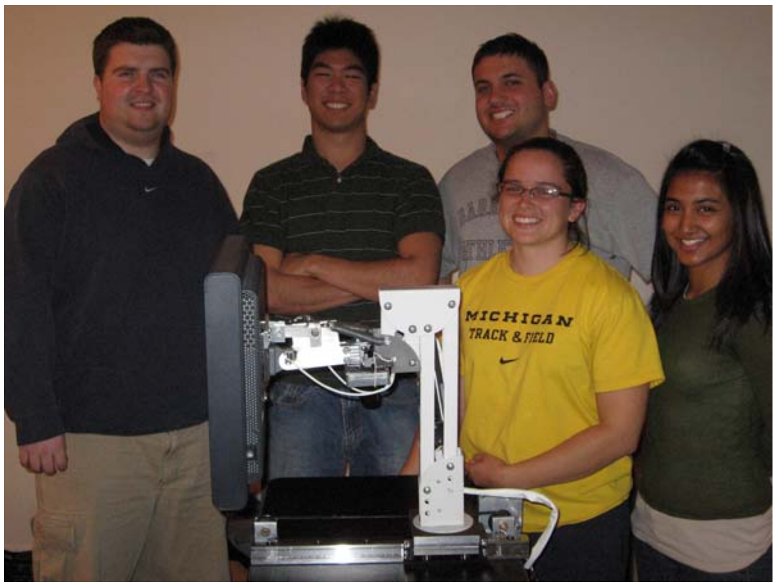
Powered Flat Panel Monitor Arm for Computer Users with Disabilities

Project 4



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Final Report

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ME 450 – Winter 07
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1 ABSTRACT

Many computer workstations are impractical for people living with disabilities and impairments. Relevant disabilities include low vision and/or musculoskeletal disorders making it nearly impossible to maneuver computer monitors to a desirable position. Past ME450 students have developed a powered arm that can electronically adjust the position of a monitor, but the design is bulky and unappealing. Thus, our goal is to design a system that is robust, cost effective, easy to manufacture, and elegant to package and install in special Ergopod workstations as seen at computing sites around campus.

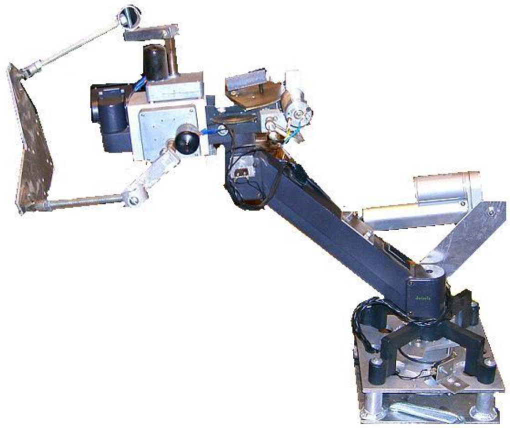
2 INTRODUCTION

Many people struggle with current desktop configurations due to physical limitations. These people who suffer from poor vision, low motor skills, or other disabilities and impairments may find it difficult or impossible to move a flat panel monitor to a desirable viewing position on most computer workstations. Taking a large step to improve this situation, the University of Michigan Adaptive Technology Computing Site (UM ATCS), the University of Michigan Program for Community Engagement in Engineering Design (ProCEED), and corporate sponsor ErgoQuest, Inc., teamed up to develop the Ergopod, which is a workstation with an electronically adjustable desktop height and is compatible with a wheelchair or recliner as shown in Figure 1.

Figure 1: Ergopod Workstation Fitted with a Recliner

The Ergopod did not fully solve the monitor positioning problem, so previous ME450 teams have worked to find an automated solution. A functioning prototype was created that accomplished the full range of motions necessary and is shown in Figure 2 on page 6. It allowed the user to position a flat panel monitor by using an electronic control box. However, the most recent model is heavy, noisy and unattractive. The purpose of this project is to redesign the system to remedy these problems, and to provide a product that is nearly market ready.

Figure 2: Winter 2004 Powered Flat Panel Monitor Arm Prototype



3 SCHEDULING

In order to complete our task of producing an automated flat panel monitor arm in a timely manner, we created a project plan. To do this, we noted each required deliverable (i.e. design reviews, design expo, final report) in addition to a few milestones set by our team. Next, we estimated what tasks needed to be completed by each milestone and how long each task would take. Our project plan is summarized in a GANTT chart shown in Appendix L. In general, we followed the plan well, however after Design Review 3 we fell about a week behind schedule. This did not prove to be a big problem because we scheduled a large amount of time at the end for extra testing.

To best utilize our time, we assigned various responsibilities to our team members, as follows. These responsibilities are in addition to information search and concept generation/development, which every team member was responsible for.

- Kevin Bouma: component selection, machining, CAD modeling
- Mita De: component selection, analysis, prototyping
- Joe De Frank: component selection, machining, CAD modeling
- Courtney Doyle: component selection, prototyping, controls, testing/debugging
- Kevin Shimotsu: component selection, machining, prototyping, testing/debugging

4 INFORMATION SEARCH

Robotic arms have been used for many applications over time, including many biomedical industries. One application of recent interest is a flat panel monitor arm for the disabled. However, little work has been done in the area of incorporating robotics into computer workstations.

Before designing our robotic system for a computer monitor, we spent time researching two areas of interest. These include current manual arms for computer monitors and robotic arms for various applications. During the development of our product, we also researched many different components, which are also discussed in this section. Additionally, we gathered information from a survey handed out at an Expo for developments in the disabled community.

4.1 Manual Arms
Most monitor arms on the market are manually operated [1]. Current arms swivel and pivot to accommodate all monitor positions. With a full range of adjustability, the arms allow users to control monitor height, focal distance, tilt and twist angle for glare reduction. These monitor arms are readily available in desk mounts, wall mounts, pole mounts, and ceiling mounts.

4.2 Robotic Arms
Manual monitor arms can be difficult for physically disabled people to operate, thus there is a demand for a robotic option. A thorough patent search showed no work in the application of automating monitor arms. The majority of related work and research involves robotic arms for flat panel televisions [2]. These arms are far too large and expensive to be utilized for the computer screen market and do not have a sufficient range of motion to meet most users' needs. One idea is to add automatic motion and controls to manual flat panel arms already on the market. Currently, this problem is addressed by the previous prototype using electronic actuators and motors. This solution, however, proved to be bulky and unmarketable. Thus, to develop a more streamlined design we looked into many robotic arms currently used in industries.

One of the more recent developments in robotic arms is in the medical field, where they have been used for prosthetic arms. These prosthetic arms feature a functional shoulder, elbow, and simple gripper. New research hopes to control the prosthetic arm electronically through the brain. To control the arm, 96 very thin electrodes are attached to the motor cortex of the brain; this is the region of the brain responsible for voluntary movement. The electrodes measure the moving rate of a neuron which is involved with the motion of the arm. With a special computer algorithm, researchers are able to find an average direction from the small sample of neurons to move the robotic arm. [3]

This particular example did not provide much insight into our problem, but it does show that robotic arms can be developed for many applications. Another application of a robotic arm is the IRB 2400 used for heavy duty machinery, seen in Figure 21 in Appendix A. These kinds of robotic arms are able to support a payload of about 22 lbs and have a maximum reach of about 4.9 ft. They are used for arc welding, die casting, injection molding, and machine tending. Also, they feature excellent motion control, such as path accuracy and position repeatability, and unlimited motion in 6 directions. However, they are very bulky weighing about 840 lbs and having a height of about 9 ft. [4]

The ST Robotics' R17 robot arm, shown in Figure 3 on the next page, is a hybrid between a Cartesian robot and an articulate robot. It is able to move along a single track at its base and has five additional degrees of freedom by the rotation of the arm joints. Each arm joint is powered by stepper motors with belt drives, while the gripper is operated with pneumatics. The total weight of the system is 48 lbs [5].

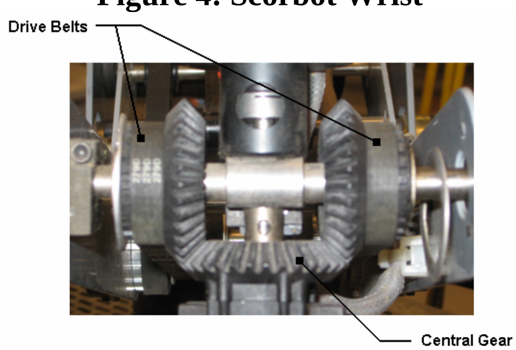
Figure 3: ST Robotics' R17

The R17 robot arm is built for high precision, high speed, and low torque manufacturing operations, which is opposite of what we need. We need a system that moves at a low, comfortable speed for disabled users, has a high torque for maneuvering a heavy monitor, and does not need high precision. In order to fit our speed/torque needs, we would need to use high gear ratios. Even though the R17 is unable to cover our most basic needs, it did help to inspire the idea of combining the concepts of both a Cartesian and articulate robot into our design. This has the advantage of keeping the system more stable because it would eliminate the need for the arm to fully extend and cantilever a heavy monitor at the end, which is the position with the highest likelihood for failure.

We obtained much insight after visiting the Pinckney High School Robotic Lab. Here, we met with Mr. Sean Hickman and were able to look at different robots. Two examples that are worth noting are the Scorbot by Intlitek and a linear track that is being designed by current students.

The Scorbot, seen in Figure 22 in Appendix A, achieves five degrees of freedom using stepper motors to actuate gears and drive belts. This system is advantageous because the components are easy to incorporate inside an arm, which allows for a more elegant packaging than the previous prototypes. There are two major disadvantages to the Scorbot. First, the payload is only 4.6 lbs [6], which is 15% of the weight we must design for. Additionally, while the wrist joint gives two degrees of freedom, it is missing the twist function. However, looking closely at how the movements are achieved will allow us to possibly incorporate the design in a way that it can achieve the twist motion. Figure 4 shows the mechanism at the wrist. Separate motors drive the left and right belts, which engage the central gear [7]. If the belts are driven in the same direction, the wrist will tilt up or down. If the belts are driven in opposing directions, the wrist will rotate clockwise or counterclockwise.

Figure 4: Scorbot Wrist



We came across a version of a Cartesian robot at the Pinckney High School Robotics Laboratory, shown in Figure 23 in Appendix A [7]. This particular design only allows automated movement in y-direction, along two tracks mounted to the table driven by a simple motor and pulley system. However, it can be easily upgraded to move in the x-direction by attaching a car and drive system along the overhead crossbar. Similarly, a drive system could be attached to the two vertical bars, allowing for motion in the z-direction. The main advantages of this system are that it would be relatively simple to design and build, and that the controller would be intuitive and easy to learn since it is based on a Cartesian coordinate system. In addition, the bottom tracks (for motion in the y-direction) could be designed to mount onto the underside of a desk so that part of the system would be concealed. Despite the simplicity that this track system would bring, it would be difficult to design it in a way that it would not dominate the workstation. Even if we hide the bottom two tracks, the large vertical tracks and the crossbar will still stand out. We would also need to attach some kind of powered wrist joint in order to get the tilt and twist motions in the monitor.

There are many manufacturers of industrial Cartesian robots. One of the manufacturers is Techno Inc. Their Cartesian robots are assembled on custom surfaces with rail boxes bolted onto the work surface. The robot, shown in Figure 24 in Appendix A offers motion in the x, y, and z directions. However, it is difficult to determine what drives the motion because the tracks are concealed. [8]

Another manufacturer of Cartesian robots is NPA. They offer systems that can be mounted to most work surfaces. The rails are concealed, but are not preconfigured into a work area. The NPA Cartesian robot, shown below in Figure 5, also offers motion in the x, y, and z directions. The NPA robot is driven along the tracks by a ball screw and collar mechanism. This mechanism provides very precise motion with no backlash. [9]

Figure 5: NPA Cartesian Robot

4.3 Components

Many different components can be used to automate the monitor arm. One suggested solution was to couple the current arm with a small hydraulic system. The idea of this solution is to use a hydraulic cylinder with the main member of the arm to achieve extension. A hydraulic cylinder, when accompanied by a hydraulic system, performs much like an electronic actuator [10]. However, instead of using an electric motor like an actuator, the hydraulic piston is moved through pressure buildup from a hydraulic fluid such as oil. The use of a hydraulic system would require an oil line to be run from a hydraulic pump which is connected to an accumulator [11]. There are concerns with using a hydraulic system which include oil leakage and the use of additional parts when compared to an electronic actuator.

Electronic linear actuators would not have the risk of oil leaks, thus providing a more promising solution. However, after researching various products, we realized that the size is a limiting factor in their use. For instance, to achieve 2 inches of extension, the smallest actuator would be 6 inches in the compressed state. For this reason, we are unable to use a linear actuator to drive the wrist joint without loosing aesthetic appeal.

Motors are required to control most of our motions. We considered using servo motors, stepper motors, and DC geared motors. Our design calls for high torque and low speed, thus we decided to use DC geared motors. Both Servo and stepper motors do not provide sufficient torque (at least not within our budget). DC motors do not provide input/output feedback, but this is not a problem as the user provides this function.

4.4 Survey

A copy of the survey is provided in Appendix B. Unfortunately the Expo was too late to incorporate the findings into our design. However, the results will be helpful in further development. We received 10 responses and summarize the findings below.

1. The general consensus is that all motions are equally important. However, the tilt and back/fourth motions were found to be slightly important.
2. The results on desk space were split between minimal and most of desk space.
3. The range of motions provided is adequate. Everyone answered yes to this question.
4. The design is aesthetically pleasing. One suggestion to increase the appeal was to add a cover over the components and wiring.
5. Many people suggested that different control panels be designed for individual needs. However the preferences are as follows:
    a. Button Size: Large
    b. Button Type: Toggle
    c. Button Force: Soft touch (minimal force)
    d. Control Instructions: Pictures
    e. Control Location: Remote

5 REQUIREMENTS AND SPECIFICATIONS

In order to properly start the design process, our team determined the customer's requirements based on the information given to us during two meetings with our sponsors. These requirements were then translated into engineering specifications. Analysis of previous prototypes led to benchmarks that serve as comparison levels with our prototype. All of the above information is organized into a Quality Function Deployment (QFD) chart shown in Appendix C.

5.1 Customer Requirements

The customer requirements for the flat panel monitor positioning system are listed in Table 1 on the next page. These requirements were developed with our sponsors, who represent two groups with needs. ErgoQuest, Inc. ultimately wants to distribute the product, and UM ATCS represents the user group. Access to actual users for testing is limited, but Jim Knox of UM ATCS works very closely with the targeted user group and serves as a good representation.

Table 1: Customer Requirements for Flat Panel Monitor Arm

• 4 deg of freedom (5 if possible)	• Reliable
• Cost effective	• Safe
• Maintain simplicity	• Quiet
• Aesthetically pleasing	• Smooth movement
• Easy to use	

Many of the requirements from each group overlap. Safety is a top priority when designing a product that is intended for a person with physical handicaps. Both groups would also like a product that is aesthetically pleasing. Most people would prefer not to use a product that is too bulky or is an eyesore in their home. This in turn pleases ErgoQuest, Inc. because it makes the product marketable. Furthermore, the prototype should maintain the simplicity of current manual arms and have simple controls to operate the system. Many users will have limited motor skills and will not be able to properly control the prototype if the controls are complex. ErgoQuest also demands a simple product in the sense that many of the components used to drive motion should be off the shelf and easily adaptable to a monitor arm. This will make the manufacturing process simple. While in motion, the unit should operate at a low audible level while maintaining smooth flat panel monitor movement. The consumer also demands a reliable product. Both customer groups desire cost effective solutions.

Initially, it was desired that the prototype have five degrees of freedom: motion in each of the three planes as well as rotation about the vertical axis and rotation about the horizontal axis parallel to the user (twist and tilt). However, after discussing our Cartesian design with Jeff Vanden Bosch, he determined that motion in the x and z directions were not necessary. He then presented a new arm which we are to use in the product. With the new arm and track, only 4 degrees of freedom are required: along the track, moving the arm, and twist and tilt rotations. A fifth degree of rotation about the horizontal axis that is perpendicular to the user is desirable, but not necessary. Motion in the z direction will be controlled by the custom tables that the arm will be mounted on.

5.2 Engineering Specifications

Our team formed the engineering specifications to meet each of the customer requirements as shown in Table 2. The engineering specifications are all meant to take the customer requirements and translate them into numbers that can be used during the design process. An example of this is converting the customer's requirement of four degrees of freedom to specific target motion ranges. These specifications were presented to our sponsors and approved.

Table 2: Engineering Specifications for Flat Panel Monitor Arm

Engineering Specifications	Target Values
Supportable Monitor Weight	At least 30 lbs
Range in y-direction	36 inches (18" over table edge)
Tilt	±45 degrees
Twist	±45 degrees
User Control Interface	'Remote'
Monitor Speed	1-2.5 inches/sec or 10-15°/sec

5.3 Benchmarking Previous Prototypes

Two previous prototypes were evaluated based on how they met our set of customer requirements. The first prototype was created in fall of 2003. This prototype is not available for us to directly evaluate, however the team in charge of the winter 2004 project evaluated it; we used the same benchmarks. The second prototype was created in winter of 2004 and was evaluated by our team. Our prototype was then benchmarked and compared to the previous attempts at solving this problem. We found that our prototype surpassed the previous two models significantly.

5.3.1 Benchmarking our prototype

The following explains how we determined the benchmark values of our prototype.

- *Aesthetically Pleasing*: we determined our model to be quite aesthetically pleasing. Our survey supports this. However, the addition of covers and paint could improve the appearance.
- *Cost Effective*: unfortunately we went over budget. However this was necessary to achieve many of the other requirements.
- *Quiet*: the motors are quieter than previous models, however they are audible and the tilt motion is particularly loud.
- *Easy to Use*: our prototype is very easy to use, as the motions are intuitive. The remote control box also adds to the ease of use. However, the toggle switches are a bit difficult to push.
- *Reliable*: after multiple runs, our prototype runs at top performance. The only fear is that after more use the limit switches may not hold because they are epoxied on rather than screwed on.
- *Safe*: the speed of the model is safe, and the limit switches stop the motion before hitting the structure. However, no systems are in place to stop the motion if the arm hit's an external body such as a wall or user.
- *4 Degrees of Freedom*: the required degrees of freedom are available and full range of motion is achieved.
- *Maintain Simplicity*: use of off-the shelf products greatly increase the simplicity. However, many of our manufactured pieces require a bit of work, thus reducing simplicity.
- *Smooth Movement*: the motion is quite smooth. There is some give in the assembly however which allows for a minimal amount of wobble.

5.4 Organization of the QFD

To construct the QFD, we first listed the customer requirements along the left and the engineering specifications across the top. Weights were assigned to each customer requirement on a scale of one to ten, ten being the most important. The triangular area above the engineering specifications is a correlation matrix. It was used to evaluate the degree of interaction. If a relationship existed between two technical specifications, it was evaluated at one of four levels: "++" and "+" represent strong and medium positive relationships; "--" and "-" represent strong and medium negative relationships. Target values for the engineering specifications were listed at the bottom of the QFD. The benchmarks for customer requirements are listed on the right hand side of the QFD.

The center of the QFD forms the relationship matrix. Here, the relationship between each engineering specification and customer requirement was evaluated. If there was a relationship, the strength of that relationship was rated with a one, three, five, seven, or nine with nine being a strong relationship. If no relationship was determined, the space was left blank. The relationship strengths and customer requirement weights were evaluated and normalized to determine the most important engineering specifications. This revealed that the track movement and arm extension are most important, and the cost of the solution is the least important.

6 CONCEPT GENERATION & EVALUATION

Our concepts were inspired by the literature search and developed through several brainstorming sessions. After compiling a large list of ideas, we evaluated a few key concepts and selected the best. We then broke the selected concept into modules that were individually evaluated.

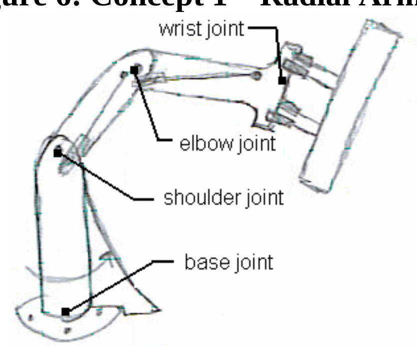
6.1 Concept Generation

After considering our research and brainstorming for many days, we decided to develop a new design rather than using the initially provided arm. Key reasons for this decision are that the provided arm is not intuitive to the user and also that moments due to the monitor will be large. Four concepts are described below.

6.1.1 Concept 1: Radial Arm

This concept, shown in Figure 6, aims to give more intuitive motion. However due to arm extension, large moments will be present. A flange attached to the base would provide additional support with minimal size increase. The idea behind this design is inspired by the human arm, as well as many current robotic arms. The arm is supported by a base which rotates about the z-axis. A shoulder joint, elbow joint and wrist joint provide similar motions to that of a human arm. The base, shoulder and elbow joints would provide x, y and z movement while the wrist would provide tilt and twist. In this particular drawing, linear actuators are used to control movement, however many other components could be used.

Figure 6: Concept 1 – Radial Arm

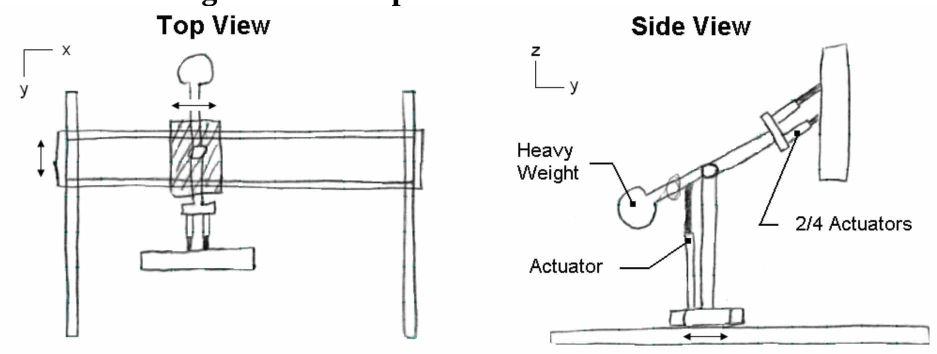


6.1.2 Concept 2: Cartesian-Articulate 1

Our second concept incorporates ideas from both the Cartesian and articulate robots that we researched. The Cartesian-Articulate hybrid, shown in Figure 7 on page 14, is similar to the ST Robotics R17 robot arm and the Cartesian robot we saw at the Pinckney High School

Robotics Lab. This design greatly reduces the moment forces because forward motion is achieved by moving along the track, rather than extending the arm. A counterweight on the arm will also help eliminate the net moment and lower the torque requirements on the chosen drive system. However, the large weight of the monitor (and counterbalance) will cause high stresses in the rails. Furthermore, this design greatly reduces the amount of desk space, appearing quite bulky, and will be difficult to adapt to different desk sizes.

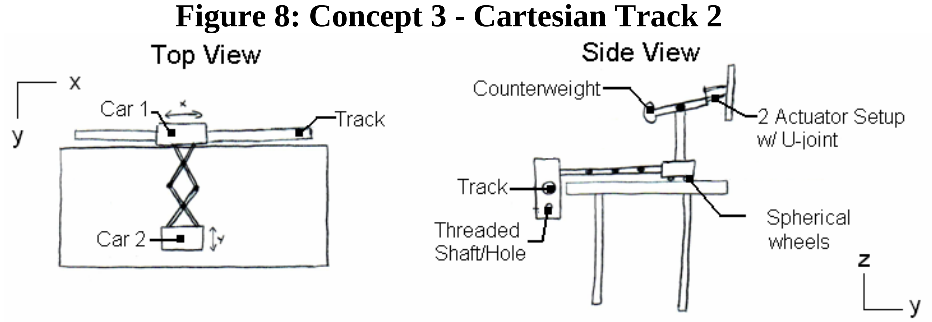
Figure 7: Concept 2 – Cartesian Track 1



6.1.3 Concept 3: Cartesian-Articulate 2

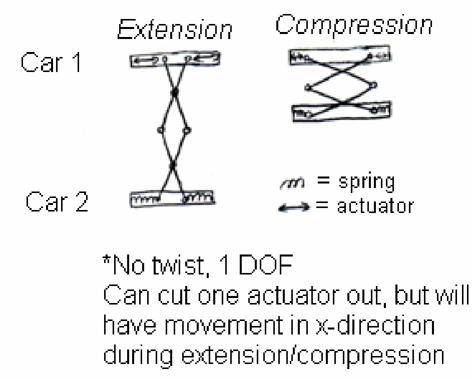
After discussing our first track idea with our sponsors, we were encouraged to further develop the idea. To improve on the previous concept, we wanted to produce a more stream-lined design and increase desk space. Movement in the x-direction would be achieved using a car driven by a threaded rod and guided by a track. The track would mount to the backside of a desk. Movement in the z-direction would be achieved by a simplified robotic arm, shown in Figure 8, similar to that in concept 2. However, instead of an actuator, we are also considering the possibility of incorporating a worm gear to power the motion in the z-direction. Worm gears have the advantage of getting a high torque with a small motor. Additionally, they cannot be back-driven, so once the monitor is moved to a certain position, the gearing system will prevent any unwanted movement.

Figure 8: Concept 3 - Cartesian Track 2



Movement in the y-direction would be achieved with the linkage system shown in Figure 9 on page 15. This 'lazy tongs' linkage is employed on scissors lifts used for various construction applications. With this linkage, we can maximize the amount of conserved desk space, as most of the desk will be accessible when the linkage is compressed. Actuators can be mounted on car 1, which are extended to push car 2 toward the front of the desk. Springs will be mounted on car 2. The function of these springs is to keep car 2 centered with respect to the linkages. Stiffness in these springs will need to be high enough to correct disturbances to the cart, but low enough that the actuators in car 1 can easily overcome them.

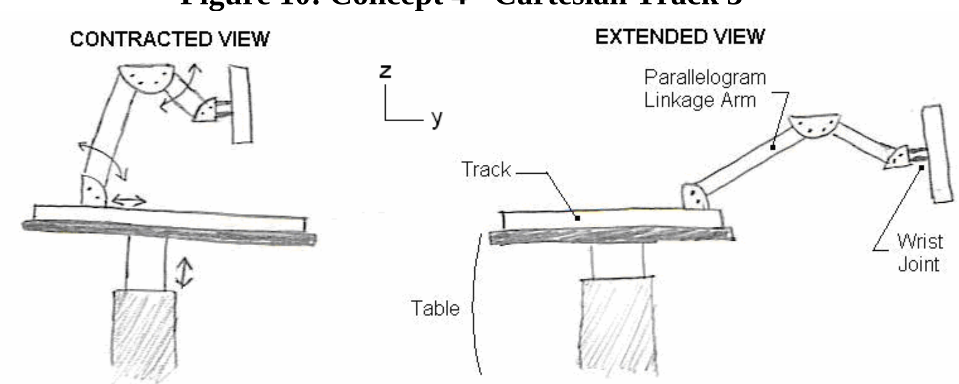
Figure 9: Concept 3 - Y-Direction Linkage



6.1.4 Concept 4: Cartesian-Articulate 3

The Cartesian concepts generated further discussion between our group and Jeff, our corporate sponsor. During a meeting, the customer requirements were relaxed, and a fourth idea was generated. This idea does not need to provide x or z direction movement. A new arm was provided which moves using interconnected parallel-bar linkages. Extending the arm will provide movement beyond the front of the desk. The arm is attached to a track which spans the desk, allowing for movement along the desk. Slight motion in the z direction is achieved by extending the arm, however most z-direction motion will be handled by the desk on which it is installed. The idea is sketched in Figure 10 below.

Figure 10: Concept 4 - Cartesian Track 3



6.2 Concept Evaluation and Selection

Our designs can be divided into two categories: Rotational Arm and Cartesian Track. We evaluated each category for 5 key requirements. These are:

- How well 4 degrees of freedom are obtained
- How easy the controls would be to use
- How well the monitor weight can be supported
- How well full range of motion can be achieved
- How aesthetically pleasing the design is

Tables 3 and 4 on the following page summarize our evaluation of the two categories. Table 3 applies to concept 1, while Table 4 applies to concepts 2-4.

Table 3: Rotational Arm Evaluation

Functional Requirement	How meets the FR	Reference / Prior Art	Analysis / Calculations	Risks / Drawbacks / Challenges	How can risk be mitigated?
4 DOF	Excellent	Previous Model	Wrist Joint provides Tilt, Twist. Base provides X-Y plane motion. Arm provides Z-Y plane motion.	User might need six degrees of freedom.	Integrate another twist about the y plane to rotate the monitor.
Ease of Controls	Okay	Previous Model	Controls aren't very intuitive.	LCD can only move in a limited range, so if user says go left, it will rotate and go left and backwards.	Complex control system to control multiple motions at the same time.
Support Monitor Weight	Okay	Previous Model	Yes, but monitor is cantilevered out causing a large moment at the base mounting. $M_{base} = M_{LCD}*X_{extension}$ This can get large.	At full extension, the monitor is cantilevered out from the base. This puts a large moment on the base mounting.	The use of a counterweight system. Fabricate original arms and joints with stronger materials.
Full Range of Motion	Okay	Previous Model	Can provide motion over a limited area of the desk.	The unit cannot hit every point on the desk due to limitations of where the system is mounted. The unit will only move within the arc of the arm. There are toggle spots that are inaccessible.	There is no real solution with this concept.
Aesthetically pleasing	Okay	Previous Model	Components will be large and bulky to support large moment.	Large components sitting outside of beams/joints.	Can fabricate arms to conceal components.

Table 4: Cartesian Track Evaluation

Functional Requirement	How meets the FR	Reference / Prior Art	Analysis / Calculations	Risks / Drawbacks / Challenges	How can risk be mitigated?
4 DOF	Excellent	Existing Models	Wrist Joint provides Tilt, Twist. Track(s) provide X and Y motion. Arm provides Z motion	User might expect 6 DOF.	Integrate another twist about the y plane to rotate the monitor.
Ease of Controls	Excellent	Existing Models	Intuitive controls move in just one direction.		
Full Range of Motion	Excellent	Existing Models	Follows a grid system of movement.	Possible loss of usable desk space. If not used properly, setup might be harmful.	Components fully retractable.
Support Monitor Weight	Excellent	Existing Models	Moment arm is small due to the shorter arm requirement.	Might require bulky components. Component might fail and be hazardous to the user.	Use counterweights to distribute the weight.
Aesthetically pleasing	Okay	Existing Models	Setup is simple and components can be concealed.	Possible scuff marks on table.	Use components with low friction.

After evaluating each design, we were ready to select the best option. To do this, we used a Pugh Chart, seen in Table 5. We chose our rotational robot arm concept as the datum and compared it to our Cartesian-Articulate hybrids. For most of the customer requirements, such as quiet and smooth movement, we are unable to determine which concept will be better as they are determined by component selection rather than concept. For these requirements, we assumed equivalent performance across each concept. After weighing the designs, concepts 3 and 4 were determined to be the best. Our sponsors were more supportive of concept 4, thus we will pursue this design for our project.

Table 5: Concept Pugh Chart

Customer Requirement	**Weight**	***Concept 1*** **Rotational Arm (Datum)**	***Concept 2*** **Cartesian-Articulate 1**	***Concept 3*** **Cartesian-Articulate 2**	***Concept 4*** **Cartesian-Articulate 3**
Aesthetically Pleasing	8	0	-	-	-
Cost Effective	6	0	0	0	0
Quiet	8	0	0	0	0
Easy to Use	10	0	+	+	+
Reliable	6	0	0	0	0
Safe	7	0	+	+	+
4 Degrees of Freedom	10	0	0	0	0
Maintain Simplicity	7	0	0	+	+
Smooth Movement	6	0	0	0	0
	Total +	0	3	4	4
	Total -	0	1	1	1
	Weighted Total	0	9	16	16

6.3 Concept Modules

As discussed above, we have selected concept 4. To continue our design process, we broke this concept into 3 modules. These modules are:

- Track
- Arm
- Wrist

Actuating components were selected for each module, as discussed in the following subsections.

6.4.1 Track Module

To achieve y-direction motion along the desk, we chose to use a manual rail system and attach a drive system. Currently, there are systems with a built in actuator that we considered using. However, the price range is well over our budget, ranging from $1400 – $2200, and most systems do not include the driving motor.

We considered three options for driving the carriage along the track. These include a belt system, a linear actuator, and a screw drive system. The ideas are compared in Table 6 on the next page. Notice that the cost effectiveness of the linear actuator has 3 '-'. This was done because the cost of an actuator is significantly more than for the belt system.

Table 6: Track Module Pugh Chart

Customer Requirement	Weight	Belt System (Datum)	Linear Actuator	Screw Drive System
Aesthetically Pleasing	8	0	+	0
Cost Effective	6	0	---	-
Quiet	8	0	0	0
Easy to Use	10	0	0	0
Reliable	6	0	0	0
Safe	7	0	0	0
Maintain Simplicity	7	0	+	0
Smooth Movement	6	0	0	0
	Total +	0	2	0
	Total -	0	1	1
	Weighted Total	0	-3	-6

From the Pugh chart, we chose to use a belt drive. The details of belt selection are further discussed in the engineering analysis, Section 7.1.

6.4.2 Arm Module

To actuate extension of the monitor arm, we chose to use a slender electromagnetic actuator, which will be placed inside the first link of the monitor arm. The first link is a parallelogram linkage; therefore, when the arm is extended and retracted, the distance between opposite pins of the parallelogram changes. The actuator will control the distance between these pins, which will ultimately control the extension of the arm.

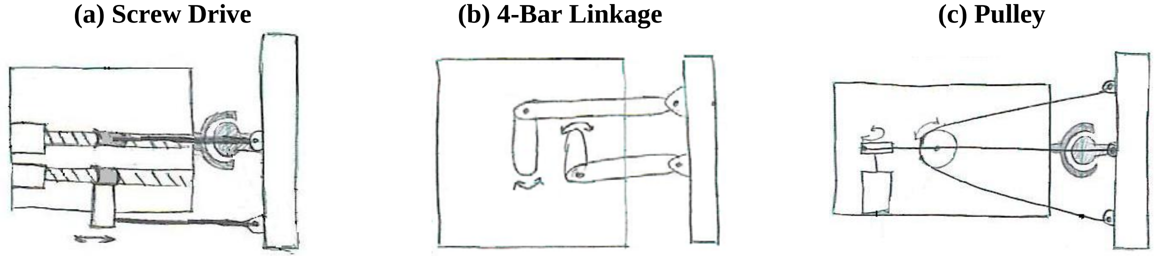
An alternate solution is a belt system similar to the Scorbot (Figure 22, Appendix A). However, this would add to assembly complication as well as decrease smooth motion.

6.4.3 Wrist Module

As stated in Section 4.3, simple linear actuators are too large to incorporate into the wrist joint. Thus, designing the wrist required the most ingenuity. We developed three concepts, shown in Figure 11. Figure 11a depicts a screw drive system, Figure 11b depicts a 4-bar linkage system, and Figure 11c depicts of a pulley system.

Figure 11: Wrist Concept Sketches

(a) Screw Drive **(b) 4-Bar Linkage** **(c) Pulley**



Each concept is evaluated in Tables 7-9 and compared in Table 10. From the Pugh chart, we initially selected the pulley concept. However after conducting engineering analysis, which is discussed in Section 7.3, we decided to develop the 4-bar linkage system.

Table 7: Screw Drive Evaluation

Functional Requirement	How it meets the FR	Reference / Prior Art	Analysis / Calculations	Risks / Drawbacks / Challenges	How can risk be mitigated?
Ease of Controls	Excellent	Previous model	Tilt/twist controls are intuitive.	Tilt and twist functions may create forces opposing the motion of the other.	Design proper alignment to ensure motions do not oppose one another.
Full Range of Motion	Excellent	Intuition	More motion can be provided by lengthening the screw.	Large moment due to monitor may back drive the motor and cause slippage along the screw.	No solution at this point.
Aesthetically pleasing	Poor	Intuition	Screws may need to be long to provide full range of motion.	Long screws may appear bulky.	Some sort of box to cover the components.

Table 8: 4-Bar Linkage Evaluation

Functional Requirement	How it meets the FR	Reference / Prior Art	Analysis / Calculations	Risks / Drawbacks / Challenges	How can risk be mitigated?
Ease of Controls	Excellent	Previous model	Tilt/twist controls are intuitive.	Tilt and twist functions may create forces opposing the motion of the other.	Design proper alignment to ensure motions do not oppose one another
Full Range of Motion	Excellent	Previous model	Twist: $M_{torque} = M_{friction} + M_{pin}$ $M_{pin} = r_{pin} \cdot \mu \cdot R$ Tilt: $M_{torque} = M_{friction} + W \cdot d \cdot \cos\theta$	Tilt: A large torque is needed to drive the motor due to rotation offset.	No solution at this point.
Aesthetically pleasing	Okay	Previous model	Components are simple and are hidden by the monitor. System can be designed better than previous model.	If linkages are large, setup might seem bulky and unattractive	Use small bars for linkage system to avoid bulkiness.

Table 9: Pulley Evaluation

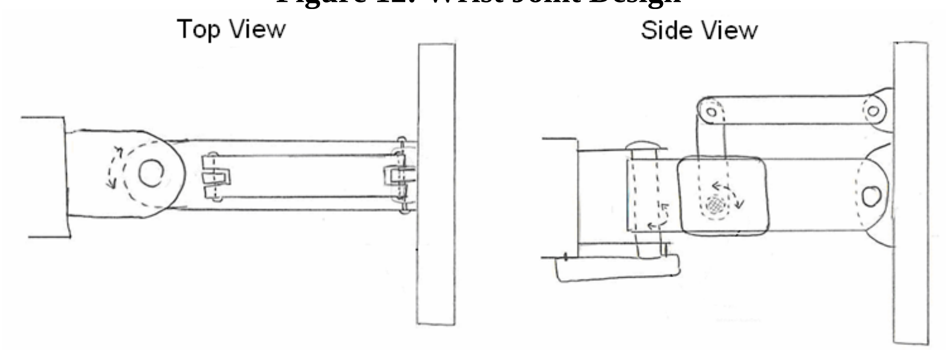
Functional Requirement	How it meets the FR	Reference / Prior Art	Analysis / Calculations	Risks / Drawbacks / Challenges	How can risk be mitigated?
Ease of Controls	Excellent	Previous model	Tilt/twist controls are intuitive.	Tilt and twist functions may create forces opposing the motion of the other.	Design proper alignment to ensure motions do not oppose one another.
Full Range of Motion	Excellent	Previous model	To achieve more movement, we simply need to rotate the motor shaft more.	A large torque is needed to drive the motor due to a compact pulley system. Slack may occur in the system.	No real solution at this point. Design tension control system.
Aesthetically pleasing	Okay	Previous model	Components are simple and are hidden by the monitor.	If the pulleys/belts are too large, setup might seem bulky and unattractive.	Use small pulleys/belts to avoid bulkiness.

Table 10: Wrist Module Pugh Chart

Customer Requirement	Weight	*Concept 1* Screw Drive (Datum)	*Concept 2* 4-Bar Links	*Concept 3* Pulleys
Aesthetically Pleasing	8	0	+	+
Cost Effective	6	0	0	0
Quiet	8	0	0	0
Easy to Use	10	0	0	0
Reliable	6	0	0	0
Safe	7	0	0	0
Maintain Simplicity	7	0	0	+
Smooth Movement	6	0	0	0
	Total +	0	1	2
	Total -	0	0	0
	Weighted Total	0	8	15

We further developed the 4-bar linkage system, and our design is depicted in Figure 12 on the following page. The twist function is achieved by simple rotation of a motor shaft. Tilting the monitor is achieved using parallelogram linkage system. This is similar to the previous ME 450 arm, however because we are only driving the tilt function and not supporting the monitor with the links, we believe it will be more aesthetically pleasing.

Figure 12: Wrist Joint Design



7 ENGINEERING ANALYSIS

Before ordering parts, we conducted analysis of the three modules. The following subsections discuss the calculations and decisions that were made. In order to simplify controls, we decided that each electric component should run on a 12 VDC power source.

7.1 Track Analysis

Analyzing and selecting parts for the track system was done in two parts. The first is selection of the guide rail. The second is selection of the drive system, which is partially dependent on the chosen rail and carriage.

7.1.1 Guide Rail Analysis

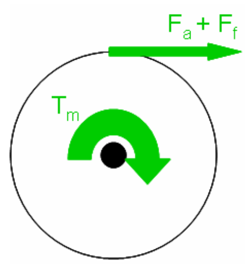
We decided to use a profile rail guide from SKF Linear Motion, which included a precisely machined rail and carriage. This size 35 carriage is able to support a load and moment far greater than the 260 N and 120 N·m needed for our system. The size 20 carriage is also able to support the loads for our design, but is not much cheaper than the size 35 and is not properly dimensioned for our arm base. The rail length we chose is 460 mm (~18 inches), which is the depth of the desk we will be mounting our system to. We were able to get this rail system at a discounted price of $250, and were told that if the system were to be put into production, our sponsor would receive even larger discounts. The specifications for this part can be found in Appendix D.

7.1.2 Drive System Analysis

After selecting a guide rail system, sizes for the belt drive needed to be chosen. We chose a XL 0.375 inch wide timing belt to be used with two 1.508 inch outer diameter steel timing pulleys. A timing belt was chosen as opposed to a v-belt because the cogs will reduce belt slippage during operation. Before analyzing for motor selection, a desired carriage speed of 1 in/s was assumed with a time of 2 seconds to reach this speed from a stop. This speed is deemed to be a safe speed for the user.

To calculate motor torque required for the carriage actuation we analyzed the forces and moments occurring at the drive pulley. First, the friction between the track and carriage was estimated using a fish scale force gauge. The weight of the load is estimated to be 30 lbs and plate weights were used to simulate the mass. The frictional force was thus measured to be approximately 4 lbs. Using Newton's second law and a desired carriage acceleration of 2 in/s^2, the force required to accelerate the mass was found to be 0.156 lbs. Adding this to the frictional force, total force at the pulley is 4.156 lbs. Using torque calculations, we found that the minimum moment supplied by the motor needs to be 3.13 in·lbs. Thus with a safety factor of two, we need a motor that provides 6.26 in·lbs of torque. The free body diagram used in these calculations is shown in Figure 13.

Figure 13: Track Motor Free Body Diagram



The Specifications for the purchased motor are given in Appendix E.

7.2 Arm Analysis

To find the force needed to move the arm, we used a fish scale to physically measure it. We needed a strong actuator that was not backdriveable, so that power is not required to hold a desired position. The actuator we chose to handle this load was ordered from SKF linear motion; specifications are located in Appendix F. We were able to get this actuator at a discounted price of $200 and were told that if the system were to be put into production, our sponsor would receive even larger discounts. This majority of the actuator will fit inside the monitor arm; however, we will need to cut a hole in one link in order to accommodate the motor.

7.3 Wrist Analysis

The wrist joint required the selection of two DC geared motors. The analysis for each was done separately and is presented below. First, the drawback of the pulley system is discussed.

7.3.1 Pulley Analysis

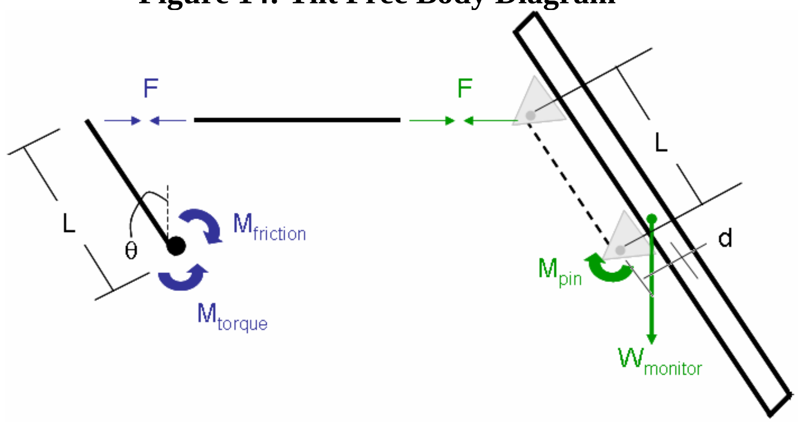
Initially, we desired to use a pulley system for wrist actuation. However, during our torque analysis, we discovered a significant drawback. Because the monitor does not pivot about its center, but rather a pin roughly 3.5" from the center, the pulley system is much more complicated than initially planned for. This offset causes the cable ends to extract/retract at different rates. After creating a 2-D mockup, we discovered that the cable could gain more than an inch of slack. This would potentially cause problems in controlling the motion.

The problem could be alleviated by designing a tension system similar to that for bike gearing. However, this significantly complicates the design, motivating us to pursue a parallelogram linkage system.

7.3.2 4-Bar Tilt Analysis

To determine the amount of torque required for the tilt function, we drew a free body diagram of the 4-bar system. This Diagram is shown in Figure 14.

Figure 14: Tilt Free Body Diagram



From this diagram, we developed two force-balance equations:

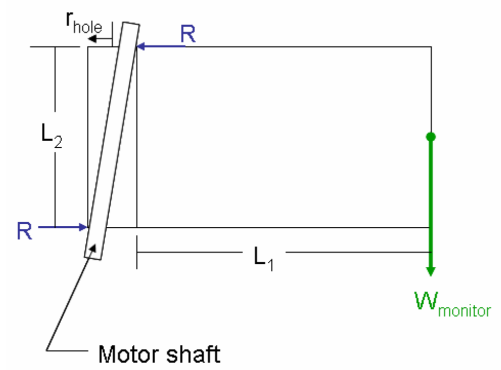
(1) $M_{torque} = L \cdot F\cos\theta + M_{friction}$ (2) $L \cdot F\cos\theta = d \cdot W_{monitor}\cos\theta + M_{pin}$

Where $M_{friction}$ is the internal motor friction and M_{pin} is the friction at the pin joint. Solving these equations, we determined $M_{torque} = d \cdot W_{monitor}\cos\theta + M_{friction}$, which will be a maximum of $d \cdot W_{monitor} + M_{friction}$ when $\theta = 0$. We assumed the weight of the monitor to act along the centerline, thus measuring d = 3.5" on our supplied monitor. M_{pin} was neglected and accounted for in the safety factor. Using these equations and a safety factor of 2, torque in excess of 80 in·lbs was required. These motors were quite expensive, so we incorporated springs to provide additional force. By doing this, we were able to purchase a motor supplying 50 in·lbs. The specifications are provided in Appendix E.

7.3.3 4-Bar Twist Analysis

The twist function will not be fighting against the monitor weight, so the required torque will be much smaller. An exaggerated free body diagram is shown in Figure 15.

Figure 15: Twist Free Body Diagram



Here, $M_{torque} = M_{friction} + M_{pin}$, we need to find M_{pin}. From the diagram, we determined $R=W_{monitor}L_1/L_2$. Using $M_{pin} = r_{hole}\mu R$, and assuming $\mu=0.5$ and a safety factor of 2, $M_{torque} =$ 18.8 in·lbs. The specifications of the purchased motor are in Appendix E.

8 FINAL DESIGN

After designing our concept and selecting components, we finalized our design. A 3-D model of our concept was drawn using Solidworks. Additionally, we designed the parts we must manufacture for complete assembly of our prototype; these parts are discussed in detail in Section 9. The materials necessary for these parts, as well as the ordered components are presented in a Bill of Materials in Appendix I. The final step in completing our model was designing and implementing the controls.

8.1 Design Models

A 3-D CAD model of our final design is shown in Figure 16 on the following page. Photos of the physical prototype are displayed in Appendix J. This model incorporates both the mechanical and electrical components. Each module is discussed in the subsections. Below our full CAD drawing are the 3-D models of the two previous prototypes, Figure 17a and b. These are provided for visual comparison.

Figure 16: 3-D CAD Drawing of Final Design

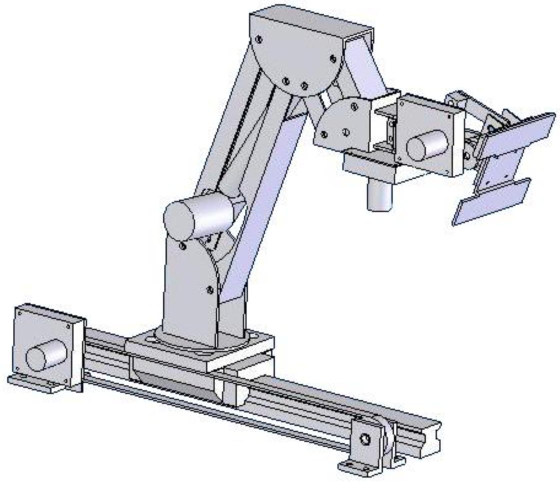
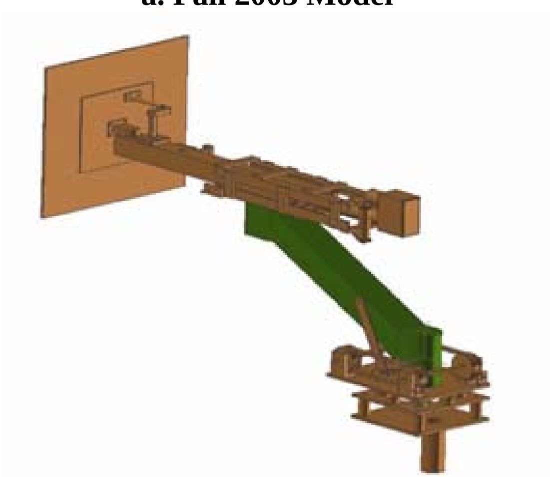
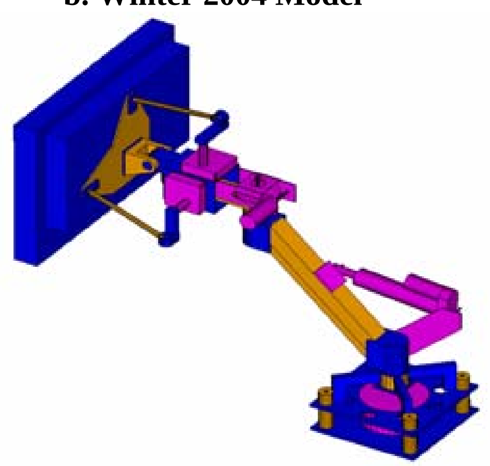


Figure 17: CAD Drawing of Previous Prototypes

a. Fall 2003 Model **b. Winter 2004 Model**



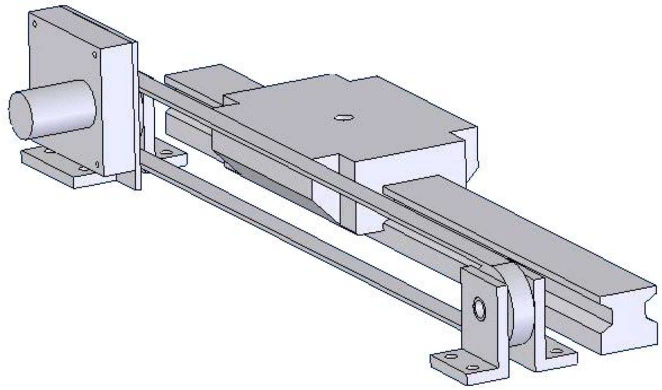


Our model is much more streamlined, particularly at the base. Large moments from the monitor required the previous groups to use a very bulky support. Using the rack design, we were able to eliminate this.

8.1.1 Track

The track module is shown in Figure 18 on page 25. This figure shows the track, carriage, belt drive system, and the arm to carriage adaptor plate. The track, carriage and belt system/motor were purchased; specifications for these parts are given in Appendices D and E. Pulley and motor mounts, as well as the adaptor plate were manufactured. Details of these parts are discussed in Section 9.1.

Figure 18: CAD Drawing of Track Module

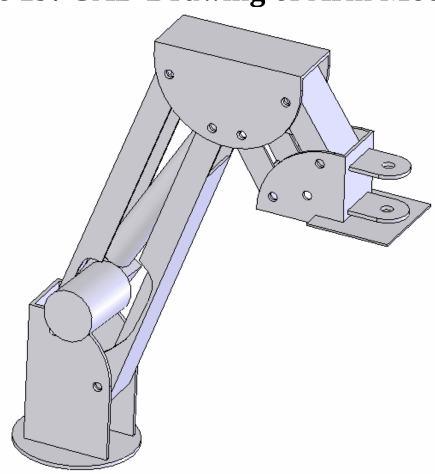


As seen, a timing belt is wrapped around two sheaves and attached to the carriage via the adaptor plate. When the motor spins the belt is engaged by the pulleys, which drives the carriage forward or backwards.

8.1.2 Arm

The arm module is displayed in Figure 19. Shown is the arm and linear actuator, which were purchased. It is not visible in the drawing, but an adaptor bracket was needed to fit the actuator. This is discussed in Section 9.2, along with the cut slot for the actuator motor. The specifications for the actuator are in Appendix F.

Figure 19: CAD Drawing of Arm Module

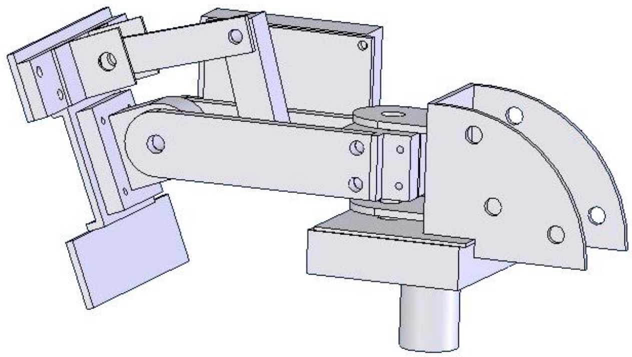


As the actuator extends, it shifts the orientation of the arm parallelogram. This causes the arm to extend. Similarly, contracting the actuator causes the arm to contract.

8.1.3 Wrist

The wrist module is shown in Figure 20 on the next page. There is a lot of detail in this module, as it is responsible for two degrees of freedom. The two motors and springs were purchased; motor specifications are in Appendix E. Many parts were manufactured for the wrist joint, which are discussed in Sections 9.3 and 9.4. These parts are the support link, two parallelogram links, motor mounts, and a monitor mount.

Figure 20: CAD Drawing of Wrist Module



One end of the support link is clamped directly to the twist motor shaft. Thus, when the motor shaft rotates, the monitor rotates through the tame angle. For the tilt function, a link running parallel to the monitor is attached to the motor shaft. A second link completes the parallelogram structure and transmits motion. So, as the motor shaft rotates, the monitor will rotate through the same angle.

8.2 Controls

Once we had a completely assembled prototype, we were able to implement controls. The control system needed to achieve two tasks: supply power to the motors when desired and cut power to the motors when motion has reached a limit. Schematics for the wiring are given in Appendix G.

The motors needed to be run in both forward and reverse directions. Because of this, a simple pushbutton would not work for controlling the motors. In order to pass both hot and ground in the two directions, we used DPDT toggle switches for each motor. By reversing the polarity, we were able to change the motor direction. In order to stop the motors when a limit was reached due to physical constraints, we incorporated limit switches. Two switches were required for each motor to complete the task.

Part of the controls was ensuring that each motion ran at a safe speed. We tried to select motors that would run at an appropriate speed, however both the track and twist motors ran a bit too fast. To reduce the speed, we needed to reduce the amount of supplied voltage. This could be accomplished by designing a voltage divider. However, we were provided with a power unit that supplied 12 VDC, 5 VDC, and 3.3 VDC. Thus, we chose to simply run the track and twist motors at the reduced 5 VDC. The arm actuator and tilt motor were run at 12 VDC.

We chose to design a control box that was small and could be brought to the user (similar to a remote control). The dimensions for this are given in Appendix H. The box was constructed from Plexiglas and epoxied together. The front panel was attached using Velcro, allowing for easy access to wiring. Plenty of excess wire was provided so that the control box could extend to the user from the table.

9 MANUFACTURING

The manufacturing of our prototype was broken down into four main components: the track system, the linear actuator, the wrist joint, and the linkage system. These components are based around an existing monitor arm which was supplied by Ergoquest. The materials used are summarized in the Bill of Materials in Appendix I. Engineering drawings of each part are supplied in Appendix K. Table 11 below summarizes the speeds used during the machining process [12].

Table 11: Summary of Machining Speeds

Material	Operation	Size	Speed
Aluminum	Milling	3/8"	~1500 RPM
Aluminum	Milling	1"	~1200 RPM
Aluminum	Drilling	>1/2"	~800 RPM
Aluminum	Drilling	<1/2"	~1000 RPM
Steel	Milling	3/8"	~1000 RPM
Steel	Drilling	13/64"	~1000 RPM
Steel	Drilling	5/8"	~350 RPM
Steel	Drilling	1 1/16	~200 RPM

9.1 Track System

The track system required us to fabricate an adaptor plate for the arm to attach to the carriage, three sheave mounts, and one motor mount. For assembly, it was necessary to attach the track and pulleys to the provided table.

9.1.1 Carriage/Arm Adaptor Plate

(Figure 32) - The adaptor plate was fabricated out of a ½" inch aluminum plate found in the machine shop. The plate allows the arm base to be rigidly attached to the carriage, and also provides a location for the belt to attach to the carriage. The plate was machined using the mill to a 4¾" by 4¼" square plate with 4 (7/16") holes and 2 (13/32") holes. These holes were counterbored using a ¾' end mill, which allows the bolt heads to lie below the surface of the plate. To attach the belt to the adaptor plate we first machined a notch on the bottom of the plate using a ⅜" end mill. This notch ensures that the belt remains horizontal while attached to the plate with belt clamps. Then, 3/16" holes were drilled using the mill to provide mounting locations for the belt clamps. The adaptor plate attached to the carriage using 4 M6x40 bolts while the base of the arm attached to the adaptor plate using 2 (⅜") bolts with locknuts. During assembly, it is important to insert the two ⅜" bolts before attaching the plate to the carriage.

9.1.2 Sheave Mounts

(Figure 33) - The sheave mounts were fabricated out of aluminum angle brackets found in the machine shop. Each of the 3 mounts were cut to 1½" wide by 2" high. 5/16" holes were drilled in the base of the mounts using a drill press. These holes allow for the mounts to be attached to the table top. To accommodate ⅜" brass press fit linear bearings ½" holes were drilled in the side of the brackets using a drill press. A piece of ⅜" aluminum bar stock was cut to length using the band saw. This bar allows the free spinning sheave to join the assembly.

9.1.3 Motor Mount

(Figure 34) - The track motor mount was made using a piece of aluminum angle bracket found in the machine shop. 2 (5/16") holes were drilled through the base of the bracket using a drill press, allowing the mounts to be attached to the table. 4 (3/16") holes and a ⅝" hole were drilled using a mill for attaching the motor. The mill was used in this case to ensure accuracy; the motor shaft must be horizontal and remain perpendicular to the track when attached to the table. Some of the motor mount hangs off of the back of the table, so to keep the design as aesthetically pleasing as possible, we machined out all of the unnecessary parts of the mount using a ⅜" end mill.

9.1.4 Assembly

All of the pieces of the track system were attached to the table by using through bolts and nuts. The track required 6 (⅜") holes to be drilled through the table using a hand drill. The holes were positioned so the track would run perpendicular to the front edge of the desk. The track is ½" longer than the table is deep, so we positioned the track with the excess hanging off the back of the table. 5/16" socket head screws and nuts were used to attach the track to the table. The pulley system required 8 (5/16") holes drilled using a hand drill. These holes are larger than the ¼" bolts used to attach the brackets to the table to allow for fine adjustments of the pulley system alignment.

9.2 Linear Actuator

In order for our purchased linear actuator to fit into the arm, it was necessary for us to fabricate an adaptor bracket as well as modify the existing arm to allow the motor to protrude out one side of the arm.

9.2.1 Linear Actuator Extension

(Figure 35) - The extension was made using a ⅝" ID steel tube. The tube was cut to length using the band saw, and 5/16" holes were drilled through each end using the drill press. The pins will fit through these holes. This piece allows for the end of the linear actuator to attach to the existing pivots in the arm using 5/16" pins.

9.2.2 Arm Modification

To allow for the motor of the linear actuator to move freely within the arm we had to machine slots in the side of the existing arm. To do this we used a ½" end mill. The tolerances on this piece were not important so we were able to machine out the slot by eye. The slot was then filed to ensure that it was both smooth and the motor would easily fit within it.

9.3 Wrist Joint

The wrist joint was the most complicated component to manufacture and was fabricated in several different parts: the tilt motor mount, the twist motor mount, the twist motor shaft connector, and the extension arms. We reused the existing monitor mount so it was not necessary to fabricate a new one.

9.3.1 Tilt Motor Mount
(Figure 36) - The tilt motor mount was fabricated out of ⅛" aluminum plate. The mill was used to drill 4 (3/16") holes, 1 (⅝") hole, 1 (5/16") hole, and 2 (¼") holes. The band saw was then used to shape the plate to be as small as possible. Bob Coury TIG welded the plate to the extension arm, ensuring that the corresponding holes on the extension arm and plate were concentric. This weld adds structural support for the motor. The tilt motor was then attached to the plate using the screws provided by the manufacturer.

9.3.2 Twist Motor Mount
(Figure 37) - When creating the twist motor mount we first had to modify the end bracket of the existing arm. To do this we used a ½" end mill to machine a slot to accept the plate where the motor would be mounted. The motor mount was made out of ⅛" steel plate found in the machine shop. The plate was cut to a size of 3"x 2¾" using the band saw. The mill was then used to drill 4 (3/16") holes and 1 (⅝") hole to allow the motor to be mounted to the plate. Bob Coury then TIG welded the plate onto the previously machined slot. The screws that were provided by the motor manufacturer were then used to mount the motor to the plate.

9.3.3 Twist Motor Shaft Clamp
(Figure 39) - The clamp was machined out of a piece of 1¼" x 1⅜" x 1¼" aluminum stock purchased from ASAP Source. The stock was first squared using a mill and a ⅜" end mill. Next, slots on both sides of the piece were machined using the same end mill in order to accept the extension arms. In these slots, 2 (¼") through holes were drill to accommodate the mounting bolts for the extension arms.

A 5/16" through hole was then drilled through the top of the piece using a mill, where the twist motor shaft would be clamped. A slot was cut through this hole using a band saw, which allows the piece to clamp onto the motor shaft. The previous hole was then reamed using a spiral flute ream, as to not catch on the slot that had just been cut. A #25 bit was then used to drill 2 holes perpendicular to where the motor shaft would be. The holes passed through the slot which had just been cut, providing a location for screws to tighten the piece around the motor shaft. Next, a 3/16" bit was used to expand one side of the 2 holes drilled with the #25 bit. A 10-24 tap was used to thread the unexpanded part of the hole.

With 2 1" long 10-24 screws we could now clamp the motor shaft into the shaft connector. Initially the connection was not strong enough, so material was removed from both sides of the piece using a ⅜" end mill. This allowed a better connection to be obtained between the motor shaft and the clamp. When the clamp was installed in the arm, a 5/16" diameter pin was inserted into the top of the connector because the motor shaft did not reach all the way through the piece. This pin also helped support the weight of the monitor. The pin was inserted through a ball bearing fitted into the end bracket of the arm. The bearing was fitted into a ¾" hole drilled into the end bracket of the arm.

9.3.4 Extension Arms
(Figures 40 and 41) - The extension arms were fabricated out of ¼" x 1⅛" x 4½" aluminum flat bar. 2 (¼") holes were drilled through one side of the arms using the mill, which allowed

the arms to be attached to the shaft connector using 2 (1½" long) bolts. On the other end, a 5/16" hole was drilled using the mill to allow for a pin joint where the monitor mount would attach. One of the arms had an additional ⅝" hole drilled to provide room for the tilt motor shaft to pass through the arm. The pin joint end was then rounded using a band saw and smoothed using a file.

9.4 Linkage System

The linkage system has three main components: the tilt motor shaft clamp, the connecting links, and the linkage mount. We found that the length of the tilt motor shaft clamp was independent of the force the tilt motor needed to provide, so we choose a length that was long enough to provide room for mounting, but not bulky. Cotter pins were used to secure all of the pins in the linkage system.

9.4.1 Tilt Motor Shaft Clamp - Parallelogram Link #1

(Figure 42) - The tilt motor shaft clamp was made out of a piece of ½" wide and 2½" long aluminum square bar found in the machine shop. At both ends of the link, a 5/16" hole was drilled using a drill press. One hole is for a pin joint with the connecting links and the other is where the tilt motor shaft will be inserted. Next, a slot was cut into one end of the link to allow the link to clamp to the motor shaft. Using a drill press, a 3/16" hole was then drilled through the end, passing through the slot. A 5/32" hole was drilled through the end of the connector opposite the motor shaft. This hole allows an eye bolt to be attached to support the springs. A ¾" long 10-24 screw and nut was used to tighten the connector around the tilt motor shaft.

9.4.2 Connecting Links - Parallelogram Link #2

(Figure 43) - The connecting links were fabricated out of ⅛" thick aluminum flat bar, ⅝"wide and 2 ¾" long, found in the machine shop. The two links were made so that they had a 5/16" hole at each end. Each hole accepted a pin to create a joint of the linkage system.

9.4.3 Linkage Mount

(Figures 44 and 45) - The linkage mount was a three piece component that attached the linkage system to the monitor mount. The plate of the linkage mount was made out of ¼" aluminum flat bar, 1" wide, found in the machine shop. The bar was cut to length using the band saw. 4 (3/16") holes were drilled into the bar using a mill. These holes were designed to correspond to the mounting holes on the monitor mounting bracket. Next 4 (# 29) holes were drilled into the bar and threaded using an 8-32 tap.

The two brackets were made out of aluminum angle brackets found in the machine shop. Each was cut to a length of 1" using the band saw. A 5/16" hole was drilled through one side of each bracket using a drill press. 2 (5/16") holes were then drilled through the opposite side of each. These holes allowed the brackets to attach to the plate. A 5/16" diameter pin was then used to attach the connecting links to the assembled linkage mount.

9.5 Other Details

In order for all of parts to fit together properly we had to modify some of the assembly components. The mounting screws that came with the motors were too long, so they had to be shortened using the band saw and filed to ensure the integrity of the threads. Also, bolts used to attach the sheave mounts to the table were not manufactured in the correct length so they were shortened in the same manner. To allow the springs to attach to the end bracket of the arm we replaced one of the existing pins with a 5/16" bolt long enough for the springs to be mounted to either side of the arm. A piece of felt was also cut to fit over the adaptor plate to hide the bolt heads and improve the aesthetics of the arm.

10 TESTING

To ensure that our prototype meet our sponsors' demands, we ran a series of tests. These include a range of motion test, a speed test, a weight test, and a reliability test.

10.1 Range of Motion

To determine if our prototype could achieve the range of motion set in our design specifications, we measured the range of motion provided by each degree of freedom. The maximum extension of the prototype was measured with a tape measure and the maximum tilt and twist angles with a protractor. The results of this test are summarized in Table 12.

Table 12: Results of Range of Motion Tests

Engineering Specifications	Target Values	Actual Values
Range in y-direction (maximum extension)	36 inches (18" over table edge)	19 inches (19" over table edge)
Tilt	±45 degrees	Upward tilt = 40 degrees Downward tilt = 50 degrees
Twist	±45 degrees	±45 degrees

We feel that our prototype met our tilt and twist range of motion target values. There was a tradeoff of 5 degrees between the top and bottom tilts, but this is acceptable because a larger tilt angle in the downward direction is necessary for the fully reclined seating position.

Our range in the y-direction exceeded our target value of extension over the edge of the table, but not our full extension length goal. We feel that this is acceptable if the system will be used exclusively by users in reclined positions, as the monitor is only comfortable to use when it is extended past the edge of the table. However, this model will not be comfortable to use if a person wants to sit up at the desk because the monitor will be much too close to their face; in the fully retracted position, the front of the monitor rests at the front edge of the desk. The cause of this problem stems from three sources: 1) The length of the wrist joint (4 inches), 2) the inability of the carriage to move beyond the belt drive mounts (4 inches), and 3) the y-direction length of the actual arm (7 inches). Our target value of 36 inches could be achieved if we were given a longer table, or if we extended the system past the back edge of the table.

10.2 Speed

To determine if the monitor moves at a speed safe for all users, we conducted speed tests both qualitatively and quantitatively. Qualitatively, we observed each speed and discussed with Jim

Knox whether or not we felt the monitor was moving at a safe speed for a disabled user. We decided that the track motion and the twist motion were slightly too fast when supplied with 12 volts, so we dropped both of these to 5 volts. However, the extension of the arm and the tilt motion felt just right when supplied with 12 volts, so we designed our wiring system accordingly.

The actual speeds of the prototype motions are listed in Table 13. Our target speed values were 1-2.5 inches/second for linear motions and 10-15º/second for rotational motion.

Table 13: Speed Test Results

Engineering Specifications	Target Values	Actual Values
Track Motion	1-2.5 inches/second	0.4 inches/second
Arm Extension	1-2.5 inches/second	1 inch/second
Monitor Tilt	10-15º/second	10º/second
Monitor Twist	10-15º/second	10º/second

Our prototype matched the target speed values for all but the track motion. We wanted to supply the belt drive motor with 7-8 volts, but we were limited by our power supply to either 5 volts or 12 volts. The target speed can be reached if the motor is supplied with sufficient voltage.

10.3 Weight

To determine if our prototype would be able to handle a 30 lb monitor, we tested each motion while applying a load of 19 lbs to our 11 lb monitor. The load was added by attaching household objects to the monitor. All motions except for the tilt motion were fully functional with the total load of 30 lbs. The tilt motion was only functional up to approximately 24 lbs. With loads larger than 24 lbs, the tilt motor stalled. This problem can be solved by using stiffer springs, or using a motor that supplies more torque.

10.4 Reliability

To ensure that the components in our prototype would not break down after repeated use, we ran reliability tests. These tests were done at Design Review #4 on 4/3/07, our poster presentation on 4/4/07, and the Design Expo on 4/12/07. We ran the tests at the Design Review and poster presentation under our control because a control box was not built at that time. Instead, we hotwired each motor to a 12 volt power source and did demonstrations for every visitor over a 2.5 hour period. At the Design Review, our first belt drive motor failed the reliability test. This motor was supplying the correct torque and speed that we needed, but one of the mounting pins for the gear train had come loose, causing the gears to slip under mild loads. To fix this problem we replaced it with a motor from the same series as our tilt and twist motors.

At the Design Expo, we encouraged every user to put our prototype through any motion they could think of. Users could trigger any combination of the four motions, and each worked flawlessly. This was a four hour event and our prototype passed without any complications.

11 FUTURE CHANGES

Our design is fully functional and meets most of our engineering specifications. However, the following engineering changes would enhance its performance and appeal. The gearmotor for the tilt function generates an undesirable amount of noise while it is running. There are more expensive gearmotors available that operate at a much quieter level, but our component selections were limited by cost. Our sponsor will need to decide if he wants to increase the budget for higher quality components.

Since our prototype is comprised of a variety of materials, it is a combination of many colors. Powder coating the metal parts of the prototype would bring unity to the system and disguise the clutter. Also, we did not make any attempt to conceal the gearmotors. Adding acrylic covers to all of our exposed parts such as the wrist joint, track, and belt drive system would enhance the aesthetic appeal of our prototype.

Furthermore, most of the wiring in the track and arm is exposed - although we did conceal it much more than previous models. Heat shrink kept the wires organized throughout the system and gave it a uniform color. However, the aesthetic appeal would be further enhanced by consolidating all of the wires into a single, multi-pin power cord, which could possibly be accomplished with a computer cable. Additionally, purchasing a controller from a company like SKF would make the user-interface more professional.

Five-minute epoxy was used to attach the limit switches to the prototype. However, we had problems with limit switches popping off while conducting maintenance. To increase the reliability of the prototype, the limit switches should be mounted with screws directly tapped into the respective components.

Our prototype has four degrees of freedom, but future designs could integrate movement from left to right along the desk giving the user more positioning options. Also, adding a monitor rotation degree of freedom would give the user the option of changing the screen orientation from horizontal to vertical viewing. Adding these would give the system a total of 6 degrees of freedom.

One way to decrease the cost of our prototype would be to use plastic parts. For example, if use plastic sheaves for the belt drive and/or plastic for the linkage system, we would reduce the cost and weight of the system. Plastic parts may not be as strong as aluminum or steel, but the sheaves and linkages do not need to bear a very large load in this application.

Finally, the track we used has a preload to approximately 120 lbs. We chose this particular preload because we overestimated the weight of our prototype to be near half of this preload. However, a carriage with no preload will most likely operate with less friction than ours, thus requiring a motor that provides less torque for our belt drive. This lower torque motor will likely be smaller and less expensive than our current one which would give the belt drive a smaller profile along the table.

12 CONCLUSIONS

Our goal in redesigning the adjustable flat panel arm was to ensure the ease of use by people with various disabilities and vision impairments while improving the aesthetics and market appeal of previous design iterations. Our customer's most important requirement for this design project was for the arm to be easy to use, without sacrificing its visual appeal, and maintaining four degrees of freedom. The engineering specifications set forth by our sponsor were to have a simple user interface, monitor extension of 18 inches over the desk, and screen tilt and twist of $\pm 45^{o}$. Furthermore, the arm must be able to support a weight of 30 lbs.

The finished prototype was very successful at meeting our goals. While greatly exceeding the aesthetics of the previous arm, this redesign achieved the majority of the engineering goals that were set forth. The full monitor extension past the desk was measured to be 19 inches. The twist of the monitor was measured to be ±45°. The monitor tilted up 40° and down 50°. The only area that fell short was in the payload of the arm. The arm maxed out at 24 lbs instead of the planned 30 lbs. This was not due to structural integrity, but the gearbox for the tilt motion stalled when this weight was exceeded.

13 ACKNOWLEDGMENTS

There are many people that our team would like to thank for making the powered flat panel arm more than just a drawing on paper. First of all, we would like to thank Jeff Vanden Bosch for being the primary financial backer of this project. Jeff is the proprietor of ErgoQuest, Inc. which specializes in actuated desks and recliners for users with disabilities. The flat panel arm is currently mounted on one of his desks. We would also like to thank our sponsors from within the University of Michigan: James Knox, ITD Adaptive Technology Coordinator, and Peter Adamczyk, Organizer of the U of M Engineering Program for Community Engagement in Engineering Design (ProCEED). To our team, James Knox represented the user of the product. In his experience with the Adaptive Technology unit, James interacts with many computer users who are confined to wheelchairs or scooters. His input helped steer our prototype to what it currently is. Peter offered insight that allowed us to streamline our design for maximal aesthetic appeal. His lab also provided us with a power supply for the Design Expo.

Our team would like to give mad props to Sean Hickman of Pickney High School. Sean runs a robotics course at the high school and allowed our team to come in and look at the robots. This was very helpful during the brainstorming stage of our project.

We would also like to thank Bob Coury and Marv Cressey. They are the machine shop technicians who aided with the machining and the welding of our various parts.

Finally, our team would like to express thanks to our professor, Shorya Awtar. Professor Awtar guided us in nearly every aspect of the project. He shared past experiences that helped steer us when selecting designs for the various subsystems within our overall design. Without Professor Awtar's guidance, our project would not be nearly as clean and complete as it is.

14 REFERENCES

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15 BIOS

Kevin Bouma – kbouma@umich.edu

Kevin is from Jenison, MI a suburb of Grand Rapids MI. He graduated from Jenison High School in 2003. He chose to pursue a degree in Mechanical Engineering at the University of Michigan because of his interest mechanics and the broad range of fields to which it applies. During previous summers Kevin has worked at Magna Donnley which specializes in the manufacturing of glass products for the automotive industry. He is planning on working after graduation and is still deciding if he wants to eventually get his Masters Degree. Kevin's main hobbies include attending sporting events and watching movies.

Mita De – mitad@umich.edu

Mita is originally from Troy, Michigan and graduated from Athens High School in 2003. Mita's interest in mechanical engineering developed after taking her first Thermodynamics class here at the University of Michigan. After researching on a one-cylinder engine with one of her favorite Professors, Dr. Jacobs, she wanted to broaden her knowledge in Mechanical Engineering. So now she has a black belt in Kempo and loves to demonstrate the "lets fight toggle position." She's in her final semester at the University of Michigan where she will be graduating with a Bachelor's in Mechanical Engineering. After working at ArvinMeritor INC, an automotive supplier, Mita knew she did not want to work in the industry and hoped to go to graduate school after college ended. In graduate school, Mita plans on receiving her Master's, concentrating on Thermodynamic sciences. Her other interests include classical Indian dancing, which she's been learning for over 15 years.

Joe De Frank –jdefrank@umich.edu

Joe is from Riverwoods, IL, a small northern suburb of Chicago, and graduated from Deerfield High School in 2003. Yes, Joe is a die-hard Chicago Bears fan and looking forward to watching them lose in the Super Bowl. Joe's interests in mechanical engineering stem from his love for the automotive industry. He chose to attend the University of Michigan with the initial intent of working for one of the major automotive manufacturers in the area; however he has since changed his career path. He has spent the previous two summers working for BelAir Manufacturing, a metal stamping facility in Chicago, IL. There Joe acted as a quality assurance technician and was required to approve parts for mass production based on initial run samples. After graduating in April of 2007, Joe will be working at the Chicago offices of LeBoeuf, Lamb, Green & MacRae, LLP, a law firm. After completing his clerkship with the firm, he plans on either attending law school to study patent law or taking a few years off to continue to work in the legal field before attending law school.

Courtney Doyle – cedoyle@umich.edu

Courtney is from Brighton, MI and graduated from Brighton High School in 2002. She is in her final semester at the University of Michigan where she will be receiving a Bachelors degree in both Mechanical and Electrical Engineering. The dual degree was prompted by her interest in Robotics, which developed while taking a course in Robotics at Pinckney High School. During her time at the university, Courtney was a member of the Women's Track and Field team, achieving a personal best of 10'6" in the pole vault. After competing for four years, she is now a manager of the team. She hopes to coach high school pole vaulters in the near future. Following graduation, she will be moving to Kissimmee, FL to work for Gatorade. There she will work in automation as a Supply Chain Associate. Eventually she plans to obtain a Masters degree in Mechanical Engineering and hopes to work in animatronics.

Kevin Y. Shimotsu – shimotz@umich.edu

Kevin was born and raised in Kailua, HI and graduated from Punahou School in 2003. He originally planned on majoring in Aerospace Engineering, but switched to Mechanical Engineering because it is applicable in a much broader range of industries. He has worked at a shipyard in Hawaii for the past four summers performing construction and maintenance on tugboats for a private contractor to Pearl Harbor. There, he learned much about the layout and fabrication end of the engineering profession. After graduating in December of 2007, Kevin hopes to work in either a shipbuilding or biomedical company. His interest in the biomedical industry developed recently because of a serious hospitalization during the Fall 2006 semester in which he got an infection in his blood and lungs and needed to withdraw from classes for a semester. Biomedical technology had literally saved his life and he wants a chance to work in this industry to help give others the same chance at life. He is planning on working after graduation and is still deciding if he wants to eventually get his Masters Degree.

16 APPENDICIES

Appendix A: *Current Robotic Arms*
These pictures are examples of current radial and Cartesian robots. The robots were found during our literature search and they helped inspire ideas during our concept generation.

Figure 21: IRB 2400

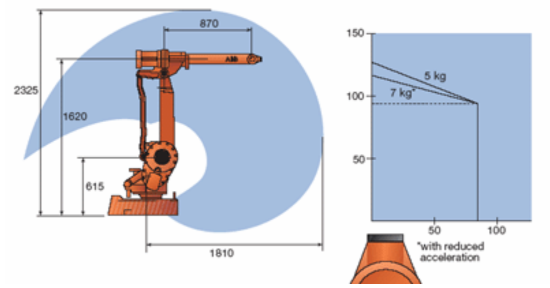


Figure 22: Intelitek's Scorbot ER-4u

Figure 23: Simple Cartesian Robot from PHS Robotics Lab

Figure 24: Techno Inc.'s Cartesian Robot

Appendix B: ***Survey***

This survey was handed out at an Expo on April 4th. The expo was to present developments for the disabled community.

Robotic Monitor Arm Survey

1. Which movement is most important? Please rank.
   - __ Up/Down
   - __ Back/Forth
   - __ Left/Right
   - __ Monitor Tilt
   - __ Monitor Twist
   - __ Monitor Rotation
   - __ Other (please specify):___________________________

2. How much available desk space do you require?
   - a. No desk space
   - b. Minimal desk space
   - c. Most of the desk
   - d. The entire desk

3. Is the range of motion adequate? If not, please specify what you would desire.
   - Forward Extension: 36” (18” beyond desk)
     - YES NO: ___________________________
   - Monitor Tilt: ± 45°
     - YES NO: ___________________________
   - Monitor Twist: ± 45°
     - YES NO: ___________________________

4. Is this model aesthetically pleasing? If no, do you have any suggestions?
   - YES NO: ____

5. The following categories refer to the control box. Please circle which you would prefer for each. Feel free to write in suggestions.

Button Size:	Large	Small	
Button Type:	Toggle	Push	Rocker (see on previous box)
Force:	Soft Touch: easy to press Hard Touch: reduces ‘accidental presses’		
Instructions:	Pictures	Words	Minimal
Location:	On Desk	On Chair	Remote Control

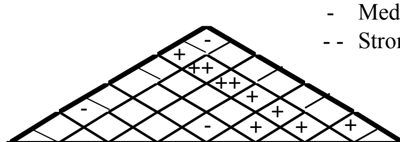
Appendix C: *QFD*

In order to properly start the design process, our team determined the customer's requirements based. These requirements were then translated into engineering specifications. Analysis of previous prototypes led to benchmarks that serve as comparison levels with our prototype. All of the above information is organized into a Quality Function Deployment (QFD) chart.

Figure 25: QFD chart

(+) => more is better
(-) => less is better

Relationships
++ Strong Positive
+ Medium Positive
- Medium Negative
- - Strong Negative



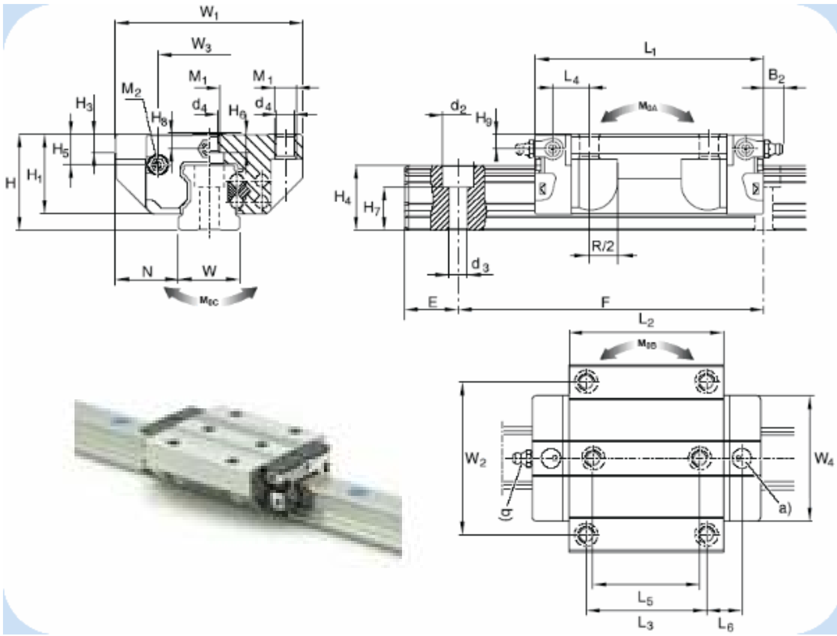
	Weight*	Supportable Monitor Weight	Track Movement	Arm Extension	Tilt	Twist	User Control Interface	Solution Cost	Monitor Speed	*Fall 2003 Design*	*Winter 2004 Design*	*Our Design*
Aesthetically Pleasing	8	1	1	1	1	1	5			1	2	6
Cost Effective	6	1	1	1	1	1	3	9		2	3	3
Quiet	8	1	3	3	3	3			3	1	1	4
Easy to Use	10						9			3	5	8
Reliable	6	3	3	3	1	1	3			1	3	6
Safe	7	9	5	5					7	2	4	7
4 Degrees of Freedom	10		9	9	9	9				5	10	10
Maintain Simplicity	7	3	3	3	3	3	7			2	4	7
Smooth Movement	6	3	3	3	3	3	9		5	1	7	9
Measurement Unit		lbs	in	in	deg	deg	-	$	in/s			
Target Value		30	18	18	45	45		500	2			
Importance Rating		**8**	**8**	**8**	**5**	**3**	**2**	**9**	**9**			
Weighted Total		114	176	176	87	52	54	49	93			
Normalized		0.14	0.22	0.22	0.11	0.06	0.07	0.06	0.12			

(Benchmarks: *Fall 2003 Design*, *Winter 2004 Design*, *Our Design*)

Key:
9 => Strong Relationship
7
5 => Medium Relationship
3
1 => Small Relationship
(blank) => Not Related

***Weights are figured on a scale of 1 to 10**
(ten being most important)

Appendix D: *Track Rail and Carriage Specifications*



Series		LLR 35					
Carriage type		Standard width, long					
Mounting holes		pass thread					
carriage width	W1	100	mm				
rail width	W	34	mm				
N		33	mm	**B2**		9.5	mm
L1		139	mm	**H9**		6.9	mm
L2		105.5	mm	**H6**		10.2	mm
H		48	mm	**H7**		20.5	mm
H1		40.4	mm	**d4**		8.5	mm
H4 1)		32.15	mm	**M_1**		M10x12.0	
H4 2)		31.85	mm	**d2**		15	mm
H3		8	mm	**d3**		9	mm
W2		82	mm	**M_2**		M3x5	
L3		62	mm	**E_{min}**		12	mm
L5		52	mm	**F**		80	mm
W3		58	mm	**Load carrying capacity**	C	55600	N
W4		68.4	mm	**static load carrying capacity**	C0	81000	N
H5		17.35	mm	**$M_{0A/0B}$**		1215	Nm
L6		28.75	mm	**M_{0C}**		1740	Nm
L4		30.25	mm	**weight of carriage**		2.25	kg
R		17	mm	**Grease nipple**		M6x8 - DIN 71412	
H8		6.9	mm				

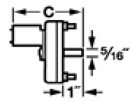
Appendix E: *Motor Specifications*

The motors were purchased off McMaster, so the specs for each are available on the same sheet. The track motor is #6409K15 from McMaster. For more detailed specs, refer to Item #2L008 from the Dayton sheet. The tilt motor is #6409K12 from McMaster. For more detailed specs, refer to Item #2L004, from the Dayton sheet. The twist motor is #6409K13 from McMaster. This does not have a corresponding motor on the Dayton Sheet.

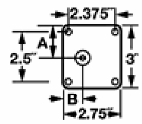
Subfractional-hp DC Gearmotors

With less than 1/100 hp, these permanent magnet gearmotors are ideal for use in small spaces such as business machines, appliances, and valve actuators. A gearmotor consists of a motor and fan matched with a geared speed reducer to lessen speed while increasing torque. Shaft has a flat to accept set screws for easy connection to your equipment.

Motors are brush style and have two terminals for electrical connection. Rotation is clockwise when facing the shaft end. To reverse rotation, switch the lead wires (follow the included wiring diagram). For speed controllers, see 7729K on page 839. Housing is die cast zinc with bronze sleeve bearings. Gears are iron and Delrin. Motor face has four 10-32 threaded mounting studs.



Side View



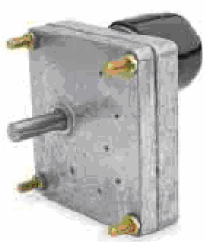
Front View

rpm	Torque, in.-lbs.	(A)	(B)	(C)	Full Load Amps		Each
12 VDC							
.6	50	1.43"	0.91"	3.45"	0.12	6409K11	$45.76
1.3	50	1.43"	0.91"	3.65"	0.45	6409K12	45.76
4	40	1.43"	0.91"	3.45"	0.68	6409K13	42.03
8	40	1.43"	0.91"	4.17"	0.73	6409K14	42.03
12	40	1.43"	0.91"	3.65"	1.3	6409K15	42.03
16	25	1.43"	0.91"	3.65"	1.4	6409K16	37.42
25	20	1.43"	0.91"	3.65"	1.3	6409K17	37.42
50	10	2.08"	1.38"	3.65"	1.2	6409K18	37.42
24 VDC							
1.2	50	1.43"	0.91"	3.45"	0.14	6409K21	45.76
4	50	1.43"	0.91"	3.45"	0.38	6409K22	42.03
8	34	1.43"	0.91"	3.65"	0.45	6409K23	42.03
12	24	1.43"	0.91"	3.65"	0.42	6409K24	42.03
17	17	1.43"	0.91"	3.65"	0.45	6409K25	37.42
25	50	1.43"	0.91"	4.17"	1.08	6409K26	37.42
47	28	2.08"	1.37"	4.15"	1.08	6409K27	37.42

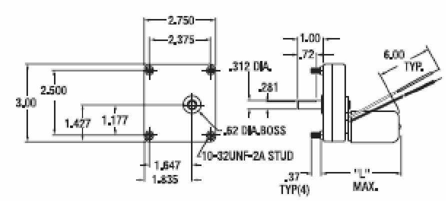
12VDC Permanent Magnet Parallel Shaft Gearmotors

Dayton

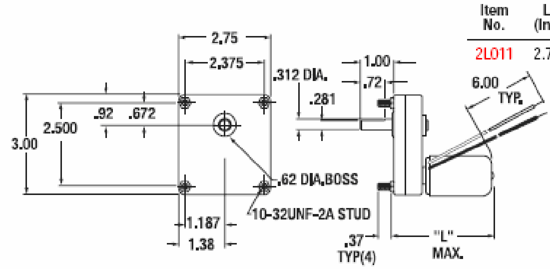
- Gearcase: Zinc die cast
- Lubrication: Grease filled
- Gears: Spur, Delrin, and Steel
- Bearings: Bronze sleeve on both case and motor
- Mounting: All position
- Rotation: Reversible
- Thermal Protection: None
- Ambient: 40°C


No. 2L003


No. 2L011



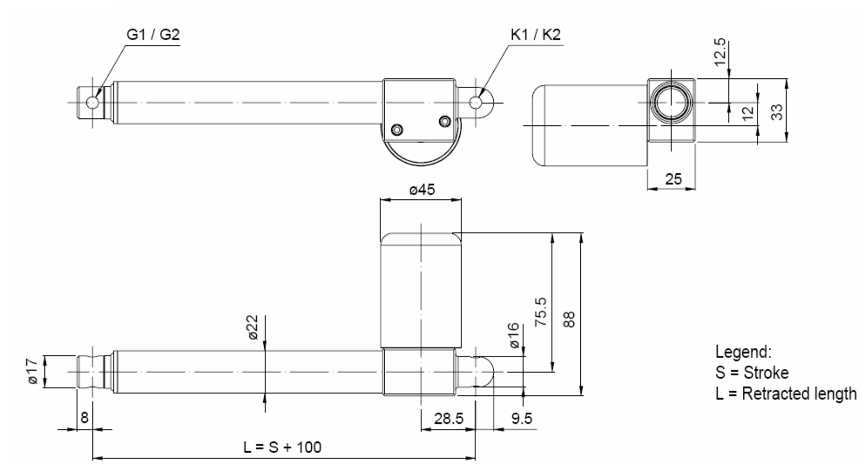
Item No.	L (In.)
2L003	2.50
2L004	2.50
2L005	3.06
2L006	3.06
2L007	3.06
2L008	3.06
2L009	3.06
2L010	3.06



Item No.	L (In.)
2L011	2.75

Nominal F/L RPM	F/L Torque (In.-Lbs.)	Overhung Load (Lbs.)	Input HP	F/L Amps at 12VDC	Gear Ratio	Item No.	$ Each	Shpg. Wt.
0.5	50	30	1/2800	0.10	7189:1	2L003	49.95	1.2
1.5	46	29	1/900	0.30	1636:1	2L004	49.95	1.1
3.4	44	28	1/425	0.50	1176:1	2L005	49.95	1.1
4.5	43	27	1/325	0.70	1217:1	2L006	46.35	1.0
8.8	41	26	1/175	1.0	524:1	2L007	46.35	1.1
12	40	24	1/125	1.3	603:1	2L008	46.35	1.2
17	30	21	1/125	1.4	394:1	2L009	41.35	1.1
25	20	18	1/125	1.3	270:1	2L010	41.35	1.6
50	10	15	1/125	1.1	146:1	2L011	41.35	1.0

Appendix F: *Arm Linear Actuator Specifications*



Technical Data

Performance

Actuator	**Max. Dynamic load (N)**	**Speed (mm/s)**	**Max. Current (A)**
CAT(R/L) 21B..../G24C	600	10-5	1.0
CAT(R/L) 21B..../G12C	600	10-5	2.0

Max. static load: (N)	1000
Protection class:	IP X4

Duty factors

Load:	No load	50% dynamic load	100% dynamic load
Duty factor:	50%	20%	10%

Options

Standard options
Right or left handed motor orientation.
With or without motor cover.

Custom options (available on request)
Encoder and feedback options
Adjustable or fixed position limit switches
Special front and rear attachments
Special colors and gear house engravings
Special wiring and connectors
Special lead screws and nut combinations

If, in any application there is a risk that the actuator mechanically runs into the end stop, we recommend that you use the limit switch option.

Appendix G: ***Wiring Schematic***

Below is the schematic that was used for wiring the system. The control box wiring is in Figure 26 and the prototype wiring is in Figure 27. The two components are connected by corresponding numbers.

Figure 26: Control Box Wiring Schematic

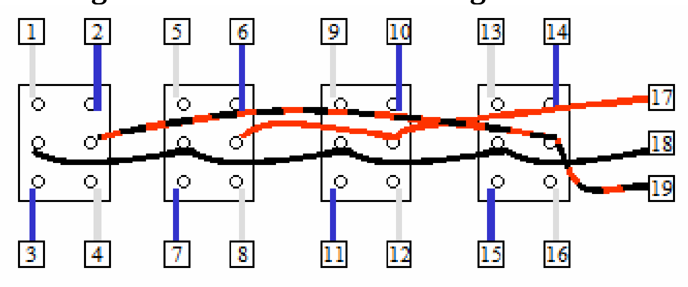
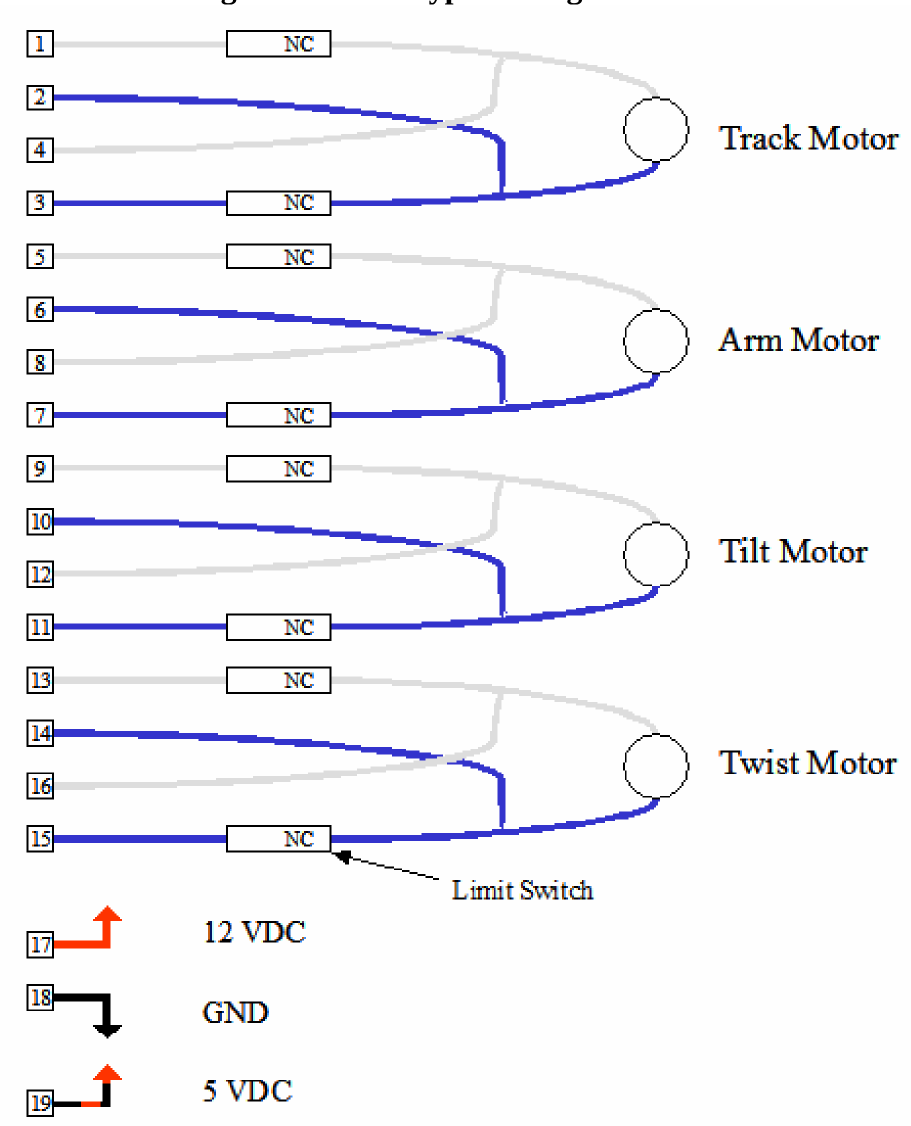


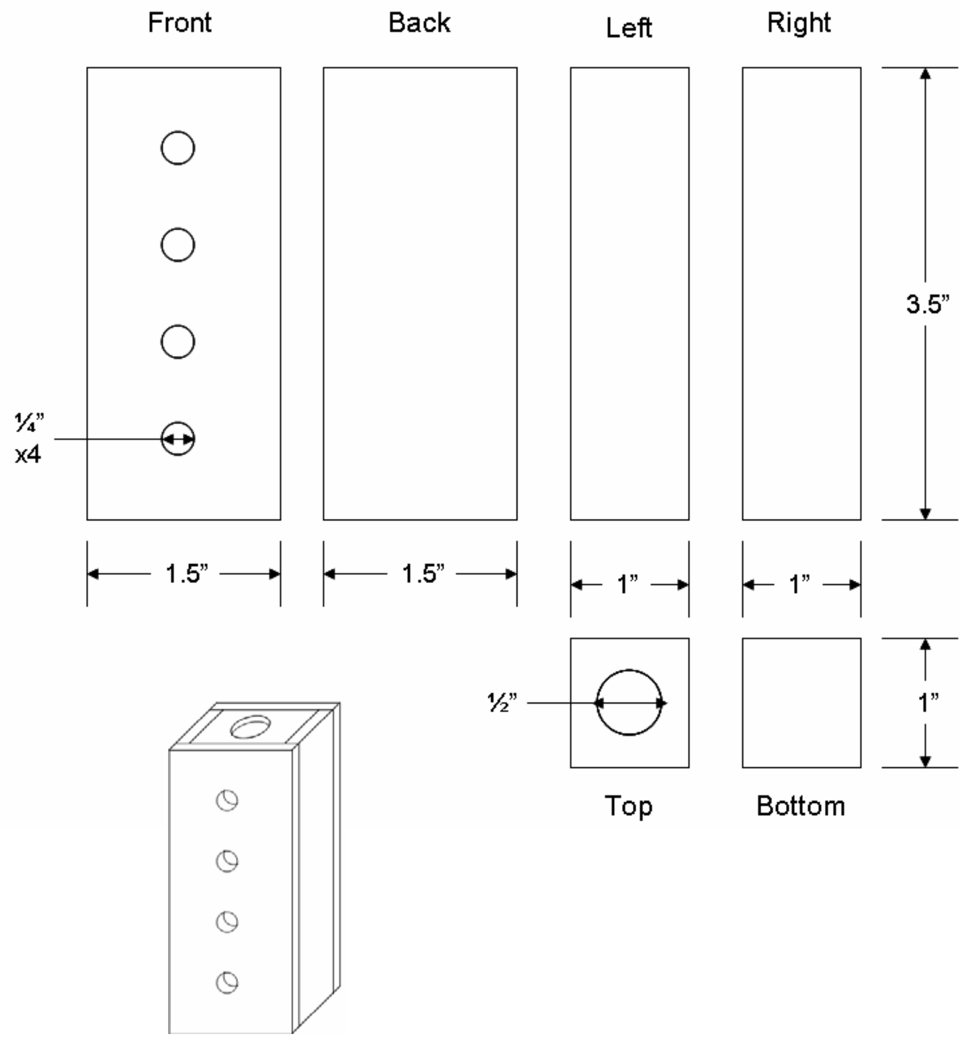
Figure 27: Prototype Wiring Schematic



Appendix H: *Control Box Dimensions*

Figure 28 shows the dimensions of the control box along with an assembled view.

Figure 28: Control Box Dimensions



Appendix I: *Bill of Materials*

Table 14: Bill of Materials

Item	Quantity	Source	Catalog Number	Cost/Part	Total Cost	Contact	Notes
12V DC Gear Motor	1	Mcmaster -Carr	6409K15	$42.03	$42.03		Track drive system
12V DC Gear Motor	1	Mcmaster -Carr	6409K12	$45.76	$45.76		Tilt Function
12V Dc Gear Motor	1	Mcmaster-carr	6409K12	$45.76	$45.76		Twist function
Profile rail guide	1	SKF	LLRHS 35 LA 1 T1 0460 P5	$250.00	$250.00	Dave (800-541-3624)	Manual track system
Electromagnetic linear actuator	1	SKF	CAT R 21BX 100 X1 K2 G2 2 G12C	$200.00	$200.00	Bob (800-541-3624)	slender actuator for inside of the arm
Aluminum Plate: 4.5x5x0.5"	1	UM Machine Shop	-		$0.00	Bob Coury	carriage-base adapter
Aluminum Plate 1.125x3.25x0.25"	2	UM Machine Shop	-		$0.00	Bob Coury	wrist joint
Aluminum 1x3x0.5"	2	UM Machine Shop	-		$0.00	Bob Coury	linkage system
Aluminum	1	ASAP Source	-	$27.42	$27.42	-	Wrist joint (shaft clamp)
Flanged ball bearing (ID = 5/16 OD = 7/8)	1	McMaster	6383K215	$3.90	$3.90	-	twist motor shaft support
3/8" hex bolts w/washers and nuts	2	Jack's Do-it Best	-	$1.00	$2.00	-	base to adapter plate mounts
40.2" XL Timing Belt	1	sdp-si	A 6R 3-204037	$8.54	$8.54		Belt for belt drive system
3/8" Timing Belt Clamp	2	sdp-si	A 6M 3M095	$5.40	$10.80		Timing belt clamp for carriage
1.508 Timing belt pulley with flange	1	sdp-si	A 6C 3-24DF03712	$15.74	$15.74		Timing belt pulley for motor
1.508 Timing belt pulley	1	sdp-si	A 6C 3-24H3712	$10.91	$10.91		Timing belt pulley loose end
M4-40 Monitor mount screws	4	Stadium Hardware	-	$0.23	$0.92		Track mount
5/16 Socket screws	6	Stadium Hardware	-	$0.55	$3.30		Track mount
5/16 Nuts	7	Stadium Hardware	-	$0.07	$0.49		Track and spring
Felt pad	1	Stadium Hardware	-	$4.29	$4.29		Adaptor Plate Cover
Steel spacer	1	Stadium Hardware	-	$0.42	$0.42		Monitor Mount
Nylon spacers	14	Stadium Hardware	-	$0.05	$0.70		Pin Joints
5-Minute epoxy	1	Stadium Hardware	-	$3.79	$3.79		Attach Limit Switches
1/4" Bolts - 2" long	10	Stadium Hardware	-	$0.25	$2.50		Pulley mounts to table
1/4" Nut	10	Stadium Hardware	-	$0.07	$0.70		Pulley mounts to table
5/16" Bolts - 3" long	1	Stadium Hardware	-	$0.32	$0.32		Attach springs
10-24 1" Long	3	Stadium Hardware	-	$0.17	$0.51		Shaft clamps
10-24 Nut	1	Stadium Hardware	-	$0.06	$0.06		Shaft clamp
8-32 3/8" Long screw	4	Stadium Hardware	-	$0.15	$0.60		Monitor Mount
5/16" Pins	3	Stadium Hardware	-	$0.42	$1.26		Pin Joints
Cotter pins	2	Stadium Hardware	-	$0.10	$0.20		Secure Pin Joints
5/16 Ball bearings	1	Stadium Hardware	-	$4.50	$4.50		Shaft Extension
M-10 Bolts-40	4	Stadium Hardware	-	$0.45	$1.80		Adaptor Plate to carriage
3/8" Bolts	2	Stadium Hardware	-	$0.50	$1.00		Arm to Adaptor Plate
Open ended timing belt	4	sdp-si	A 6R 3-C037	$2.97	$11.88		Track System
Shipping costs from Mcmaster	3	Mcmaster-carr	-	$3.95	$11.85		Shipping Costs
Limit switch with pin	3	Aven Inc	-	$2.84	$8.52		Limit switch for arm
Limit switch with roller	3	Aven Inc	-	$4.20	$12.60		Limit switch for arm
Limit switch with lever	2	Aven Inc	-	$3.00	$6.00		Limit switch for arm
1/16" shrinkable tube	1	Aven Inc	-	$0.87	$0.87		Limit switch for arm
Female solderless terminal	2	Aven Inc	-	$1.18	$2.36		Limit switch for arm
Male solderless terminal	2	Aven Inc	-	$1.18	$2.36		Limit switch for arm
DPDT Mini Toggle Switch	4	Ebay	-	$1.35	$5.40		Limit switch for arm
1/2" Shrinkable tube	1	Aven Inc	-	$2.02	$2.02		Limit switch for arm
3/16" Shrinkable tube	1	Aven Inc	-	$1.16	$1.16		Limit switch for arm
1/8" Shrinkable tube	1	Aven Inc	-	$0.91	$0.91		Limit switch for arm
Shipping costs from Ebay	1	Ebay	-	$3.10	$3.10		Limit switch for arm
Total					$759.25		

Appendix J: ***Prototype Photos***

The following are pictures taken of the final physical prototype.

Figure 29: Full Assembly (Right and Left Views)


Figure 30: Wrist Joint (Right and Left Views)

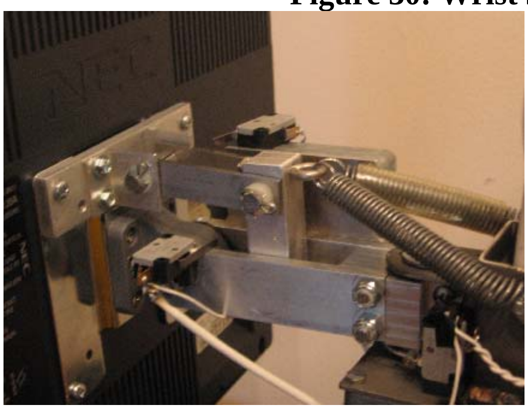
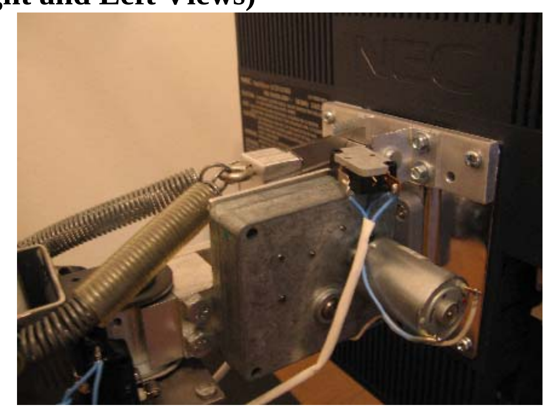



Figure 31: Track Module

Appendix K: ***Engineering Drawings***

The pages in this appendix present the engineering drawings for each part we manufactured.

Figure 32: Carriage/Arm Adaptor Plate - Eng. Drawing

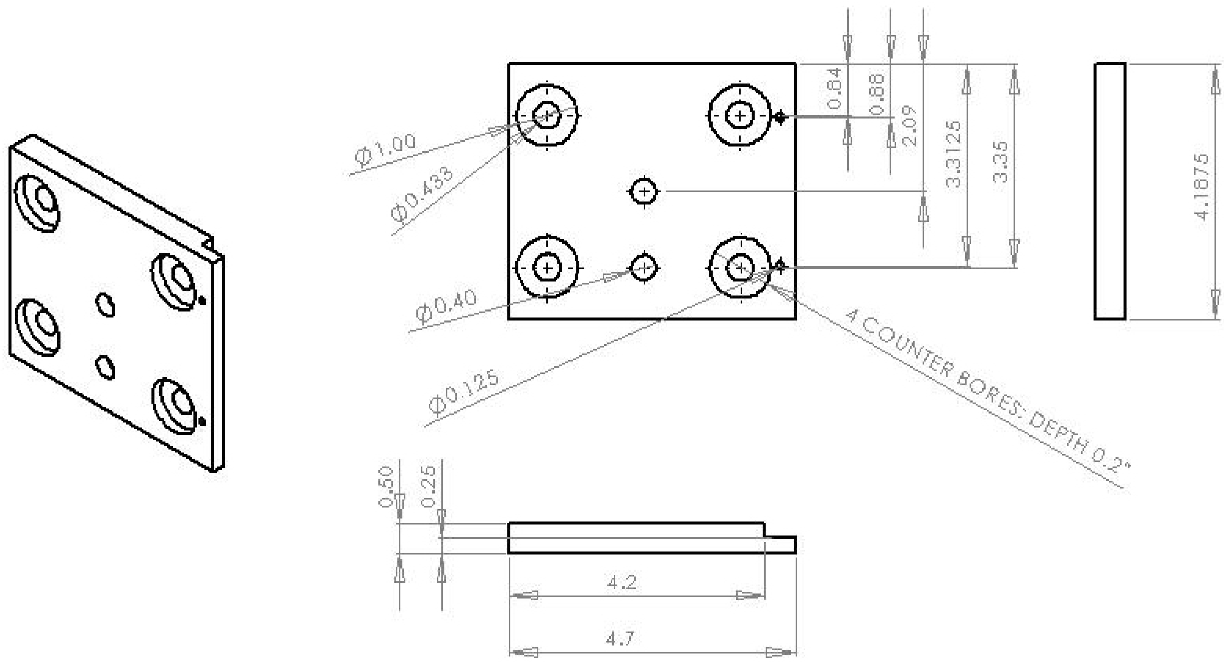
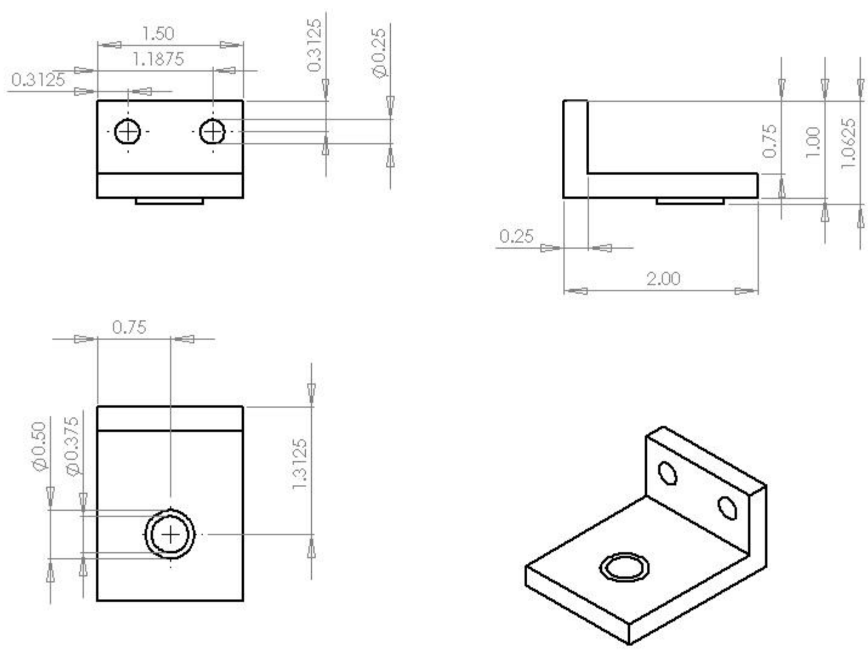


Figure 33: Sheave Mount - Eng. Drawing



Appendix K (cont): ***Engineering Drawings***

Figure 34: Belt Drive Motor Mount - Eng. Drawing

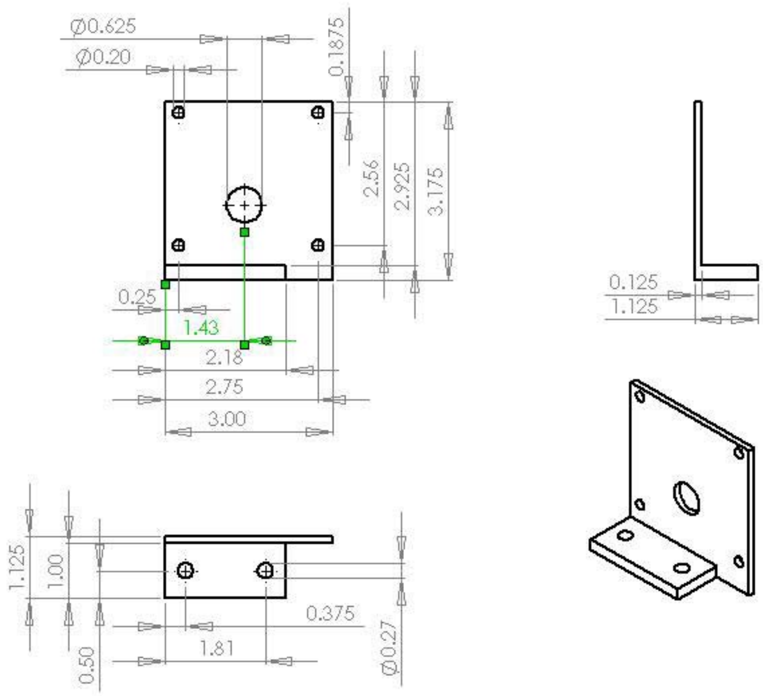
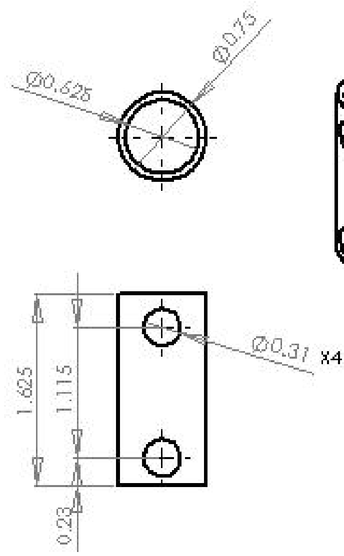


Figure 35: Linear Actuator Extension – Eng. Drawing



Appendix K (cont): ***Engineering Drawings***

Figure 36: Tilt Motor Mount – Eng. Drawing

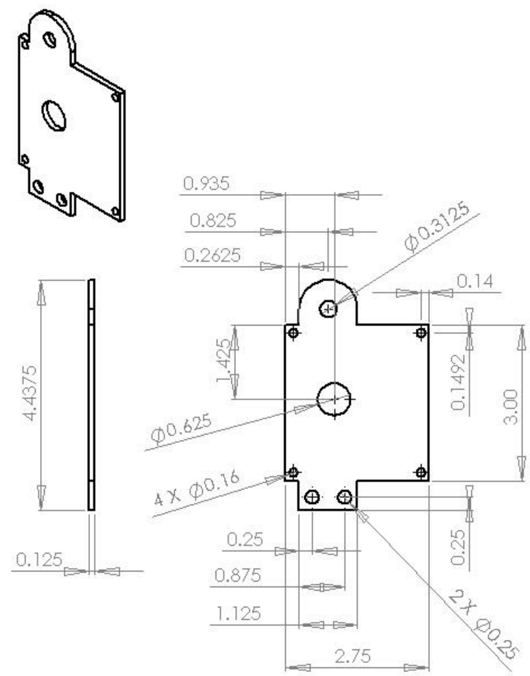
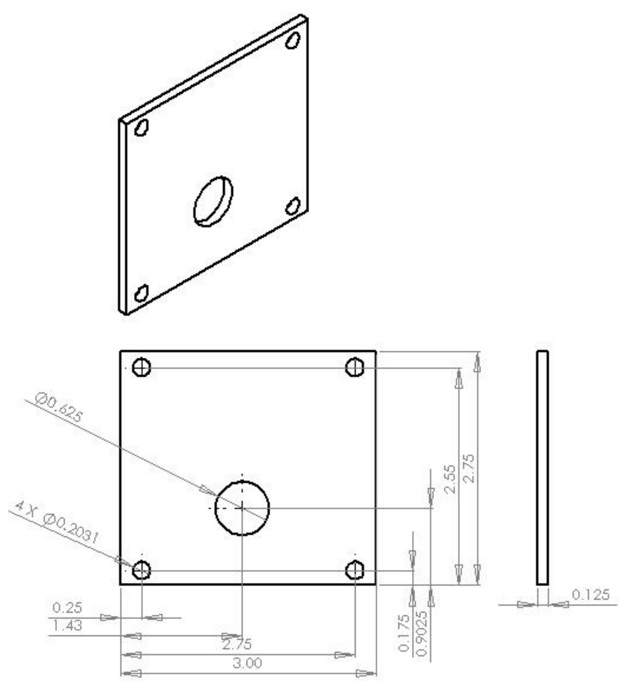


Figure 37: Twist Motor Mount – Eng. Drawing



Appendix K (cont): ***Engineering Drawings***

The main wrist support consists of three pieces. The pieces are oriented and assembled as shown in Figure 36. Figures 37-39 show the engineering drawings of the three parts.

Figure 38: Assembly of Wrist Support

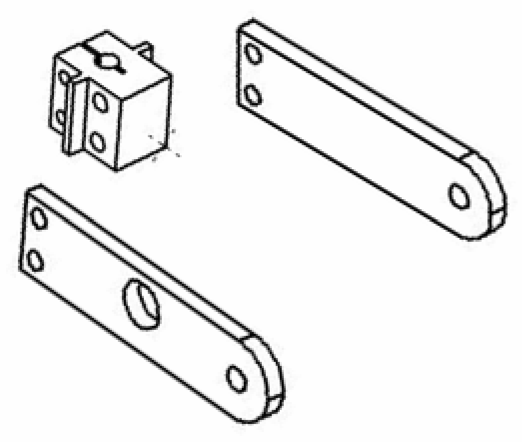
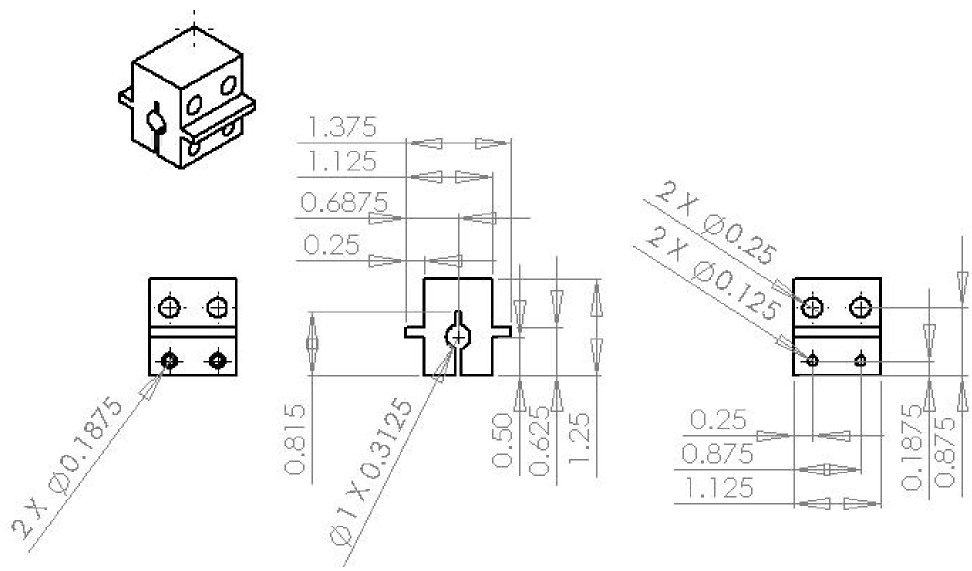


Figure 39: Twist Motor Shaft Clamp - Eng. Drawing



Appendix K (cont): ***Engineering Drawings***

Figure 40: Wrist Joint Left Arm – Eng. Drawing

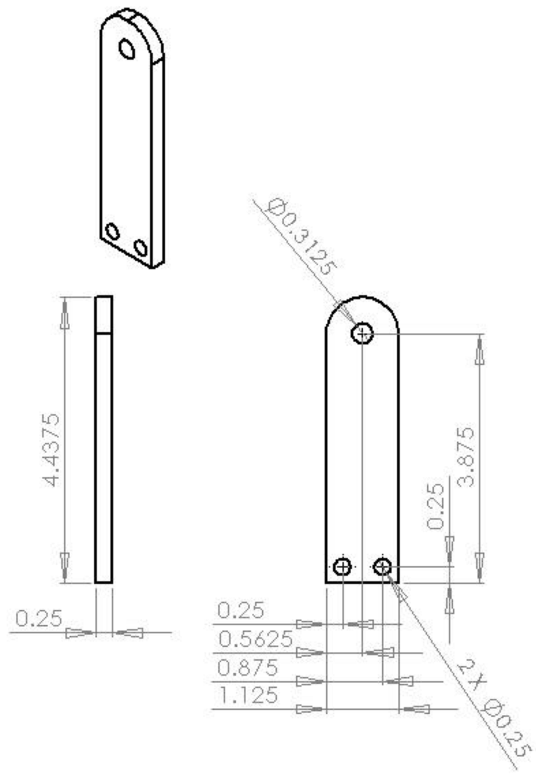
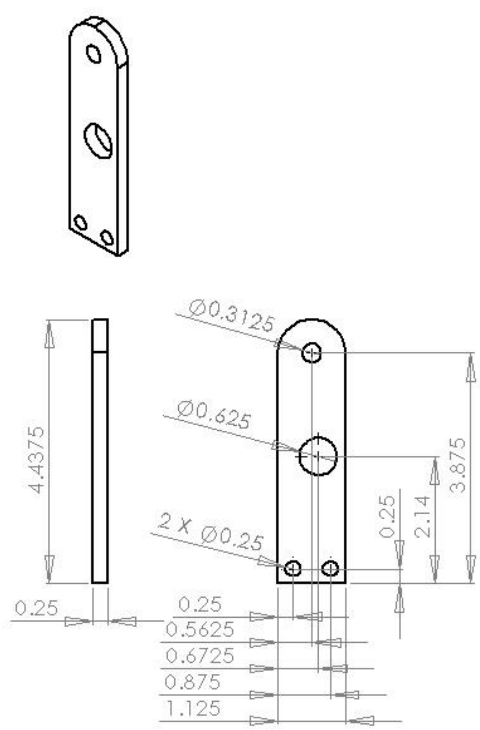


Figure 41: Wrist Joint Right Arm - Eng. Drawing



Appendix K (cont): ***Engineering Drawings***
These links form the parallelogram structure that produces the tilt motion.

Figure 42: Parallelogram Linkage #1 - Eng. Drawing

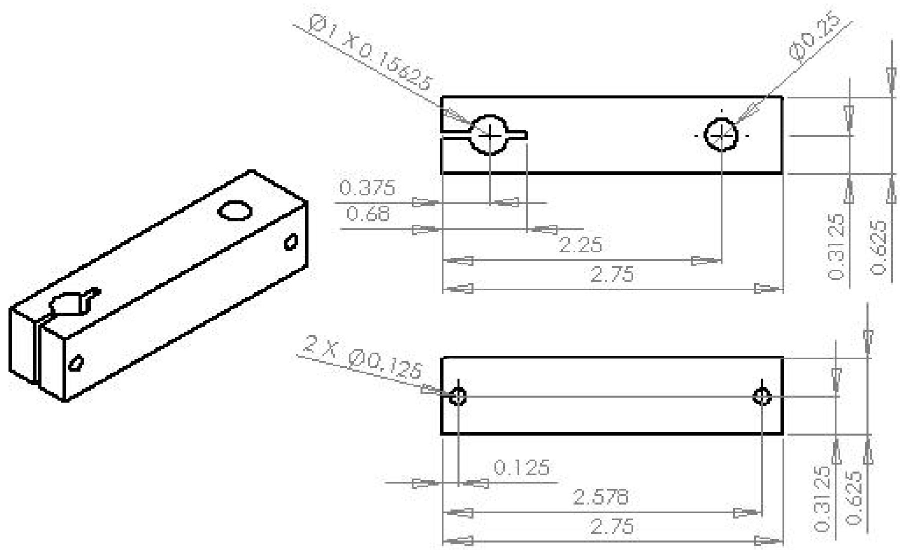
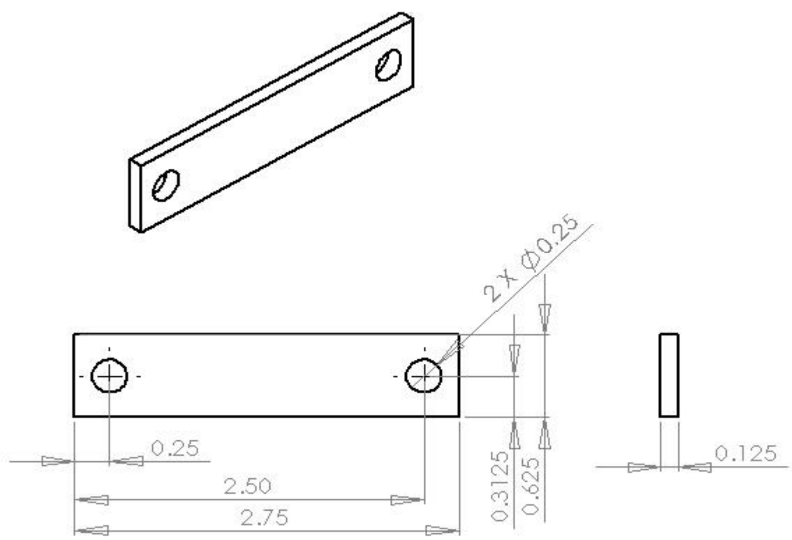


Figure 43: Parallelogram Linkage #2 - Eng. Drawing



Appendix K (cont): ***Engineering Drawings***
These parts allow our parallelogram structure to attach to the monitor mounting plate.

Figure 44: Linkage Mounting Bracket - Eng. Drawing

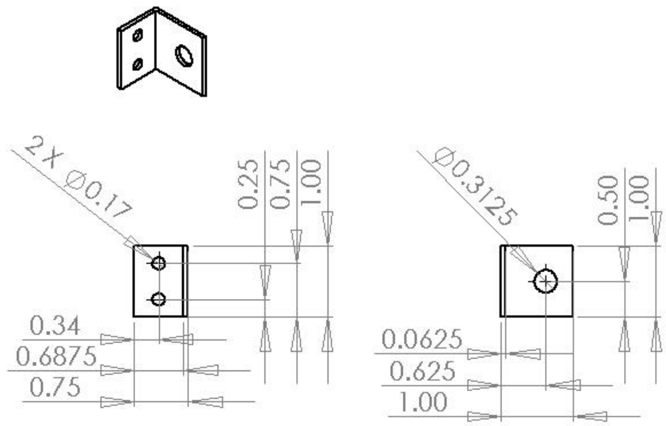
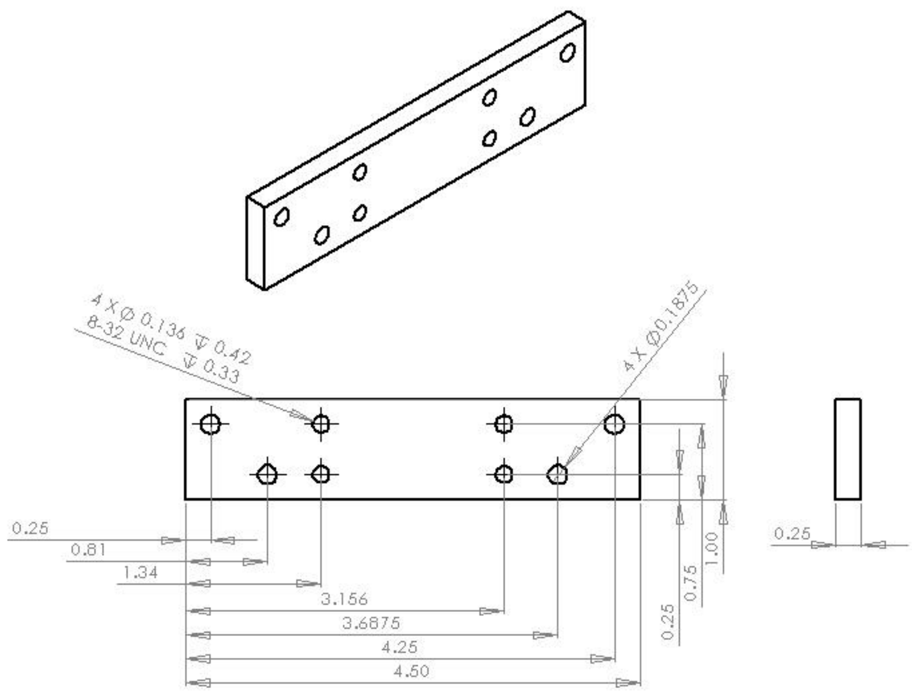


Figure 45: Linkage Mounting Plate - Eng. Drawing



Appendix L: *GANTT Chart*

We noted each required deliverable (i.e. design reviews, design expo, final report) in addition to a few milestones set by our team. Next, we estimated what needed to be done and how much time we needed to do everything necessary for each milestone.

Figure 46: GANTT Chart