DEVELOPMENT OF A ROBOTIC MANIPULATOR TO ASSIST DISABLED CHILDREN

GATEWAY ENGINEERING COALITION
CONCURRENT DESIGN AND MANUFACTURING PROJECT 1998

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I.   ABSTRACT

This year's Gateway project, funded by the National Science Foundation, has developed a robotic manipulator to assist challenged children who are confined to wheelchairs. The multi-university design was accomplished utilizing concurrent engineering methodology. This project was a joint venture between Cooper Union, Drexel University, New Jersey Institute of Technology, The Ohio State University, and the University of Pennsylvania. From the initial design conceptualization to the finished project, undergraduate engineering students integrated design and manufacturing processes. Phase I required each team to develop a conceptual design for the manipulator using specified design criteria, established at UPenn in October 1997. Following a critique of the five conceptual designs at Cooper Union in January 1998, the teams combined their engineering expertise and resources to manufacture a prototype manipulator.   Each university was assigned a specific task in Phase II of the project. These five subsystems were presented and finalized at the University of Pennsylvania in April 1998. The final design was presented at UPenn on April 26, 1998.

II.   INTRODUCTION

MULTI-UNIVERSITY DESIGN PROJECT CONCEPT

The intent of the Gateway Coalition in establishing this multi-university design project was to develop the human relation skills of the undergraduate students. Combining traditional classroom teaching methods, with practical application of the undergraduate engineering course content accomplished this objective. The learning gained by the students encourages and enhances their teamwork skills, which are necessary for today's industry. One goal of this design project was to provide significant interaction among the schools, enabling students to openly communicate and cooperate to overcome inevitable technical problems. Concurrent Engineering methodology was necessary in the development of the project. It served as a powerful tool to enhance the interaction between the teams utilizing advanced communication systems. Concurrent Engineering integrates marketing, manufacturing, design, and provides requirements that should be followed from the projects initial conceptualization until the prototype is finished.

PROJECT LOGISTICS

The five universities, Cooper Union, Drexel University, New Jersey Institute of Technology, The Ohio State University and University of Pennsylvania took part in this year's project. Each school was involved with the development and manufacturing of the wheelchair-mounted robotic manipulator. The student teams were introduced to the project and to each other at an initial design meeting, which took place in October 1997, at the University of Pennsylvania. At this meeting, the scope and the goals of the project, along with the requirements and chosen design specifications were discussed in detail. At the conclusion of this meeting, each university set up a World Wide Web page on the Internet so that each student team could view weekly project updates and progress reports. The project consisted of two phases. Phase I took place from October 1997 to January 1998, and Phase II lasted from January to May 1998. The five schools used frequent video-conferencing and electronic mail to communicate with each other during both phases, as well as some on-site visits to a few the universities.

DESIGN CONFERENCE AT UNIVERSITY OF PENNSYLVANIA

On October 12, 1997 the student teams representing various disciplines of engineering from the five universities, along with their graduate and faculty advisors, assembled at the University of Pennsylvania for an introductory design meeting. Dr. Vijay Kumar, faculty advisor for the University of Pennsylvania, introduced the intent and goals of the project. It was instructed that the teams would combine engineering backgrounds to develop a robotic manipulator, which would assist challenged children. The project consisted of two phases. In the first phase, each school would independently develop a kinematic design for the manipulator. The second phase would require all five universities to work as a team, in an effort to manufacture a prototype manipulator. The teams discussed the scope and timeline of the project and worked profusely to develop design constraints. For most of the meeting, each team voiced opinions on who should be the candidates for such a design concept. Once the teams agreed on the assembled design specifications and constraints for the project, the advisors were informed of the students' obligations. The meeting was adjourned with specific instructions for each university's design team for the two phases of the project.

GOAL OF THE PROJECT

For this year's Gateway-sponsored Concurrent Engineering project, the goal was to develop a robotic manipulator which will assist a children who are confined to wheelchairs and have limited use of their arms and hands. Using Concurrent Engineering principles, in which the phases of the project are completed sequentially, the teams from Cooper Union, Drexel University, New Jersey Institute of Technology, The Ohio State University and University of Pennsylvania, worked independently on Phase I of the project. Each university developed an optimal kinematic configuration of the manipulator. The teams presented their ideas at the January design meeting, at which the most sufficient and economical design configuration of the manipulator was selected. In Phase II, the teams combined engineering disciplines to work together and exchange ideas to generate a prototype manipulator. The final design of the manipulator, as well as the prototype model, was presented at the final meetings in late April for the faculty advisors and the members of the Gateway Coalition. A working demonstration of the prototype ensured that the design of the manipulator is sufficient for production.

SCOPE OF THIS REPORT

This design report, prepared in conjunction with members from all five teams, will ultimately describe the design configuration for the working prototype of the manipulator, as well as each school' s role in the two phases of the project. The report is divided into eight subsections, arranged in the following order:

- **Background:** The report will discuss previous work from past industry and university projects related to this year's project. A market analysis will then be discussed to inform the reader of the current market for the product as well as the need for such a device.
- **Problem Statement:** A concise statement of need will educate the reader with the intent of the project, a description of the design's end-user, and the design configuration's solution to the problem.

- **Phase I:** Each of the five universities' preliminary kinematics designs and key features will be discussed in detail for Phase I of the Gateway project.
- **Design Specifications for Prototype:** Using feedback from the January design meeting, the design configuration will be revised to allow for the manufacturing of the manipulator in Phase II of the project. The highlights of the January meeting will be discussed, followed by the chosen configuration of the manipulator using key elements from each teams' preliminary design specification.
- **Phase II:** This subsection will consist of discussions pertaining to the manufacturing of each portion of the robotic manipulator. Drexel was responsible for the design of the arm skeleton and base of the manipulator. University of Pennsylvania focused on the power transmission for the arm and the motor selection. Cooper Union concentrated on the user interface design and the development of the program code to control the actuation of the motors. The Ohio State University will prepare the graphical simulation and Finite Element Analysis for the final prototype design. Additionally, they will serve as the project manager, scheduling, overseeing and interjecting when necessary.
- **Logistics:** This subsection will describe the methods of the five teams used when communicating their ideas and opinions to each other outside of the design meetings. It will mention the extensive use of video-conferencing between the schools as well as frequent use of electronic mail and the teams' World Wide Web pages for the project. Three design meetings of all five universities will be discussed in further detail as to how the final design, manufacture and assembly decisions were accomplished. Finally, this subsection will be completed with a conclusion for the effectiveness of these communication tools utilized in this project.
- **Concluding Remarks:** The overall opinions and concerns of the project's design and format will be discussed here. Teams will have the opportunity to express their thoughts on the project's achievements, the important aspects of the project, lessons learned, and what can be done in another engineering project to improve product development.
- **Appendices:** Programming code, along with a presentation, part and assembly drawings and a comprehensive parts lists will be included in this subsection.

III. BACKGROUND

Before any attempt to develop a conceptual design of the manipulator, it was necessary to research the current status of robotic design. To date, only two similar devices have been marketed: the Helping Hand, which sold about 10 units at a cost of $10,000 before the company went bankrupt, and the MANUS, which has sold about 100 units and continues to sell more at a cost of $65,000. Both companies found it difficult to market these devices mostly due to possible users being unconvinced of the devices' benefits and usability.

The Helping Hand is a wheelchair-mounted manipulator that operates on five degrees of freedom. It is made out of a lightweight plastic material, similar to polyvinylchloride. It is actuated by electric servomotors, and is controlled by a computer microprocessor interface. Movement of the device is only based on joint control; as a result the computer interface moves one joint at a time to reach a destination. This motion is not only unstable (jerky), but does not simulate the human arm

The MANUS Manipulator also mounts to a wheelchair, however it operates on seven degrees of freedom. It is made out of a lightweight aluminum and is also actuated by electric servomotors. The main difference between the Helping Hand and this manipulator is that all the motors are mounted in the base, decreasing the weight of the arm itself. This is an advantage over the Helping Hand because unstable motions are eliminated. More importantly, this device is controlled by end point manipulation. This means that the computer interface (a

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keyboard) calculates the most favorable path to a destination, and moves all joints simultaneously to reach this point.

The four leading disabilities in which people could benefit from a wheelchair-mounted robotic arm are Multiple Sclerosis, Cerebral Palsy, Spinal Muscular Atrophy, and Amyotrophic Lateral Sclerosis. Although MS and ALS do not affect children six to fourteen years of age, a market for the device still exists for people with these disabilities. Overall, 1,040,000 (including 55,000 children) in the United States have one of these disabilities. Through general marketing analysis, it was derived that 15, 630 people (including 1,578 children) in the U.S. would probably purchase such a device.

Most health insurance carriers would cover 100% of the cost for an assistive device if a person's physician presents a case on the patient's behalf describing how the device would dramatically improve the quality of the patient's life.

SURVEY OF POWERED WHEELCHAIR USER REQUIREMENTS (DREXEL)

PREVIOUS DEVICES AND MARKETING DIFFICULTIES

There are only two wheelchair mounted robotic arms out on the market currently, the Helping Hand and the MANUS. Kinetic Rehab Instruments (KRI) produced the Helping Hand; they have since gone out of business. It is controlled by a joystick interface and has four degrees of freedom not including the gripper. This device is priced around $10,000. A company called Exact Dynamics produces the MANUS. It is controlled by a sixteen key, keypad interface and has seven degrees of freedom. This device is priced around $65,000. In all, a total of 5 Helping Hand and about 55 MANUS devices were sold.

The marketing difficulties are the same for both of these devices. Those who have heard about robotic devices aren't convinced about the benefits and the usability of the devices. Therefore potential users of a wheelchair mounted robotic arm are finding alternative solutions. For example: smart homes, environmental control systems and human assistants. In addition to high cost, another problem is that most people have never heard of rehabilitation robotics. A better market strategy is necessary to convince potential users to choose robotics as a solution.

GENERAL STATISTICS OF WHEELCHAIR USERS

In rehabilitation robotics, many good designs have failed. This can be attributed to some basic design flaws, such as cost, ergonomics and difficulties utilizing controls. It is critical for a designer in today's cost competitive market to determine the requirements of potential users of rehabilitation robotics.

There were several surveys completed in the US and Europe to investigate and evaluate the needs and abilities of the disabled. However, there have been very few surveys of robotic aids with focus on electric-wheelchair users with little or no upper limb mobility. One such survey, completed in United Kingdom shows the following age distribution of electric-wheelchair users.
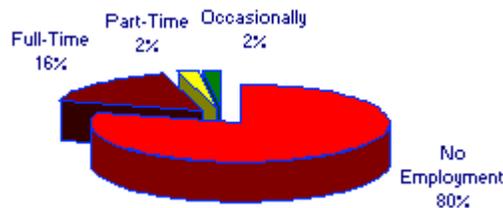
Age Distribution of Electric-Wheelchair Users

| Age	Distribution of Users
Under 16	6%
16 - 35	40%
36 - 65	46%
Above 65	8%

It is clear from the above statistics that there are more adult users of electric-wheelchairs than there are children. According to the same survey the average electric wheelchair user is 40 years old, single (68%), living at home (58%) and without any paid employment (80%).
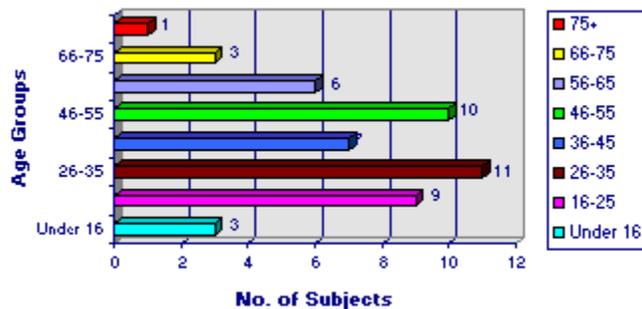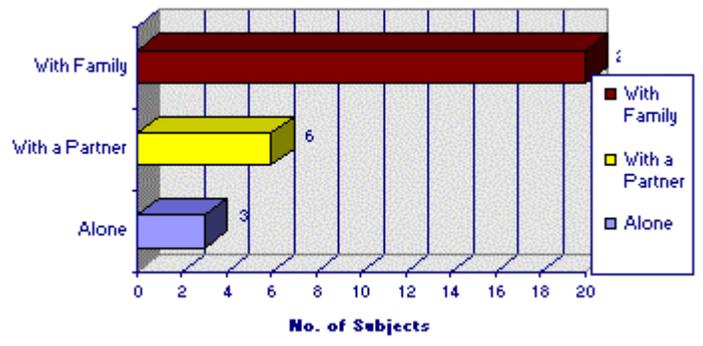

Employment Status of Electric-Wheelchair Users

Marital Status of Electric-Wheelchair Users
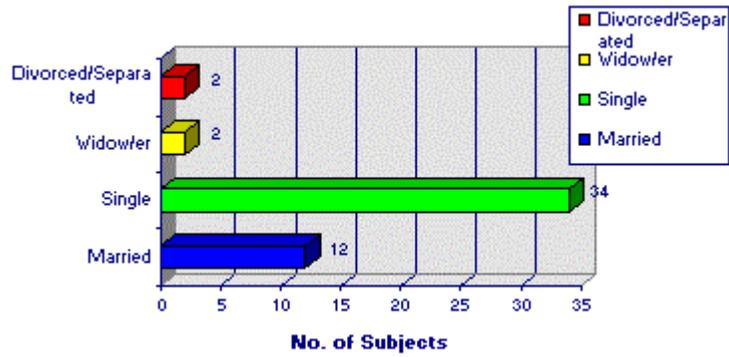
Further, the average user is likely to be male (56%) than female (44%). This may be due to the high number of spinal cord injuries caused by male participation in dangerous sports such as diving, skiing, martial arts, etc. On the other hand, women users are usually those that suffer from conditions resulting from old age because they live longer. The majority of wheelchair users are those living at home, followed by those living in hospitals, care homes or hostels. Hence the majority of the robotic aids must be designed to operate within the confines of the home environment and must be adjustable enough to serve the needs of both adult and children for a larger market share. Of the subjects living at home, the majority receives help from family members with no outside care.

Input device familiarity

Type of Input Device	Familiar Users
Joystick	84%
Remote Control	72%
Head Movement Sensor Roller ball Control Chin Operated Control Eye Movement Control Ultrasonic Sensor Voice Activated Sip & Puff Switches Mind Switch (EEG based)	Less than 5%

In terms of choice of an input device, the majority of disabled people are familiar with joystick and remote control. That is, they will not hesitate to use such an input device. Another survey revealed that a mobile robotic aid device would be of far greater use than a workstation-based device.

GENERAL STATISTICS OF PEOPLE WITH DISABILITIES

When designing a robotic manipulator, it is important to know the characteristics of the population and the disabilities of whom will be using the device. Devices can be optimally designed based on the functionality needed by the user population. Robotic arms are thought of as a technology, which could assist people who had minimal use of their hands and arms. By understanding the demographics of this population, robotic devices for augmenting hand function could be designed and marketed accordingly. The number of people who could make use of such a device is not specifically known. There are several factors that make it difficult to determine such a number. First, the degree of hand and arm functionality is almost never recorded in association with disability statistics. Second, some severely disabling conditions are progressive in nature, yet the progression varies widely from individual to individual. With other conditions, there is recovery or a gain in functionality with wide variations in the gain. Third, some severely disabling conditions are correlated to severe cognitive impairments rendering the use of this technology problematic. Despite these constraints, valuable information is known about the incidence and prevalence of specific disabling conditions associated with minimal use of hands and arms.

PREVALENCE OF DISABILITY AMONG CHILDREN

Comparisons among age groups are difficult because the NHIS definition of the expected "major activity" of a child changes from play for those under age 5 to school attendance for those aged 5 to 17. Only a small fraction (0.6 to 0.7%) of children of any age are reported as being unable to perform their major activity. While only 1.4% of children under 5 are classified as being limited in the amount or kind of play activities they can engage in. Older children are reported as far more likely to be limited in school attendance (5.0%, including those who attend or need to attend special schools or classes). Only 0.7% of young children (under age 5) are reported as limited in activities other than play, but not in play. A larger fraction of older children (2.0%) are limited in

activities other than school attendance, but not school itself; many of these children may not be able to engage in certain types of play.

Overall, 5.5% of children and adolescents ages 5-17 have disabilities related to schooling. This may include an inability to attend school, a need for special education, or a limitation in the amount of school attendance. Finally, 1.2% are limited in school attendance, but are not reported to attend or need special classes. Thus, of those children with school-related disabilities, 58.1% attend special schools or classes. An additional 9.6% are considered by their parents or guardians to need special schools or classes, however they do not attend them. Of the 1.7-million school-age children classified as requiring special education, 85.8% actually receive it. The main gender difference in school-related disability involving special education is as follows: boys are significantly more likely than girls to attend special schools or classes (3.9 versus 2.4%). Overall, 6.3% of boys and 4.5% of girls have school-related disabilities. Children from poor families attend special schools and classes at nearly twice the rate of those who are not poor (5.2 versus 2.8%, respectively). The rate of needing but not receiving special education also differs by a similar factor (1.0 versus 0.4%). Clearly, the different disabilities have implications for different types of products but, however, show that significant market exist.

PREVALENCE OF DISABILITY WORLDWIDE

The United Nations estimates that about 10% of the population in various countries may be considered disabled. However, there is great variation in the incidence of disabilities in the statistics from different countries. These differences may be caused by different criteria for reporting, degrees of industrialization, rate of traffic accidents, participation in wars etc.

Percentage of Disabled People in Different Countries

Country	Percentage
Denmark	10.0- 12.0%
Finland	5.2- 8.3%
France	5.0- 8.3%
BRD	10.8- 13.1%
Ireland	3.3 - 5.0%
Italy	1.7- 17.1%
Luxembourg	10.0- 11.0%
The Netherlands	9.5%
Norway	12.0%
Portugal	7.4%
Spain	25.0%
Sweden	12.0%
Switzerland	1.6%
U.K.	7.3%
Canada	13.0%

Many countries have social service provisions that provide financial aid for specialist devices. However, it has been recognized that not all people in other countries are financially impoverished and that a large number have sufficient income for the purchase of such a device. For those who are not so fortunate, varying degrees of state support are available. The Government support varies significantly from country to country.

To obtain a realistic estimate of the number of people with disabilities in other countries, it seems necessary to make individual estimates of specifically defined impairments and disabilities.

Percentage of Disabled People with Reduced Functions Worldwide

Type of Disability	Percentage
Blind	0.2
Partially sighted	2
Profoundly deaf	0.1 - 0.2
Hard hearing	10.0 -15.0
Cannot speak clearly	0.4
Cannot use fingers	0.2
Cannot use one arm	0.2

MULTIPLE IMPAIRMENTS

A considerable number of disabled people have more than one form of impairment. For example, of 1,000 people who are deaf and blind:

- 120 are totally deaf and blind
- 500 have residual sight and hearing
- 300 are mobility impaired
- 100 are intellectually impaired
- 650 have to be described as severely handicapped besides being deaf and blind

Several statistical surveys have been reviewed in order to obtain the most relevant estimates of the number of disabled people. The material available shows a need for the passing of uniform criteria that defines the term "disability".

TYPES OF DISABILITIES (PROSPECTIVE RECIPIENTS OF A WHEELCHAIR-MOUNTED ROBOTIC ARM)

MULTIPLE SCLEROSIS (MS)

Multiple sclerosis is an inflammatory disease of the central nervous system that damages the insulating material that surrounds the nerve fibers in the brain, spinal cord, and optic nerves. The insulating material is lost in "multiple" areas leaving scars called "scleroses". Flare-ups of these scars prevent the conduction of nerve impulses in the central nervous system. These flare-ups can last for days or weeks. MS most often strikes women in their 20's and 30's at a rate twice that of men. The disease is most common among Caucasians, especially those of northern European ancestry. MS occurs most frequently in regions of temperate climate.

In the U.S., it is estimated that approximately 300,000 people have MS, and another 200 cases are diagnosed each week. It is also estimated that 3 million people worldwide have MS. MS is rarely fatal and usually shortens the life expectancy by 10%. About 2% of people with MS experience severe muscle weakness and/or severe sensory disturbance of the upper limbs. This translates to approximately 6,000 people in the U.S. and 60,000 people worldwide who can make use of the wheelchair-mounted robotic arm. Since the disease is almost exclusively restricted to people of northern European ancestry living in temperate climates, a high percentage of these people should be accessible through advertising and should have access to funding resources for the device. Although MS almost never strikes children, there still exists a market for the device for people with MS.

CEREBRAL PALSY (CP)

Cerebral palsy is a condition caused by physical damage to the brain, usually occurring before, during, or shortly following birth. Specifically, CP is caused by insufficient oxygen reaching the fetal or newborn brain, traumatic birth injury, infections during pregnancy, brain infections, brain hemorrhages, or post-natal head injuries such as those resulting from motor vehicle accidents, falls, or child abuse. "Cerebral" refers to the brain and "palsy" refers to the lack of motor control. CP is the most prevalent life-long physical disability in America. A child or adult with CP may experience seizures, mental retardation, and impairments of sight, hearing, or speech. CP is not a progressive disease, does not cause death, and is not curable. CP, however, does respond positively to therapy.

In the U.S., it is estimated that 700,000 children and adults have CP, and 8,000 new cases are reported each year. It is also estimated that 3,500 to 4,000 infants are born with CP and an additional 1,500 pre-school age children acquire CP as a result of accidents or abuse. Most cases of CP can be categorized as having diplegia, which affects only the lower limbs and accounts for 175,000 people in the U.S. Hemiplegia, which affects only one side of the body and accounts for 235,000 people in the U.S., or quadriplegia, which affects all four limbs and accounts for 235,000 people in the U.S. Many people with quadriplegia CP still have some moderate movement in their upper limbs. A conservative estimate of "many" could be 1/4, or 60,000 people. This estimate takes into account that "many" is not a definitive number and some of these people have mental retardation and lack the capacity to operate such a device. This translates to an approximation that 60,000 people in the U.S. could make use of a wheelchair-mounted robotic arm.

SPINAL MUSCULAR ATROPHY (SMA)

Spinal muscular atrophy is a disease of the cells in the spinal cord responsible for activities such as crawling, walking, head & neck control, and swallowing. SMA mainly affects the muscles closest to the trunk of one's body. Weakness in the legs is generally greater than weakness in the arms. Unaffected by SMA are the senses,

feelings, and intellect. Children with SMA may sit unsupported, but usually require assistance to come to a sitting position. A fine tremor is common in the outstretched fingers. In the child, juvenile, and adult types of SMA, a person usually shows a general weakness in the respiratory muscles, placing a burden on the tummy muscles. Other symptoms are trouble walking or getting up from a sitting or bent over position. People with type I SMA usually die before age 2. People with type II SMA usually die between age 3 and adulthood. People with type III SMA do not usually show symptoms of the disease until age 35 nor do they die due to the disease but require more and more assistance as time goes on.

Approximately 10,000 people in the U.S. and 235,000 people worldwide have SMA. Since the breakdown of people with each type of SMA varies greatly, one can only assume (for marketing purposes) that the distribution is equally spread over the three types; 6,700 people in the U.S. and 157,000 people worldwide have type II or type III SMA, which are the only types who could make use of the device.

AMYOTROPHIC LATERAL SCLEROSIS (ALS): (Lou Gehrig's disease)

Amyotrophic lateral sclerosis is a fatal neurodegenerative disease that attacks specialized nerve cells called motor neurons, which control the movement of voluntary muscles. "Amyotrophic" refers to a loss of muscle mass, "lateral" refers to the nerve tracks that run down both sides of the spinal cord, and "sclerosis" refers to the scar tissue that remains after the disintegration of nerves occurs. ALS usually affects people 16 through 77 years of age. It is estimated that 30,000 people in the U.S. have ALS with 5,000 new diagnosed each year, and 150,000 people worldwide have ALS. ALS affects men more than women at the rate of 2:1.

The symptoms of ALS usually begin with persistent muscle twitch, muscle fatigue, or muscle wasting associated with the hands, lower legs, trunk, eye movement, speech and/or swallowing, and is usually accompanied by cramps. 1/3, or 10,000 ALS patients, complain of upper limb weakness and 1/3, or 10,000 ALS patients, complain of lower limb weakness. As the disease progresses, patients lose the ability to dress and feed themselves, sit up, walk, or even speak. The ultimate cause of death is respiratory failure. The bodily functions that remain intact until or near death are the control of excretory functions, sexual function, eye movement, and intellect. The death rate caused by ALS is as follows: 50% of people die 3 years after diagnosis, 25% after 5 years, 15% after 10 years, and 10% after 20 years.

Overall, an approximation of 10,000 people in the U.S. could make use of a wheelchair-mounted robotic arm. Although ALS does not usually affect people under the age of 16, there still exists a market for the device for people with ALS.

FUNDING SOURCES FOR REHABILITATIVE DEVICES

Many private health insurance companies were contacted in reference to their coverage concerning assistive devices, in particular a wheelchair-mounted robotic arm. These companies included Amerihealth, which carries licensing to sell Blue Cross and Blue Shield in southern New Jersey, Aetna, which recently bought U.S. Heathcare, and Prudential Health. With all of these health insurance companies, coverage is basically the same. The child's physician would have to legitimately make a case on the patient's behalf that this device would dramatically increase the quality of life for that particular child. If a legitimate case can be made, then the device should be covered 100 percent. However, what exactly is a legitimate case and a dramatic improvement in the quality of life? Each case is taken on a case by case basis.

Other than private health insurance carriers, there are also state and federal funding sources for example, Medicare. Medicare, or social security as it is better known, normally supports Americans ages 65 and older. However, in special cases, when a person is a paraplegic or is severely handicapped, Medicare will cover some of his/her healthcare costs. As a general rule, Medicare does not cover any of the costs of orhotics, but in this case, the robotic arm is not considered an orthotic device.

The process of actually getting compensation begins with the either the patient or the provider of the device submitting an application to Medicare for funding. A nurse employed by Medicare takes each application on a case by case basis. If the application is approved, then Medicare will cover up to 80% of the total cost of the device. If the application is denied, the provider or the patient can begin an appeal process to seek funding.

Other charity groups have been set up to help offset the cost of devices such as the arm. These include the Lions Club, Kiwanis, Rotary Club, Pilot International, and the National Easter Seals Society. Other grants are available from non-profit groups such as The Commonwealth Fund. This fund in particular gives grants to companies or groups such as the Gateway Coalition to help offset the costs of bringing to reality life enhancing devices. An application must be filed and then approved to receive compensation. These grants intended for the designer / provider of the device rather than the end user.

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The following is a summary of the number of prospective recipients of a wheelchair mounted robotic arm. These statistics are for the United States only. However, with the exception of multiple sclerosis, worldwide statistics are approximately 10 times that of the United States. Multiple sclerosis is the exception because it is almost exclusively restricted to Caucasians of European ancestry living in temperate climates.

DISEASE	A	B	C	D	E	F
MS	300,000	0	6,000	0	1,135	0
CP	700,000	50,000	60,000	5,000	11,340	945
SMA	10,000	5,000	6,700	3,350	1,265	633
ALS	30,000	0	10,000	0	1,890	0
totals	1,040,000	55,000	82,700	8,350	**15,630**	**1,578**

Legend:

Column A: number of people who could make use of the device.
Column B: number of people between the ages of 6 and 14 who have the disease.
Column C: number of people who have the disease and could make use of the device.
Column D: number of people between the ages of 6 and 14 who have the disease and could make use of the device.
Column E: number of people who will probably receive the device.*
Column F: number of people between the ages of 6 and 14 who will probably receive the device.*

*A formula was used to derive these numbers, taking into consideration accessibility through advertising, access to funding, surveys of prospective buyers, and a conservative safety factor. The above referenced

equation is as follows:

(number of people expected to purchase device) =
   (number of people who could use the device) x 0.90 x 0.84 x 0.25   where,

0.90 is an educated guess that accounts for the fact that not all people are accessible through advertising and/or do not have access to funding sources.

0.84 which is based on a survey in which 84 out of 100 prospective users said they would consider purchasing the device.

0.25 is an educated guess that it is conceivable that 25% of people who would consider purchasing the device will actually take the necessary steps for purchasing the device.

The top four disabilities for prospective users of a wheelchair-mounted robotic arm have been analyzed in this report. The number of children as well as adults who have these disabilities have been reported to show the total amount of people who could possibly use the device. Although the targeted audience of this report is children 6 to 14 years of age, a much larger market exists for adults with disabilities. In fact, approximately 10 adults for every child 6 to 14 years of age could use the device. At a ratio of 10:1, the adult market cannot be ignored. Overall, a total of 15,630 people, 1,578 which are children 6 to 14 years of age, would probably buy the device. It is recommended that the device be designed to be of use to children. As well as adults or a larger scaled version be designed specifically for adults.

The most limiting factor in the marketing research for this device was the extremely short time period allowed for the research. Because this report has a deadline near the beginning of the project rather than at the end, a very limited amount of information could be researched. The same four disabilities were researched this year as were last year due to the unnecessary rushed nature of this particular portion of the project. More attention should have been given to the world market of the device. Also, there are disabilities other than those researched in this report that could yield potential users of the device. Some of these disabilities may include rheumatoid arthritis, spinal cord injury, muscular dystrophy, and any other disability that prevents a wheelchair-stricken person from manipulating objects from floor level to the surface of a tabletop. It is difficult to find disabilities in which people could benefit from a wheelchair-mounted robotic arm. It is recommended that several disability specialists be surveyed in order to get a more precise idea on which disabilities the device could help benefit the most and where the larger markets exist.

It is also recommended that a school offering degree programs in marketing be involved in future projects. A marketing-engineering coalition would greatly enhance the productivity of the overall project. The equations and derivations contained within this report reflect the thinking process of engineers and are only an educated guess to what seems like the best way to perform this type of analysis.
Based upon the findings of only the four disabilities contained within this report, there appears to exist only a very small market, an even smaller market for children 6 to 14 years of age, for a wheelchair-mounted robotic arm. If it is the intention of the marketers to market this device for the purpose of profit, it is recommended that the effort be terminated. However, if the intention is to add more purpose, self-sufficiency, and pride to a small group of individuals who could not otherwise do so through conventional methods, it is recommended that the efforts set forth by the Gateway Coalition continue and the coalition further its work in this almost totally unexplored field of technology.

IV. PROBLEM STATEMENT

STATEMENT OF NEED

People with disabilities constitute a large percentage of the American population. This included those who have difficulty using their hands and arms to control and manipulate their environment. In order to live their daily lives, they must be under constant supervision, should a problem or difficulty occur. Often, this requirement is not met because such care is hard to find due to lack of assistance or for financial reasons. If a robotic manipulator could be designed and manufactured for these people, the need for constant supervision could be reduced drastically or even eliminated. The robotic arm could assist them in their daily activities, like picking things up from the ground or exploring their immediate environment. Furthermore, if such a device was simple to operate it could be used by younger patients. Also, a robotic arm would rebuild confidence and self-esteem lost in the depths of the illness. The aim of this project is to design a lightweight, easy to use, and low-cost robotic manipulator, which could act as an extension for the affected people to regain their independence from the disease.

DESIGN SPECIFICATIONS

The initial meeting on October 12, 1997 in Philadelphia, Pennsylvania served as a brainstorming session for ideas and restrictions that would be applicable for a child in a wheelchair. Some of the issues that were discussed included; adaptability to wheelchairs, speed, user interface, power supply, safety and expense. Final minimum parameters were then settled upon:

- 30.5 cm reach from the front wheel of the chair
- 60 degree sweep angle
- Maximum cost of 4,000 dollars
- Each linkage must move no more than 0.2 to 0.5 m/s
- Lift a one pound mass
- Lift an object of 7.5 cm in diameter

These constraints define the minimum motion and application that the robotic device shall accomplish. They were selected since the primary market being targeted is a child with disabilities that is restricted to a wheelchair. The primary market also yields that safety and ease of use are major factors to be considered in the design. As a result, the speed of the arm needed to be limited to prevent injury and to minimize rapid movements. It was resolved that end point control would be utilized due to the child user having limited arm and hand movement. The end point control would also be the most simplistic form of manipulation while allowing the child to have full range within their environment.

V.   PHASE I

Using the design requirements as determined by the five student teams, it was decided that each university would use the first phase of the project for developing an independent conceptual design. In addition to their kinematic design considerations, each university was assigned a specific task to research to aid in the final design and manufacture of the manipulator. The research reports were assigned as follows:

- **Drexel University**- Marketing Research
- **The Cooper Union**- User Interface
- **University of Pennsylvania**- Controls
- **New Jersey Institute of Technology**- Graphical Simulation
- **The Ohio State University**- Kinematic Analysis

THE COOPER UNIVERSITY

CONCEPTUAL DESIGN

 Fulfillment of the design requirements:

1. **Light Weight.** To meet this requirement a material with a high strength/weight ratio was chosen. The use of aluminum and a thermoplastic fulfilled the strength requirements while keeping the weight to a minimum.
2. **Mountable on a wheel chair.** This requirement restricted the overall size of the base or housing. A typical electrical wheelchair [1] was chosen and the housing was design based on the dimensions of the wheelchair.
3. **Easy to Maneuver.** This requirement had an influence on the degrees of freedom of the manipulator. Five degrees of freedom were found to be sufficient to cover the motion required. This determined the number of motors and linkages to be used.
4. **Low Cost.** The utilization of standard components and materials fulfilled this requirement.
5. **Easy to Manufacture.** Attention was paid in the design to minimize extraneous profiles or components with non-uniform thickness.
6. **Safety.** Due to the fact that children are the intended users, and that the robot arm is intended for indoors as well as outdoors use, all moving parts were covered and designed to operate at low speeds.

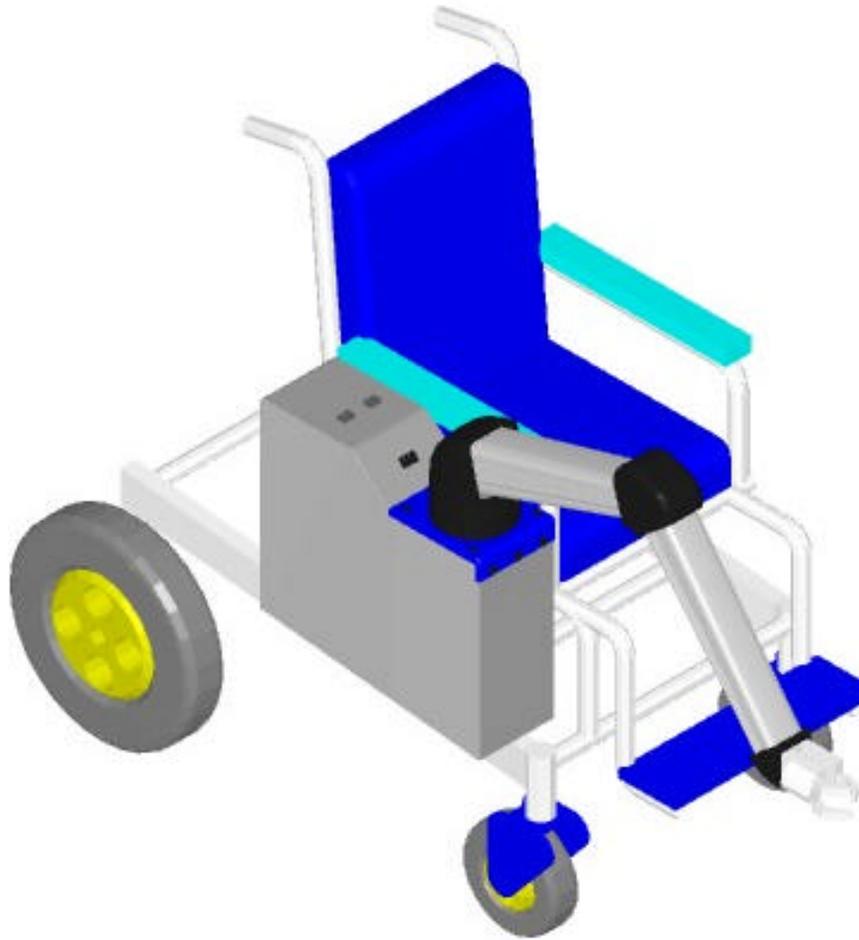# The Cooper Union Robotic Arm (C.U.R.A) 1000

Figure 1: The **"C.U.R.A 1000 "**

DEGREES OF FREEDOM

The **C.U.R.A 1000** has five degrees of freedom. Two rotations come from the base and shoulder. One additional degree of freedom is needed to swing the forearm about the elbow joint. And the gripper operates with two other degrees of freedom. One degree permits the rolling of the gripper in the longitudinal axis of the wrist and the other the pitching of the wrist itself.
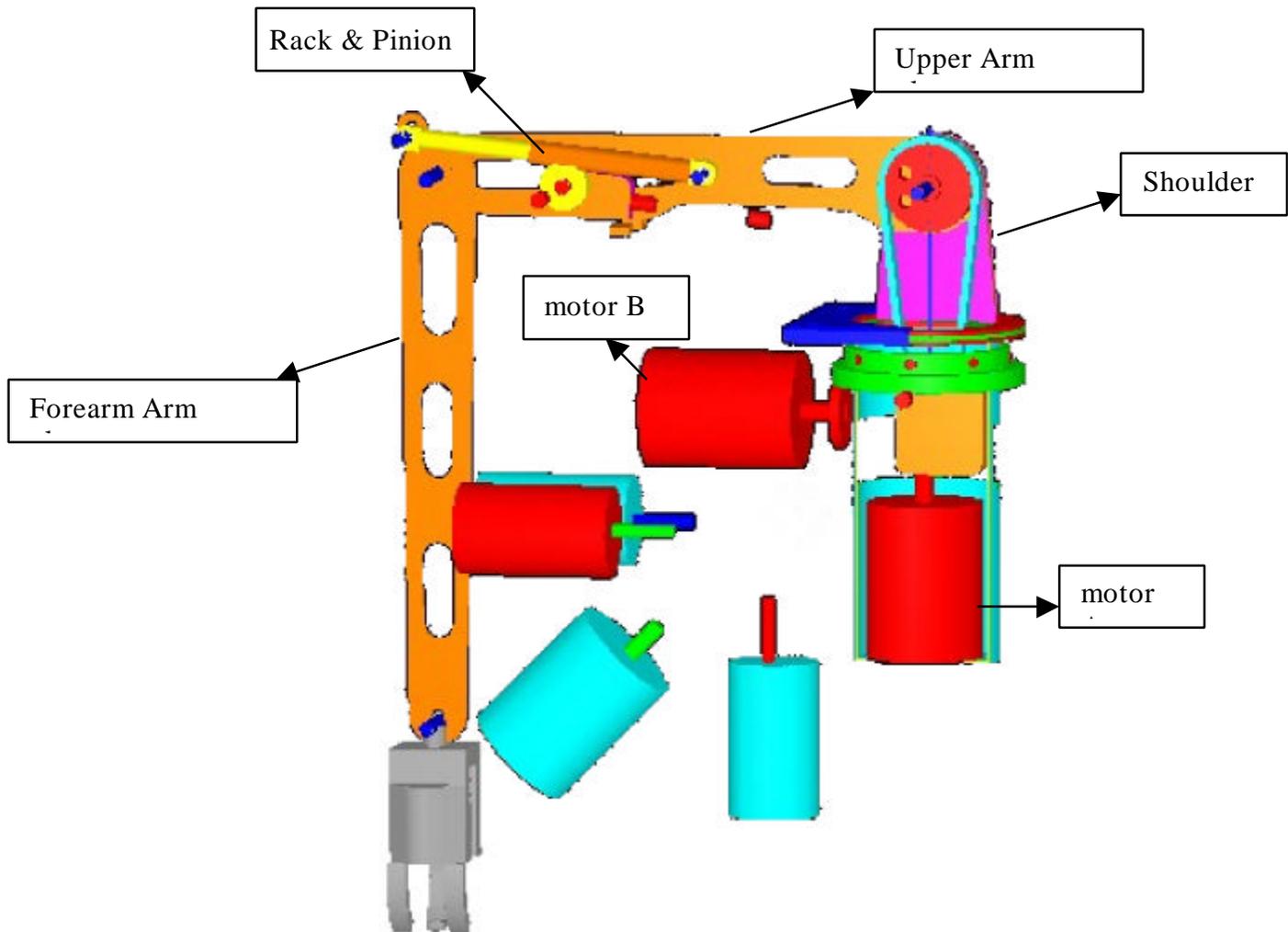
TRANSMISSION

Figure 2: Basic Components and Transmission

- Motor A provides rotation of Upper Arm by moving the belt Shown.
- Motor B provides base rotation of the shoulder.
- The other motors are used to provide motion for a rack and pinion mechanism and gripper.

The rotation of the shoulder about the Y-axis is provided through a geared ring bolted to the upper part of a cylinder housed in the base, which is connected to a motor through a small pinion. The cylinder itself is free to rotate around the vertical axis through two thrust ball bearings. The shoulder and arm assembly rotate about a vertical axis with a maximum sweep angle of 270 degrees, measured from the left-hand side of the user. The 270-degree sweep angle is required so that the arm may be put into its rest mode. The angular displacement of the upper arm on any vertical plane is obtained by using a motor that is fixed inside the base cylinder. This motor is connected to a 90-degree converter, which in turn connects to a small flywheel through a belt. The arm assembly is able to pivot about the shoulder with a sweep angle of 135 degrees, when the zero is considered to

be the upward vertical position. **Figures 3 and 4** illustrate the arm's vertical and horizontal workspace respectively.
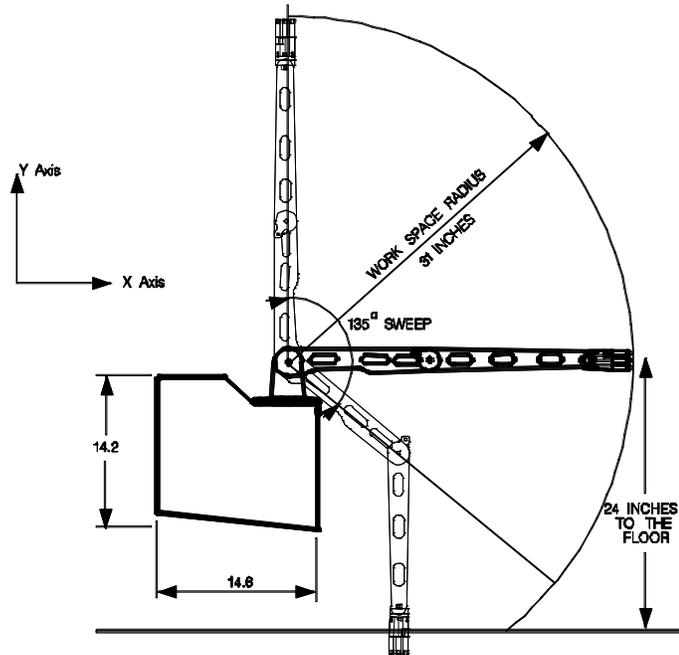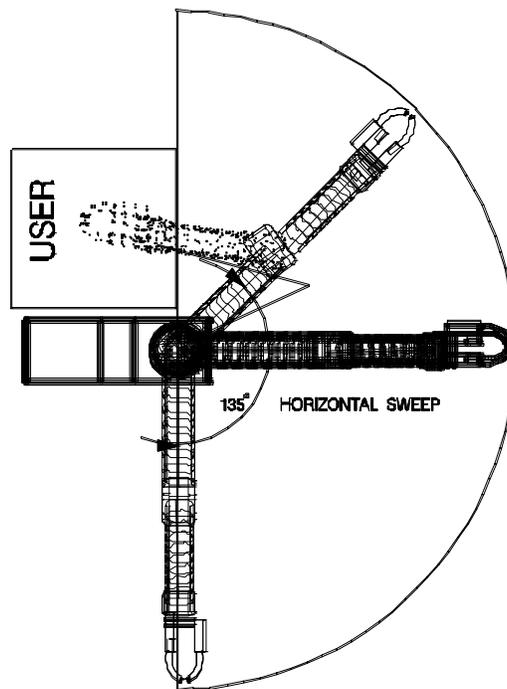

Figure 3: Vertical Workspace

Figure 4: Horizontal Work Space

Figure 5, on the next page shows how the forearm is able to pivot on the elbow joint by the use of a rack and pinion system. The rack and pinion system is actuated through the use of a flexible shaft, which receives torque from a motor located in the base of the arm. In the same way, the roll and pitch motions of the gripper are achieved through the use of flexible shafts, which receive torque from motors located at the base. **Figure 6** shows how the flexible shafts are used to provide motion for the gripper as well as to actuate the rack and pinion.
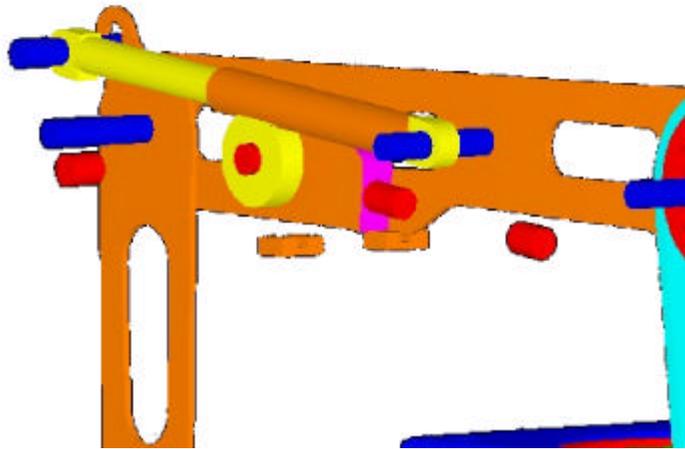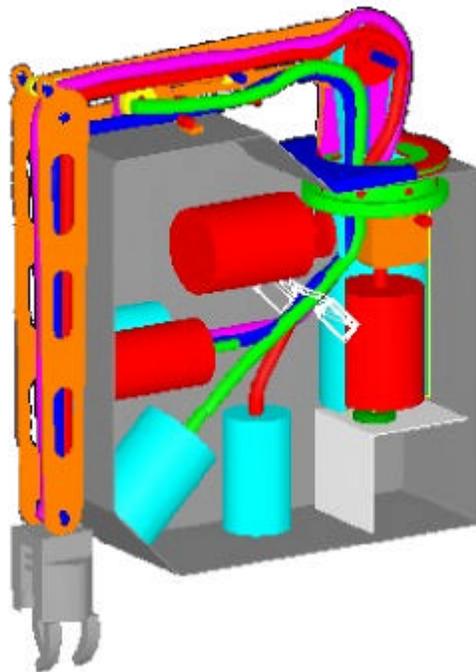

Figure 5: Rack Pinion Mechanism

Figure 6: C.U.R.A. 1000 with Flexible Shafts Implemented

DIMENSIONS OF THE FOREARM AND UPPER-ARM

The followig figures show the dimensions of the component plates of the
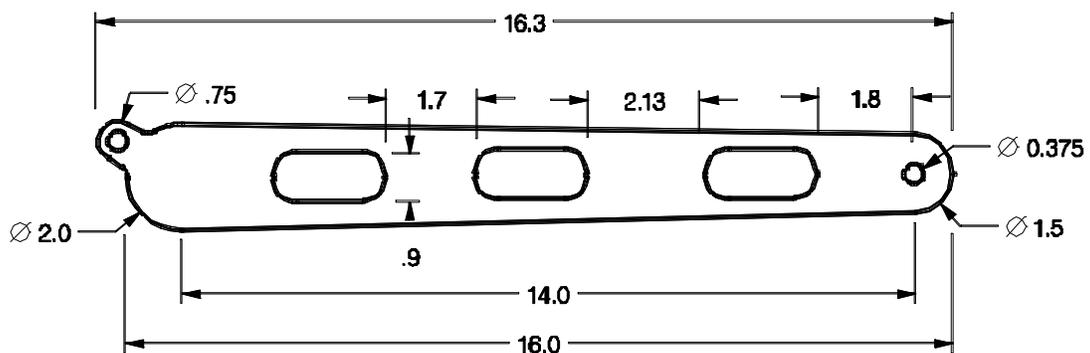Forearm and Upper-arm. Each of these plates has a thickness of 1/16 of an inch.

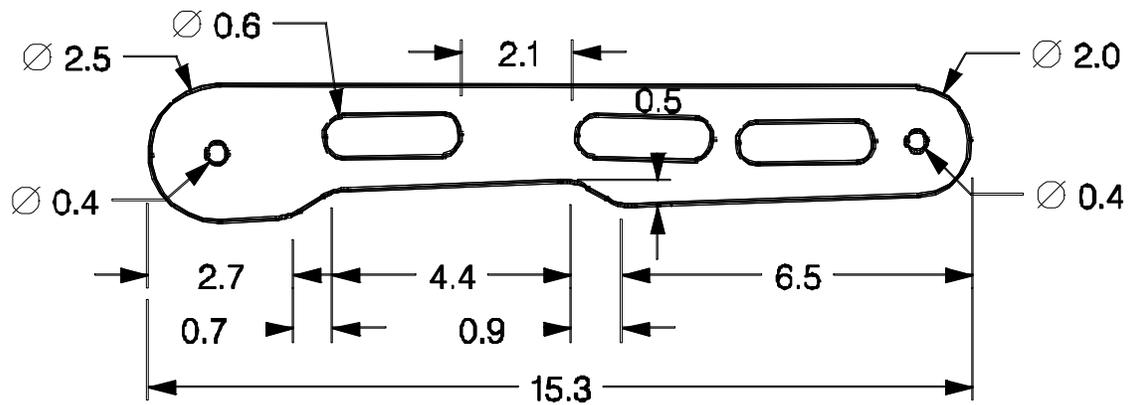
Figure 7: Forearm Dimensions

Figure 8: Upper-Arm Dimensions

The dimensions shown in these two figures were used to calculate the stresses and torques presented in the next section.

STRENGHT REQUIREMENTS

A stress analysis on the component members of the arm gave the strength requirements. This analysis was done by assuming that the material used for the arm's plates was aluminum 1060, which has a density of 0.0977lb/in^3 at room temperature. The values obtained can be used to optimize the cross section thickness of the arm's component plates. **Figure 6** shows how the two plates that compose the forearm are assembled; similarly the Upper-arm is also made of two plates. In Appendix II, there is an explanation of the model used to obtain the values presented in **Table 1**.

Table 1. Torque & Stresses (Model 1000)

Component	Torque	Tensile/Comp Stress (highest value)	Shear Stress (highest value)	Bearing Stress
Shoulder	119.18 lb-in	-	-	-
Arm plates	-	1459.2	27.1 psi	
Rack and Pinion	65.46 lb-in	-	-	1176 psi

Table 2. Mechanical Properties of 1060 Aluminum

Yield Point Strength	4000 psi
Shear Strength	7000 psi

SECOND DESIGN FOR THE COOPER UNION ROBOTIC ARM (C.U.R.A. 1001)

DEGREES OF FREEDOM

Figure 9 shows the second design of the robotic arm. This design was done with the intent of reducing critical factors such as overall weight and size, which in turn reduces the strength requirements. In addition the esthetics and storage capabilities of the design were improved. The **C.U.R.A. 1001** is a five degree of freedom robot. Two degrees of freedom result from two rotations at shoulder. One additional degree of freedom is needed to swing the forearm about the elbow joint, and the other two degrees of freedom are associated with the rolling and pitching of the gripper.
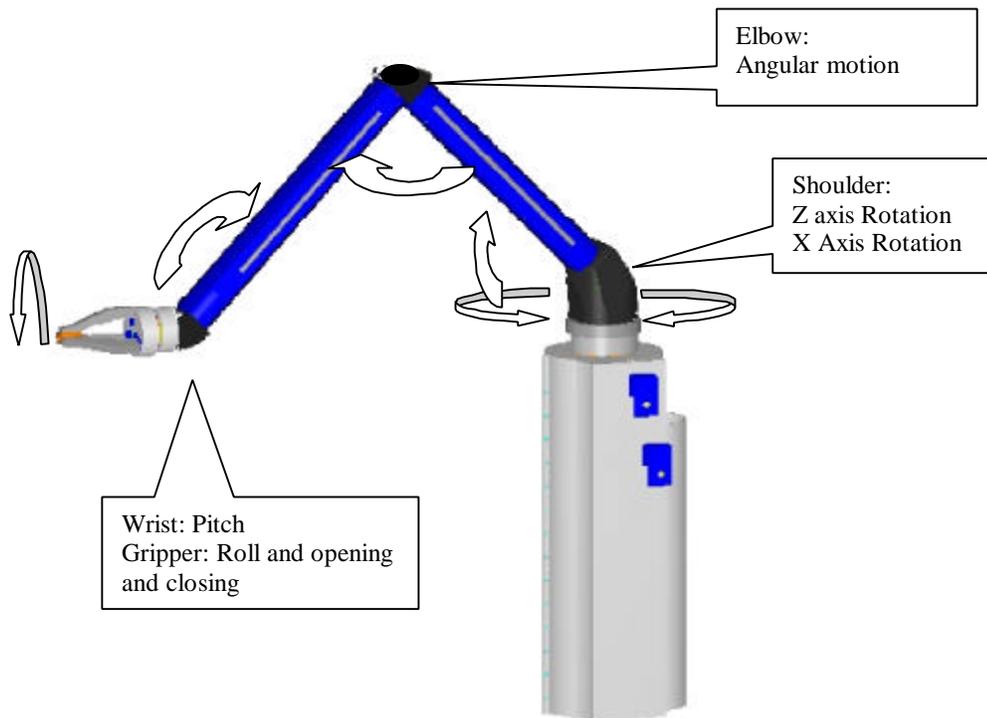

Elbow:
Angular motion

Shoulder:
Z axis Rotation
X Axis Rotation

Wrist: Pitch
Gripper: Roll and opening
and closing

Figure 9: The **"C.U.R.A. 1001"**

TRANSMISSION

In order to reduce the overall weight and the amount of material used to manufacture one unit, the space occupied by the base was optimized. Therefore the base consists of cylindrical shell, which houses the motors, electronics and transmission elements. The motors are installed in two levels of the cylindrical shell, thus creating a very compact sub-unit. This concept is illustrated **Figure 10**.
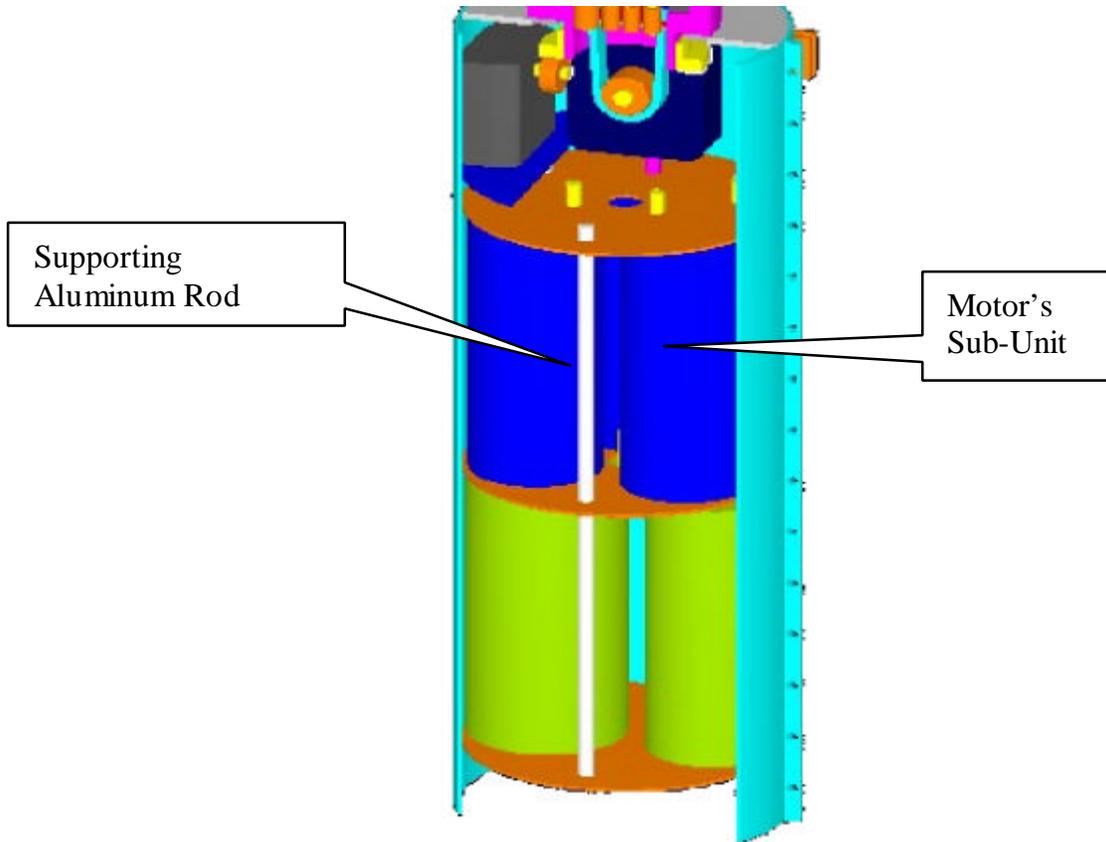

Figure 10: Arrangement of the Motors within the Base

The transmission of the second design is very similar to the transmission system used in the first design (C.U.R.A.1000). Flexible shafts, which transmit torque to the different joints of the arm, constitute the basic transmission component. However, the method of producing torque at the shoulder and elbow was refined. The shoulder level transmission mechanism of the C.U.R.A.1001 is illustrated in **Figure 11.**
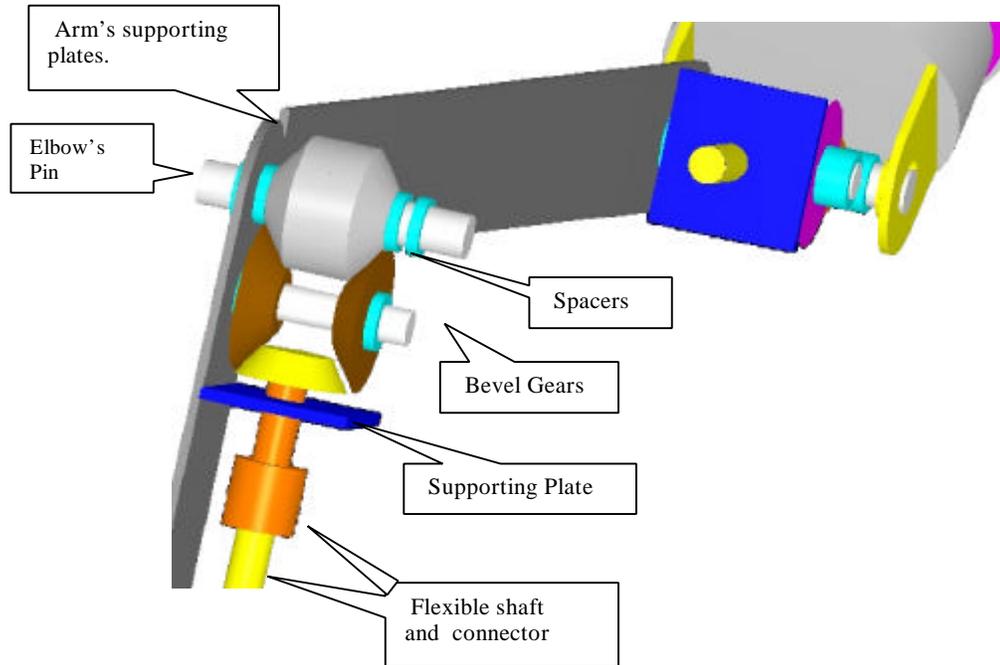
Figure 11: Transmission at the Shoulder Assembly

Two rotations are achieved at the shoulder assembly, one in the z-axis and one parallel to any vertical plane (within the workspace). The rotation about the z-axis is obtained by the use of a pancake direct drive DC motor, which is connected to a rack and pinion mechanism. Through the use of trust bearings, the shoulder is free to rotate in this axis. Another direct drive DC motor is used to achieve the pivoting motion of the arm about the shoulder assembly. As illustrated in **Figure 11**, an assembly of bevel gears is used to provide 90^0 transmission of the torque provided by the DC motor to the spur gears attached to the upper-arm plates. The first set of bevel gears (on the base) transmit torque to the second set of bevel gears (shoulder) through the use of Snap-On-Off connectors. The shoulder bevel gears in turn transmit motion to the arm through spur gears.

Bevel gears were also utilized to transmit torque at the elbow joint. **Figure 12** shows a detailed diagram of the elbow joint transmission setup.

Figure 12: Transmission at the Elbow Joint

As illustrated by **Figure 12**, at the elbow joint a flexible shaft is used to rotate a set of bevel gears. This system transmits torque to the forearm and makes it to pivot around the elbow pivot pin. The same principle is used to achieve the pitch motion of the wrist.

GRIPPER

Figure 13 shows the conceptual design of the gripper. It incorporates the same feature of Snap-On-Off capabilities present in the shoulder assembly. This allows for very easy interchangeability with other grippers without the need to modify the whole arm. It features rubber tips to improve gripe, and the changing geometry of the fingers allows for more flexibility when objects with different shapes need to be picked up.
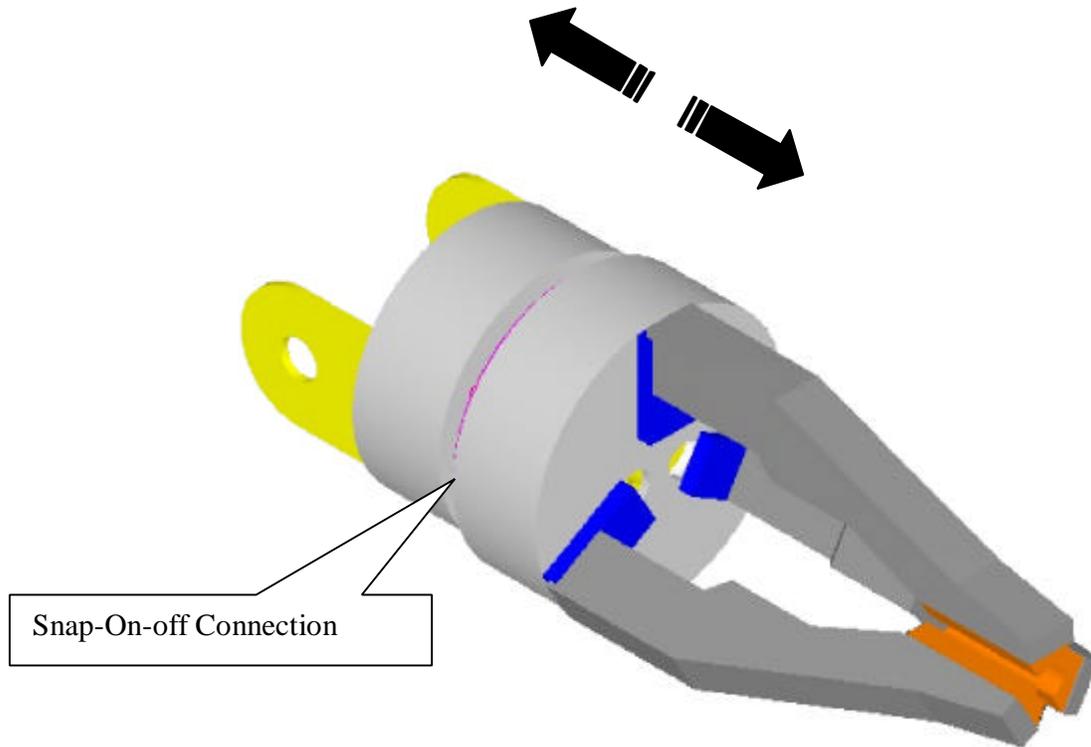
Figure 13: Gripper

As mentioned earlier, the pitch motion of the wrist is achieved through the same mechanism used in the elbow. The Rolling motion of the gripper is achieved through the use of a flexible shaft and rack and pinion system, similar to the one used in the shoulder assembly. The teeth of the rack are enclosed in a steel bushing. In a similar way, the opening and closing of the gripper is achieved by transmitting torque to a spiral plate, which causes the fingers to move along radial guides. This causes the gripper to close to a point at the center and open to the necessary radius, up to a maximum of 2". The conceptual design of the gripper assembly is illustrated in **Figure 14.**
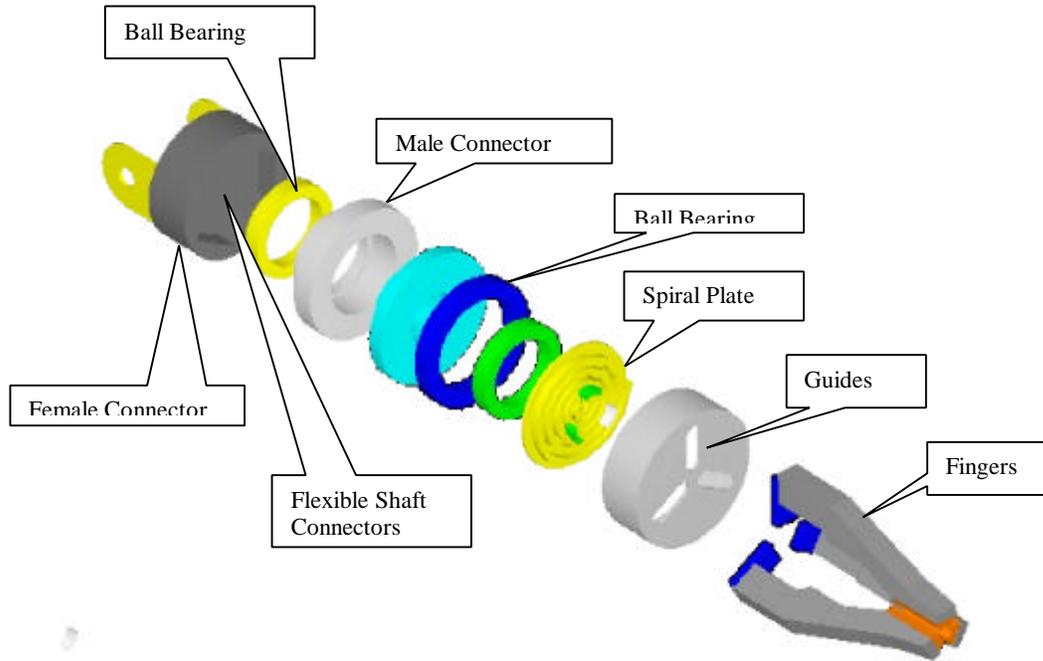
Figure 14: Gripper Assembly

WORKSPACE AND DIMENSIONS

The workspace of the second design (C.U.R.A.1001) is similar to the workspace of the first design. The shoulder and arm assembly rotate about a vertical axis with a maximum sweep angle of 270 degrees, measured from the left-hand side of the user. For the first design (C.U.R.A.1000) this 270 degrees rotation was required in order to place the arm in its rest position. For the C.U.R.A.1001 is not required for shoulder and arm assembly to rotate 270 degrees, rather this maximum angle is a safety concern, so that the arm does not operate in the space occupied by the user. The arm assembly is able to pivot about the shoulder with a sweep angle of 135 degrees, when the zero is considered to be the upward vertical position. **Figures 3 and 4** illustrate the arm's vertical and horizontal workspace respectively.

As illustrated in **Figure 15**, **the** overall length of the arm, including the gripper, is 32.5". The lengths of the arm assembly components are as follows, the forearm measures 14", the upper-arm 13" and the gripper has a length of 5.6". Both forearm and upper-arm are tapered, and at a cross-section near the elbow assembly the forearm has the following overall dimensions, 1.15" width by 1.75" height. The overall dimensions of the upper-arm at a cross-section near the shoulder assembly are 1.3" width by 1.5" height. The cylindrical base of the arm has a ~~~ght of 15" and a diameter of 5.25". On **Figure 15,** the storage compartment is shown. This compartment, ~ch is located at the back of the base, has a diameter of 1.25" and it was designed with the purpose of being used to store the arm, when it is taken apart at the shoulder assembly through the use of the snap-on-off connection.
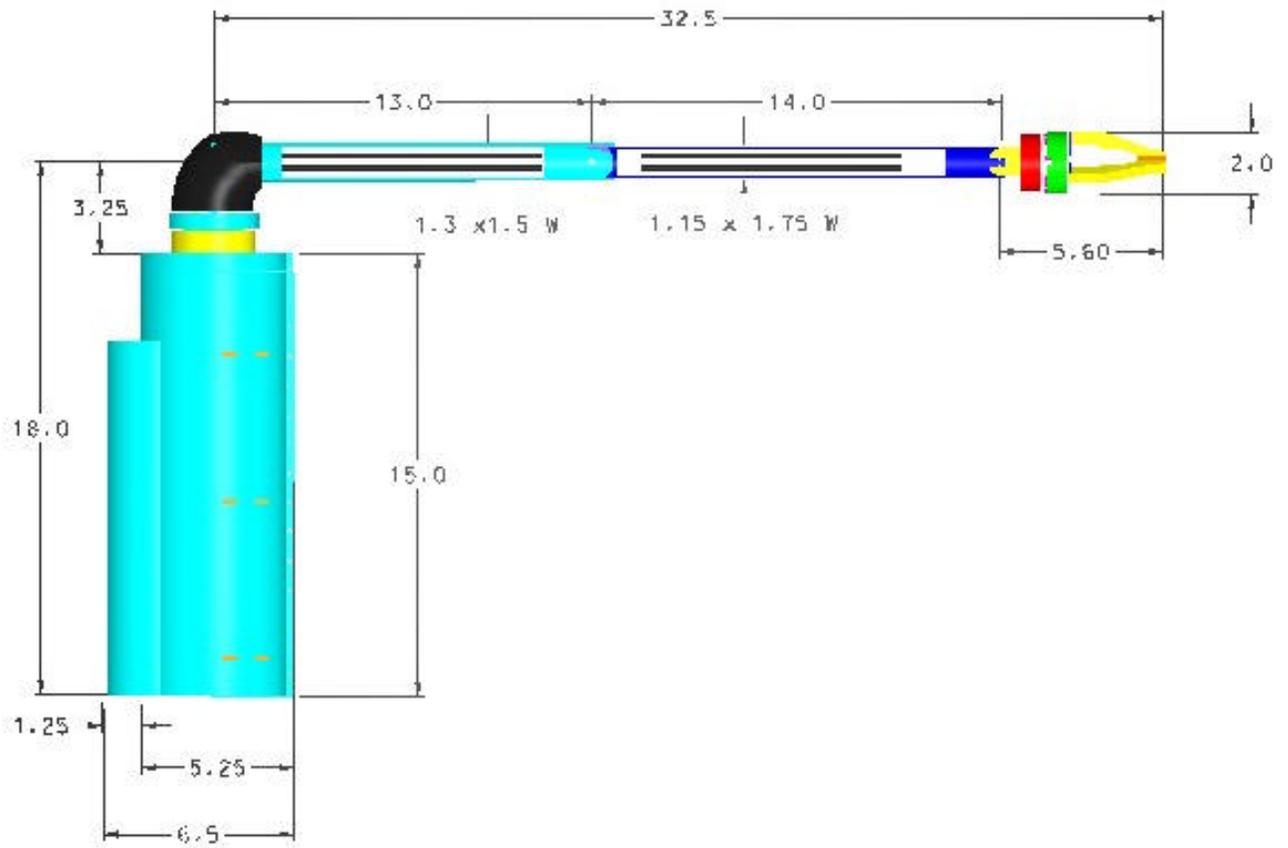
Figure 15: Dimensions

STRENGTH REQUIREMENTS

The width of the component plates of the upper-arm was reduced by 0.8 inch, and the forearm was reduced by 0.5 inch. As a result the weight of the arm was reduced, which ultimately resulted in reduction of the moment at each joint. Tables 3 and 4 show the strength requirements for the C.U.R.A.1001. In addition, by reducing the overall width of the arm, a more slender and more pleasing to the eye design was achieved. Plastic with vivid colors can be used for the base and cover in order to please the taste of children, with no further need of repainting or re-coating as in the case of metal covers.

Table 3. Torque & Stresses (Model 1001)

Component	Torque	Tensile/Comp Stress (highest value)	Shear Stress (highest value)
Shoulder	104.8 lb-in	-	-
Arm plates	-	2200.0 psi	45.0 psi
Elbow	40.4 lb-in	-	-

Table 4. Mechanical Properties of 1060 Aluminum

Yield Point Strength	4000 psi
Shear Strength	7000 psi

FLEXIBLE SHAFTS

As mentioned earlier, Flexible Shafts are used to provide torque to the elbow joint and to provide torque for the pitch and roll of the gripper. Since the elbow joint has greater torque requirements than the gripper, in this section the authors shall cover the process of choosing a flexible shaft for the elbow joint. In choosing a flexible the two main factors that must be taken into account are the torque requirement and the minimum radius. For the application being considered in this report the torque requirement for the elbow joint is 40.4 lb-in, as indicated in **Table 3**, plus .4 lb-in of startup torque. The minimum bend radius may be calculated using a formula provided by *S.S. White Technologies Inc.* catalogue on flexible shafts. According to the aforementioned catalogue the minimum bend radius is given by:

$$R = \frac{X^2 + Y^2}{4X}$$

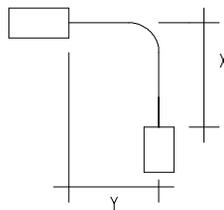Where X and Y are distances shown in the following figure:

Figure 15: x-y

Using this formula and the dimensions from Figure **15**, a minimum bend radius of 6" was calculated for the shaft providing torque to the elbow joint. Consulting the aforementioned catalogue the 6" minimum bend radius flexible shaft will provide a maximum torque of 34 lb-in, thus a gear ratio of 1.2 must used in order to obtain the 40.8lb-in torque required at the elbow joint. A copy of the *S.S. White Technologies Inc.* catalogue is provided in Appendix III.

FEATURES

In this section the authors shall summarize the progress done in creating a second design for the C.U.R.A. The design of the C.U.R.A.1001 tries to incorporate features that enhance the flexibility of the system as compared to the first design. One of the most important features of the second design is the implementation of a rapid Snap-On-Snap-off system, which allows for easy interchangeability of components. Figure 16 shows how it is possible to achieve the separation of the shoulder from the base. The same mechanism is used to separate the gripper from the arm at the wrist joint. The authors believe in the importance of this feature due to the ease of maintenance and the increase in flexibility considering the possibility of future modifications.
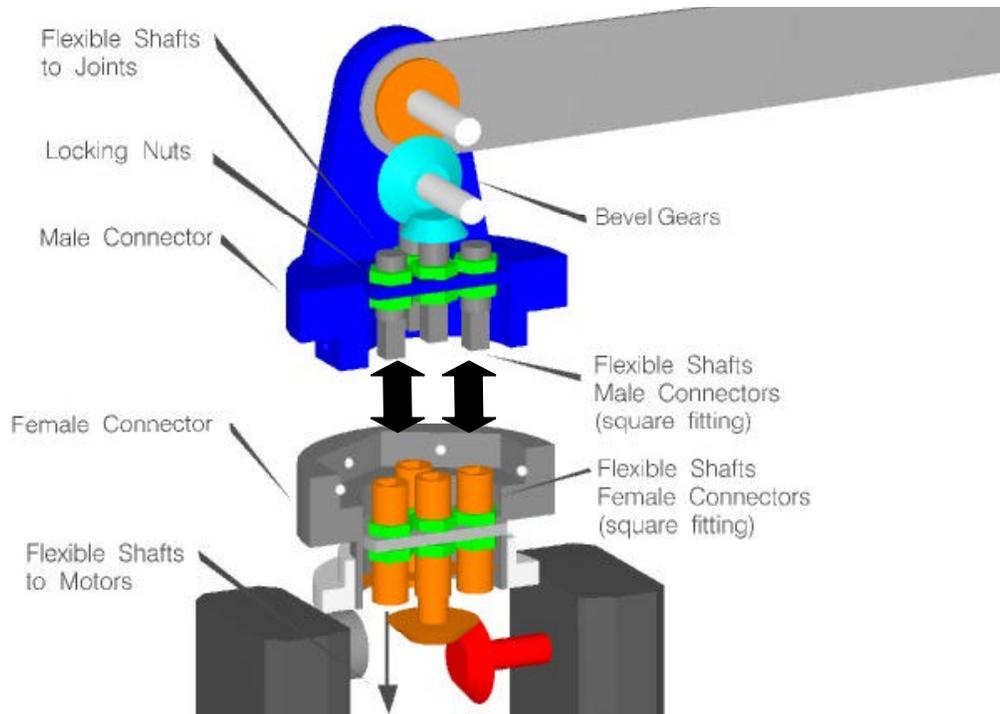
Figure 16: Detached View of the Snap-On Mechanism.

Another feature that was incorporated in the second design was the ability to rapidly mount and dismount the robotic arm from the wheelchair. This facilitates storage and gives more flexibility to the user. This is an important feature due to the fact that the user may want to be outdoors without the inconvenience of taking the arm with him or her. Figure 17 shows the bracket and the locking mechanism, used to mount the C.U.R.A.1001 into the wheelchair. By introducing the base brackets into the bracers, and turning the knobs, it is possible to lock the robotic arm in place.
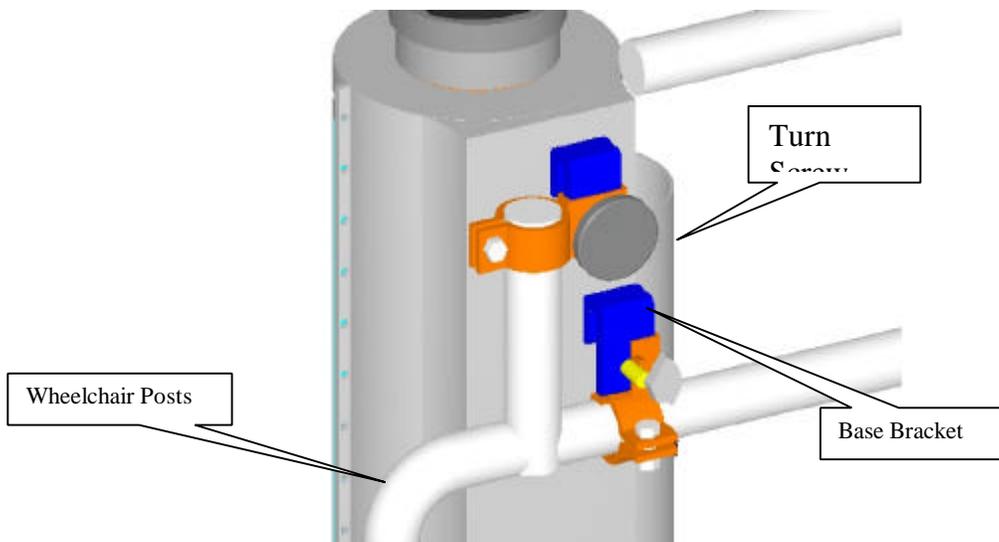

Figure 17: Base Mounting Mechanism

The location of the arm with respect to the wheelchair, as in the first design was determined to maximize workspace. Thus the arm should be mounted on the front left or front right post of the wheelchair. The whole unit fits vertically in either of the front posts of "ANY" wheelchair. This feature becomes very important because in comparison to the first design, which was based in a specific wheelchair, the second design can be mounted in most if not all wheelchairs. The only requirement to secure the unit is the existence of a vertical and a horizontal post. **Figure 18** shows the mounting location of the robotic arm with respect to the wheelchair.
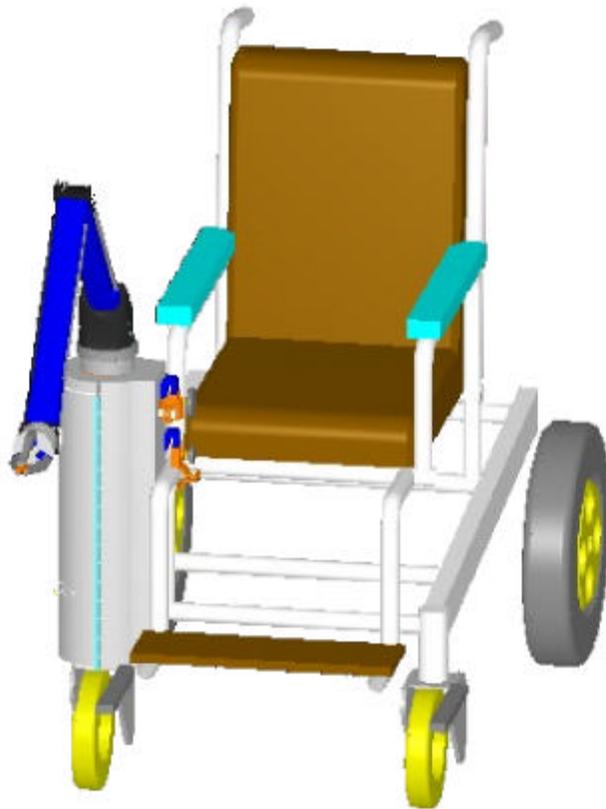
Figure 18: Robotic Arm's Location with Respect to the Wheelchair

MATERIAL SELECTION

The material selected for the housing or base was a thermosetting plastic. For example polycarbonate can be used for this application because of its high impact strength and good electrical insulating properties. Its low density, 0.043 lb/in^3, make it suitable to be used for the cover of the manipulator.

The material selected for the supporting plates was aluminum 1060. It is basically pure aluminum with a composition of 99.60 % mineral aluminum. Some the reasons for this choice include the fact that aluminum has very good resistance to corrosion and good formability. This aluminum alloy has a low overall strength, wen compared to other aluminum alloys, but considering the strength required this does not represent a problem. Transmission elements such as shafts and gears are stainless steel. Fastening elements are carbon steel.

USER INTERFACE

The Cooper Union Team was assigned the responsibility of researching the available user interface devices and choosing one for incorporation in this conceptual design. In order to decide on the type of user interface to be incorporated we have considered the following criteria:

-The device must be small, rigid and durable.
-It must be easy to operate and calibrate.
-The device must be fully functional in the limited space provided for operation.
-The device must be able to provide three dimensional control of the manipulator, and preference shall be given to devices that have buttons which can be programmed to control other required functions.
-The device can be operated with one hand.
-The device should be inexpensive when compared with other devices available on the market.

The commercially available user-input devices may be divided into three broad categories. These are mechanical devices, motion tracking devices and voice control devices.

Mechanical input devices send strings of information to a processor when triggered by changes in the position of the device. The user may move, twist or click on the device in order to generate an electric signal, which can be interpreted by a computer. Mouse, trackball and joystick are examples of such mechanical input devices. Mechanical input devices are generally inexpensive, easy to operate, and requiring only one hand to operate them. The user can learn how to operate these devices very quickly. In addition, mechanical input devices typically come with control software to interface them with a computer, which can be easily altered to meet the needs of specific applications. Nevertheless, most of these devices are designed for transmitting two-dimensional motions. They do not have simultaneous three-dimensional control incorporated into them, and usually it is necessary to utilize a button to achieve motion control on a third dimension. Other operational problems include user fatigue, and metacarpal syndrome.

Motion tracking devices generate data by sensing the motion of objects or people present in the surroundings. For the project treated in this report it is possible to use one of these devices by setting it to read the motion of a part of the user's body, say the head. Usually these devices are easy to operate and intuitive; by using one of these devices we would extend the use of the arm to people who cannot use their upper limbs. Fatigue from the part of the user is severely reduced when compared with mechanical input devices. On the other hand these devices are rather expensive and it may be hard to obtain high accuracy and precision of operation because of the dependence on the motion of the user.

Voice control devices transfer sound into electrical signals and by matching the sound with stored patterns in order to decode the message sent by the user. If the sound sent by the user matches a stored pattern then the device will transmit a programmed output. From the user's point of view these devices are easy to operate and do not require much physical effort. By using one of these devices the manipulator could be used by individuals who cannot move their upper limbs. Nevertheless, voice control devices are expensive, the software required to use these devices is rather complex, the interpreter must be tailored for each individual, and precision control is difficult to obtain.

DEVICES CONSIDERED

After considering the advantages and disadvantages of each of the different categories of input devices our team decided to focus on mechanical and motion tracking devices. Thus, the following devices were considered:

Mechanical Input Devices:
1. Spacetech Space Orb 360
2. Logitech Cyberman II
3. Logitech First Mouse +
4. Logitech MAGELLEAN 3D mouse
5. Polhemus 3BALL

Motion Tracking Devices:
1. Polhemus Insidetrack
2. Ascension PCBird

THE SPACE ORB 360

After considering the devices listed above, our team decided to choose the 3D joystick known as the Space Orb 360 shown in **Figure 19**. Our choice is based on the fact that this joystick is rather inexpensive, and it is a 3D controller, which offers six degrees of freedom maneuverability in a 3D environment. It provides direct control of displacement motion in a 3D space plus rotation about each one of the axes. The device is small enough to be attached to the armrest of a wheelchair, and it is possible to operate it with only one hand.

Other specifications of the Space Orb, provided by the manufacturer included the following:
Force and Torque Sensitivity - The Power Sensor ball senses and translates the force applied to it into speed. Thus, low level of force application translates into low speed and the more force one applies, the faster the controlled device will move.

Six Rapid Action Buttons- The six buttons on the Space Orb can be customized to perform specific functions.

Ergonomic Design- The device's design takes into account ergonomic considerations in order to reduce stress and hand fatigue.

System Requirements- Available RS-232 Serial/COM port with 9 or 25 connector,
a 486 DX or higher computer, and a operating environment such as MS-DOS 5.0+ or Windows 95.

Figure 19: The Space Orb 360

WHEELCHAIR AND HOUSING DIMENSIONS

INVACARE manufactures automated wheelchairs for children. On their "Action Storm Series" they offer a 12"x12" and 14"x14" seat sizes. The maximum overall width of the chair is about 26.5"; which is the distance between the outer surface of the two back wheels. Each wheel is 2.5" thick and the frame is 21.5" wide. The seats are assembled in the base frame and centered on it. Considering a 12"x12" in seat size with a arm rest of 2" wide, the clearance available for placing the housing is 5.25"; this if we want the overall width of the assembly, composed by the wheelchair and the housing, to remain the same. Another dimension to consider is the overall depth of the wheelchair frame, although this dimension is not so critical as the overall width. INVACARE's wheelchairs have a overall frame depth of 25". In order to fit the housing of the manipulator within the total area occupied by one of INVACARE's wheelchairs, it should be no more than 5.25" wide and 25" long. The housing of "C.U.R.A. 1000" was designed to meet these requirements. The two figures on the next page show the dimensions of the housing and INVACARE's Action Storm Junior® wheelchair.
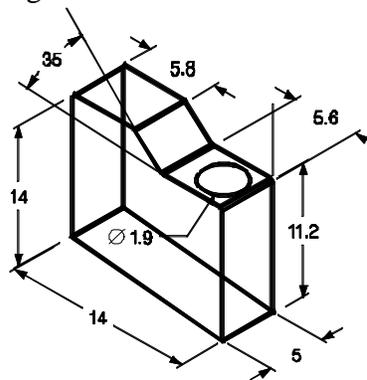

Figure I-1: Housing Dimensions

Action Storm Junior, dimensions.

Overall maximum width:
 -26.5 in

Seat:
-12x12 or 14x14 in

Wheel Thickness:
-2.5 in

Overall depth:
-25 in

Figure I-2: The Action Storm Junior® Wheelchair

STRESS AND TORQUE CALCULATIONS

The stress calculations for the upper-arm were done by modeling the arm as a cantilever beam with a concentrated load at its tip. The value of the concentrated load was obtained by combining the weight of the gripper with the weight of the object to be picked, while the value for the distributed load was obtained from considering the combined weight of the forearm and Upper Arm. Similar assumptions were made for the forearm; the only difference is that the distributed weight for the forearm contained only the weight of the forearm itself.

The maximum tensile and compressive stresses due to transverse loading were found using the following relation:

$$s = \frac{MC}{I}$$

Where M is the maximum moment, encountered at the base of the beam. C is half of the height of the beam and I is the moment of inertia.

The maximum shear stress was found using the formula:

$$t = \frac{VQ}{tI}$$

Where V is the maximum shear force on a cross-sectional area of the beam, t is the thickness of the beam, I is the moment of inertia and Q is obtained by the following formula (considering the beam has a rectangular cross-section):

$Q = (1/2$ of cross-section area of beam$)$ x $(1/4$ of height of the beam$)$

THE DREXEL UNIVERSITY ROBOTIC ARM

INITIAL CONSIDERATIONS

Figure 20: The Wheel Chair

Wheelchair selection plays a large role when trying to determine the mounting features of the arm. A definite location must be defined when determining the overall length of the arm.

When selecting a wheelchair, we must follow the specification that this arm is to be used by a child. Therefore, the chair must be a "junior" style model. Keeping this in mind, we found that the Action Storm Series junior style chair is more than adequate. If you refer to the picture below, you can see that the seat small in size. This leaves a large portion of the structure available for mounting the arm to. It was decided that the arm would mount on top of the strut on the side of the chair. This strut is approximately 12" off the ground. This distance will be needed when calculating the overall length of the arm.

ARM STRUCTURE

The first thing that needed to be done before designing the arm was to determine the minimum length required in order to achieve specification #3. Simply figuring out the total height off the ground to the "shoulder" joint did this. It was found that by assuming a 6" high base along with the 12" high strut that the shoulder joint will be 18" off the ground. By knowing this height along with the object being 12" away from the chair, we can use Pythagorean theorem to find the overall length of the arm. This value was found to be 21.64". In knowing this value, we assumed that each link must be at least 10.82" lg. Once this value was attained, we then started to design the arm.

Once the arm was designed, the volume of the plates was calculated and the weight was then assumed. The overall weight is needed to determine the needed torque from the motors selected to drive the links.

DRIVE SYSTEM

In this design we will be using D.C. motors along with timing belts and pulleys to transmit power to the links. When choosing the motors, we needed to first find the torque required from the motors in order to raise and lower the arm. The torque was calculated by multiplying the length by the given loads of the arm. For the "forearm" we had to calculate the structural weight along with add the gripper weight. The "bicep" was done the same way but with the total weight of the "forearm" assembly, and the structural weight of the "bicep". The estimated loads of the "forearm" and "bicep" were applied directly to the center of the member. By making this calculation we determined our torque required in oz.-in.. We also had to make similar calculations when choosing the motors for the gripper assembly and for the base rotation.

Finding the appropriate timing belts and pulleys depended directly on what the torque of the motor driving that specific belt was. In our case, a ¼ " wide belt will be used throughout the arm. In order to prevent a "jerking" effect, the belts will be made out of a urethane polyester, which has the highest damping effect, along with minor tensioning devices.

STRUCTURAL MATERIALS

The structure of the arm is to be made out of aluminum and plastics. The base and side plates of the arm will be made from aluminum. Aluminum was chosen because of its durability and lightweight characteristics. It is also very cheap in cost and very easy to machine.

The top and bottom plates of the arm will be made from a lightweight plastic. This was decided upon primarily because there is no reason to use aluminum in these areas. There is little structural support being supplied from these plates, they just serve as a safety protection device to keep hands away from the belts.

DESIGN CONCEPT

OVERALL CONCEPT
The arm shown in fig.21 below has 5 D.O.F. plus the gripper. These five degrees of freedom are:
1. Base rotation
2. Shoulder rotation
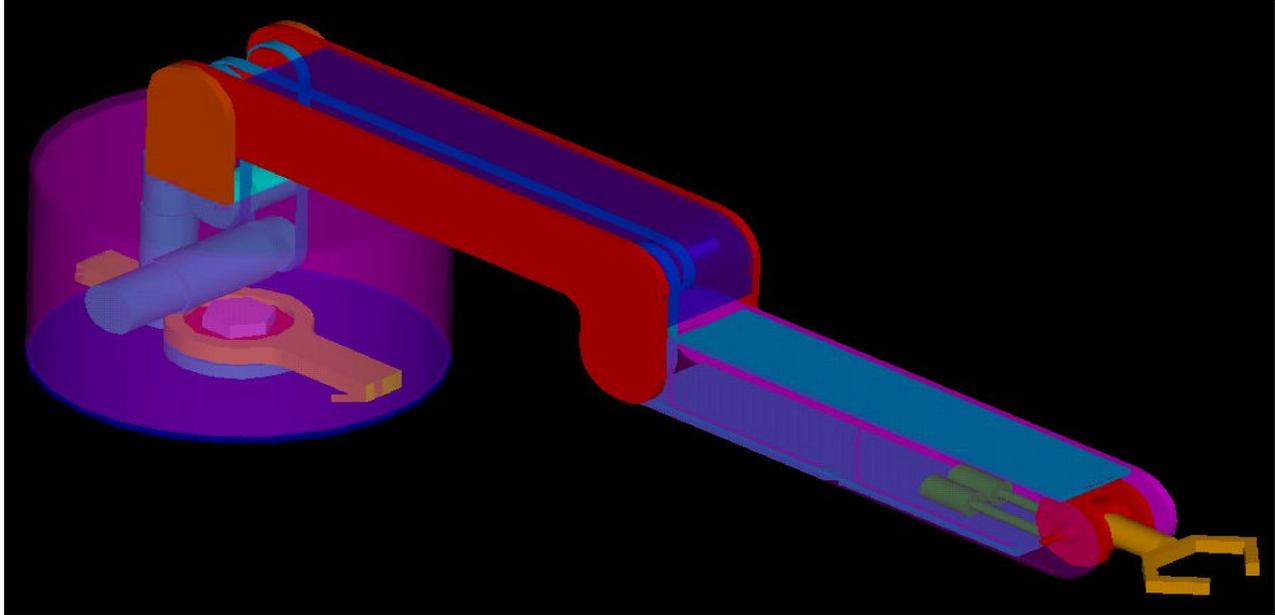3. Elbow rotations
4. Wrist pitch
5. Wrist roll

Figure 21

It contains three motors in the base along with two additional motors in the forearm. Its features provide a simple, lightweight arm that has the adequate arm reach along with a folding option when not in use.

Two of the three motors in the base are used horizontally along with timing belts and pulleys in order to drive the elbow and shoulder joints. The other stands vertical and uses a direct gear drive to perform a base rotation.

ELBOW ROTATION

The elbow rotation is done be driving a motor in the base that is attached to a pulley and belt system to the shoulder joint. From here, there is another belt that connects to the elbow joint in the same manner. From this elbow joint there is another pulley / belt system that is directly below the center, 90 degrees from the other. This is the belt that allows us to fold and extend the forearm. This process is shown in figures 22- 25 respectively.
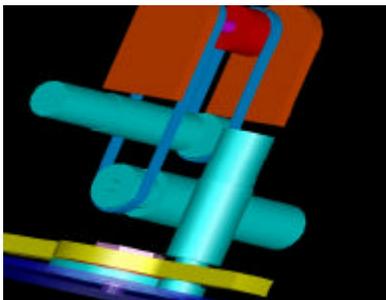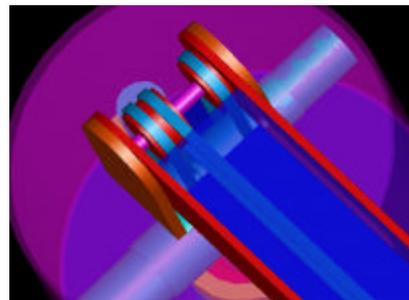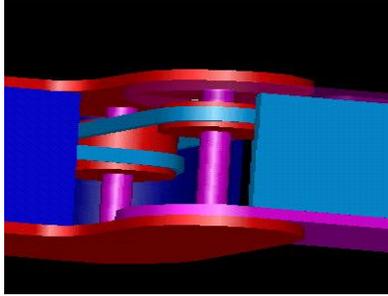

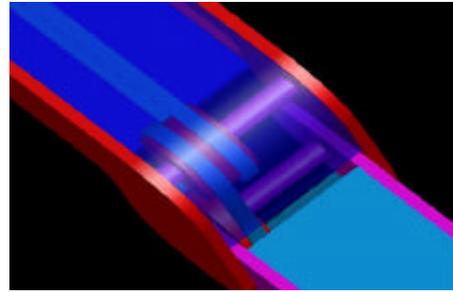
Figure 22

Figure 23

Figure 24

Figure 25

SHOULDER ROTATION

The shoulder rotation is done very similarly to the elbow joint. It has a horizontal motor in the base with a pulley attached to it. This pulley is driving a belt which is connected to another pulley at the shoulder joint. This allows the shoulder to raise and lower as needed. (See figs. 26 & 27)
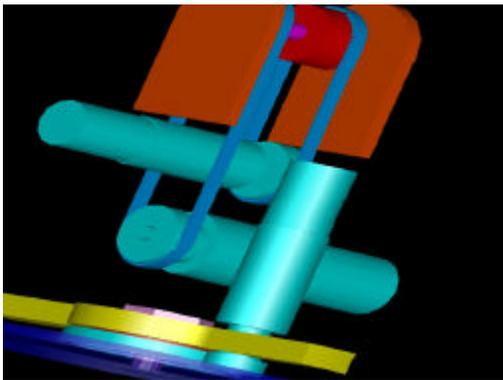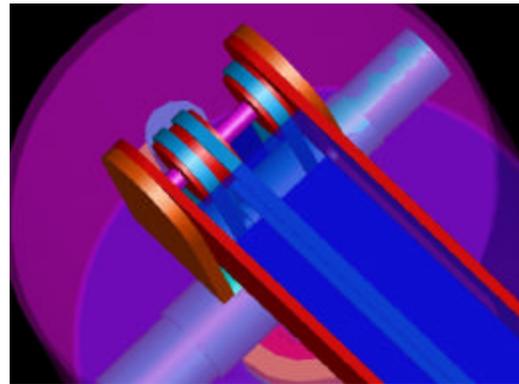

Figure 26

Figure 27

BASE ROTATION

The base rotation uses a vertically aligned motor that drives directly to a large spur gear located on the wheel chair mounting plate. The combination of a thrust bearing in the center of the base and an oil impregnated thrust washer on the outer perimeter along with the motor drive, we are able form an assembly that allows a relatively smooth rotation. It also allows us to affix the entire assembly to the chair. This is shown above in figure 27 along with the AutoCad section view in as well as in Figure 28 below.
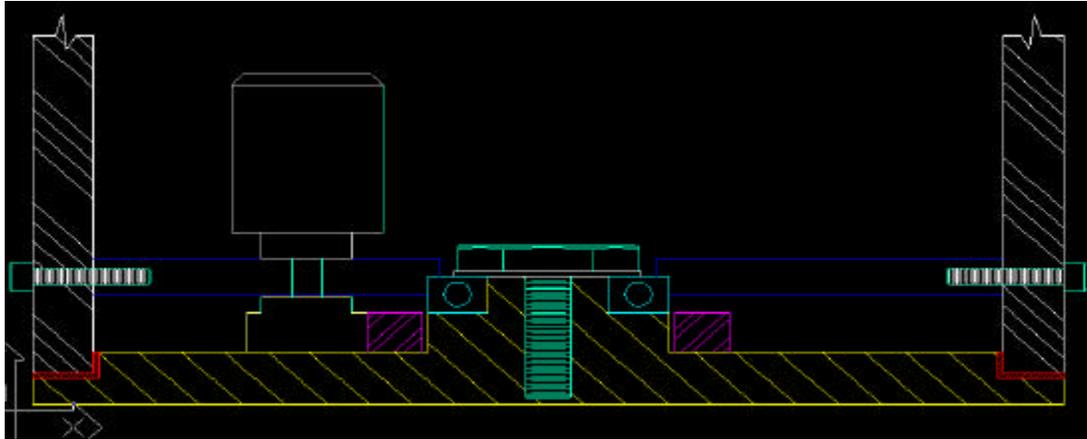
Figure 28

WRIST PITCH & ROLL

The wrist joint is probably the most complicated joint in this whole assembly. It contains two small motors that are mounted in the forearm (fig.29). These motors drive directly to individual spiral gears. The spiral gears(fig.30) are attached to a differential set-up that allows the pitch and roll . This differential is shown in figure 31. A pitch is applied when both motors are spinning in the same direction and by rotating the motors in opposite directions from each other attains a roll effect.

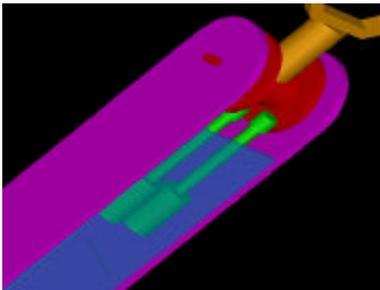**Figure 29**

Figure 30

Figure 31

Figure 32

The gripper (fig. 32) is the same as the one used in last year's device. However, instead of using an additional motor to pull the cable and close the gripper, a solenoid may be used.

ARM REACH

The total reach of the arm exceeds the required length of 12" by about 3-5". When mounted to the chair it is estimated to reach approximately 15-17" past the mounted area (fig.33). It can also be folded and tucked away when not in use as shown in figure 34. The length of the arm when folded in half is approximately 16 inches.
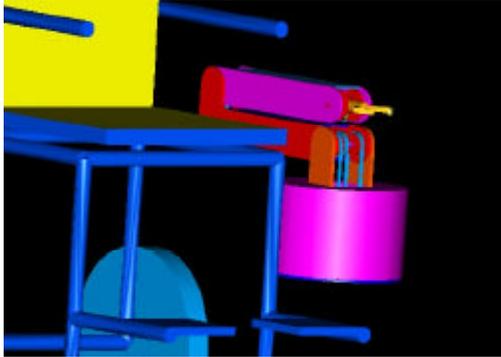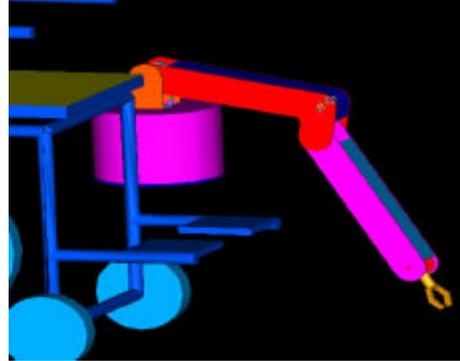

Figure 33

Figure 34

Overall, all of the above features are very small and lightweight as compared to last year's design. The total weight is approximated to be less than 15 lbs and the overall height when closed is around 10 inches high. The design is also very simple to make as well as simple to assemble. The motors in the elbow allow less belt and pulleys to be used which cuts down on the size required for the base. No large transmissions are needed either.

MOTOR SELECTION

The motor selection of this project is critical when assuming how the arm will function. The motors play a large roll in the overall weight of the device, therefore small motors with large torques must be found. These requirements were found in the Micro Mo Electronics catalogue. These motors, when used with the appropriate gearheads can supply a great deal of torque and cut down on the size and weight of the arm. These motors are used throughout the assembly.

TIMING BELT SELECTION

The belts chosen were found in the Sterling Instruments (Stock Drive Products) catalogue. These belts are ¼" in width and have an "XL" pitch. They are purchased by the number of teeth determined by the center to center location. If a urethane polyester belt is used, very little tensioning is needed because these belts are the highest in damping. They also display a high tensile strength.

APPROXIMATE COST

- Material (aluminum) $50.00
- Motors & gearheads $1645.00
- Timing belts $100.00
- Gripper assembly $300.00
- Bearings $150.00
- Gears / Pulleys $150.00
- Other $50.00
- <u>TOTAL APPROX. COST</u>: $2445.00

CONCLUSION / SUMMARY

In concluding this design, we feel it is necessary to point out the advantages and improvements of our model. The advantages and improvements of this arm assembly list as follows:

- It is lightweight
- The parts are easily machinable
- Uses the battery power supplied from the wheelchair
- Can be easily mounted due to the small base
- There are less belts and chains
- It is compatible
- Base rotation is usable
- No large transmissions are needed
- Assembly can be very easy
- Relatively inexpensive

For all the above reasons, we feel that an optimal design has been achieved and all the requirements were met.

CONCLUSION

Based on the information given and design provided, we feel that this design is optimal in many ways. It is very easy to make and small in size. Also, the weight of the assembly is less than that specified in the requirements which makes transportation very easy.

Along with these aspects, we introduce the idea of being able to fold the device when not in use. This is something that was not introduced into any devices that are out on the market nor are they on last year's project. Finally, cost is also very low.

THE OHIO STATE ROBOTIC ARM

DESIGN OPTIONS

Background research and benchmarking has proven to be an invaluable "project planning" tool. Difficult design issues and team priorities have been simplified by utilizing these techniques. By consulting local experts in the fields of robotics and manufacturing, the group has been able to attain an abundance of information. An examination of last year's final report that focused on the highlights and failures of the project was also beneficial. Additional data was acquired by exploring past projects and corresponding with former team members.

The robotic arm design criteria, as specified in the product description, contains only general requirements that can be subjected to individual interpretation. It became evident that supplementary design guidelines needed to be placed on this project. Some of these objectives were implemented so a functional device could be created. Other goals were classified as improvements to the already existing specifications. The decision was made that the arm must:

- Light as possible
- Compact
- Easily manufactured
- Have as many stock parts as possible
- Simplistic in design
- Reach longer than 30.5 cm from the front of the wheelchair
- Cost effective

These new criteria led the group to a variety of design possibilities. One idea that was proposed was to have the arm's vertical height be adjustable while remaining on the chair. This would expand the reach of the arm while keeping the device's size compact. To accomplish this, a device would be needed to move the arm to a desired vertical location. A linear positioning table appeared to be the simplest solution. An example of this first choice can be seen below (Figure 35)
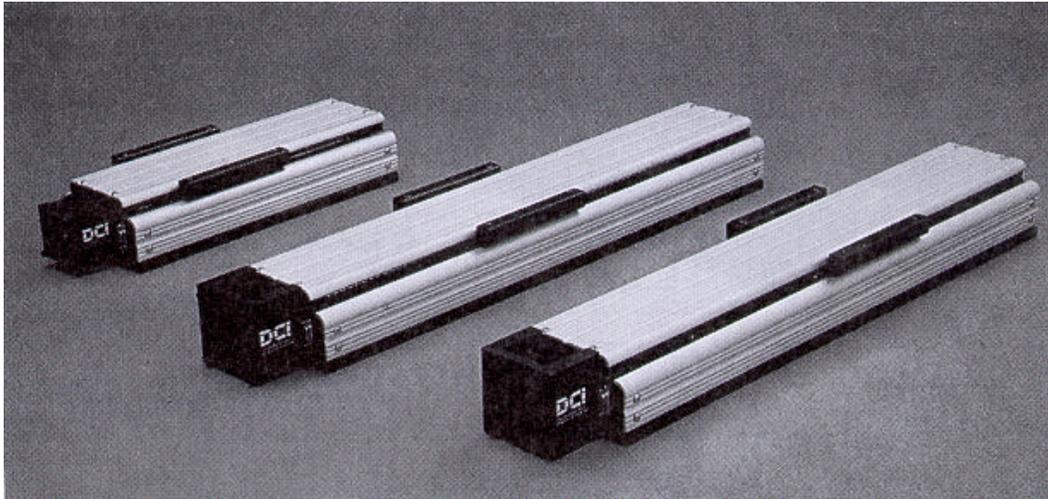
Figure 35: Linear Positioning Table

A linear table could be easily mounted to the wheelchair and to the arm itself due to the base being readily provided. The most discouraging dilemma that came with using the linear table was the weight. The table would be too heavy to place on a child's wheelchair without imposing balancing issues. Another problem that concerned the design team was the cost. It is not good manufacturing practice to have a majority of the projects cost placed on one device when designing a multiple component system.

An alternative to the linear table for moving the robotic arm was a lead screw. A lead screw would weight significantly less and still be easy to install.   An important consideration when utilizing a lead screw is the issue of lock up. If the lead screw became unbalanced the mechanism could possibly become immovable. To resolve such a problem a lead screw elevator would need to be designed by the group. A basic lead screw that was investigated can be seen below (Figure 36)
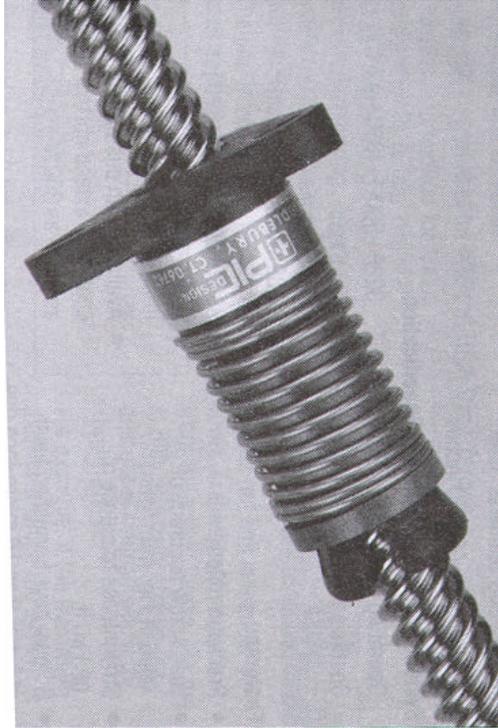
Figure 36: Lead Screw

One major advantage of using a lead screw is that unlike linear tables that must be selected from limited sizes, lead screws may be bought in virtually any size and length. They can even be trimmed to a desired length, enabling them to fit numerous specifications. Although there will be more labor involved in designing and manufacturing a lead screw elevator, the ability to design to size and minimize the expense makes the lead screw a better choice.

Reducing the size and weight of the robotic arm remains the highest priority for the project. The size and weight of the last year's base was a direct result of the selected transmission system. The Ohio State University took a new approach this year by eliminating the transmission completely. By investigating the research being done at other institutions around the world it became evident that Servomotors could replace the transmission system (Figure 37). By mounting Servomotors directly on the manipulator joints a complex transmission system should not be required. This arrangement can also decrease costs by reducing the number of parts that must be manufactured and purchased.
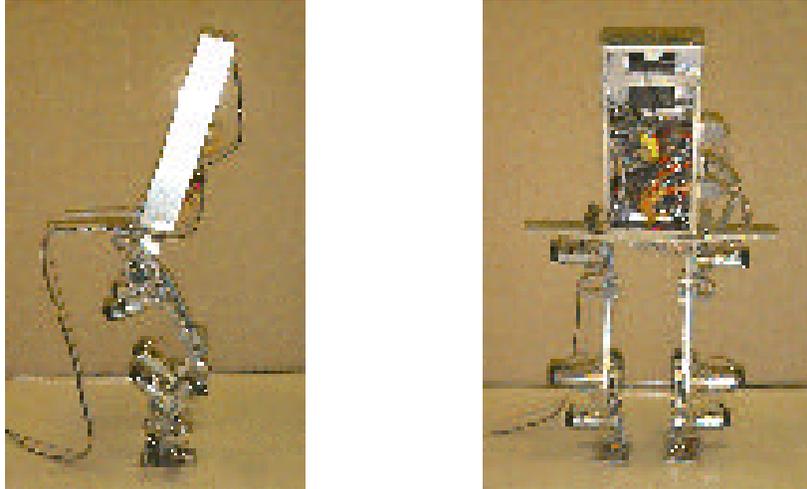
Figure 37: University of New Hampshire Robotic Research

In an effort to keep the arms weight minimal, methods of gravity balancing were considered. By counteracting the effects of gravity on the arm linkages, the torque requirements of the motor could be significantly reduced, thus allowing smaller motors to be used. Possible methods of gravity balancing include implementation of counterweights, linear springs or torsion springs. Counterweights were quickly discarded since they added excessive weight and increased the inertia of the arm. Linear and torsion springs may reduce the effects of gravity while keeping the robotic arm lightweight and compact. To allow linear springs to apply uniform weight counterbalancing throughout the range of motion on the arm, four-bar linkages may be employed as described in A Simple Technique to Gravity Balance Articulated Mechanism by Raham.

When constructing the arm's linkages it was essential to select material that was strong yet low in weight. The linkages had the potential of being the heaviest components of the robotic arm if an improper material was chosen. Both Aluminum and Steel were candidates for the project. However, it was recognized that even Aluminum would add unnecessary weight to the final design. Plastic was a possible alternative, yet lacked the required material strength. To provide additional reinforcement it was decided that Kevlar Fiber could be wrapped around the plastic rods.

The conceptual design of the wrist allowed for a multitude of creative proposals. It was known that the number of degrees of freedom in the wrist could considerably affect the usefulness of the manipulator. Existing designs for robotic wrists generally have from 1 to 3 degrees of freedom. This enables the component to move left, right, up, down, and/or rotate. At a minimum, the user should be able to move the gripper up and down so it can grasp objects at any height with ease. In order to grab unusually shaped objects, the wrist will need to be able to rotate to any angle desired. A design incorporating a differential similar to last year's robotic arm was chosen. The differential has the ability to move to a desired position, while also providing torque reduction without additional gearing.

Grippers from several sources were exhaustively considered. Large selections of commercial grippers were readily available for robotic use. However, many of these grippers are intended for a manufacturing environment (Figure 38) and therefore inappropriate for the project.
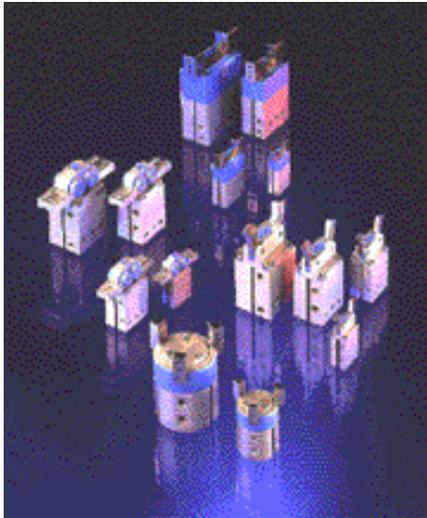
Figure 38: Industrial Grippers

An additional problem with many of the commercially available designs was that they only provide linear motion when actuated. Since rotary action was a preferred design option the gripper will need to be designed in house.
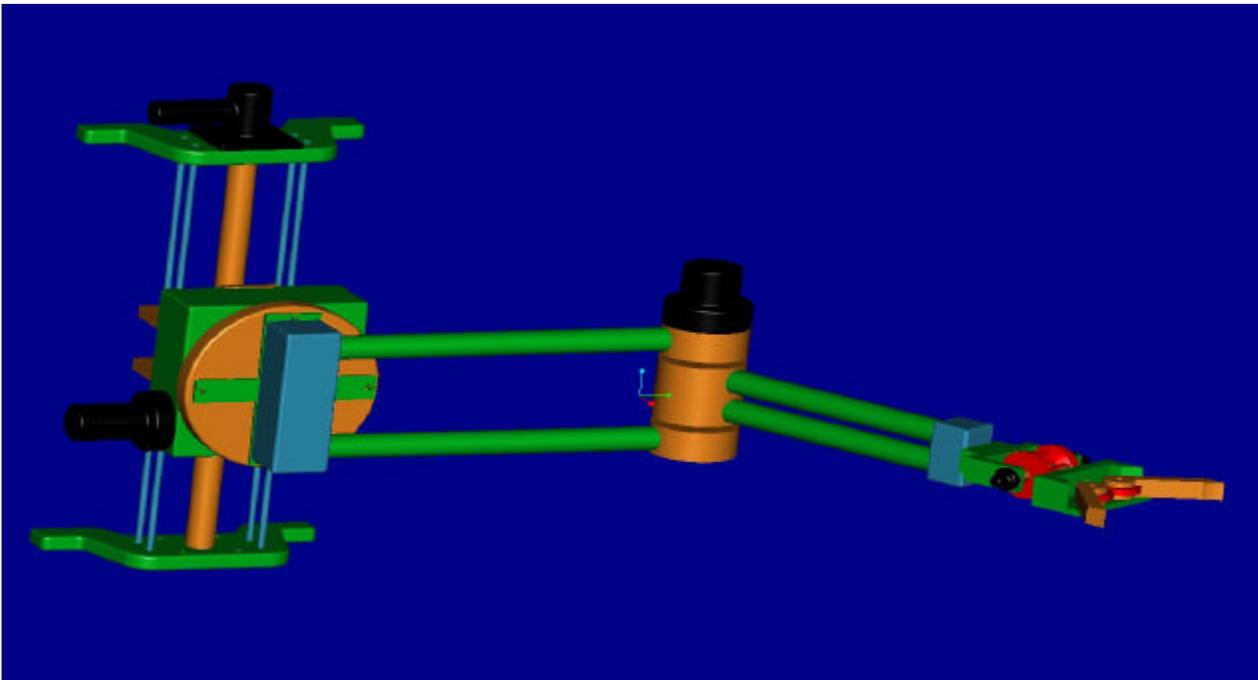
FINAL DESIGN

Figure 39: Final Robotic Arm Design

ARM LINKAGES

The first and most detrimental consideration in designing the arm's links was the weight. Last years project exemplified that utilization of Aluminum would add excessive mass. By soliciting advice from other student design groups and building upon our own past experiences The Ohio State University turned to an alternative material, composites. Composites would enable the group to meet the required safety criteria by adding additional flexibility and reducing the metal content of the arm. Several different materials were meticulously researched and compared. Lexan plastic wrapped with Kevlar fabric and resin proved to provide the specified strength and weight while maintaining a low cost and availability.

Next, The Ohio State University group determined the lengths of each linkage. After concluding that a 12 inch reach from the front of the child's wheelchair was necessary, the preliminary lengths (Appendix A) were chosen. An additional factor that quickly became evident was the issue of compactness. To comply with both specifications the resulting shoulder to elbow length was 14.50 inches with a length of 10.75 inches from the elbow to wrist.

Having materials and lengths chosen, the cross section and shape of the linkages could then be designated. It was essential to sustain a modest weight while designing a safe product. The final design contains four solid cylindrical links, each having a 1 inch diameter. Figure 40 displays the shoulder to elbow linkage and the elbow to wrist linkage.
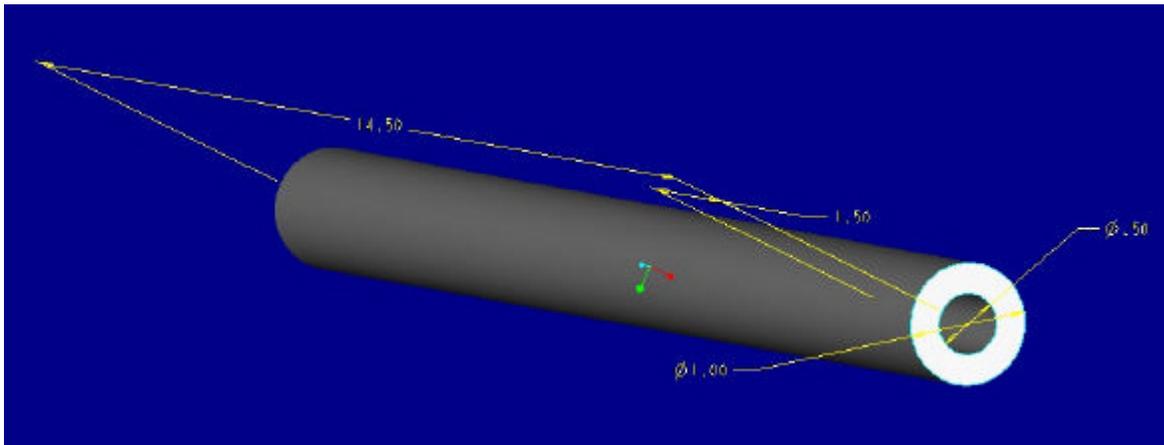
(a) Shoulder to Elbow
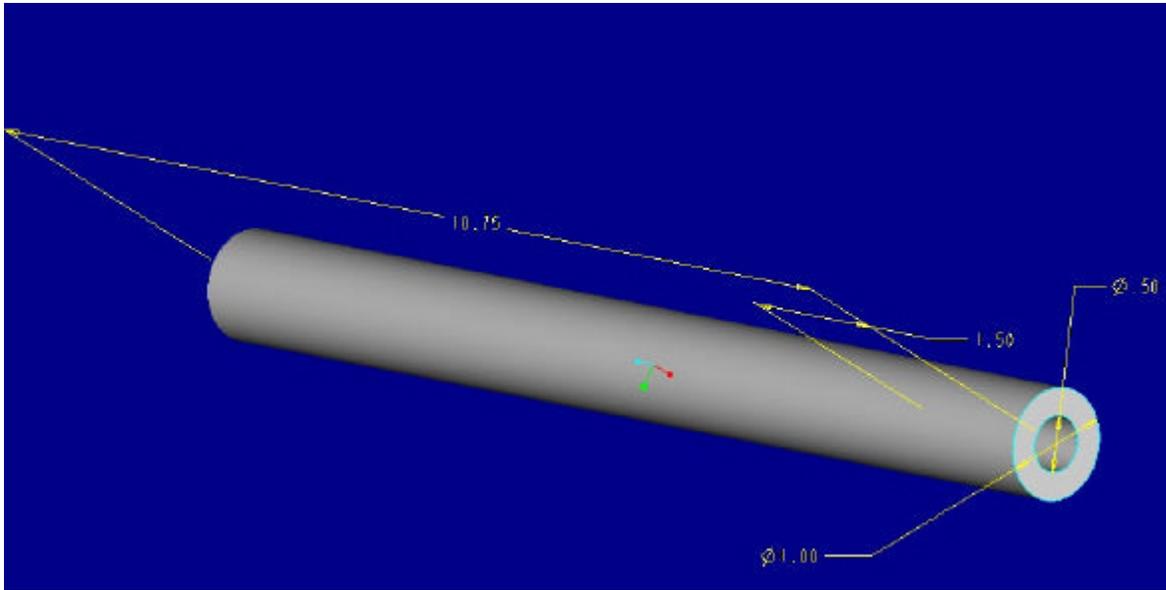
(b) Elbow to Wrist

Figure 40: Linkage Shape

By having four cylindrical parts the arm has been designed for manufacturing while having eliminated the potential hazard of sharp edges. In addition, the circular cross sections provide a simplified solution to the problem of connecting the linkages to the elbow joint. Each Lexan linkage will be tapped so that they screwed directly on to the elbow joint. This design will provide a simplistic assembly and tear down of the robotic arm.

To ensure that the specified linkages could withstand the possible forces that the arm may encounter, a stress analysis (Appendix B and C) and bending analysis (Appendix D) were performed. Anticipating that the range of in-service loading conditions would be greater than the group predicted, factors of safety were also calculated. Even applying a simplistic analysis for the worst predicament, the arm maintains a high degree of safety as seen below in Table 1:

Table 1: Stress and Bending Considerations

Stress and Bending Considerations				
	Normal Stress (psi)	Shear Stress (lbf)	Stress Safety Factor	Bending (in)
Linkage at Shoulder	64.02	***	234.30	***
Linkage at Elbow	63.32	7.95	240.70	***
Linkage at Elbow Threading	8600		1.74	
Linkage from Shoulder to Elbow	***	***	***	0.0013
Linkage from Elbow to Wrist	***	***	***	0.0019

51

ELBOW JOINT

The elbow joint became a critical portion of the final design. The joint must incorporate all four links into a solid, non-rusting construction that can fully rotate with motors attached. To accomplish such an unattainable feat an in-house component was designed (Figure 41 & 42).
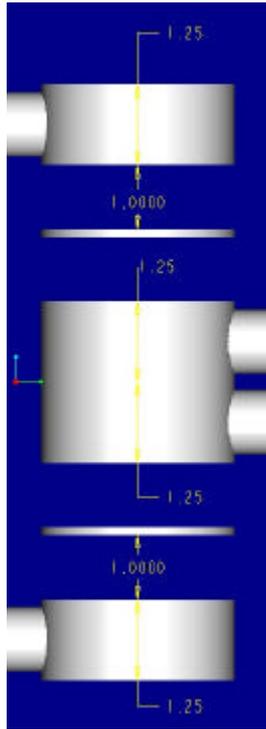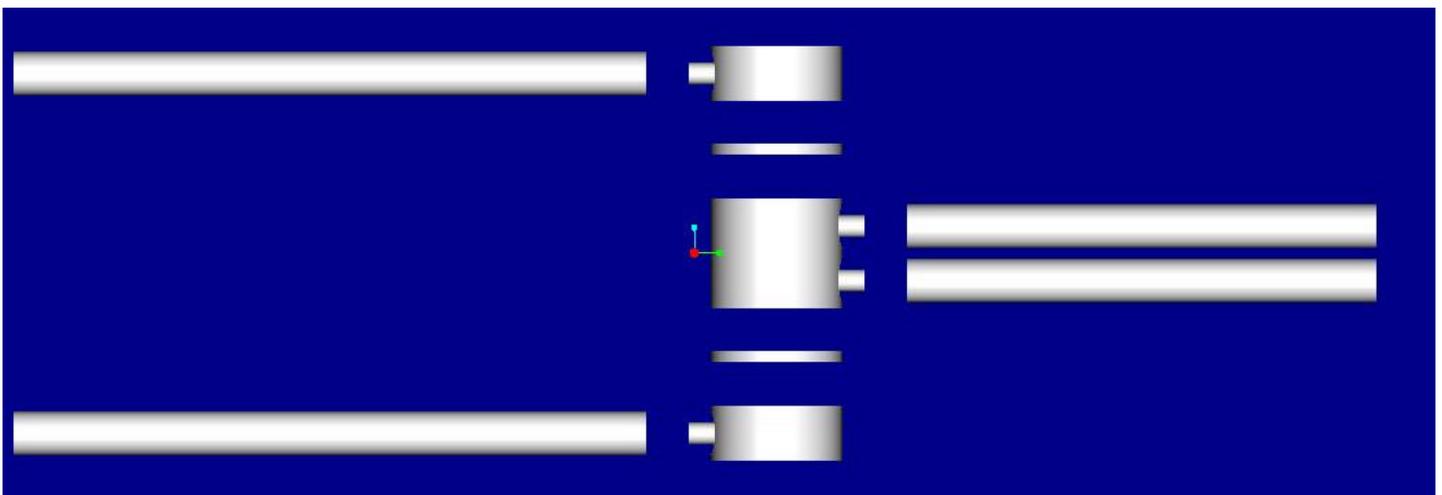

Figure 41: Elbow Joint

Figure 42: Exploded View of Elbow Joint and Linkages

After consulting with a qualified machinist it was decided that Aluminum would be used to manufacture each section of the elbow joint, including the 0.50 inch diameter shaft. The threaded pins that extrude 0.50 inches from the joint and have diameters of 0.675 inches will provide locations where the tapped Lexan rods can be connected. To reduce the frictional wear that will occur during the arms rotation Stainless steel bearing were inserted. This design will produce an uncomplicated yet strong connection between the linkages and the elbow joint. The advantage of the elbow joint's design is that is can be quickly machined and assembled at a low cost. The Ohio State University is equipped with the material, machines and experience personnel to produce such a component.

ROTARY TABLE AND LINEAR TRANSLATION

To abide by the design specifications set forth by the Gateway Coalition the group felt it was essential for the robotic arm to rotate and vertically translate. These two degrees of freedom will maintain an acceptable weight and area of reach, while allowing for shorter link lengths.

After careful consideration and exploration into last year's robotic arm design it was concluded that purchasing a rotating base (Figure 43) would be the most efficient option. With the time limitations that face the Gateway design teams it was good manufacturing practice to procure as many off the shelf items as possible. By eliminating the construction of the rotating base an abundance of manpower can be directed towards other components. More time and effort can be focused on perfecting the final design and construction of each team's portion of the arm. Additionally by purchasing the rotation base the size and weight will be drastically reduced compared to the prototype that was manufactured last year (Figure 44).
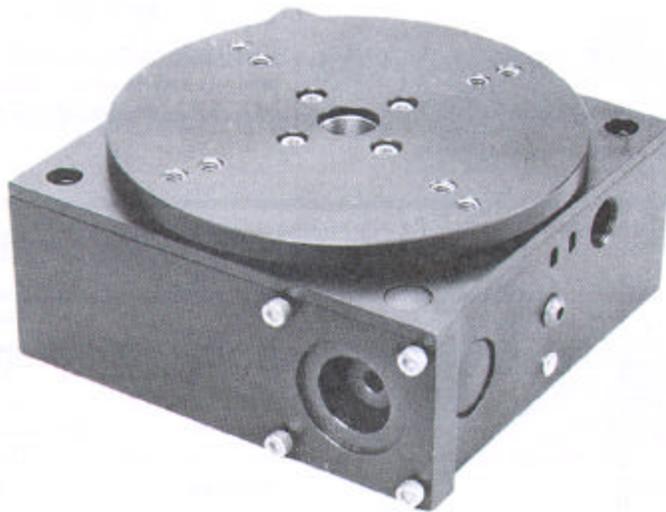
Figure 43: Rotating Base
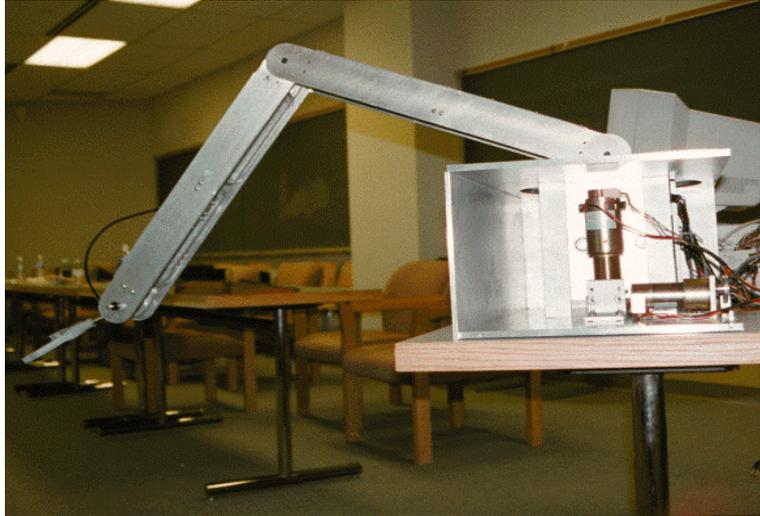
Figure 44: 1997 Gateway Final Prototype

The unit rotating the arm is a rotary table that includes a 120 oz-in motor. The total weight of the proposed module is 13.50 pounds and is only 6.00 inches square with a height of 2.50 inches. The robotic arm will be mounted to the rotary table by a squared fixture with rounded corners (Figure 45).
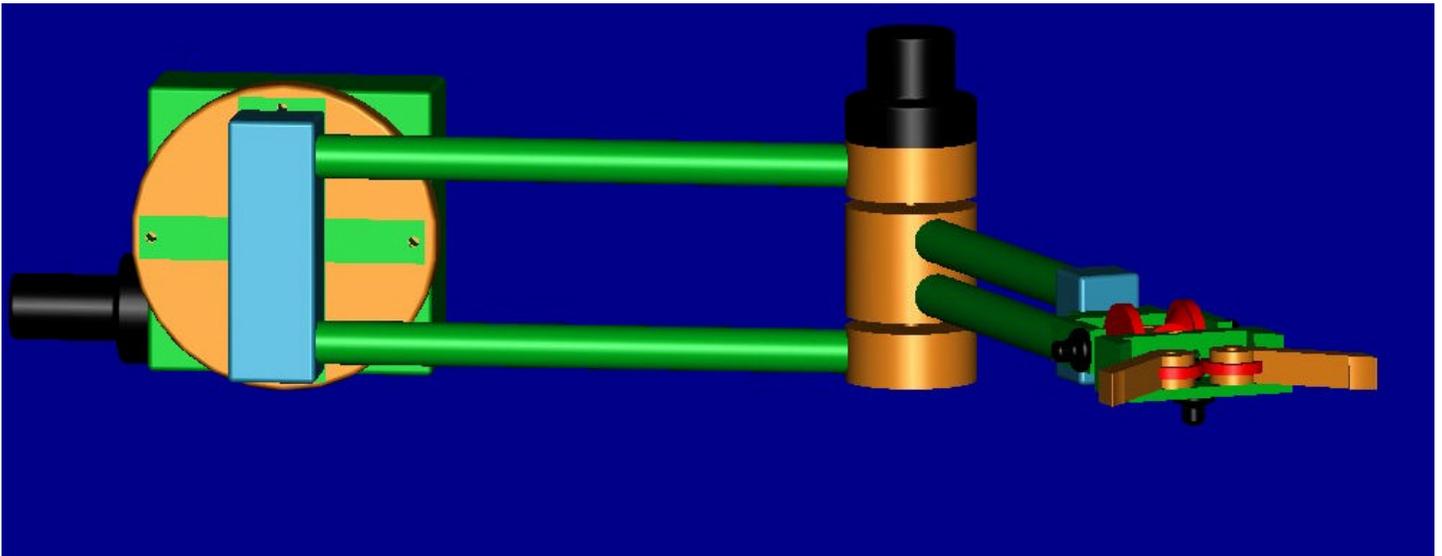
Figure 45: Robotic Arm Mounted on Rotary Table

Having weight and cost limitations made linear translation of the arm a laborious task to achieve. As mentioned in the design options linear tables were considered, yet not as practical as lead screws. The only dilemma with employing lead screws was the possibility of lock-up. To circumvent this issue, the design needed to be as simplistic as possible to guarantee precise manufacturing and assembly. Figure 46 shows the final design for linear translation of the robotic arm.
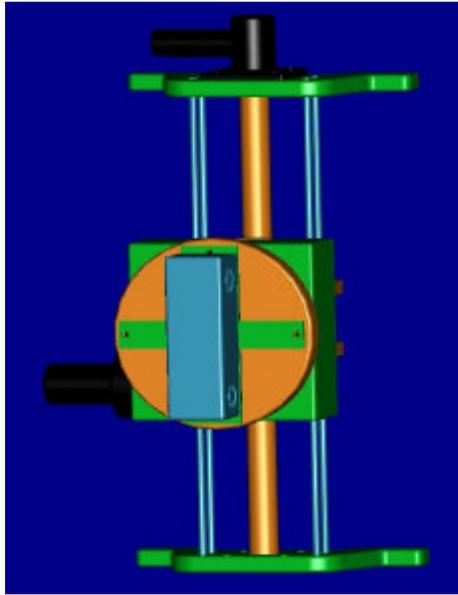
Figure 46: Linear Translation Design

The lead screw has been specified to be 303 stainless steel with a Teflon S self lubricating coating to prevent rusting and to limit friction. Threading considerations resulted from the desired speed constraints. To maintain a velocity lower than 0.2 m/s a 2200-RPM stepper motor with a 275-RPM right angle drive will turn a 10-thread/in ACME lead screw. A further criterion, lock-up, was resolved by placing the rotating base in coordination with four linear bearings on four steel support rods, two of each on either side of the base. These rods will be mounted firmly to the wheelchair using an in-house mount.

WRIST

The wrist on the robotic manipulator allows for "fine tuning" of the gripper. It enables the user to effortlessly pick up an object in all possible arm configurations. To accomplish these movements, the wrist needs at least two degrees of freedom. It was decided that the wrist would have the ability to pitch and roll. As a result, the gripper will seldom have problems grabbing objects at various heights. Furthermore, by rolling the wrist the robotic arm can be used to grasp unusually shaped objects and items that may not be perpendicular to the ground.

The design chosen to achieve a pitch and roll motion used a geared differential. This allows two motors rigidly attached to the upper arm to achieve both rolling and pitching motions smoothly and reliably. Another benefit was that by using such an arrangement both motors work together, reducing the amount of torque needed from each motor. To pitch the wrist both motors rotate in the same direction. Additionally, they will rotate in opposite directions to produce a roll.

GRIPPER

The design of the gripper was a significant part of the entire arm assembly. Since commercially available grippers are either too heavy or are not suitable for general use, it was decided to design a gripper. The

component must be as lightweight as possible due it's location on the arm. Its robust design was kept simple, resulting in a minimum number of parts to ensure reliable operation. The gripper was designed to be directly driven by a small motor. Aluminum will be employed to ensure low weight, high strength, and high machinability.

The chosen gripper consists of two shaped fingers that are rigidly mounted to gears (Figure 47). A small servomotor on the top of the assembly drives the gripper directly. The required gripper speed will be made possible by the built-in gear reduction of the servomotor. Gears shall be enclosed to prevent the child operator from contacting them.
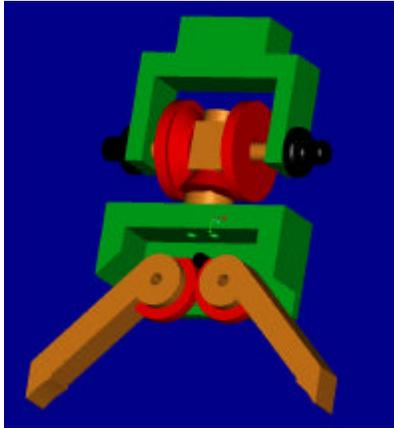
Figure 47: Gripper Assembly

The fingers of the gripper are similar to the ones used in the previous year's design. They are shaped to be versatile in grasping objects of different shapes. Each finger has a "H" cross-section to keep the digits lightweight. Rubber pads on the gripping surfaces of the fingers improve its ability to pick up slippery objects and will prevent scratching and damage.

PROTECTIVE COVERS

As a precaution it was imperative to enclose potentially hazardous portions of the automated arm. A rubber sleeve is to be place around the lead screw to prevent an accidental injury during linear translation. Furthermore, an additional rubber sleeve will be place around the wrist where pinch points are evident. To make sure loose wires are contained, clear ABS plastic tubing will enclose wires to the Lexan/Kevlar linkages.

MOTOR, TORQUE AND PART SPECIFICATIONS

Table 2: Calculated Torque Requirements

CALCULATED TORQUE REQUIREMENTS		
Position	Torque With Out Safety Factor (oz-in)	Torque With Safety Factor (oz-in)
Vertical Positioning/ Lead Screw	34.51	69
Shoulder/ Rotating Table	1881.6	3763.2
Elbow Joint	509.7	1018.4
Wrist	9.7	19.38
Gripper	20	40

Table 3: Motor Specifications

MOTOR SPECIFICATIONS	
Position	Torque (oz-in)
Lead Screw	20
Lead Screw Drive	72
Shoulder/ Rotating Table	3200
Rotating Table Motor	120
Elbow Joint	2525
Wrist	27.8
Gripper	62.5

Table 4: Part Specifications

PART SPECIFICATIONS							
Part	Weight (oz)	RPM	Gear Ratio	Diameter (in)	Length (in)	Depth (in)	Gear Base (in)
Lead Screw Motor	20.00	2200.00	***	2.00	3.00	***	2.25 x 2.25
Right Angle Drive	4.00	275.00	8/1	***	1.00	0.75	***
Lead screw	9.60	***	10 turns/in	0.375	12.00	***	***
Lead Screw Tracks	4.80	***	***	0.25	12.00	***	***
Rotating Table	176.00	4.00	1/180	6" table top	8 x 8	2.50	***
Rotating Table Motor	40.00	720.00	***	2.50	4.00	***	***
Elbow Joint Motor	17.60	7.00	***	2.22	2.00	***	***
Wrist Motor	2.49	13.60	483.66/1	0.866	2.89	***	***
Differential	7.50	***	5/1	1.500	2.00	1.50	***
Gripper Motor	3.52	35.00	150/1	1.45	2.40	***	***

SAFETY CONSIDERATIONS

During the design process it was essential that the group considered a multitude of safety considerations. Due to the robotic arm's application the medical profession became an ideal source for gaining data on safety concerns. Throughout medical establishments in the United States the trend has been to reduce the amount of metal products that surround patients, especially children. As a result, industry has been encouraged to produce medical products made of alternative materials such as plastic and rubber. Any exposed metal that is found in hospitals is generally stainless steel, to guarantee that rusting and corrosion does not occur. It has also been strongly recommended that sharp edges and pinch points not be exposed to the patient in the design of a robotic arm.

The Ohio State University incorporated the above and additional safety considerations into the final design of the robotic arm. To avoid having the entire structure manufactured out of metal products, the group resolved to use Kevlar fiber and Lexan plastic for the linkages. The advantage of using the Lexan plastic wrapped with Kevlar fiber weave is that the linkages will maintain the strength of steel with additional flexibility. As a result if the child operator strikes the arm against an object while moving it, the linkage will have the ability to flex without causing severe damage to the robotic arm. The rotating base has been specified to ensure that no backlash can occur. This feature is mandatory to secure the arm in its position and prevent slippage during

power termination. Additionally, all of the selected motors were specified with a factor of safety in the range of 1.5 to 2.0. Motors that are located on the wrist and elbow have slip bearings included to prevent the motors from producing torque over their maximum limit. In an effort to reduce pinch points special precautions were taken in the areas of the lead screw and wrist. Both of the regions will employ rubber sleeves over the potentially hazardous areas. Rubber will also be utilized on the gripper digits to prohibit objects that are being lifted up from slipping. Any possible loose wiring will be contained in ABS plastic tubing against the arm links. Finally, to eliminate the possibility of exposed sharp corners additional machining will be implemented. Each individual portion of the robotic arm that necessitates machining will also be required to have its edges rounded.

COST ANALYSIS

Part Description	Qty	Supplier	Time to Receive	Material	Modification	Cost	Total
Gripper							
Servo Motor	1	Sterling Instruments	1 week	***	None	$62.69	$62.69
0.50" Gear	2	Sterling Instruments	1 week	Steel	None	$22.00	$44.00
0.0625" Pinion Gear	1	Sterling Instruments	1 week	Steel	None	$22.00	$22.00
0.125" U-Plate	1	OSU	2 weeks	Aluminum	dimension, drill, round	$4.00	$4.00
Digits	2	OSU	2 weeks	ABS Plastic	dimension, drill, round	$1.00	$2.00
Finger Pads	2	Columbus Medical Supply	1 week	Rubber	None	$2.00	$4.00
Circular Base	1	OSU	2 weeks	Aluminum	dimension, drill, round	$4.00	$4.00
Fasteners	4	Hardware Store	Immediate	Steel	None	$0.10	$0.40
Wrist							
Servo Motor	2	Sterling Instruments	5-7 days	***	None	$170.00	$340.00
Differential	1	Sterling Instruments	5-7 days	Steel	None	$261.85	$261.85
U-Casing	1	OSU	2 weeks	Aluminum	dimension, drill, round	$4.00	$4.00
Sleeve	1	Hobby Store	Immediate	Rubber	None	$5.00	$5.00
Fasteners	6	Hardware Store	Immediate	Steel	None	$0.10	$0.60
Elbow Joint							
Stepper Motor	1	Sterling Instruments	5-7 days	***	None	$110.00	$110.00
Bearing	2	Berg	1 week	Steel	None	$45.00	$90.00

Shaft	1	Hardware Store	Immediate	Steel	cut to length	$2.50	$2.50
Elbow Joint Connection	3	OSU	3 weeks	Aluminum	dimension, drill, tap, thread	$5.00	$15.00
Fasteners	3	Hardware Store	Immediate	Steel	None	$0.10	$0.30
Base							
Rotating Base	1	Minmark	1 week	Steel	grooves	$2,000.00	$2,000.00
Stepper Motor	1	Minmark	1 week	***	None	$450.00	$450.00
Shoulder Bracket	1	OSU	2 weeks	Aluminum	dimension, drill, round	$4.00	$4.00
Fasteners	8	Hardware Store	Immediate	Steel	None	$0.20	$1.60
Arm Links							
Kevlar Fiber	1			Kevlar	cut to length	$20.00	$20.00
1.00" Delrin/Lexan Rod	4				cut to length, drill	$25.00	$100.00
Kevlar Resin	1			***		$40.00	$40.00
Vertical Assembly							
Stepper Motor	1	Servo Systems	2 days		None	$12.50	$12.50
Right Angle Reduction	1	Sterling Instruments	1 week	Steel	None	$237.40	$237.40
0.375" Lead Screw	2	Pic Design	1 week	Stainless Steel/Teflon Coating	None	$25.10	$50.20
0.25" Rod	4	Pic Design	1 week	Stainless Steel	None	$20.00	$80.00
0.25" Linear Bearing	4	Pic Design	1 week	Stainless Steel	None	$20.00	$80.00
Braces	5	OSU	2 weeks	Aluminum	dimension, drill, round	$5.00	$25.00
Fasteners	10	Hardware Store	Immediate	Steel	None	$0.20	$2.00
							$4,075.04

KINEMATIC ANALYSIS

To determine the velocity of the manipulator it is necessary to apply forward kinematics to the robotic arm. Forward kinematics is a static geometrical problem of computing the position and orientation of the free end also known as the end effector of the manipulator. Matrices are formed to describe the position of each joint relative to the previous joint. Utilizing these matrices a transform matrix can be found for each linkage. The transform matrices are essential for finding the Jacobian equation and the resulting velocity of the manipulator.

The initial step that should be performed is to create a simplified illustration of the robotic arm that includes each relevant joint and linkage (Figure 14). It is required that each joint rotates about their respective z-axis. The positive direction of each joint's z-axis can be determined by applying the right-hand rule to each individual joint.
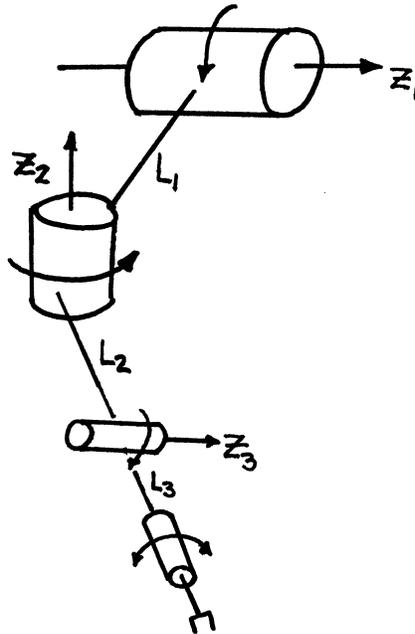

Figure 48: Robotic Arm Illustration

Step two requires that transform matrices are determined for each linkage. These matrices (Eq.1) represent the rotation and translation that a joint has to perform in order to achieve the following joint's position.

$$T_s = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{(Eq. 1)}$$

Variables *n, o* and *a* symbolize the rotation of the joint into the respective *x, y* and *z* direction. Translation of the previous joint to the succeeding joint's position is represented by the *p* variables. The following matrices should be employed to describe the rotation of the joint about the x, y and z-axis (Eq.2).

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & Cq & -Sq \\ 0 & Sq & Cq \end{bmatrix} \qquad \begin{bmatrix} Cq & 0 & Sq \\ 0 & 1 & 0 \\ -Sq & 0 & Cq \end{bmatrix} \qquad \begin{bmatrix} Cq & -Sq & 0 \\ Sq & Cq & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(a)   (b)   (c)

Where (a) is the rotation about the x-axis, (b) is the rotation about the y-axis and (c) is the rotation about the z-axis. Additionally, *Cq* and *Sq* represent cos (θ) and sin (θ). For example, if trying to determine the transform matrix of joint 2 relative to joint 1 ($^1T_2$) each joint should be sketched keeping one axis coincident (figure 49).
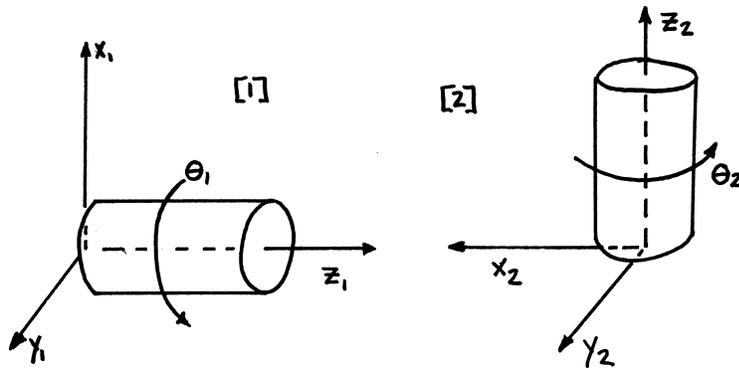

Figure 49: Transform of Joint 1 to Joint 2 with Coincident Axis

To move joint 1 into the position of joint 2 the following movements must occur:

1. Translation along the z1-axis a distance of L1
2. Rotation about the y1-axis an angle of 90°
3. Rotation about the z2-axis an angle of 90°

Knowing the exact actions that need to take place, a matrix describing each motion should be formed. The transform matrix can then be calculated by multiplying the three 4x4 matrices together (Eq.3).

$$
\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L1 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\qquad
\begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\qquad
\begin{bmatrix} Cq2 & -Sq2 & 0 & 0 \\ Sq2 & Cq2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

(Translation along z1) (Rotation about y1) (Rotation about z2)

$$
{}^{1}T_{2} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ Sq2 & Cq2 & 0 & 0 \\ -Cq2 & Sq2 & 0 & L1 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Above, the final transform matrix of joint 2 relative to joint 1 can found (Eq.4). This procedure should be performed at the initial joint and repeated for each joint until reaching the manipulator. The resulting transform matrices for The Ohio State University robotic arm can be found below.

$$
{}^{0}T_{1} = \begin{bmatrix} Cq1 & -Sq1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ Sq2 & Cq1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^1T_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ Sq2 & Cq2 & 0 & 0 \\ -Cq2 & Sq2 & 0 & L1 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^2T_3 = \begin{bmatrix} Cq3 & -Sq3 & 1 & L2 \\ 0 & 0 & 0 & 0 \\ -Sq3 & -Cq3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^3T_4 = \begin{bmatrix} 0 & 0 & -1 & -L3 \\ Sq4 & Cq4 & 0 & 0 \\ Cq4 & -Sq4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

The final link end effector position can be determined relative to the base of the robot by multiplying the matrices found above.

$$
{}^0T_4 = {}^0T_1\, {}^1T_2\, {}^2T_3\, {}^3T_4
$$

The transform matrix ${}^0T_4$ is a critical element for finding the Jacobian equation. The intent of the Jacobian equation is to find the velocity of the manipulator. By multiplying the Jacobian equation by each motor speed it is possible to find the resulting velocity at the endpoint of the manipulator

LINK LENGTHS AND DIMENSIONS

Wheel Chair   Standard Table

30"

Mount pt.
11.5" high
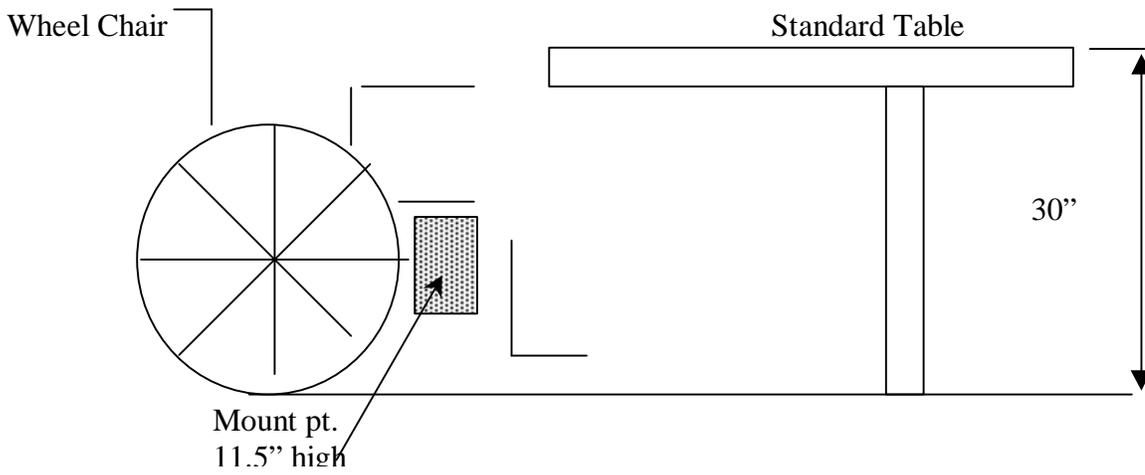
Assumptions:
1) 30 " Table height
2) Mounting point is 11.5" off the ground
3) Elevator travel is 12"

I. Total link lengths

12"
Elevator
Travel

30"
Table Height

11.5"
Mounting Point .99

17"   12" reach
"toe"
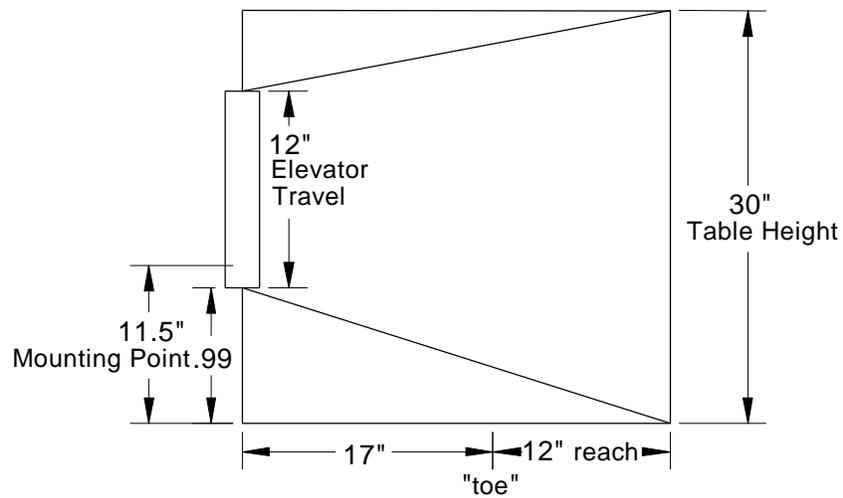
Total length without elevator

$L_{total} = [(17"+12")^2 + 18.5"^2]^{1/2} = 34.4"$
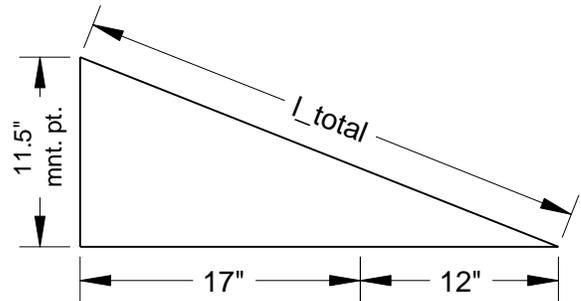
Total length if elevator is used

$L_{total} = [(17"+12")^2 + 9.0"^2]^{1/2} = 30.4"$
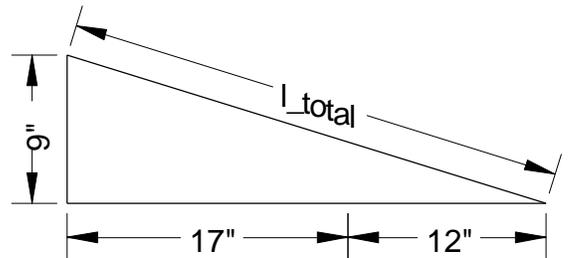
Savings in overall length by using elevator

Percent difference $= [34.4-30.4]/34.4 = 11.6\%$

II. Work Space
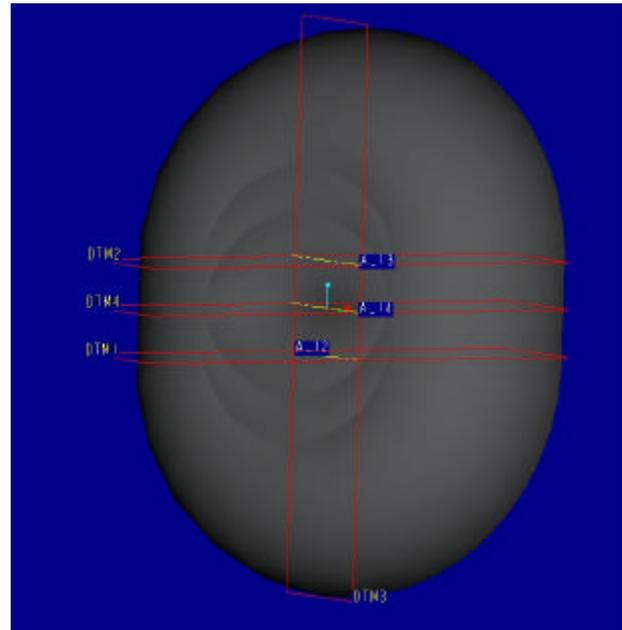
Key:

DM2 – Top of lead screw

DM1 – Bottom of lead screw

Dm4 – Center position

Although the workspace defined by the robotic manipulator may appear unusual, it was the result of our unique design. The workspace shown fulfilled the design requirements by utilizing a lightweight and compact package. The end result produced a 15.5-inch depth of reach and 72 inch height ability.

STRESS ANA LYSIS

$l_1 = 14.5"$ $l_2 = 10.75"$ $l_3 = 4.75"$
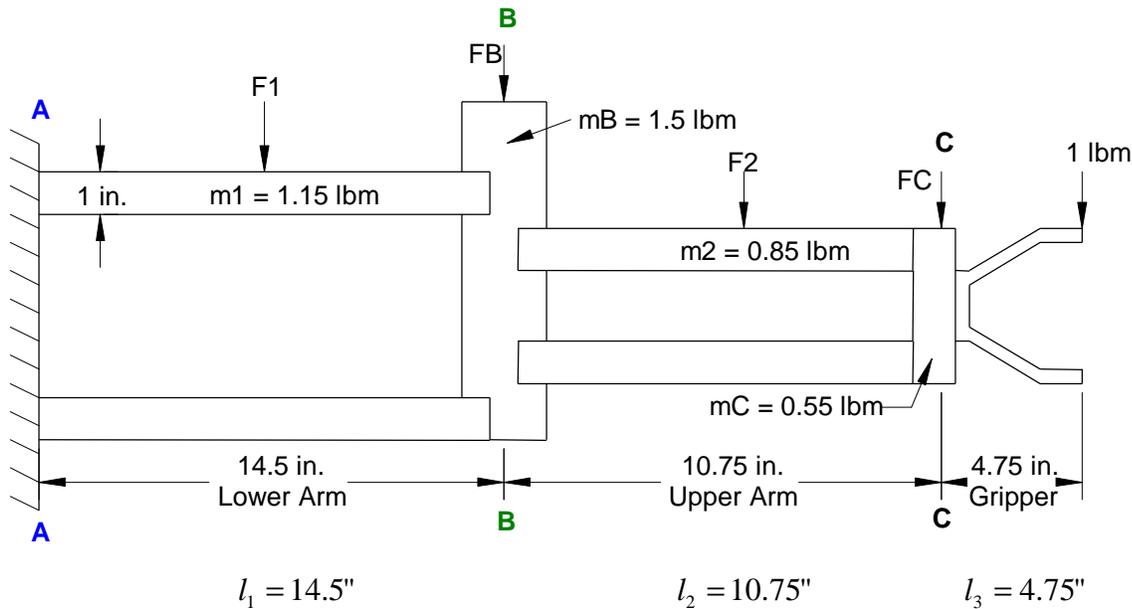
Assumptions:
1) Assume masses and lengths as shown in drawing
2) Masses are lumped as shown
3) Density is the same as aluminum, $\rho = 0.1012$ lbm/in^3
4) Link diameters are chosen based on minimum limit for machining pin connections

- Check stress in arm to see if link diameters are sufficient
- Neglect shear stress in the arm links, since it is much smaller than the tensile stress

I. Calculate stress of links at section AA
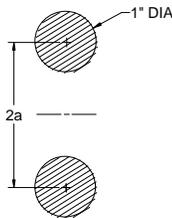
Area moment of inertia for a circle $\bar{I}_x = \frac{\pi R^4}{4} = 0.0491$ in^4

Area moment of inertia of section AA $I_{AA} = 2 \cdot (\bar{I}_x + A_1 a^2) = 3.363$ in^4

Moment $M = 2m_1 g\left(\frac{l_1}{2}\right) + m_B g(l_1) + 2m_2 g\left(l_1 + \frac{l_2}{2}\right) + m_C g(l_1 + l_2) + mg(l_1 + l_2 + l_3)$

$M = 116.3$ in-lbf

Assume 2a = 3 in.
c = a+D$_1$/2 = 2 in.

Normal Stress $\qquad$ $s_{AA} = \dfrac{Mc}{I_{AA}} = \dfrac{116.3 in-lbf \cdot 2.0 in}{3.363 in^4} =$ 64.02 psi

Yield strength $\qquad$ S$_y$ = 25,000 psi for Aluminum

$\qquad\qquad\qquad$ S$_y$= 15,000 psi for Delrin/Lexan

Factor of safety $\qquad$ $h_s = \dfrac{S_y}{s_{AA}} = \dfrac{15000\, psi}{64.02\, psi} = 234.3$

II. Calculate Stress of links at section BB
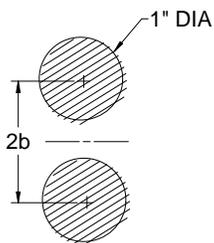
Area moment of inertia for a circle $\qquad$ $\bar{I}_x = \frac{\pi R^4}{4} = 0.0491$ in^4

Area moment of inertia of section BB $\qquad$ $I_{BB} = 2 \cdot (\bar{I}_x + A_2 b^2) = 0.4909$ in^4
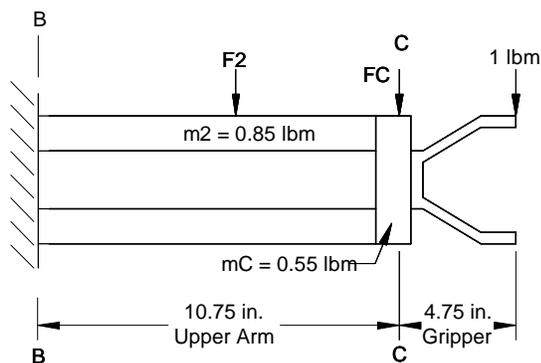
Moment $\qquad$ $M = 2m_2 g\left(\frac{l_2}{2}\right) + m_C g(l_2) + mg(l_2 + l_3) =$ 30.59 in-lbf

Assume 2b = 1 in.
c = b+D$_2$/2 = 1.0 in.

Normal Stress $\qquad s_{BB} = \dfrac{Mc}{I_{BB}} = \dfrac{30.59 in-lbf \cdot 1.0 in}{0.4909 in^4}$ = 62.32 psi

Yield strength $\qquad S_y$ = 25,000 psi for Aluminum

$\qquad\qquad\qquad\qquad$ S_y = 15,000 psi for Delrin/Lexan

Factor of safety $\qquad h_s = \dfrac{S_y}{s_{BB}} = \dfrac{15000\,psi}{62.32\,psi}$ = 240.7

III. Calculate stress of elbow/wrist links at the threaded elbow connection

Key:

Black – Lexan link

Red – Threaded elbow pin
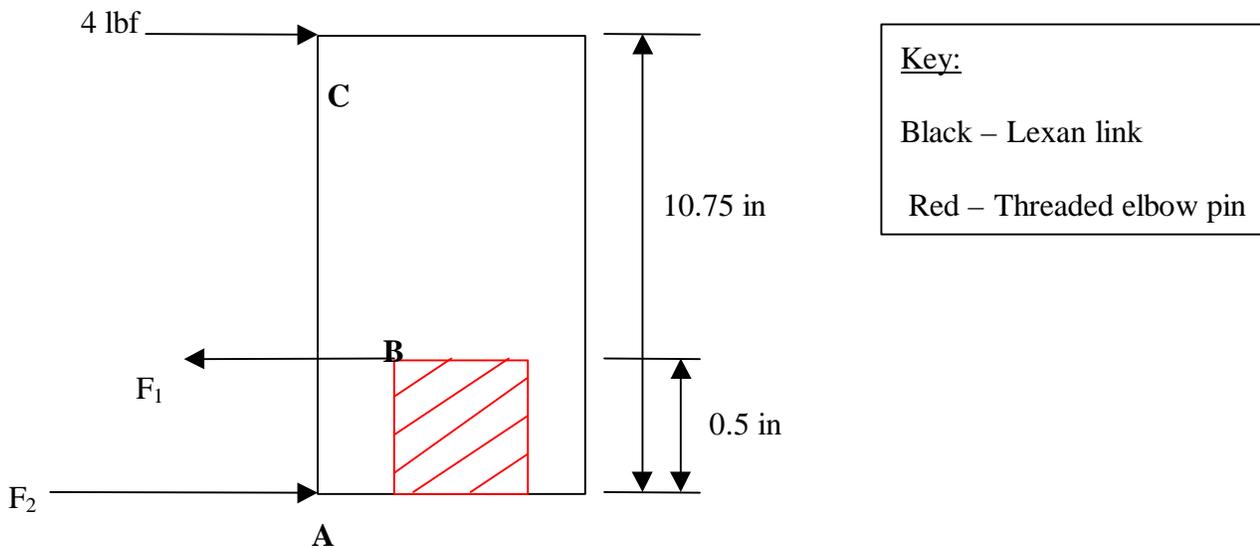
Assumptions:
1) Total weight is at the end of the link, in the gripper
2) Static conditions
3) Opposing gravity
4) 4 lbf force is being applied
5) Forces are acting on a small area of 0.1 x 0.1 inches

$\Sigma\, Fx = 4 + F_2 = F_1$

$\Sigma\, M_A = F_1(0.5) - 4(10.75) = 0$

$\therefore$ F1 = 86 lbf
$\quad$ F2 = 82 lbf

Using assumed area $\sigma = F / A$
$\sigma = 86/0.01$ = 8600 psi

MOMENT AND SHEAR ANALYSIS

I. Moment and Shear analysis on elbow shaft
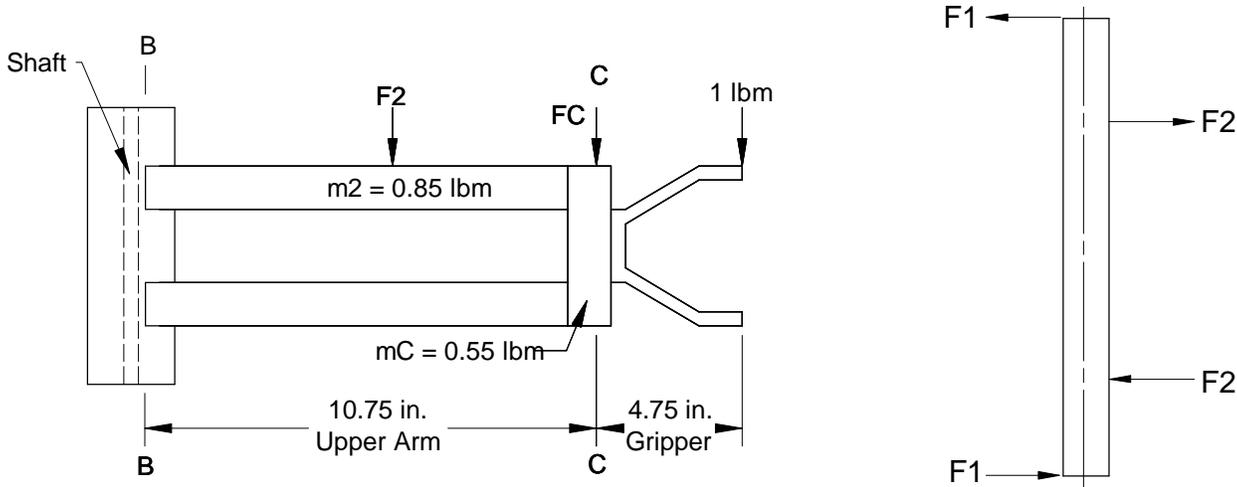
First find F2 by summation of forces about point **O**.
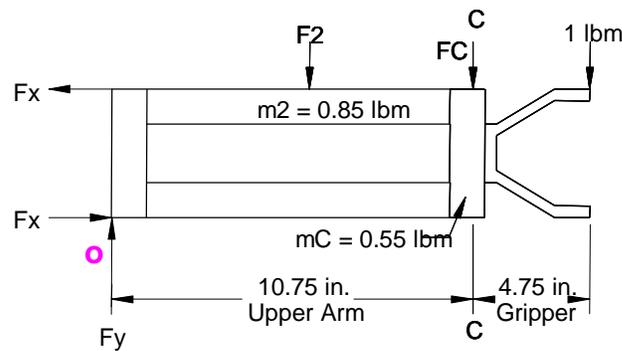
$$\sum M_o = F_{Rx}(2b + D_2) - \left[2m_2 g\left(\tfrac{l_2}{2}\right) + m_C g\left(l_2 + \tfrac{l_3}{2}\right) + mg\left(l_2 + l_3\right)\right] = 0$$

$$\sum F_x = F_{Rx} - F_{Rx} = 0$$

$$\sum F_y = F_{Ry} - (m_2 + m_C + m)g = 0$$

$$F_2 = F_{Rx} = \frac{2m_2 g\left(\tfrac{l_2}{2}\right) + m_C g\left(l_2 + \tfrac{l_3}{2}\right) + mg\left(l_2 + l_3\right)}{2b + D_2} = 15.95 \text{ lbf}$$

Next find F_1 by summing moments about the center of the shaft.

$$F_1 = \frac{2m_2 g\left(\frac{l_2}{2}\right) + m_C g\left(l_2 + \frac{l_3}{2}\right) + mg\left(l_2 + l_3\right)}{2a + D_1} = 7.975 \text{ lbf}$$
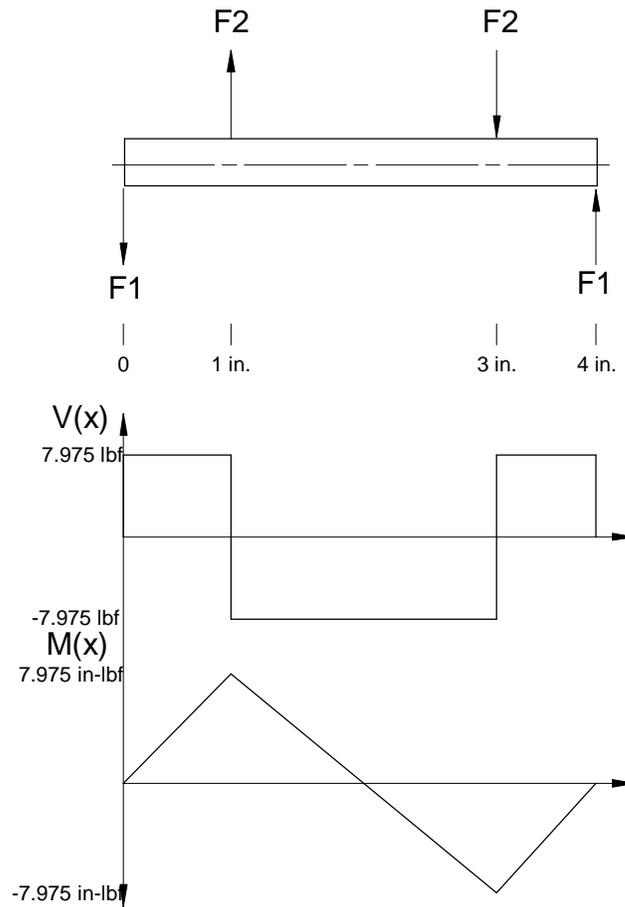
BENDING ANALYSIS

Assumptions:
1) Massless links
2) Forces are applied as shown
3) Length and diameter of arms as shown
4) Arms can be considered cantilevered beams
5) Arm is an epoxy matrix wrapped around a high strength plastic rod
6) Since epoxy matrix is mush stiffer than core, neglect inner core stiffness
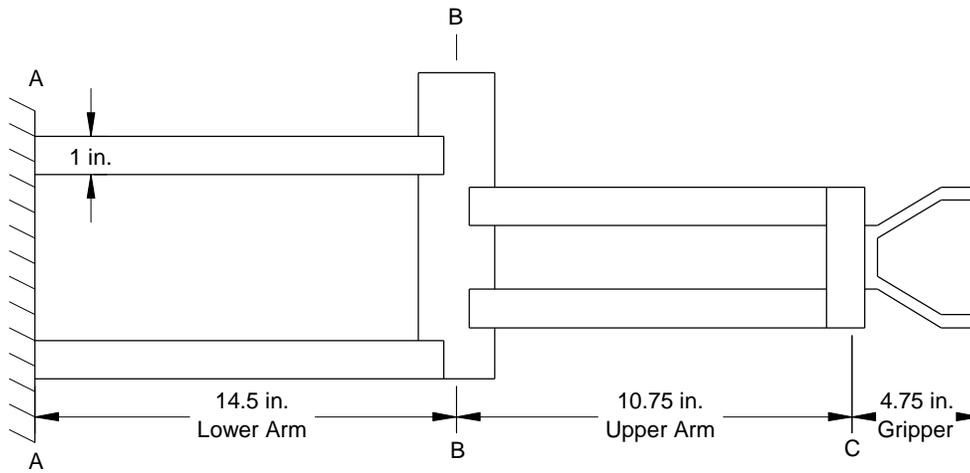
I.   Bending in Upper Arm
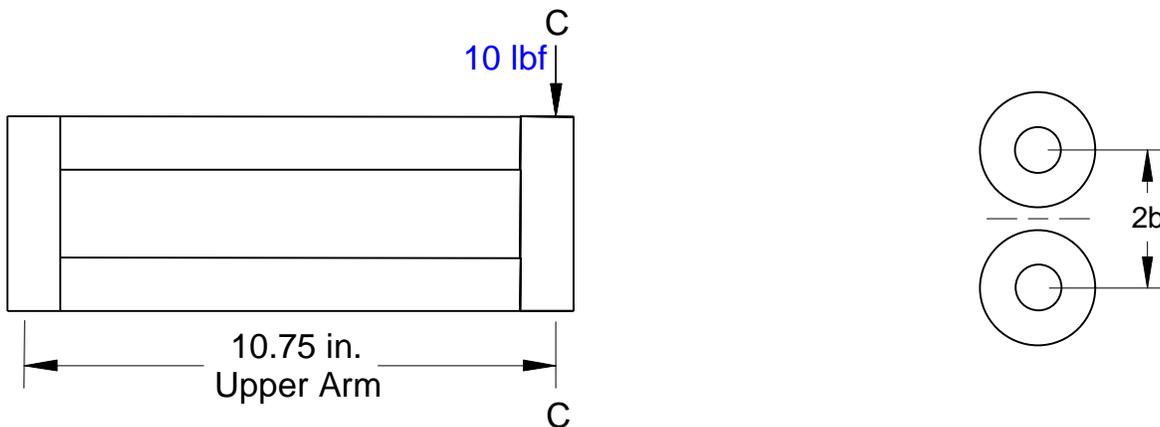
Assume a 10 lbf force applied to the end of the upper arm as shown

y = deflection

y' = slope

$$y'' = \frac{M(x)}{EI}$$

Finding the shear, moment, slope, and deflection diagrams:
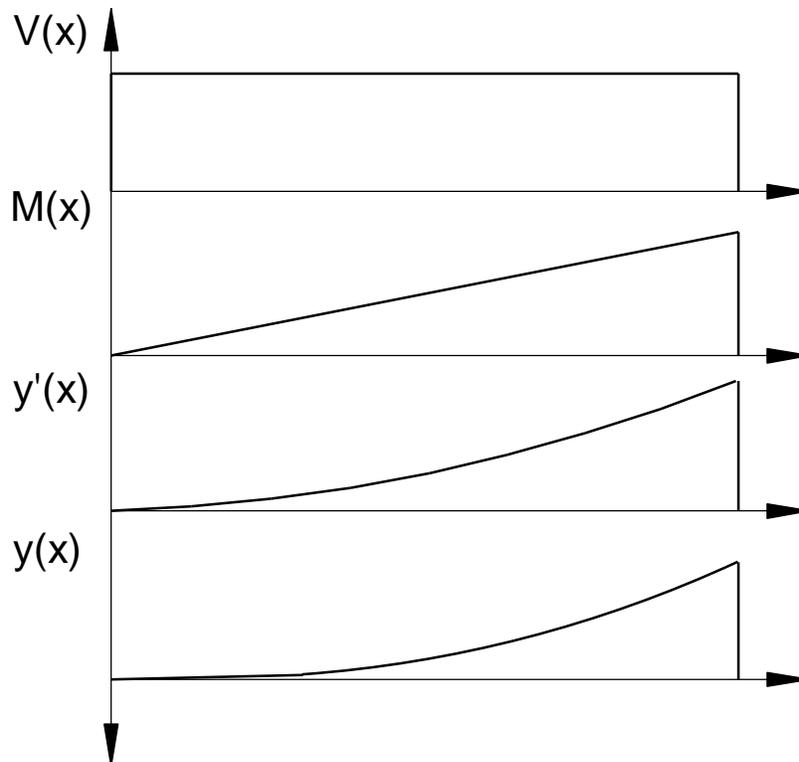
$$M(x) = F \cdot x = 10 \text{ lbf x}$$

$$y' = \int \frac{M(x)}{EI} = \tfrac{1}{2} \tfrac{1}{EI} F x^2$$

$$y = \iint \frac{M(x)}{EI} = \tfrac{1}{6} \tfrac{1}{EI} F x^3$$

$$y_{max} = \delta = \tfrac{1}{6} \tfrac{1}{EI} F (l_2)^3$$

For Kevlar

$E = 28 \times 10^5$ psi

$I = I_{BB}$ as previously calculated

$l_2 = 10.75$ in.

$y_{max} = 0.0019$ in

II. Bending in Lower Arm

14.5 in.
Lower Arm
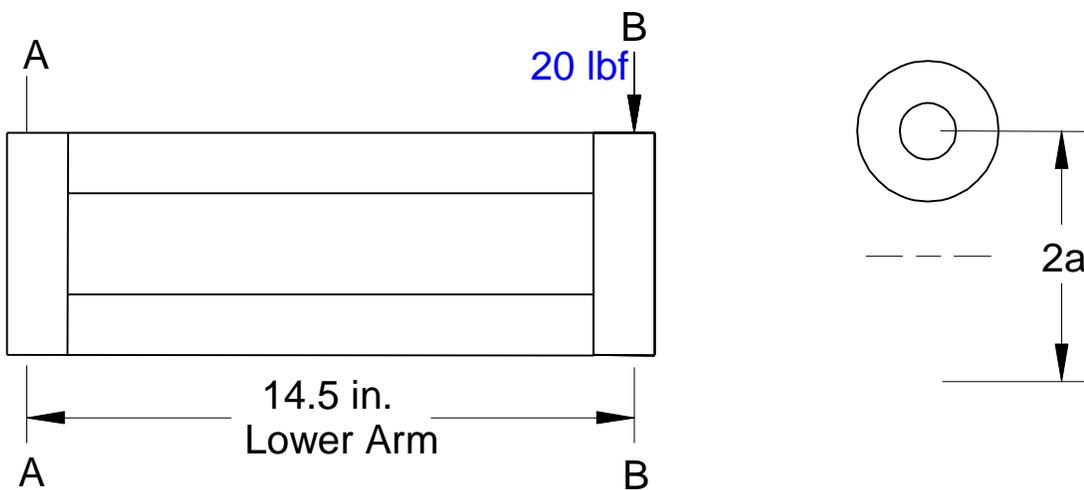
Assume a 20 lbf force applied to the end of the upper arm as shown

$y = $ deflection

$y' = $ slope

$y'' = \dfrac{M(x)}{EI}$

Finding the shear, moment, slope, and deflection diagrams:
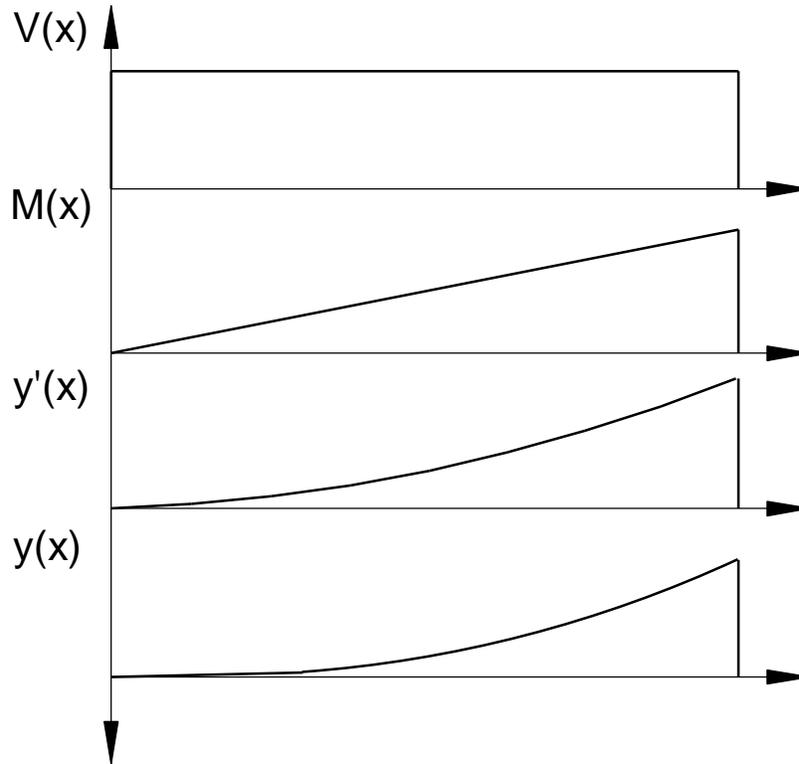
$M(x) = F \cdot x = 20 \text{ lbf x}$

$y' = \displaystyle\int \frac{M(x)}{EI} = \frac{1}{2}\frac{1}{EI} Fx^2$

$y = \displaystyle\iint \frac{M(x)}{EI} = \frac{1}{6}\frac{1}{EI} Fx^3$

$y_{max} = \delta = \frac{1}{6}\frac{1}{EI} F(l_2)^3$

For Kevlar

$E = 28 \times 10^5$ psi

$I = I_{AA}$ as previously calculated

$l_1 = 14.5$ in

$y_{max} = 0.0013$ in

TORQUE ANALYSIS
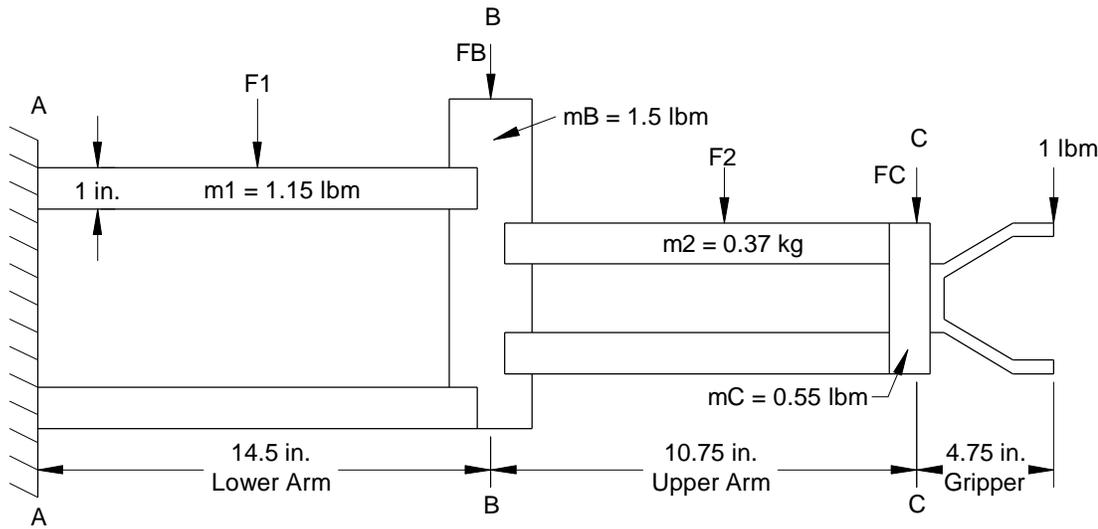
Assumptions:
1) Assume masses and dimensions as shown in the drawing.
2) Masses are lumped as shown
3) Density is the same as aluminum, $\rho = 0.1012$ lbm/in^3

I. Calculate torque required in the shoulder

Assume torque required is that needed to overcome gravity effects only

Torque $\qquad T = 2m_1 g\left(\frac{l_1}{2}\right) + m_B g\left(l_1\right) + 2m_2 g\left(l_1 + \frac{l_2}{2}\right) + m_C g\left(l_1 + l_2 + \frac{l_3}{2}\right) + mg\left(l_1 + l_2 + l_3\right)$

$\qquad\qquad T = 117.6$ lbf-in $= 1881.6$ oz-in

If we allow for a safety factor, $\eta_s = 2$

T = 1881.6 oz-in (η_s)

$\quad = 1881.6(2) = 3763.2$ oz-in

However assuming a 180:1 gear ratio,

$T = \dfrac{3763.2 \text{ oz - in}}{180} = 20.9$ oz-in

78

II. Calculate torque required at the elbow
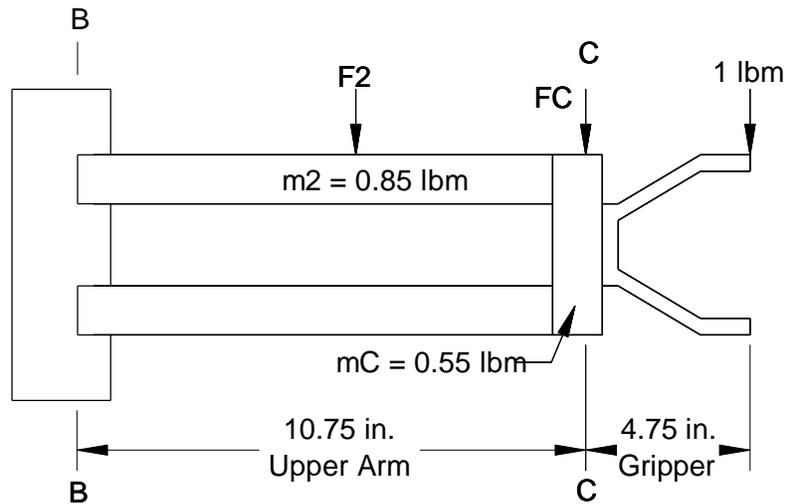
Assume torque required is that needed to overcome gravity.

Torque
$$T = 2m_2 g\left(\tfrac{l_2}{2}\right) + m_C g\left(l_2 + \tfrac{l_3}{2}\right) + mg\left(l_2 + l_3\right)$$

$$T = 31.86 \text{ lbf-in} = 509.7 \text{ oz-in}$$

If we allow for a safety factor, $\eta_s = 2$

$T = 509.7$ oz-in (η_s)

$\quad = 509.7\,(2) = 1018.4$ oz-in

III. Calculate torque required at the wrist

Torque
$$T = m_C g\left(\tfrac{l_3}{2}\right) + mg\left(l_3\right)$$

$$T = 6.06 \text{ lbf-in} = 96.9 \text{ oz-in}$$

Since there are two motors each motor can take half the torque.

$$T = \frac{96.9 \text{ oz - in}}{2} = 48.5 \text{ oz-in}$$

If we allow for a safety factor, $\eta_s = 2$

$T = 48.5$ oz-in η_s

$\qquad = 48.5\ (2) = 96.9$ oz-in

Assuming a 5:1 gear radius ratio:

$$T = \frac{96.9\ \text{oz-in}}{5} = 19.38\ \text{oz-in}$$

III. Calculate torque needed at gripper

Assumptions:
    1) Static coefficient of friction between rubber and aluminum $\mu = 0.3$
    2) Gripper is 3 in long
    3) Gear reduction of 8:1

Find the force needed to lift a 1 lb object:
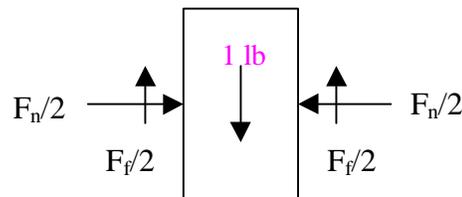
Normal force $F_N = F_F / \mu = 1$ lbf $/0.3 = 3.33$ lbf

Torque $\qquad T = F_F\ l_g = 3.33$ lbf * 3 in = 10 lbf-in = 160 oz-in

If we allow for a safety factor, $\eta_s = 2$

$T = 160$ oz-in η_s

$\qquad = 160\ (2) = 320$ oz-in

Assuming a 8:1 gear radius ratio:

$$T = \frac{320\ \text{oz-in}}{8} = 40.0\ \text{oz-in}$$

CALCULATE TORQUE NEEDED FOR LEAD SCREW

Assumptions:
1) Maximum torque needed is that to overcome static friction
2) Static coefficient of friction for steel $\mu = 0.15$
3) Assume lead screw mean diameter $d_p = 0.5$ in
4) Assume screw lead of 0.1 in (10 threads pre inch)

Find the torque needed to lift a 40 lb object from rest:
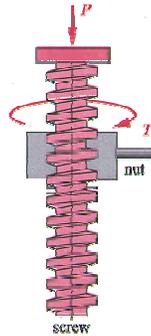
Torque $\quad T = \dfrac{Pd_p}{2}\dfrac{(\mu\pi d_p + L)}{(\pi d_p - \mu L)} = \dfrac{40lbf \bullet 0.5in}{2}\dfrac{(0.15\pi 0.5in + 0.1in)}{(\pi 0.5in - 0.15 \bullet 0.1in)} = 34.51$ oz-in

Where:
T = Torque to lift mass
P = Load
d_p = Mean diameter of lead screw
L = Lead
μ = Static coefficient of friction

If we allow for a safety factor, $\eta_s = 2$

$T = 34.51$ oz-in η_s

$\quad = 34.51$ oz-in (2) = 69.0 oz-in

Table 5: Material Properties

Material	Fiber Content, %	Density, g/cm^3 (lb/in^3)	Tensile Strength, ksi (MPa)	Compressive Strength, ksi (MPa)	Tensile Modulus, 10^5 psi (GPa)	Flexural Modulus, 10^5 psi	
Delrin (Acetal)	N/Ap.	1.42 (0.052)	8-10	5	4-5	4	
- Glass-fiber reinforced	20-40%	1.55-1.69	9-18	11-17	8-15	8-13	
Lexan (Polycarbonate)	N/Ap.	1.20 (0.043)	9-11	12	3.5	3	
- Glass-fiber reinforced	20-40%	1.24-1.52	12-25	14-24	7.5-17	7.5-15	
Kevlar (Aramid)							Kevla
- Kevlar 49 – Epoxy	60%	1.34	34.1 (235)	203.2(1400)	110	30	Unidi
- Kevlar 29 – Epoxy	53%	1.33	16	19	N/Av.	28	Unidi
Graphite – Epoxy Resin							
- T300/5208	70%	1.58 (0.057)	217.7 (1500)	217.7(1500)	262.7 (181)	14.9	Unidi
- High modulus	45%	1.55 (0.056)	122 (840)	128 (883)	275 (190)	10 (6.9)	Unidi
Gray Cast Iron		7.19 (0.26)	15-30	25	120	N/Av.	
Low Carbon Steel	N/Ap.	7.8 (0.28)	29-33	28	300	300	
Stainless Steel		7.92 (0.29)	30-35	30	280	280	
Aluminum, Wrought		2.6-2.8 (0.10)	6-27	N/Av.	100	100	
Aluminum, Die Cast		2.6-3.0 (0.09)	8-26	9	100	100	
Magnesium, Die Cast		1.81 (0.07)	8-30	10-14	65	65	

- Sources: 1. ASM Engineered Materials Reference Book, ASM International. 1989

2. An Introduction to the Analysis of Laminated Composite Materials, G. H. Staab, The Ohio State University. 1

THE PENN ROBOTIC ARM

BASIC ELECTRONIC DESIGN

The first step in producing an electronic control system is to analyze the goals desired. For our case we are looking for transmission of information from a user to a set of independently controlled motors. In this process we will need to translate the user input into data through a transducer. At this point the data must be manipulated so that it represents the form necessary to move the motors in the desired way as according to the user. A number of alternatives for this objective are available and we will start analyzing them with the breakdown of possible electronic components needed. There will also be a need from electronic equipment such as power supplies, wiring and other miscellaneous items, which are not in the focus of this report.

COMPONENT ALTERNATIVES

In this section we will break down necessary equipment into various alternatives, what their purpose is and briefly discuss how each is used.

INPUT DEVICE—This device, or transducer, acts to take in data from a user and transmit it to a processor. The most common form of transducers on the market today for electronics include mice, keyboards, joysticks and game controllers. Other technologies are becoming available constantly and provide strong alternatives such as voice activation or infrared remote controllers. Last year the Gateway team picked a standard off-the-shelf joystick because of users high familiarity rate with the transducer type and because of its ability to control up to three axes with the proper type. Joysticks are prevalently analog transducers and this held true with last years'. This led to its only flaw in that it was inaccurate at high precision levels. Other than that the joystick proved to be easy to use, program and to operate with the system. It is usually connected to either a communications port or a game port on a computer. For this year, transducers suggested include a joystick by Microsoft that is digital and contains all axes in easy forms of buttons and slides. This will keeps the simplicity of the previous years design along with the same success and at the same time eliminates the precision problem. Voice recognition is simply not a viable option for easy operator control. Keyboard use is very simple and would yield 100% accuracy all of the time but would be bulky. Mice and related trackballs just don't have the flexibility to control the three axes needed. Remote infrared control is another viable option. As interesting as is seems, remote functionality is not needed as the entire system is within inches of the controller at all times.

CODE—This is the part of the electronics system that acts as the glue to hold everything together and make it all function properly. Without getting into the high level coding, the electronics code deals with the actual high and low bit data travel between components. Unlike the controller, there are a number of different possible approaches to the use and construction of code. One of the main questions you must ask is how much work do you want done and where. If you are using a central computer to do most of the processing,

most of your code is going to run on the computer. In this case a generally accepted language is C. There are many alternatives to this language, all with their benefits, but for our standpoint, C code is the most widespread and easy to use. It will allow easy manipulation by all experienced designers and will allow for future enhancements by non-team members. Another option would be to lessen or eliminate the use of a computer and transfer responsibilities of processing power to other sources and eliminate all coding. This option will be discussed in more detail below. An important question when programming your devices: How much of your work needs to be done in real-time? The use of interrupts for PCs is common in real-time coding. This is the process where the computers tasks are interrupted at certain periodic intervals to do a predetermined job, in this case, determining user input relative to motor position or speed or both, calculating corrections and sending them. This option is relatively hard to work with for a programmer because it creates computer malfunctions when erroneous code doesn't work properly. The alternative is not to use interrupts. This method does not provide the most prompt responses and is less accurate, however it is much easier to work with and allows the use of operating systems such as Windows and other high level OSs. This is the technique we suggest since the time lag is of minor consequence since it is usually only a small fraction of a second. We suggest doing some of the work by small microprocessor boards, which do run in real-time. We can then write less code and not worry about real-time issues.

```
                                              Parallel I/O            Port B and C
                                              8255 chip - 24 bits
                                                                  Gnd  – Gnd
                      LM629                                        HI   – CO
                                    control lines                 CS   – B0
                                          6                       RD   – B1   – C4 (STRB -- 8255)
 position/velocity   data            data lines      Port A       WR   – B2
 profile generator   transfer                        A0-A7        PS   – B3
                                          8                       B4   – C6 (ACK -- 8255)
                                                                  RST  – B5
        +
        Σ           digital        sign        direction
        –           PID filter     magnitude
                                                PWM
 quadrature
 decoder                                      LMD18201
                                              H - Bridge
                                                               Host Computer
             INdex, Chan A, Chan B                             (Usually PC)
                                              DC Motor
                                         quadrature
                                         incremental encoder
```

BOARDS—These are the circuit boards that carry out all of the functions not performed by the transducer and the central computer, if one is used. There are many different configurations and arrangements of boards that could be used to accomplish the tasks at hand, including putting all of the functions as hardwired logic gates on a single printed circuit board. The most generally accepted practice is to use a computer for processing power, at least to start the design phase. If this is the case, then a data acquisition board or data I/O board will be required to interface the computer and transducer(s) to the motor controllers and motors. There are a number of possible digital I/O boards available as well as analog. Since we are using a computer that works digitally and a motor that works with digital control, it makes sense to use a digital controller. Whether a PCI or

ISA or an alternative bus method is used is really irrelevant. The motors also need to be controlled in a certain way (we suggested using small microcontrollers). This could be one through code and the use of the computer, however, this requires extensive programming and reduces system efficiency. There have been alternatives created on the market for this problem. Motion control chips are small simple purpose processors that do a few tasks cheaply and efficiently. The CPU in the computer would be wasted if it had to do all of the trajectory and calculations required for the motors itself. Therefor the use of a motion controller chip represents a way to reduce the load required by the computer and increase response time as well as efficiency. However, we could not find any all-in-one boards that work as data acquisition as well as motion controller and amplifiers. So the process needs to be elongated through the introduction of a motion control board. These are readily available on the market but lack the definition needed for a project as specific as ours without large costs. The advantage is that all final calculations and amplification as well as feedback is processed outside the computer, out of the scope of code, providing efficiency and easy of operation and design as well as reduced costs of design. The solution we suggest is to create an in-house board with a motion controller chip, amplifier and a digital clock for time stamping and other basic functions. If this is to be the case, breakout boards might be needed to differentiate between wires and their functionality, at least in the prototyping stage. These are relatively standard and any will do. Of the chips on the market used for motion control, the most cost effective and efficient found was made by National Semiconductor, called the LM629. Information on these and other National Semiconductor chips can be viewed at http://www.national.com/pf/LM/LM629.html. Other manufactures of microcontroller and driver chips can be viewed at http://www.newmicros.com/txs7056.html.

MOTORS—These are the instruments for the movement of the arm links. The motors basic requirements are to be able to move at a specified speed with a specified torque, to report position and speed data through the use of an encoder, to be cost effective and be able to integrate into a system with our configuration. Last years motors were chosen from Pittman for two main reasons. First, they fit the space and torque requirements with the use of gearboxes and gear trains. Second, they were very cost effective compared to competition. These models also come with encoders for quadrature use. This means that there are two signals sent relaying the position of the motor relative to the encoder at 90° phase shift, giving four times the accuracy. We used a model last year with a 500-line encoder and quadrature, producing 2000 counts for every revolution. Another advantage of Pittman motors is that their encoders are bi-directional, meaning that they work both in forward and reverse. So with the 2000 counts, ample torque production and bi-directional functionality, these motors still represent the best alternative. This year we are recommending the same motor and encoder combination from Pittman, only with a little less mass and torque output due to the reduced size requirements of the arm.

COMPUTERS—Control of the processes and processing power is usually concentrated within the computer through use of controller code and a central processing unit. Computers can vary greatly but the most common platform is that of the PC. Ranging from 8088 based Intel computers to power PCs to Alpha, Sun and other workstations and on up. For our purposes the minimum cost is the highest priority assuming they all can

accomplish the same tasks effectively. Last year we used an old Intel based 286 computer. This year our designs have been based on the same platform since it accomplished all of the necessary tasks last year and proved to be very cost effective. The only concern with using this as a processing and controlling unit is that it cannot be readily fit onto a wheelchair with all of the additional equipment needed. The conclusion is that a smaller processing and control unit must be used. One option is the aforementioned printed circuit board in which all functions of the electronics except the transducers and motors are kept on the same silicon board, roughly the dimensions of a small stack of paper. This would reduce the size of the entire arm drastically and increase efficiency of production comparatively. The problems arise in the design of such a board and the manufacturing. Design and debugging time and costs would reach astronomical levels for such a project and all manufacturing would need to be outsourced. Another option would be to use a microcomputer-on-a-board system. In such a system all of the key functions of a motherboard are shrunk to roughly 5"x 7" or smaller and there is room for addition of any Intel based processor or similar type as well as ram and an expansion board that would be used for the digital I/O. With programs being stored in flash ROM, there would be no need for a hard drive, floppy drive or other peripherals that take up much needed space. In fact, even the power supply can be substituted for the wheelchair's on-board power, as with the rest of the arm functionality. Examples of this type of product are covered extensively on the World Wide Web. Some example manufactures include Versa Logic and Advantech. Prices are around $900 for a Pentium class board with plenty of RAM and ROM.

POSSIBLE DESIGNS & CONFIGURATIONS

With the components mentioned above, it is very easy to visualize many different design alternatives, ranging from the all-on-a-board idea with one circuit board, transducer and a set of motors with no coding used, to a highly decentralized process where there isn't even a central computer. Some of the most feasible and cost effective options are the following:

1. Printed Circuit Boards
Pros:
- Very centralized
- Compact
- Low power requirements
- Easy to manufacture and assemble in large quantities

Cons:
- Very high design costs and complexity
- Difficult to diagnose problems
- Debugging complexity

2. Central Computer

<u>Pros</u>:
- Easy to design effective systems
- Common platform, interoperability
- Plenty of processor power with easy interface

<u>Cons</u>:
- Can be expensive
- Too bulky, must be minimized after testing
- High power consumption

3. Mini-Computer

<u>Pros</u>:
- Small and easily reproduced
- All functionality required of a desktop
- Relatively easy to program
- Low power consumption

<u>Cons</u>:
- Fairly expensive

Cost, Performance & Realism

The cost of the items above range widely. A digital I/O board or data acquisition board can have A/D or D/A or both onboard plus mounds of other functions built in. Price range from a few tens of dollars to ten thousand and even some higher than that for special purposes.

Example Configuration

In this section we will discuss one example configuration that we have completed extensive designs for and have been working on the synthesis of a prototype. We will explain in detail all of the components of its electrical system here, what they do and how they do it.

In our system, the flow of data is basically a circular pattern with the exception of the transducer, which never receives data, but always transmits. The rest of the cycle can continue on from the computer, which receives data from both the transducer (joystick) and the encoder. From the computer data travels to the digital I/O board to the breakout boards and on to the motor control boards mentioned above that we constructed in house. Next the signal is sent through an amplifier to beef up current and then sent on the to motors. The motors position is determined using the encoder which in turn transmits it back to the motion controller chip and from there back to the digital I/O in the computer where the computer reprocesses the new position data and calculates relative velocity data from that.

The different components include:
ENCODER—an encoder works by attaching a disk with notches on its perimeter where light can pass. A light emitting diode (LED) is able to show through the encoder at

certain positions only. On the opposite side of the disk from the LED is a photoreceptor or a phototransistor. This relays position data to the system. By having two LED's you can effectively quadruple the position data. Through position over time analysis you can determine effective velocity.

DECODER AND COUNTER—The analog signal from the encoder is sent back to the motor control boards where it is time stamped by a counter measured by an on-board clock. The number is converted to digital using binary from 2^0 to 2^{31}. This is done using high as a 1 and low as a 0, standard for digital logic. A 1 usually is represented with a dc 5V impulse and 0 by 0V. The 1's and 0's are assigned a bit from 0 to 7 to generate the digital number used by the computer. Usually 8 bits of data are sent at once but larger numbers can be used. Reading each channel separately allows the data to be received eight bits at a time and a 32-bit number is created by adding.

DIGTIAL I/O BOARD—Once the number is produced by assigning ones to the appropriate slots from 0 to 7, the information is set to a digital I/O board. The I/O board consists of an average of 96 bits. Each eight bits consists of a port, which is assigned a location in the computer's memory. The eleven outputs (eight bit locations and three selection slots) of the motor controller are connected to slots on the board. After a number is requested in the software it is then transmitted back to the I/O board where the information is received by the amplifier. Digital I/O is a method of sending and receiving data. Each bit can be set high or low to perform a task. Eight bits together can be read to receive a number. In comparison, A/D or D/A boards receive or send variable levels of voltage instead of dc 5V and 0V. The voltage signal is converted to a number by the A/D board by assessing the best estimate of position with respect to time and converting this data to binary for digital use. This method is slower than digital I/O and can cost thousands of dollars for good equipment. We chose a 192 bit digital I/O.

AMPLIFIER—This simply amplifies the signal to be sent to the motors so that it has enough power to drive the motors. Since the motor control board was the last stop for the signal before reaching the motors, there is a power supply connection on the motor control boards for the actual motors. This runs through an amplifier modulated by the weak signal of the controller chip. This weak signal is duplicated by the power supply signal only in a highly amplified state through the use of pnp or npn junctions. The motor is then driven by this signal.

MOTION CONTROL—There are several methods of motion control available as discussed above. Motion control involves gathering data on position and calculating velocity data from this data and together with user input data is translated into a new desired behavior for the motors by the processing unit involved, whether it is a CPU on a computer or a motion controller chip. We chose to use a motion controller chip because it allows easy time stamping and efficient calculations without using up large portions of system resources of the computer. Another reason for this method is the availability of quasi-real time data flow and computation. By having a clock on the motor control boards with the motion controller chip, we can time stamp data and all computations done by the motion controller chip. At the same time we don't need to use interrupts on

the computer which can cause extreme instability during the design phase. Real time control also requires a large amount of coding. The large code needed to execute makes the process slower. Imagine if you had to execute the code in your C program 1000 times a second. That would slaughter resources and produce drastic lags and inefficiency.

Cost Structure

Number	Component	Cost	Quantity	Total
1	192-bit I/O	$200	1	$200
2	Cabling	$15	5	$75
3	Breakout Board	$50	3	$150
4	Power Supply	$100	1	$100
5	LM629 & Board	$175	4	$800
6	Clock	$4	4	$16
Total				$1,341

VI. SPECIFICATIONS FOR PROTOTYPE DESIGN

DESIGN CONFERENCE AT COOPER UNION

Following the design presentations of each university at the January 1998 meeting, the five teams sat down to discuss the key features of each team's kinematic design configuration. After an open forum critique of each university's design, the final plans and specifications were determined for the prototype manipulator. Also, it was decided that each school's team would assume a particular responsibility to assist in the fabrication and the finalized design configuration.

DESIGN CONFIGURATION OF PROTOTYPE

The final design configuration of the prototype was based on several key elements presented by each university at the design conference. The manipulator was to operate using five and one half degrees of freedom (including the open/close actuation of the gripper). The robotic arm will simulate the action of a human arm. It will consist of three joints: a shoulder joint, an elbow joint, and a wrist joint. In addition, two arm links (upper and lower) will be attached. The five and a half degrees of freedom represent the pitch of the shoulder, the pitch of the elbow, and the pitch and roll of the wrist joint. The motors will be mounted inside the base of the manipulator to decrease the weight of the arm itself. The prototype will be made out of a durable yet lightweight material for this first application.

PHASE II

After noting the best features of each presentation, the students assigned each university a specific task for the second phase of the project – the manufacture of a prototype manipulator. Cooper Union generated the program code to control the manipulator and designed the user interface. Drexel University designed the skeleton of the prototype manipulator, including the base of the arm. University of Pennsylvania headed the design of the transmission system for the manipulator that will provide motion to the arm. This task included choosing the proper belts and sprockets to satisfy motion requirements. Finally, The Ohio State University performed the graphical simulation and Finite Element Analysis. The graphical simulation was accomplished using Interactive Pre-Assembly, while IDEAS was employed for the Finite Element Analysis. Additionally, Ohio State served as the project managers. It was their responsibility to oversee and assist with any calculations or part specification, and organize the manufacturing of the final prototype. All universities worked closely and communicated frequently to accomplish these design tasks and goals.

A. ARM

Before the skeleton for this year's arm could be designed, it was crucial to investigate the previous prototype. A Finite Element Analysis was performed by The Ohio State University on the 1996-97 Gateway robotic arm. Looking below is a figure of the meshed arm. There is a shaft constraint on one side and a four-pound force exerted on the other that represents the weight of the gripper and object to be lifted.
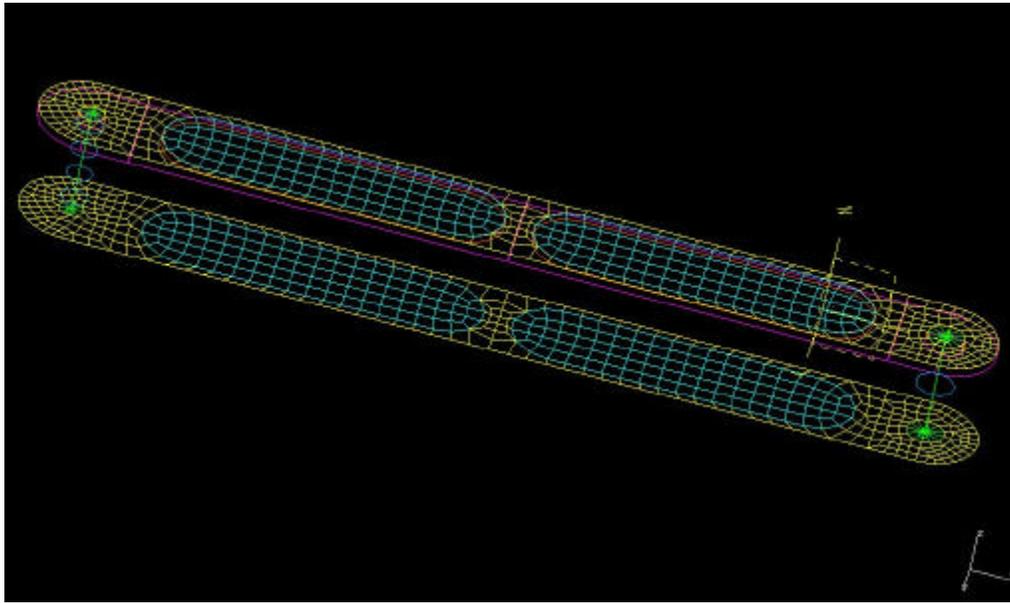
Figure 50: Meshed Skeleton

Figure 51 below depicts the results of the FEA analysis. Stresses that have been produced result in a factor of safety of 30. The stresses also indicate that there is no danger of failure around the milled out sections. This information along with a minute deflection of the beam indicates that the arm is too thick and should be reduced. This will reduce the weight and cost of the part.
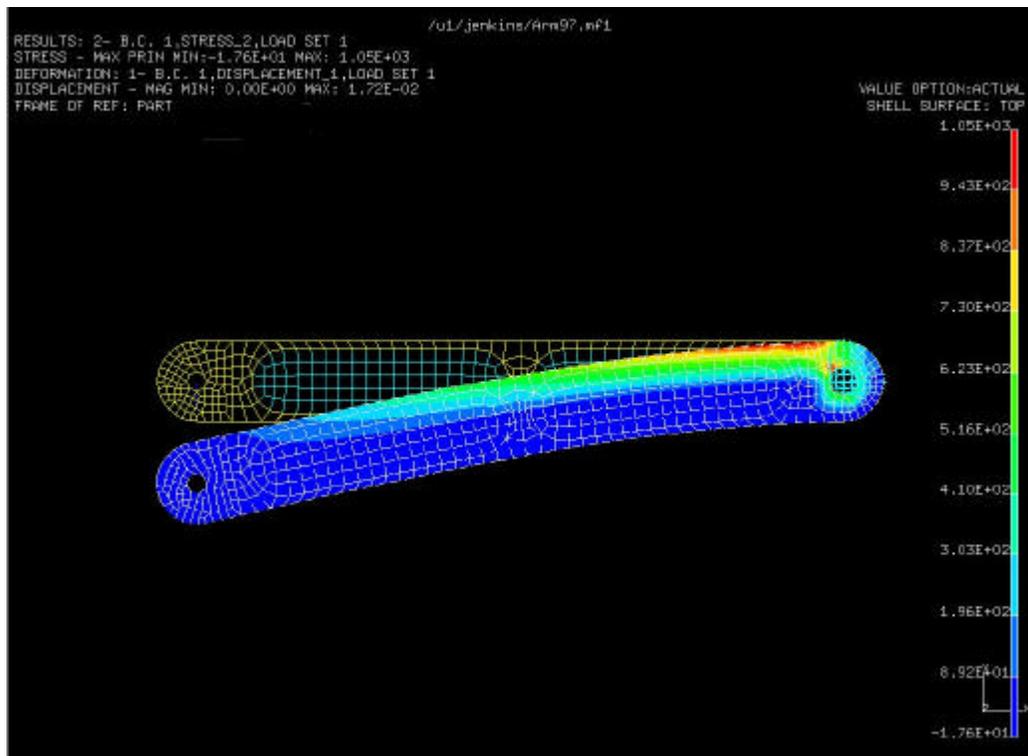
Figure 51: Stress and Deflection Analysis

SHOULDER ASSEMBLY

The arm's most critical point was the shoulder assembly. This was where the arm or "links' connect to the supporting base. Also bending stress on the arm an extreme at this conjunction both in dynamic and static loading.

The first task in making the shoulder assembly was to consider how to maintain a center location of the links in respect to the base. Teflon spacers and snap rings were used in coordination with a 3/8 " diameter pin. This pin was then mounted to the side plates of the base assembly. This configuration insured no slipping, precise location of the links, and allowed rotation for the arm to move up and down.

Next was a problem of transient motion of the arm with respect to the shoulder mount. To relieve this problem a 5" cast iron gear was mounted to the left side of the base plate and directly attached to a motor. This allowed the rotation required, with a little help from the control systems.

One last item to consider was how the shoulder joint would allow the elbow joint to move. A simple setup was finally decided upon. One 5" gear was fixed to a timing belt pulley using #10 screws and press fitting an Oilite bushing to align the two pieces. A

timing belt was then attached from this pulley directly to the elbow joint. **Figure 52** below is a picture of the finalized shoulder mount.
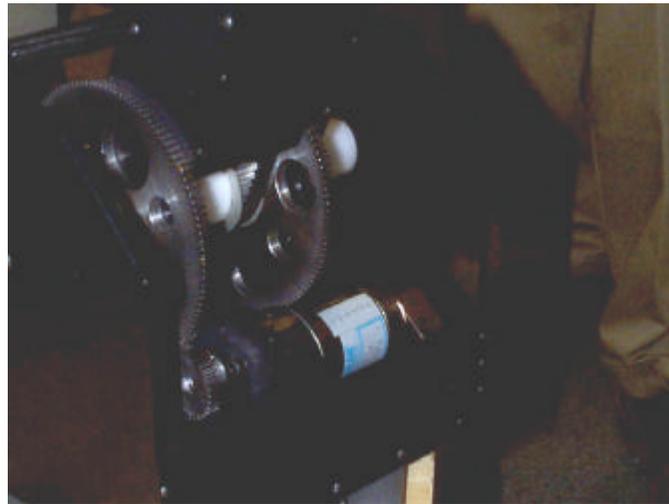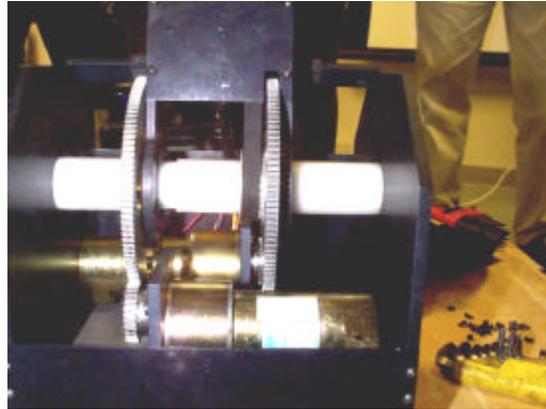
Figure 52: Shoulder Assembly

ELBOW ASSEMBLY

The elbow assembly was consistent of a very simple concept, to bend the two separate links of the arm. To ascertain this feat two pulleys were mounted together using Locktite #420 super adhesive as well as press fitting two 1/8" dowel pins through the two pulleys. Left and right side Teflon spacers were also used to allow proper positioning of the pulley assembly. A third pulley was mounted to the left side plate of the forearm section by using a delrin riser and #6 screws. This pulley was also drilled and tapped. Assembling the pulley to the side of the plate allows transmission from upper to lower arm movement. The figures below depict the described information above.
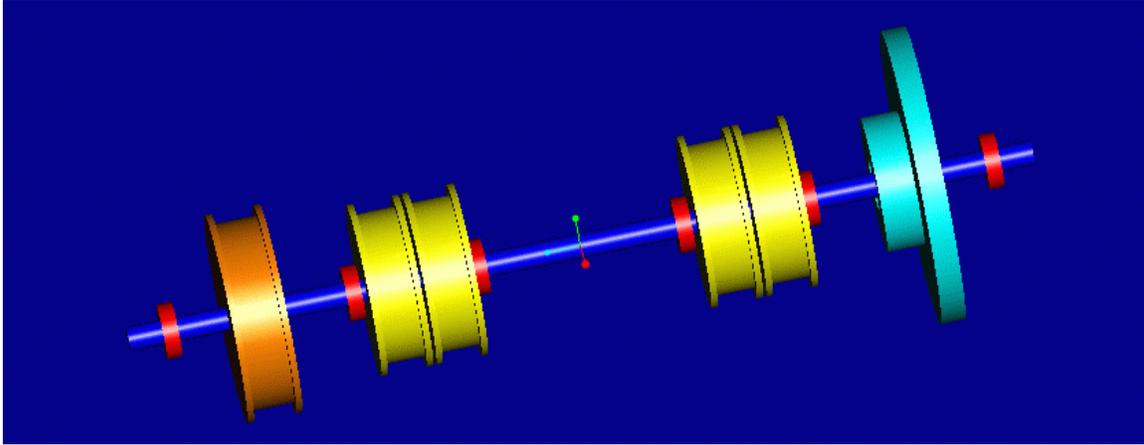
Figure 53: Pro Engineering Elbow Pulley Representation
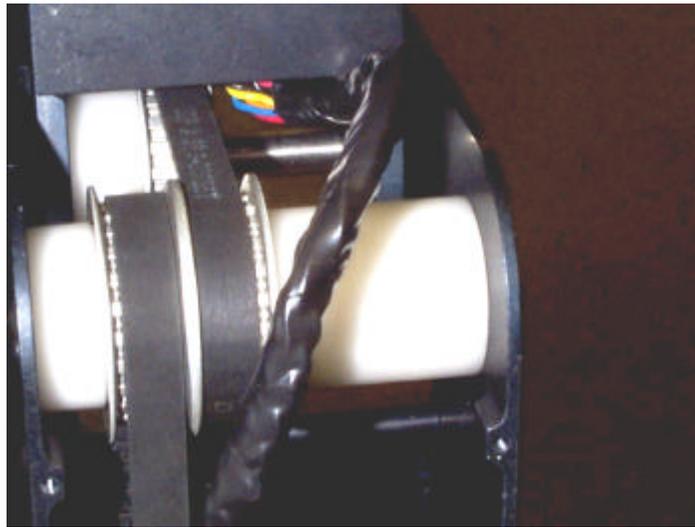
Figure 54: Actual Elbow Pulley System

BASE ASSEMBLY

The base plate was the key part in holding the shoulder assembly to the wheelchair while permitting full rotation of the arm. Time and money considerations did not allow mounting to an actual wheelchair so a wooden box was fabricated to model the wheelchair mounting.

A base plate was fabricated with an 80mm O.D. bearing pressed into the center. A shaft was placed in this bearing for the shoulder to ride on while rotating. This allowed smooth, low friction movement and thus a lower torque rated motor to be used to drive the rotation.   Now, to assure that the bearing would hold in place a retaining ring was used.

The gears used to obtain the rotation were two-fold. First, a 6" diameter gear was bored to fit over the 80mm O.D. bearing and mount to base plate. Second, a 1" diameter gear was drilled, tapped and faced for mounting to the base rotation motor. Last of all, the correct motors were mounted to the base to drive the system

Figure 55: Base Plate

B. POWER TRANSMISSION SYSTEM

TORQUE CALCULATIONS

Torque is needed to provide all movement of the arm. All of the robot's tasks would have to be considered in order to perform torque calculations. The torque calculations performed were done assuming the arm was in its worse case scenario situation. It was done assuming the arm was held straight out as seen in **Figure 56**. In this position it would need the greatest amount of torque to keep it up. Torque calculations were done for each movement including the shoulder extension, elbow extension, the roll and pitch of the wrist, and the base sweep. Using **Figure 56** and the formula for the moment taken about a point, $M_o = Fd$, where M_o is the moment taken about a point, F is the force, and d is the distance the force is from that point, we can derive equations for the moments at each joint.
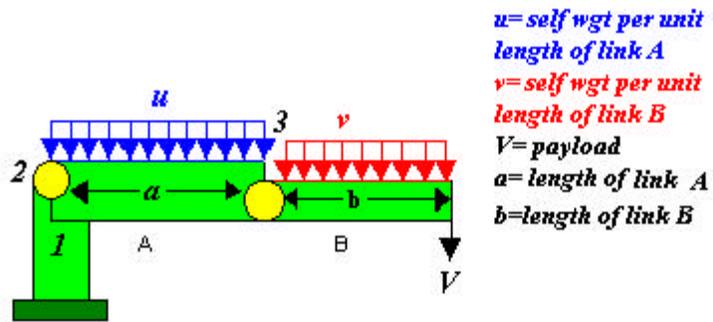
Figure 56: Force Diagram on Modeled Arm

After the integration of the weight distributed along each link, "u" and "v", the self weight per unit length of links A and B, respectively, can be replaced with one concentrated weight, W, at each link's center of mass. The base can also be replaced with a force, R=(2W+V), as shown in the **Figure 57** below.
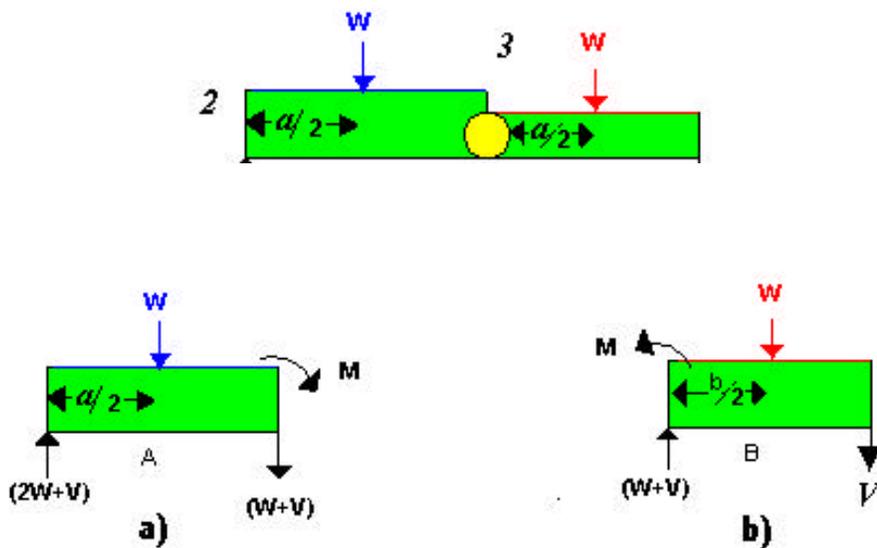
Figure 57: Force Breakdown on Modeled Arm

To derive the equation for each joint's moment each link was looked at separately. The elbow joint's moment was found by replacing the first link with a reaction force as shown in figure 2b. Then, using each force and its distance from the elbow joint, we calculated the moment.

Joint	Torque Required	Max Torque Available
Shoulder	2124.8 oz-in	2500 oz-in
Elbow	752 oz-in	2500 oz-in
Wrist	80 oz-in	160 oz-in

These calculations take into account the weights of the arm, the gripper, the payload, and the transmission. Estimating that the lengths and weight of each link. Link A would be 15.6 inches. Link B would be 12 inches. Both links were estimated to weigh about two pounds. The length of the gripper was estimated to be four inches. The payload and weight were estimated to weigh 2.5 pounds together.

MOTOR SELECTION

These are the instruments for the movement of the arm links. The motors basic requirements are to be able to move at a specified speed with a specified torque, to report position and speed data through the use of an encoder, to be cost effective and be able to integrate into a system with our configuration. Selecting two types of motors for our arm. Each had several advantages that were useful. Pittman motors for the base sweep, shoulder swivel, and elbow extension. MicroMo motors were used for the pitch and roll of the wrist as well as the opening and closing of the gripper. The choice was made for Pittman motors, for two main reasons. First, they fit the space and torque requirements with the use of gearboxes and gear trains. Second, they were very cost effective compared to competition. These models also come with encoders for quadrature use. This means that there are two signals sent relaying the position of the motor relative to the encoder at 90°-phase shift, giving four times the accuracy. Using a model of last year's arm with a 500-line encoder and quadrature, producing 2000 counts for every revolution. Another advantage of Pittman motors is that their encoders are bi-directional, meaning that they work both in forward and reverse. So with the 2000 counts, ample torque production and bi-directional functionality, these motors still represent the best alternative. The MicroMo motors were small and lightweight. This allowed us to use them in different spots of the arm without adding to the required torque that would be needed with the extra weight of another heavier motor.

PULLEYS AND TIMING BELTS

Selection of timing belts and timing belt pulleys were very important in the design of the arm. Timing belts are used for transferring motion or power from one wheel or shaft to another. Timing belt pulleys are simple machines used to change the direction and point of application of a pulling force. Pulleys were used in our design to transfer the torque from several motor output shafts to various sections of the arm. Pulleys were used for the elbow extension. We used the method of motion transfer power transmission known as a belt drive system. In transmissions, you find an assembly of gears and associated parts by which power is carried from an engine or motor to a load as in an automobile, a machine tool or in our case, an arm-type manipulator. Our belt drive system takes the

torque given through the motor and the gear ratios and transfers that torque to the needed joints through the use of belts and pulleys.   The figure below depicts part of the pulley system used.
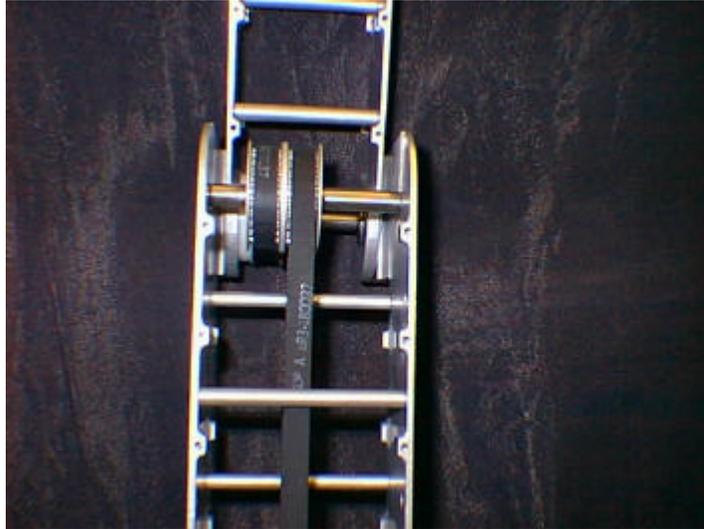
Figure 58: Elbow Pulley System

Calculations were also done to find out what belts and pulleys would be used. Calculations required finding the breaking strength of each belt that would be needed to withstand the stress it would obtain from the torque driving it around each pulley. As the value of the breaking strength of a belt increases its required thickness increases also. The equation used for this calculation was:

$$T_h - T_l = t / R$$

T_h is the high force about the pulley, T_l is the low force about the pulley, t is the torque at that joint and R is the radius of the pulley. T_l 's value should be approximately zero. After this calculation was done we compared different belt materials such as Kevlar and polyester and chose which material best suited our purposes depending on their different breaking strengths. **Figure 59** is an example of the calculation is below:

$$t = 1500 \ in\text{-}oz \qquad T_h - T_l = t\,/R$$
$$R = .5 \ in \qquad T = (1500 \ in\text{-}oz)\,/(.5 \ in)$$
$$T = 3000 \ oz = 187.5 \ lb$$

BREAKING STRENGTH:
Polyester - 1000 lbs per in.

The widths available are
1/4", 5/16",and 3/8".

For 1/4" belt:
    strength is equal to
$$\frac{1000 \ lbs}{1 \ in} \times \frac{1}{4} \ in = 250 \ lb$$
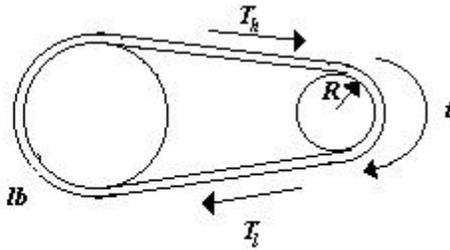
In this case, this belt is good enough.

Figure 59: Example Calculation for the Pulley System

Nylon covered, fiberglass reinforced, neoprene belt with a belt width of 3/8 in was chosen. This was much more strength than we needed giving us extra safety.

GEAR SELECTION

A gear is a toothed wheel or machine element that meshes with another toothed element to transmit motion. Gears are capable of changing speed or direction. And gears also aid in the transfer and creation of torque. Using different gear ratios, we used the torque given to us by our Pittman motors, 500 in-oz, and created the extra torque needed for the joints.

The one-inch gear attached to the shoulder motor's output shaft directly drives the five-inch shoulder gear. With this design we did not need to use a chain to transfer the torque from the shoulder motor to the shoulder joint. The one-inch gear attached to the elbow motor's output shaft directly drives a five-inch gear on the shoulder shaft. Next a pulley that is bolted to this five-inch gear transfers the torque up to another pulley on the elbow shaft through the use of a timing belt (as seen below).
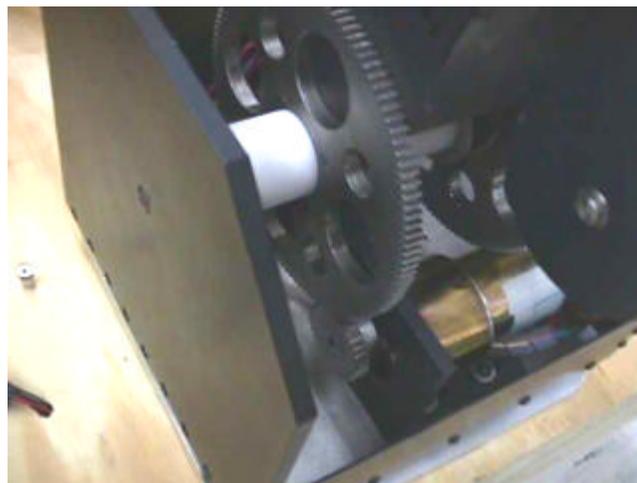
Figure 60: Shoulder Gear Setup

GRIPPER ASSEMBLY

The gripper assembly consists of the gripper, a spring, a bike cable and its housing, a pulley, and a MicroMo motor. The MicroMo motor powers the gripper. When the MicroMo motor is not powering the gripper it is in its open position. The MicroMo motor winds the bike cable around the pulley that is attached to its shaft and closes the gripper. See **Figure 61** and **Figure 62** below.
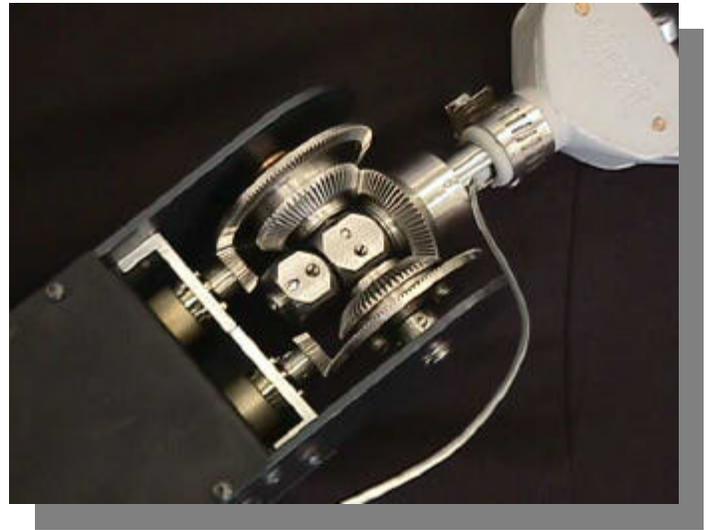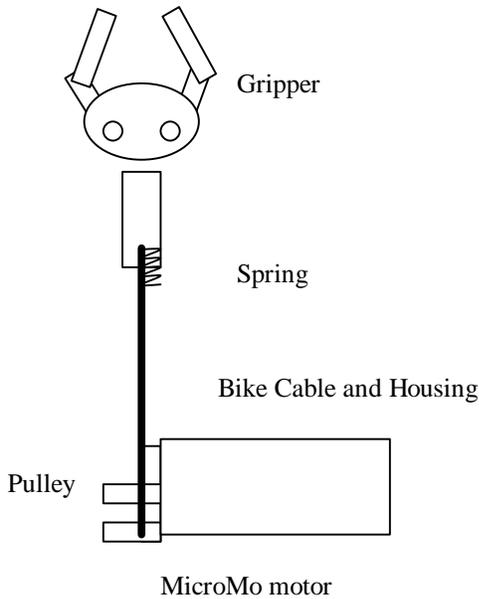
Figure 61: Diagram of Gripper System   **Figure 62:** Actual Gripper System

C. MANIPULATOR KINEMATICS

The kinematics analysis of a manipulator consists of the development of a mathematical model, which will describe the motion of the mechanism as it articulates. Considering that a manipulator may be thought as a chain of rigid bodies (links) connected in a chain by joints, then by affixing frames to each of the component links will help us to develop mathematical relations between the various links that constitute the mechanism. For illustration purposes let's consider **Figure 63,** which shows two links (link i and link i-1) of a mechanism, with a reference frame attached to each one of the joints.
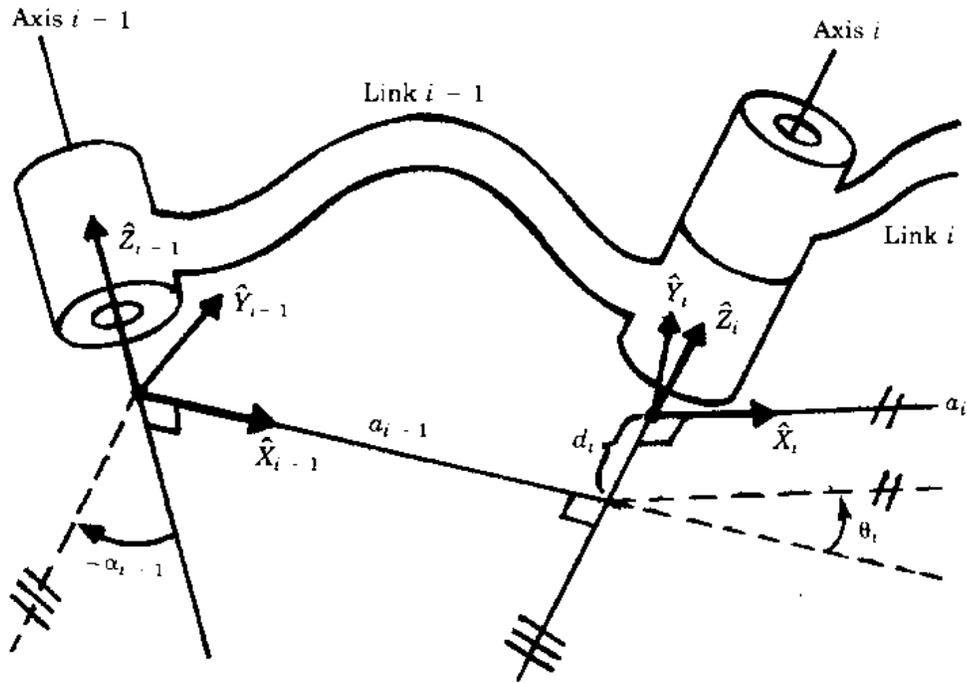
ai-1 = distance from Z_{i-1} to Z_i measured along X_{i-1}

αi-1 = angle between Z_{i-1} and Z_i measured about X_{i-1}

di = distance from X_{i-1} to X_i measured along Z_i

θ_i = angle between X_{i-1} and X_i measured about Z_i

Figure 64: Link Frames [1]

The four link parameters described above (ai-1, αi-1, di, θ_i) are used to write a transform, which defines frame {i} relative to frame {i-1}. Furthermore, by concatenating transforms that relate adjacent links, the position and orientation of link n relative to link 0 may be obtained. The transform relating link {i} to link {i-1} is written as:

$$
{}^{i-1}_{i}T = \begin{bmatrix} \cos q_i & -\sin q_i & 0 & a_{i-1} \\ \sin q_i \cos a_{i-1} & \cos q_i \cos a_{i-1} & -\sin a_{i-1} & -\sin a_{i-1}d_i \\ \sin q_i \sin a_{i-1} & \cos q_i \sin a_{i-1} & \cos a_{i-1} & \cos a_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}
$$

By writing the individual link transforms for The Gateway Coalition Robotic Arm and subsequently concatenating them, the position and orientation of the gripper (link 4) with respect to the base frame, denoted by frame{0}, was obtained. This transform, which is

denoted by ^0_4T is given in expression (10). In order to obtain ^0_4T the schematic diagram of The Gateway Coalition Robotic Arm shown in **Figure 65** was used.
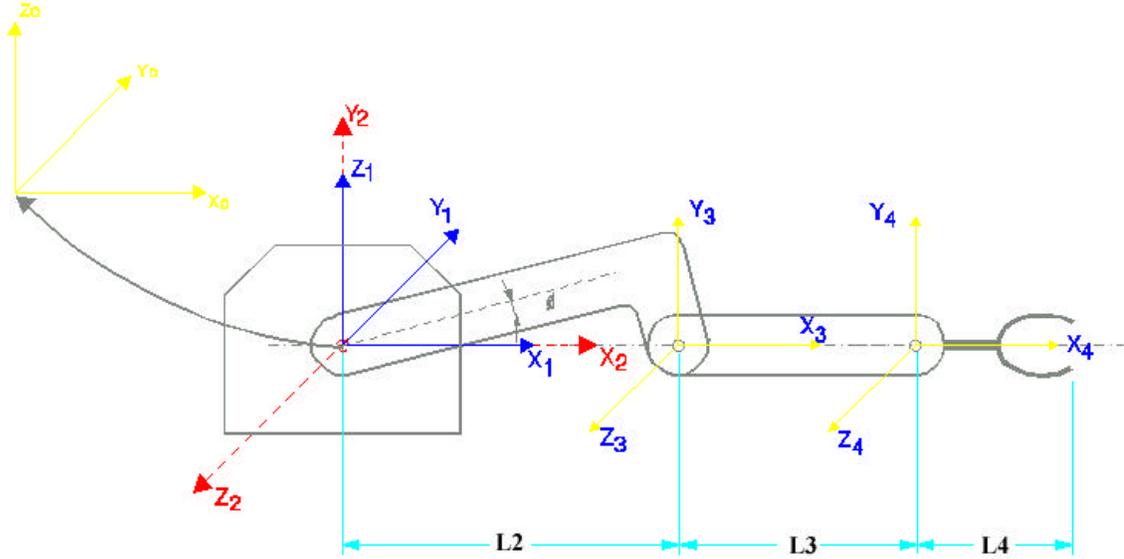
Figure 65: Schematic Diagram of the Gateway Coalition Robotic Arm

As per **Figure 65,** all frames are placed at the joints that connect the four component links together. Frame {0} is affixed to a nonmoving part of the base of the arm, frame {1} is affixed to the rotating portion of the base of the arm, frame {2} is attached to upper arm (link2), frame {3 } is affixed to the forearm and frame {4} is affixed to the gripper. Thus, using **Figure 65** a considering that:

$$L2 = d2/\cos\phi$$
$$C\theta i \text{ represents Cos } \theta i$$
$$S\theta i \text{ represents Sin } \theta i$$

the following link transforms were obtained.

$$^0_1T = \begin{bmatrix} Cq1 & -Sq1 & 0 & 0 \\ Sq1 & Cq1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$(5)$$

$$^1_2T = \begin{bmatrix} Cq2 & -Sq2 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ Sq2 & Cq2 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$(6)$$

$$
{}^2_3T = \begin{bmatrix} Cq3 & -Sq3 & 0 & L2 \\ Sq3 & Cq3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

(7)

$$
{}^2_3T = \begin{bmatrix} Cq4 & -Sq4 & 0 & L3 \\ Sq4 & Cq4 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

(8)

The result of concatenating these link transforms is shown in expression (10), where s1 represents $\text{Sin}(\theta_1)$, c34 represents $\text{Cos}(\theta_3 + \theta_4)$, etc....

$$
{}^0_4T = \begin{bmatrix} c2c3c34 - c1s2s34 & -c1c2s34 - c1s2c34 & s1 & (L2c2 + L3c23)c1 \\ s1c2c34 - s1s2s34 & -s1c2s34 - s1s2c34 & -c1 & (L2c2 + L3c23)s1 \\ s2c34 + c2s34 & -s2s34 + c2c34 & 0 & L2s2 + L3s23 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

(10)

The last column of the above matrix (10) gives the X, Y, Z coordinates of the joint connecting link 3 to the gripper. In order to obtain the X, Y, Z coordinates of the end effector (tip of the gripper), the transform given in (10) must be multiplied by a transform known as the tool transform ($^4_T T$).

$$
{}^4_T T = \begin{bmatrix} L4 \\ 0 \\ 0 \\ 1 \end{bmatrix}
$$

(11)

As a result the X,Y,Z coordinates of the end effector may written as:

x = [L2 cos(θ_2) + L3 cos (θ_2+θ_3) + L4 cos(θ_2+θ_3+θ_4)]cos(θ_1)

y = [L2 cos(θ_2) + L3 cos (θ_2+θ_3) + L4 cos(θ_2+θ_3+θ_4)]sin(θ_1)   (12)

z = L2 sin(θ_2) + L3 sin(θ_2+θ_3) + L4 sin(θ_2+θ_3+θ_4)

In addition, since a gear differential was used for the gripper, pitch and roll are decoupled and can be analyzed separately. Thus pitch and roll may be written as:

pitch = $\theta_2 + \theta_3 + \theta_4$

(13)

roll = θ_5

D. VELOCITY ANALYSIS

In robotics, the purpose of the velocity analysis is to relate Cartesian velocities of the end effector of the manipulator to joint angle velocities, and vice-versa. This is accomplished through the use of a matrix of partial derivatives, know as the Jacobian matrix. For example, the Cartesian velocities of the end effector of a manipulator are expressed in terms of the joint angle velocities as follows:

$$
\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dots \end{bmatrix} = J \begin{bmatrix} \dot{q}1 \\ \dot{q}2 \\ \dot{q}3 \\ \dots \end{bmatrix}
\tag{14}
$$

Conversely the joint angle velocities may be expressed in terms of the end effector Cartesian velocities by inverting the Jacobian matrix and rewriting the above expression as follows:

$$
\begin{bmatrix} \dot{q}1 \\ \dot{q}2 \\ \dot{q}3 \\ \dots \end{bmatrix} = J^{-1} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dots \end{bmatrix}
\tag{15}
$$

For the Gateway Coalition Robotic Manipulator the end effector Cartesian velocities may be obtained by taking the partial derivatives of expressions (8) and (9) with respect the joint angles (θ1, θ2, θ3, θ4, θ5). By taking these partial derivatives and separating terms:

dx = [-L2 cos(θ2) sin(θ1) - L3 cos(θ2+θ3) sin(θ1) - L4 cos(θ2+θ3+θ4) sin(θ1)] **dq1** +
[L2 cos(θ1) sin(θ2) + L3 cos(θ1) sin(θ2+θ3) + L4 cos(θ1) sin(θ2+θ3+θ4)] **dq2** +
[L3 cos(θ1) sin(θ2+θ3) + L4 cos(θ1) sin(θ2+θ3+θ4)] **dq3** +
[L4 cos(θ1) sin(θ2+θ3+θ4)] **dq4**   (16)

dy = [L2 cos(θ2) cos(θ1) + L3 cos(θ2+θ3) cos(θ1) + L4 cos(θ2+θ3+θ4) cos(θ1)] **dq1** +
[L2 sin(θ1) sin(θ2) + L3 cos(θ1) sin(θ2+θ3) + L4 sin(θ1) sin(θ2+θ3+θ4)] **dq2** +
[L3 sin(θ1) sin(θ2+θ3) + L4 sin(θ1) sin(θ2+θ3+θ4)] **dq3** +
[L4 sin(θ1) sin(θ2+θ3+θ4)] **dq4**   (17)

$$\mathbf{dz} = [L2 \cos(\theta2) + L3 \cos(\theta2+\theta3) + L4 \cos(\theta2+\theta3+\theta4)] \mathbf{dq2} +$$
$$[L3 \cos(\theta2+\theta3) + L4 \cos(\theta2+\theta3+\theta4)] \mathbf{dq3} + [L4 \cos(\theta2+\theta3+\theta4)] \mathbf{dq4} \qquad (18)$$

$$\mathbf{dpitch} = \mathbf{dq2} + \mathbf{dq3} + \mathbf{dq4}$$

$$\mathbf{drool} = \mathbf{dq5} \qquad (19)$$

By representing equations (16) through (19) in matrix format the following Jacobian matrix is obtained:

$$J = \begin{bmatrix} (-L2c2-L3c23-L4c234)s1 & (L2s2+L3s23+L4s234)c1 & (L3s23+L4s234)c1 & L4c1s234 & 0 \\ (L2c2+L3c23+L4c234)c1 & (L2s2+L3s23+L4s234)s1 & (L3s23+L4s234)s1 & L4s1s234 & 0 \\ 0 & L2c2+L3c23+L4c234 & L3c23+L4c234 & L4c234 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

As mentioned previously the inverse of the Jacobian is used to express the joint angle velocities in terms of the end effector Cartesian velocities. The inverse of the Jacobian is the matrix we need for this project, because our interest is on calculating how fast and in what combination the various joint angles should change in order to move the arm in a x, y or z direction with a certain velocity. The Jocobian inverse, with proper corrections for gear ratios, was written into the control code presented in Appendix A.

The joint angle velocities are not the angular velocities required from the motors in order to obtain a certain Cartesian velocity. The angular velocities of the motors must be translated into joint angle velocities through the use of a matrix containing gear ratios and couplings:

$$\begin{bmatrix} \dot{f}1 \\ \dot{f}2 \\ \dot{f}3 \\ \dot{f}4 \\ \dot{f}5 \end{bmatrix} = \begin{bmatrix} r1 & 0 & 0 & 0 & 0 \\ 0 & r2 & 0 & 0 & 0 \\ 0 & r3 & r3 & 0 & 0 \\ 0 & r4 & r4 & r4 & r4 \\ 0 & r5 & r5 & r5 & -r5 \end{bmatrix} \cdot \begin{bmatrix} \dot{q}1 \\ \dot{q}2 \\ \dot{q}3 \\ \dot{q}4 \\ \dot{q}5 \end{bmatrix} \qquad (20)$$

Where r1, r2, r3, r4, r5 are the gear ratios between the joints and the respective motors.

E. USER INTERFACE AND CONTROL SYSTEM

In order for the user to operate the arm, a control system and user interface were setup so that information may be transmitted from the user to the arm. The main components of this system are as follows. On the user's end an input device must be used so that data may be transmitted from the user to a processor. In addition, information must be transmitted from the processor to the motors and vice versa. Thus a control system with a feedback loop was used to exchange information between the processor and the motors. **Figure 66** is a schematic diagram of the user interface and control system used in the Gateway Robotic Manipulator. For simplicity only two motors are shown. However the reader should keep in mind that six motors were used. Each motor is controlled by one control board and each breakout board interfaces two control boards with the processor via an I/O board.
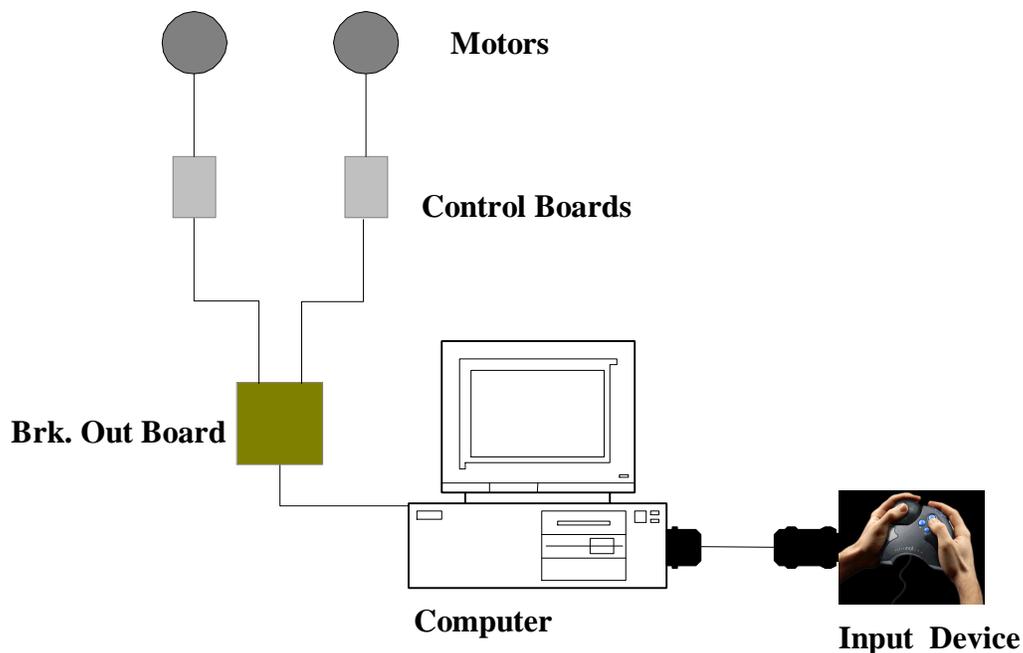
Figure 66: User Interface and Control System

As a result of the research done by Cooper Union during phase one of the project, this year's input device is a joystick known as the Space Orb 360. The choice of this joystick was based on the fact that it is rather inexpensive and it provides direct control of displacement in a 3-D space plus rotation about each one of the axes. In addition the Space Orb is small enough to be attached to the armrest of a wheelchair, it may be operated using only one hand, and its design takes into account ergonomic considerations. It is a digital joystick and it can be interfaced with a processor through an RS-232 serial port. Its system requirements are a 486-DX or higher processor and an operating environment such as MS-DOS 5.0+ or Windows 95.

Computer

The computer is the piece of hardware that will store our control code, the joystick drivers required for the joystick to function, and it will also run the control code on its processor. Thus for this project a computer is required in order to interface the joystick with the rest of the hardware that directly runs the motors. For demonstration purposes a PC with a 486-DX processor was used. However it would not be practical to mount such system into a wheelchair for the purpose of operating the Gateway Robotic Manipulator. Obviously this is so because of the bulkiness of a PC, which results from having attached to it many peripherals such as a hard drive, floppy drive, graphics card etc... This problem may be solved by using a single-board computer. Single-board computers are very compact systems, which have incorporated into one board the processor, graphics card, Flash ROM (which replaces the use of a hard drive), along with serial, parallel, keyboard and mouse I/O. In addition these systems may also come with an ISA bus interface, thus making it possible to interface the 196-bit I/O board that is being currently used. Toronto Microelectronics is one of the companies selling these systems for price under $500 for a 486-DX processor. Such a system could easily be mounted on a wheelchair and it may be possible to power this computer by using the 12volt batteries of the wheelchair.

Control System Hardware

By control system hardware we mean the portion of the hardware that allows the exchange of information between the computer processor and the motors. This system was conceived at University of Pennsylvania for 1996/97 Robotic Manipulator project. And it is comprised of the following elements:

196-bit Digital I/O Board

This board is housed inside of the PC and permits the exchange of information between the LM629 chips and the processor. Each one of its eight ports may send and receive information from one of the LM629 chips. Since the Gateway Coalition Robotic Manipulator uses six motors on its transmission system, six ports of the I/O board were associated with the six LM629 chips used. This was done by properly assigning, on the control code, the base address of each of the ports to each of the control chips.

Breakout Boards

The breakout boards are used to properly wire the control boards to the 196-bit I/O board.

Control Boards

The two main components of the control boards are the LM629 chip and the 1802 H-Bridge, both manufactured by *National Semiconductor*. The LM629 is a motion control processor, which has the ability to perform the computational tasks required by real time control. This chip is designed to work DC servomotors, and so it has incorporated in

itself a position decoder, a summing junction, digital PID loop compensation filter, and a trajectory profile generator. When the LM629 is in operation, to start a movement, a host interface controller downloads acceleration, velocity and target position values to the trajectory generator. The received data is sampled and at each sample interval these values are used to calculate a new demand or a set point position. These data values era fed into the summing junction. On another input of the summing junction the LM629 position decoder feeds the actual position of the motor into the summing junction. The actual position is subtracted from the demand position, to form an error signal, which is fed into a PID filter. Using this error signal and the data downloaded by the host interface the PID filter generates two pulse width modulated signals, one is a sign PMW and another is a magnitude PMW. These two PMW signals are used by the LMD18201 H-Bridge, and the sign PMW determines in what direction the motor rotates, while the magnitude PMW determines how fast the motor rotates.

Encoder

The position decoder receives the actual motor position data from an optical encoder attached to the motor shaft.
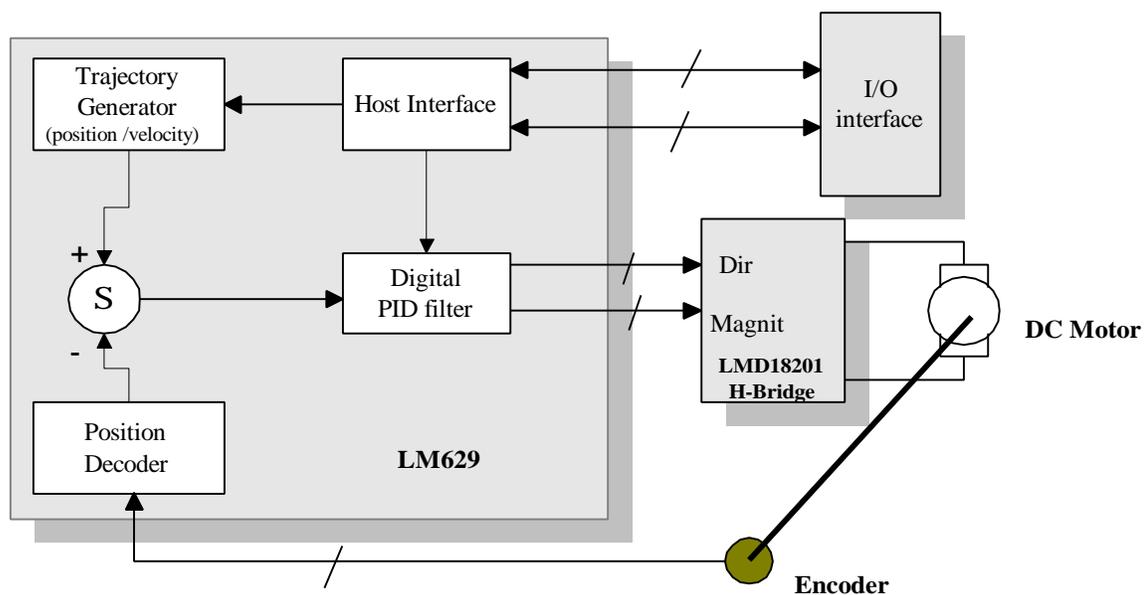
Figure 67: Control System

Figure 67 shows the control system hardware comprised of the 196-bit I/O board, LM629 control chip, LMD 18201 H-Bridge and encoder. For simplicity the breakout board was not included.

Control Code

The work done on the control code, written in velocity mode, consisted of adapting this code from the 1996/97 project to the current arm design. The first step was to alter the joystick code supplied by *Spacetec IMC* so that the output values from the joystick were less sensitive to small displacements of the joystick ball. As a result the x, y, z displacements and spinning only happens when the user pushes, pulls or spins the joystick ball much harder than before. In addition, the joystick code was integrated into the motor control code. As a result the output data values from the joystick were written into specific base addresses of the I/O board, which correspond to specific motors. Furthermore, code constants referring to motor specifications such as gear ratio and encoder CPR (counts per revolution) values were altered according to the new motor's specifications. Finally, a kinematics function based on the velocity analysis, presented in the beginning of this paper was added to the control code so that the proper joint angle motion could be obtained in order for the arm to move in the desired direction.

F. THE FINAL PRODUCT

The schools involved in the 1997 Gateway Coalition Project convened on April 23 at Drexel University to give the final presentation to members of the National Science Foundation. Representatives from the participating schools are shown in **Figure 68** below.

Figure 68: Gateway Coalition Student Representatives at the April 23 meeting

The presentation included contributing pieces from each school. A synapses of the working arm can be seen below.
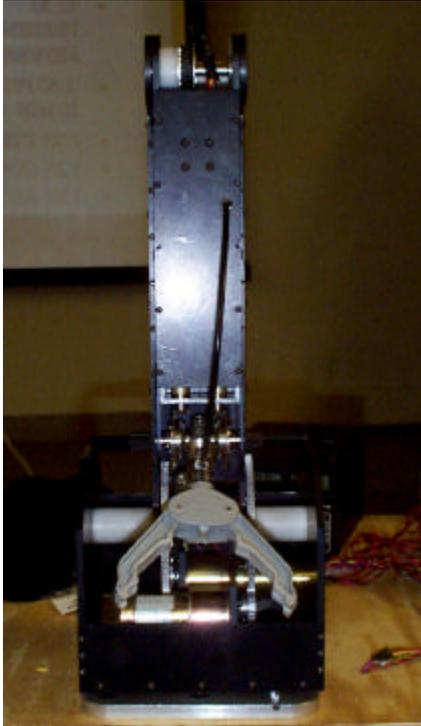
Figure 69: a) Vertical Picture of the Complete Arm b) Arm Picking up a Coke Can

VII. PROJECT LOGISTICS

COMMUNICATION

The nature of this design and manufacturing constitutes massive and detailed communication, considering that five different colleges and universities, separated geographically, must complete individual aspects of the project, yet work as a single unit to accomplish one common goal. Communication between schools has been and continues to be one of the major concerns when considering the restraints on the completion of the project. Communication between schools was attempted and was moderately successful using several different methods. Messages and ideas were shared through video-conferencing, the worldwide web, e-mail, telephone calls, and faxes.

Videoconferences using Telnet were one of the most successful forms of discussion. All team members could be seen and heard, as opposed to a closed, one on one phone conversation. As the Gateway teams quickly discovered, everyone could not be heard at once. The transfer of sound by videoconference is very sensitive to interference. The most successful conferences were achieved by assigning one particular person from one particular school to host or control the conference. Activating the "mute" button when

another party is speaking also seemed to be successful in minimizing interference. Cooper, Drexel, Ohio State and Pennsylvania conferenced at least once a week. This resulted in a lot of dead time for the individual schools at times, but it allowed everyone to be involved and interject in the discussion. The main problem with getting all of the schools together simultaneously was obviously satisfying schedules so that all or most members of each team could meet at a specific time each week.

The Internet and worldwide web were also used fairly effectively. Each school developed a web page, and one of the major goals established at the January meeting was to have each school update their page on a weekly basis. Several drawings of parts and concepts were posted for the Gateway Coalition's use of updated information. Schedules were also posted as to when each school was available for video-conferencing. A sample of the Ohio-State web page can be seen below.
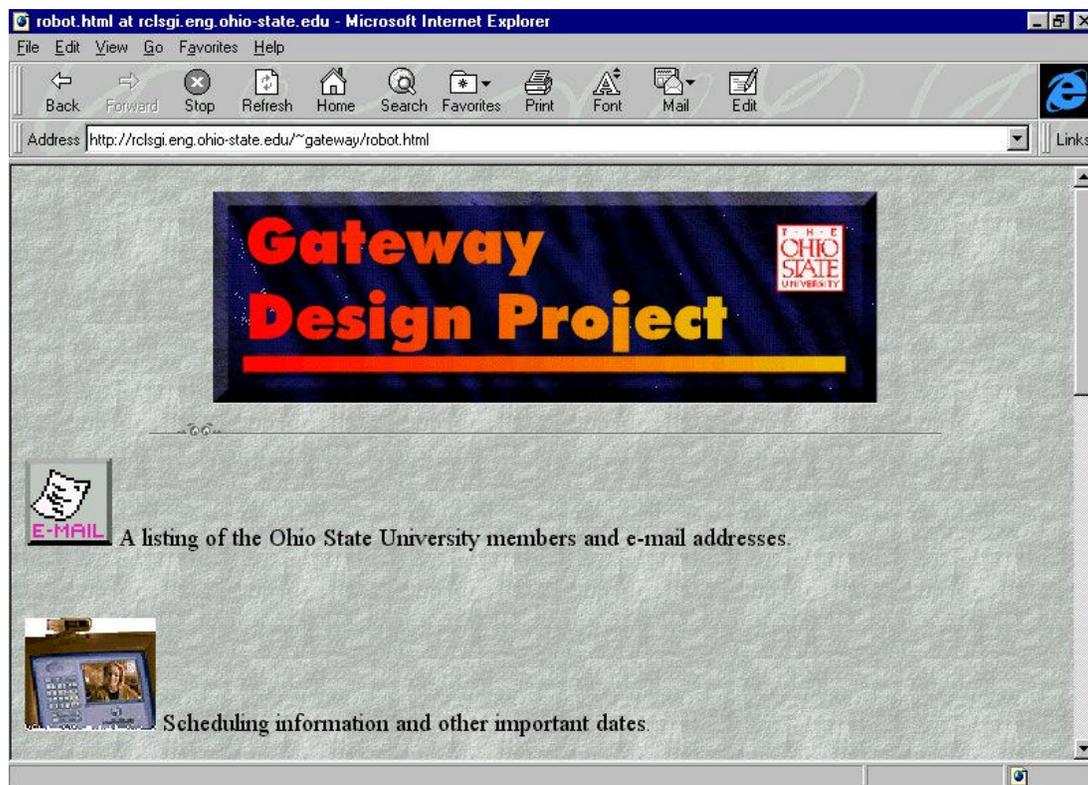
Figure 70: The Ohio State University's Gateway Web Page

Messages through e-mail were also used, serving as a method of sending simple dimension information, posing questions and answers, and setting up videoconferences and concurrent meetings. Dimensioned drawings and sketches were also sent by e-mail through IGES files.

Telephone calls were obviously used to get in touch with one another, proving to be more effective than e-mail at times and less effective at others. This depended on whether or not the requested party was available or near his or her phone. Fax machines proved to be useful in sending drawing printouts and part lists and numbers. Phones and fax

machines were also the main method by which parts and materials were inquired and ordered.

In conclusion, it is obvious that communication was one of the most important and demanding aspects of this project. Time and patience are vital, as well as having an open mind to alternative ideas and suggestions. Communication was given an honest attempt, but needs to be further assessed in future projects. In deciding upon task responsibilities in the future, the Gateway coalition may want to consider assigning the most closely related tasks to the schools in close proximity to one another. The communication aspect of the project was a helpful learning experience and allowed for engineering students from some of the finest colleges and universities in the country to share ideas and contribute to such a worthy project.

VII. APPENDIX

APPENDIX A: CONTROL CODE

```
/* velocity code */
/* Solomon Steplight and Tom Sugar */
/* Motor control with LM629 */
/*Revised:Cooper Union, Spring 1998,Gateway robot project 1997-98, by Bingxie Zhang
/***********************************************************************
*****
* This code is designed for motion control using the LM629 chip for the    *
* 1996-97 Gateway robot design project. This code was designed to output    *
* all the necessary encoder and hexadecimal values for the motor's shaft     *
* and desired position values to accurately monitor the motor's motion.      *
*************************************************************************
****/

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <dos.h>
#include <conio.h>

#include <signal.h>
#include <ctype.h>
#include <string.h>

#include "testctl.h"

#ifdef __WATCOMC__
#include <I86.h>
#endif

#define Pi 3.1415926
//Velocity convertion factor for Pittman Motors: 0.1rad/s -> Counts/Sample
#define Vel_Conv 4604920.774
//Velocity convertion factor for Micro Motors: 1rad/s -> Counts/Sample
#define Vel_Conv2 66487.4

#define baseaddr 0x300
#define RESET    0x00
#define RSTI     0x1D
#define MSKI     0x1C
#define LFIL     0x1E
#define UDF      0x04
#define LTRJ     0x1F
```

```c
#define STT      0x01
#define DFH      0x02
#define RDRP     0x0A
#define RDDP     0x08
#define RDRV     0x0B
#define RDDV     0x07
#define RDSIG    0x0C

#define OFFSET1  0*Pi/180;
#define OFFSET2  -9.462*Pi/180;
#define OFFSET3  -(90-9.462)*Pi/180;
#define OFFSET4  0*Pi/180;
#define OFFSET5  0*Pi/180;


double angle[5], mtrspeed[5];
double ang1, ang2, ang3, ang4, ang5;
int a, bb, c, d;
char num [5];
long pos_val1,pos_val2;
unsigned char POSHI, POSLO, high, low;
int THETA,w,j,i;
long junk, count, position;

FILE   *FPos;

int k=0;
int cnt=0;
unsigned char stat;
long MotPos[6];
long          offset[6];
float         MotAng[6], JoiAng[6];
float         MotGRatio=218.42;
float         MotGRatio2=415.0;
int           Noise = 120;


void inv_kin(double, double, double, double, double, double, double, double, double,
double);
void desired_pos();
void wr_cmd(unsigned char, int);
unsigned char rd_st(int);
void chk_bsy(int);
void wr_data(unsigned char, unsigned char, int);
long rd_data(int);
void load_traj(int , long);
```

```c
void load_traj2(int, long);
void UpdateFile();
void load_pos_traj(int , long );
void JointControl(int,int,int,int,int,int);
void PositionControl(int,int,int,int,int,int);

/* ******************************************** */
/*    bit 0 CS            */
/*    bit 1 RD and STRB(8255)  */
/*    bit 2 WR            */
/*    bit 3 PS            */
/*    bit 4 ACK(8255)        */
/*    bit 5 RST            */

char Pause ()

        char c;
        printf ("\n\nPress Enter to continue...");
        while ((c = getchar()) != '\n') {        }
        return c;


void chk_bsy(int w)

 int ST;

 outp(baseaddr+(w*4+1),(0x36 & 0xff));                /* set ps and cs low */
 outp(baseaddr+(w*4+1),(0x34 & 0xff));            /* set rd low */
 ST =  inp(baseaddr+(w*4));                    /* read in value */
  while (ST & 0x01)                        /* check for busy bit low */

        ST = inp(baseaddr+(w*4));

  outp(baseaddr+(w*4+1),(0x36 & 0xff));             /* bring rd back up high */
 outp(baseaddr+(w*4+1),(0x3e & 0xff));            /* keeping cs low */


unsigned char rd_st(int w)

 unsigned char status;

 outp(baseaddr+ (w*4+1),(0x36 & 0xff));            /* send ps and cs low */
 outp(baseaddr+(w*4+1),(0x34 & 0xff));            /* send rd low */
 status = (unsigned char) inp(baseaddr+(w*4));     /* read value */
 outp(baseaddr+(w*4+1),(0x36 & 0xff));            /* send rd high */
 outp(baseaddr+(w*4+1),(0x3e & 0xff));            /* send ps high and leave cs low */
```

```c
    return(status);


void wr_cmd(unsigned char CMD, int w)


  outp(baseaddr+(w*4+1),0x36 & 0xff);          /* cs and ps low */
  outp(baseaddr+(w*4),CMD);

  outp(baseaddr+(w*4+1),0x22 & 0xff);          /* write and ack low */
  chk_bsy(w);

  outp(baseaddr+(w*4+1),0x26 & 0xff);          /* bring write up */
  outp(baseaddr+(w*4+1),0x3e & 0xff);          /* bring ack up and ps up at the same
                                                  time */
  /* outp(baseaddr+1,0x3e & 0xff); */          /* leaving cs low */



void wr_data(unsigned char HIdat, unsigned char LOdat, int w)

  outp(baseaddr+(w*4+1),0x3e & 0xff);          /* pull ps high and set cs low */
  outp(baseaddr+(w*4), HIdat & 0xff);
  outp(baseaddr+(w*4+1),0x2a & 0xff);          /* send write and ack low */
  chk_bsy(w);
  outp(baseaddr+(w*4+1),0x2e & 0xff);          /* bring the wr back up */
  outp(baseaddr+(w*4+1),0x3e & 0xff);          /* bring ack up */

  outp(baseaddr+(w*4), LOdat & 0xff);
  outp(baseaddr+(w*4+1),0x2a & 0xff);          /* send write and ack low */

  chk_bsy(w);
  outp(baseaddr+(w*4+1),0x2e & 0xff);          /* bring the wr back up */
  outp(baseaddr+(w*4+1),0x3e & 0xff);          /* bring ack up and leave cs low */



long rd_data(int w)
{ long lmvalue, cur_theta;
  long dataval;

  lmvalue = 0;
  dataval = 0;

  chk_bsy(w);
  outp(baseaddr+(w*4+1),0x3e & 0xff);           /* pull ps high and set cs low */
```

```c
    outp(baseaddr+(w*4+1),0x3c & 0xff);              /* send rd low */
    dataval = (long) inp(baseaddr+(w*4));            /* read high byte value */
    outp(baseaddr+(w*4+1),0x3e & 0xff);              /* send rd high */
    lmvalue = (dataval << 24);

    chk_bsy(w);
    outp(baseaddr+(w*4+1),0x3e & 0xff);              /* pull ps high and set cs low */
    outp(baseaddr+(w*4+1),0x3c & 0xff);              /* send rd low */
    dataval = (long) inp(baseaddr+(w*4));             /* read low byte value */
    outp(baseaddr+(w*4+1),0x3e & 0xff);              /* send rd high */
    lmvalue = lmvalue + (dataval << 16);

    chk_bsy(w);
    outp(baseaddr+(w*4+1),0x3e & 0xff);               /* pull ps high and set cs low */
    outp(baseaddr+(w*4+1),0x3c & 0xff);              /* send rd low */
    dataval = (long) inp(baseaddr+(w*4));            /* read high byte value */
    outp(baseaddr+(w*4+1),0x3e & 0xff);              /* send rd high */
    lmvalue = lmvalue + (dataval << 8);

    chk_bsy(w);
    outp(baseaddr+(w*4+1),0x3e & 0xff);              /* pull ps high and set cs low */
    outp(baseaddr+(w*4+1),0x3c & 0xff);              /* send rd low */
    dataval = (long) inp(baseaddr+(w*4));             /* read high byte value */
    outp(baseaddr+(w*4+1),0x3e & 0xff);              /* send rd high */
    lmvalue = lmvalue + dataval;

/*  cur_theta = ((lmvalue * 360)/(2000 * 5.9)); */
    cur_theta = lmvalue;

    return(cur_theta);

void desired_pos()

    int r;
    double *mtrarr;

    mtrarr=mtrspeed;
/*  for(r=0; r<5; r++) {
    printf("Pre Velocity value to load: %lf \n", *(mtrarr+r));


        for(r=0; r<3; r++) {
        angle[r] = ( (((*(mtrarr+r))/(2.0*Pi)) * 500.0 * 4.0 * 16.777216);
//   printf("Velocity value to load: %lf \n", angle[r]);

        for(r=3; r<5; r++)
```

```c
                    angle[r] = ( (((*(mtrarr+r))/(2.0*Pi)) * 15.0 * 4.0 * 16.777216);


void  inv_kin(double dx, double dy, double dz, double dp, double dr, double theta_1,
double theta_2, double theta_3, double theta_4, double theta_5)



 double a, b, c, d, e, f, g, h;

 double s1, s2, s3, s4, s23, s34, s234, c1, c2, c23, c234;

 double k1, k2, k3, k4, k5, r1, r2, r3, r4, r5;

 double L2, L3, L4;

 double dtheta_1, dtheta_2, dtheta_3, dtheta_4, dtheta_5;

 double dphi_1, dphi_2, dphi_3, dphi_4, dphi_5;
 int i;
 double junk1,junk2;

 k1 = 1.0;
 k2 = 3.0;
 k3 = 2.0;
 k4 = 1.0;
 k5 = 1.0;
 r1 = 218.42;;
 r2 = 218.42;;
 r3 = 218.42;;
 r4 = 415.0;
 r5 = 415.0;
 L2 = 15.815;
 L3 = 12.0;
 L4 = 6.0;

/* change motor angles back to joint angles for Graeme's code */
junk1 = theta_2;
junk2 = theta_3;
theta_1 = theta_1/(k1*r1);
theta_2 = theta_2/(k2*r2);
theta_3 = -junk1/(k2*r2) + theta_3/(k3*r3);
theta_4 = -junk2/(k3*r3) + (theta_4 + theta_5)/(2.0*r4);
theta_5 = (theta_4 - theta_5)/(2.0*r4);

theta_1= theta_1+OFFSET1;
```

```
theta_2= theta_2+OFFSET2;
theta_3= theta_3+OFFSET3;
theta_4= theta_4+OFFSET4;
theta_5= theta_5+OFFSET5;

 s1   = sin(theta_1);
 s2   = sin(theta_2);
 s3   = sin(theta_3);
 s4   = sin(theta_4);
 s23  = sin(theta_2 + theta_3);
 s34  = sin(theta_3 + theta_4);
/* s234 = sin(theta_2 + theta_3 + theta_4); */

 c1   = cos(theta_1);
 c2   = cos(theta_2);
 c23  = cos(theta_2 + theta_3);
 c234 = cos(theta_2 + theta_3 + theta_4);

 a = L2*c2 + L3*c23 + L4*c234;
 b = L2*s3;
 c = L2*c2 + L3*c23;
 d = L2*s2 + L3*s23;
 e = L3*s4 + L2*s34;
 f = L3*s3 + L4*s34;
 g = L2*L3*s3;
 h = L3*s3;

 if ((a < -0.001) || (a > 0.001))

   dtheta_1 = (-s1/a)*dx + (c1/a)*dy;

 else

   dtheta_1 = 0.0;

 if ((b < -0.001) || (b > 0.001))


   dtheta_2 = ((-c1*c23)/b)*dx + ((-s1*c23)/b)*dy + (s23/b)*dz + ((L4*s4)/b)*dp;
   dtheta_3 = ((c1*c)/g)*dx + ((s1*c)/g)*dy + (-d/g)*dz + ((-L4*e)/g)*dp;


 else

   dtheta_2 = 0.0;
   dtheta_3 = 0.0;
```

```c
if ((h < -0.001) || (h > 0.001))

  dtheta_4 = ((-c1*c2)/h)*dx + ((-s1*c2)/h)*dy + (s2/h)*dz + (f/h)*dp;

else

  dtheta_4 = 0.0;

dtheta_5 = dr;

dphi_1 = k1*r1*dtheta_1;
dphi_2 = k2*r2*dtheta_2;
dphi_3 = k3*r3*dtheta_2 + k3*r3*dtheta_3;
dphi_4 = k4*r4*dtheta_2 + k4*r4*dtheta_3 + k4*r4*dtheta_4 + k4*r4*dtheta_5;
dphi_5 = k5*r5*dtheta_2 + k5*r5*dtheta_3 + k5*r5*dtheta_4 - k5*r5*dtheta_5;

mtrspeed[0] = dphi_1;
mtrspeed[1] = dphi_2;
mtrspeed[2] = dphi_3;
mtrspeed[3] = dphi_4;
mtrspeed[4] = dphi_5;
for (i=0;i<5;i++)
  printf("dphi's: %lf \n",mtrspeed[i]);
/* mtrarray = mtrspeed;
return(mtrarray); */

void load_traj(int w, long j)

        chk_bsy(w);
        wr_cmd(LTRJ,w);
        high = 0x08;
        low = 0x08;

        chk_bsy(w);
        wr_data(high,low,w);                    /* trajectory data will be loaded */
                                                /* 6 pairs of data should follow */
        POSHI =  (unsigned char) (j >> 24);
        POSLO =  (unsigned char) (j >> 16);
        high =POSHI;
        low = POSLO;
   // printf("high and low value %d\n\r %d\n\r ", high, low);
        chk_bsy(w);
        wr_data(high,low,w);                    /* load position byte */
        POSHI =  (unsigned char) (j >> 8);
```

```c
            POSLO =  (unsigned char) (j);
            high = POSHI;
            low = POSLO;
  //        printf("High and low value %d\n\r %d\n\r", high, low);
            chk_bsy(w);
            wr_data(high,low,w);
            chk_bsy(w);
            wr_cmd(STT,w);

void load_traj2(int z, long j)
            chk_bsy(z);
            /*wr_cmd(DFH,z);*/
            wr_cmd(LTRJ,z);
            high = 0x18;
            low = 0x08;
            chk_bsy(z);

            wr_data(high,low,z);                          /* trajectory data will be loaded */
                                                          /* 2 pairs of data should follow */
                                                          /* load velocity 32 byte word,relative
            POSHI =  (unsigned char) (j >> 24);
            POSLO =  (unsigned char) (j >> 16);
            high =POSHI;
            low = POSLO;
  //        printf("high and low value %d\n\r %d\n\r ", high, low);
            chk_bsy(z);
            wr_data(high,low,z);                          /* load position byte */
            POSHI =  (unsigned char) (j >> 8);
            POSLO =  (unsigned char) (j);
            high = POSHI;
            low = POSLO;
//          printf("High and low value %d\n\r %d\n\r", high, low);
            chk_bsy(z);
            wr_data(high,low,z);
            chk_bsy(z);
            wr_cmd(STT,z);

void load_pos_traj(int z, long j)
 /*
            Load the position of the motor so motor can return home *
            or some prerecorded positions.                         *
*/
            unsigned char stat;

            chk_bsy(z);
            /*wr_cmd(DFH,z);*/
```

```c
        wr_cmd(LTRJ,z);
        high = 0x00;
        low = 0x0A;
        chk_bsy(z);

        chk_bsy(z);
        wr_data(high,low,z);                        /* trajectory data will be loaded */
                                                    /* 4 pairs of data should follow */

        high = 0x00;
        if (z <3)
                low = 0x15;
        else
                low = 0x02;
        chk_bsy(z);
        wr_data(high,low,z);                        /* velocity integer */
        high = 0xff;
        low =  0xff;
        chk_bsy(z);
        wr_data(high,low,z);                        /* velocity fractional word */
                                                    /* load position 32 byte word */
        POSHI =  (unsigned char) (j >> 24);
        POSLO =  (unsigned char) (j >> 16);
        high =POSHI;
        low = POSLO;
        /*printf("high and low value %d\n\r %d\n\r ", high, low);*/
        chk_bsy(z);
        wr_data(high,low,z); /* load position byte */
        POSHI =  (unsigned char) (j >> 8);
        POSLO =  (unsigned char) (j);
        high = POSHI;
        low = POSLO;
        /*printf("High and low value %d\n\r %d\n\r", high, low);*/
        chk_bsy(z);
        wr_data(high,low,z);
        chk_bsy(z);
        wr_cmd(STT,z);

        junk = 0;
        for (i=0;i<2000;i++)
         junk = junk + 1;


void Chip_Initial (int w)

 /*Initialize LM629N-8 Motion Controller Chip*/
        outp(baseaddr+(w*4+3),0xC1);  /* sets up the parallel port */
```

```c
junk = 0;
for (i=0;i<500;i++)
  junk = junk + 1;

outp(baseaddr+(w*4+1),0x3f);
outp(baseaddr+(w*4+1),0x1f);                    /* set reset bit to low */
junk = 0;
for (i=0;i<500;i++)
  junk = junk + 1;
outp(baseaddr+(w*4+1),0x3e); /* always keeping the cs bit low */

                /* ***************************** */
junk = 0;
for (i=0;i<20;i++)
  junk = junk + 1;

stat = rd_st(w);
printf("RESETING CHIP \n");
printf("status byte immediately after reset by pin: %d\n",stat);
chk_bsy(w);
stat = rd_st(w);
printf("status byte after reset by pin: %d\n",stat);
count = 0;
while ((stat != 0x84) & (stat!=0xC4))

  chk_bsy(w);
  stat = rd_st(w);
  count ++;
  if ((stat == 0x84) || (stat == 0xC4))
 printf("status byte after reset by pin: %d and number of tries: %ld\n",stat,count);

chk_bsy(w);
wr_cmd(RESET, w);
chk_bsy(w);
stat = rd_st(w);
printf("status byte after reset command: %d\n",stat);
count = 0;

junk = 0;
for (i=0;i<20000;i++)
  junk = junk + 1;

while ((stat != 0x84) & (stat!=0xC4))

  chk_bsy(w);
```

```
        stat = rd_st(w);
        count ++;
            printf("status byte after reset command: %d and number of tries
%ld\n",stat,count);

 chk_bsy(w);
 wr_cmd(MSKI, w);
 chk_bsy(w);
 wr_data(0x0,0x0, w);
 chk_bsy(w);
 wr_cmd(RSTI, w);
 chk_bsy(w);
 wr_data(0x0,0x0, w);
 chk_bsy(w);
 stat = rd_st(w);
 printf("status byte after reseting interrupts, 1: %d\n",stat);
 count = 0;
 while ((stat != 0x80) & (stat!=0xC0) & (count < 10))

        chk_bsy(w);
        stat = rd_st(w);
        printf("status byte after reseting interrupts, 2: %d\n",stat);
        count++;

/********* now ready to load the filter coefficients and trajectory */

        chk_bsy(w);    /* 8 bit port */
        wr_cmd(0x05,w);

        chk_bsy(w);   /* setting home position */
        wr_cmd(DFH, w);


/* ************* Load the Filter Parameters ****************** */
       junk = 0;
       for (i=0;i<2000;i++)
        junk = junk + 1;

       chk_bsy(w);
       wr_cmd(LFIL,w);
       chk_bsy(w);
       stat = rd_st(w);
       printf("status byte after LFIL, 1: %d\n",stat);
       chk_bsy(w);
       wr_data(0x00,0x0a,w);                          /* Hi byte loads the derivative
                                                          sampling rate
```

```c
                                                    /* Hi byte of 0 = 256us sampling rate
                                                    /* Lo byte informs data to be loaded,
                                                    load Kp data */

                    /* bit 3 load Kp data
                     bit 2 load Ki data
                     bit 1 load Kd data
                     bit 0 load il data */

 chk_bsy(w);
 stat = rd_st(w);
 printf("status byte after LFIL data loading, 1: %d\n",stat);

 high = 0x007f >> 8;
 low = 0x007f;
 chk_bsy(w);
 wr_data(high,low,w); /* load Kp data MSB first */
 high = 0x00;
 low = 0x01;
 chk_bsy(w);
 wr_data(high,low,w);
 chk_bsy(w);
 stat = rd_st(w);
 printf("status byte after Kp and Kd data loading, 1: %d\n",stat);

 chk_bsy(w);
 wr_cmd(UDF,w);
 chk_bsy(w);
 stat = rd_st(w);
 printf("status byte after UDF command, 1: %d\n",stat);

junk = 0;
for (i=0;i<2000;i++)
  junk = junk + 1;

chk_bsy(w);
wr_cmd(MSKI,w);
chk_bsy(w);
wr_data(0x0,0x0,w);
chk_bsy(w);
wr_cmd(RSTI,w);
chk_bsy(w);
wr_data(0x0,0x0,w);
chk_bsy(w);

stat = rd_st(w);
printf("status byte after reseting interrupts : %d\n",stat);
```

```
        chk_bsy(w);
        wr_cmd(LTRJ,w);
        high = 0x00;
        low = 0x20;

        chk_bsy(w);
        wr_data(high,low,w);                    /* trajectory data will be loaded */

        chk_bsy(w);
        wr_data(0x00,0x00,w);                   /* acceleration integer */
        chk_bsy(w);
        if (w < 3)
                wr_data(0x02,0x3f,w);           /* acceleration fractional word */
        else
                wr_data(0x00,0x3f,w);

                                                 /* load position 32 byte word */


void UpdateFile()

/* Write the Motor Position data in the "pos.dat" File
**/

        FPos = fopen ("pos.dat", "w");
        for (i=0;i<=6;i++){
                fprintf(FPos,"%ld \n",MotPos[i]);

        fclose(FPos);



void JointControl(int X, int Y, int Z, int XR, int YR, int ZR)

int motorcall, sum;
long MotVelo, pos;

        sum = abs(X)+abs(Y)+abs(Z)+abs(XR)+abs(ZR);

        motorcall = 0;
        if (X != 0)
                MotVelo = abs(X/Noise)*0.1*Vel_Conv;
                if (X >0)
                        load_traj(motorcall, MotVelo);
                else
                        load_traj2(motorcall, MotVelo);
                chk_bsy(motorcall);
```

```
                wr_cmd(RDRP,motorcall);
                chk_bsy(motorcall);
                pos = (long) rd_data(motorcall);
                MotPos[motorcall+1] = offset[motorcall+1]+pos;
                MotAng[motorcall+1]=
MotPos[motorcall+1]/(MotGRatio*500.0*4.0)*360.0;
                //delay(20);

        else
                load_traj(motorcall,0);

        motorcall = 1;
        if (Y != 0)
                MotVelo = abs(Y/Noise)*0.1*Vel_Conv;
                if (Y >0)
                        load_traj(motorcall, MotVelo);
                else
                        load_traj2(motorcall, MotVelo);
                chk_bsy(motorcall);
                wr_cmd(RDRP,motorcall);
                chk_bsy(motorcall);
                pos = (long) rd_data(motorcall);
                MotPos[motorcall+1] = offset[motorcall+1]+pos;
                MotAng[motorcall+1]=
MotPos[motorcall+1]/(MotGRatio*500.0*4.0)*360.0;
                //delay(20);

        else
                load_traj(motorcall,0);

        motorcall = 2;
        if (Z != 0)
                MotVelo = abs(Z/Noise)*0.1*Vel_Conv;
                if (Z >0)
                        load_traj(motorcall, MotVelo);
                else
                        load_traj2(motorcall, MotVelo);
                chk_bsy(motorcall);
                wr_cmd(RDRP,motorcall);
                chk_bsy(motorcall);
                pos = (long) rd_data(motorcall);
                MotPos[motorcall+1] = offset[motorcall+1]+pos;
                MotAng[motorcall+1]=
MotPos[motorcall+1]/(MotGRatio*500.0*4.0)*360.0;
                //delay(20);
```

```
        else
                load_traj(motorcall,0);

        motorcall = 3;
        if (ZR != 0)
                MotVelo = abs(ZR/Noise)*0.5*Vel_Conv2;
                if (ZR >0)
                        load_traj(motorcall, MotVelo);
                else
                        load_traj2(motorcall, MotVelo);
                chk_bsy(motorcall);
                wr_cmd(RDRP,motorcall);
                chk_bsy(motorcall);
                pos = (long) rd_data(motorcall);
                MotPos[motorcall+1] = offset[motorcall+1]+pos;
                MotAng[motorcall+1]=
MotPos[motorcall+1]/(MotGRatio2*15.0*4.0)*360.0;
                //delay(20);

        else
                load_traj(motorcall,0);

        motorcall = 4;
        if (XR != 0)
                MotVelo = abs(XR/Noise)*0.5*Vel_Conv2;
                if (XR >0)
                        load_traj(motorcall, MotVelo);
                else
                        load_traj2(motorcall, MotVelo);
                chk_bsy(motorcall);
                wr_cmd(RDRP,motorcall);
                chk_bsy(motorcall);
                pos = (long) rd_data(motorcall);
                MotPos[motorcall+1] = offset[motorcall+1]+pos;
                MotAng[motorcall+1]=
MotPos[motorcall+1]/(MotGRatio2*15.0*4.0)*360.0;
                //delay(20);

        else
                load_traj(motorcall,0);

        if (sum != 0)
                UpdateFile();


void PositionControl(int X, int Y, int Z, int XR, int YR, int ZR)
```

```
double ang[5];
double dx,dy,dz,dp,dr;
int      sum;

        for (i=0;i<=5;i++)
                ang[i] =0;
        dx =0; dy =0; dz =0; dp=0; dr=0;
        sum =0;
        if (X != 0)
                dx = abs(X)/X*1.8;
                sum = sum +dx;

        if (Y != 0)
                dy = abs(Y)/Y*1.8;
                sum = sum +dy;

        if (Z != 0)
                dz = abs(Z)/Z*1.8;
                sum = sum +dz;

        if (XR != 0)
                dp = abs(XR)/XR*1.8;
                sum = sum +dp;

        if (ZR != 0)
                dr = abs(ZR)/ZR*1.8;
                sum = sum +dr;


        //Read Angle Data From the Encoder
        for(i=0;i<=4;i++)
                chk_bsy(i);
                wr_cmd(RDRP,i);
                chk_bsy(i);
                MotPos[i+1]= rd_data(i);
                if (i <3)
                        ang[i] = (double) (MotPos[i+1]) * ((2.0*Pi)/(2000.0));
                else
                        ang[i] = (double) (MotPos[i+1]) * ((2.0*Pi)/(15.0 *4.0));


                UpdateFile();
                inv_kin(dx,dy,dz,dp,dr,ang[0],ang[1],ang[2],ang[3],ang[4]);
                desired_pos();
                for(i=0;i<=4;i++) /*****Make sure this line is correct****/
```

```c
                if(angle[i]>0)
                        load_traj(i, angle[i]);
                else if(angle[i]<0)
                        load_traj2(i, -1.0*angle[i]);
                else
                        load_traj(i, 0);


void main( int argc, char *argv[] )

        short       key_pressed =0;
        char        c;
        testcontrol_t _far *Control;
        int         X,Y,Z,XR,YR,ZR,z,Button;
        union REGS       xr;

    if ( argc >= 3 )
            /* Extract the pointer to the Control structure from argv[] */
      sscanf( argv[2], "%lu", &Control );
      for (i=0;i<=6;i++) {
                MotPos[i]=0;
                offset[i]=0;
                MotAng[i]=0;

        if ((FPos = fopen ("Pos.dat", "r")) != NULL) {
                for (i=0;i<=3;i++){
                        fscanf(FPos, "%ld", &offset[i]);
                        MotPos[i] = offset[i];
                        MotAng[i]=MotPos[i]/(MotGRatio*500.0*4.0)*360.0;
                        printf("Angle%d is %f \n",i,MotAng[i]);

                for (i=3;i<=6;i++){
                        fscanf(FPos, "%ld", &offset[i]);
                        MotPos[i] = offset[i];
                        MotAng[i]=MotPos[i]/(MotGRatio2*15.0*4.0)*360.0;
                        printf("Angle%d is %f \n",i,MotAng[i]);


        z=0;
        while (z<=5)

                Chip_Initial(z);
                load_traj(z,0);
                z++;
```

```c
while ( !key_pressed)

        int86( Control->intnum, &xr, &xr );
        // Filter Noise
        X = (abs(Control->axes[0]) > Noise) ? Control->axes[0] : 0 ;
        Y = (abs(Control->axes[1]) > Noise) ? Control->axes[1] : 0 ;
        Z = (abs(Control->axes[2]) > Noise) ? Control->axes[2] : 0 ;
        XR = (abs(Control->axes[3]) > Noise) ? Control->axes[3] : 0 ;
        YR = (abs(Control->axes[4]) > Noise) ? Control->axes[4] : 0 ;
        ZR = (abs(Control->axes[5]) > Noise) ? Control->axes[5] : 0 ;
        Button = Control->buttonmask ;

        clrscr();
        printf ("X = %d; %d \n", X,abs(X));
        printf ("Y = %d; %d \n", Y,abs(Y));
        printf ("Z = %d; %d \n", Z,abs(Z));
        printf ("ZR = %d; %d \n", ZR,abs(ZR));
        printf ("XR = %d; %d \n", XR,abs(XR));
        printf("pos_val1 %ld\n",MotPos[1]);
        printf("pos_val2 %ld\n",MotPos[2]);
        printf("pos_val3 %ld\n",MotPos[3]);
        printf("pos_val4 %ld\n",MotPos[4]);
        printf("pos_val5 %ld\n",MotPos[5]);


//              delay(10);
        //Joint Contorl Mode

        if ((Button % 2) == 1)
                load_traj(5,10000);
        else if (((Button >>1) % 2) == 1)
                load_traj2(5, 10000);
        else
                load_traj(5,0);
        if (Button == 4)
                JointControl(X,Y,Z,XR,YR,ZR);
        else
                PositionControl(X,Y,Z,XR,YR,ZR);

        if(kbhit())

                if ((c=getch()) == 'q')
                        key_pressed = 1;             // Exit on key press
break;

        // While
```

```
        else
                printf("SpaceWare is not installed!");

exit:
for(i=0;i<=6;i++)
        MotPos[i]=0;
UpdateFile();
for(d=0; d<=4; d++)
        load_pos_traj(d,0);


//Stop Gripper
        z =5;
         chk_bsy(z);
         wr_cmd(RESET,z);
```

APPENDIX B: MICRO MOTOR CALCULATIONS

DC Servo Series	RPM	Torque [oz-in]	Weight [oz]	Gearbox
816	13,000	0.03	0.130	Planetary
1336	9,000	0.57	0.811	14/1, 15/2,3,5,8
1524…R	10,000	0.35	0.780	15/1,2,3,5,8 16/7,A
1727	7,000	0.71	0.980	16/7
2224…R	8,000	0.71	1.620	22/2,5,8 23/1
2342…CR	7,000	2.27	3.100	3.71:1 to 55,000:1
Pittman				
GM9234	5,900	2.87	10 oz	

APPENDIX C: GRIPPER CALCULATIONS

Initial Calculations		
16 oz for gripper at an average of 2"	=	32 oz-in
32 oz for payload at an average of 4"	=	128 oz-in
		-------------
		160 oz-in total
Results		
160 oz-in/2 = 80 oz-in/motors * 150% for safety	=	120 oz-in/motor

APPENDIX D: COST ANALYSIS

CONTROL SYSTEMS

Component	Unit cost	Quantity	Total
192-bit I/O board	$200	1	$200
Cabling	-----------------------	-----------------------	$75
Breakout board	$50	3	$150
LM629 & Board	$175	6	$1050
Power supply	$150	1	$150
Joystick	$100	1	$100
Total			$1725

***skip Three Pages for other cost analysis

APPENDIX E: TEAMWORK

Things To Be Covered

- Why have teams?
- Definition of a team
- Team basics
- Team performance Curve
- Building team performance
- Dealing with obstacles

Why Have Teams?

- Teams gets better results than a collection of individuals working within confined job roles and responsibilities.
- Teams provide:
  - Multiple skills
  - Judgements
  - Various experiences

Definition Of A Team

"A team is a small number of people with complementary skills who are committed to a common purpose, performance goals, and approach for which they hold themselves mutually responsible."

Jon R. Katzenbach
Douglas K. Smith

Definition Of A Team

- Small Number
  - From 2 to 25
  - Larger groups have trouble interacting constructively
- Complimentary Skills
  - Technical or functional expertise
  - Problem-solving and decision-making skills
  - Interpersonal skills
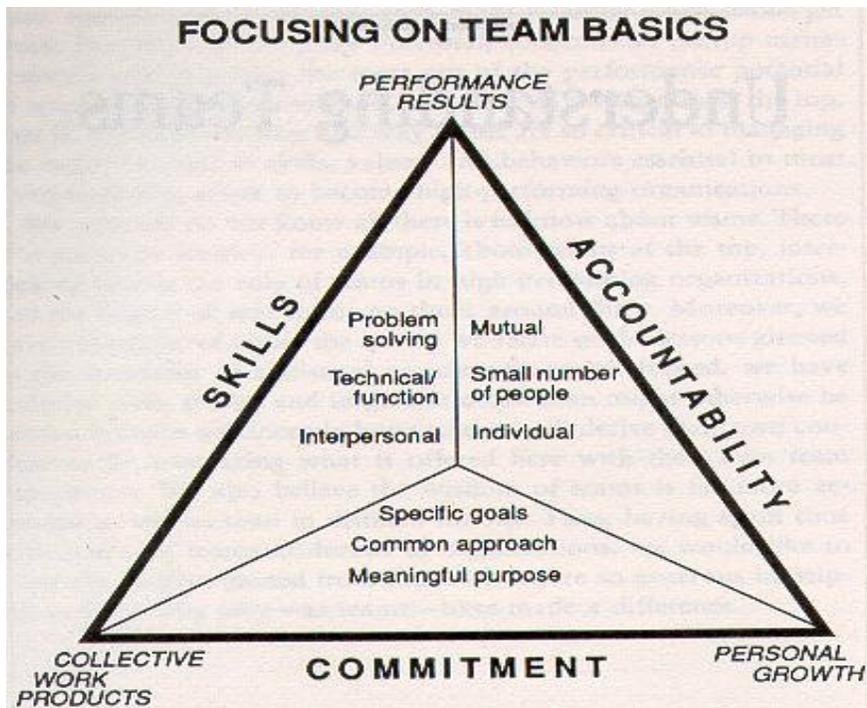
Definition Of A Team

- Committed to a common purpose
  - A common meaningful purpose sets the tone and aspiration.

- Committed to a common approach
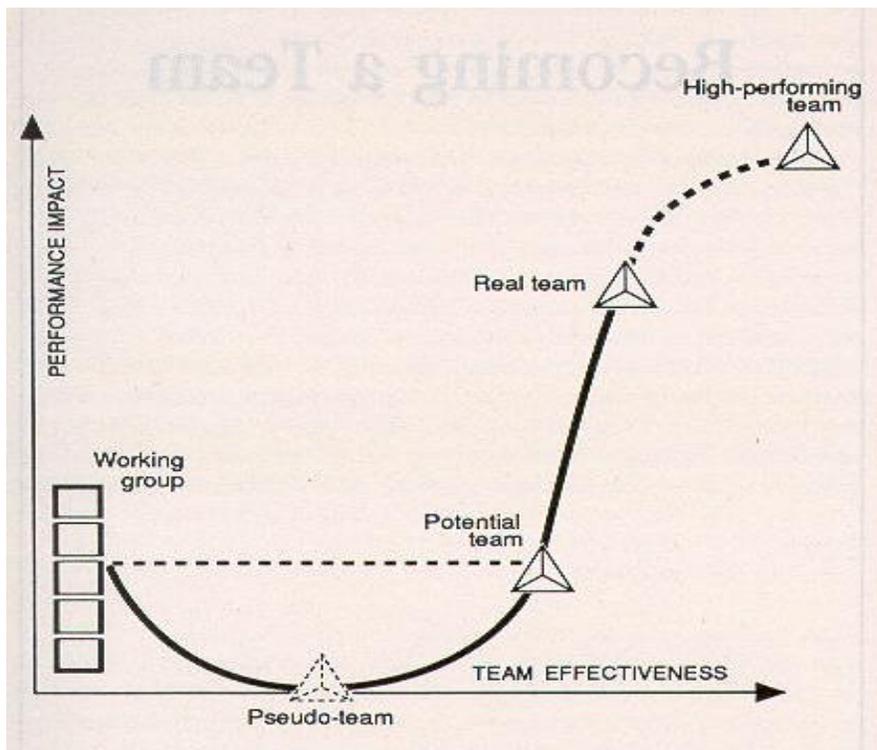 - How they will work together to accomplish their purpose.

Why Teams Perform Well

- Bring together complementary skills and experiences that exceed those of any individual.
- In Jointly developing clear goals and approaches, teams establish communications that support real-time problem solving.

Why Teams Perform Well

- Teams provide a unique social dimension that enhances the economic and administrative aspects of work/school.

- Teams have more fun.

FOCUSING ON TEAM BASICS

PERFORMANCE RESULTS

SKILLS

ACCOUNTABILITY

Problem solving   Mutual

Technical/ function   Small number of people

Interpersonal   Individual

Specific goals
Common approach
Meaningful purpose

COLLECTIVE WORK PRODUCTS

COMMITMENT

PERSONAL GROWTH

Becoming a Team

Team Performance Curve

- Working group
  - No significant performance needed.
  - Members interact to share information and make decisions.
- Pseudo-team
  - Significant performance need.
  - No focus on a collective performance and is not really trying to achieve it.

Team Performance Curve

- Potential Team
  - Performance is needed.
  - The group is really trying to improve its performance.
- Real Team
  - Performance is needed.
  - Equally committed to purpose, goals, and working approach and mutually accountable.

The "How-To" Recipe For Building Team Performance

- Establish urgency and direction
  - All team members need to believe the team has urgent and worthwhile purposes.
  - The more urgent and meaningful the more likely a real team will emerge.
- Select members based on skills and skill potential, not personalities
  - Technical and functional
  - Problem solving
  - Interpersonal

The "How-To" Recipe For Building Team Performance

- Pay attention to first meetings and actions.
  - Initial impressions mean a great deal.
- Set some clear rules of behavior.
  - Develop rules of conduct to help achieve the teams purpose and performance.
  - Attendance, discussion, confidentiality, constructive confrontation and contributions

The "How-To" Recipe For Building Team Performance

- Set and seize upon a few immediate performance-oriented tasks and goals
  - Advancement towards key milestones will forge the team together.
- Challenge the group regularly with fresh facts and information
  - New information provides an understanding of the performance challenge, thereby helping the team to create a common purpose and set goals.

The "How-To" Recipe For Building Team Performance

- Spend <u>lots</u> of time together
  - Scheduled and unscheduled meetings.
  - Creative insights as well as personal bonding require impromptu and casual interactions.
- Positive feedback, recognition and reward
  - "Giving out gold stars"
  - Positive reinforcement encourages continued contributions.

Dealing With Obstacles

- Approaches to getting unstuck
  - Revisit the basics.
  - Go for small wins.
  - Inject new information and approaches.
  - Take advantage of facilitators or training.
  - Change the team's membership, including the leader.

"Wisdom Of Teams"

By focusing on performance and team basics as opposed to trying to "become a team" most small groups can deliver the performance results that require and produce team behavior.

"Wisdom Of Teams"

"Real teams are deeply committed to their purpose, goals and approach. High-performance team members are also very committed to one another. Both understand that the wisdom of teams comes with a focus on collective work-products, personal growth, and performance results. However, meaningful, "team is always a result of pursuing a demanding performance challenge."