARM');
else
    Robot=robot(L, 'JACO');
end

%  Initialize robot end effector position.  IP = Initial Position
IP=fkine(Robot, IA);

%  List or read final position points
points=[12.5400   10.0000  -14.367;
12.5400  -3.5000   -14.367;
12.5400  -13.500   -14.367;
12.5400   10.0000  -7.367;
12.5400  -3.5000   -7.367;
12.5400  -13.500   -7.367;
12.5400   10.0000   1.633;
12.5400  -3.5000    1.633;
12.5400  -13.500    1.633;
12.5400   10.0000   9.613;
12.5400  -3.5000    9.613;
12.5400  -13.500    9.613;
12.5400   10.0000   14.633;
12.5400  -3.5000    14.633;
12.5400  -13.500    14.633;
12.5400   10.0000   21.613;
12.5400  -3.5000    21.613;
12.5400  -13.500    21.613;
12.5400   10.0000   33.633;
12.5400  -3.5000    33.633;
12.5400  -13.500    33.633;
12.5400   10.0000   39.613;
12.5400  -3.5000    39.613;
12.5400  -13.500    39.613;
-1.0000   10.0000  -14.367;
-1.0000  -3.5000   -14.367;
-1.0000  -13.500   -14.367;
-1.0000   10.0000  -7.367;
-1.0000  -3.5000   -7.367;
-1.0000  -13.500   -7.367;
-1.0000   10.0000   1.633;
-1.0000  -3.5000    1.633;
-1.0000  -13.500    1.633;
-1.0000   10.0000   9.613;
-1.0000  -3.5000    9.613;
-1.0000  -13.500    9.613;
-1.0000   10.0000   14.633;
-1.0000  -3.5000    14.633;
-1.0000  -13.500    14.633;
-1.0000   10.0000   21.613;
-1.0000  -3.5000    21.613;
-1.0000  -13.500    21.613;
-1.0000   10.0000   33.633;
-1.0000  -3.5000    33.633;
```

Appendix A Continued

```
-1.0000  -13.500    33.633;
-1.0000   10.0000   39.613;
-1.0000  -3.5000    39.613;
-1.0000  -13.500    39.613;
-8.0000   10.0000  -14.367;
-8.0000  -3.5000   -14.367;
-8.0000  -13.500   -14.367;
-8.0000   10.0000  -7.367;
-8.0000  -3.5000   -7.367;
-8.0000  -13.500   -7.367;
-8.0000   10.0000   1.633;
-8.0000  -3.5000    1.633;
-8.0000  -13.500    1.633;
-8.0000   10.0000   9.613;
-8.0000  -3.5000    9.613;
-8.0000  -13.500    9.613;
-8.0000   10.0000   14.633;
-8.0000  -3.5000    14.633;
-8.0000  -13.500    14.633;
-8.0000   10.0000   21.613;
-8.0000  -3.5000    21.613;
-8.0000  -13.500    21.613;
-8.0000   10.0000   33.633;
-8.0000  -3.5000    33.633;
-8.0000  -13.500    33.633;
-8.0000   10.0000   39.613;
-8.0000  -3.5000    39.613;
-8.0000  -13.500    39.613;
-14.0000   10.0000  -14.367;
-14.0000  -3.5000   -14.367;
-14.0000  -13.500   -14.367;
-14.0000   10.0000  -7.367;
-14.0000  -3.5000   -7.367;
-14.0000  -13.500   -7.367;
-14.0000   10.0000   1.633;
-14.0000  -3.5000    1.633;
-14.0000  -13.500    1.633;
-14.0000   10.0000   9.613;
-14.0000  -3.5000    9.613;
-14.0000  -13.500    9.613;
-14.0000   10.0000   14.633;
-14.0000  -3.5000    14.633;
-14.0000  -13.500    14.633;
-14.0000   10.0000   21.613;
-14.0000  -3.5000    21.613;
-14.0000  -13.500    21.613;
-14.0000   10.0000   33.633;
-14.0000  -3.5000    33.633;
-14.0000  -13.500    33.633;
-14.0000   10.0000   39.613;
-14.0000  -3.5000    39.613;
-14.0000  -13.500    39.613;
-15.0000   4.2500    15.4000;
-15.0000   6.0000    15.4000;
```

```
-15.0000   10.0000   15.4000;
-15.0000   14.0000   15.4000;
-15.0000   16.7500   15.4000;
-15.0000  -3.5000    15.4000;
-15.0000  -13.500    15.4000;
-15.0000   4.2500    28.900;
-15.0000   6.0000    28.900;
-15.0000   10.0000   28.900;
-15.0000   14.0000   28.900;
-15.0000   16.7500   28.900;
-15.0000  -3.5000    28.900;
-15.0000  -13.500    28.900;
-15.0000   4.2500    31.9000;
-15.0000   6.0000    31.9000;
-15.0000   10.0000   31.9000;
-15.0000   14.0000   31.9000;
-15.0000   16.7500   31.9000;
-15.0000  -3.5000    31.9000;
-15.0000  -13.500    31.9000;
-19.0000   4.2500    28.900;
-19.0000   6.0000    28.900;
-19.0000   10.0000   28.900;
-19.0000   14.0000   28.900;
-19.0000   16.7500   28.900;
-19.0000  -3.5000    28.900;
-19.0000  -13.500    28.900;
-19.0000   4.2500    31.9000;
-19.0000   6.0000    31.9000;
-19.0000   10.0000   31.9000;
-19.0000   14.0000   31.9000;
-19.0000   16.7500   31.9000;
-19.0000  -3.5000    31.9000;
-19.0000  -13.500    31.9000];



%  Examine size of points matrix for loops
l=size(points);
p=l(:,1);

%----------Point Input by User---------%
FP=input('Final Point, i.e [30 10 15]:  ');
    FP=[1 0 0 FP(1,1);
        0 1 0 FP(1,2);
        0 0 1 FP(1,3);
        0 0 0 1];

figure (1)
plot(Robot,IA);
axis([-20 40 -40 20 -20 40])
hold on;
plot3([IP(1,4), FP(1,4)],[IP(2,4), FP(2,4)],[IP(3,4), FP(3,4)],'-b');
view(40,15);
```

```
set(figure (1),'WindowStyle','docked');
% drivebot(Robot);
M=[1 1 1 0 0 0];
TC=ctraj(IP,FP,100);
angles=ikine_Johnny(Robot,TC,IA,M)
Manip=maniplty(Robot,angles);

for i=1:99
    i
    angles1=angles(i,:);
    angles2=angles(i+1,:);
    delta_angles=(angles2(1,1)-angles1(1,1))^2+(angles2(1,2)-
angles1(1,2))^2+(angles2(1,3)-angles1(1,3))^2+(angles2(1,4)-
angles1(1,4))^2+(angles2(1,5)-angles1(1,5))^2+(angles2(1,6)-
angles1(1,6))^2
    if delta_angles>1
        disp('Singulrty cat iz in your manipz makin dem useless')
        %Manip=0;
        flag=1;
        fprintf('Manipulability = 0\r')
        fprintf('Flag = 1\r');
        break
    end
end

pause(0.2);
plot(Robot,angles);
%----------Point input by user----------%

%----------131 Points----------%
% plot(Robot,IA);
% set(figure (1),'WindowStyle','docked');
% hold on;
% FManip_mat=zeros(p,1);
% flag_mat=zeros(p,1);
%
%  for i=1:p
%     Point=i;
%     FP=[1 0 0 points(i,1);
%         0 1 0 points(i,2);
%         0 0 1 points(i,3);
%         0 0 0 1];
%     FP_mat=[points(i,1) points(i,2) points(i,3)];
%     plot3([IP(1,4), FP(1,4)],[IP(2,4), FP(2,4)],[IP(3,4), FP(3,4)],'-
b');
%     m=100;
%     TC=ctraj(IP,FP,m);
%     M=[1 1 1 0 0 0];
%     angles=ikine_Johnny(Robot,TC,IA,M);
%     Manip=maniplty(Robot,angles);
%     FManip_mat(i,:)=Manip(100,:);
%
%     for j=1:99
%         j;
```

```
%         angles1=angles(j,:);
%         angles2=angles(j+1,:);
%         delta_angles=(angles2(1,1)-angles1(1,1))^2+(angles2(1,2)-
angles1(1,2))^2+(angles2(1,3)-angles1(1,3))^2+(angles2(1,4)-
angles1(1,4))^2+(angles2(1,5)-angles1(1,5))^2+(angles2(1,6)-
angles1(1,6))^2;
%         if delta_angles>1
%             disp('Singulrty cat iz in your manipz makin dem useless')
%             sing_manip=0;
%             flag=1;
%             fprintf('Manipulability = %g\r',sing_manip)
%             fprintf('Flag = 1 in step %g of point %g\r',j,i);
%             break
%         else
%             flag=0;
%         end
%     end
%
%     flag_mat(i)=flag;
%
%     plot(Robot,angles);
%  end
%
%  M_Manip=max(FManip_mat);
%  FManip_mat=FManip_mat./M_Manip;
%----------131 Points----------%

%  Write data to Excel files
% if type==1
%     xlswrite('K:\USF docs\Thesis\MatLab
Programs\Johnny\iARM_final_position_manipulabilities',[FManip_mat
points flag_mat],1,'B2');
% else
%     xlswrite('K:\USF docs\Thesis\MatLab
Programs\Johnny\JACO_final_position_manipulabilities',[FManip_mat
points flag_mat],1,'B2');
% end

%  Use figure 2 to plot manipulability curve
% figure (2)2
% plot([1:100],Manip(:))
% if type==1
%     title('iARM Simulation at [12.54 10 6.18]')
% else
%     title('JACO Simulation at [12.54 10 6.18]')
% end
% xlabel('Trajectory Step')
% ylabel('Manipulabilty')
```

Modified ikine Function from the Robotics Toolbox

```
%IKINE Inverse manipulator kinematics
%
```

```
%   Q = IKINE(ROBOT, T)
%   Q = IKINE(ROBOT, T, Q)
%   Q = IKINE(ROBOT, T, Q, M)
%
% Returns the joint coordinates corresponding to the end-effector
transform T.
% Note that the inverse kinematic solution is generally not unique, and
% depends on the initial guess Q (which defaults to 0).
%
%   QT = IKINE(ROBOT, TG)
%   QT = IKINE(ROBOT, TG, Q)
%   QT = IKINE(ROBOT, TG, Q, M)
%
% Returns the joint coordinates corresponding to each of the transforms
in
% the 4x4xN trajectory TG.
% Returns one row of QT for each input transform.  The initial estimate
% of QT for each time step is taken as the solution from the previous
% time step.
%
% If the manipulator has fewer than 6 DOF then this method of solution
% will fail, since the solution space has more dimensions than can
% be spanned by the manipulator joint coordinates.  In such a case
% it is necessary to provide a mask matrix, M, which specifies the
% Cartesian DOF (in the wrist coordinate frame) that will be ignored
% in reaching a solution.  The mask matrix has six elements that
% correspond to translation in X, Y and Z, and rotation about X, Y and
% Z respectively.  The value should be 0 (for ignore) or 1.  The number
% of non-zero elements should equal the number of manipulator DOF.
%
% Solution is computed iteratively using the pseudo-inverse of the
% manipulator Jacobian.
%
% Such a solution is completely general, though much less efficient
% than specific inverse kinematic solutions derived symbolically.
%
% This approach allows a solution to obtained at a singularity, but
% the joint angles within the null space are arbitrarily assigned.
%
% For instance with a typical 5 DOF manipulator one would ignore
% rotation about the wrist axis, that is, M = [1 1 1 1 1 0].
%
%
% See also: FKINE, TR2DIFF, JACOB0, IKINE560.

% Copyright (C) 1993-2002, by Peter I. Corke

% MOD.HISTORY
% 2/95  use new 2-argument version of tr2diff(), cleanup
% 3/99  uses objects
% 6/99  initialize qt before loop
% 2/01  remove inv(base) xform, since it is included in fkine
% 10/01 bug in mask for <6 axes
% $Log: ikine.m,v $
```

```
% Revision 1.4  2002/04/14 10:15:41  pic
% Fixed error message text.
%
% Revision 1.3  2002/04/01 11:47:13  pic
% General cleanup of code: help comments, see also, copyright, remnant
D-H/dyn
% references, clarification of functions.
%
% $Revision: 1.4 $

function [qt, jaco] = ikine(robot, tr, q, m)
    %
    %  solution control parameters
    %
    ilimit = 1000;
    stol = 1e-4;

    n = robot.n;

    if nargin == 2,
        q = zeros(n, 1);
    else
        q = q(:);
    end
    if nargin == 4,
        m = m(:);
        if length(m) ~= 6,
            error('Mask matrix should have 6 elements');
        end
%       if length(find(m)) ~= robot.n
%           error('Mask matrix must have same number of 1s as robot
DOF')
%       end
    else
        if n < 6,
            disp('For a manipulator with fewer than 6DOF a mask matrix
argument should be specified');
        end
        m = ones(6, 1);
    end


    tcount = 0;
    if ishomog(tr),     % single xform case
        nm = 1;
        count = 0;
        while nm > stol,
            e = tr2diff(fkine(robot, q'), tr) .* m;
            dq = pinv( jacob0(robot, q) ) * e;
            q = q + dq;
            nm = norm(dq);
            count = count+1;
            if count > ilimit,
```

```
                error('Solution wouldn''t converge')
            end
        end
        qt = q';
    else            % trajectory case
        np = size(tr,3);
        qt = [];
        jaco = [];
        for i=1:np
            nm = 1;
            T = tr(:,:,i);
            count = 0;
            %while nm > stol,
                e = tr2diff(fkine(robot, q'), T) .* m;
                jaco = (jacob0(robot, q));
                dq = pinv( jaco(1:3,:) ) * e(1:3);
                q = q + dq;
                nm = norm(dq);
                count = count+1;
                if count > ilimit,
                    fprintf('i=%d, nm=%f\n', i, nm);
                    error('Solution wouldn''t converge')
                end
            %end

            qt = [qt; q'];
            tcount = tcount + count;
        end
    end
```

Appendix B Manipulability Test Program Results

iARM Manipulability Results

Point #	n	x	y	z	Flag
1	0.055275593	12.54	10	-14.367	0
2	0.085938649	12.54	-3.5	-14.367	0
3	0.049402161	12.54	-13.5	-14.367	0
4	0.074095993	12.54	10	-7.367	0
5	0.044779783	12.54	-3.5	-7.367	0
6	0.110826697	12.54	-13.5	-7.367	0
7	0.053201388	12.54	10	1.633	0
8	0.071277372	12.54	-3.5	1.633	0
9	0.026486488	12.54	-13.5	1.633	0
10	0.11258697	12.54	10	9.613	0
11	0.115165972	12.54	-3.5	9.613	0
12	0.106619586	12.54	-13.5	9.613	0
13	0.11775211	12.54	10	14.633	0
14	0.113736152	12.54	-3.5	14.633	0
15	0.122489185	12.54	-13.5	14.633	0
16	0.097245799	12.54	10	21.613	0
17	0.093275274	12.54	-3.5	21.613	0
18	0.107730469	12.54	-13.5	21.613	0
19	0.004518418	12.54	10	33.633	0
20	0.0282378	12.54	-3.5	33.633	0
21	0.001910317	12.54	-13.5	33.633	0
22	0.067526887	12.54	10	39.613	0
23	0.027375673	12.54	-3.5	39.613	0
24	0.082850336	12.54	-13.5	39.613	0
25	0.072787072	-1	10	-14.367	0
26	0.052828538	-1	-3.5	-14.367	0
27	0.024615075	-1	-13.5	-14.367	0
28	0.018964577	-1	10	-7.367	0
29	0.044078664	-1	-3.5	-7.367	0
30	0.231231261	-1	-13.5	-7.367	0
31	0.078196656	-1	10	1.633	0
32	0.019413565	-1	-3.5	1.633	0
33	0.444797873	-1	-13.5	1.633	0
34	0.103531036	-1	10	9.613	0
35	0.006075601	-1	-3.5	9.613	0
36	0.436159748	-1	-13.5	9.613	0
37	0.093947987	-1	10	14.633	0

Appendix B Continued

38	0.005438778	-1	-3.5	14.633	0
39	0.310991086	-1	-13.5	14.633	0
40	0.069759334	-1	10	21.613	0
41	0.262203347	-1	-3.5	21.613	0
42	0.366173813	-1	-13.5	21.613	0
43	0.02652284	-1	10	33.633	0
44	0.334655494	-1	-3.5	33.633	0
45	0.313202184	-1	-13.5	33.633	0
46	0.007761552	-1	10	39.613	0
47	0.290870143	-1	-3.5	39.613	0
48	0.194439811	-1	-13.5	39.613	0
49	0.085739202	-8	10	-14.367	0
50	0.195597885	-8	-3.5	-14.367	0
51	0.057129814	-8	-13.5	-14.367	0
52	0.04053471	-8	10	-7.367	0
53	0.474867779	-8	-3.5	-7.367	0
54	0.409972925	-8	-13.5	-7.367	0
55	0.0778767	-8	10	1.633	0
56	0.517717093	-8	-3.5	1.633	0
57	0.363102957	-8	-13.5	1.633	0
58	0.12231688	-8	10	9.613	0
59	0.346933851	-8	-3.5	9.613	0
60	0.515538528	-8	-13.5	9.613	0
61	0.121976082	-8	10	14.633	0
62	0.211725858	-8	-3.5	14.633	0
63	0.329253468	-8	-13.5	14.633	0
64	0.102690136	-8	10	21.613	0
65	0.242367064	-8	-3.5	21.613	0
66	0.954254029	-8	-13.5	21.613	0
67	0.035429332	-8	10	33.633	0
68	0.261641508	-8	-3.5	33.633	0
69	0.805981658	-8	-13.5	33.633	0
70	0.020817679	-8	10	39.613	0
71	0.198922938	-8	-3.5	39.613	0
72	0.554740686	-8	-13.5	39.613	0
73	0.008212181	-14	10	-14.367	0
74	0.022041	-14	-3.5	-14.367	0
75	0.233765328	-14	-13.5	-14.367	1
76	0.096255456	-14	10	-7.367	0
77	0.175276	-14	-3.5	-7.367	0

Appendix B Continued

78	0.601991208	-14	-13.5	-7.367	0
79	0.039950929	-14	10	1.633	0
80	0.342932694	-14	-3.5	1.633	0
81	1	-14	-13.5	1.633	0
82	0.113432495	-14	10	9.613	0
83	0.31168515	-14	-3.5	9.613	0
84	0.79353705	-14	-13.5	9.613	0
85	0.12701286	-14	10	14.633	0
86	0.289176472	-14	-3.5	14.633	0
87	0.750035337	-14	-13.5	14.633	0
88	0.112940213	-14	10	21.613	0
89	0.297994567	-14	-3.5	21.613	0
90	0.823120587	-14	-13.5	21.613	0
91	0.011498922	-14	10	33.633	0
92	0.21076605	-14	-3.5	33.633	0
93	0.793042653	-14	-13.5	33.633	0
94	0.067748088	-14	10	39.613	0
95	0.11006723	-14	-3.5	39.613	0
96	0.443902888	-14	-13.5	39.613	0
97	0.158356071	-15	4.25	15.4	0
98	0.146379704	-15	6	15.4	0
99	0.122395884	-15	10	15.4	0
100	0.087061171	-15	14	15.4	0
101	0.048362961	-15	16.75	15.4	0
102	0.286382097	-15	-3.5	15.4	0
103	0.748876087	-15	-13.5	15.4	0
104	0.10149531	-15	4.25	28.9	0
105	0.087186838	-15	6	28.9	0
106	0.056011982	-15	10	28.9	0
107	0.012108849	-15	14	28.9	0
108	0.03127322	-15	16.75	28.9	0
109	0.253675025	-15	-3.5	28.9	0
110	0.847938237	-15	-13.5	28.9	0
111	0.072889298	-15	4.25	31.9	0
112	0.057855522	-15	6	31.9	0
113	0.023238546	-15	10	31.9	0
114	0.024540051	-15	14	31.9	0
115	0.06884733	-15	16.75	31.9	0
116	0.219769587	-15	-3.5	31.9	0
117	0.800264559	-15	-13.5	31.9	0

Appendix B Continued

118	0.066696454	-19	4.25	28.9	0
119	0.048899656	-19	6	28.9	0
120	0.004818067	-19	10	28.9	0
121	0.052465716	-19	14	28.9	0
122	0.100725431	-19	16.75	28.9	0
123	0.184628076	-19	-3.5	28.9	0
124	0.624510828	-19	-13.5	28.9	0
125	0.029544656	-19	4.25	31.9	0
126	0.011660843	-19	6	31.9	0
127	0.033211862	-19	10	31.9	0
128	0.089331818	-19	14	31.9	0
129	0.132064653	-19	16.75	31.9	0
130	0.141171813	-19	-3.5	31.9	0
131	0.53288402	-19	-13.5	31.9	0

Appendix B Continued

JACO Manipulability Results

Point #	n	x	y	z	Flag
1	0.061744609	12.54	10	-14.367	0
2	0.188853956	12.54	-3.5	-14.367	0
3	0.207565225	12.54	-13.5	-14.367	0
4	0.003270493	12.54	10	-7.367	0
5	0.290981372	12.54	-3.5	-7.367	0
6	0.418142932	12.54	-13.5	-7.367	0
7	0.003190943	12.54	10	1.633	0
8	0.219381082	12.54	-3.5	1.633	0
9	0.244169992	12.54	-13.5	1.633	0
10	0.00146159	12.54	10	9.613	0
11	0.082188037	12.54	-3.5	9.613	0
12	0.045609963	12.54	-13.5	9.613	0
13	0.011807624	12.54	10	14.633	0
14	0.028324914	12.54	-3.5	14.633	0
15	0.033892392	12.54	-13.5	14.633	0
16	0.073800485	12.54	10	21.613	0
17	0.030523673	12.54	-3.5	21.613	0
18	0.129792456	12.54	-13.5	21.613	0
19	0.419018586	12.54	10	33.633	0
20	0.321526469	12.54	-3.5	33.633	0
21	0.564825701	12.54	-13.5	33.633	0
22	0.296865721	12.54	10	39.613	0
23	0.39963587	12.54	-3.5	39.613	0
24	0.12384544	12.54	-13.5	39.613	0
25	0.092361027	-1	10	-14.367	0
26	0.509388679	-1	-3.5	-14.367	0
27	0.850745961	-1	-13.5	-14.367	0
28	0.129525435	-1	10	-7.367	0
29	0.516689333	-1	-3.5	-7.367	0
30	1	-1	-13.5	-7.367	0
31	0.15967936	-1	10	1.633	0
32	0.38380573	-1	-3.5	1.633	0
33	0.954215257	-1	-13.5	1.633	0
34	0.098231476	-1	10	9.613	0
35	0.017715086	-1	-3.5	9.613	0
36	0.086534567	-1	-13.5	9.613	0
37	0.006362211	-1	10	14.633	0
38	0.016617981	-1	-3.5	14.633	0

Appendix B Continued

39	0.505874413	-1	-13.5	14.633	1
40	0.038695304	-1	10	21.613	0
41	0.297801555	-1	-3.5	21.613	0
42	0.30057577	-1	-13.5	21.613	0
43	0.12940816	-1	10	33.633	0
44	0.283392181	-1	-3.5	33.633	0
45	0.083443459	-1	-13.5	33.633	0
46	0.373022162	-1	10	39.613	0
47	0.062876361	-1	-3.5	39.613	0
48	0.007420385	-1	-13.5	39.613	0
49	0.080392274	-8	10	-14.367	0
50	0.096478568	-8	-3.5	-14.367	0
51	0.479404602	-8	-13.5	-14.367	0
52	0.126518187	-8	10	-7.367	0
53	0.029382374	-8	-3.5	-7.367	0
54	0.473690813	-8	-13.5	-7.367	0
55	0.155034306	-8	10	1.633	0
56	0.024976912	-8	-3.5	1.633	0
57	0.640572	-8	-13.5	1.633	0
58	0.090852295	-8	10	9.613	0
59	0.001120183	-8	-3.5	9.613	0
60	0.054525461	-8	-13.5	9.613	0
61	0.016354199	-8	10	14.633	0
62	0.002794997	-8	-3.5	14.633	0
63	0.114846918	-8	-13.5	14.633	0
64	0.017001974	-8	10	21.613	0
65	0.663379931	-8	-3.5	21.613	0
66	0.40261054	-8	-13.5	21.613	0
67	0.00292769	-8	10	33.633	0
68	0.515258416	-8	-3.5	33.633	0
69	0.420783337	-8	-13.5	33.633	0
70	0.328436535	-8	10	39.613	0
71	0.10803708	-8	-3.5	39.613	0
72	0.162977984	-8	-13.5	39.613	0
73	0.078127593	-14	10	-14.367	0
74	0.170357741	-14	-3.5	-14.367	0
75	0.395348944	-14	-13.5	-14.367	0
76	0.163025985	-14	10	-7.367	0
77	0.369910262	-14	-3.5	-7.367	0
78	0.395991992	-14	-13.5	-7.367	0

Appendix B Continued

79	0.155014972	-14	10	1.633	0
80	0.38712849	-14	-3.5	1.633	0
81	0.664825603	-14	-13.5	1.633	0
82	0.068937966	-14	10	9.613	0
83	0.070983277	-14	-3.5	9.613	0
84	0.337434945	-14	-13.5	9.613	0
85	0.008203596	-14	10	14.633	0
86	0.089571244	-14	-3.5	14.633	0
87	0.308020236	-14	-13.5	14.633	0
88	0.03566496	-14	10	21.613	0
89	0.548020691	-14	-3.5	21.613	0
90	0.842826859	-14	-13.5	21.613	0
91	0.094696344	-14	10	33.633	0
92	0.418127068	-14	-3.5	33.633	0
93	0.496941971	-14	-13.5	33.633	0
94	0.140317324	-14	10	39.613	0
95	0.082168212	-14	-3.5	39.613	0
96	0.031022486	-14	-13.5	39.613	0
97	0.048422016	-15	4.25	15.4	0
98	0.044810482	-15	6	15.4	0
99	0.032199056	-15	10	15.4	0
100	0.103748569	-15	14	15.4	0
101	0.161039101	-15	16.75	15.4	0
102	0.127360617	-15	-3.5	15.4	0
103	0.297781849	-15	-13.5	15.4	0
104	0.138730233	-15	4.25	28.9	0
105	0.031549776	-15	6	28.9	0
106	0.071478164	-15	10	28.9	0
107	0.418240518	-15	14	28.9	0
108	0.543018728	-15	16.75	28.9	0
109	0.59534022	-15	-3.5	28.9	0
110	0.77468385	-15	-13.5	28.9	0
111	0.088275642	-15	4.25	31.9	0
112	0.022259628	-15	6	31.9	0
113	0.096843003	-15	10	31.9	0
114	0.563494754	-15	14	31.9	0
115	0.638156931	-15	16.75	31.9	0
116	0.476203524	-15	-3.5	31.9	0
117	0.609322814	-15	-13.5	31.9	0
118	0.038528446	-19	4.25	28.9	0

Appendix B Continued

119	0.098194811	-19	6	28.9	0
120	0.205108826	-19	10	28.9	0
121	0.623794497	-19	14	28.9	0
122	0.687777379	-19	16.75	28.9	0
123	0.327361557	-19	-3.5	28.9	0
124	0.692765536	-19	-13.5	28.9	0
125	0.23339968	-19	4.25	31.9	0
126	0.123334025	-19	6	31.9	0
127	0.274566582	-19	10	31.9	0
128	0.631136184	-19	14	31.9	0
129	0.520159374	-19	16.75	31.9	0
130	0.171456367	-19	-3.5	31.9	0
131	0.447448763	-19	-13.5	31.9	0

Appendix C Sample Experimental Survey

Experimental Evaluation of WMRAs Survey

To the Participant

Thank you very much for electing to be a part of this study for the experimental evaluation of Wheelchair-Mounted Robotic Arms (WMRAs). The outcomes of this study will serve to identify desirable design features of WMRAs and input devices so that future production systems will further increase the quality of life of the user. Furthermore, the study will promote both the justification of prescribing WMRAs to enhance quality of life through the standardized testing method, and awareness for the emerging assistive robotics industry.

The following survey will be used to quantitatively compare and contrast each WMRA and input device. At the conclusion of the testing phase for each task, please rate the ease of use of both the WMRA manipulator and its input device based on the indicated numerical ranking scale. Ease of use ranking and time of performance will be recorded for each of up to four (4) tasks completed by up to six (6) WMRAs.

Candidate Information

Please provide the following candidate information. The information will be used to arrive at accurate final outcomes at the conclusion of the study.

- Candidate initials: ___________________________
- Date of birth: ___________________________
- Sex: ☐ Male ☐ Female
- Primary disability: ___________________________
- Number of years in a wheelchair: ___________________________
- Secondary Disability or other chronic health problems: ________________
- Wheelchair
    - Make: ___________________________
    - Model: ___________________________
    - Joystick: Right ☐ Left ☐

- What input device(s) do you currently use to control your wheelchair and/or other assistive devices?

  ____
- How long have you used your current input device(s)? ________________
- What functions do you see that can benefit from WMRA assistance? _____
- Can you independently drink from a glass? ____________________
- What is the highest elevation you can reach manually? __________

Please use the following tables to record the ease of use ranking information for each WMRA and input device. Record the ease of use by using a numerical ranking scale ranging from '1' – lowest ease of use, to '5' – highest ease of use. Use a single mark to indicate the ease of use for an individual task. Record time of performance using standard 'hour':'minute':'second' format (i.e. six minutes and thirty-one seconds = 00:06:31)

Appendix C Continued

Ease of Use Survey – Time of Performance Record

iARM

Input Device: ______________ Would this device increase independence? ☐ Yes ☐ No ☐ Neutral

Task		1	2	3	4	5		Trial 1	Trial 2	Trial 3
Light Switch – Flip Toggle	Ease of Use						Time of Performance	:	:	:
Cabinet – Low								:	:	:
Table Top – Drink								:	:	:
Door – Knob								:	:	:
Duplicate Task		1	2	3	4	5		Trial 1	Trial 2	Trial 3
	Ease of Use						Time of Performance	:	:	:
Input Device										
ID inc./dec. Ease of Use?								Inc.	Dec.	Neu.

JACO

Input Device: ______________ Would this device increase independence? ☐ Yes ☐ No ☐ Neutral

Task		1	2	3	4	5		Trial 1	Trial 2	Trial 3
Light Switch – Flip Toggle	Ease of Use						Time of Performance	:	:	:
Cabinet – Low								:	:	:
Table Top – Drink								:	:	:
Door – Knob								:	:	:
Duplicate Task		1	2	3	4	5		Trial 1	Trial 2	Trial 3
	Ease of Use						Time of Performance	:	:	:
Input Device										
ID inc./dec. Ease of Use?								Inc.	Dec.	Neu.

Overall Experimental Assessment

- What input device do you prefer? ____________________________
- What, if any, side would you prefer a side-mounted WMRA to be attached to your wheelchair?

  ____

- Is mounting position important to you? ________________________________
- What, if any, additional functions do you see that can benefit from WMRA assistance?

  ____

- How often per day do you see yourself using a WMRA, if at all?

☐ Constantly ☐ Many ☐ A few ☐ Seldom ☐ Not at all

- Are you comfortable with modifications being made to your wheelchair, including but not limited to the addition of bolt holes in the wheelchair frame or other structural members, in order to make it WMRA compatible?

  ____

- Of the WMRAs you operated today, which do you prefer and why?

  ____

- Of the WMRAs you operated today, what would you change to have them better suit your needs?
  - iARM: ______________________________________
  - JACO: ______________________________________