2005

Design, Construction and Testing of a Wheelchair-Mounted Robotic Arm

Kevin D. Edwards
University of South Florida

Scholar Commons Citation
Edwards, Kevin D., "Design, Construction and Testing of a Wheelchair-Mounted Robotic Arm" (2005). *Graduate Theses and Dissertations.*
https://scholarcommons.usf.edu/etd/2867

Design, Construction and Testing of a Wheelchair-Mounted Robotic Arm

By

Kevin D. Edwards

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science of Mechanical Engineering
Department of Mechanical Engineering
College of Engineering
University of South Florida

Major Professor: Rajiv Dubey, Ph.D.
Glen Besterfield, Ph.D.
Daniel Hess, Ph. D.

Date of Approval:
July 14, 2005

Keywords: wmra, rehabilitation, reconfigurable, machine design, adl, assistive

Table of Contents

List of Tables

List of Figures

Design, Construction and Testing of a Wheelchair - Mounted Robotic Arm

Kevin D. Edwards

ABSTRACT

A wheelchair-mounted robotic arm (WMRA) was designed and built to meet the needs of mobility-impaired persons, and to exceed the capabilities of current devices of this type. The mechanical design incorporates DC servo drive, with all actuator hardware at each individual joint, allowing reconfigurable link lengths. It has seven principal degrees of freedom and uses a side mount on a power wheelchair. A simple, scalable control system allows coordinated Cartesian control, and offers expandability for future research, such as coordinated motion with the wheelchair itself. Design payload including gripper is 6 kg, and the total arm mass with controller is 14 kg. These and other design attributes were confirmed through testing on the completed prototype.

This paper discusses the current state of the art in WMRAs; describes the design goals and user requirements for this device; explains the component selection process; discusses details of the mechanical design, electrical system and low-level controller; covers manufacturing concerns; and describes the testing of the completed arm. Suggestions for further development are also included.

Chapter One:

Introduction

1.1 Motivation

A wheelchair mounted robotic arm can enhance the manipulation capabilities of mobility-impaired persons, and reduce dependence on human aides. Unfortunately, the present state of the art for this application has not met with much commercial success, which may be due to poor usability and low payload. It is difficult, cumbersome, and sometimes impossible to accomplish everyday tasks with the WMRAs currently on the market. This project attempts to surpass previous devices in terms of performance, while maintaining cost competitiveness.

Data from the US Census Bureau Statistical Brief of 1993 showed that over 34 million Americans had difficulty performing functional activities. Of this number, over 24 million were considered to have severe disabilities. Every year more and more people become disabled in a way that minimizes their use of upper extremities. These can be motor dysfunctions due to accidents, disease, aging, or genetic predispositions.

The field of Rehabilitation Robotics has been created in an attempt to increase the quality of life and to assist in activities of daily living. Rehabilitation Robotics addresses assistive technologies as well as the traditional definition of rehabilitation: increasing or expanding the individual’s mental, physical, or sensory capabilities. The primary focus of

Rehabilitation Engineering and robotics is to increase the quality of life through increasing functional independence, and decreasing the costs associated with the assistance required by the individual.

We are interested in people who have limited or no upper extremity mobility. Robotic aids used in these applications vary from advanced limb orthosis to robotic arms. Persons that benefit from the devices are those with severe physical disabilities, which limit the ability to manipulate objects. These devices increase self-sufficiency, and reduce dependence on caregivers. The following are examples of those who could benefit from a robotic arm.

In the case of spinal injury or dysfunction, robotic aids are most appropriate for individuals with spinal deficiencies ranging from cervical spine vertebra 3 through cervical spine vertebra 5. Below the cervical spine vertebra 5, individuals often can be served with simpler, more traditional assistive technology. Persons with these injuries can generally make use of their upper limbs, and robotic arms are not necessary, nor significantly improve quality of life. Similarly, persons with spinal fractures above cervical spine vertebra 3 are also not served well by robotic assistance. Injuries are usually so debilitating with this type of injury that a respirator and daily attendants are required, thereby reducing the benefit of assistive devices.

Other individuals that could benefit from a robotic arm are persons with neuromuscular deficiencies such as multiple sclerosis.

Since persons with the above disabilities require mobility assist devices, such a power wheel chair, this power wheelchair is the natural platform for adding further mobility assistance. There have been several attempts in the past to create commercially viable wheelchair mounted robotic arms. The power wheelchair not only provides an excellent structure with which to mount the device, but also provides a power supply. Currently there are only two commercial WMRAs available, the *Manus* (Exact Dynamics, Inc., Netherlands) and the *Raptor* (Applied Resources, Inc, NJ USA).

1.2 Objectives

The main objective of this thesis was to design and build a prototype WMRA. This manipulator had to be lightweight, able to carry a 4 kg payload at full reach, and be capable of Cartesian control. In addition, it had to be cost competitive with other WMRAs and with traditional human assistants. This paper discusses the many decisions that led to a product meeting these and other specific requirements.

Chapter Two:

Background

2.1 History of Rehabilitation Robotics

There have been various attempts over the years to create robotic assistants for individuals with various levels of disabilities. For over 30 years research has progressed in the field with only partial commercial success.

An early attempt at telemanipulators was done at the Case Institute of Technology during the early 1960's. The Case system was a floor mounted, powered exoskeleton. The operator controlled the device by wearing a head-mounted light source that triggered light sensors in the environment. By looking at specific points in the room, the operator could trigger the light sensors, and initiate one of several preprogrammed gestures that were stored on magnetic tape. A later development allowed for Cartesian movement and direct control of individual joints, along with myoelectric signals for velocity control.

One of the first attempts at rehabilitation robotics included the Rancho "Golden" arm, designed in 1969 at Rancho Los Amigos Hospital in Downy, California (Reswick 1990). The arm was an electrically driven 6 DOF robotic arm mounted to a powered wheelchair, and was controlled at the joint level by an array of tongue-operated switches. Further discussions on the topic of the controllability of the arm commented on both successes and failures the design and those successes with the project can be attributed to the important role that proprioceptive feedback plays in the control of extremities (Allen et al., 1972). These were pioneering research projects that often provided a framework for future development.

This early work expanded the field of assistive robotics to the wide variety of devices found today. Different design goals and approaches to the problem have yielded many typs of robotic devices. For clarity, assistive robotics can be divided into several categories:

1. Workstation robots, which are for stationary, well-structured environments.
2. Mobile assistive robots, which travel about the room and have a manipulator arm.
3. Wheelchair mounted robotic arms (WMRAs) that mount a manipulator arm onto the individual's wheelchair to provide assistance throughout the day.

2.2 Workstation Based Systems

The very first rehabilitation robotics applications focused on using commercially available industrial manipulators and modifying them for rehabilitation applications.

A factor limiting the use of industrial robotic arms in rehabilitative robotics roles is the basic differences in operational requirements. Industrial arms are designed to work at high speed and accuracy in an environment where there are no humans. For applications in a human intensive workspace, assistive robotic arms must be mechanically limited to low velocities and accelerations. Further, high stiffness and accuracy found in industrial robots is unnecessary in rehabilitation.

One workstation robot example is The Robotic Aid Project. This was an attempt to create a system for users with quadriplegia, by adapting an already commercially available industrial robotic arm. This was the integration of a PUMA 250 arm, microprocessor, multi-line monochrome display and speech synthesis and recognition systems. The PUMA 250 is shown in Figure 2.1. Limitations with the speech recognition systems of the day and computational deficiencies limited the success of the program. The computational power of computers of the day did not allow for real time inverse kinematics of the arms, which limited the arm to replaying preprogrammed actions. Individual joints of the arm could be manipulated but coordinated real time multi-joint maneuvers were impossible.

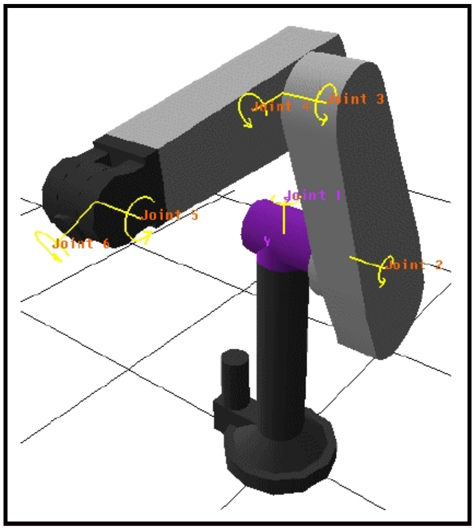

Figure 2.1: Puma 250 Arm

As more application-specific robotic arms and computers with increased computational power became available, arms with controllers could now be mounted onto mobile platforms. At first these systems were simple rolling bases, and later they increased in complexity and degrees of freedom to include powered mobile robots.

Handy-1 is a robotic arm mounted to a non-powered wheeled base to assist in very specific activities of daily living (ADL). Handy-1 was developed in 1988 to provide persons with severe disabilities assistance at mealtimes. The unit is capable of providing assistance in personal hygiene, eating, and the application of make-up. During user trials women specifically asked if the unit would be capable of putting on cosmetic products. Shortly after the trials, the design was upgraded with a new tray and gripper accessory. Each task has a specific tray to accomplish its goal. Handy-1 is shown in Fig. 2.2 and is based on a 5-DOF, lightly modified industrial manipulator (Topping 1999).

Figure 2.2: Handy-1

In the feeding mode, the operator controls the robot through an interface that uses lights that move across the available food trays, and a button to select the item desired. Once the button is pressed the robot scoops up the food and brings it to a predetermined place near the operator’s mouth. Once the user has consumed the food, he presses another button, and the robot returns to the food selection mode.

This assistive device does not eliminate the need for a personal assistant but allows for individuals to have an increased level of self-sufficiency. In user trials, almost invariably the users believed the device significantly increased their quality of life.

The Wessex robot (Bath Institute of Medical Engineering) is a trolley-mounted mobile robot with modified SCARA geometry. A SCARA arm has two revolute joints in the horizontal plane, allowing it to reach any point within a horizontal planar workspace defined by two concentric circles. In modified SCARA configuration most of the joints operate in the horizontal plane. All vertical movement is achieved through the use of a single vertical actuator. The Wessex suffered from several shortcomings; one example was its limited reach making it unable to pick up items off the ground. The arm also had limited reach beyond the tray at the top of the trolley. The trolley was not powered and was pushed into location by the daily assistant. In user trials the operator felt limited by its programmability and fact that the trolley was not powered. The user felt that if the trolley were able to be remote controlled it could be used to retrieve or manipulate objects within the same room. For example, the operator could adjust the thermostat or retrieve a drink from an attached kitchen (Hillman and Gammie 1994).

The RAID workstation shown in Fig. 2.3 was designed to be a workstation assistive robot system. It is comprised of a 6 DOF robotic arm mounted onto a linear track in a well-controlled environment (Dallaway 1992). In the figure the manipulator can be seen near the top of the shelf in the center of the cabinet.

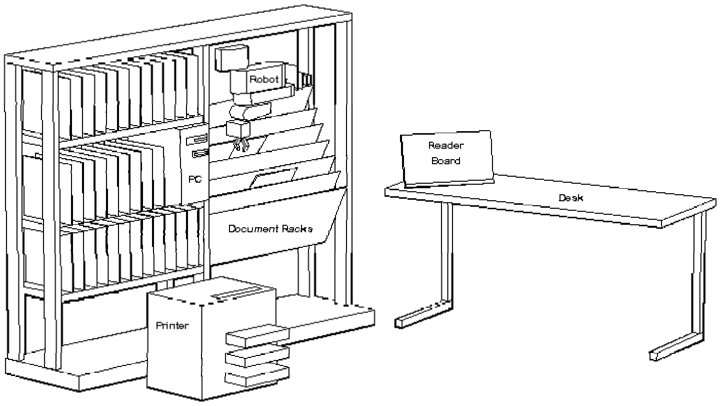

Figure 2.3: RAID Workstation

The RAID system benefits greatly from the formal structure provided by the workstation environment. This organization allows the manipulator arm to repeatedly move and acquire items needed by the operator using preprogrammed functions and routines.

Another robotic arm under development is The Robotic Assistive Device is by the Neil Squire Foundation in Vancouver, Canada. The RAD is a 6 DOF workspace mountable manipulator that uses a serial port computer interface. The manipulator is controlled through a graphical user interface (GUI), utilizing icons to symbolize predefined tasks. The arm can be mounted on various surfaces and has good repeatability at 3mm, and relatively large payload capacity of 4.3 kg. Most rehabilitation specific manipulators have maximum payloads of 2 kg or less (Squire 2004).

Figure 2.4: Robot Assistive Device

A similar system is The ProVAR (Stanford, CA), which is based on a Puma 260 robotic arm, and is designed to operate in a vocational environment. The ProVAR manipulator shown in Fig. 2.5 is the next generation of the DeVAR system and expands upon the previous research by reducing operating costs and increasing overall usefulness (Katevas 2000).

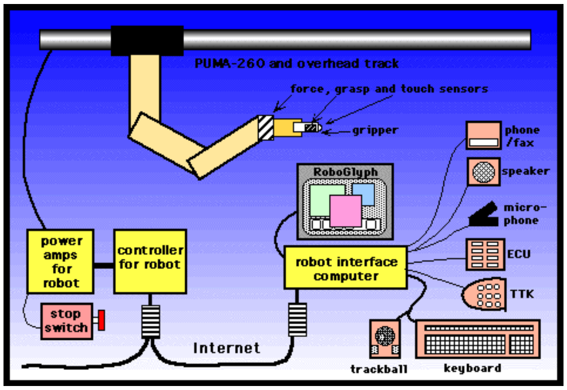

Figure 2.5: ProVAR System

The ProVAR uses a web-based virtual environment to model the functionality of the manipulator. In this way the operator can examine potential arm movements for a given task and if the simulation is successful the action can be performed. The primary goals for ProVAR are more functionality per dollar, easier operator control, and higher system reliability compared with the previous generation of vocational assistive robots.

2.3 Mobile Systems

The Mobile Vocational Assistant Robot (MoVAR), shown in Figure 2.6, utilized an omnidirectional mobile platform mounting a PUMA-250 robotic arm, remote viewing camera, force sensors and gripper proximity sensors.

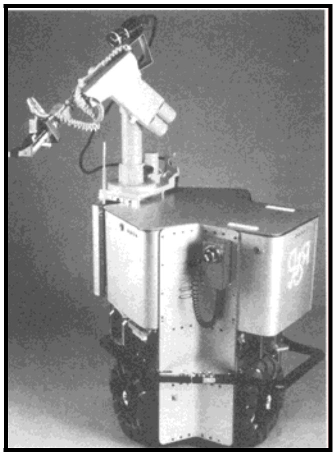

Figure 2.6: MoVAR

MoVAID is an advanced version of the MoVAR system design specifically for home use. MoVAID increases the effectiveness of the previous model by applying the lessons learned in the laboratory to assist in common tasks around the home such as cleaning and food preparation. MoVAID incorporates a variety of sensing devices both mounted to the manipulator and the base. In Figure 2.7, MoVAID can be seen along with various sensors located on the arm. Sensors mounted to the first link of the arm include a pair of cameras used for stereo vision, and a laser localization system used in task execution. MoVAID also uses homing beacons, placed around a room, to navigate. In addition to position detection, the unit also has ultrasonic detectors and an active bumper that disable the device should an impact occur.

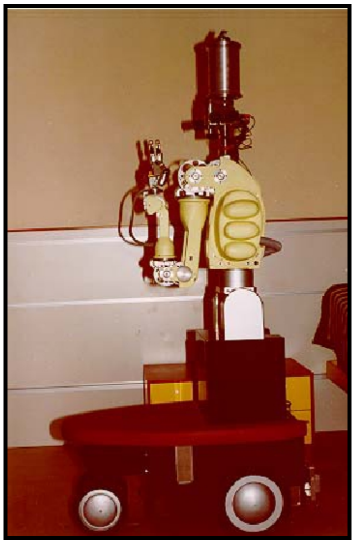

Figure 2.7: MoVAID

The robotic arm is an 8 DOF arm, and the gripper has three fingers with two degrees of freedom. The gripper was specifically designed as a prosthetic device that provides the manipulator with excellent dexterity. The increased dexterity provided by the gripper over more traditional end effectors allows MoVAID to be more effective in the unstructured environment of a home.

2.4 Integrated Robotic Systems

Further integration of robotic arms and other sensors has led to some increasingly capable designs. Although still in development, they offer even greater potential as assistive devices. For example, the FRIEND system is a Manus arm integrated with stereovision and dedicated computer control and specialized software. Beside the standard programming methods the FRIEND system, shown in Fig. 2.8, is capable of being programmed via a haptic interface glove. The haptic glove allows the operator / programmer to feel what the robot feels through feedback to the user. A Haptic glove is donned, and the action, such as pouring a glass, is completed and then stored into the computer for future use. The action can then be replayed as a user function. The user may also control the arm verbally using an integrated voice recognition system (Borgerding et al.).

Figure 2.8: FRIEND Robotic System

Another example of an integrated system is the TAURO. This system uses off-the-shelf components such as a power wheelchair, ultrasonic sensors, camera and computers. TAURO is a mobile service robot being developed for inspection, stocktaking and documentation tasks in indoor environments. The TAURO system integrates the movement of the wheelchair and the operation of the manipulator. In this way if the goal is out of reach, of the manipulator the wheelchair will move on a path toward the goal until the manipulator is within reach. This coordinated control is a significant advance in the use of WMRA. Although not specifically designed for rehabilitation robotics, it would be readily adaptable to the task. The TAURO system can be seen in Figure 2.9.

Figure 2.9: TAURO Robotic System

2.5 Research WMRAs

Wheelchair mounted robotic arms (WMRAs) combine the idea of a workstation and a mobile robot. WMRAs mount a manipulator arm onto a power wheelchair. In the past, manipulators have been so large and heavy as to hinder the operator's ability to maneuver the chair.

Currently there are two production wheelchair mounted robotic arms: The Manus, manufactured by Exact Dynamics; and the Raptor, manufactured by Applied Resources. Other WMRAs under development are the Helping Hand System, Weston Arm from the United Kingdom, and the Asimov from Sweden.

Under development is The Helping Hand system (Kinetic Rehabilitation Instruments, Hanover Massachusetts), which is a 5 DOF robotic arm. Its design is modular in nature and can be mounted to the side of a power wheelchair. It is controlled at the joint level via switches controlling each individual motor (Sheredos et al. 1995).

Another arm under development is The Weston robotic arm (Bath Institute of Medical Engineering), shown in Figure 2.10. This is the continuation of the trolley mounted “Wessex” robot. It uses a vertical actuator mounted to a wheelchair with the main rotary joints (shoulder, elbow, and wrist), constrained to move in the horizontal plane. This arm approaches the design rather differently than others. The first joint of the arm (the shoulder) is prismatic, which actuates in a sliding motion along a track. This necessarily makes The Weston arm larger than both the Manus and the Raptor designs. The other joints of the arm utilize a modified SCARA design as described in the Wessex manipulator.

Figure 2.10: Weston Arm

Another arm currently under development is the Asimov (Bolmsjo et al.). The Asimov is a modular design, with its control system and motors are distributed throughout the arm. A computer rendering of the Asimov is shown in Figure 2.11. The modularity of the design allows for multiple mounting locations and various workspace geometries. This approach of modularity shows great promise in creating one robotic system that can be used in both mobile or workstation environments. Asimov models have been shown with all three possible mounting positions: front, side and rear. Without physical models to test the efficacy of the design it is unknown how well the design would integrate into real world applications.

Figure 2.11: Asimov Arm

2.6 Commercially Available WMRAs

2.6.1 The Manus

The Manus manipulator arm is fully deterministic manipulator: It can be programmed in a manner comparable to industrial robotic manipulators. The Manus has been under development since the mid 1980's and entered into production in the early 1990's. A picture of Manus mounted onto a Permobil Max90 wheelchair is shown in Figure 2.12. It is a 6 DOF arm, with sevomotors all housed in a cylindrical base.

Figure 2.12: Manus Arm

2.6.2 Raptor

Another production WMRA is the Raptor [Applied Resources, Inc.], which mounts the robotic arm to the right side of the wheelchair. This manipulator has four degrees of freedom plus a planar gripper and can be seen mounted to a power wheelchair in Figure 2.13. The user directly controls the arm with either a joystick or 10-button controller. The Raptor uses an 8 position joystick-like input device that is mounted to the armrest of the wheelchair. Typically, the joystick that controls the manipulator arm is located on the armrest opposite to the input device that controls the steering of the power wheelchair. Because the Raptor does not have encoders, the manipulator cannot be pre-programmed in the fashion of industrial robots. This compromise was done to minimize overall system cost and make the product more readily available to the public. The simplicity the Raptor arm allows it to cost half that of the MANUS arm given the current exchange rate.

Figure 2.13: Raptor Arm

The Raptor uses an 8 position joystick-like input device that is mounted to the armrest of the wheelchair. Typically, the joystick that controls the manipulator arm is located on the armrest opposite to the input device that controls the steering of the power wheelchair.

2.7 WMRA Moutning Postitions

All power wheelchairs have different structural designs. There are several possible mounting locations for a WMRA (Warner and Prior 1994). The mount may be in the front, side or rear of the wheelchair. Thus, there are several possible ways to mount an assistive robotic arm. In order to mount a robotic arm to a power wheelchair, several design considerations must be met. Foremost is the safety of the operator. The mount must be sturdy and rigid and not compromise the structural integrity or the functionality of the chair in any way. Next, the robotic arm must be mounted in such a way that it does not excessively increase the width of the wheelchair. Often, powere wheel chairs are near the maximum width that allows access through standard doors, etc. For some mobility devices that have the frame hidden under a fairing, mounting may be more difficult. Some mounting positions may not be possible with all commercially available power wheelchairs and custom brackets may need to be fabricated to facilitate mounting. All of these factors must be considered.

2.7.1 Rear Mount

One of the potential benefits of a rear-mounted arm is that it will not increase the width of the wheelchair when not in use. Assuming that the arm can be able to be stowed behind the wheelchair, the arm would not create a distraction for individuals interacting with the person. Additionally a rear-mounted arm would not be a physical obstruction during transfer into and out of the wheelchair.

Rear mount units suffer from placement issues. Due to excessive link lengths required to design a robotic arm with a dorsal (rear) mounting there are higher torques and loads on the bearings that further increase weight and size. Manipulation in front of the chair is also reduced. One possibility is to have a support provided for the arm, on the side near the front of the wheelchair. The arm would be swung around from the stowed position, and then locked into a rigid support. This would combine the convenience of a side mount with the stowage capability of a rear mount.

At this time there are no commercially available WMRAs that are mounted to the rear of the wheelchair. It should be noted that there is an optional rear-mounting bracket available for the Raptor but this eliminates most of the ability of the arm to reach directly in front of the chair.

2.7.2 Side Mount

Like front mounted manipulators, side mount units also have deficiencies such as increasing the width of the power wheelchair. With the side mount located lower than the armrest (under the wheelchair) the arm will always add at least the width of the first link to the width of the wheelchair. This makes it even more difficult to for the operator to maneuver through doorways and tight hallways. This exacerbates mobility problems already encountered with power wheelchair users. The side mount also requires longer link lengths to allow for manipulation of objects in front of the power wheelchair. These increased link lengths require larger and more powerful motors and gear-heads to move and stabilize the links actuation. These factors often increase the weight and cost of designing arms for this application.

The Raptor is a side-mounted arm. The primary joint motor of the robotic arm is an exposed gear motor, and it must be mounted onto the frame of the wheelchair under the seat. The motor is slightly in front of the operators lap and the first rotational axis is horizontal, oriented laterally to the wheelchair (i.e. parallel with the drive wheel axles). The side mount is mostly hidden underneath the chair and when the arm is not it use and when stowed, the Raptor arm can be relatively innocuous. However, when the arm is retracted and not in use, the Raptor is below the operator's waist level and is fairly unobtrusive.

2.7.3 Front Mount

The front mount offers greater access to the operator's immediate working environment. The lap, tray top on arm rests, and the mouth location can all be considered the immediate environment of the operator. Manipulating objects in these areas is optimized with this mounting location. Due to the high mounting point the front mount near the knee allows for good access to high objects such as items on shelves or operating doors on high cabinets. Objects in front of the chair are also readily manipulated.

The Manus utilizes a front mounting location to the left of the operator’s left knee. The first joint of the arm rotates about the z-axis (floor to ceiling) and is located approximately 5 cm above the level of the armrest of the power wheelchair. This location allows for ready manipulation of objects that are above the plane of the wheelchair seat, and most importantly the operator’s face and lap.

However, the front mount style also has limitations. The first is the visual distraction of having a large piece of technology between the operator and those they are interacting with. This was noted as a hindrance in long-term Manus trials (Eftring and Boschian 1999). The mounting location also limited the ability of the operator to put their legs under desks, tables, and sinks in clinical evaluations. Also, front mount limits access to tables and other furniture that requires driving the legs of the individual under the object. Because there are many standards that have been set forth to allow individuals in mobility assist devices to maneuver close to desks and sinks this is a significant limitation. Another complaint from surveyed users was that, even when fully retracted, a front-mount arm inhibits the user from being able to move close to a table or a sink. Finally, users have also commented that the front mounting makes the manipulator arm obtrusive and can create uncomfortable social tensions with people unfamiliar with robotic technology.

2.8 Control System Types

WMRAs, like any robotic system, have two types of control system options, closed loop or open loop. Closed loop control is more capable, but open loop control is less expensive. For robotic devices intended to be affordable in the consumer market, the decision to use an open or closed loop scheme is non-trivial.

2.8.1 Closed Loop Control

Closed loop systems are in common use in industrial robotics applications. These closed loop systems permit accurate repeated motions of robotic manipulators. Most specifically these systems are most effective in the structured environments such as rehabilitation workstations. These rehabilitation workstations mimic the habitat originally designed for the industrial robot the manufacturing cell. These are highly structured environments, which permit high productivity due to eliminating positioning variances. These systems are very useful in rehabilitation robotics applications by allowing preprogrammed actions and gestures. Preprogrammed gestures can be as simple or as complicated as required such as reaching for a light switch or eating and drinking.

Closed loop control also allows further integration of the arm into more complicated and intelligent systems that can assist the operator. These assist functions may include stereo vision, object recognition, target distance determination, etc. The MANUS system is a version of a closed loop system. A joystick and a keypad control the manipulator. The joystick used to manually operate the manipulator is shown in Figure 2.14. Manus can also carry out coordinated control of multiple joints with preprogrammed gestures using the 16-button keypad shown in Figure 2.15. Gestures can be taught to the Manus and stored for future use via the keypad. With the use of the two input devices the operator can run preprogrammed routines or directly control the manipulator in real time. The controller converts the inputs from a haptic interface into a signal that directly controls the robotic arm. There may be a direct or indirect link between the input device and the output signal. This may be a simple proportional control or more complex method where input position is converted into arm velocity output.

The downside to closed loop systems is their higher initial cost. The drives for the links must have encoders or some other form of feedback to the controller. Often the increased productivity, programmability, and system interoperability can compensate for this increased cost by offering more “bang for the buck”.

Figure 2.14: Manus Joystick Controller

Figure 2.15: Manus Keyboard Controller

2.8.2 Open Loop Control

An open loop controller places all error correction responsibility on the human operator. The operator continuously directs the arm into its final position. This type of system is inherently tolerant of positioning errors from a variety of causes. These errors may be inherent in the robotic device such as play in the motors, gears, bearings or compliance within the links due to loading or environmental conditions such as thermal effects, wind, and movement of the base with respect to the reference frame.

The ability of the open loop controller to tolerate and correct for various types of error is because the operator continuously updates its position correcting any errors that may occur during the manipulation. The operator actually considers the sum of all the errors and moves the arm according to the actual perceived position of the end effector and not what the arms internal sensors are telling the operator.

Because computer-controlled, coordinated motion is not possible, motion is limited to one joint at a time. Open loop control thus requires higher levels of concentration and eye hand coordination than other forms of control, which may be programmed or assisted. This is more taxing for the operator and this fatigue can limit the use of the assistive robotic device. Because of the human in the operational loop an open loop system is unable to make precisely reproducible motions. These cost-saving measures may not be justified in light of the reduced performance of the end product.

Chapter Three:

Design

3.1 Design Goals

An entirely new WMRA has been developed at the University of South Florida. The goal was to produce an arm that has better manipulability, greater payload, and easier control than current designs. The arm is also reconfigurable, which increases the number of applications, and returns more benefit from the engineering investment.

3.1.1 Mechanical Constraints

3.1.1.1 Weight

In a mobile application, minimal weight is of primary importance. Power wheelchairs have a rated payload, and a heavy arm reduces the payload available for the user. Our goal was to have a total system mass under 14 kg, including the arm, controller, and all peripherals.

3.1.1.2 Mounting Location

As found in our previous research[xviii], side mounting is preferable overall because it provides the best balance between manipulability and unobtrusiveness. However, care must be taken to prevent widening of the power chair. The new arm is mounted as far forward and upward as possible while still in a side mount configuration, and only increases chair width by 7.5cm. This mounting location allows the arm to be stowed by folding it back and then wrapping the forearm behind the seat. It virtually disappears when not in use, especially when the arm is painted to match the chair. This is good because most users want the assistance, without the stigma that these devices often bring.

The arm must be slightly longer than with a forward mount, requiring greater shoulder joint torque and heavier gearboxes. This is compensated by the inherent efficiency of harmonic gearheads used in the drivetrain, allowing greater payload at less weight than the MANUS.

3.1.1.3 Stiffness

This is one of the greatest differences between our WMRA and a typical industrial manipulator. As we anticipate teleoperation will be the most common use for the robot, great precision is not required. With a human participating at all times, inaccuracy due to a compliant structure is easily and transparently corrected. Recognizing this allowed the structure to be made much lighter than an industrial manipulator with the same payload. However, the low stiffness and large backlash of other WMRAs is an impediment to accurate control. With this design, we attempted to find an optimal balance, and arrived at a structure stiffer than other WMRAs, but less stiff than an industrial manipulator.

3.1.1.4 Payload

This manipulator is intended for use in Activities of Daily Living, and for job tasks typical of an office environment. As such, it is important that the arm be strong enough to move objects that are common in these environments. A gallon jug of milk is a good upper limit for a typical around-the-house object that must be manipulated. As this is an approximately 4 kg mass, this was set as the baseline payload for the arm at full horizontal reach. Then, an extra margin of 2 kg was added to allow for a choice of end effector that would also be capable of this load. After all, what use is a strong arm with a weak hand? The 4 kg useful payload is significantly larger than the 1 kg payload of the Raptor.

3.1.1.5 Reconfigurability

Even though a side mount was chosen for this prototype, it is important to note that the basic design can be adapted to a front or rear wheelchair mount, or a fixed workstation mount. The arm can be specialized for these workspaces by adjusting link lengths. Longer lengths can be specified for a rear mount on a power chair, but this will necessarily reduce payload and reduce manipulability in front of the chair. Reconfigurability places a strong constraint on the drivetrain type, to be discussed in section 3.2.

3.1.1.6 Power Supply and Consumption

In the power wheelchair industry, a 24-volt lead-acid battery pack is standard, and is the natural choice for the power supply of a WMRA. All motors, controllers, input devices, sensors and so on must be able to work with 24vdc, or through a voltage regulator at under 24vdc. Typically, two Group 24 gel cell lead-acid batteries are used, providing roughly 73 amp-hours of capacity.

Energy consumption is important as well. A power chair is expected to run all day on a single charge, and users would reject an arm that worked well but left them stranded!

Therefore, efficient power electronics, motors and drivetrain were chosen to keep power consumption low.

Merely powering the control electronics takes 0.35A, but a motor may use up to 4A during heavy use. While holding position, consumption ranges from 0.5A with no payload, to 1.7A with a 6kg load and the arm fully outstretched. This is because no brakes are used, and current must be applied to hold position. Average use will depend on application, but for typical household and office work this will be roughly 2A. This draw on a 73Ah battery would allow 37.5 hours of continuous operation, assuming only the arm was used. A typical day with 6 hours of arm use would consume 12Ah, leaving 61Ah, or 84% of battery capacity for the traction motors. This would reduce a typical 30 km driving range to 25 km – negligible for most users. Intensive arm use is likely to be in one location, and charging while the arm is in use is an option to extend battery life.

3.1.2 Cost Constraints

Of course, cost and ease of manufacture have been considered from the beginning, and the new WMRA has to exceed the performance of current WMRAs without increasing cost. We feel that cost has not been the major hurdle to widespread adoption of these devices, but rather poor utility and difficulty of use. The target was to come between the Raptor and Manus systems in terms of cost, while exceeding the performance of both. In hard numbers, we expect that this system can be produced and sold profitably at 30,000 USD retail. Details may be found in Appendix A: Cost Estimate.

3.1.3 User Requirements

People want a useful payload, and a simple intuitive control. A major drawback of the Raptor system is the single-joint, noncartesian controller. Raptor lacks encoders and therefore control is manual, one joint at a time. Quadrature encoders are a cost-effective way to provide closed-loop control. The controllers of the new WMRA have PWM voltage regulation, and have built-in support for acceleration limits. The controllers communicate with the host PC over a RS-485 serial link, which is daisy chain connected to each one. The system easily scales to control grippers or even the base wheelchair, all through one standard control system.

Extra degrees of freedom are a sure way to improve manipulability. This is evidenced by the considerable increase going from Raptor’s 4 DOF to the 6 DOF of MANUS. Our new design incorporates 7 joints, allowing full 6 DOF pose control even in difficult regions of the workspace, such as reaching around the wheelchair, or up to a high shelf.

Reconfigurable arm lengths allow greater leverage on the engineering input, as a single basic design may be adapted to numerous applications. This is only practical with electric drive and actuator placement directly at each joint. The MANUS, for example, houses all drive motors in the base and uses a complex drivetrain involving gears and synchronous belts to drive the joints and gripper. Reconfiguration in this context means a complete redesign. The new USF WMRA design requires only a few hundred dollars in parts and an hour of a technician’s time to reconfigure it according to the user’s needs and the desired uses of the arm.

3.2 Types of Systems Considered

Some ideas were more seriously considered than others, but before beginning design we spent quite a while researching possible ways to actuate and read the position of our arm.

Actuation:

1. Stepper motors with gearboxes at each joint
2. Steppers with screw jacks
3. DC servos, gearboxes, directly acting on joints
4. DC servos with screw jacks
5. Servo or stepper motors at base, driving gearboxes or screws using flexible drive shaft
6. Hydraulic pump and electric valves in base, cylinders on arm
7. Same but pneumatic - would require electric brakes
8. Master/slave hydraulic system, driven by electric motors
9. Muscle wire

Most actuation alternatives were restricted due to our requirement for reconfigurability. Imagine changing the length of an arm that is driven through linkages or flex cables from motors in the base. So many parts would have to change, it would be a whole new design. Muscle wire was rejected because it is weak, slow and inefficient; pneumatics was thrown out due to positioning difficulty and compressor noise. We decided to drive the joints electrically through harmonic gearheads, with the entire actuator positioned at each joint.

The only serious choice was whether to use stepper or servo motors. Due to recent improvements in servo controllers, the cost of this option is not much higher than for stepper motors. Brush DC servomotors allow closed-loop control, and are much quieter, lighter and more efficient than steppers. For these reasons, DC Servo drive was selected.

Position sensing:

1. Limit switches to prevent damage
2. Steppers with limit switches for initialization
3. Potentiometers at joints
4. Relative optical encoders at motors, limit switches
5. Absolute optical encoders at joints
6. LVDT on inboard or outboard hydraulic cylinder or on screw jacks

Options 1 and 2 do not allow servo control and were rejected. Option 3 was considered, but potentiometers are electrically noisy and have a poor life span. Absolute encoders are very attractive because they do not require an initialization routine. However, for the required resolution they are rather expensive, adding $2000 or more to the overall robot cost. Mounting at the joint is required, and is more difficult than at the motor. LVDTs and resolvers were considered as well, but they are analog devices not supported by our controllers. They are also more expensive than quadrature encoders.

Quadrature encoders, mounted on the motors, were selected for their ease of integration, accuracy, simplicity and low cost. Optical limit switches ease initialization upon power-up. These encoders are also directly supported by the controller hardware we selected, unlike many other sensor types. These are the most common feedback devices in servomotor robots. It is no coincidence that Pittman manufactures motors with quadrature encoders built-in.

3.3 Final Design

3.3.1 Kinematic Arrangement

The arm is a 7-DOF design, using 7 revolute joints. Revolute joints were chosen over prismatic and other types because of their better packaging and mechanical simplicity. The basic layout is anthropomorphic, with joints 1, 2 and 3 acting as a shoulder, joint 4 as an elbow, and joints 5, 6 and 7 as a wrist. The 3 DOF shoulder allows the elbow to be positioned anywhere along a spherical surface, whereas with the Raptor arm, elbow movement is limited to a fore-aft circle.

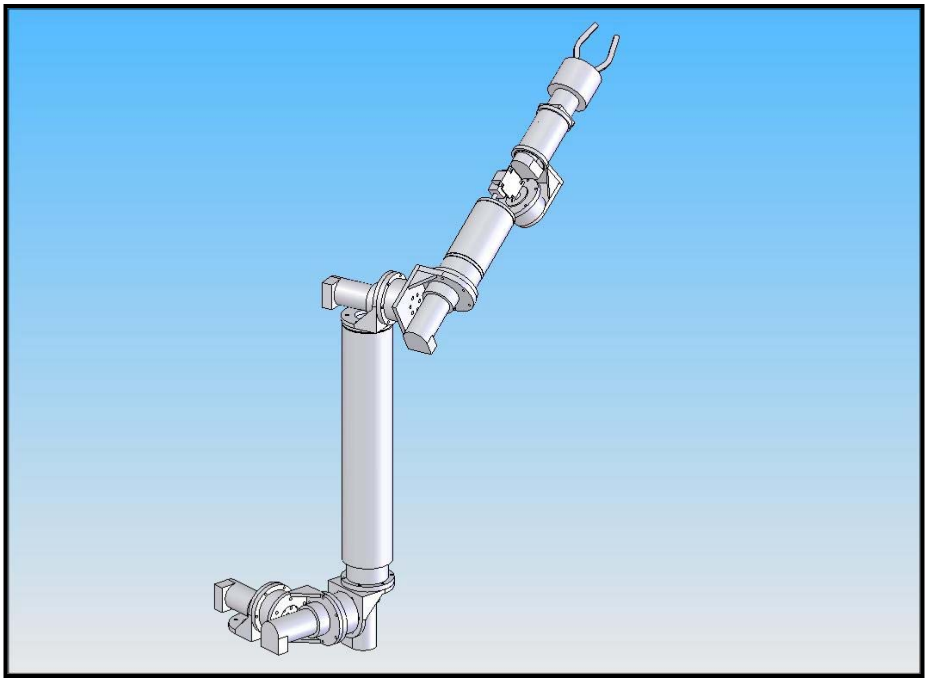

Figure 3.1: Complete SolidWorks Model of the USF WMRA

Throughout the arm, adjacent joint axes are oriented at 90 degrees. This helps to meet two goals: Mechanical design simplicity and kinematic simplicity. Machining parts on a conventional milling machine is easier with right angles. And the coordinate transform equations simplify greatly, with sines and cosines of these angles becoming ones and zeroes (especially the zeroes are appreciated!). All adjacent joint axes intersect, also simplifying the kinematics.

There was a choice to be made in the wrist kinematics. While 3 degrees of freedom are certainly required here for maximum manipulability, there were two primary ways to arrange this. One is with each successive joint oriented at 90 degrees. The other is to place the middle joint at 45 degrees to the others. The advantage of this nonorthogonal layout is that it can help reduce difficulty due to singularities in the equations. However, the packaging of this layout was quite unattractive, and a much more aesthetically pleasing layout was developed, helped by a 90-degree gearbox. This elegantly places the joint 6 motor inside the forearm tube, rather than protruding out the side of the forearm. Section 3.3.5, Wrist Design, describes the wrist in more detail.

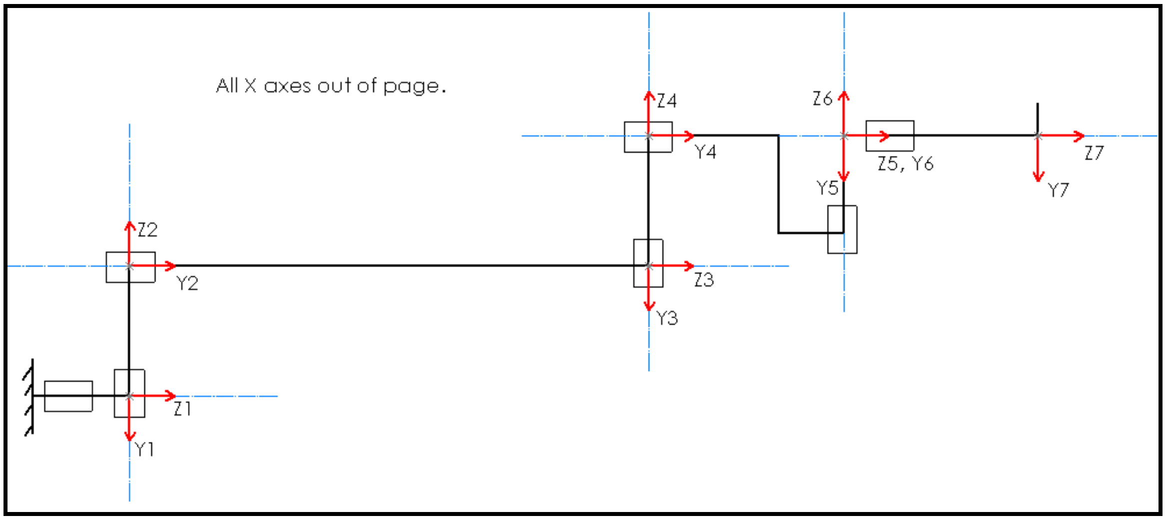

Figure 3.2: Kinematic Diagram, with Link Frame Assignments

Table 3.1 – DH Parameters for the USF WMRA

i	α_{i-1} (degrees)	a_{i-1} (mm)	d_i (mm)	θ_i
1	0	0	0	θ_1
2	90	0	146	θ_2
3	-90	0	549	θ_3
4	90	0	130	θ_4
5	-90	0	241	θ_5
6	90	0	0	θ_6
7	-90	0	179	θ_7

3.3.2 Component Selection

Emphasis was placed on using off-the-shelf parts wherever possible. The basic arrangement for each joint is a high-reduction gearhead, a motor with encoder and spur-gear reduction, and a bracket that holds these two parts and attaches to the two neighboring links.

3.3.2.1 Gearhead Selection

Next the question was which gearboxes to use. For joint 1, in the shoulder, the required torque output is roughly 100 Nm. As our servomotors on joints 1 through 4 have only 1.2 Nm output after their built-in gearboxes, reduction of nearly 100:1 is required. Planetary gears were considered, but the desired torque and reduction required a large, 180mm long gearbox. This would pose a significant packaging problem.

Harmonic drive gearheads were chosen because they can achieve 100:1 reduction in a single stage, with only 64mm axial length. In addition, they have bearings suitable for supporting overhung loads, enabling the next arm segment to be bolted directly to the output flange of the gearhead. This greatly simplifies the design, reducing weight and cost through lower part count.

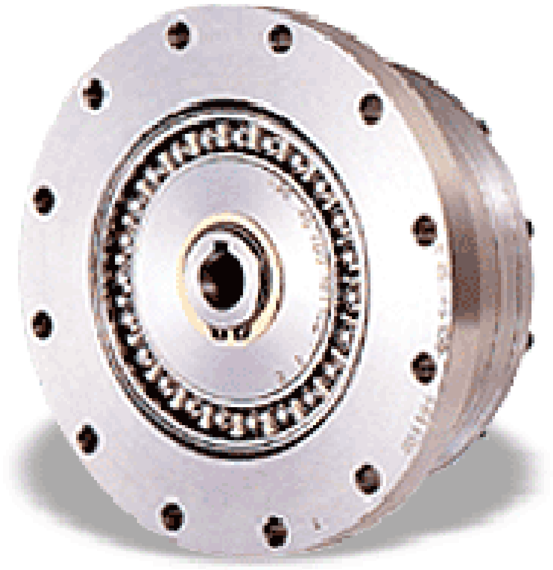

Figure 3.3: HD Systems Harmonic Drive Gearhead

Gearheads were chosen based on required overhung loads and torques, with the size of gearhead gradually reducing in each more distal joint. This is not a closed-form problem, because the weight of one gearhead affects the torque required of the more proximal joints. Once the basic type of gearhead was selected, information on the available sizes was collected, namely the mass and recommended maximum torque. Maximum recommended torque here was taken to be the lesser of two specifications from the manufacturer: Maximum output torque and maximum overhung torque. A simple spreadsheet model of a horizontally outstretched arm was made, which accounted for link lengths and self-weight of the structure. The target payload (taken here to mean the end effector and object grasped totaling 6 kg) was also applied to the end of the arm.

For each joint, the torque due to gravity acting on the more distal joints was applied. For instance, joint 4 was subjected to the torque from the weight of joints 6 and 7, plus the payload. The weight of a joint was taken as the sum of the gearhead, motor with encoder, an aluminum bracket at 500g, and the link tube attached to it. The link lengths were specified, and the spreadsheet gave the required gearhead size that would meet the torque applied to it. An example spreadheet, showing torque estimates, is included in Appendix C: Joint Torque Calculations.

The goal was to find an optimal selection of gearheads that would meet payload and reach requirements, with minimum total arm weight. This model allowed many design iterations to be quickly evaluated, once the spreadsheet was set up. Because the maximum torque increases stepwise with one size larger gearhead, it was found that some combinations were much more efficient in terms of payload/structure mass ratios. Eventually a combination was found that met all requirements and had evenly stressed components. The selected gearheads are shown in Table 3.2.

Table 3.2: HD Systems Gearhead Selections for Each Joint

Joint	Model Selected	Torque (N m)	OD (mm)	Mass (kg)
1	CSF-25	140	107	1.50
2	CSF-25	140	107	1.50
3	CSF-20	70	93	0.98
4	CSF-17	46	79	0.68
5	CSF-17	46	79	0.68
6	CSF-14	19.5	73	0.52
7	CSF-11	6.6	58	0.15

3.3.2.2 Motor Selection

Brush DC motors were chosen because they are the least expensive way to achieve servo control. While brushless motors are a future possibility, performance gains are dubious, and would increase the cost of the robot by roughly $1000. The marginal increase in efficiency is relatively unimportant, and gear train noise is already greater than commutator noise. The main benefits for brushless motors are increased service life before maintenance, and possibly better packaging. We maintain that Brush DC servo drive is the best overall compromise for a WMRA.

Once maximum joint torques were known, and targets were set for joint speeds, and the gearhead ratios were selected, motor selection could begin. The goal here was to minimize weight and bulk, while meeting performance specifications, and without incurring undue cost. Pittman motors were selected that are off-the-shelf, meet all performance criteria, and have integrated gearboxes and encoders. Joints 1 through 4 use Pittman model GM9234C212-R3. While the elbow (joint 4) has a lower torque demand than joints 1 through 3, the same motor was used to reduce part inventory required. As much less torque is required at the wrist, smaller gear motors are used to reduce weight. Pittman model GM8724S009 motors actuate joints 5 and 7, and a similar motor, model 8322S003, drives joint 6. For good packaging, the gearhead on joint 6 is driven through a precision right-angle gearbox, allowing the motor to be hidden inside the link tube. Since the right angle gearbox has a reduction of 5:1, the motor does not have an integrated gearbox.

All 7 motors are designed to operate on 0 - 24 VDC. The larger motors stall at about 4 amps, which is the limit of our controllers but still safe (the controllers automatically limit current to prevent damage). The duty cycle at full current is only 25%, but tests have shown this to be acceptable – even during extended use the motors barely rise above room temperature. This is because full rated power is only rarely required in normal use.

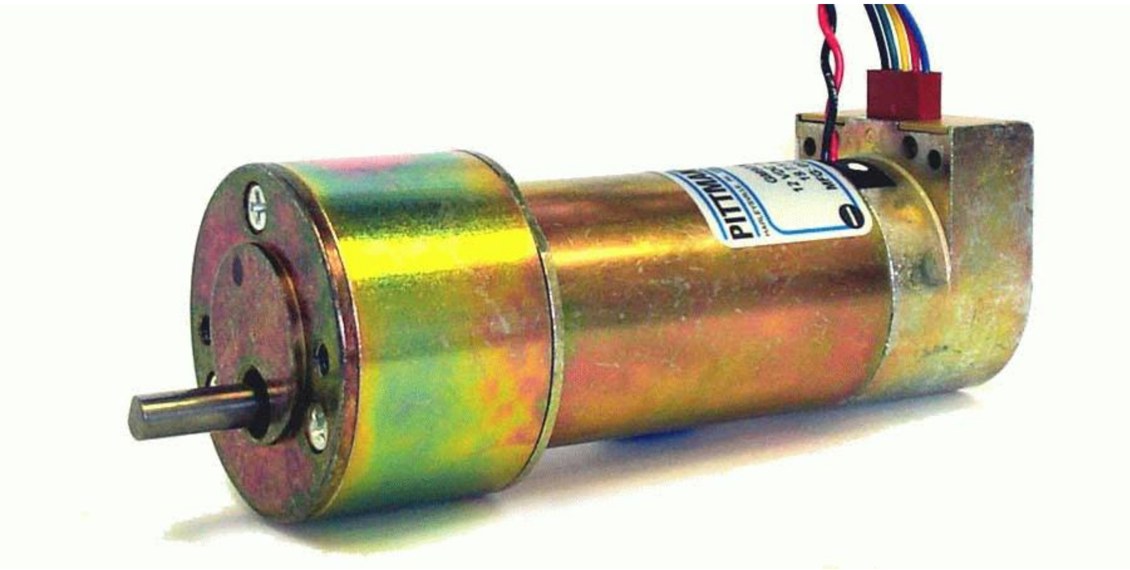

Figure 3.4: Pittman PMDC Brush Motor with Gearbox and Encoder

Table 3.3: Motors Used in USF WMRA

Motor Type	Applied to	Weight (g)	Speed (RPM)	Continuous Torque (Nm)	Stall Torque (Nm)
GM9234C212-R3	Joints 1-4	505	900	0.431	2.147
8322S003	Joint 6	218	7850	0.011	0.052
GM8724S009	Joints 5 & 7	316	1400	0.102	0.297

3.3.2.3 Encoders

Quadrature encoders on the motors provide relative motion information. The arm is initialized using optical limit switches mounted at the output side of each gearhead. Pittman produces motors with integrated encoders, and these were used to reduce cost and design complexity. One note: with 500 count/revolution encoders and 600:1

reduction between the motor and gearhead output, 300000 counts per output flange revolution are recorded. This is excessive for the application, but does not cause any ill effects, and is useful for accurate velocity and acceleration measurement. The PIC-SERVO boards read the encoders directly and only report position back to the main controller when queried, so serial bus traffic is unaffected by the high encoder resolution.

3.3.2.4 Controllers

If there was any doubt that DC servo actuation was the right choice, the PIC-SERVO controller removed it. At 5cm x 7.5cm, this unit has a small microprocessor that drives the built-in amplifier with a PWM signal, handles PID position and velocity control, communicates over a simple RS-485 serial link, and can be daisy-chained up to 32 units. It can also read quadrature encoders, limit switches, an 8 bit analog input, and supports coordinated motion control. It is a bargain at just $150 per controller.

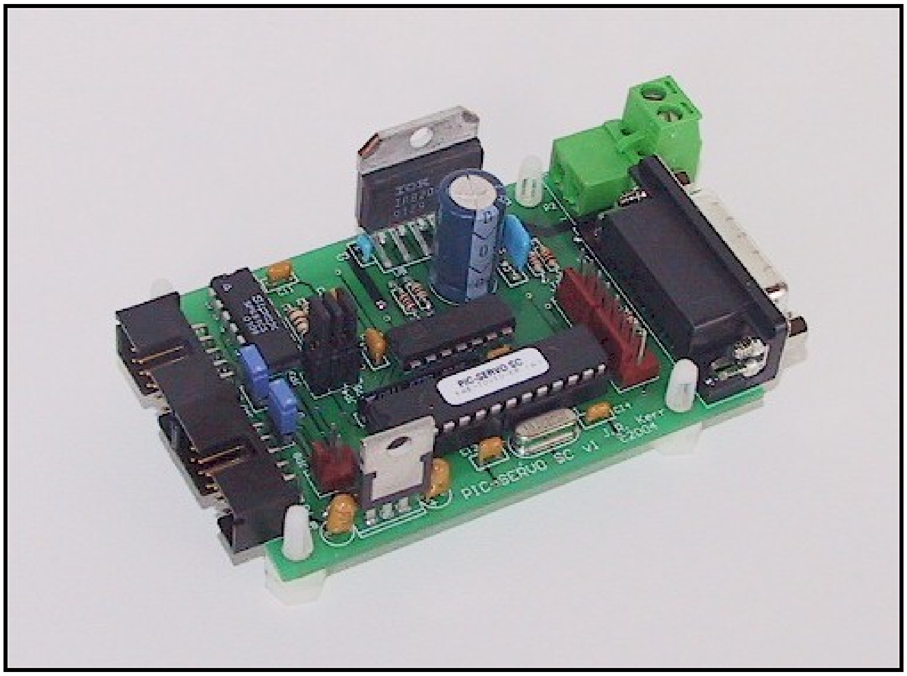

Figure 3.5: J.R. Kerr PIC-SERVO Controller Board

Here are the basic specifications for this motor controller:

1. PIC-SERVO SC Motion Control Board
2. Part Number: KAE-T0V10-BDV1
3. Motor Type: DC Servo Motor (brush-type)
4. Driver Ratings: 3A cont./6A peak, 12-48vdc
5. 32-bit position, velocity and acceleration control
6. Trapezoidal and velocity profiling permit on-the-fly parameter changes
7. 16 bit PID servo gains can be changed on-the-fly
8. Multiaxis coordinated motion control support
9. 2 or 3 channel encoder input, limit switch inputs, hall sensor inputs
10. Optional Step and Direction inputs
11. Amplifier includes overcurrent, overvoltage, undervoltage and thermal overload protection
12. May also be used with external amplifiers
13. 4-wire RS485 communications interface can be connect to additional controllers (up to 32 total)
14. Nominal size: 5cm x 7.5cm

These controllers handle all of the necessary low-level tasks, freeing up resources on the main computer and also preventing a bottleneck in the serial interface. Software development was eased by the carefully documented example code included with the controllers.

3.3.3 Material Selection

6061 Aluminum was chosen for the joint brackets because of machinability, weldability, relatively low cost, good strength-to weight ratio, and availability. This material was also chosen for the link tubes, for the same reasons. Steel was considered but rejected due to its high density. In many places, the thickness of a bracket is not determined by strength or stiffness, but by simple packaging constraints. Steel would unacceptably increase mass in these areas.

Composites were considered for the link tubes. Especially carbon fiber/epoxy was investigated, due to the increase in stiffness and reduction in weight possible. Aluminum was ultimately chosen, although payload could be increased by 0.5 kg or more using carbon/epoxy. Perhaps this could be an upgrade option in a production arm, as the link tubes are easily changed out. Carbon fiber becomes especially attractive for a long-reach option, and may make a rear-mount arm more feasible. This is an area we will explore in our future development of this arm.

3.3.4 Joint Design

Once all components were selected, design of each joint was rather straightforward. The typical arrangement for a joint is to have a gearhead and motor held together by an angle bracket. This bracket mounts to the previous joint or link. The output flange of the gearhead attaches to the next joint bracket or link.

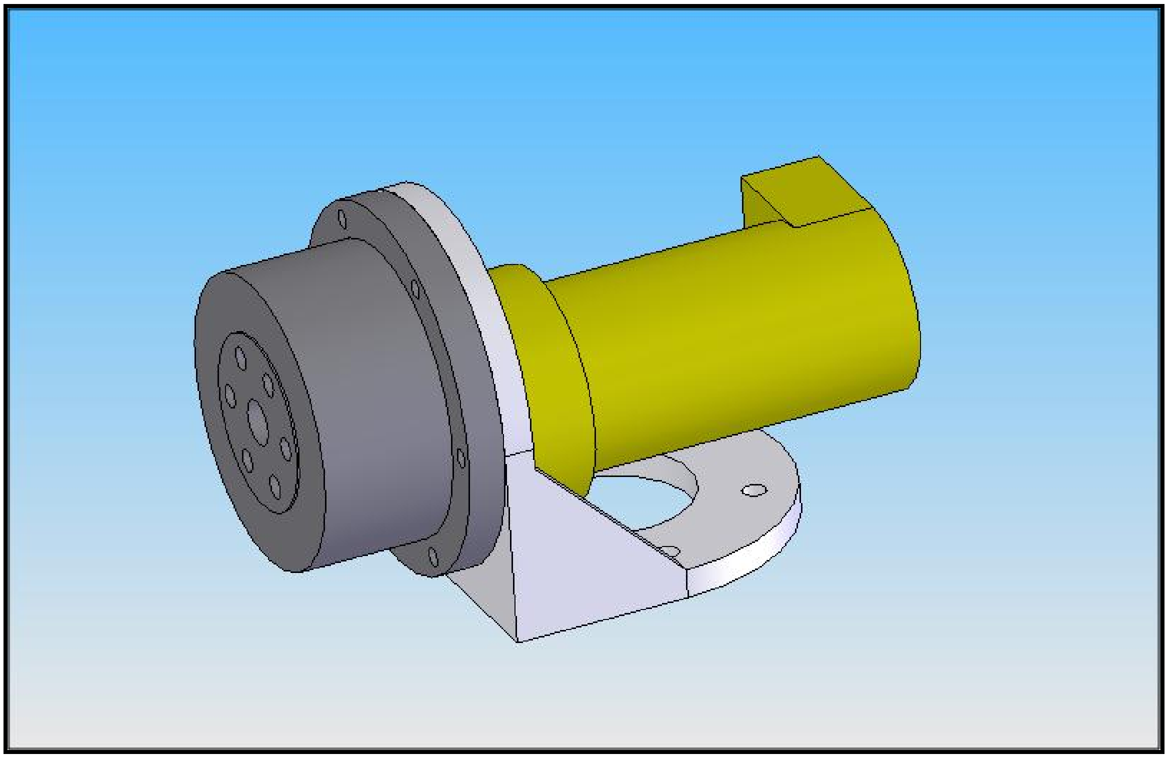

Figure 3.6: Typical Joint Design, Showing Motor, Gearhead and Bracket

Joints 1 – 4 were designed this way, and produced from single blocks of 6061 aluminum. Billet construction was chosen for its high strength-to-weight ratio and high dimensional accuracy.

3.3.5 Wrist Design

As noted before, there were two basic choices for a 3-DOF wrist: Orthogonal and nonorthogonal. The following renderings show each type of wrist. For clarity, obscuring brackets have been omitted.

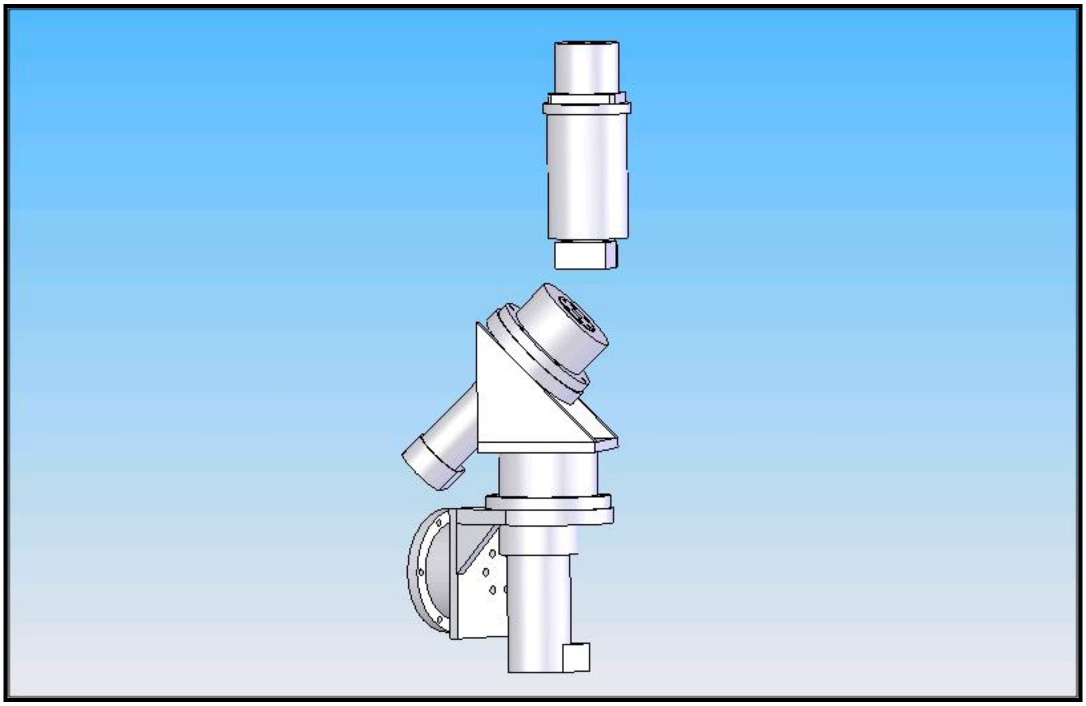

Figure 3.7: Nonorthogonal Wrist Concept

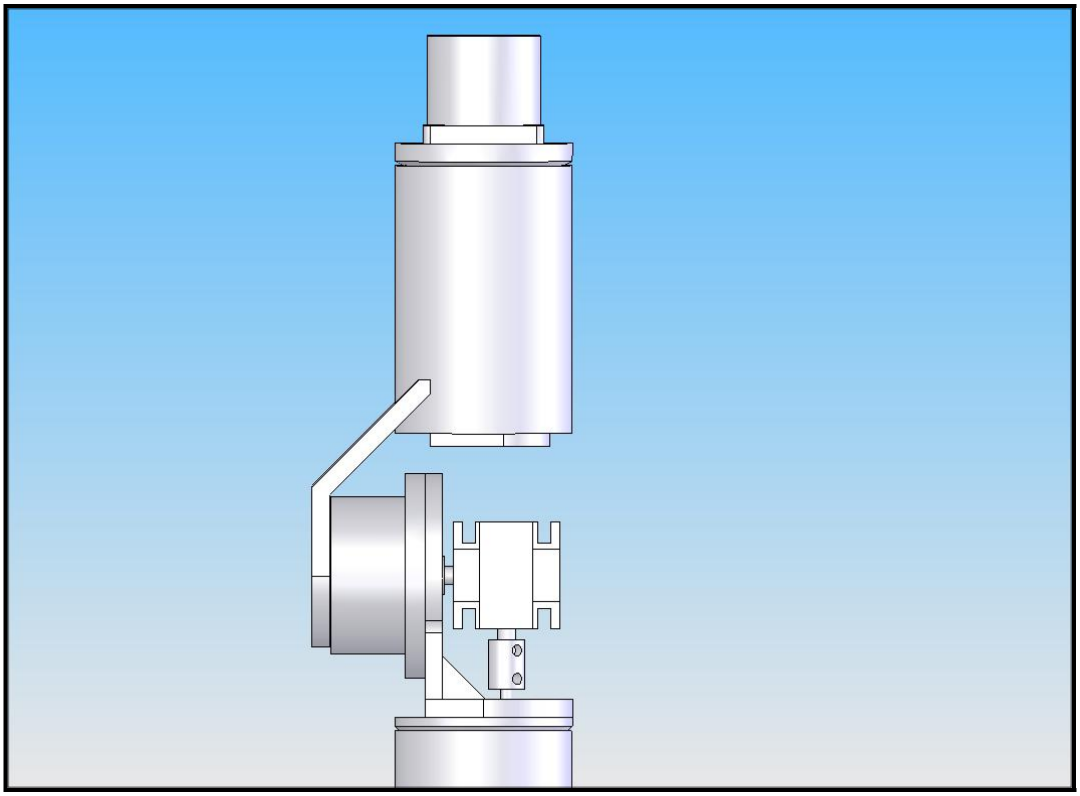

Figure 3.8: 3-DOF Orthogonal Wrist Concept

The conventional orthogonal arrangement was selected due to better packaging. All three axes are mutually orthogonal and all axes converge at a single point. This is common in industrial manipulators, such as the Puma 560. It is done to simplify the kinematic equations and guarantee a closed-form inverse kinematic solution. As this manipulator is intended for use on a wheelchair, processor power is limited and a numerical inverse-kinematics routine would be unacceptable.

The brackets for the wrist (joints 5, 6 and 7) were designed to be fabricated from machined plates, which reduces production time and cost. Joint 5 is much like the rest of the arm, with an angle bracket holding the motor and gearhead at a right angle to the output flange of Joint 4.

Joint 6 has a design unlike the others in this manipulator. A right angle gearbox between the motor and gearhead greatly improves packaging, but does increase complexity of design. A single bracket was designed to hold all 3 parts in proper alignment, and to carry the load to the link tube and joint 5.

Joint 7 is coaxial with the last link, so that no matter the pose of the arm, rotation about this axis is assured. The gearhead mounts to a flange welded to the end of the link tube, and the motor is hidden inside this tube. Again, this was done to improve appearance of the arm.

3.3.6 Control System

While the details of the high-level control system is outside the scope of this design project, it is appropriate to discuss here the provisions made for such a system.

This is a fully deterministic manipulator arm. Each joint controller is individually addressable, and can be controlled in position, velocity, or current (torque) mode. In position mode, velocity and acceleration limits may be specified for smooth operation. These controllers automatically track position and velocity data; the central computer need only query each controller when necessary. This greatly reduces bandwidth required.

Data for the entire arm is interfaced to the main computer using a single serial link. The PIC-Servo controllers use RS-485, and a hardware converter interfaces this with the RS-232 port on our host PC. The host PC right now is an older IBM laptop, running Windows 2000. However, the communications protocol is simple and open, and could be adapted to virtually any hardware/software platform with an RS-232 port. We now also have an Rs-485/USB 1 adapter, allowing this arm to be used on any PC with a USB port.

Some of my ideas for future development of the control system are included in the "Future Work" section of Chapter Six.

3.3.7 Final Design Overview

Figure 3.7 shows the complete assembly model of this arm. It is shown in a pose typical of a right-hand side mount, although either side mount is possible without mechanical modification. Motor covers have been left off to show more design details. And of course, the gripper shown is only representative; any of a wide range of grippers can be used. We have a BarrettHand BH-8 that can be mounted to various manipulators in our lab, including this one.

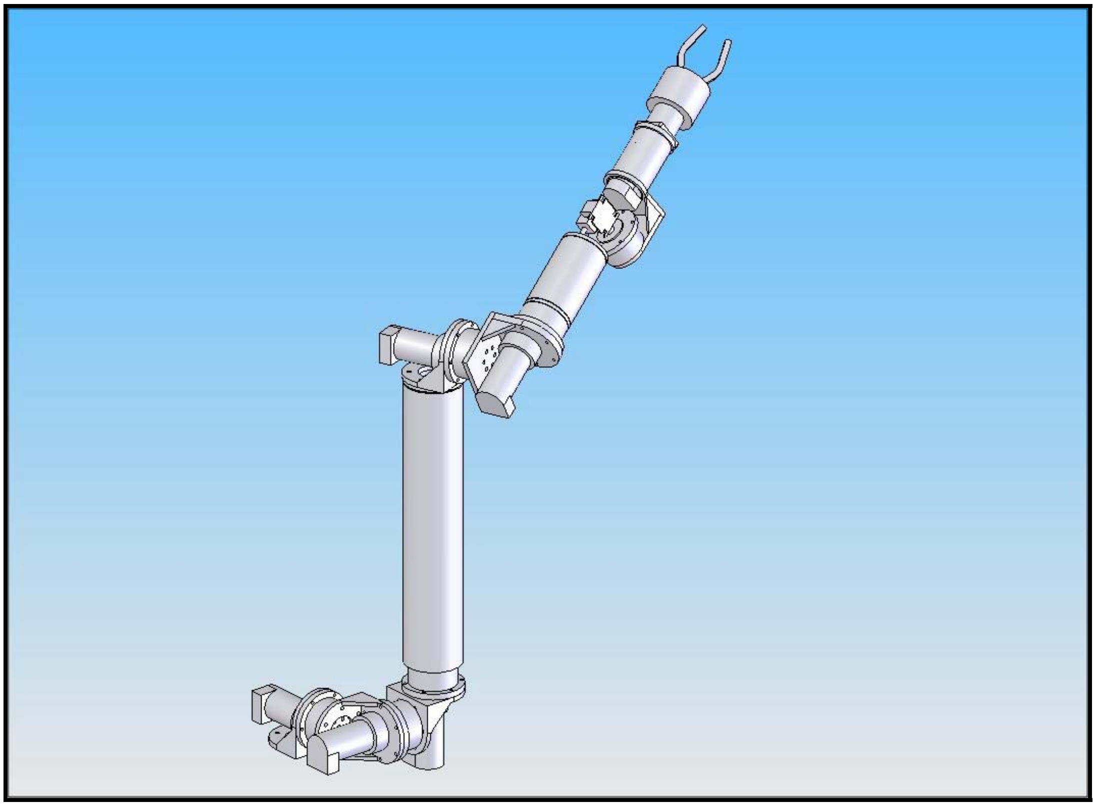

Figure 3.9: Complete SolidWorks Model of the USF WMRA

Chapter Four:

Construction

4.1 Considerations for Manufacture

This WMRA was entirely built by graduate and undergraduate students working for the Rehabilitation Engineering and Technology Program at USF. Due to this, it was designed to be made with the equipment available in our robotics machine shop. All machining was done with a conventional milling machine (with a rotary table) and with a conventional lathe. All welding was done on our Hobart TIG welder. While some parts could be made to look a little fancier with CNC equipment, we felt that having all production done in-house was much more valuable. Especially for a prototype such as this, having a close-knit design/build team speeds production. Inevitable problems are quickly recognized and corrected, whereas in a typical “over-the-wall” engineering production environment such errors can cost days. In addition, simple manufacturing techniques will help to reduce production cost in the future.

Figure 4.1: Undergraduate Research Assistant Andrew Bridges Milling a Joint Bracket

4.2 Completed WMRA

Figure 4.2: Completed Arm on Power Chair

Chapter Five:

Testing

5.1 Safety Tests

Of course, safety is a primary concern with any product, but this is especially the case for a WMRA, as we may assume that the user is unable to move out of the way of the manipulator. A balancing act is necessary, because the arm must be slow and weak for safety, but not so much that users reject it. Fortunately, WMRAs do not have to operate at the high speeds and accelerations of industrial manipulators. Here we outline some simple safety testing done on our prototype.

One feature of the PIC-Servo controllers is a software-selectable current limit. As current is proportional to motor torque, this is a simple and effective way to limit the force that may be accidentally applied to the user. Some simple tests were done to see if the controllers responded quickly enough to avoid harm to the user. The arm was intentionally run at full speed, with the current limit set to maximum, directly into the body of a volunteer (the head researcher on this project).

Figure 5.1: Automatic Shutdown when Force Limit is Exceeded

The tests did not cause any damage to the user or to the arm. However, some discomfort was experienced. One suggestion that can be implemented in the control system is a virtual “safety bubble” around the user, inside of which the maximum speed and force of the arm are limited. Maximum joint torque is only required when reaching straight out, far away from the user. This safety improvement would therefore cause no noticeable decrease in performance. Another control possibility is to have joint torque limits set lower than maximum all the time. When a larger force is required, the GUI would prompt the user with an “Are You Sure?” message. This would help prevent unintentional use of the full force of the manipulator.

It should be noted that these safety tests are not meant to certify this robot for any purpose other than research. The intent here is to merely get some estimate of the risk involved in development and use of the robot. Much more rigorous testing will be done later.

5.2 Stiffness Testing

The stiffness required of this manipulator is much less than for an industrial manipulator. This is because teleoperation is the normal control mode, and the working environment is unstructured anyway. The user easily corrects any compliance errors in the arm. However, too much compliance would annoy the user. Good stiffness leads to a feeling of quality construction.

Stiffness was tested by extending the arm straight out in front of the wheelchair. A dial indicator was set to measure deflection in the vertical direction, and then a known mass was applied to wrist plate at the end of the arm. Deflections were measured at the wrist plate (100.3 cm from axis 1), joint 4 (50.8 cm from joint 1) and directly on the joint 1 gearhead. These deflections are shown in Table 5.1:

Table 5.1: Arm Deflections vs. Applied Load

Load (kg)	Wrist Deflection (mm)	Elbow Deflection (mm)	Joint 1 Deflection (mm)
2	4.4	1.8	0.2
4	8.7	3.7	0.4
6	13.3	5.5	0.7

Deflection is essentially linear with applied load. While not noted in the table, these deflections are recovered upon removal of the load, to within 0.1mm.

Figure 5.2: Arm Stiffness Measurement

Backlash is another matter. More so than excessive compliance, backlash can make a device feel shoddy. Fortunately, Harmonic Drive gearheads have virtually zero backlash, as demonstrated during testing.

For the application, stiffness and backlash values are excellent. Compare this to the Raptor arm, which at the end effector has +/- 50mm of play in all directions.

5.3 Strength Testing

Each joint was individually tested for the maximum load it could lift. This was done by placing the arm in a pose most adverse for the joint in question. For example, the arm was placed fully outstretched, pointing forward parallel with the ground. Weights were progressively added, and the joint was given full power to try to raise the weights.

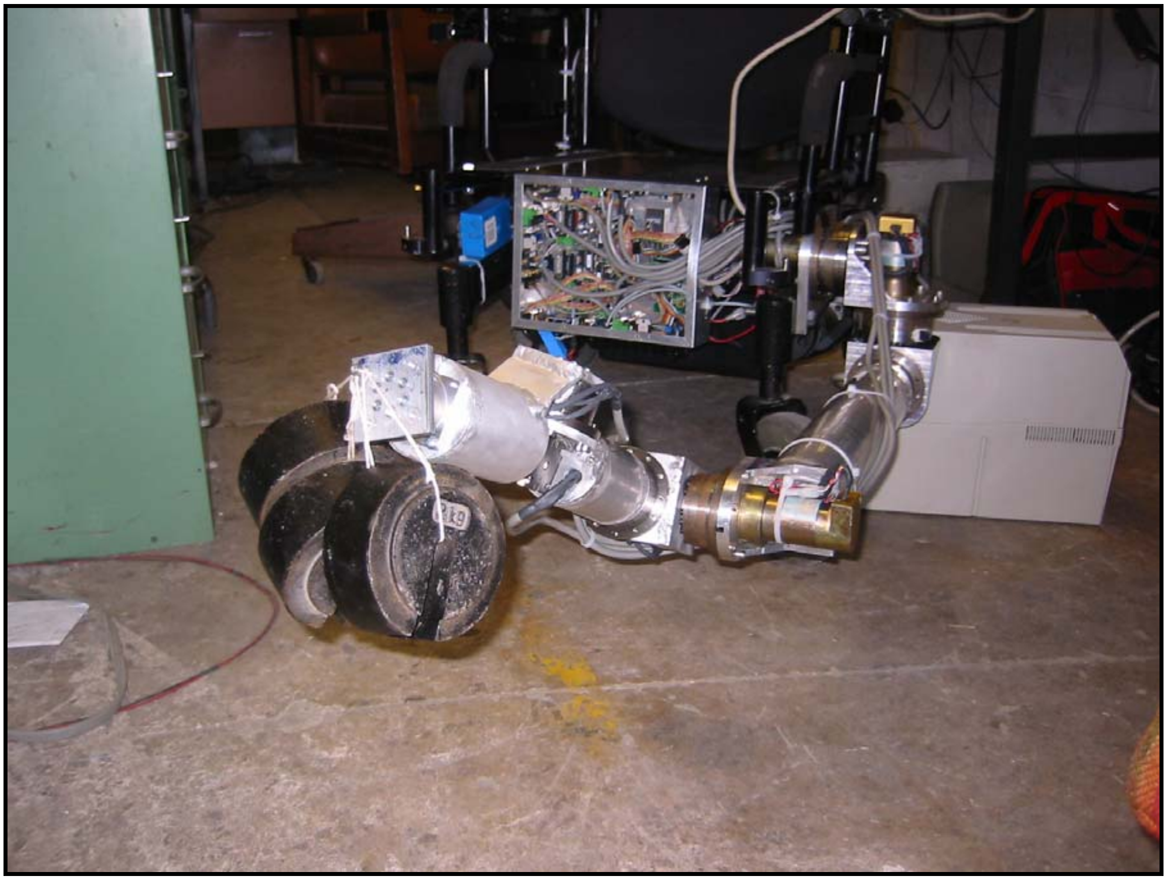

Figure 5.3: Strength Testing of Joint 1

Table 5.2: Maximum Joint Loads

Joint	Max Load (kg)	Note
1	6	
2	6	
3	6	2/3 power used
4	6	Only uses 1/2 power to lift 6kg
5	6	2/3 power used
6	6	

All joints were tested up to the design load. However, some joints met this load with less than full power. Testing shows that joints three and four are overpowered, and smaller motors could be substituted here.

Joint 7 was tested differently as it does not have a moment arm already attached to it. A mechanic's torque wrench was attached, and the maximum torque of this joint was found to be 25 N-m, sufficient for all anticipated tasks.

5.4 Joint Speed Measurements

The maximum, unloaded speeds of each joint were measured using a known arc (90, 180, or 360 degrees as geometry permitted). Time to traverse this arc was measured with a stopwatch and joint angular velocities in RPM were calculated. From this, and the distance from the joint axis to the wrist plate, a maximum wrist plate linear velocity was calculated.

Table 5.3: Joint Speed Measurements

Joint	RPM	Wrist Distance (mm)	Wrist Speed (m/s)
1	5.8	889	0.54
2	5.8	889	0.54
3	7.1	508	0.38
4	10.0	508	0.54
5	11.0	254	0.29
6	6.5	254	0.18
7	16.0	0	0.00

In practice, maximum speeds will be limited by the controllers to less than these values, especially when the end effector is near the user.

5.5 Energy Consumption Testing

With any battery-operated device, energy use is very important. In this case it is especially so because if the arm were to discharge the wheelchair's battery, the user may be stranded. A digital multi-meter was set to current sensing mode and connected inline with the power feed from the wheelchair battery. Then, various operations were tested and power consumption recorded. The results are shown in Table 5.4.

Table 5.4: Power Usage

Condition	Current (A)
Idle - all motors off, controller only	0.36
Holding self-weight outstretched	0.58
Holding 6kg fully outstretched	1.70
Lifting 6kg with joint 1	3.30

While more testing will be instructive, a reasonable estimate is that typical household and office tasks will lead to an average current of 2 Amperes. Six continuous hours of arm use would therefore consume 12 Ah. This would leave a 73 Ah battery (group 24 gel cell) with 61 Ah for propulsion, or 84% of capacity. Thus, driving range would be reduced, from perhaps 30 km to 25 km. This should be acceptable for most users. If not, most manipulation occurs with the platform stationary, such as at an office desk. The arm is capable of plugging the wheelchair's charger into the socket without any assistance, allowing a recharge during the workday.

5.6 Further Testing

While the inverse-kinematic controller software is not yet complete, some testing was done to demonstrate the large, usable workspace of the manipulator. The following figures show the workspace envelope extremes, the ease of reaching doorknobs on both the left and right, and how the arm may be unobtrusively parked behind the chair.

Figure 5.4 – WMRA in a Feeding Pose

Figure 5.5 – Low-Right Reach

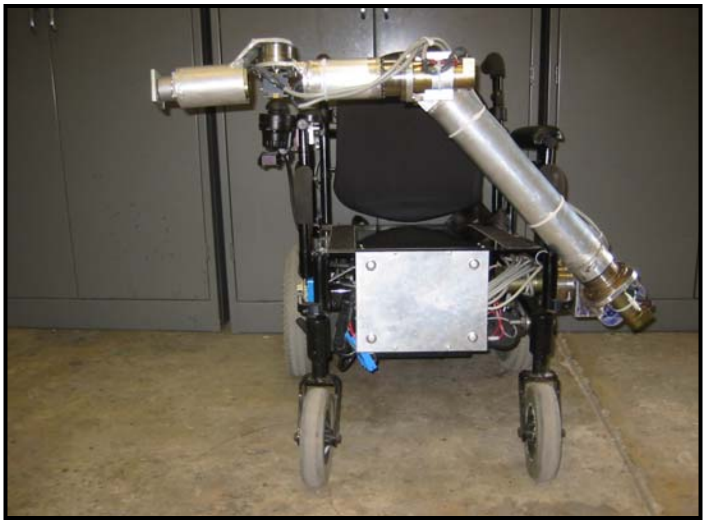

Figure 5.6 – Mid-Right Reach

Figure 5.7 – Left Side Doorknob

Figure 5.8 – Right Side Doorknob

Chapter Six:

Summary and Future Work

6.1 Design Summary

Table 6.1 – USF WMRA Specifications

Arm Mass	12.5	kg
Max reachable height above floor	1.37	m
Chair width increase with side mount	7.5	cm
Average Current Draw	2	A
Design Payload (including gripper)	6	kg
Deflection at design payload	13.3	mm
Degrees of Freedom	7	
Actuator Type	Brush DC Servo	
Transmission	Harmonic Drive	
Controller Type	Pic-Servo SC	

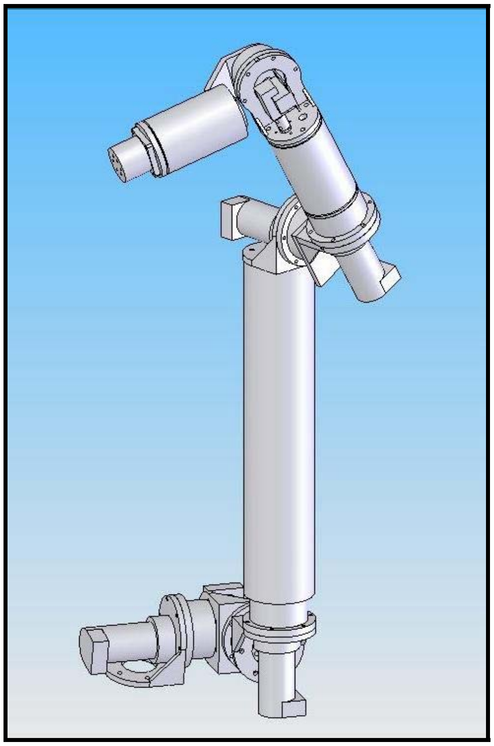
Figure 6.1 – SolidWorks model


Figure 6.2 – USF WMRA as Built

6.2 Design Insights

6.2.1 Degrees of Freedom

Invest in degrees of freedom. Increasing the joint count from just 4 up to 6 or 7 does increase cost somewhat, but makes the arm much more versatile.

6.2.2 Reconfigurability

Reconfigurable arm lengths allow greater leverage on the engineering input. This is only practical with electric actuators placed at the joints. The MANUS, for example, houses all drive motors in the base and uses a complex drivetrain to drive the joints and gripper. Reconfiguration in this context means a complete redesign. Our design requires only a few hundred dollars in parts and an hour of a technician's time.

6.2.3 Side Mounting

Side mounting is preferable overall. However, care must be taken to prevent widening of the power chair. Our arm is mounted as far forward and upward as possible while still in a side mount configuration, and does not significantly increase chair width. This allows the arm to be parked by folding it back, then wrapping the forearm behind the seat. The arm must be slightly longer than with a forward mount, requiring greater shoulder joint torque and heavier gearboxes. This is compensated by the inherent efficiency of harmonic gearheads used in our drivetrain, allowing greater payload at less weight than the competing MANUS.

6.2.4 Cartesian Control

Cartesian control is necessary. Raptor lacks encoders and therefore control is just single joint at a time, with a human doing all the work. Quadrature encoders are a cost-effective way to provide closed-loop control.

6.3 If I Had To Do It Again…

There are several areas where improvements can be made, primarily in better packaging. This is very important for improving aesthetics and increasing user acceptance. The following are some of my thoughts on how to make an even better arm.

Joints 3 and 4 could be improved with some rearrangement. The motor for joint 3 hangs out a bit. If the motor-gearhead assembly was turned around 180 degrees, the motor could be neatly placed inside the main arm link tube. Likewise, the motor for Joint 4 could be placed inside the main link tube, by using a right angle gearbox. These modifications would not change the performance or kinematics of the robot, but would certainly help to improve the appearance.

While the wrist of this robot is functional and reasonably compact, I think improvement is possible. I have two ideas that may be investigated in future design projects: A differential drive in the wrist and a nonorthogonal joint arrangement.

Because of the actuator-at-the-joint servo arrangement in this robot, there is a necessary offset of roughly 15 cm between the intersecting axes of the wrist and the final output flange to which the gripper mounts. In tight areas, this offset can restrict the range of possible orientations, and so it is desirable to reduce it. This is accomplished in other manipulators by use of a differential gear train, which allows the three motors to be housed in the forearm. This can reduce the offset from the wrist axes intersection to the output flange, from 15 cm to perhaps 5 cm. The drawback is increased complexity and some backlash.

A nonorthogonal wrist, also known as a 3-roll wrist, is another possible arrangement. While all 3 joint axes would intersect as before, the middle joint (joint 6 in this case) would be placed at an odd angle relative to joint 5, perhaps 45°. The advantage here is that this can help avoid singularities in the inverse kinematic solution, leading to more satisfying operation. I think this would make an interesting future project.

6.4 Future Work

This was a project to design and build a WMRA, up through the PC interface layer. Of course, a robot is useless without a good control system, and my work finishes with simple single-joint control. The next step for our group is to develop a Cartesian control scheme based on this hardware. As this arm is fully programmable, I expect this process to be readily doable. This and other extensions of my work are listed here.

6.4.1 Develop High-Level Controller

Features of the control system are already under consideration. The finished system will incorporate multiple input devices, to accommodate various user abilities. The main control mode will likely be velocity control, but there will also be provision for user-programmable positions. This will greatly speed repetitive tasks.

6.4.2 Orientation Locking

One simplification for the user is an option to lock the end effector orientation. This can come in two varieties. First is a 3-DOF lock. This is useful for such a task as sliding open a drawer, where any orientation change is undesired. Second is a 2-DOF lock. This allows the gripper to rotate about the world z-axis, thus keeping a glass of water level. Controlling the three position variables is plenty of work for a human, without the added complication of constantly leveling an object.

6.4.3 Gripper Development

The gripper itself is another consideration. We have a mount for the BarrettHand BH-8, but its power supply is too bulky to be truly portable. This is a smaller project, but developing a small power supply for the BH-8, that runs off the 24VDC wheelchair battery, will make the system truly portable again.

6.4.4 Trials

Once the arm is fully operational, trials will begin. One aspect of these trials will be testing various link lengths against a set of tasks. Some tasks require a longer reach, such as reaching a high kitchen shelf or into a freezer. But longer lengths will reduce manipulability close to the mount, reduce payload somewhat, and also appear bulkier when stowed. Only real-world testing can determine what the best general-purpose dimensions are.

Testing won't end with normal-ability researchers playing with hardware. Disabled volunteers will be enlisted to try out the device in our model apartment. Their comments will be noted and used to further develop the arm, especially the controls, GUI, and input devices. At a later stage, the arm may be lent to a disabled person to try out in a true real-world test.

6.4.5 Integration with Power Chair

Yet another upcoming project deals with integration between the WMRA and the power wheelchair itself. As the chair possesses two degrees of freedom, with PMDC motors, retrofitting it to be a true Servo system is not difficult. We plan to mount encoders to each gear motor, and replace the stock control system with two more PIC-

Servo controllers (and suitable power amplifiers). The controllers will then be installed with the arm's daisy chain of controllers, providing seamless integration from the hardware perspective. Once the platform is operational, work will begin on coordinated motion of the total arm-wheelchair system. This will lead to interesting capabilities, such as opening and holding doors while driving through.

6.4.6 Machine Vision Assist Functions

Another area we have been developing separately is machine vision. This system uses a camera on the end effector, coupled with advanced software that recognizes user-selected objects and provides an assist function to home in on an object. This eases what can be a tedious process for the user.

6.5 Conclusion

A wheelchair-mounted robotic arm (WMRA) was designed to meet the needs of mobility-impaired persons, and to exceed the capabilities of current devices of this type. The mechanical design incorporates DC servo drive with actuators at each joint, allowing reconfigurable link lengths and thus greater adaptability to a range of workspaces. Seven principal degrees of freedom allow full pose control, even while operating in the constricted workspace afforded by a side mount on a power wheelchair. A simple, scalable control system allows coordinated Cartesian control, and offers expandability for future research, such as coordinated motion with the wheelchair itself.

We feel that this design will surpass previous attempts at building wheelchair mounted robotic arms that are truly useful and convenient. Subsequent testing, and ultimately the market, will determine if we are right.

References

Reswick J.B., "*The Moon over Dubrovnik -- A Tale of Worldwide Impact on Persons with Disabilities*," Advances in External Control of Human Extremities, 1990.

J.R.Allen, A. Karchak, Jr., E.L.Bontrager, “Design and Fabrication of a Pair of Rancho Anthropomomorphic Arms”, Technical Report, The Attending Staff Association of the Rancho Los Amigos Hospital, Inc, 1972

T.Rahman, S.Stroud, R.Ramanathan, M.Alexander, R.Alexander, R. Seliktar, W. Harwin. “Consumer Criteria for an Arm Orthosis, Applied Science and Engineering Laboritories.” www95.homepage.villanova.edu/rungun.ramanathan/ publications/t_and_d.pdf

M.J. Topping. “The Development of Handy-1, A Robotic System to Assist the Severely Disabled”, Proc ICORR ’99, 244-249

Hillman and Gammie. “The Bath Institute of Medical Engineering Assistive Robot.” ICORR ’94, 211-212

Dallaway JL, Jackson RD (1992) “RAID - a Vocational Robotic Workstation.” *Proceedings of the third International Conference on Rehabilitation Robotics.*

Neil Squire Foundation, “Robotic Assistive Device.” http://www.neilsquire.ca/rd/projects/RobotApp.htm

N. Katevas (Ed), “Mobile Robotics in Health Care Services.” IOS Press Amsterdam, 2000, pp. 227-251

H.F.M. Van der Loos, VA/Stanford Rehabilitation Robotics Research and Development Program: “Lessons Learned in the Application of Robotics Technology to the Field of Rehabilitation.” *IEEE Trans. Rehabilitation Engineering*, Vol. 3, No. 1, March 1995, pp. 46-55.

Bernhard Borgerding, Oleg Ivlev, Christian Martens, Nils Ruchel: “FRIEND Functional Robot Arm with User Friendly Interface for Disabled People.” Institute of Automation Technology (IAT) http://www.iat.uni-bremen.de/Projekte/HTML_e/FRIEND.htm

S. Sheredos, B. Taylor, C. Cobb, E. Dann. “The Helping Hand Electro-Mechanical Arm.” Proc. RESNA ’95, 493-495, Vancover, Canada (1995)

G. Bolmsjö, M. Olsson, P. Hedenborn, U. Lorentzon, F. Charnier, H. Nasri: “Modular Robotics Design - System Integration of a Robot for Disabled People”

Warner, P.R and Prior, S.D. "Investigations Into the Design of a Wheelchair-Mounted Rehabilitation Robotic Manipulator." Proceedings of the 3rd Cambridge Workshop on Rehabilitation Robotics, Cambridge University, England, April 8 1994.

Holly A. Yanco. "Integrating Robotic Research: a Survey of Robotic Wheelchair Development." *AAAI Spring Symposium on Integrating Robotic Research*, Stanford, California, March 1998.

H.Eftring, K.Boschian, “Technical Results from Manus User Trials.” Proc. ICORR ’99, 136-141

Edward McCaffrey, “Kinematic Analysis and Evaluation of Wheelchair Mounted Robotic Arms.” University of South Florida, Novermber 13, 2003.

APPENDICES

Appendix A Cost Estimate

Adaptive technologies must not only work well but must be affordable. The following is a brief estimate of the production cost of the USF WMRA.

Table Appendix A.1: Cost Estimate

Item	Cost
7 controllers	$897.33
7 motors	$1,064.00
USB adapter	$80.00
Wiring, connectors	$200.00
PC controller	$1,125.00
Human Interface hardware	$2,000.00
2 CSF-25 Gearheads	$1,615.00
1 CSF-20	$680.00
2 CSF-17	$1,275.00
1 CSF-14	$552.50
1 CSF-11	$467.50
Plastic covers	$750.00
Aluminum stock	$500.00
Fasteners and hardware	$300.00
Gripper (undecided)	$3,000.00
Machine Time (75 hours @ $60/hr)	$4,500.00
Assembly (10 hours @ $25/hr)	$250.00
Overhead ($250k/yr, 50 units)	$5,000.00
Total	$24,256.33

Prices for some parts, such as the motors, controllers, and gearheads, are based on price breaks given for large-quantity purchases. While rudimentary, this production cost estimate shows that we have met our goal of producing a capable arm that can be sold at retail for approximately $30000. The main variability in the estimate comes from the gripper design not yet being finalized, plus the “Overhead” catch-all category. The human interface hardware also may vary in cost, depending on individual needs.

Appendix B Kinematic Transformation Matrix

Notes: t1 is the angle of joint 1, θ_1. T is the 4x4 transformation matrix relating the wrist plate frame back to the base frame. Each element is separated into one paragraph. Each row is enclosed in brackets []. Units of length are millimeters.

T =

Row 1
[((((cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*cos(t4)-cos(t1)*sin(t2)*sin(t4))*cos(t5)-(cos(t1)*cos(t2)*sin(t3)+sin(t1)*cos(t3))*sin(t5))*cos(t6)+(-(cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*sin(t4)-cos(t1)*sin(t2)*cos(t4))*sin(t6))*cos(t7)-(((cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*cos(t4)-cos(t1)*sin(t2)*sin(t4))*sin(t5)+(cos(t1)*cos(t2)*sin(t3)+sin(t1)*cos(t3))*cos(t5))*sin(t7),

-((((cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*cos(t4)-cos(t1)*sin(t2)*sin(t4))*cos(t5)-(cos(t1)*cos(t2)*sin(t3)+sin(t1)*cos(t3))*sin(t5))*cos(t6)+(-(cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*sin(t4)-cos(t1)*sin(t2)*cos(t4))*sin(t6))*sin(t7)-(((cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*cos(t4)-cos(t1)*sin(t2)*sin(t4))*sin(t5)+(cos(t1)*cos(t2)*sin(t3)+sin(t1)*cos(t3))*cos(t5))*cos(t7),

-(((cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*cos(t4)-cos(t1)*sin(t2)*sin(t4))*cos(t5)-(cos(t1)*cos(t2)*sin(t3)+sin(t1)*cos(t3))*sin(t5))*sin(t6)+(-(cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*sin(t4)-cos(t1)*sin(t2)*cos(t4))*cos(t6),

-179*(((cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*cos(t4)-cos(t1)*sin(t2)*sin(t4))*cos(t5)-(cos(t1)*cos(t2)*sin(t3)+sin(t1)*cos(t3))*sin(t5))*sin(t6)+179*(-(cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*sin(t4)-cos(t1)*sin(t2)*cos(t4))*cos(t6)-241*(cos(t1)*cos(t2)*cos(t3)-sin(t1)*sin(t3))*sin(t4)-241*cos(t1)*sin(t2)*cos(t4)+130*cos(t1)*cos(t2)*sin(t3)+130*sin(t1)*cos(t3)-549*cos(t1)*sin(t2)+146*sin(t1)]

Row 2
[((((sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*cos(t4)-sin(t1)*sin(t2)*sin(t4))*cos(t5)-(sin(t1)*cos(t2)*sin(t3)-cos(t1)*cos(t3))*sin(t5))*cos(t6)+(-(sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*sin(t4)-sin(t1)*sin(t2)*cos(t4))*sin(t6))*cos(t7)-(((sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*cos(t4)-sin(t1)*sin(t2)*sin(t4))*sin(t5)+(sin(t1)*cos(t2)*sin(t3)-cos(t1)*cos(t3))*cos(t5))*sin(t7),

Appendix B (Continued)

-((((sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*cos(t4)-sin(t1)*sin(t2)*sin(t4))*cos(t5)-
(sin(t1)*cos(t2)*sin(t3)-cos(t1)*cos(t3))*sin(t5))*cos(t6)+
(-(sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*sin(t4)-
sin(t1)*sin(t2)*cos(t4))*sin(t6))*sin(t7)-
(((sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*cos(t4)-
sin(t1)*sin(t2)*sin(t4))*sin(t5)+(sin(t1)*cos(t2)*sin(t3)-
cos(t1)*cos(t3))*cos(t5))*cos(t7),

-(((sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*cos(t4)-sin(t1)*sin(t2)*sin(t4))*cos(t5)-
(sin(t1)*cos(t2)*sin(t3)-cos(t1)*cos(t3))*sin(t5))*sin(t6)+
(-(sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*sin(t4)-sin(t1)*sin(t2)*cos(t4))*cos(t6),

-179*(((sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*cos(t4)-sin(t1)*sin(t2)*sin(t4))*cos(t5)-
(sin(t1)*cos(t2)*sin(t3)-cos(t1)*cos(t3))*sin(t5))*sin(t6)+179*
(-(sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*sin(t4)-sin(t1)*sin(t2)*cos(t4))*cos(t6)-
241*(sin(t1)*cos(t2)*cos(t3)+cos(t1)*sin(t3))*sin(t4)-
241*sin(t1)*sin(t2)*cos(t4)+130*sin(t1)*cos(t2)*sin(t3)-130*cos(t1)*cos(t3)-
549*sin(t1)*sin(t2)-146*cos(t1)]

Row 3
[(((sin(t2)*cos(t3)*cos(t4)+cos(t2)*sin(t4))*cos(t5)-sin(t2)*sin(t3)*sin(t5))*cos(t6)+
(-sin(t2)*cos(t3)*sin(t4)+cos(t2)*cos(t4))*sin(t6))*cos(t7)-
((sin(t2)*cos(t3)*cos(t4)+cos(t2)*sin(t4))*sin(t5)+sin(t2)*sin(t3)*cos(t5))*sin(t7),

-(((sin(t2)*cos(t3)*cos(t4)+cos(t2)*sin(t4))*cos(t5)-sin(t2)*sin(t3)*sin(t5))*cos(t6)+
(-sin(t2)*cos(t3)*sin(t4)+cos(t2)*cos(t4))*sin(t6))*sin(t7)-
((sin(t2)*cos(t3)*cos(t4)+cos(t2)*sin(t4))*sin(t5)+sin(t2)*sin(t3)*cos(t5))*cos(t7),

-((sin(t2)*cos(t3)*cos(t4)+cos(t2)*sin(t4))*cos(t5)-sin(t2)*sin(t3)*sin(t5))*sin(t6)+
(-sin(t2)*cos(t3)*sin(t4)+cos(t2)*cos(t4))*cos(t6),

-179*((sin(t2)*cos(t3)*cos(t4)+cos(t2)*sin(t4))*cos(t5)-
sin(t2)*sin(t3)*sin(t5))*sin(t6)+179*(-sin(t2)*cos(t3)*sin(t4)+cos(t2)*cos(t4))*cos(t6)-
241*sin(t2)*cos(t3)*sin(t4)+241*cos(t2)*cos(t4)+130*sin(t2)*sin(t3)+549*cos(t2)]

Row 4
[0, 0, 0, 1]

Appendix C Joint Torque Calculations

As this is a serial chain robot, torques at each joint may be modeled by summing the torque contributions of each more distall part. For example, Joint 7 sees only the torque due to mass at the gripper, the payload, shown here as 8.24 Nm. Joint 1 must resist torques from all six other joints plus the payload. These are listed in the bottom row of the spreadsheet, and when summed they equal 98.79 Nm.

Inputs to the spreadsheet are the distances between each part, the type of gearhead used, and the payload. The distances shown represent the arm in a horizontal, full outstretched position. The gearheads shown are the ones selected in the final design. The payload is 6 kg, for a weight of 58.86 N.

Table Appendix C.1: Available Harmonic Drive Gearhead Specifications

Gearhead model	Torque (N m)	Weight (N)
CSF 11	12	1.47
CSF 14	19.5	5.08
CSF 17	46	6.69
CSF 20	70	9.63
CSF 25	140	14.72

Table Appendix C.2: Joint Torque Design Spreadsheet

Joint	Distance from next (m)	Gear-head type	Weight at Joint (N)	tgrip	t7	t6	t5	t4	t3	t2	total torque	Rated Torque	ok?
Grip	0.14	0	58.86								0.00	0	Yes
7	0.06	11	4.41	8.24							8.24	12	Yes
6	0.11	14	8.52	11.77	0.26						12.04	19.5	Yes
5	0.00	17	10.61	18.25	0.75	0.94					19.93	46	Yes
4	0.49	17	18.46	18.25	0.75	0.94	0.00				19.93	46	Yes
3	0.12	20	19.44	47.09	2.91	5.11	5.20	9.05			69.36	70	Yes
2	0.10	25	24.53	54.15	3.44	6.13	6.47	11.26	2.33		83.79	140	Yes
1	0.00	25	24.53	60.04	3.88	6.98	7.53	13.11	4.28	2.45	98.28	140	Yes

For a selected gearhead type in column C, the spreadsheet automatically fills in the appropriate joint weight. This joint weight accounts for the gearhead weight plus the motor, bracket, and the previous link tube weights.

The rated continuous torque is also automatically filled into column M. The individual torque components are calculated, and summed in column L. As a final check, the calculated torques are compared to the rated torques, shown in column N.

This spreadsheet was used to quickly evaluate dozens of design possibilities. Since each part affects the more proximal joints, optimization starts at the distall end and works inward. Various link lengths were tried, and then the minumim gearhead sizes were found for each joint.

Gearhead torque ratings do not scale linearly with gearhead masses. Smaller gearheads generally carry less torque per unit mass. As self-weight is very important, it was found that by increasing total arm mass just 20%, from 9 kg to 11 kg, available payload nearly doubled, from 3.5 kg to 6 kg. This was considered to be an improvement, for much greater performance was found without much increase in either cost or weight.