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Design and Testing of a Lightweight Modular Seven-Degree-of-Freedom Robot Arm for Mobile Use

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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Department of Mechanical Engineering
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Dedication

To my wife, Alexis, for all of her support and encouragement especially during my graduate degree and thesis. To my Parents for their encouragement and for always being there for me. To my family and friends who have helped in numerous ways throughout college.

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ABSTRACT

Wheelchair-bound individuals who have limited or no upper-limb usage have difficulty with picking and placing of objects, opening doors, and other activities of daily living (ADLs), such as turning on a light switch or drinking from a cup. A wheelchair-mounted robot arm (WMRA) would aid individuals with completing ADLs and increase their independence, therefore an improved WMRA has been designed. Building upon previous WMRA research and incorporating research from industrial robot arms, carbon fiber tubing is the main component for the structure of the arm, a novel development for WMRAs. Factors that go into WMRA design include weight, speed, safety, robustness, cost, and the anticipated tasks. Many of these factors, such as weight, speed, and cost, can be improved upon compared to previous WMRAs by using carbon fiber materials.

The use of carbon fiber enables the arm to be strong, but also lighter weight than other WMRAs. Testing was conducted on the pultruded carbon fiber tubing to ensure that the structure of the arm could withstand the necessary bending and tensile forces for the arm to hold up to 3.85kg, the standard weight of a gallon of milk, at the end effector. The arm's carbon fiber frame also allows

the motor and sensor wiring to run internally, which improves the arm’s safety and aesthetics, while protecting it from the arm’s external environment.

Lightweight high-torque motors, harmonic drives, newly designed carbon fiber frame, and a stand-alone 8-axis motion-control board, allow the arm to weigh less, have a longer overall length, be more robust, and be safer electronically than the previous University of South Florida WMRA, which was shown through prototype testing.

Chapter 1 Introduction

1.1 Motivation

The problem is that wheelchair-bound individuals who have limited or no upper-limb usage have difficulty with picking and placing of objects, opening doors, and other activities of daily living (ADLs), such as turning on a light switch or drinking from a cup. Lacking in manipulation capabilities, they are less independent. Numerous robotic assistive devices can aid people in completing tasks, but none have had much commercial success. One major commercial obstacle is that many assistive devices are workstations, set up in one location for a specific set of tasks. Immobile workstations are much less useful compared to mobile assistive devices, according to surveys later discussed, which have begun to have more success because they can assist people in multiple dynamic environments. However, the current commercial mobile devices are either heavy and difficult to transport, or have a small payload capacity, limiting their abilities. I hypothesize that construction of a power wheelchair-mounted robot arm (WMRA), which is a transportable assistive device that can aid individuals with limited upper and lower-limb mobility, will help people in completing ADLs. The WMRA that is constructed must improve upon previous WMRA designs, which are not widely used outside of research at this time.

In order for the WMRA to have more commercial success, the weight must be reduced and the payload needs to be increased. Reducing the overall weight of the robot arm that is attached to the power wheelchair will reduce the power consumption of the chair and arm, allowing longer system usage before the batteries need to be recharged. A lighter weight WMRA will also be less restrictive on the allowable user weight, because the WMRA is an aftermarket modification and power wheelchairs are rated for a maximum weight capacity, by the manufacturer.

Industrial robot arm companies have begun to use composite materials, such as carbon fiber, as major structural components to reduce weight while keeping the necessary structural strength. Composites have also been used in robot arms for space applications needing a lightweight design, but they have not been widely used in the field of rehabilitation robotics, specifically for WMRAs. Utilizing these composites in the construction of a WMRA can help reduce the weight of the overall design.

Currently, the most widely used commercial WMRA is the Manus, which weighs 14.3 kg, but only has a maximum payload of 1.5 kg [1]. Increasing the payload would allow the user to do more tasks, such as open doors, which can require more force than the payload capabilities of the Manus. Also, more freedom is allowed for the reconfiguration of the arm's link-lengths, which can easily be adjusted for completion of a certain set of tasks, if the arm is modular.

The wheelchair-mounted robot arm has the potential to enhance the quality of life and reduce the cost of care for people with different types of disabilities. Specifically, people with cerebral palsy, quadriplegia, multiple sclerosis, and upper-spinal-cord injuries would benefit from the use of a robot arm system. People, who already use a power wheelchair for mobility and have limited upper-limb control, could use the WMRA to facilitate specific activities. The power chair is easily equipped with a robot arm because it has a DC power source, batteries, which is required to power the control board and motors that drive each joint. Power wheelchairs are generally heavy and therefore act as a solid base for the robot arm to be attached without the fear of the chair tipping over during use. It is important that the user feel comfortable with the arm and not have any fears of injury from its use for the future success of the assistive device.

The topics discussed in this research are the background of rehabilitation robotics, design features, hardware and materials, manufacturing and assembly, testing and results, conclusions, and future work. Chapter 2 is used to inform people of the previous work related to wheelchair-mounted robot arm and lightweight robot arm designs. Chapters 3 and 4 show why certain features were included in the design of the arm and how these features were made possible with the use of hardware, such as harmonic drives and an 8-axis motion control board. Chapter 5 goes into detail about the machining and assembly of the arm, while Chapter 6 discusses the testing of the constructed prototype and the results that were collected. Lastly, Chapters 7 and 8 describe the conclusions that were reached and the necessary work that needs to be completed in the future for the research to progress.

1.2 Design Goals

The main goal of this research is to design a WMRA that is light and robust by incorporating the use of carbon fiber and polycarbonate tubes into the frame of the arm, while also improving the safety of the arm. Other goals include reducing the weight compared to the previous WMRAs, designing the arm in such a way to allow the wiring to run internally, reducing power consumption, and having a working payload of 3.85 kg at the end effector, to ensure the user can pick up most household items including a gallon of milk. The design should be lightweight because this will extend the use time by reducing power consumption of the chair and the arm. A lighter weight arm will also be less restrictive on the weight of the user because this is an aftermarket modification to a wheelchair. Also, the joint arrangement should remain the same as the previous University of South Florida WMRA (WMRA-I), as it has been tested and shows that the arm kinematics enable object manipulation in most of the areas around the wheelchair easily [2].

Chapter 2 Background

2.1 Rehabilitation Robotics

Rehabilitation Robotics is concentrated on helping persons with disabilities to augment their manipulation capabilities and is a section of Rehabilitation Engineering, which encompasses work with assistive devices, such as prosthetics, and any powered device designed to help rehabilitate or assist people. The field of Rehabilitation Robotics has been around since the 1960's, when the Case Institute of Technology began working on a powered orthosis which later led to the development of the Rancho Arm [3]. The Rancho Arm had six-degrees-of-freedom and was controlled through a series of tongue switches. This arm uses metal rods as the frame for each of the individual links, which can be seen in Figure 1.

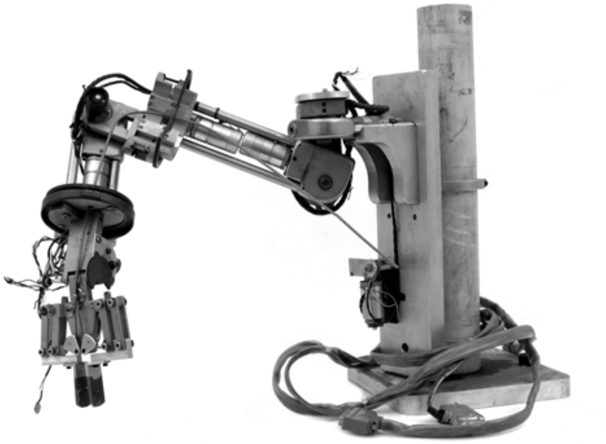

Figure 1. Six-Degree-of-Freedom Rancho Arm [4]

The field has come a long way since the Rancho Arm and is now comprised of three major categories of assistive robotic devices which are the workstation, the wheelchair-mounted robot arm, and the autonomous mobile robot [5]. The workstation is a robotic system that is not mobile and is used in a known structured environment, while the autonomous mobile robot is used to manipulate objects in unstructured environments which is made possible through the use of sensors. The autonomous mobile robot allows the user to stay in place and complete tasks in other areas of the environment, such as another room in the home, remotely. The main topic of this research is the wheelchair-mounted robot arm, which is a mobile robot that is attached to the user's wheelchair and therefore interacts with the environment close to the user. This device allows the user to manipulate objects throughout the day in multiple unstructured environments, such as the home and the grocery store, which is not possible with the workstation or the autonomous mobile robot due to transporting issues.

2.1.1 Workstations

The workstation is a system that is used to interact with a known structured environment and can complete a specific set of tasks that relate to one another closely. The Handy-I is a workstation that was designed in England to complete tasks within the small workspace around the five-degree-of-freedom, Cyber 310, robot that it utilizes [6]. It was designed to help the user complete the task of eating and is capable of handling up to seven different types of food on its tray at one time. The user controls the system by pressing buttons which signal the arm to pick up food from a specified area of the tray by going through a preprogrammed motion. This system has height adjustability and is moveable because it is mounted onto a base with casters, but it is not mobile in the sense that the user can easily transport it themselves without the help of a human aide.

Another workstation is the Robot for Assisting the Integration of the Disabled, known as the RAID system, which is designed to help people with disabilities operate a computer without a human aide. The RAID system uses a six-degree-of-freedom RTX robot arm, which was used by 38% of workstation robots for manipulation and is capable of handling pieces of paper, books, as well as cd-roms and other office supplies as needed [7]. There is an extra degree-of-freedom designed into the RAID system by attaching the arm to a linear track that allows it to have a much larger workspace. The workspace is specifically structured to enable the RTX arm to organize and use different types of office materials and a computer.

The RAID system is not mobile because it is a workstation and it is fairly large as well. It is capable of performing office work type tasks by assisting users with the robot arm in a specific structured environment, as seen in Figure 2, but it is not capable of performing tasks in an unstructured or changing environment. This is good for the workplace or in the home, but a more versatile way of completing numerous ADLs would be desired over a workstation system.

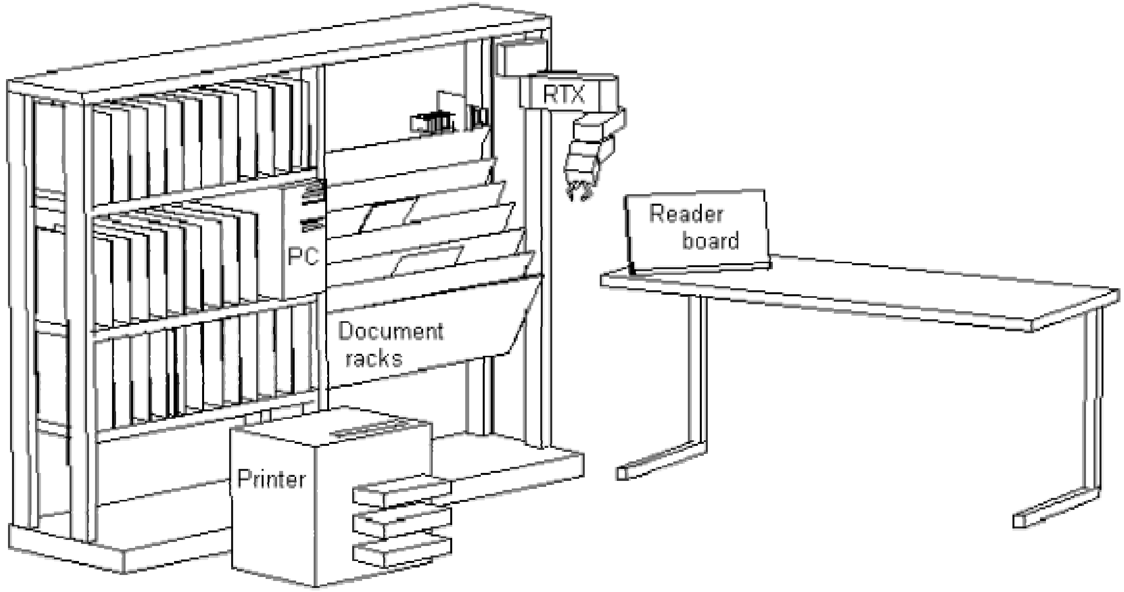

Figure 2. The RAID Workstation Showing the Structured Environment [6]

The RAID system and the Handy-1 have both since been redesigned into the EPI-RAID and the Handy-II respectively. Both of these systems perform their tasks well, but are limited in not only the variety of tasks that they can conduct, but also in their mobility for use in multiple locations. The wheelchair-mounted robot arm is however mobile and is capable of helping the user complete a variety of tasks that would normally prove to be difficult and time consuming, if possible at all. Surveys have shown that possible end users believe that a mobile device would be much more useful to them than a workstation system [8].

2.1.2 Wheelchair-Mounted Robot Arms

The wheelchair-mounted robot arm is a robot arm that is attached to a power wheelchair for the purpose of aiding the user in completing tasks. The idea of the WMRA began from the testing and results of the previous workstation research along with input from possible end users.

The Wolfson robot is a workstation for a desk in the home environment that utilized the Selective Compliance Assembly Robot Arm (SCARA) for manipulation purposes, which was beneficial because all of the power and control wiring was located internally for necessary safety and aesthetic reasons. User tests of the Wolfson system showed that people did not want to do all of their daily tasks in one place, which they would normally be done in multiple areas of the home [9]. This testing showed the need for a smaller, mobile system which was later designed and named the Wessex robot.

The Wessex robot was first developed out of the need for a mobile system rather than a workstation based system for the ability to use the robot in multiple environments. The arm was redesigned to make it more compact and the links of the arm were built from rectangular aluminum tubing. The control system was also made smaller to fit within the base which the arm would be attached. It was first mounted to a non-powered trolley which would allow a human aide to transport the robot system to different rooms of the home as needed. This however, still restricts the independence of the user who is unable to transport the robot arm themselves, which therefore led to the Wessex arm being modified and mounted to a power wheelchair. The system known as the Weston Wheelchair-Mounted Assistive Robot was attached to a power chair along with a telescoping mast which allows it to have vertical movement for grasping objects at various heights [10].

The Weston arm adds roughly, 10 cm of width to the chair that it is attached to and unable to fold to the rear of the chair when it is not in use. It was noted that the design has the arm mounted closer to the rear of the chair compared to other wheelchair-mounted robot arms. This was to reduce the visual impact the robot arm had on the user in hopes that it would be more widely accepted by users. The arm is removable by a human aide; however the telescoping mast is not easily, or quickly, removed from the chair. Figure 3 shows the arm in its folded position and its mounting location near the back of the chair.

Figure 3. The Weston Wheelchair-Mounted Assistive Robot [9]

The Assistive Robot for Disabled, or ARDIS, is another wheelchair-mounted robot arm system. This specific system was not just the addition of the robot arm to a power wheelchair, but was also the modification of the power wheelchair base to allow omni-directional motion. The base of the chair was modified by the use of four mecanum wheels, which are wheels that have rollers attached to the hub at 45 degrees to the contact surface, that replace the original wheels. These mecanum wheels allow the chair to move in any direction without having to turn the chair in the direction of the desired motion. This gives the user more maneuverability options in conjunction with the robot arm manipulation capabilities.

The robot arm that is attached to the base is located toward the front on the right side of the chair. The arm has four degrees of freedom, two of which make up the shoulder joint, one acts as the elbow, and the last one is for rotation at the wrist [11]. The entire system of the arm and the omni-directional base, shown in Figure 4, has seven degrees of freedom, but they are controlled independently unlike the University of South Florida wheelchair-mounted robot arm which has a combined mobility and manipulation system that is designed to control both the arm and the power wheelchair simultaneously.

Figure 4. The Assistive Robot for Disabled (ARDIS) Omni-Directional Base [11]

The KARES-II is another wheelchair-mounted robot arm. It is the improved design of the KARES-I and was developed at the Korea Advanced Institute of Technology (KAIST) as a six-degree-of-freedom robot arm with all revolute joints, mounted to the front right side of a Partner P/W6000 power wheelchair [12]. The robotic arm constructed from aluminum, seen in Figure 5, uses a tube frame structure, similar to that of the WMRA-I, with the link lengths being optimized for the 12 predefined tasks that the arm was designed to complete. The joint configuration of the arm is similar to the PUMA-560 joint configuration in that it has three joints very close to the end effector for pitch, roll, and yaw, movements during manipulation and the first three joints for gross movement of the arm structure. The first three joints are driven by a cable transmission system which means it is not a modular robotic arm and therefore cannot easily be changed for a certain set of specific tasks.

Figure 5. The KARES-II Robot Arm [12]

The arm also has multiple human robot interfaces which include a visual servoing-based control, eye movement control, a haptic suit, and voice perception for controlling the robot arm. The current design has the wiring for the sensors located outside of the arm structure. Further testing of the KARES-II has led to further adjustments of the visual servoing-based control due to issues with the vibration of the system during movement of the wheelchair base.

The Raptor is another wheelchair-mounted robot arm that has four degrees of freedom, as seen in Figure 6, similarly to that of the ARDIS in configuration. It is a commercially available arm that mounts to the side of the user's power chair. The Raptor system does not have any encoders or other sensory feedback and therefore Cartesian control is not possible, requiring the user to control each joint individually.

Figure 6. Raptor Wheelchair-Mounted Robot Arm [2]

The user interface is either a joystick or a 10-button keypad and the arm can be used as a stand alone system or be mounted to a wheelchair. This device may prove to be slightly more difficult than other robot arms for users to control because there is not a Cartesian mode of control and individual joint control may take more concentration and time to complete tasks than other control interfaces.

The Manus is a six-degree-of-freedom robot arm that also has a linear vertical lift and a gripper which are driven by a series of cables that run throughout the structure of the arm. The Motors that drive the cables and joints are mounted inside the main base of the arm. It was designed and developed by Exact Dynamics in the Netherlands and can be used as a table top system or can be attached to a wheelchair for WMRA usage. It is currently being widely used for research applications in the field of rehabilitation robotics because of its design and availability. The Manus arm has a usable length of 80cm and weighs 14.3kg while being able to hold a maximum payload of 1.5kg [1]. This means that it is capable of manipulating objects that are just over 10 percent of its own weight. The arm mounts to the front left side of the wheelchair which is a good position to be able to manipulate objects in front of the user, but it also adds a considerable width to the chair because its base is 13.5cm in diameter.

The two main control modes that can be used to operate the arm are the Cartesian control mode and the Joint control mode. The Manus has a standard four by four button keyboard for controlling the arm at multiple speeds and for switching between control modes. This keyboard is the usual interface between the user and the MANUS Manipulator; however the majority of research that is currently being conducted on WMRAs involves the improvement of the human-robot interface. Much of this research has been conducted using the MANUS Manipulator arm as the mechanical component because it is a commercially available product, but can be difficult to use when controlling it with the standard four by four button keypad [13]. Many researchers analyzed the abilities of the MANUS and have also developed new interfaces to improve the ease of use of the device, but limited research has been conducted recently on the improvement of the mechanical design of WMRAs. The Manus arm is seen in Figure 7, showing the gripper, wheelchair attachment, and joint arrangement.

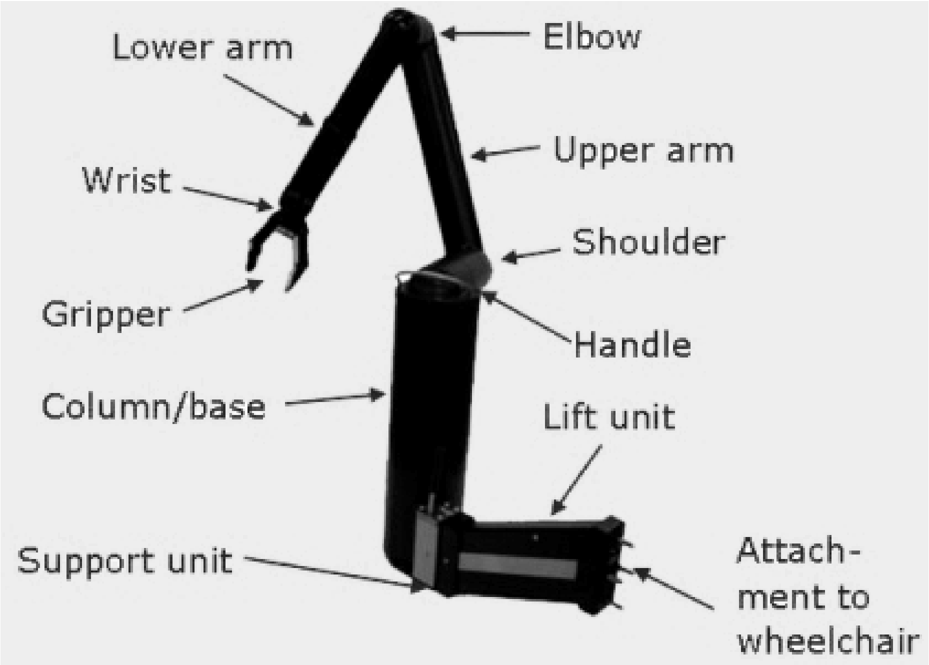

Figure 7. MANUS Wheelchair-Mounted Robot Arm [13]

One research group has recently designed a visual interface to simplify wheelchair-mounted robot arm control [14]. In order to accomplish this, the

MANUS Manipulator arm was fitted with a small camera at the gripper, eye in hand approach, to provide the user with a visual interface. The user simply selects the quadrant of the touch screen that the desired object of manipulation lies in. Then the screen automatically zooms in and the process is repeated a second time, while the gripper of the manus moves to the proper location for manipulation of the object. This now means that the visual interface is showing 1/16th of the view that was originally displayed. This allows for a simple alignment of the gripper with the desired object through gross movement, but it does not currently allow fine adjustments for proper orientations of objects through the interface [14]. Other interface research includes the use of joysticks and haptic devices, as well as devices that use the eye as input for people with no upper-limb mobility to control the robotic device.

2.1.3 University of South Florida WMRA-I

The University of South Florida has developed a wheelchair-mounted robotic arm (WMRA-I) system for the purpose of combined mobility and manipulation [2,15,16]. It is comprised of a seven-degree-of-freedom robot arm, a gripper, and a power wheelchair. The current system is designed to use Matlab to control the arm and the chair motion with a single graphical user interface (GUI) which can be used to control the end effector in Cartesian space.

The arm has seven revolute joints and a gripper, which is powered by a Faulhaber coreless DC servomotor. The motor is ideal for the gripper design because it is compact but is still capable of producing 6N of grasping force at the gripper paddles. It is also compatible with the rest of the arm motors, as it too, requires a 24V power source, which is provided by the wheelchair batteries. An adjustable slipper clutch was incorporated into the design to prevent damaging the motor and over exerting force on fragile objects that are gripped by the metal paddles. The gripper paddles were designed with multiple tasks in mind such as grasping door knobs, picking up small or thin objects, and picking up tapered objects as well [17]. The paddles, shown in Figure 8, were designed in such a way to allow them to adjust to an angle that gives the maximum contact area between the paddles and the object of manipulation. This adjustability is ideal for cups or other object that are tapered. There is a four bar linkage that the paddles are attached to that allow them to open to a maximum distance of 120mm for picking up large objects.

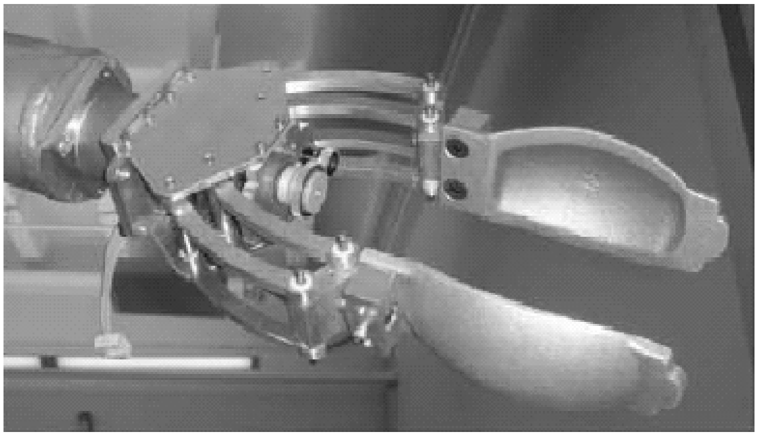

Figure 8. The WMRA-I Gripper with Paddles for Grasping

The arm design uses aluminum 6061-T6 for the structure of the links as well as for the brackets that attach the various links to one another, which does not allow for the wiring of the motors to run internally. This also means that in order to reconfigure the robot, the new link lengths must be made through a welding process which many people do not have access to and therefore would be another cost incurred by the user. Harmonic drives are utilized at each joint in the design for their high torque handling capabilities and are driven by brushed DC Pittman motors, which have integrated gear heads with gear ratios of 5.9:1 and encoders with 512 counts per turn resolutions. This resolution is however increased because the Pittman motors are interfaced with harmonic drives which have gear ratios up to 160:1. There is a motor mounted at each of the joints which allows for the reconfiguration of the arm, as there are no internal belts or pulleys driving the joints. The fully assembled WMRA-I with external wiring is shown in Figure 9.

Figure 9. WMRA-I Fully Assembled and Attached to a Wheelchair

The main control interface for the WMRA-I is through the use of a touch screen GUI which is used to control the arm as well as the chair motion. Other control interfaces that have been tested include the spaceball, which has six degrees of freedom, and the P300 Brain Computer Interface (BCI) which is being developed in the psychology department at the University of South Florida. The BCI uses a cap with electrodes to sense brain activity during use while viewing a series of symbols on a computer. This technology may one day allow individuals with no mobility to use and benefit from the WMRA. Other possible methods of control were considered such as a joystick and the Phantom Omni, which is a six-degree-of-freedom device that provides force feedback.

The WMRA-I motion controller was designed by JKerr and ten JKerr PIC servo boards, one of which is shown in Figure 10, are connected in series to the controller. This means that each joint has its own servo-control board, but the information for one motor must travel through each of the previous motors' servo boards. This causes problems with the processing time of commands that are given to the arm and is believed to be a major cause of the robustness problems that have occurred with the arm.

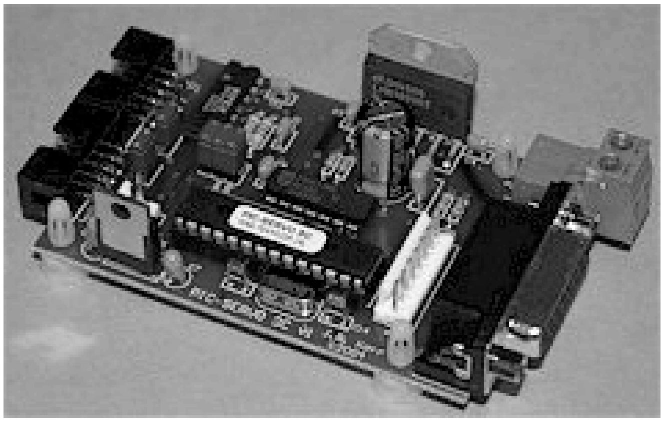

Figure 10. JKerr PIC SC Integrated Control Board [18]

The robot arms that have been discussed thus far have either payload limitations which restrict the items that can be manipulated or they add more than 13.75 kg (30lbs) to the weight of the chair. Utilizing lightweight materials in the design and prototype has the potential to reduce the weight while keeping a substantial payload capability. This ability is seen in industrial robot arms, such as DLR's lightweight robot arm, which have high payload to weight ratios.

2.2 Lightweight and Composite Robot Arm Designs

One way to reduce the weight of wheelchair-mounted robot arms is to incorporate strong, lightweight materials such as composites into their design as well as design the arm with light efficient gear heads and drives.

2.2.1 DLR Lightweight Robot Arm

The DLR research group has been working on producing the lightweight robot (LWR) arm for industrial usage, specifically for packaging robots, but it also has attributes that allow it to be used for human interaction. They have developed two LWR arms previous to the current arm, both of which have been improved upon in multiple areas. The LWR-I is a seven-degree-of-freedom robot arm that used carbon fiber for its structure. It also utilized double-planetary gear heads and torque sensing for control, both of which proved to be issues for manufacturing or robustness. DLR then developed the LWR-II which used harmonic drive gear heads instead of the double-planetary gears as well as incorporating a feedback system for joint torque and motor and link position. All of the electronic systems were housed inside the arm, eliminating the external control box, which most industrial robots have.

They have improved upon the two previous designs by reducing weight in a number of ways. In order to accomplish the lightweight design, DLR has been utilizing carbon fiber as a structural member once again and has developed their own modular drive system and lightweight piezo-brakes to further reduce the weight of their design [19]. LWR-III also uses harmonic drives as the gear head for each individual joint, due to their high gear ratio and torque to weight ratio. This version however has had the harmonic drives redesigned which reduced the overall weight of the harmonic drives by 60%. Each joint is composed of the strong lightweight RoboDrive actuator developed by DLR as well as the harmonic drive, safety brake, power supply and the necessary control boards, all of which is housed inside the carbon fiber frame for that joint. Figure 11 shows the component arrangement for a single joint.

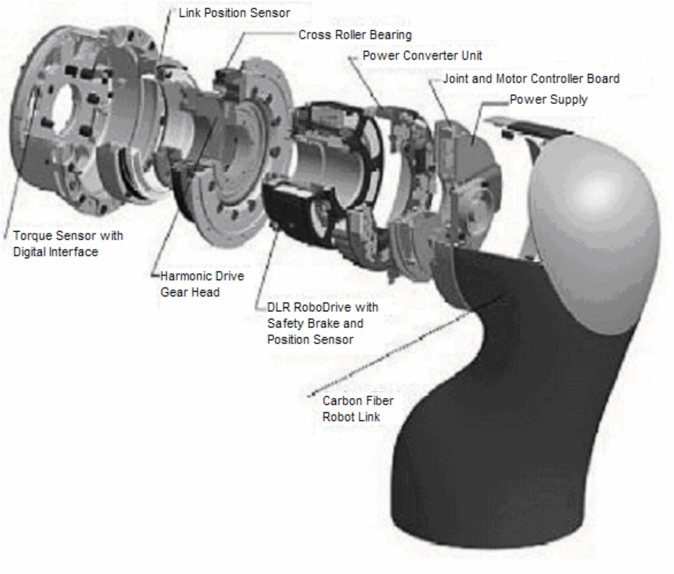

Figure 11. Joint Components of DLR’s Lightweight Robot Arm Design [19]

The carbon fiber parts were designed and then analyzed using simulation and finite element analysis to see if they needed to be thicker in certain areas for strength and thinner in other areas for weight savings. The parts were then produced by HighTex using a method called Tailored-Fiber-Placement (TFP), where the carbon fibers are aligned with the direction of the high stresses that the part will endure which are found through simulation and finite element analysis (FEA) [20]. The arm weighs 13.5 kg and has a load capacity of 15kg, while still having speed capabilities of 180 degrees per second at its joints. The arm also incorporates a lightweight ball joint designed for increased fine manipulation purposes.

2.2.2 KAIST Composite Robot Link

The stiffness and dampening of the structure of robot arms is important for the accuracy and motion of the arm. In the case of the wheelchair-mounted robot arm the user can adjust for minor errors in the movement of the arm and misalignment through the user interface, but the dampening abilities of the structure are important because it reduces vibrations which may cause users not to trust the device.

Carbon fiber materials have been used to redesign the third link of a six-degree-of-freedom robot arm by a research group at KAIST and testing showed that the stiffness and dampening were increased more than five times that of using aluminum or steel for the same purpose [21]. The final design that was used for the third link was a round tube of laminate carbon fiber that is also the outer shell of the link, as well as a carbon fiber yoke that was designed and tested using finite element analysis. This research shows that using carbon fiber has many benefits for the mechanical design of the robot arm especially for mobile applications where weight and vibrations are an issue.

2.3 Americans with Disabilities Act Standards

The American Disabilities Act (ADA) was passed by Congress in 1990 and contains five titles [22]. Titles II and III relate to this research because they are concerned with physical accessibility in public areas as well as transportation. The ADA standards state that any accessible route must be a minimum of 36 inches in width and protrusions must not limit the width below 32 inches wide. This means that the arm should add as little width as possible to the chair. Also, the minimum knee clearance height on built in desks and counters is 27 inches, which would require the side mounted arm to fold to a height of less than 27 inches from the ground if it is not in use and also be able to reach above a height of 29 inches to pick up and place items during use.

There is a vast set of standards which regulate the dimensions of the space around doorways which are too many to go into details. However, these set standards do allow space for a standard wheelchair to easily maneuver to a position for the user to open the door and would not restrict complete movement of a chair with a slightly larger width due to the addition of the robot arm. The minimum width for a door in all public places is 32 inches and the handle or rail used to open the door may not be mounted higher than 48 inches from the ground. The use of an elevator needs to be considered during the design of a wheelchair-mounted robot arm. The minimum door widths of elevators with doors centered and offset are 42 inches and 36 inches respectively. The control mechanism for the elevator and any other necessary devices must be between 15 inches and 48 inches from the ground. All of these standards are important to the design and use of the wheelchair-mounted robot arm, because it needs to be capable of opening doors, and picking and placing objects on standard counters in public areas as well as in the home.

The background information including ADA standard as well as the assistive robot arms and industrial robot arms have helped in deciding which features should be included in the new WMRA design, WMRA-II. Table 1 is a comparison of the previous assistive and lightweight robot arms, including features such as weight and the number of degrees-of-freedom.

Table 1. Comparison of Assistive and Lightweight Robot Arms

Device Name	Year	Mobile	Degrees-of-Freedom of Arm	Control type	Payload (kg)	Weight (kg)	Internal Wiring	Increased Chair Width (mm)	Modular
Rancho Arm	1960	No	6	Joint	---	---	No	---	No
Weston Arm	2002	Yes	6	Joint/Cartesian	---	---	Yes	120	No
ARDIS	2003	Yes	4	Joint	---	---	Yes	---	No
KARES-II	2003	Yes	6	joint	2.3	---	No	---	No
Raptor	1996	Yes	4	Joint	1	---	Yes	---	No
Manus	1990	Yes	6 + gripper and lift	Joint/Cartesian	1.5	14	Yes	135	No
WMRA-I	2005	Yes	7	Joint/Cartesian	4.5	13.75	No	75	Partially
DLR LWR Arm	2002	No	7	Joint/Cartesian	15	13.5	Yes	N/A	Yes

Comparing the various qualities of the robot arms in Table 1 shows that the arms have varying abilities and also shows that none of the previous arms have all of the possible qualities that would be desired in a WMRA. Many of the arms are not modular and the two that are modular either have external wiring or are not mobile systems. This comparison of qualities helps to decide which features should be designed into the WMRA-II because many of the features have been previously studied. The kinematics, for example, for the raptor and the manus were studied to compare their abilities to reach certain areas around the wheelchair [2]. The results show that arms with more than six degrees-of-freedom have better capabilities to reach objects around the chair due to the redundancy of the arm. Table 1 also shows the ability of a lightweight arm, the DLR LWR arm, to lift a payload greater than the weight of the arm, which means that using carbon fiber is a viable structural component for the WMRA-II.

Chapter 3 Design

3.1 Design Features

The new wheelchair-mounted robot arm (WMRA-II) is, when compared to current designs, Raptor, Manus, and the current University of South Florida WMRA-I, lighter, has a longer reach, and has higher speed capabilities. This was made possible due to the light-weight materials and careful selection of the motors. This new design also improves upon robustness, safety, and aesthetics which is shown in Chapter 6, about testing and results. Table 2 shows the design goals of the WMRA-II compared to the WMRA-I prototype that are discussed in detail throughout Chapter 3 and Chapter 4.

Table 2. Comparison of WMRA-I and WMRA-II

Feature	WMRA-I	WMRA-II
Weight (kg)	13.75	11.5 or Less
Wiring	External, No Locking Mechanism at Encoder	Improve Connection Integrity
External Cover	No	Yes
Control Board	1 Board for Each Motor	1 Board for All Motors
Length (mm)	1082	1100 or Greater
Modularity	Entire Links Must Be Welded	Links Assembled with Machine Screws
Motors	Brushed, Two Motors Mounted External to Arm Links	Use Brushless Motors When Possible Mount All Motors Internally
Joint Speed	1 RPM for Joint 1	Increase Joint Speeds by 25%
Communication	Limited by Control System	Utilize Control Board with Fast Communication Ability
Degrees-of-Freedom	7	7
Payload (kg)	4.5	3.85 or Greater

3.1.1 Summary of Tasks

There have been a number of surveys conducted on WMRAs as well as other robotic aids to find out what capabilities the user looks for in an assistive device. The researchers at KAIST came up with a set of twelve tasks that they determined to be significant through close work with individuals that had spinal injuries to the C4 or C5 locations [23]. These tasks included picking up objects, opening and closing doors, turning light switches on or off, and opening and closing drawers. These are all important tasks for people to be capable of completing without a human aide for their personal independence.

Another survey of potential users was conducted in the United Kingdom to define what tasks users would want a robotic aid to be able to help them complete [8]. The highest rated task by potential users was to reach, stretch, and grip, while reaching to the floor was third of all tasks listed by the users. This survey also found that 84% of the people in the survey were interested in testing and possibly buying a wheelchair-mounted robot arm.

Two other surveys of wheelchair-mounted robot arms were conducted on the Manus and the Inventaid arm, which is a six-degree-of-freedom robot arm that uses pneumatics for actuation [24]. The survey of the Manus showed that all 13 participants wanted to be able to pick and place a book, while other important tasks included turning knobs and picking up objects from shelves. The survey of the Invetaid arm was conducted with 7 participants with muscular dystrophy, who also rated picking up objects from the floor, opening doors, reaching high, and operating light switches in the top five capabilities they would like in a robotic arm.

These surveys have helped in deciding what capabilities the new wheelchair-mounted robot arm should have. It was determined that the main tasks that the arm should be capable of are:

- Picking and placing objects at various heights
- Opening and closing doors, drawers, and cabinets.
- Operating light switches.
- Lifting objects that weigh less than 3.85kgs.

Other tasks that seem within the capacity of a robotic arm that would prove useful include operating elevators, sinks, and appliances.

3.1.2 Reduced Weight

The desired weight of any robot arm depends on its function and the payload that it is expected to manipulate. Robot arms with high payloads usually weigh more because larger payloads require larger motors and stronger links. Another factor that affects the designed weight of a robot arm is the purpose of the arm. This design is for mobile applications, specifically for use as a WMRA, so it is vital that the arm be as light as possible to reduce battery consumption without losing structural integrity and robustness of the overall design.

This design uses pultruded carbon fiber tubes as the structural member of each of the three main links of the arm. Pultrusion is a continuous manufacturing process that pulls composite material through resin and then a hot die to produce a piece with a constant cross section by curing the resin while it passes through the die. Carbon fiber is strong and lightweight which helps to reduce the weight of the arm design without losing structural integrity. Three carbon fiber tubes spaced 120 degrees apart and attached to aluminum brackets at the ends, as seen in Figure 12, make up each link of the arm.

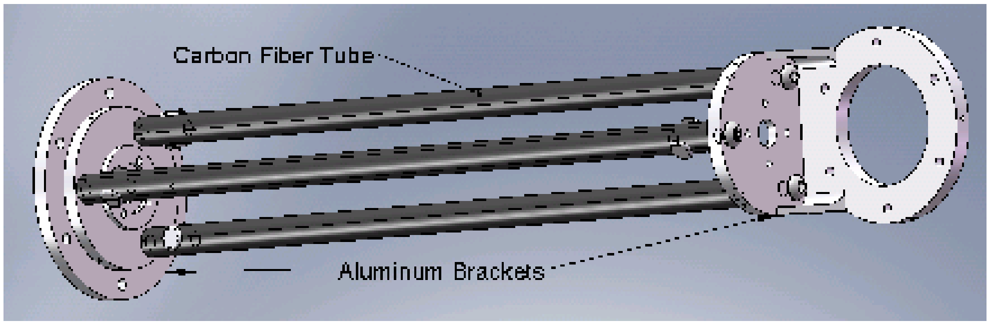

Figure 12. Carbon Fiber Tube Structure Attached to Brackets at Ends

This design also allowed the links to be slightly smaller in diameter than the previous WMRA-I, which means that the aluminum brackets are smaller, further reducing the weight of the arm. Using carbon fiber tubes also allows the arm's wiring to be housed internally. Other materials such as titanium, steel, and tungsten were also looked into, but were ruled out due to higher cost and weight.

The motors and gear heads that are chosen can impact the weight of the arm considerably. This is shown with the total weight of the WMRA-II motors being 38% less than the total weight of the WMRA-I motors, includes the weight of the integrated planetary gear head and encoders for both arms. The motors chosen for the WMRA-II were from Maxon Precision Motors while the previous design utilized Pittman motors. The DC motors from Maxon are lighter, as seen by the weight reduction of 38%, but they also have higher torque to weight ratios than the Pittman motors. Harmonic drives were utilized in the WMRA-II, because planetary gear heads were either heavy or incapable of handling the necessary torques.

3.1.3 Payload

The payload of the arm is important because the maximum payload will restrict the user from manipulating any object over that weight. This is seen with the commercially available Manus as its maximum payload is 1.5kg. The payload for the new WMRA was determined by the weight of a standard gallon of liquid, for example water, milk, or orange juice, which weighs 3.85kg or 8.5lb. This will also allow the user to easily manipulate many other objects in the home and public environments. The payload of 8.5lb exceeds the maximum force requirement of 5lb to open an interior fire door set by ADA standards [20]. The previous WMRA-I has a maximum payload of 6kg including the weight of the gripper, although maximum load tests were not conducted with a gripper and therefore the weights were not located at the point of manipulation. Many wheelchair-mounted robot arm grippers are not capable of the grasping force necessary to hold 6kg, which makes the arm payload more than the possible manipulation payload. Therefore, the arm's motors are larger than needed and the aluminum links are thicker than they need to be for the wheelchair-mounted robot arm application.

3.1.4 Polymer Cover and External Support

The current WMRA-I does not have an external housing that protects the motors, wiring, and gear heads from the external environment. The wiring is external, therefore it could get caught on other objects in the environment causing it to disconnect the signal from the encoder or the power from the motors. On the WMRA-I, encoder disconnection would cause the motor to drive out of control in short bursts for a period of time and possibly cause harm to the user or others in the vicinity. This, therefore, is a major safety concern for a robotic device operating in close proximity to people.

The new WMRA-II was designed to have a lightweight plastic cover which fits close to the arm, but also allows enough room for the wiring of the arm to run internally. This will prevent the wires from catching on anything in the environment, thus improving the safety of the WMRA system.

Two different plastics, polycarbonate and acrylonitrile butadiene styrene (ABS), were selected for the design because they are both lightweight and resist impact damages well. The major links of the arm will have polycarbonate covers mounted directly to the aluminum brackets, while the 90 degree joints or joints that make up the shoulder, elbow, and wrist will be protected with an ABS cover. The polycarbonate tubes are also important for support of the arm because the carbon fiber tube structure has limited torque handling capabilities. The polycarbonate tubes hold the majority of the torque of the arm, as well as help to prevent deflection due to loads at the end effector. SolidWorks was used to conduct analysis on the torque handling capabilities of the polycarbonate tubes to ensure that they will be capable of handling the torque loads that will be placed on them. The results of these analyses are discussed later. Figure 13 shows the polycarbonate tubes used for each link and the ABS plastic covers for the 90 degree angle joints. Link 1 seen in the figure requires the highest torque handling ability because it is located closest to the arm's base and has the largest torque load of 36.91Nm placed on it.

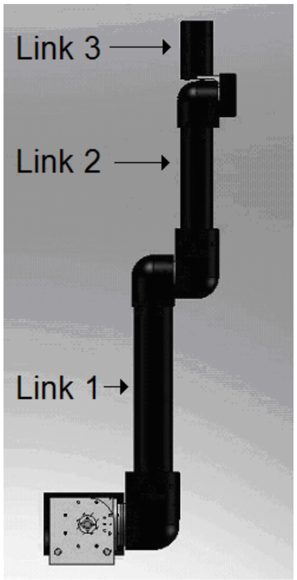

Figure 13. SolidWorks Rendering of Arm with Plastic Covers and Link Labels

The 90 degree joints have custom made covers which are made through vacuum forming due to the fact that they contain compound curves. It is more expensive to have the aluminum molds made for accurate vacuum forming of polycarbonate; therefore ABS plastic was used because it can be vacuum formed using wood molds with good accuracy. ABS is also a good alternative because it is less expensive and has an impact resistance similar to that of polycarbonate. It is important to use plastics that are lightweight, but still have good impact resistance because the arm will impact other objects in the environment at some point.

The arm cover was designed with a small gap between the carbon fiber tubes and the cover itself so that deflections that may occur in the plastic during an impact would not cause damage to the carbon tubes. Lastly, the cover is mounted to the aluminum brackets throughout the arm by machine screws with standoffs where necessary. The detailed drawings of the covers can be found in Appendix B.

3.1.5 Safety Features

Currently there is research being conducted to mount proximity sensors as well as cameras for vision sensing onto the WMRA-II as a preventative measure for object avoidance and recognition for manipulation purposes. There are also virtual barriers built into the programming for the WMRA-I, which prevent the arm from contacting the user and the wheelchair itself [14]. This same virtual wall should be used in the programming of the WMRA-II to help prevent injury to the user. These are ways that the arm and user can also be protected in a changing environment using software and programming. The control board of the arm also has numerous safety features included high current and high voltage warnings, which prevent damage and loss of communication, in the event that the power wires running from the battery malfunction or are inadvertently disconnected during use.

3.1.6 Kinematics

The kinematic arrangement of the new WMRA is similar to that of the WMRA-I because the joint configuration has remained the same. It was shown in previous research on the joint space analysis of the Manus and the Raptor that an arm with more degrees of freedom will have more access to the area around the wheelchair, but the arm-mounting location on the wheelchair can affect this greatly [25]. If the arm is mounted higher on the wheelchair base then it will have access to higher objects and also be able to access the floor as well. If the arm is mounted low on the chair, the ground will limit the workspace of the arm by restricting downward movement and the wheelchair may have to move in order to pick up items on the ground, in close proximity to the chair. The WMRA-I is a seven-degree-of-freedom arm and therefore is capable or reaching most areas around the power wheelchair more effectively than arms with lower degrees-of-freedom. This is because a seven-degree-of-freedom system is redundant, meaning that it can reach any point in space with multiple arm orientations, similar to a human arm. Arms with fewer degrees-of-freedom will have greater probability of reaching singularities during motion. Therefore, the same joint configuration as the WRMA-I has been chosen for this design with slight variations in the link lengths and the diameters of the links, which allow the use of the carbon fiber tubes and which makes the joints more compact.

Although the joint configuration is the same for the WMRA-II as the WMRA-I, the WMRA-II design does take advantage of the fact that the links are thinner. This reduced the offset distance between the center of link one and the center of link two by 40.5mm (D4 in Figure 14), while the length of link three (D7 in Figure 14) has been reduced by 18mm to make the wrist design more compact allowing for increased precision during small movements. Also, the first three joints have been redesigned to be more compact which is seen in D1 and D2 of the Denavit-Hartenberg parameters of Table 3. The WMRA-I had values of 110mm and 146mm for D1 and D2 respectively while the new WMRA has decreased these values to 102.7mm for D1 and 132.8mm for D2. This amounts to a reduction of 13.2mm of D2, which reduces the width that the new WMRA adds to the wheelchair. This is beneficial because every millimeter that is reduced in the width of the arm helps the user's maneuverability in small, tight areas. The overall length of the arm was increased from the previous WMRA design by 5cm, increasing its workspace and allowing it to reach items higher and farther away than the WMRA-I can reach.

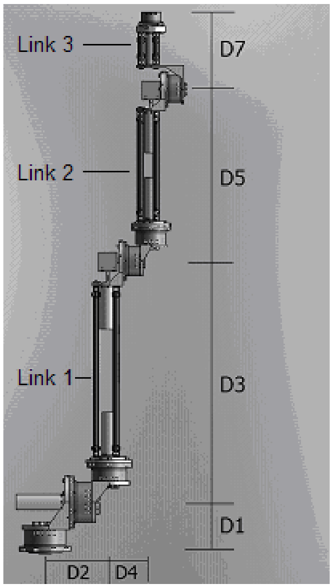

Figure 14. Arm's Denavit-Hartenberg Parameters Drawing

Table 3. Denavit-Hartenberg Parameters of the WMRA-II

i	α	A	d (mm)	θ_ι
1	0	0	102.7	θ_1
2	90	0	132.8	θ_2
3	-90	0	501.78	θ_3
4	90	0	89.5	θ_4
5	-90	0	357.16	θ_5
6	90	0	0	θ_6
7	-90	0	160.85	θ_7

Chapter 4 Hardware and Materials

There are many hardware components that go into the design of this robot arm:

- Harmonic drive gear heads
- DC servo motors – motion actuators
- Right angle bevel gear heads
- Control and amplifier boards
- Wiring components.
- Materials

Often component selection had to be conducted simultaneously because one piece of hardware can greatly affect the selection of another. Therefore, a torque calculation was conducted in Microsoft Excel to ensure that all of the drive components of the arm are robust and capable of handling the necessary forces and torques that will be placed on them during use. This torque calculation takes into account the weight of each of the components that is closer to the end effector in relation to the joint being analyzed. The calculation equation is a summation of all the torques that affect a particular joint due to each individual motor, gear head, aluminum bracket, link structure, and the payload. The weight and exact perpendicular distance of each part from the joint is known and used in the calculation. The distance between the harmonic drive 7, location of F_4 in

Figure 15, and the center of the gripper paddles is also known to be 5in. Figure 15 shows the arm orientation for maximum torque of joint 2 and a few of the forces that affect joint 2 at specific perpendicular distances.

The torque equation is:

$$T = \sum_{i=1}^{n} \left[\left(F_i\right)\left(r_i\right) \right]$$

where, T is the torque at the joint due to the summation of the forces (F_i) multiplied by the perpendicular distance to the component (r_i) for each component that affects the joint from 1 to n.

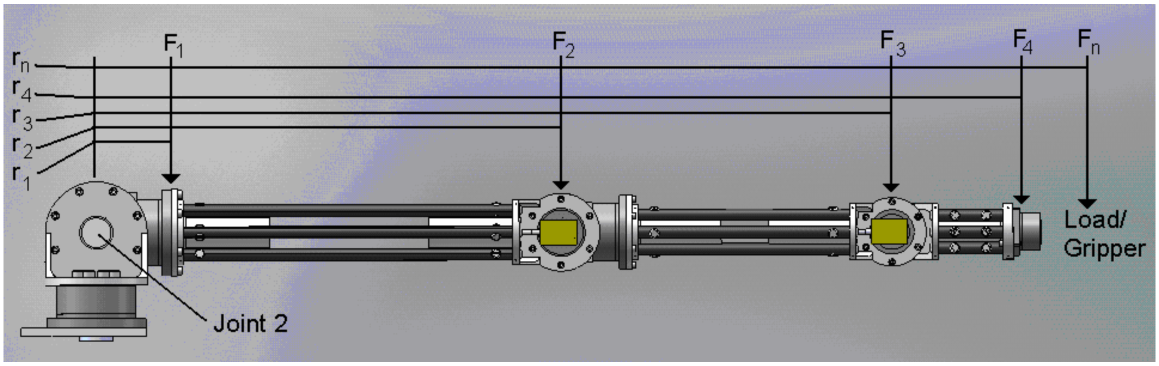

Figure 15. Forces of Parts (F) and Perpendicular Distances I from Joint 2

The required torque and the actual torque capability of each of the joints can be found in Table 4. The torque for the joints closer to the end effector are less because they do not have to lift the hardware of the joints closer to the wheelchair.

Table 4. The Torque Required for Each Individual Joint

Joint #	Torque Required [Nm]	Actual Torque [Nm]
1	82.67	97.96
2	81.70	97.96
3	36.91	44.17
4	36.32	37.04
5	14.02	
6	14.02	16.51
7	4.35	5.85

4.1 Drive Components

4.1.1 Harmonic Drives

Harmonic-drive gear heads are often used for lightweight robotic applications, which include DLR's LWR arm. This is because they are lighter than other alternatives, such as planetary gear heads that are capable of handling equal torques. They are also capable of much higher torques than alternatives that weigh the same as the harmonic drive gear heads. Smaller motors can be used because the harmonic drives are capable of high torques and reduction ratios in a single stage, which further reduces the weight of the design. All seven of the harmonic drives for this application have reduction ratios of 100:1.

These high reduction ratios and torques are possible due to the design of the harmonic drive which has three main components including the wave generator, the flex spline, and the circular spline seen in Figure 16. The flex spline is attached to a ball bearing and deforms due to the rotation of the wave generator, and then the circular spline and the flex spline align causing the flex spline to rotate a very small amount. The input rotates hundreds of times to the one rotation of the flex spline, which rotates in the opposite direction of the input.

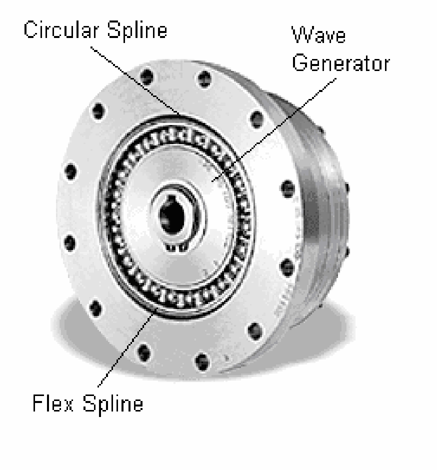

Figure 16. Components of a Harmonic Drive Gear Head [26]

Harmonic-drive gear heads are also ideal because they come standard with a flange input and output for attaching moving components. If other gear heads were chosen, then a coupler would have to be used to mount the moving components, as many output shafts are not capable of handling the large axial and radial loads that are placed on the drive output. Thus, the harmonic drive further reduces weight compared to its alternatives because it does not require the extra couplers.

The torque handling capabilities of the harmonic drives were designed to be higher than the necessary joint torques because the harmonic drives are the most costly part of the design. If the torques being produced at the output of the harmonic drive due to the motor torques were higher than the rated torques of the harmonic drives, then damage would occur. Table 5 shows the maximum sustained torque for each harmonic drive which is higher than the torque required at each joint previously seen in Table 4.

Table 5. Harmonic Drive Torque Handling Capabilities

HARMONIC DRIVES		
Joint	Weight (kg)	Maximum Average Torque (Nm)
1	1.5	108
2	1.5	108
3	0.98	49
4	0.68	39
5	0.68	39
6	0.52	17
7	0.15	8.9

Another feature that makes the harmonic drive useful in this application is that it has a short axial length, which allows the joints to be as compact as possible. Using other gear heads would require the joint to be longer axially by nearly 4 times in some cases for a planetary gear head with an equal torque handling capability. A gear head of this size would require the joints to be driven with belts and pulleys connecting the motor and gear head to the joint, while housing the motor someplace else on the frame of the wheelchair, reducing the modularity of the design.

4.1.2 Motor Selection

The motors utilized in this design are Maxon Precision Motors, which have higher torque to weight ratios than most other DC motors including that of the Pittman motors used for the WMRA-I. The first four joints require high torques because they have to lift the payload at the end effector, but they must also compensate for the weight of the rest of the arm. Therefore stronger brushless motors were chosen for the joints closest to the base while lighter, brushed motors were implemented for the joints closest to the end effector. The brushless motors have a longer life and greater efficiency than brushed motors.

All of the motors have a planetary gear head attached to them, which means that there is a two stage gear system, because harmonic drives are also used. The first two joints have planetary gear heads with gear ratios of 51:1 while joints 3, 4, 5, 6, and 7 have ratios of 23:1, 18:1, 19:1,19:1, and 14:1 respectively. These planetary gear heads use ceramic gears for higher precision and torque handling capabilities over the standard metal gears. It again is important to make sure that the gear head is capable of handling the torque being produced by the motor to ensure that no damage will occur during normal operation.

Magnetic resonance encoders were chosen as the feedback sensor for the motor position. These sensors were chosen for their accuracy as well as their compact size. They attach directly to the end of the motor and do not increase the diameter of the motor and gear head assembly. All of the encoders have a resolution of 500 counts per revolution (cpr) except for motor seven which has a resolution of 512 cpr. These resolutions are then enhanced with the planetary gear head and the harmonic drive gear head reduction ratios. All of the encoders have a positive and negative signal for channel A, channel B, and the index. The integrated planetary gear head, magnetic resonance encoder, and the motor can be seen in Figure 17.

Figure 17. Maxon Precision Motor Components [27]

The four brushless motors also have integrated Hall Effect sensors which allow for immediate recognition of the joint location by the control board. Each of these motors has a total of three poles for powering the motor and a total of three Hall Effect sensors, each of which have a single signal output. The same power wire and ground were used in parallel to run to both the Hall Effect sensors and the encoders because they require the same voltage input.

All of the motors including the gripper motor were chosen to require a 24 volt power source due to the fact that most power wheelchairs have a set of two 12V batteries in series, which provide 24 volts. This allows for easy integration of the WMRA system onto the wheelchair without any addition of batteries, but it is necessary to integrate a voltage reducer to produce the necessary power inputs for the control board.

4.1.3 Right-Angle Gear Heads

The robot arm needs to be as compact as possible to prevent parts such as motors from sticking out from the frame of the arm, which could cause the motor to catch on an object in the environment. This was accomplished by integrating two right angle bevel gear heads into the design at joints 4 and 6. These are small 1:1 ratio gear heads that are much lighter in weight compared to other right angle gear heads and were found to fit within the space provided at the right angle joints, which allows the motor to be housed within the link rather than protruding out of the arm space as in the WMRA-I. The right angle gear head easily fits inside the ABS plastic cover which improves the aesthetics of the design because the motors and the gear heads do not protrude from the arm as in the WMRA-I. The gear head has a steel housing and has an oil lubrication inside, which is rated for the life of the component. The assembly of joint 4 is displayed in Figure 18 and shows the compact size of the right angle gear head with dimensions, 1.5in by 1.5in by 1.0625in.

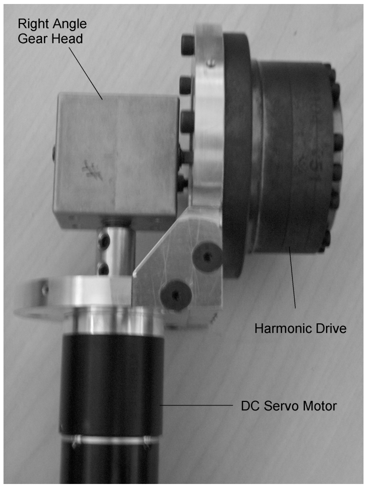

Figure 18. Joint 4 with Right Angle Gear Head and Harmonic Drive

There are right angle gear heads that are lighter, but they are made with plastic housings and were not capable of handling the torque provided by the motors at the speeds that they will be required to run. These other gear heads also had much shorter life cycles. The input and output shafts were machined to have a flat side for easy mating with the motor shaft and the harmonic drive input. The motor shaft connection was made with a solid shaft coupler to ensure good transmission of motion through the right angle gear head.

4.2 Electronic Systems

4.2.1 Control System Hardware

It is vital to have a good control board that is capable of processing all of the necessary inputs and outputs for the control and feedback of the motors. The Galil Motion Control board used in this application, the DMC-2183, is capable of running up to eight motors simultaneously. The control board runs each axis on a separate circuit rather than having the amplifier boards daisy chained together. In the WMRA-I design, the separate PIC-servo boards used for each joint were daisy chained together in series and is believed to be a major contributor to the problem with the robustness of the WMRA-I system. This is due to the fact that the signal information being sent to and from the last motor of the arm must be sent through each of the boards to reach that joint. This occurs while the other boards are also handling commands for the joint which they are supposed to control. This may cause information to be lost or sent too slowly for it to reach the necessary joint.

The Galil motion controller has a separate circuit, which runs through a 96-pin DIN connection to the amplifier board, for each axis that it communicates with. This allows the control board to run with a minimum servo update time of 650 microseconds while running all eight motors.

The motion controller has two amplifier boards attached to it through two 96 pin DIN connectors, which are seen in Figure 19 at the top left side of the control board in white. The amplifier for the first four axes is the AMP 20540 and is capable of running brushless, brushed, and stepper motors. In the case of this robot arm, it powers four brushless motors. The other amplifier board, which will run the four axes farthest from the wheelchair base, is the AMP 20440 which is capable of controlling brushed and stepper motors. However, the AMP 20440 will only be used to power the four brushed motors of the arm.

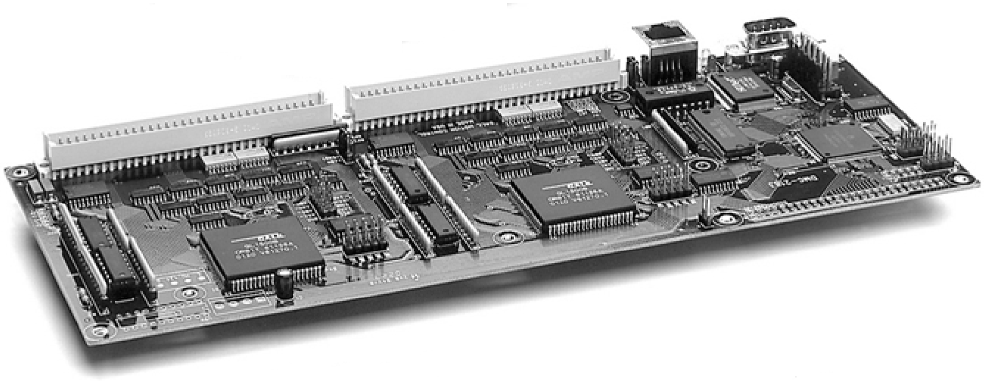

Figure 19. Galil Motion Control's DMC 2183 Board without Amplifiers [28]

This direct connection amplifier setup is compact and allows the board to be mounted much easier on different mobile platforms compared to that of the WMRA-I control board box (Figure 20), which was made to house the numerous control boards that run the arm. The box dimensions are 7in by 13in by 4in while the new control board dimensions are only 4.25in by 10.75in by 3in including both of the amplifier boards attached. The 3in height is actually only at a small part of the control board and is due to a heat sink that is used to keep the AMP 20540 board cool.

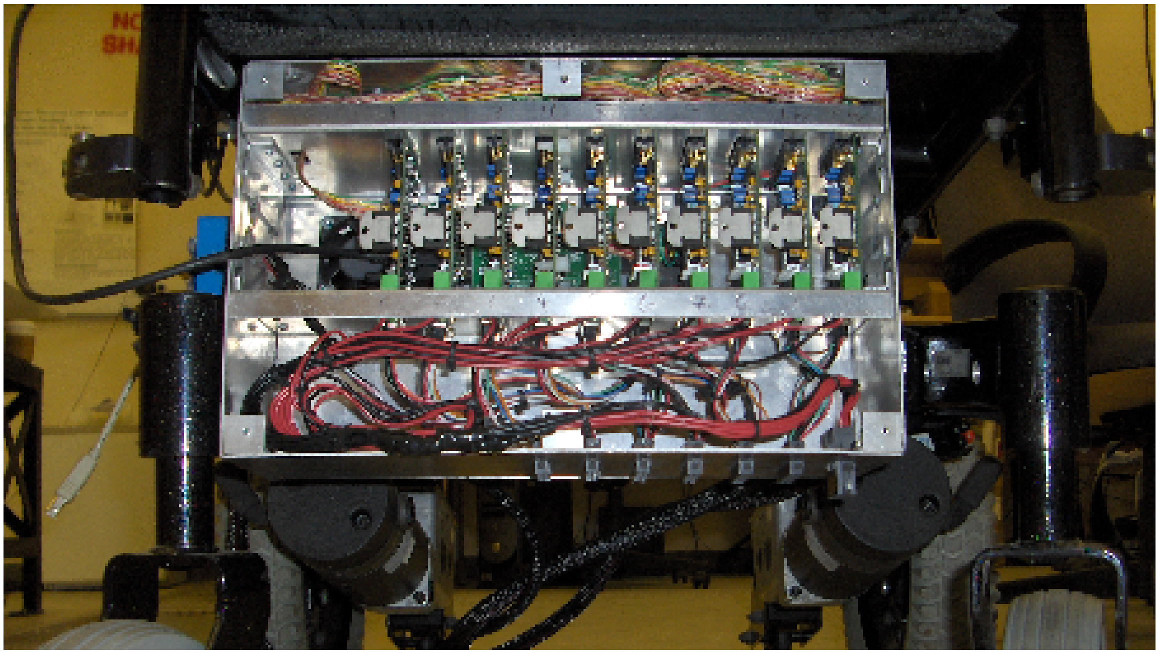

Figure 20. Control Boards and Large Housing of WMRA-I

The Galil motion controller uses a GUI interface, known as Galil Tools, that allows the user to send commands to the arm through a two letter command system. This software also has a capability that allows the user to put a scope on each joint to measure the joint torque and the joint position and voltage simultaneously, in real time. The PID control gains can be set using an automatic tuner in this program which eliminates the possibility of gain errors due to user setup. The accuracy of the tuner allows the WMRA-II to reach the commanded encoder position precisely while the WMRA-I may be 10 encoder counts away from the commanded position when it stops due to the gains being slightly off.

The control board connects to the computer to receive commands from Galil Tools through a serial cable or an Ethernet cable. This communication can be used to set the controller settings for the motor configuration that is being used and then this setup with all of the gains and other motor information will be saved even after disconnection.

The connection of the power inputs into the control board are -12V, +12V, and +5V. In order to accomplish this, a voltage reducer can be used inline with the batteries. The amplifier boards accept 24V, so there is no need to change the voltage from the batteries to the amplifier boards.

4.2.2 Wiring

The wiring of a robot arm is a very important aspect of its hardware. If the wiring fails for any reason then the robot arm will not work properly and has the potential to injure anyone in the vicinity of the arm. Therefore, it is very important to ensure that all connections are made properly and also ensure that the wiring is sufficient for the power and signal that it will be transmitting.

Preventative measures have been taken in this design to make sure that there is no interference and that all connections are made with locking mechanisms to prevent disconnection during use. This problem was noted in the WMRA-I design which does not have locking connectors for the wires attaching to the encoders of the motors depicted in Figure 21. This causes disconnection of some of the encoders on a regular basis during use, which causes the motor to move in rapid intervals.

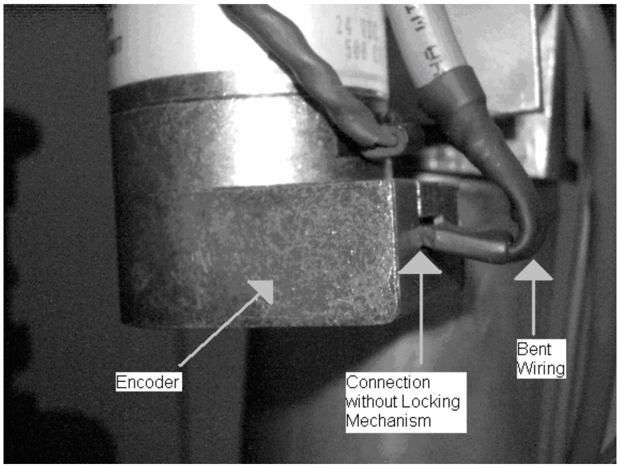

Figure 21. Connector Attached to Encoder without a Locking Mechanism

All of the power connectors to the control board and to the motors are Molex mini-fit or 3M locking connectors. The encoder and Hall Effect sensors also have locking connectors at the motor end and a high density D-sub 15 connector at the control board for a safe mechanical connection. The various locking connectors used for the gripper's motor and controller connection are pictured in Figure 22. These preventative wiring measures are necessary safety features of a WMRA because it will be used in close proximity to people.

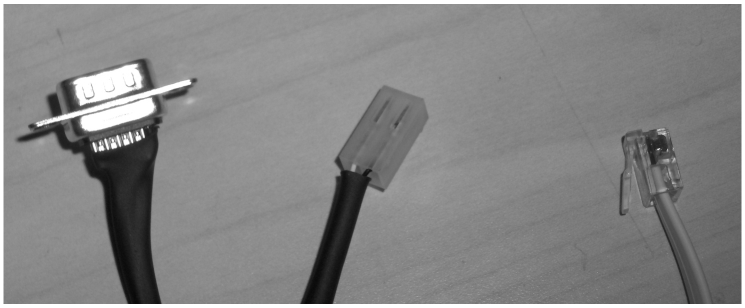

Figure 22. Locking Connectors for Gripper

The wires used for the connection of all of the encoders as well as the Hall Effect sensors are 26 AWG and run inside a single cable with a polyvinylchloride (pvc) coating on the outside and a metal shielding which is ground to the control board. This shielding is used to help prevent any interference caused by running the power wires close to the signal wires of the Hall Effect sensors and the encoders. The power wires are 22 AWG and are run inside a separate pvc coated cable. The only motor that has the power and signal wires running in the same cable is the gripper motor, which uses a phone line cable with six wires to connect the power as well as the 512 cpr, resolution encoder. This setup was designed with the gripper and has since then been tested and has shown no signs of any interference problems.

4.3 Structural Components

There are four main materials used to design this arm which are aluminum 6061-T6, carbon fiber, polycarbonate, and ABS. The aluminum material is used to make the brackets which the harmonic drives and motors mount to in order to align with one another. This material was chosen because it is lightweight and easy to machine compared to other materials such as steel and titanium, while still being cost effective compared to other options. It is a lighter weight material, therefore more of the motor power can be used toward lifting and manipulating objects, than if a material like steel were to be used.

Each of the aluminum brackets were designed to mate the proper components together, to allow the desired joint configuration, and to be as light as possible without compromising the structural integrity of the arm. In order to accomplish this each of the brackets was designed in SolidWorks and analyzed using CosmosWorks, as seen in Figure 23. Each of the brackets were tested for torque and force loading, which were used to determine if the bracket needed to be thicker for reinforcement or if it could be reduced in thickness for weight savings. Each bracket was designed to limit the maximum deflection, under full load, to less than 0.5mm.

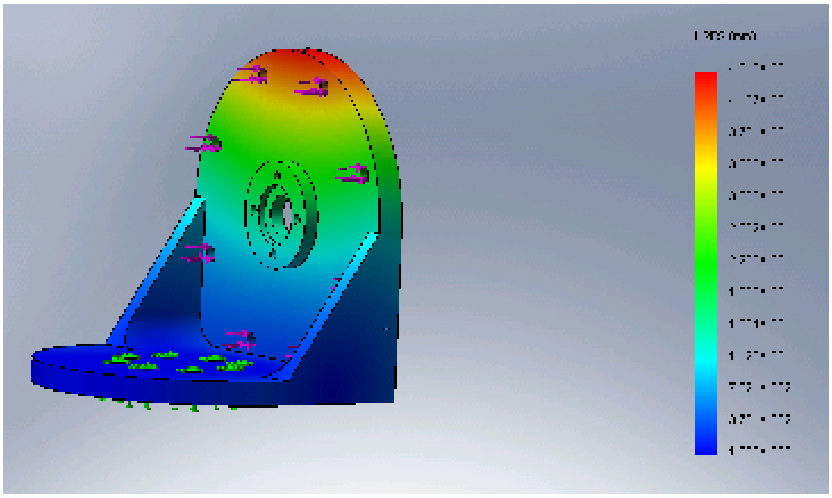

Figure 23. CosmosWorks Results of Aluminum Bracket Testing

The other major component of the arm structure was the carbon fiber tubing that was used to make up the frame between the individual brackets. The carbon fiber tubes were attached to the brackets by a machine screw which connected to an aluminum insert placed inside the tube. An aluminum post-screw was then placed through a cross hole that allowed the rigid attachment of the insert to the tube. The frame design increases the modularity of the arm because the carbon fiber tubes can be easily changed with tubes of a different length, while the WMRA-I would require the welding of brackets and aluminum tubes to change the arm link lengths. Changing the kinematics is also cheaper for the WMRA-II because the carbon fiber tubing is less expensive than the aluminum materials and it does not require the labor of welding, only limited machining. The complete properties for the carbon fiber tubes can be found in Appendix D.

The carbon fiber material was chosen for the application because it is strong and very lightweight. Unfortunately, carbon fiber is brittle and therefore, difficult to machine into the necessary parts with good accuracy.

The polymer materials, polycarbonate and ABS, used for the external structural support and cover of the arm, were chosen for their lightweight and their ability to withstand impacts without cracking. Figure 24 shows the individual link design with the carbon fiber frame inside and the external support of the polycarbonate tube. The detailed drawings of the aluminum brackets, polycarbonate tubes, and carbon fiber tubes can be found in Appendices A, B, and C respectively.

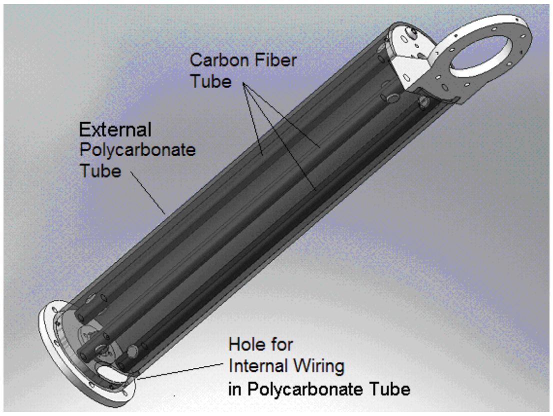

Figure 24. External Polycarbonate and Internal Carbon Fiber Link Structure

Chapter 5 Manufacturing and Assembly

All of the components of the arm were machined at the University of South Florida machine shop. The aluminum bracket components were machined using manual milling machines which amounts to numerous man hours considering that all of the brackets are custom. Each of the brackets that mate a harmonic drive to a motor has to have a boss on one side to allow ample space for the motor shaft to connect to the input bore of the harmonic drive. There are also numerous counter sunk holes required for clearance of the harmonic drive over the machine screws that mount the motor to the bracket, depicted in Figure 25. The detailed drawings can be found in Appendix A.

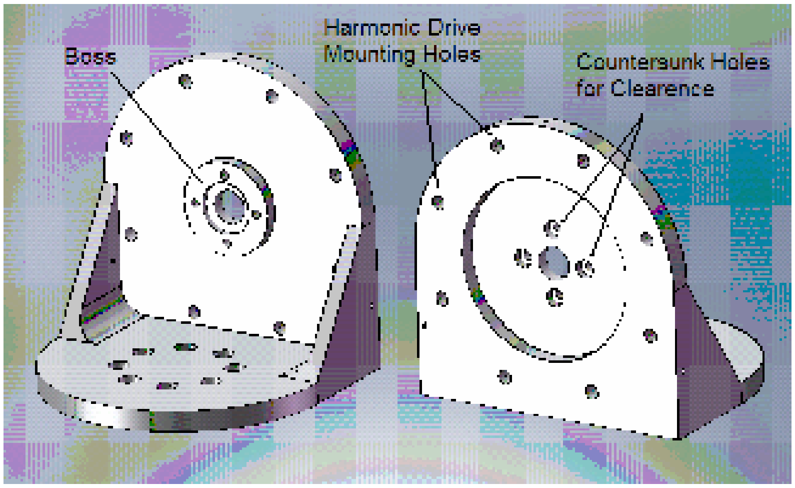

Figure 25. Boss and Mounting Holes for Motors and Harmonic Drives

The machine shop also fabricated the inserts for the carbon fiber tubes that allow the mechanical connection to the aluminum ends. These inserts were designed to be 0.4 inches in diameter for a snug fit to the inside diameter of the tube and have a ¼ – 20 UNC steel helicoil thread to help prevent damage or tear-out failure of the inserts threads. The inserts make it possible for the arm to be assembled using simple machine screws while the WMRA-I has numerous brackets that are welded directly to the aluminum tubes that make up the links. This gives the WMRA-II an increased modularity compared to the WMRA-I because the link lengths can be changed without welding any parts. The WMRA-II arm simply needs to have the framework removed and replaced with new parts of different lengths by removing the machine screws and reusing them with the new frame parts. The WMRA-II is easier to assemble because it can be put together with machine screws, building from the base to the end effector while the WMRA-I requires the use of welding tools to complete the assembly of individual links.

The carbon fiber tubes were cut to length and had a cross hole drilled through them. This proved to be more difficult than expected due to the brittle properties of the material. The carbon fiber had the tendency to split down the length of the tube in the direction of the carbon fibers which run axially down the length of the tube. The tubes had variations in their lengths up to 1/8in which is detrimental to the assembly of the arm because it will cause higher stresses in certain areas as well as cause the DH parameters to be different than designed. In order to compensate for this problem some carbon tubes were fabricated separate from the machine shop tubes to ensure that they were the correct length and free of fractures due to machining processes.

Chapter 6 Testing and Results

Testing must be conducted to ensure that the device works properly and is capable of being used on a mobile platform, specifically a power wheelchair. Many different types of tests can be conducted to ensure that this is the case including:

- Tensile testing of the carbon fiber tubes after machining
- Polycarbonate tube analysis
- Speed testing of the individual joints
- Simultaneous motion testing of all of the individual joints
- Analysis of the power consumption during different joint motions
- Weight analysis

A test setup was designed to provide the necessary power requirements to complete the testing. The test setup used three different power sources to accomplish the necessary voltage inputs of the control board and the two amplifier boards. The control board inputs of -12V, +12V and +5V were accomplished through connecting two power sources in series with the -12V source of one supply and the +12V source of the other supply to a common ground. This allowed the two power sources to provide the -12V and +12V connections that were not hooked to ground which produced the necessary inputs for the control board. The +5V for the controller and the +24V for the amplifier boards were connected directly to the power source without modification of the output. The wiring diagram for the test setup is shown in Figure 26. This setup is for testing purposes only and the control board can be mounted to the wheelchair to receive its power from the wheelchair batteries after incorporating voltage reducers or a DC to DC converter from Galil Motion Controls.

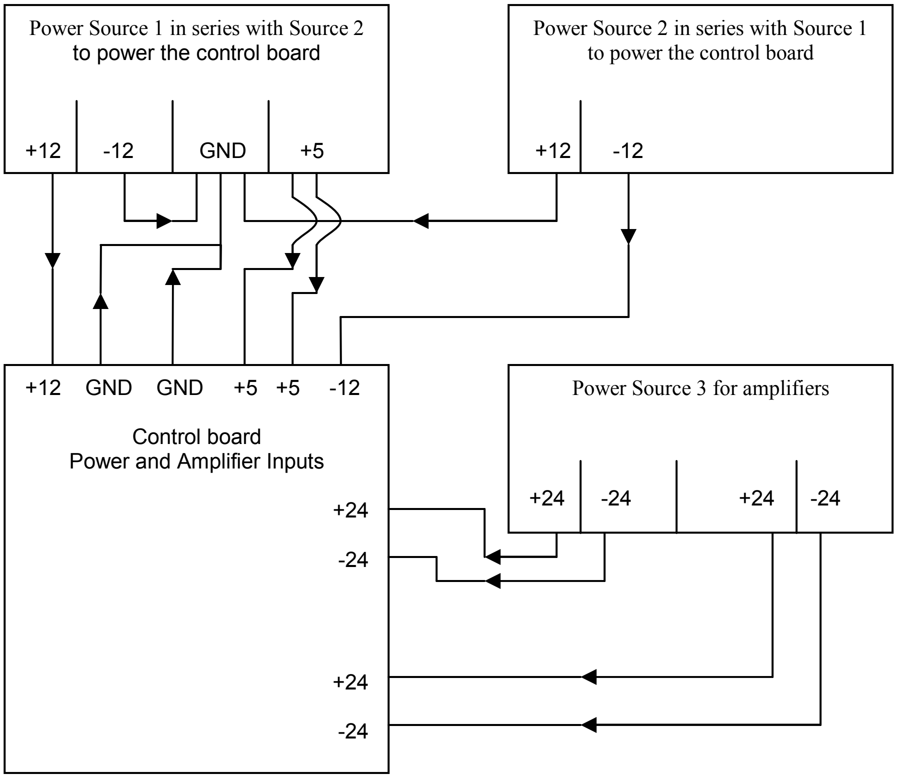

Figure 26.   Test Setup for Control Board Inputs

6.1 Carbon Fiber tube Tensile Testing

The pultruded carbon fiber tubes were machined to be a certain length and also had a hole machined at each end of the tubes for connecting them to the aluminum brackets at the ends by an aluminum insert placed in the tube's ends. Therefore, tensile tests were conducted to ensure the forces required to lift the load would not cause the insert to rip out of the aluminum tube. Two of the three test setup tubes were viable for testing, but the third tube was damaged during machining due to overstress. Both of the tubes that were tested were capable of handling loads up to 150 lbf before the tubes failed due to a tear-out failure at the ends where the aluminum inserts attach. This type of failure was expected because that was the weakest point, due to the increased stress around the machined hole. Figure 27 shows the data from the tensile test of the carbon tubes and shows the failure at over 150 lbf. The complete failure occurs around a displacement of 0.023in, where the force drops significantly and then levels off. This leveling off effect is due to the insert continuing to be partially connected to the tube end throughout the test.

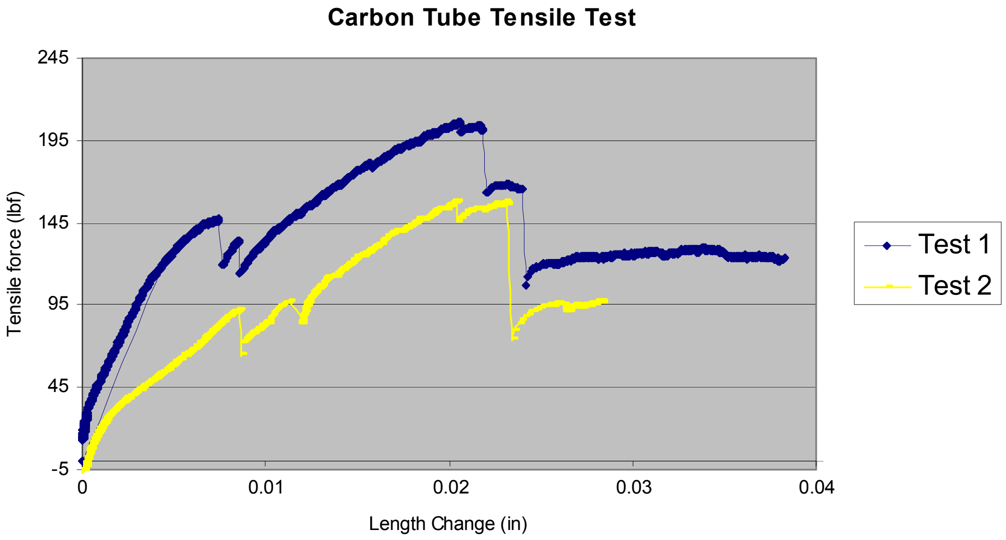

Figure 27. Tensile Test Results of Two Carbon Tube Specimens

This test provided the necessary information to ensure that the strength of the carbon fiber tubes used in conjunction with the polycarbonate tubes would be able to manipulate the full load at the end effector. The carbon fiber tubes alone are unable to support the full load at the end effector due to this tear-out failure at the end of the tube, depicted in Figure 28. Therefore, polycarbonate tubes were tested to ensure that they will support the necessary loads to ensure the carbon fiber frame will not be damaged.

Figure 28. Carbon Fiber Tube Failure

6.2 SolidWorks Analysis of Polycarbonate Tube

The external polycarbonate tubes were designed to be a load bearing members as well as be a part of the cover of the arm to protect the motors and the wiring from the external environment. The polycarbonate tubes will bear a large portion of the torque that is induced in the links during motions including the full load and no load conditions at the end effector. The tube that is utilized for the first link will have the largest torques placed on it during motion and was analyzed using SolidWorks with Cosmos to ensure that it would not fail. Figure

29, seen below shows the polycarbonate tube's rotational deflection due to the maximum torque forces that will be placed on it during use.

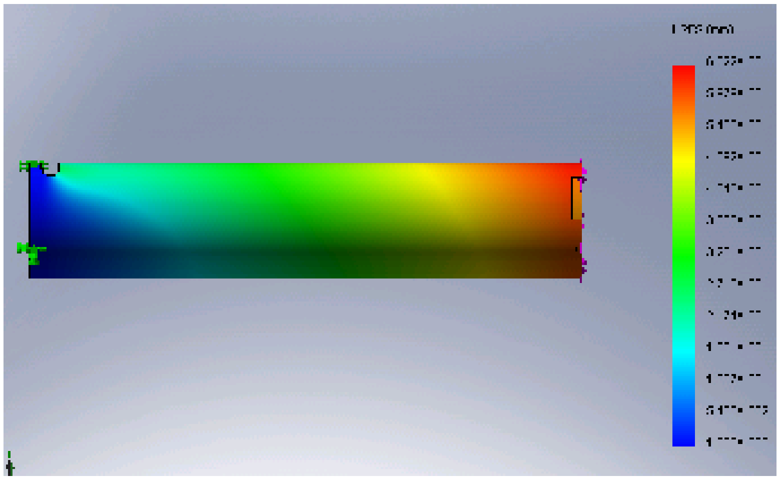

Figure 29. CosmosWorks Analysis of Torque Load on Polycarbonate Tube

The maximum displacement of 0.65mm under the maximum torque of 37Nm is not substantial because the tasks to be conducted do not require extremely high precision and the user can make corrections to the end effector location due to minor deflections of this nature. This small deflection means that the end effector will not be in the exact location that it is expected to be if one were to calculate its position using the joint angles and link lengths. This, again, is not a major problem because the user is in the control loop and can make the necessary corrections when conducting tasks. Even when the system is upgraded and has greater autonomy, it would be desirable to have a system where the user can interrupt tasks and make adjustments as needed when picking and placing objects.

Analysis of the polycarbonate tube was also conducted to ensure it could handle the end loads due to the weight of the rest of the arm and the payload.

This analysis was set up similar to a cantilever beam with the forces that exist at the polycarbonate tube end, 8kg, distributed among the physical mounting and contact points between the aluminum bracket and the tube. These locations are seen in Figure 30 at the tip of the arrows, designating the forces, at the right end of the tube. Figure 30 also shows the stresses throughout the tube structure under load. The analysis shows that the polycarbonate tube is capable of handling the load and is well under the yield stress, 7 X 10^7 N/m^2, of the material.

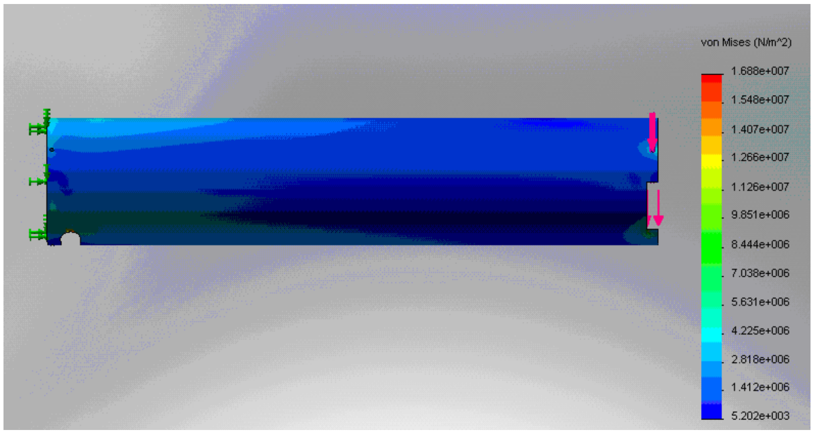

Figure 30. CosmosWorks Analysis of End Load on Polycarbonate Tube

The tensile forces that are placed on the structure during full load at the end effector exceed the 150lb limit of the carbon fiber tubes. Analysis was conducted to show that the polycarbonate tubes can withstand the tensile forces necessary to ensure that the carbon tubes do not fail. Figure 31 shows that analysis with the complete tensile load being placed at two of the machine screw mounting locations. The stresses remained well below the yield stress of the material and the displacement, seen in Figure 32, remained just below the displacement of the carbon fiber tubing during the physical tensile testing. The displacements were close under equal loads, which means that both materials, carbon fiber and polycarbonate, will be sharing the tensile load. This ensures that the carbon fiber tube will not exceed its tensile load limitations that were found to be 150lbs during testing.

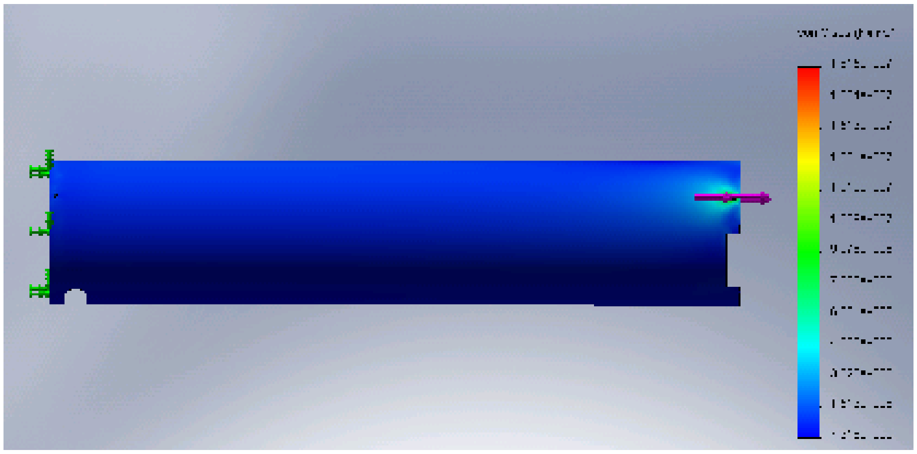

Figure 31.	CosmosWorks Analysis of Tensile Load on Polycarbonate Tube

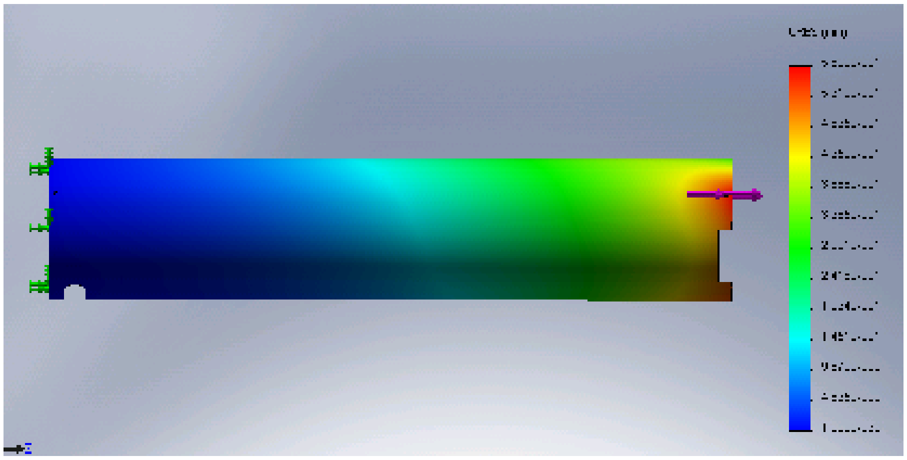

Figure 32.	Displacement of Polycarbonate Tube Under Tensile Load

## 6.3	Speed Testing of Joints

The speed capabilities of the individual joints are important because previous assistive robot arms have been tested and surveys have shown that the users feel that it takes too long to conduct certain tasks because the system has a difficult user interface or the arm moves too slowly to conduct a task efficiently [24]. These two problems are linked because the speed of the arm movement should not be increased unless the interface is able to be controlled easily and quickly to prevent damage to the arm or people around it.

The speed of the WMRA-I system and the new WMRA were both tested for maximum speed at which the arms do not fail due to overload or inability to accelerate or move from a difficult position. The tests were conducted under no load conditions. Each joint was rotated through an angle of 90 degrees during which the motion was timed. The gains for the new arm were set up using the automatic tuner capability of the Galil Motion Control board while the WMRA-I used the standard gains that have been used in the past. The joints were run at the maximum speed at which the arms did not fail due to communication or mechanical slipping at the joints. The results of the speed testing in Table 6 show that the new arm is capable of higher speeds in all of the joints.

Table 6. Joint Speed Comparison of WMRA-I and New WMRA

	WMRA-I	New WMRA	
Joint	Speed (RPM)	Speed (RPM)	% Increase
1	1	1.68	68
2	1	1.68	68
3	1	NA	NA
4	1.25	3	140
5	1.5	2.9	93.33333333
6	1.67	3	79.64071856
7	1.25	4.15	232
8	18 seconds from fully open to fully closed		0

Gains in speed can be seen at every joint throughout the new WMRA system compared to that of the WMRA-I system. Any speed gains are especially significant for the first three joints because these are the slowest moving joints and could potentially slow the user's ability to complete a task, which could mean the user could complete the task faster without the aid of the arm.

6.4 Simultaneous Joint Motion Testing

Testing was conducted to show that all of the joints can be run simultaneously with the current motor configuration, control board, amplifier boards, and wiring. In order to conduct this test the joints were moved at the same time to specified known points that would be reached at the same time. The program found in Appendix F was created and used in the Galil tools command interface in order to accomplish the desired motion. The motors were run to the specified point and then back to the position which the arm had started prior to the movement. This testing showed the ability of the arm to accomplish full mobility of all of its joints during motion and that it is robust enough to run without loss of information from the host pc to the control board for long periods of time. Figure 33 shows the arm during one of the simultaneous joint analyses and the test setup can also be seen with the power sources and control board.

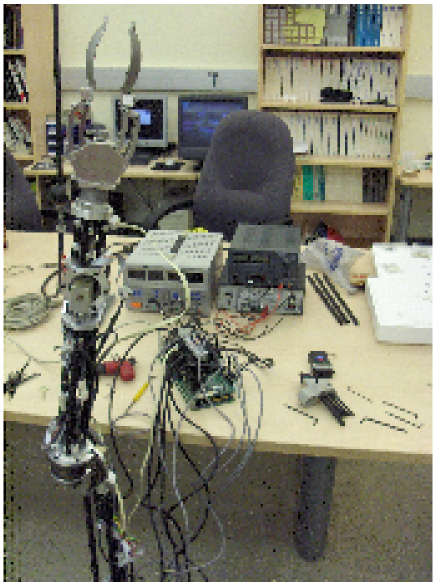

Figure 33. Robot Arm during Simultaneous Motion Testing

6.5 Power Consumption

The power consumption of the arm will affect the usage time greatly. If too much power is required to drive the arm then the continuous use time will decrease. The power consumption of the arm also reduces the power available for the wheelchair to move while using its own drive motors. The current and voltage were measured from the power sources during motion of all the motors simultaneously. This measurement was also conducted when there was no arm movement.

The control board uses a +5V as well as +12V and -12V source which were monitored during use. The +5V source provides a constant 1.48A current to the control board regardless of whether the arm is in motion or not. The both 12V sources provide a combined 40mA current to the board during motor usage and while the motors are not in use.

Two Amplifier boards, the 20540 and the 20440, from Galil Motion Control were utilized. The 20540 supply for the brushless motors provides less than 10mA when the motors are not providing motion to the arm even in an outstretched position. This is due to the high gear ratios of the harmonic drives in combination with the high gear ratios (51:1) of the planetary gear heads. In the WMRA-I, the planetary gear heads have low gear ratios at 5.9:1 and therefore the arm is easier to back drive and also means that the motors require more current when the arm is not in motion to hold the static position of the arm. The total current of the WMRA-I system when the system is idle is 0.38A while the new system is nearly 0A due to this higher gear reduction in the planetary gear head.

When all of the brushless motors are running simultaneously for motion, the current output is 0.5A. The 20440 amplifier powers the four brushed motors and when all four motors are running at the same time with no load at the end effector, the current output is roughly 0.7A depending on the orientation of the arm.

6.6 Weight Analysis

The weight is an important aspect of the design, as it not only affects the maximum weight of the end user, but also affects the power consumption of the wheelchair. The largest contributor to the weight of the arm is the harmonic drive gear head, comprising of 53 percent of the weight of the entire system including the weight of the control board and the wiring. The total weight of the arm is 11kg which is 2.75kg (just over 6lb) lighter than the previous design.

The carbon fiber tubing has a density of 1.5g/cm^3 while the aluminum used to make the links of the WMRA-I has a density of 2.71g/cm^3. Through calculations of the volume it was determined that the carbon fiber tubing and frame structure design amounts to a weight reduction of 0.5kg compared to using the aluminum structure in the WMRA-I. The motors also contributed a significant weight reduction compared to the previous arm. The total weight of the new motors is 1.89kg providing a weight savings of just over 0.5kg compared to using the Pittman motors of the previous design. The Maxon Motors helped reduce the weight and size of the drive components, while not sacrificing torque and efficiency which made them ideal for this application. The overall weight savings is due to a number of changes, but ultimately helped to reduce the power consumption of the arm and also reduces the added weight to the chair which will its run time as well as the allowable weight of the user.

6.7 Safety of Wiring

During the testing of the arm for joint speed analysis as well as the simultaneous motion of all the joints together, it was noted that none of the motors experienced a disconnection of encoder or power wires for any reason. Therefore, none of the motors were in motion at any point in time when it was not directed to be in motion. It was also noted that the testing was conducted over a period of a few hours, during which the control system was on for periods of up to half an hour. The communication between the control board and the motor was never lost during this time, showing an increased robustness compared to the WMRA-I daisy chained control boards which have a tendency to lose communication with the motors.

Chapter 7 Conclusions

A prototype of a lightweight robot arm for mobile use was built for use as a WMRA. The arm was tested and analyzed to show that the arm improves upon previous WMRAs, specifically the WMRA-I, in areas of weight, speed, robustness, modularity, and safety.

The weight of the WMRA-II is 6lbs less than the WMRA-I. The lightweight motors, smaller aluminum bracket, and the carbon fiber frame made this weight reduction possible. Reducing the weight of the mobile arm allows the wheelchair batteries to last longer because the motors of the arm and the wheelchair have a smaller payload to move, therefore less power is consumed. Power consumption was also reduced by incorporating higher ratio planetary gear heads into the prototype. These gear heads make the joints harder to back drive than in the WMRA-I joints, causing less power to be consumed by the motors while the arm is trying to hold a static position (against gravity).

The speed of each of the individual joints was tested. Each joint of the WMRA-II is more than 50% faster than the WMRA-I because the Maxon Motors utilized are capable of high speeds, but still have high torque abilities. These higher speeds will allow the user to complete tasks in a more timely fashion, increasing the efficiency of the assistive device. Simultaneous motion to a specified point was tested to ensure the system is capable of controlling all of the motors at the same time without losing communication. The arm was capable of moving all of the joints to specified locations and stopping simultaneously. This testing showed the robustness of the controller, as it was used for extended periods of time without communication loss or undesired motions.

The modularity of the arm has been improved through the use of the carbon fiber frame of the arm. The previous WMRA requires new aluminum brackets to be welded in order to change the link lengths while the WMRA-II only requires the changing out of the carbon fiber tube and poly carbonate tube that make up the structure of the link. Therefore, the reconfiguration of the arm for specified tasks can be completed with less labor and material costs for the WMRA-II.

The WMRA-II improves upon safety in a number of ways, including controller robustness or reliability, use of locking wiring connections, and use of an external housing. The prototype uses a Galil controller that helped improve the robustness of the system. This also increases the safety of the arm because miscommunications could cause the arm to move in undesired ways and cause injury to the user. Locking wiring connections are another feature of the WMRA-II that improve upon safety by ensuring the wires do not disconnect during use which would again cause undesired motion and possible injury. The cover of the arm was not implemented on the prototype, but was designed to protect the arm’s internal parts, motors, carbon fiber frame, and wiring, from the external environment. This would increase the safety because the wires would not be damaged during contact of the arm with the environment, which is possible in the

WMRA-I system. Table 7 is a comparison of the two robot arm prototypes and shows the numerous improvements that have been implemented in the WMRA-II design.

Table 7. Comparison of WMRA-I and WMRA-II

Feature	WMRA-I	WMRA-II
Weight (kg)	13.75	11
Wiring	External, No Locking Mechanism at Encoder	Internal, Locking Mechanisms at Connections
External Cover	No	Yes
Control Board	10 Boards Daisy Chained	1 Board, Increased Robustness
Length (mm)	1082	1132.5
Modularity	Limited due to Welding of links	Machine Screws Increase Modularity
Motors	Brushed, Two Motors Mounted Outside Arm Links	Brushless and Brushed, All Housed Inside Arm Links
Joint Speed	1 RPM for Joint 1	Over 50% Increase at Each Joint Compared to WMRA-I
Communication	Limited by Control System	No Limitation Found, More Robust
Degrees-of-Freedom	7	7
Payload (kg)	4.5	Untested

This prototype utilized carbon fiber and polycarbonate tubes to build a lightweight frame for the WMRA-II system which has not been done in the past for wheelchair-mounted robot arm research. The system also integrated necessary lightweight, robust, and efficient technologies needed in a sophisticated mobile robot arm for future improvements and testing.

Chapter 8 Future Work

This research has covered the design of the WMRA-II which is the second generation that has been designed at the University of South Florida, but there is much work to be done to improve the system and to further the research.

8.1 Storage Mechanism

The first major improvement is the addition of an automated mechanism that will allow the arm to be stored at the back of the chair when it is not is use or to the other side of the chair for more versatility in tight spaces. This will make the arm less intrusive and more desirable to end users. There are numerous ways that this could be accomplished including a track mechanism that goes around the frame of the chair, but this may cause the width of the chair to increase too much and hinder the mobility of the chair through small places. Another possible solution would be a four bar mechanism that swings the arm to different locations around the frame of the chair. This type of mechanism would not work on the current wheelchair, the Invacare 3G, because it has a frame structure under the user's seat. However, it would be a more viable method on new wheelchairs models such as the Corpus series by Permobil. These power chairs have a single mounting post to connect the seat to the base, which is also a hydraulic lift mechanism. This leaves plenty of space to mount a mechanism safely under the user's seat.

8.2 Harmonic Drive Housing

Another, major improvement to the design of the arm would be the design of aluminum housings for the components, sold separately, of the harmonic drive gear heads. The current steel housings that are available account for over 70 percent of the weight of each of the harmonic drives, which means designing aluminum housings, will reduce the weight at each joint. This will allow for higher payloads at the gripper because less of each individual joint's torque will be used to lift the arm components. Any increase in the payload makes the arm more versatile to the user because it is capable of lifting more objects.

8.3 Sensor Integration

Other on going research is currently working toward the integration of a sensory suite onto the wheelchair platform. This includes the use of a camera for vision and object recognition, bump sensors to prevent the chair from impacting objects, and proximity sensors for object avoidance. All of these features will help to increase the safety of the device which is necessary for the future of the WMRA and its widespread use as an efficient assistive device. Some Limit switches may also be able to be implemented to prevent the arm from moving to close to the user. The Galil motion controller used in this application has 16 uncommitted analog inputs and outputs on the 20540 amplifier and 8 on the

20440 amplifier that can be used to help integrate sensors directly with the system, if the sensor uses TTL technology. The sensor could also be powered through the amplifier boards as well which have multiple power and ground outputs. Any other additional research for increasing the autonomy of the system would be beneficial.

8.4 Further Testing

The testing of the torque and payload capabilities has yet to be completed because the necessary polycarbonate tubes were not available upon construction of the prototype. Testing the torque and payload abilities will ensure the safe operation of the arm by setting a limit to the weight of the objects that can be manipulated. These tests should be conducted in the worst case scenario, the arm completely outstretched horizontally for joint 1, for each joint and link. Testing should be conducted using a gradual increase in the load that the individual joints and links lift until the maximum payload is reached, while also noting the current and power needs in order to lift the load. This information can be used to calculate the battery life during normal operation and maximum payload operation to compare the power consumptions of the WMRA-I and WRMA-II more accurately. Another, valuable test would be to time how long it takes the arm to conduct certain tasks such as open doors or pick and place objects at various heights. This will help to compare the arm to future designs or modifications, sensor integration or program modifications, that will allow the arm to be more autonomous or controlled more easily.

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Appendices

Appendix A Aluminum Bracket Detailed Drawings

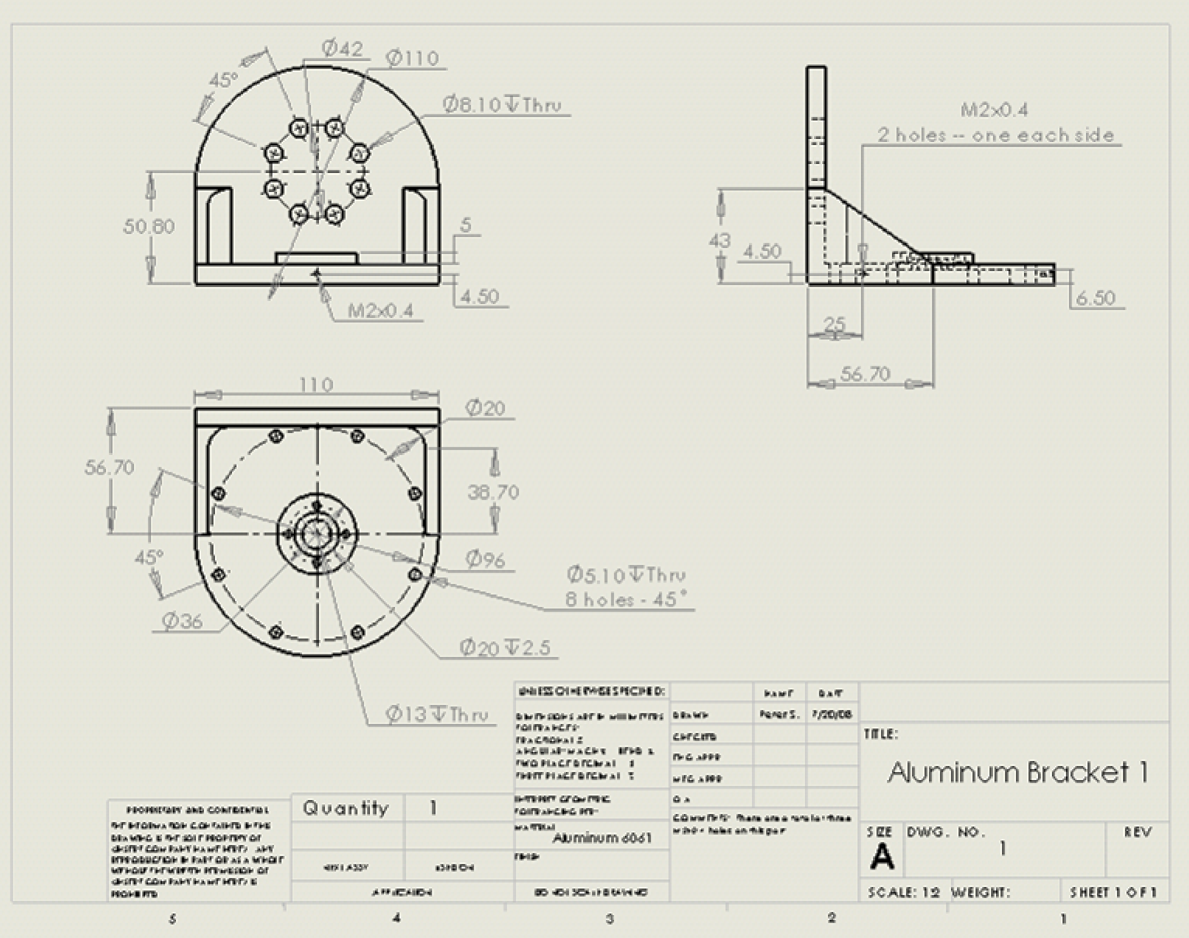

Figure 34. Aluminum Bracket Between Joints 1 and 2

Appendix A (Continued)

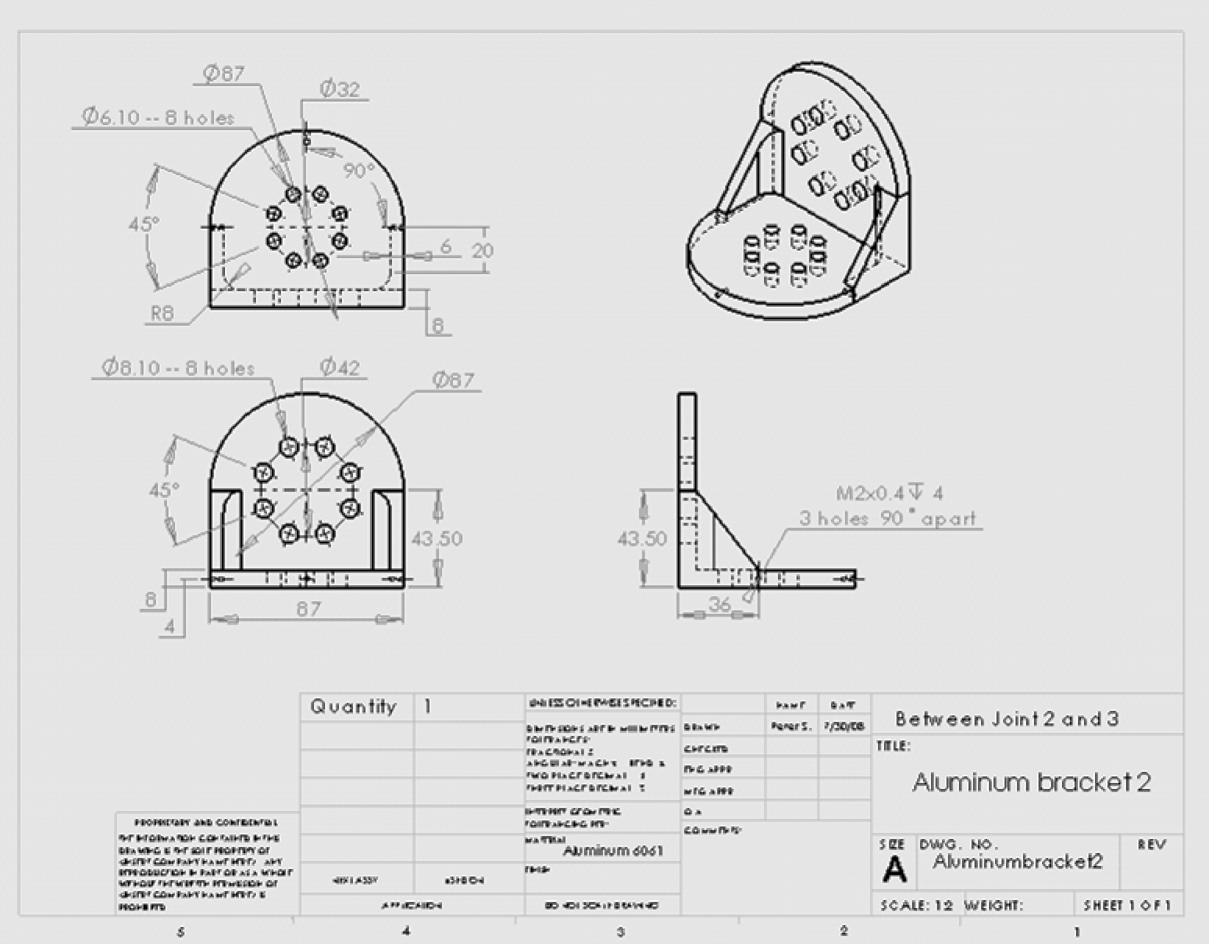

Figure 35. Aluminum Bracket Between Joints 2 and 3

Appendix A (Continued)

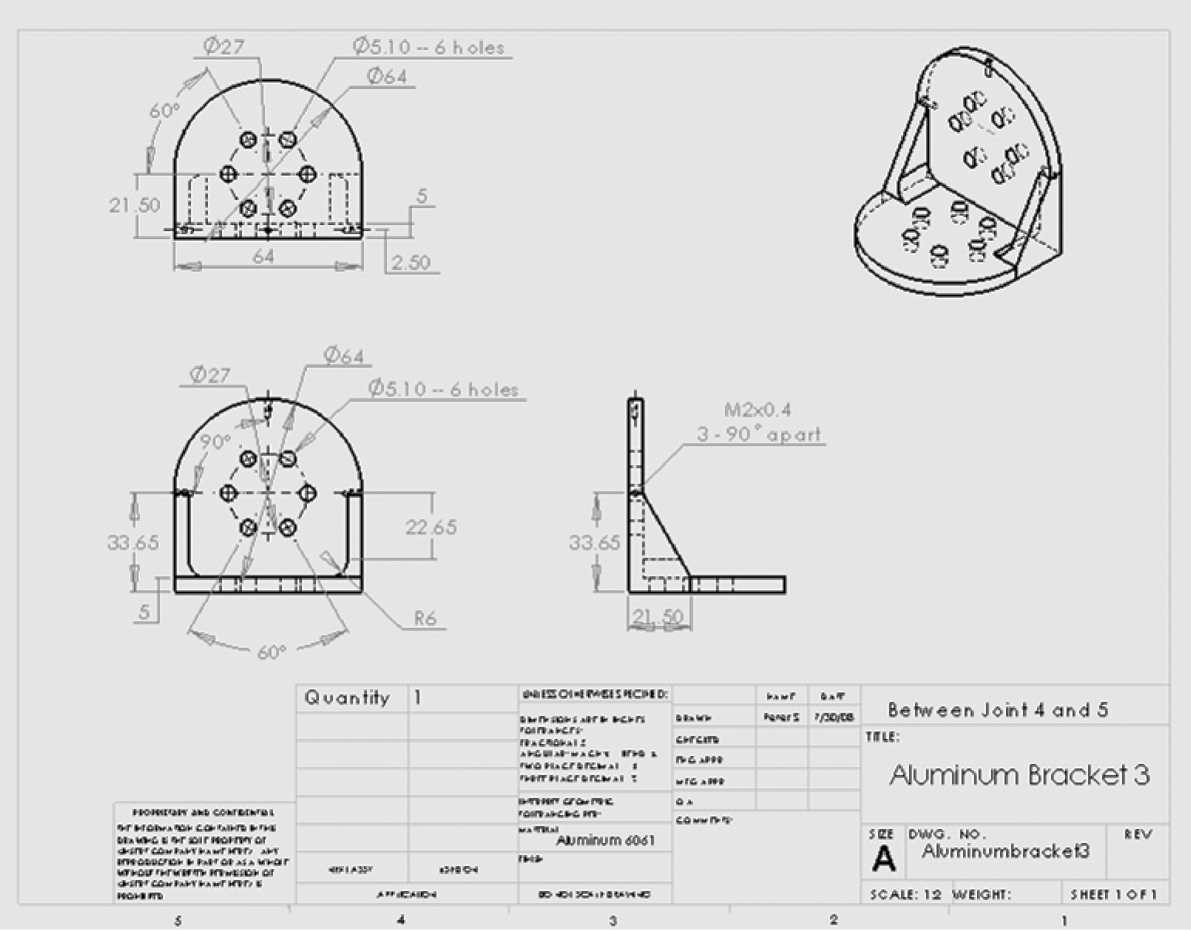

Figure 36. Aluminum Bracket Between Joints 4 and 5

Appendix A (Continued)

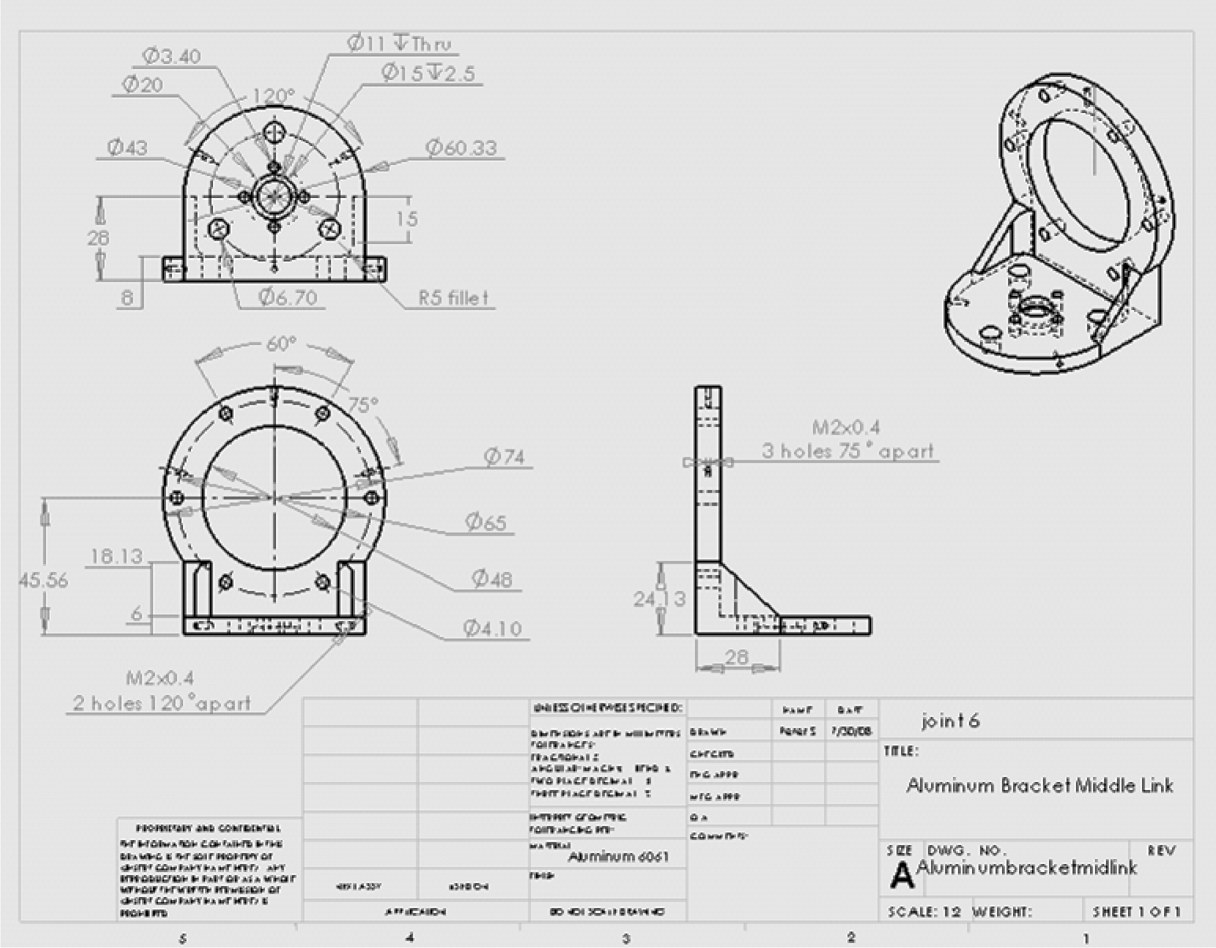

Figure 37. Aluminum Bracket of Joint 6

Appendix A (Continued)

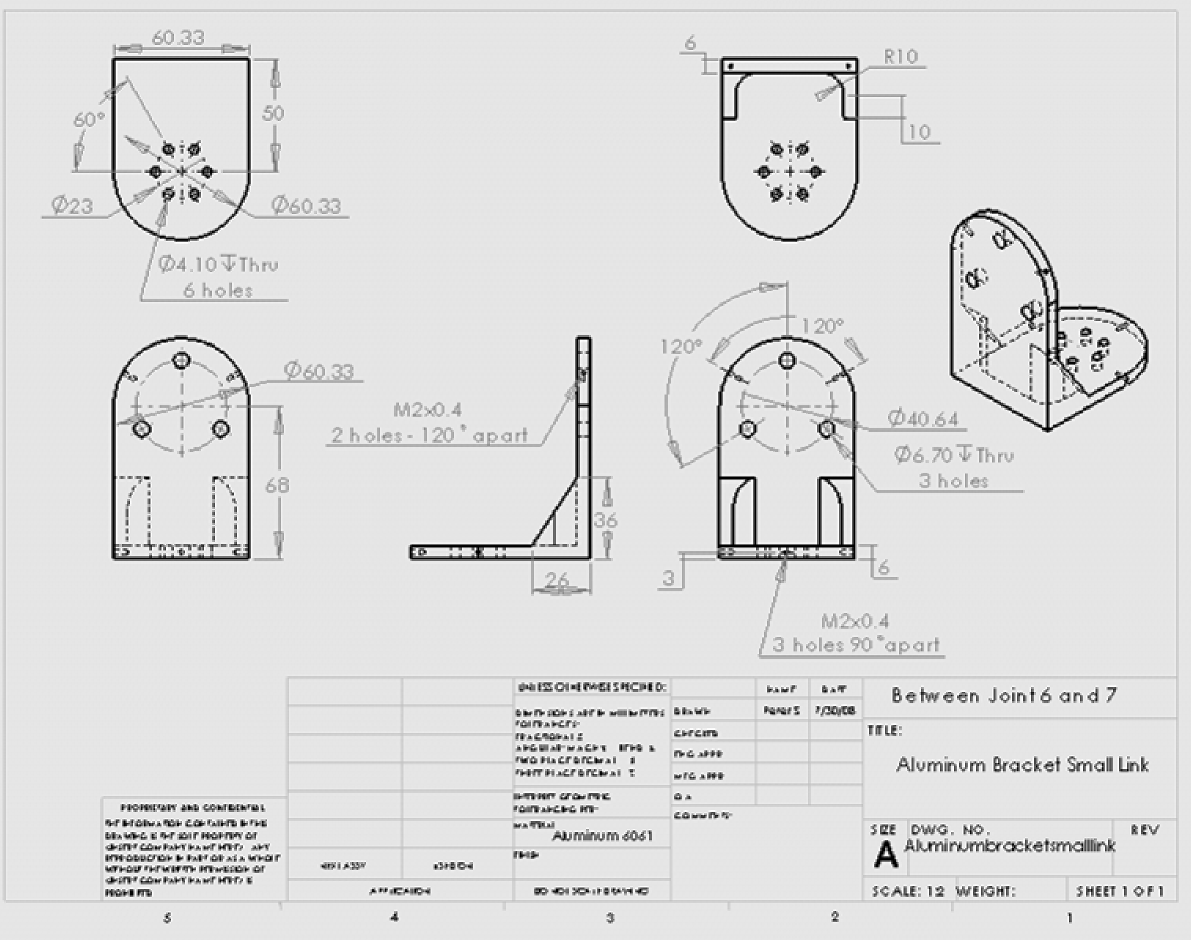

Figure 38. Aluminum Bracket Between Joints 6 and 7

Appendix A (Continued)

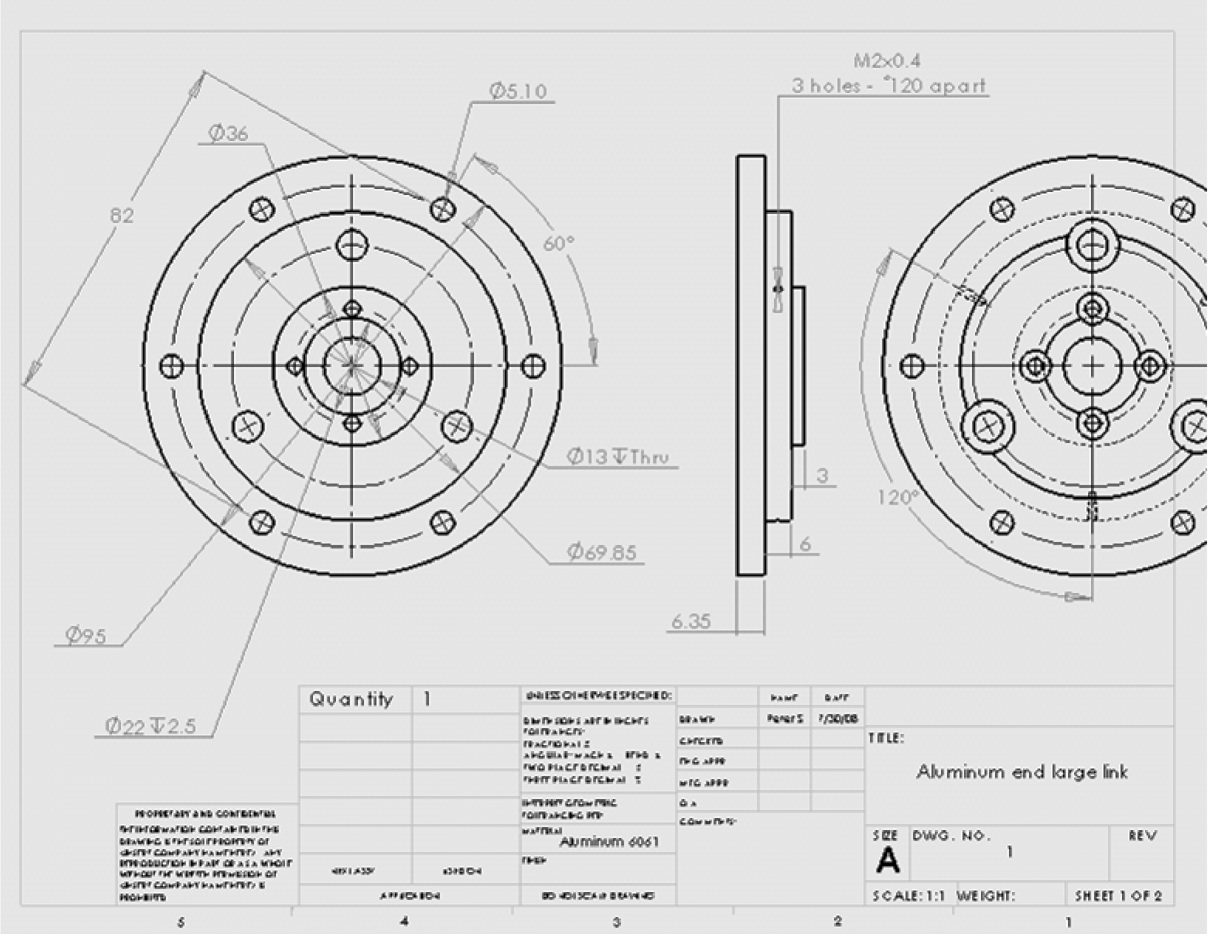

Figure 39. Aluminum End of Large Link Front and Side View

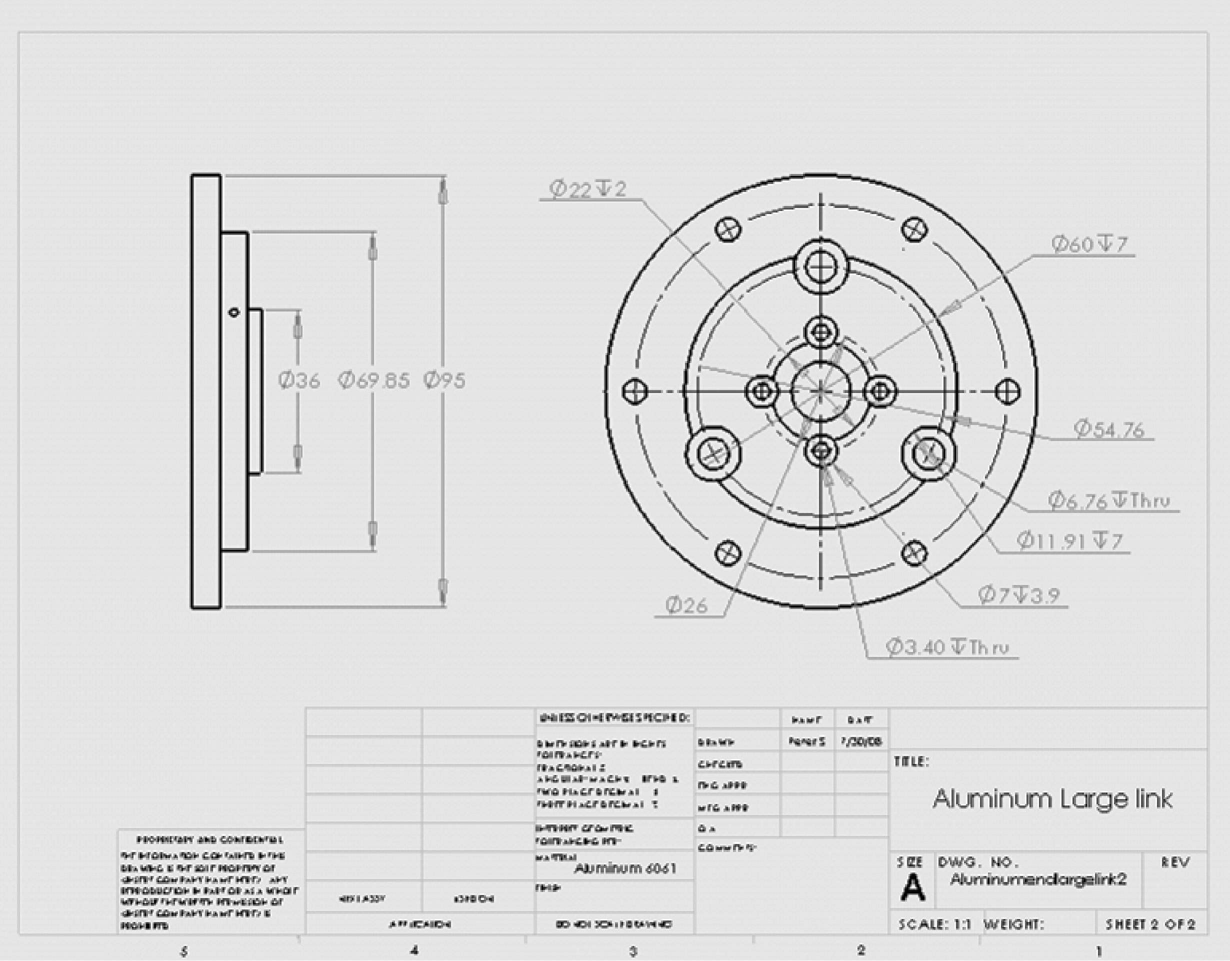

Figure 40. Aluminum End of Large Link Back View

Appendix A (Continued)

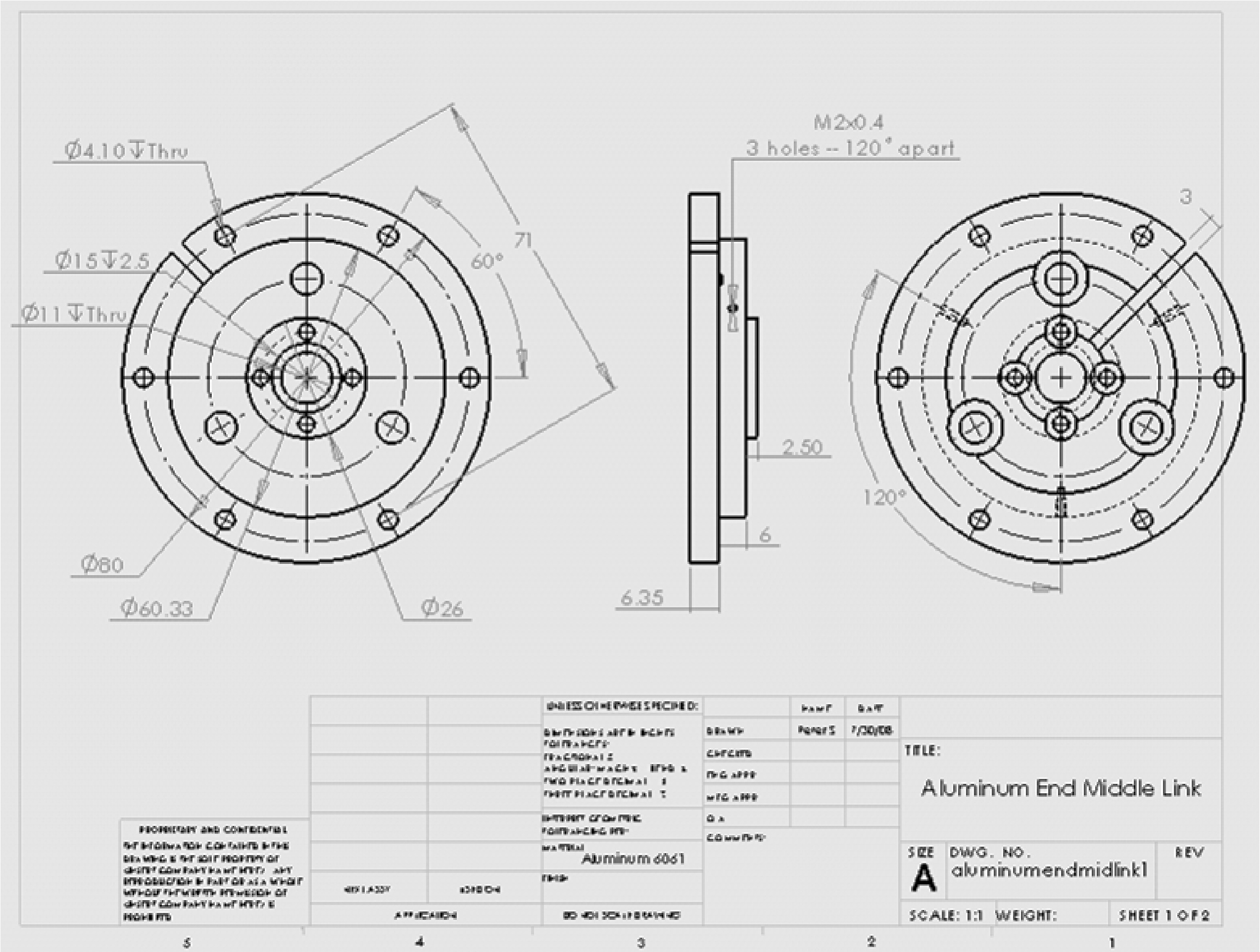

Figure 41. Aluminum End of Middle Link Front and Side View

Appendix A (Continued)

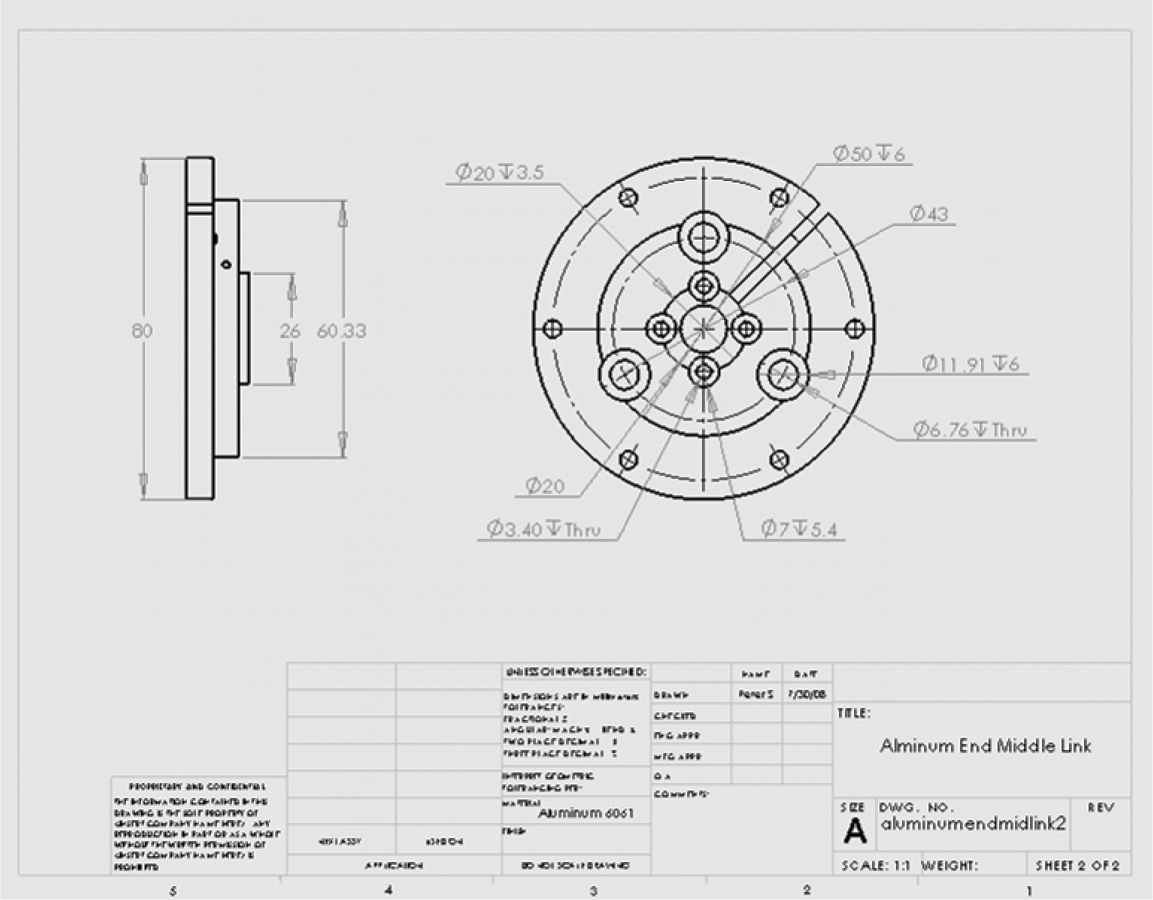

Figure 42. Aluminum End of Middle Link Back View

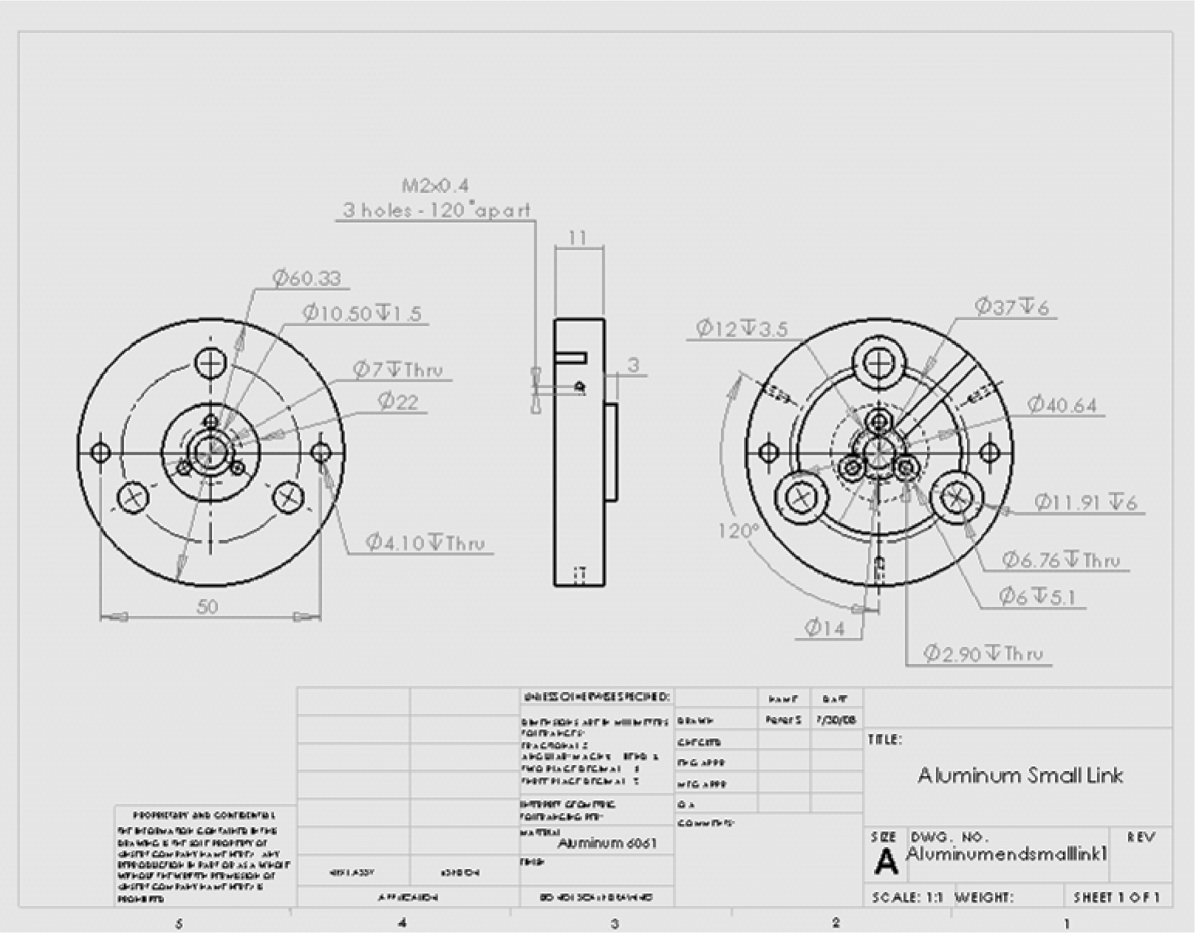

Figure 43. Aluminum End of Small Link Front, Side, and Back View

Appendix A (Continued)

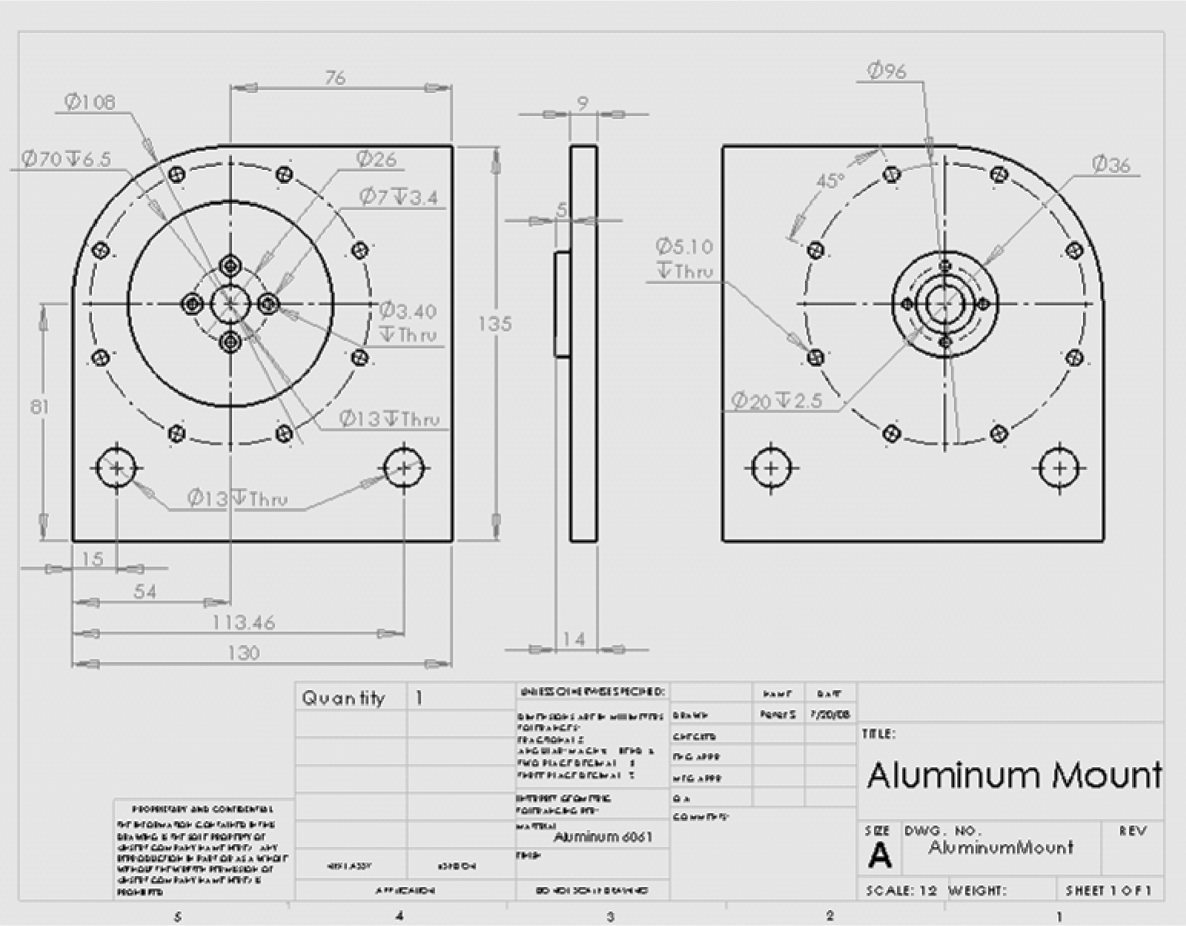

Figure 44. Aluminum Mount for Mobile Platform

Appendix B Plastic Cover Detailed Drawings

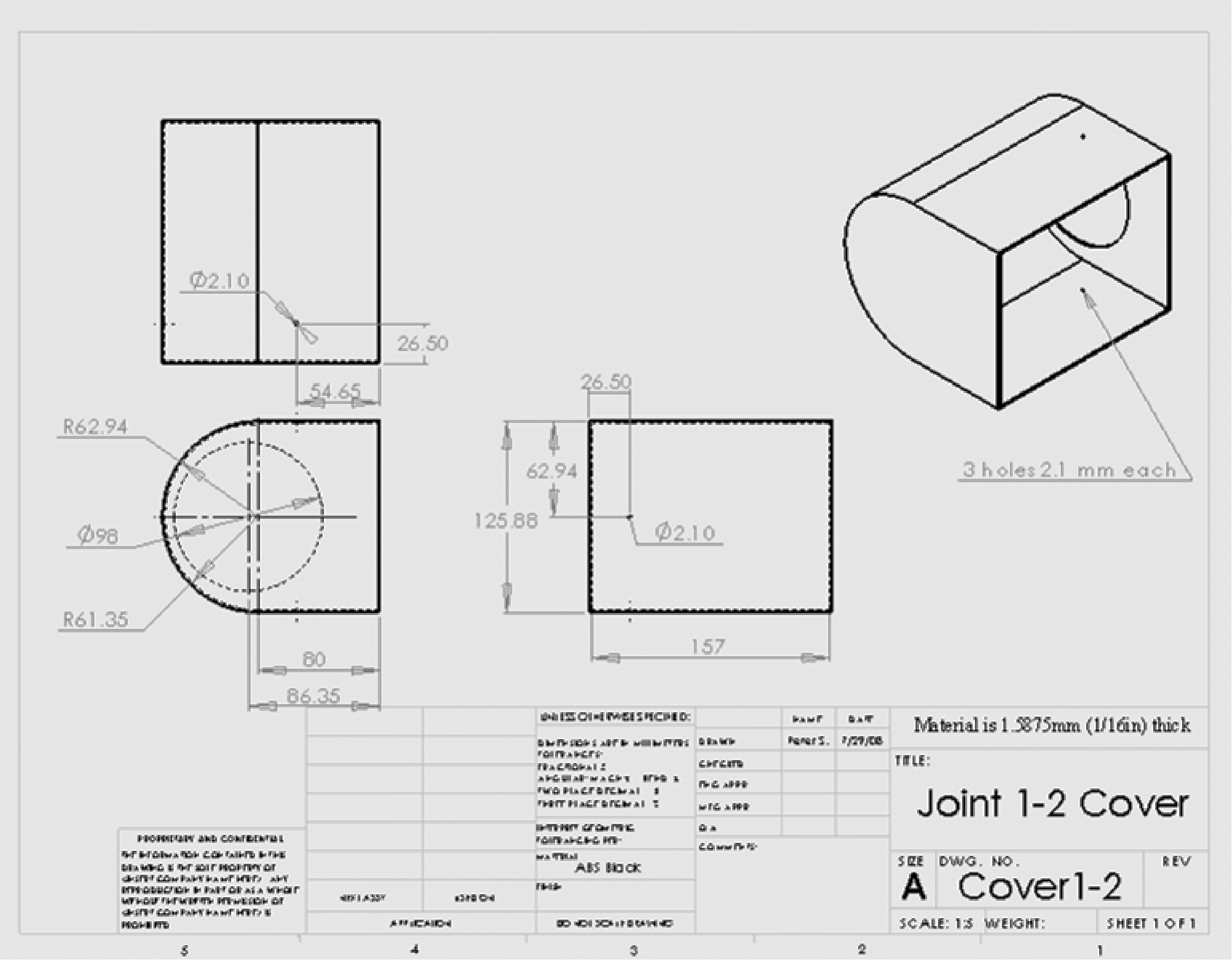

Figure 45. Plastic Cover of Joints 1 and 2

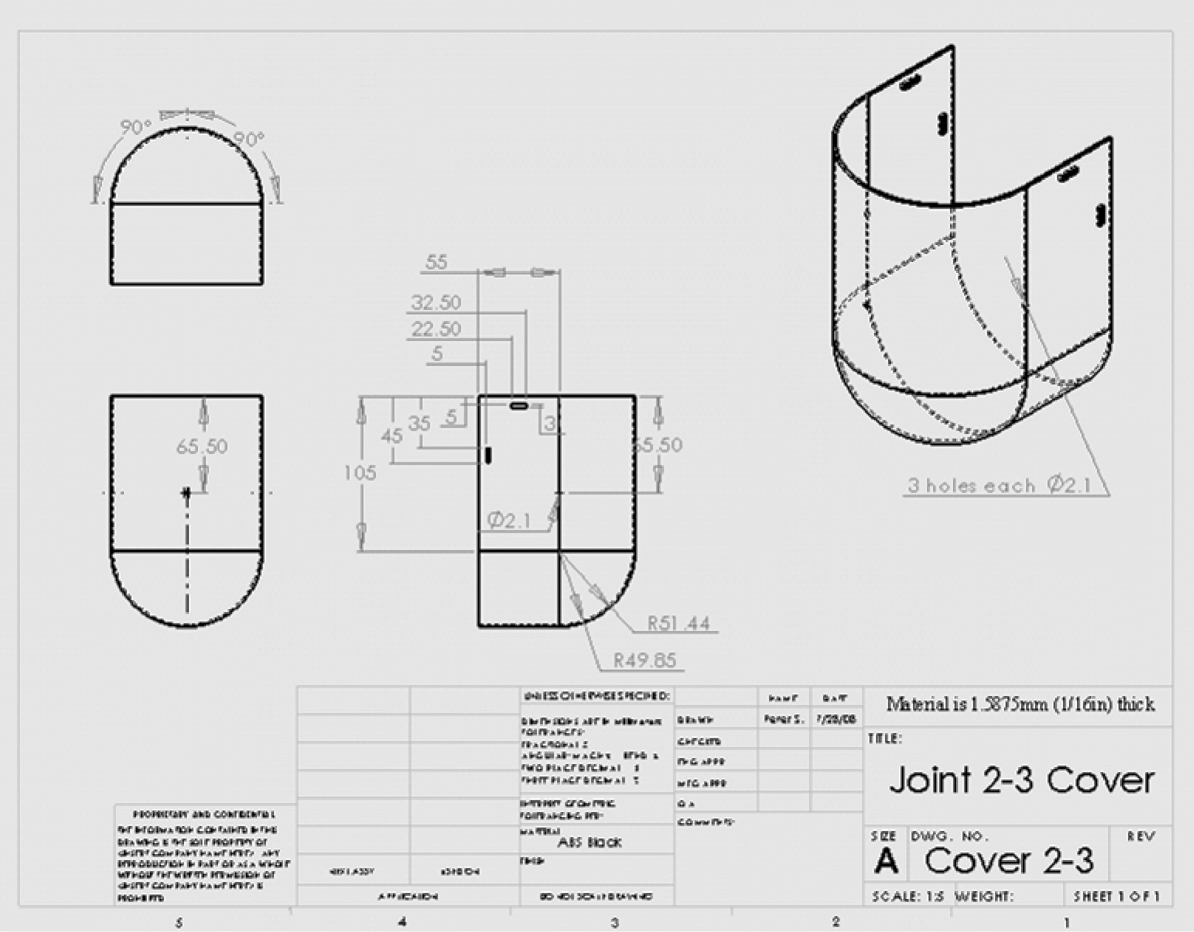

Figure 46. Plastic Cover of Joints 2 and 3

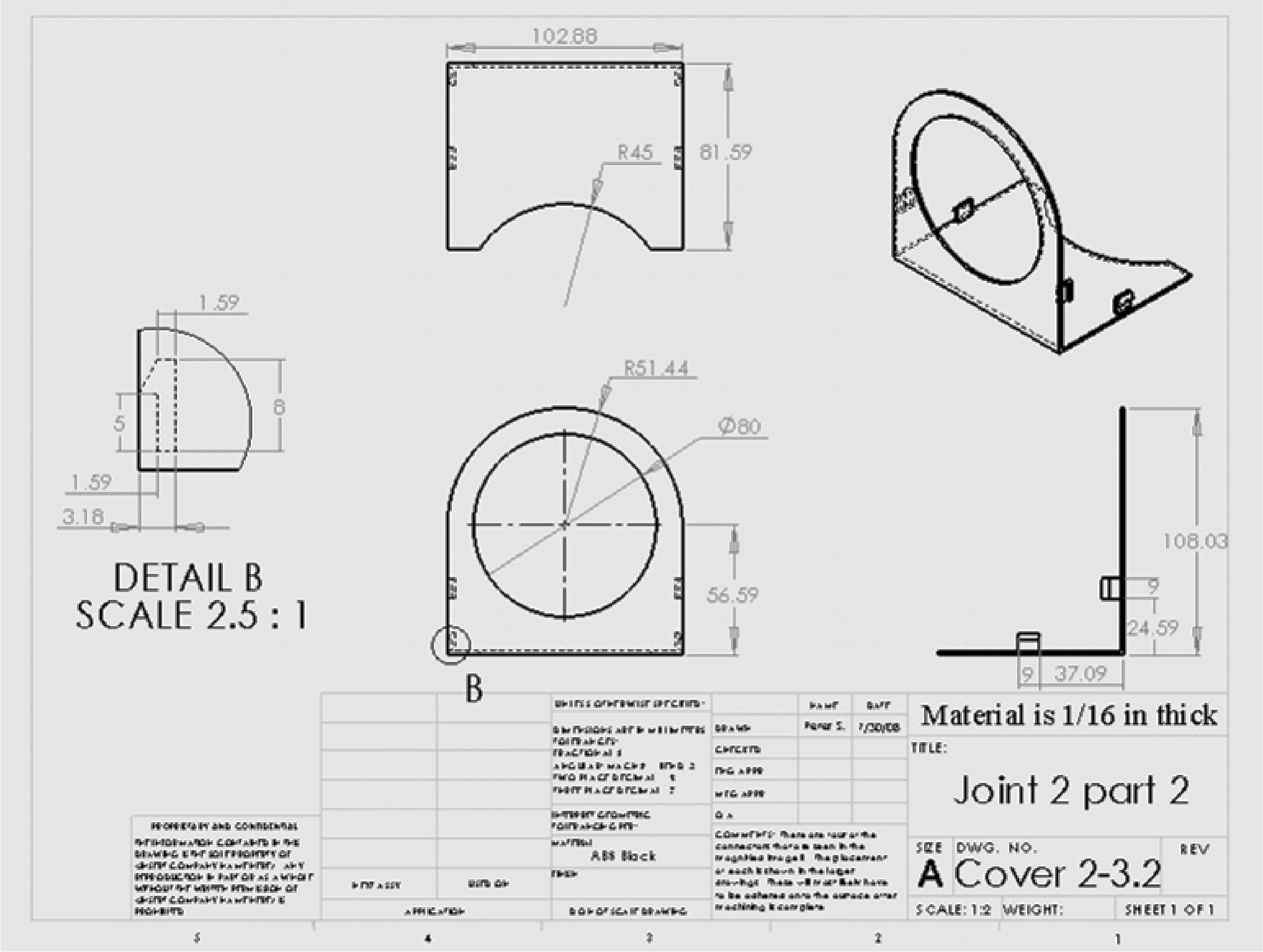

Figure 47. Plastic Insert for Joints 2 and 3 cover

Appendix B (Continued)

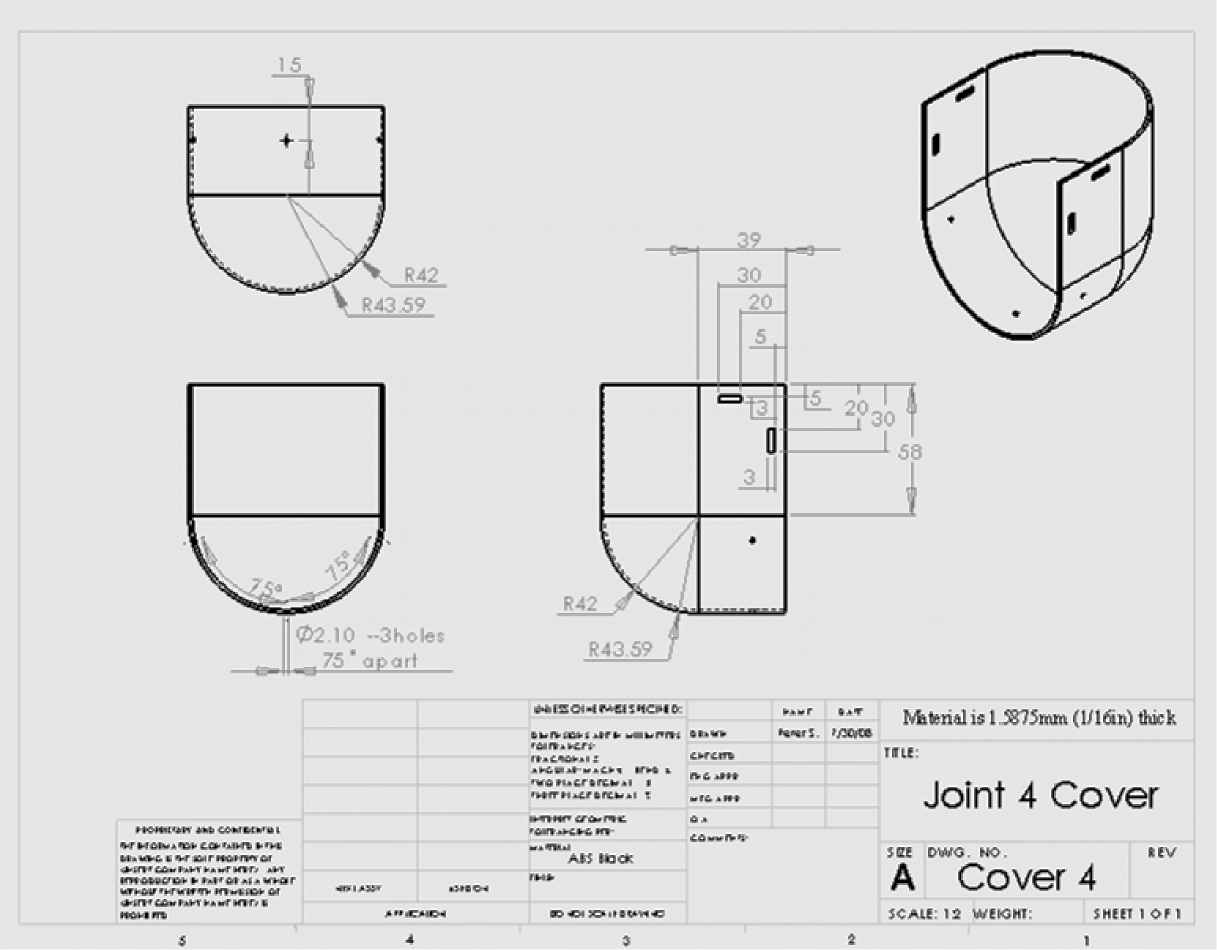

Figure 48. Plastic Cover for Joint 4

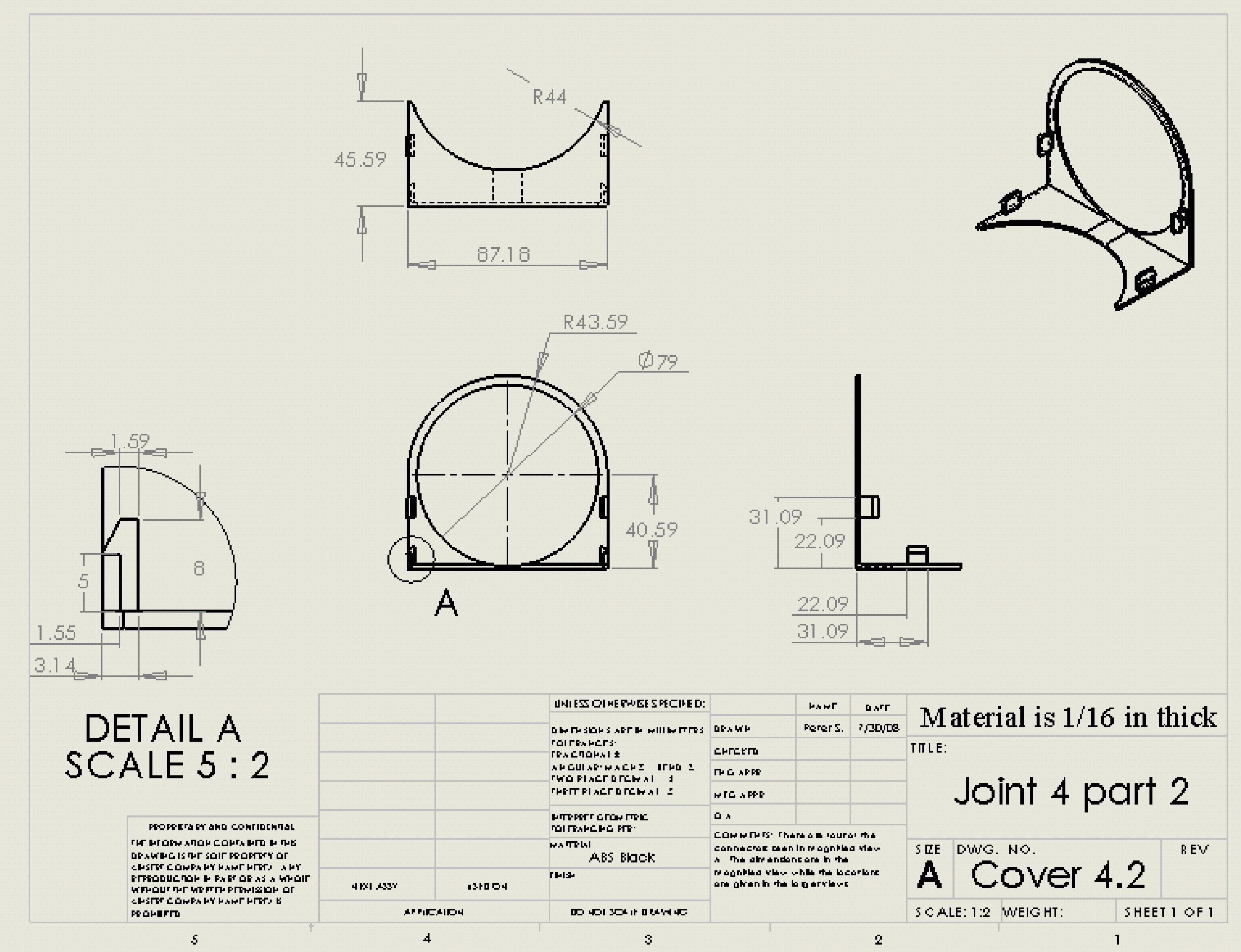

Figure 49. Plastic Insert for Joint 4 Cover

Appendix B (Continued)

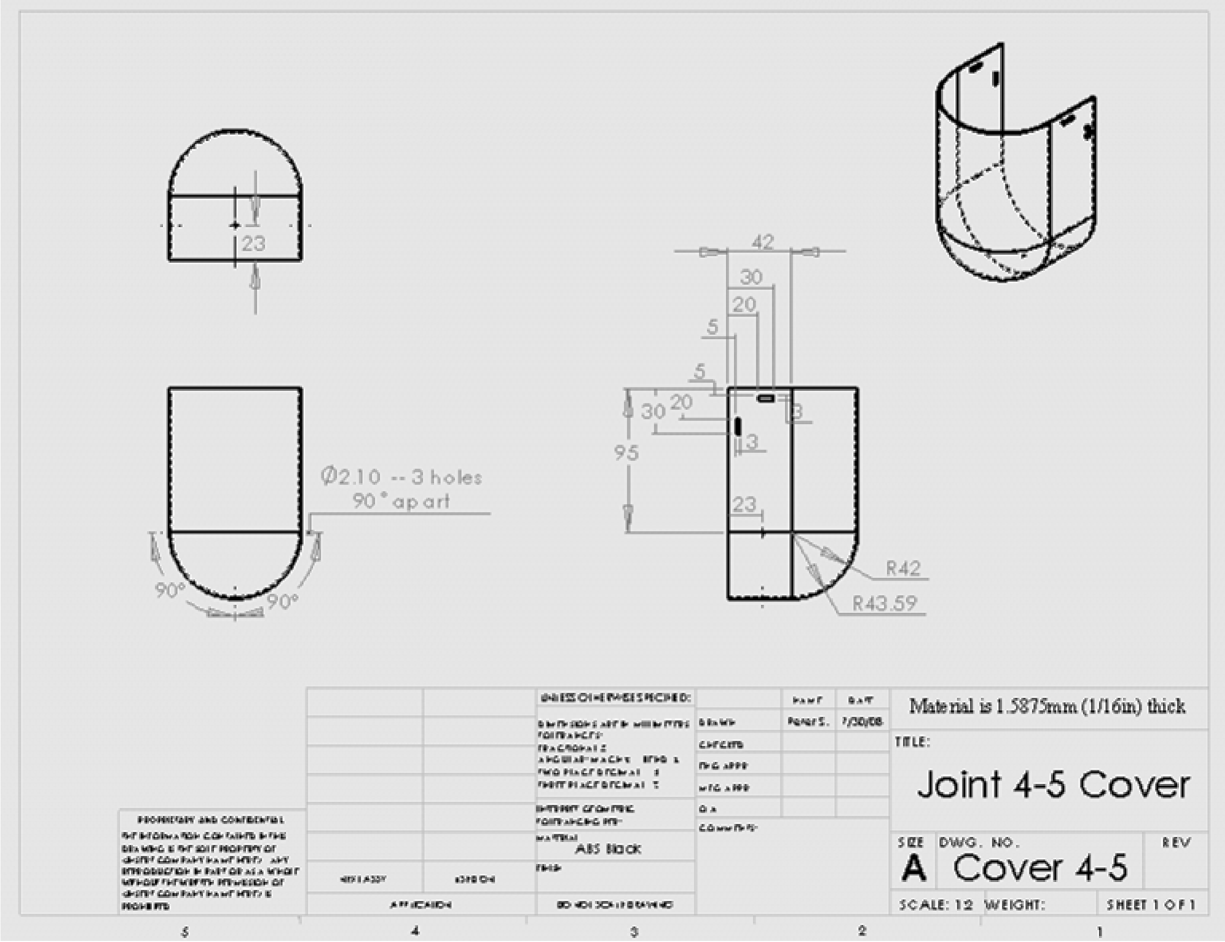

Figure 50. Plastic Cover for Joint 5

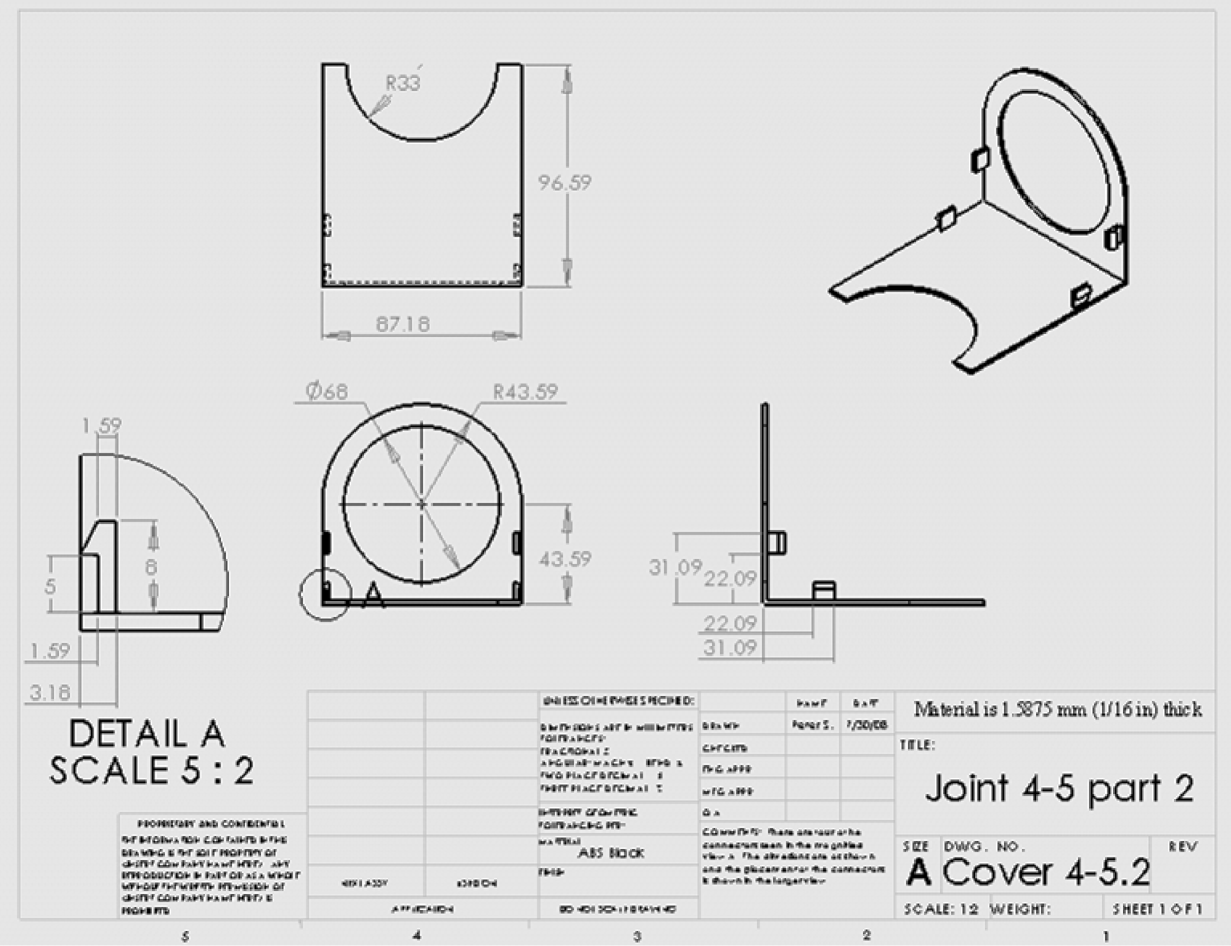

Figure 51. Plastic Insert for Joint 5 Cover

Appendix B (Continued)

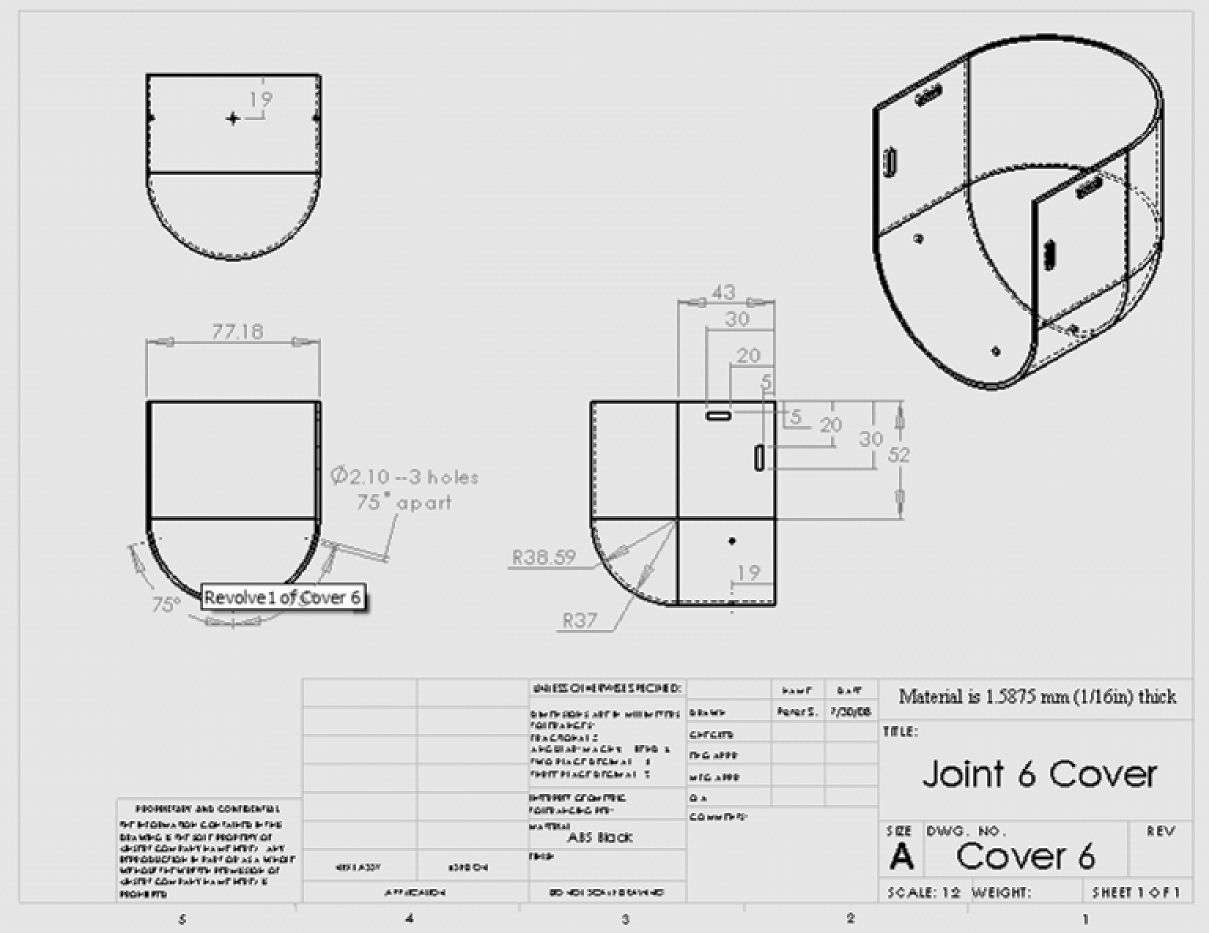

Figure 52. Plastic Cover for Joint 6

Appendix B (Continued)

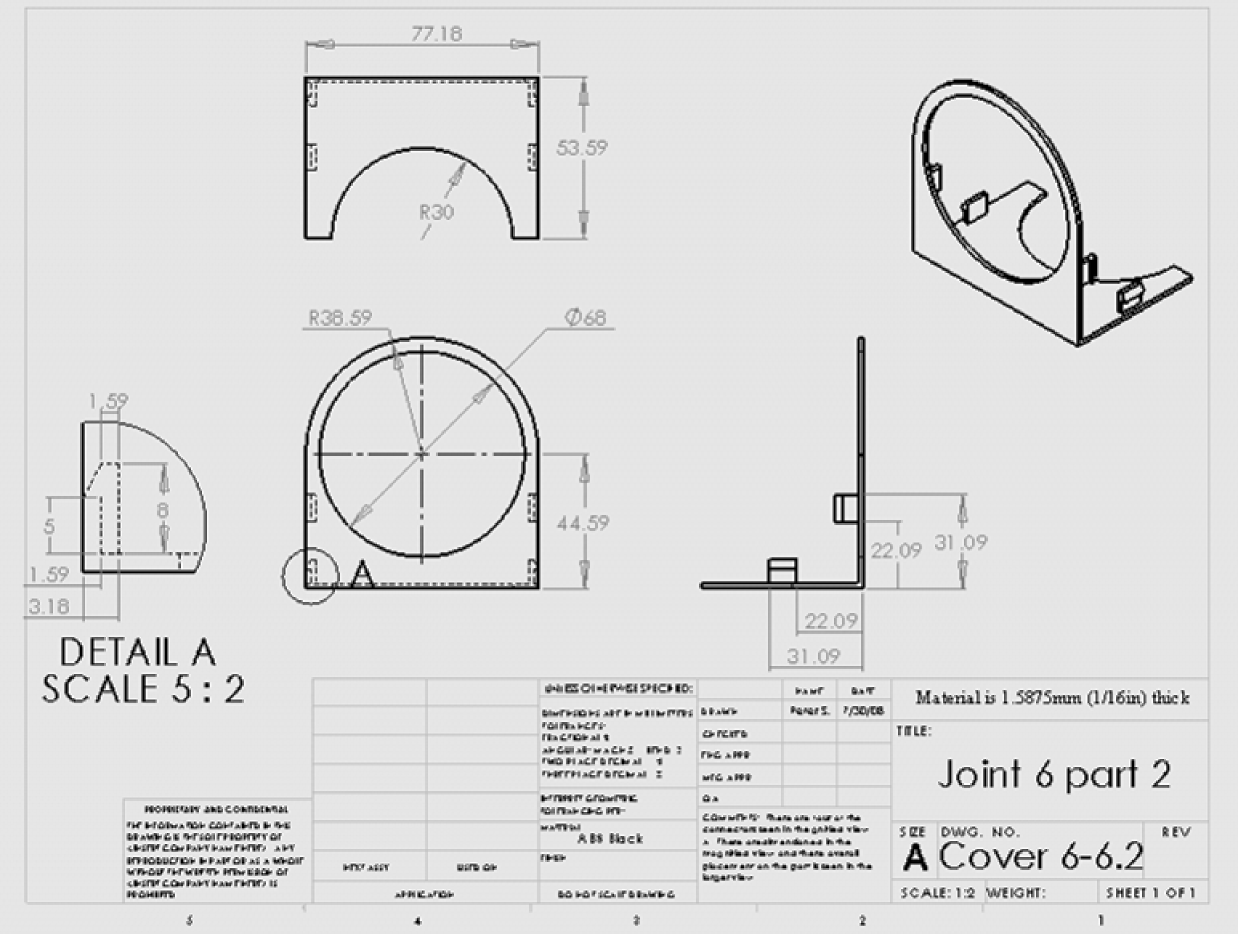

Figure 53. Plastic Insert for Cover of Joint 6

Appendix B (Continued)

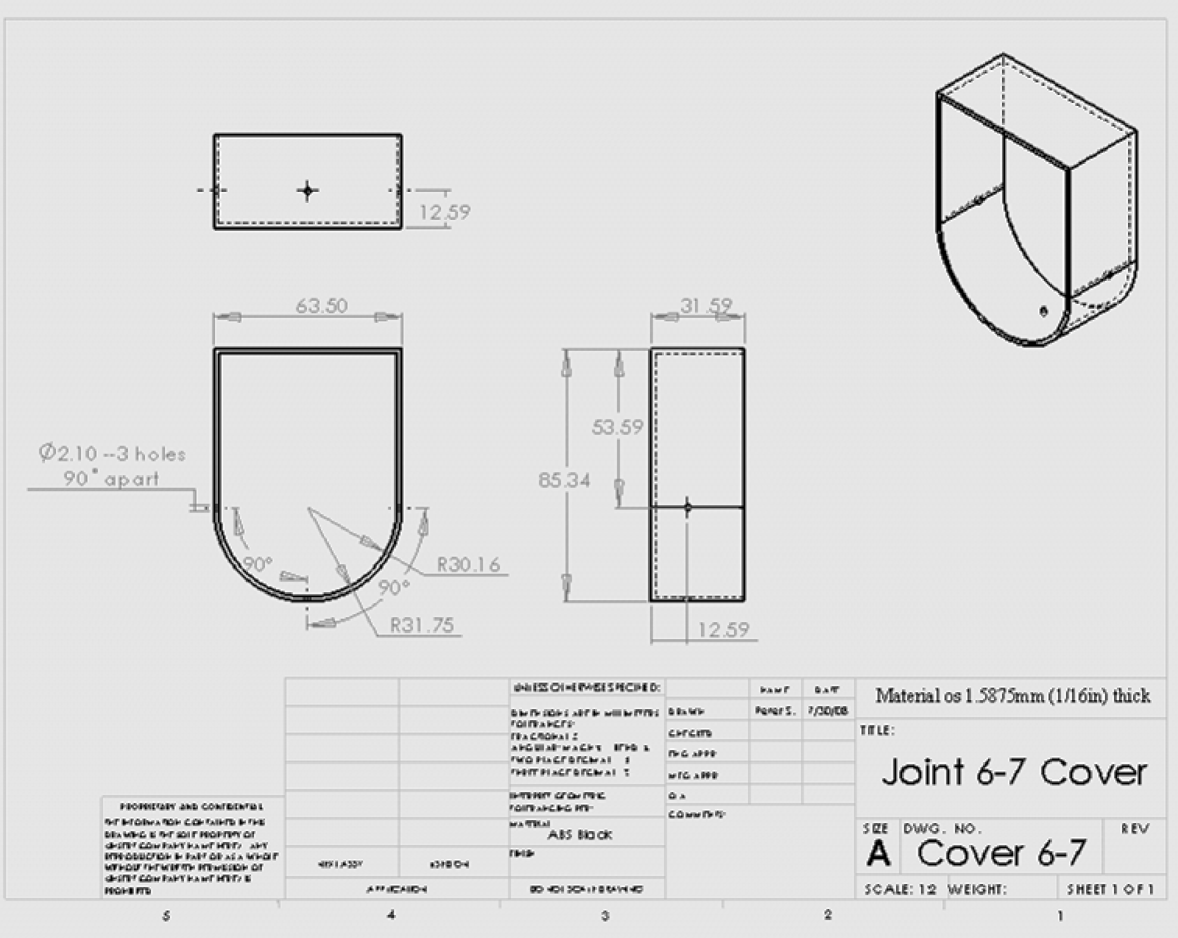

Figure 54. Plastic Cover of Joint 6 and 7

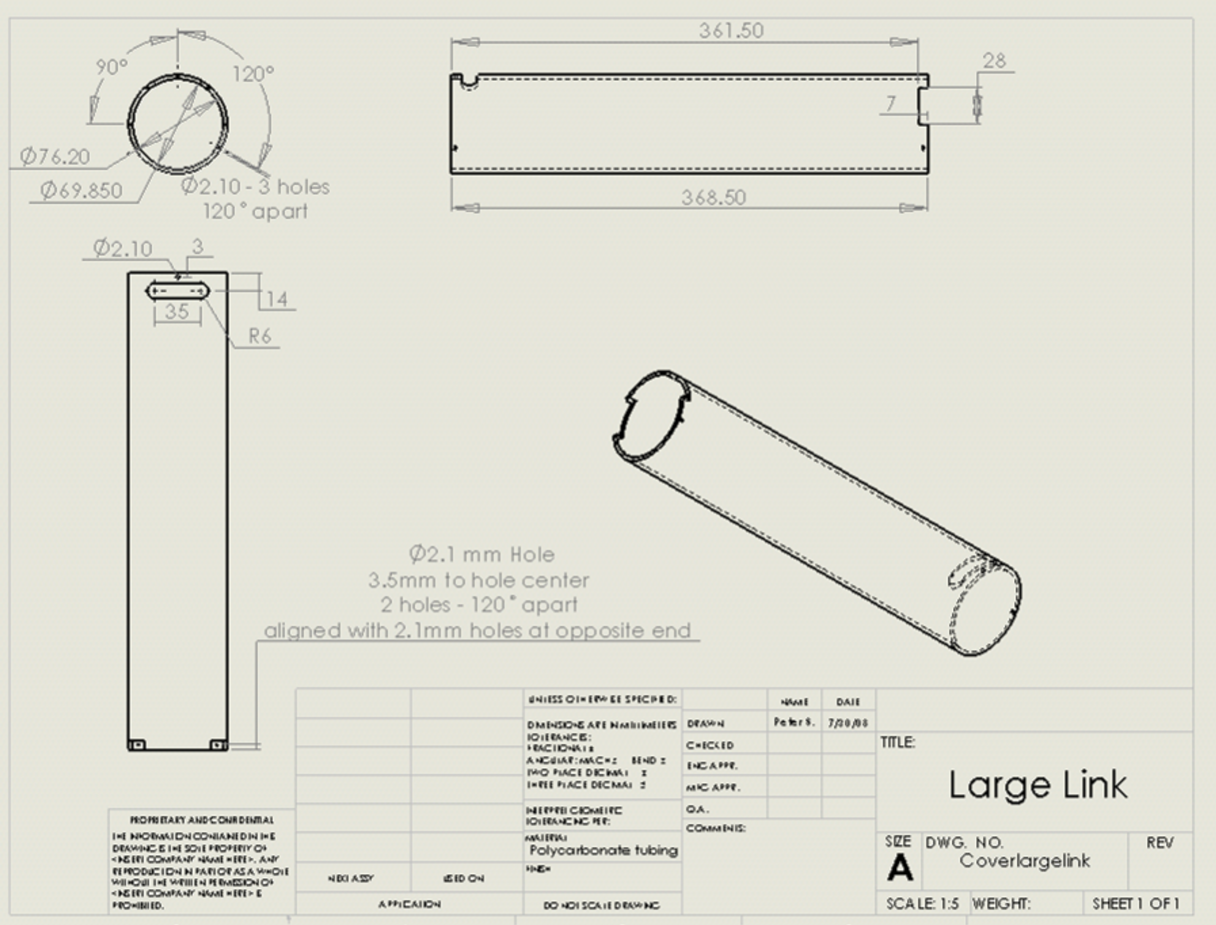

Figure 55. Polycarbonate Cover for the Large Link (Link 3)

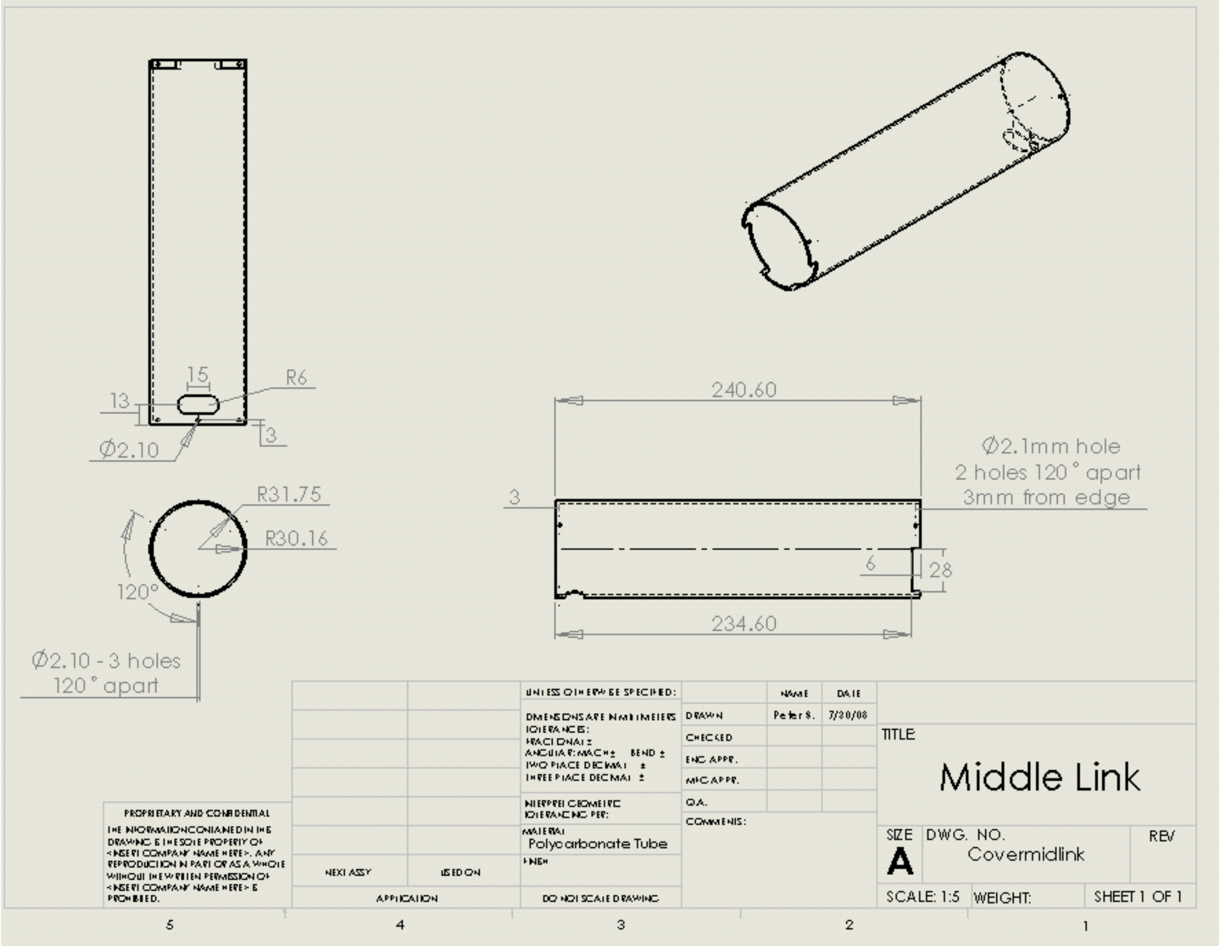

Figure 56. Polycarbonate Cover for the Middle Link (Link 2)

Appendix B (Continued)

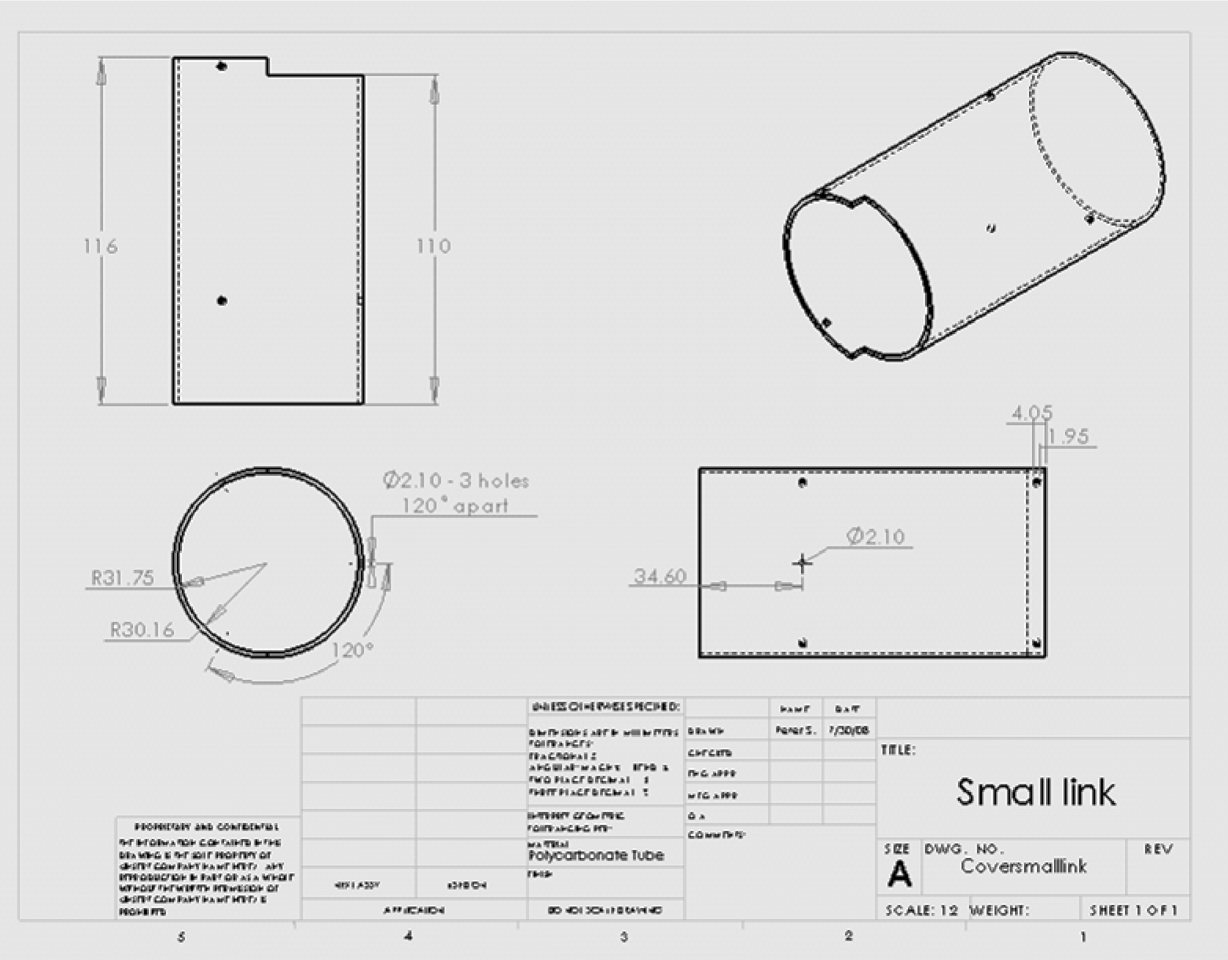

Figure 57. Polycarbonate Cover for the Small Link (Link 3)

Appendix C Carbon Fiber Tube Detailed Drawings

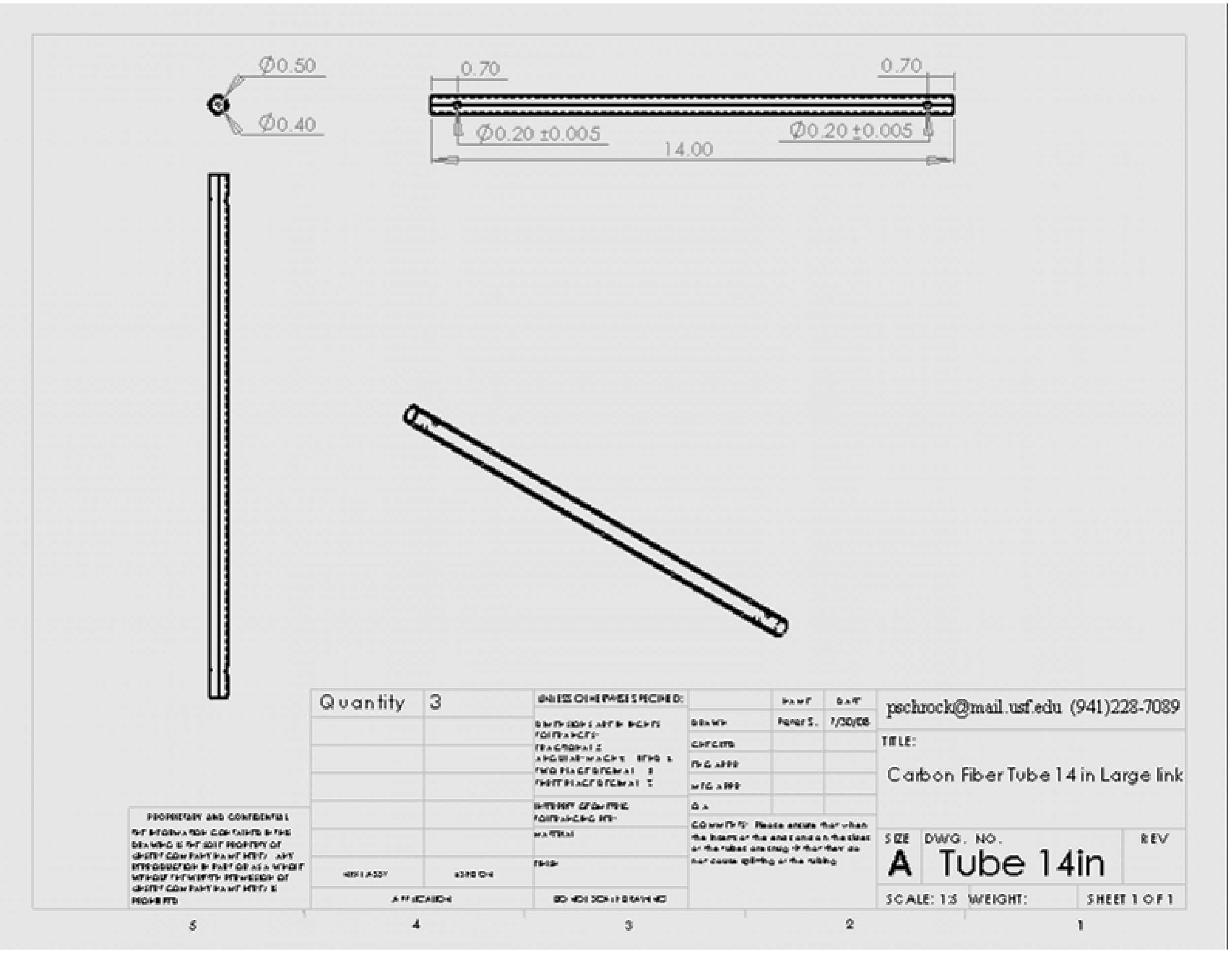

Figure 58. Carbon Tube for Large Link Frame

Appendix C (Continued)

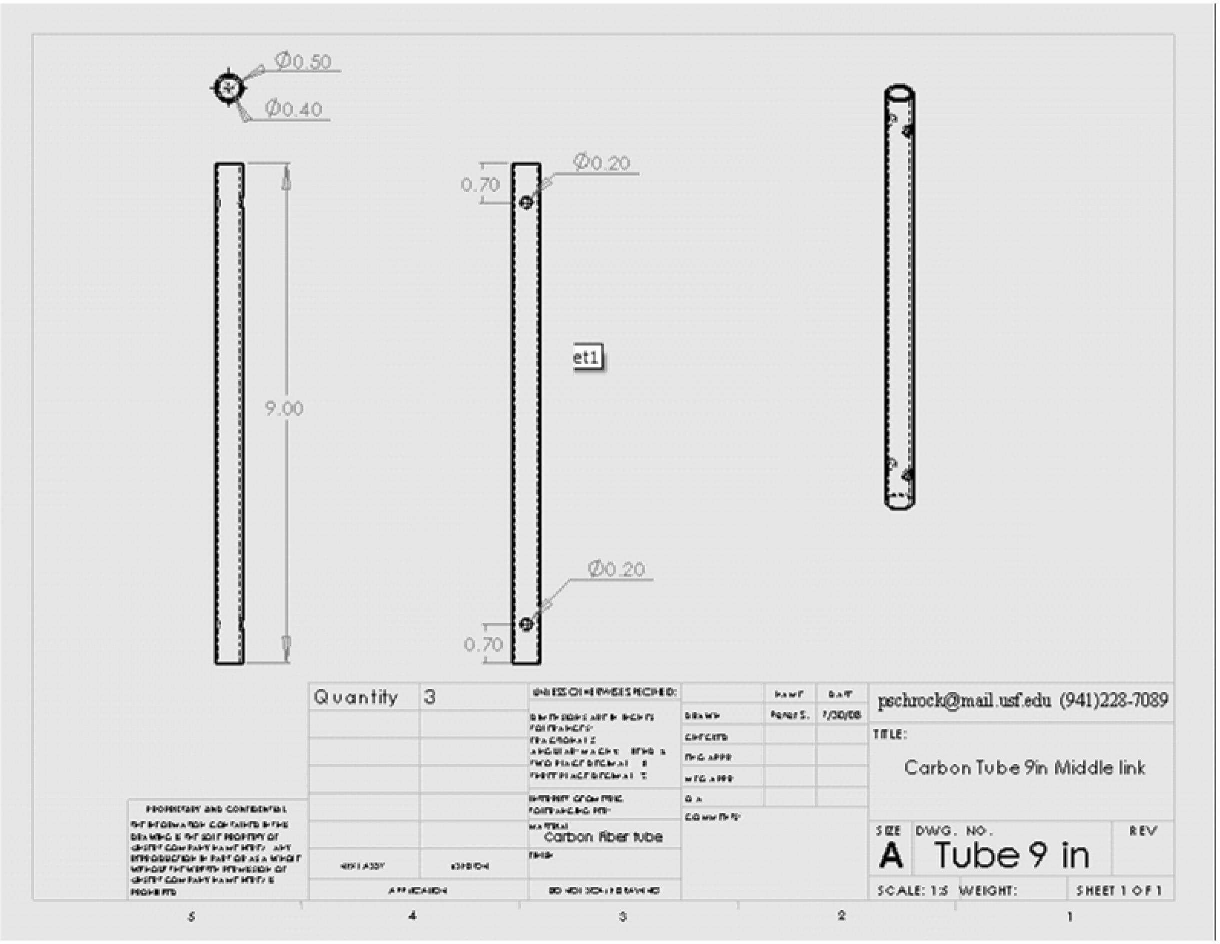

Figure 59. Carbon Tube for Middle Link

Appendix C (Continued)

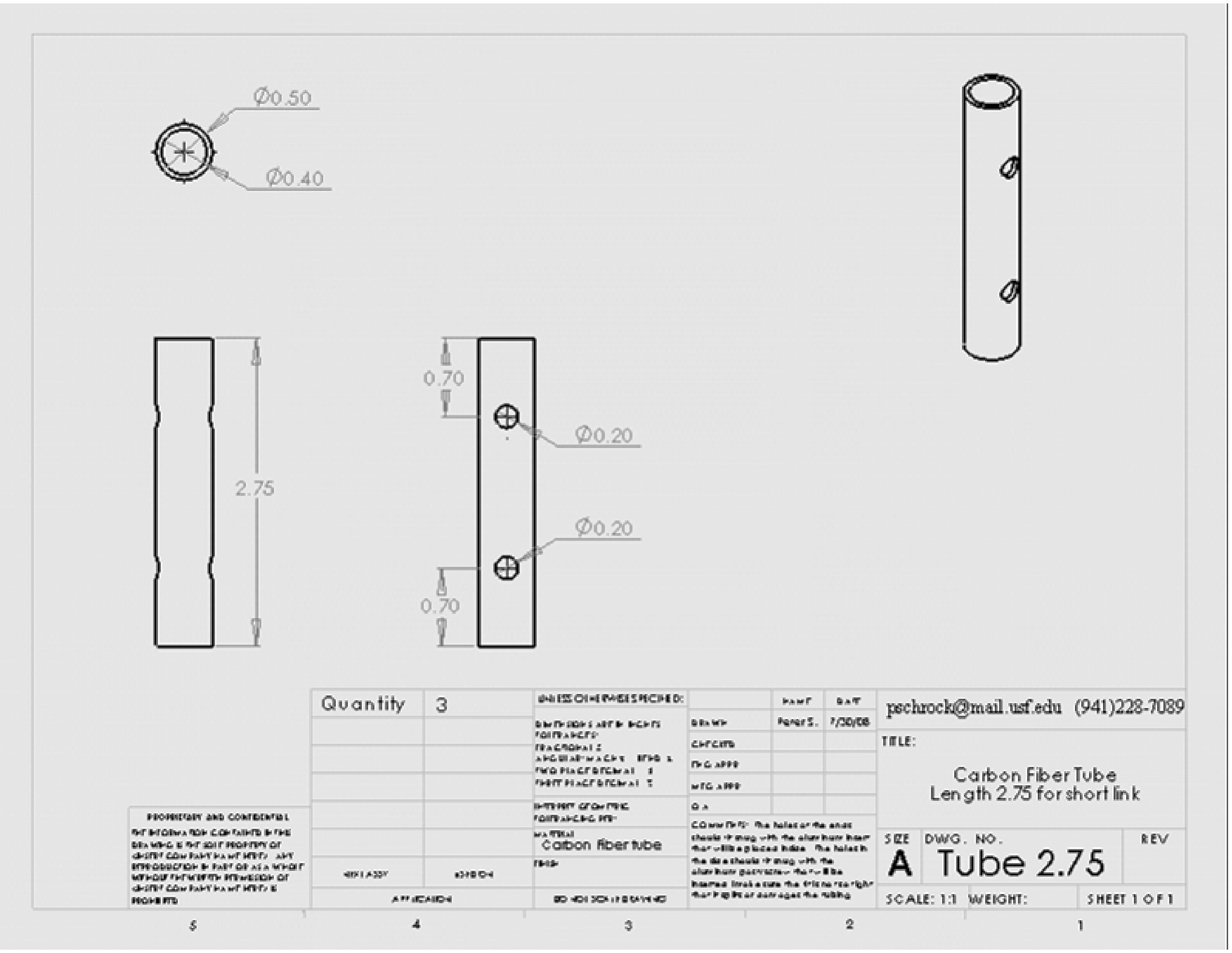

Figure 60. Carbon Tube for Small Link

Appendix D Carbon Fiber Tube Properties

Table 8. Pultruded Carbon Fiber Tube Properties

TYPICAL PROPERTIES:	CARBON FIBER TUBES:
TENSILE STRENGTH	280 ksi / 1.93 GPa
TENSILE MODULUS	19.5 msi / 134 GPa
FIBER VOLUME	60%
ULTIMATE TENSILE STRAIN	1.40%
ULTIMATE SHEAR STRENGTH	6.0 ksi / 41.3 MPa
FLEXURAL STRENGTH	240 ksi / 1.65 GP3
FLEXURAL MODULUS	18.5 msi / 128 Gpa
DIAMETER TOLERANCE	.000 / .003"
THERMAL EXPANSION COEFFICIENT	0.1 ppm/°F / .2 ppm/°C
DENSITY	.054 lbs/in3 / 1.5 g/cm3
GLASS TRANSITION TEMPERATURE	100°C
MATRIX MATERIAL	Bisphenol Epoxy Vinyl Ester

Appendix E Wiring and Connector Hardware

Table 9. Motors 1 Through 4 Wire Connections for Power and Encoder

Motors 1 - 4				
Power Wires	Wire size (AWG)	Wire Color	Control Board End Pin Number 4-pin connector	Motor End Pin Number 4-pin connector
Motor Winding 1	22	Red	2 [A]	1
Motor Winding 2	22	Black	4 [B]	2
Motor Winding 3	22	White	3 [C]	3
Encoder Wires	Wire Size (AWG)	Wire Color	Control Board End Pin Number D-sub 15 pin	Motor End Pin Number 10-pin connector
5V (Vcc)	26	Light Green	15	2
Ground	26	Red	5	3
A-	26	Yellow	8	5
A+	26	Brown	3	6
B-	26	Orange	7	7
B+	26	Black/White	2	8
I-	26	Red/White	6	9
I+	26	Black	1	10
Hall Sensor	Wire size (AWG)	Wire Color	Control Board End Pin Number D-sub 15 pin	Motor End Pin Number 6-pin Connector
Hall 1	26	Blue	10	1
Hall 2	26	White	13	2
Hall 3	26	Pink	14	3
Ground	26	Red	5	4
5V (Vcc)	26	Light Green	15	5

Appendix E (Continued)

Table 10. Motors 5 and 6 Wire Connections for Power and Encoder

Motors 5 & 6				
Power Wires	Wire size(AWG)	Wire Color	Control Board End Pin Number 2-pin Connector	Motor End Pin Number 2-pin connector
Negative (-)	22	Black/Green	Negative	Negative Lead
Positive (+)	22	Red/White	Positive	Positive Lead
Encoder Wires	Wire Size (AWG)	Wire Color	Control Board End Pin Number D-sub 15 pin	Motor End Pin Number 10-pin connector
5V (Vcc)	26	Light Green	15	2
Ground	26	Red	5	3
A-	26	Yellow	8	5
A+	26	Brown	3	6
B-	26	Orange	7	7
B+	26	Black/White	2	8
I-	26	Red/White	6	9
I+	26	Black	1	10

Appendix E (Continued)

Table 11. Motor 7 Wire Connections for Motor and Encoder

Motor 7				
Power/Encoder Wires	Wire size(AWG)	Wire Color	Control Board End Pin Number D-sub 15 pin/2-pin	Motor End Pin Number 10-pin connector
Negative (-)	22	Black	Negative	4
Positive (+)	22	Red	Positive	1
5V (Vcc)	26	Light Green	15	2
Ground	26	Red	5	3
A-	26	Yellow	8	5
A+	26	Brown	3	6
B-	26	Orange	7	7
B+	26	Black/White	2	8
I-	26	Red/White	6	9
I+	26	Black	1	10

Table 12. Motor 8 Wire Connections for Gripper Motor and Encoder

Motor 8				
Power/Encoder Wires	Wire size(AWG)	Wire Color	Control Board End Pin Number D-sub 15pin/2-pin	Motor End Pin Number 6-pin connector
Negative (-)	22	Black	Negative	5
Positive (+)	22	White	Positive	6
5v (Vcc)	22	Green	15	3
Ground	22	Red	5	4
A+	22	Yellow	3	1
B+	22	Blue	2	2

Appendix F Galil Tools Simultaneous Motor Movement Program

```
SP 80000,80000,80000,80000,80000,80000,80000,80000;
```

Speed setting for each axis to 80000 encoder counts per second

```
AC 150000,150000,150000,150000,150000,150000,150000,150000
```

Acceleration setting for each axis set to 150000 counts per second^2

```
DC 150000,150000,150000,150000,150000,150000,150000,150000
```

Deceleration setting for each axis set to 150000 counts per second^2

```
SH
```

Start Here command for motors to start motion from current position

```
PAA=-400000
PAB=-400000
PAD=-400000
PAE=400000
PAF=400000
PAG=400000
PAH=-400000
```

Absolute position movement from zero point to specified point all of which are equal in magnitude

```
BG
```

Begin motion of all axes