Design and Manufacture of an Electro-Mechanical Hand Position Tracker

by

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Submitted to the Department of Mechanical Engineering
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Abstract

This thesis discusses the conceptual design, manufacture, and assembly of a device that tracks the movements and position of a user's hand. This device will be used for stroke patients undergoing rehabilitation using robotic aids, monitoring their use of their unimpaired hand, particular when performing bimanual tasks. This device uses a system of linkages and potentiometers to track the angles of the wrist, as well as the MCP and CMC joints of the index finger and the thumb. This allows a simple model of the hand to be constructed on the computer in x, y, and z dimensions. In addition, a base was designed and built to locate the absolute position of the hand in three dimensions. The potentiometers are then connected to a computer where the movements can be viewed.

Thesis Supervisor: Hermano Igo Krebs
Title: Senior Principal Research Scientist & Lecturer

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1. Introduction

1.1. *Purpose*

The purpose of this thesis is to create an electromechanical hand position tracker. This work was done in the Newman Laboratory for Biomechanics and Human Rehabilitation, intended to be used in conjunction with the MIT MANUS project, which is further described in section 2.2.

The hand position tracker is for use on the unimpaired hand of stroke patients undergoing rehabilitation. While MIT MANUS allows for tracking the paretic hand that is undergoing rehabilitation, there currently does not exist a device for tracking the non-paretic hand, which is useful in measuring progress and delivering therapy in performing bimanual tasks (see section 2.3).

1.2. *Outline of chapters*

In order to understand the need and background of the project, chapter 2 describes the causes, symptoms, and treatments for stroke, provides information about the MIT MANUS project, and also outlines the need to track bimanual tasks. Chapter 3 looks specifically at the hand, and provides background on the joints, degrees of freedom, and grasps the hand is capable of executing. Chapter 4 describes the functional requirements for the project based on patient and researcher needs, while chapter 5 goes into detail about the design considerations and design choices. Chapter 6 discusses the manufacturing processes and minor design changes that occurred though several iterations. Chapter 7 looks at the interaction between the physical apparatus and the computer, including the mathematical models used. Finally, chapter 8 concludes by discussing the achievements of the project, proposed improvements, and future work.

2. Background

2.1. Stroke

2.1.1. Causes

A stroke, also called a cerebrovascular accident, occurs when the blood supply to the brain is interrupted or stopped. The portion of the brain that loses blood dies and neuronal function is lost when the brain no longer receives adequate amounts of glucose and oxygen.

There are two main forms of stroke. The first, called an ischemic stroke, occurs when a blood vessel in the brain is blocked, either by a clot that is gradually built up within the brain, or a traveling particle or debris that originates elsewhere but is eventually lodged in the brain. The blockage that results restricts blood flow to the brain, thus resulting in the stroke. Hemorrahagic stroke, the second form, occurs when a blood vessel is ruptured and bleeds into the skull. The surrounding brain tissue cells are damaged by the resulting bleeding, and parts of the brain beyond the leak are also affected by the lack of blood now reaching them [1].

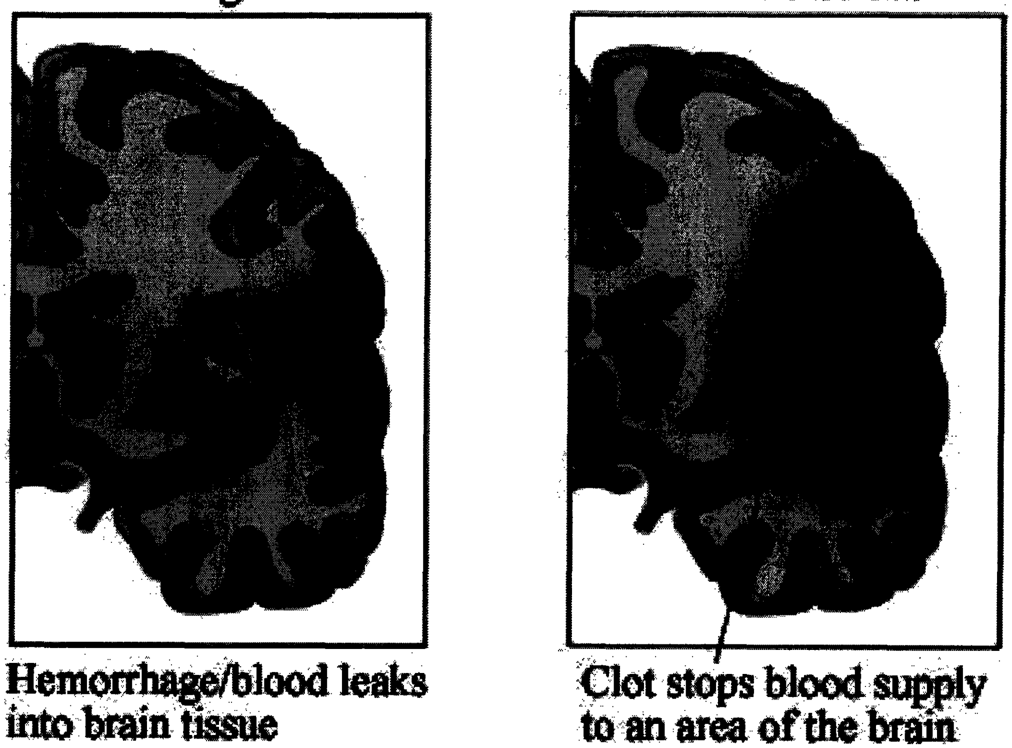


Figure 2.1: The two main forms of stroke [2].

In the United States, stroke is currently the leading cause of adult permanent disability, and the third leading cause of death. Factors that increase the probability of experiencing a stroke include previous family history of stroke, increased age, high blood pressure, cigarette smoking, diabetes, obesity, and cardiovascular disease [1].

2.1.2. Symptoms

Symptoms occur immediately, and should be treated at once. They vary from case to case, but usually involve one or more of the following: numbness, paralysis or weakness on the face, arm or leg, usually localized to one size of the body; difficulty speaking or understanding speech; blurred, decreased, or double vision; dizziness, loss of balance or coordination; sudden, severe headache accompanied by stiff neck, facial pain, pain between the eyes, vomiting, or altered consciousness; and confusion, problems with memory, spatial orientation or perception [1].

2.1.3. Treatment

Treatment varies depending on the type of stroke and how quickly the victim can reach emergency services. In some cases, blood pressure increases dramatically and clears the stroke, but for some classes of ischemic stroke, a doctor must remove the cause of the blockage. The most non invasive way to do this is though injection of a clot busting (thrombolytic) drug into the bloodstream though the veins. This may be the most effective way to treat a stroke, resulting in the greatest chance of a full recovery; however, this must be administered within three hours of the stroke. After this time window, the risks associated with clot busting drugs outweigh the possible benefits. In addition, this treatment is only effective for ischemic strokes; in fact it could severely worsen a hermorrahagic stroke.

For ischemic strokes, surgery to remove the plaque that is blocking the artery may be recommended. In addition, drugs that could prevent future clots could be prescribed, including anti-platelet drugs or anticoagulants.

Hemorrhagic stroke are most often treated or prevented using aneurysm clipping and arteriovenous malformation removal surgeries [1].

2.1.4. Rehabilitation

Because stroke affects entire portions of the brain, and has a wide range of symptoms and side affects, rehabilitation can involve a number of different treatments, including speech therapy and physical therapy. Research has shown that despite damage to brain cells that affect certain functions, nearby cells carry the ability to adapt and undergo changes in function and shape, taking on the function of the damaged cells. Thus, a primary goal in rehabilitation is to train the patient to relearn skills lost in the stroke [1].

2.2. *MIT Manus*

The MIT Manus is a robotic system used for stroke rehabilitation. Originally designed to aid in rehabilitation of the patient's arm, later robots were developed to include rehabilitation of the hand and legs. The robot is used in conjunction with traditional rehabilitative practices done with a physical or occupational therapist. In a therapy session, the robotic brace is secured on the patient, and the patient is asked to perform a movement though a computer screen prompt. If the patient is unable to perform the task his or herself, the robot provides moves the limb to the desired position or provides enough assistance to allow the patient to complete the task. Clinical trials have shown that use of the robotic therapy increases movement and improves the patient's overall function.

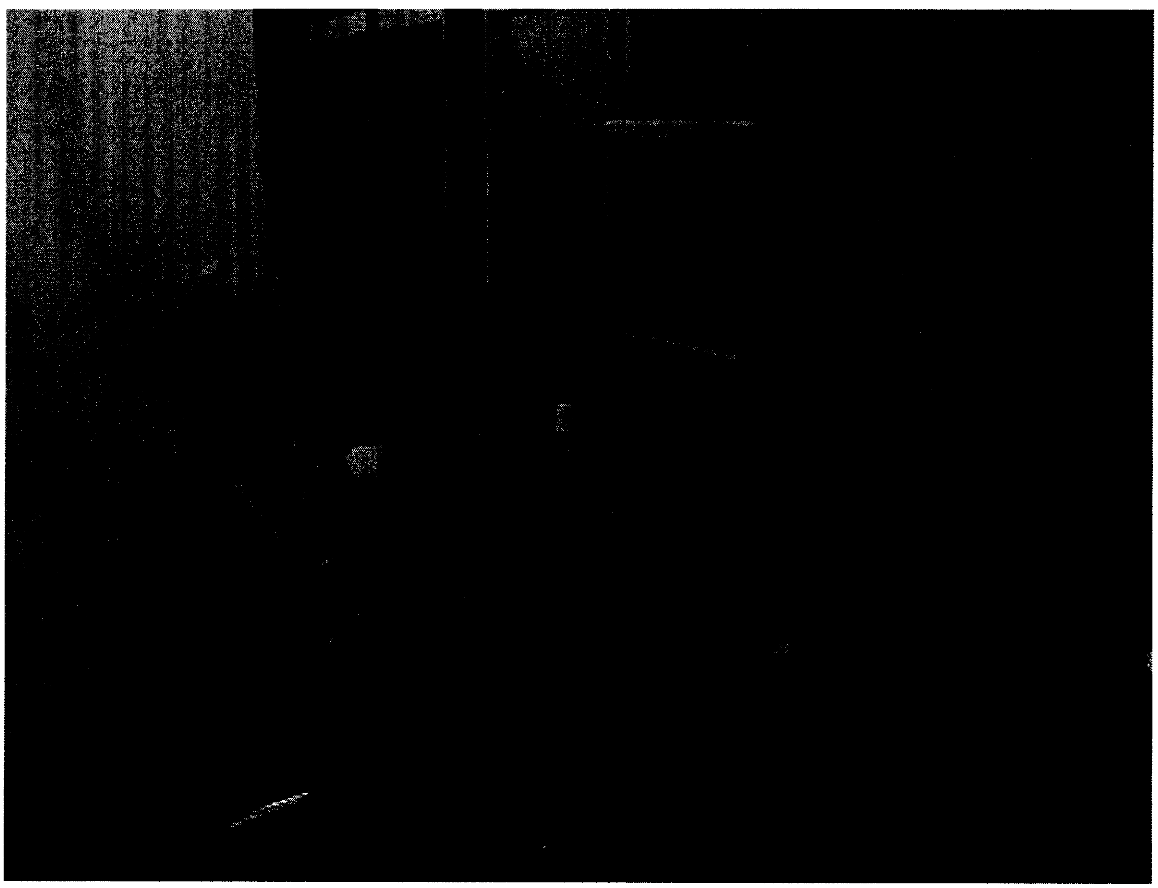


Figure 2.2: A patient using the MIT MANUS robot.

2.3. *Bimanual tasks*

Bimanual tasks are tasks that use both hands cooperatively. An example would be opening a jar, which requires one hand to grasp the jar and the other hand to turn the lid. This requires coordination between the two hands to perform differing tasks. While the current MIT MANUS robot can test and aid tasks that require a single hand, there is no current mechanism to measure and train the ability of both hands to work together in bimanual tasks.

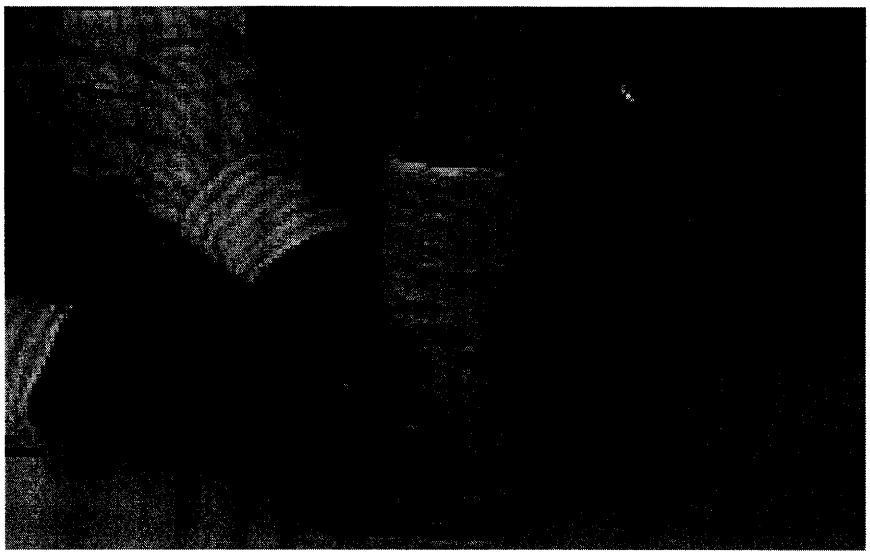


Figure 2.3: A stroke patient opening a jar with the help of a physical therapist. [3]

3. Hand anatomy and function

3.1. Joints

The human hand is comprised of a number of joints that provide motion in varying degrees and varying degrees of freedom. The fingers contain twelve joints. At the base of the finger at the knuckle is the metacarpophalangeal (MCP) joint, which provides two degrees of freedom by allowing movement in two planes. Beyond the MCP joint at the end of the first phalange is the proximal interphalangeal (PIP) joints. Between the second and third phalanges of the finger are the distal interphalangeal (DIP) joints. Both the PIP and DIP joints allow one degree of freedom.

In addition, the thumb also has three joints associated with it. First is the carpometacarpal joint (CMC). This joint is located at the base of the thumb, near the wrist. Where the thumb begins to extend from the hand is the metacarpophleangeal (MP or MCP) joint, followed by the interphalangeal (IP) joint. Like the MCP joint in the fingers, the CMC joint allows for motion in two planes, but it also allows for rotation as well, providing a third degree of freedom. The MP and IP joints allow for one degree of freedom [4].

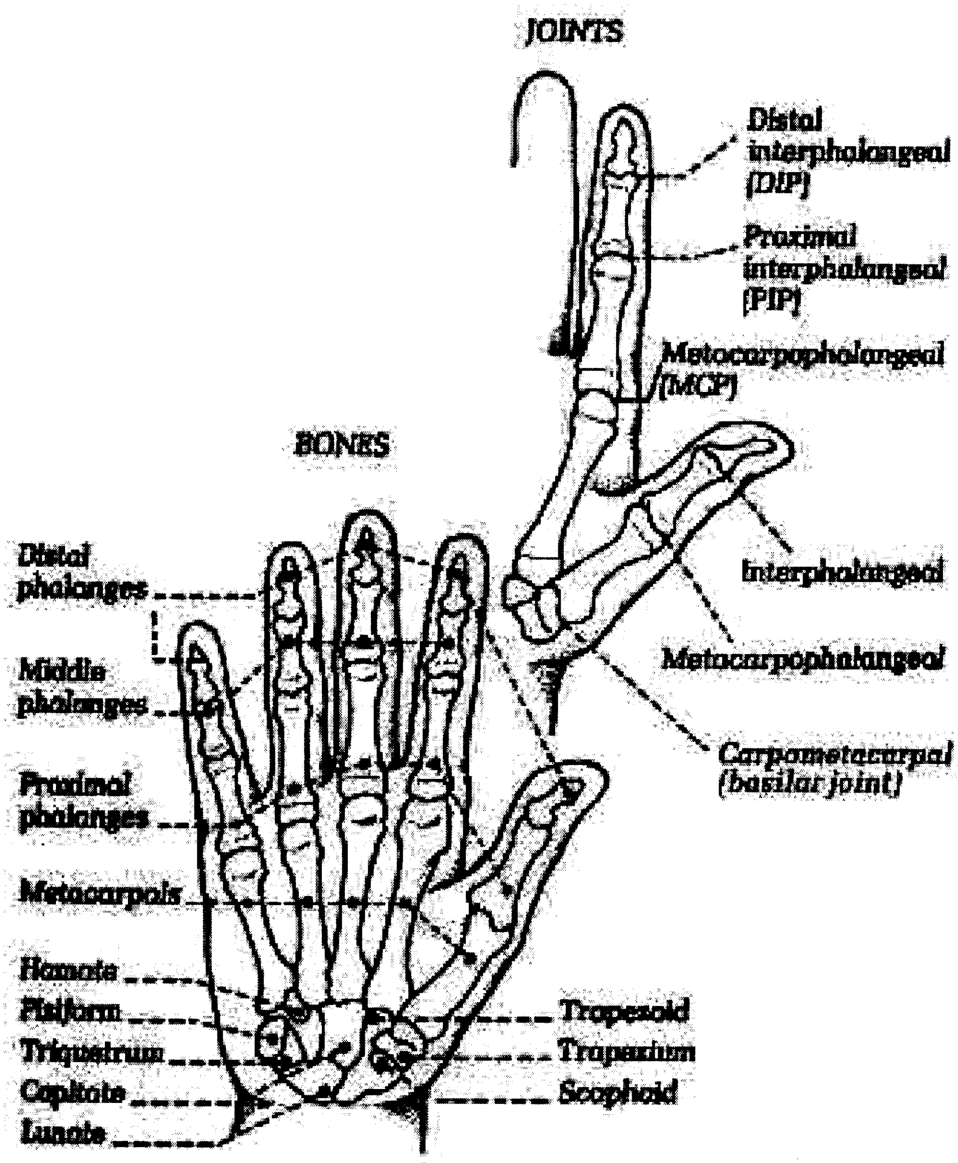


Figure 3.1: Anatomy of the hand [5].

Degrees of freedom in the hand are generally measured in two planes. Abduction and adduction occur when the joints are actuated such that the fingers move along the plane of the palm, and towards or away from the center line of the hand. Flexion and extension occur when the fingers are actuated in the plane perpendicular to the palm.

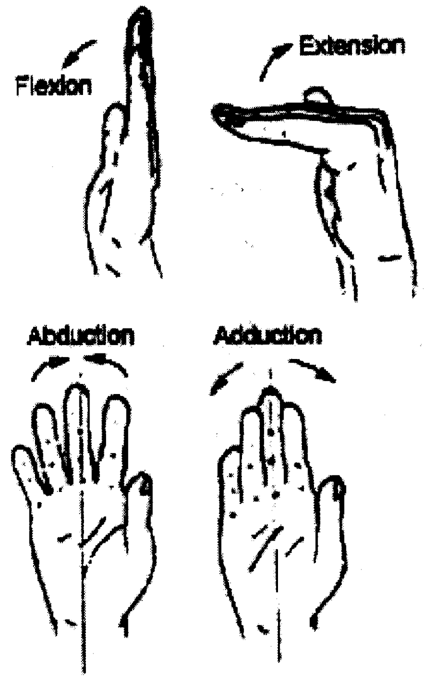


Figure 3.2: Flexion/Extension and Abduction/Adduction in the MCP joints [6].

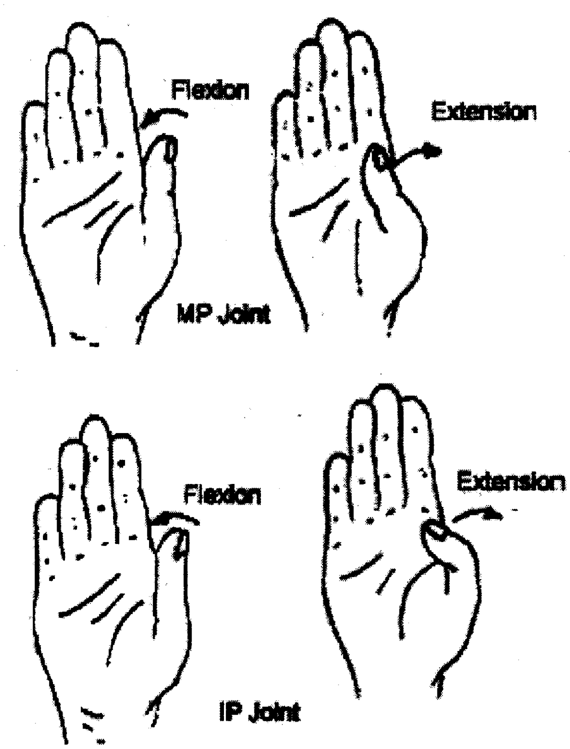


Figure 3.3: Flexion/Extension in the MP and IP joints of the thumb [6].

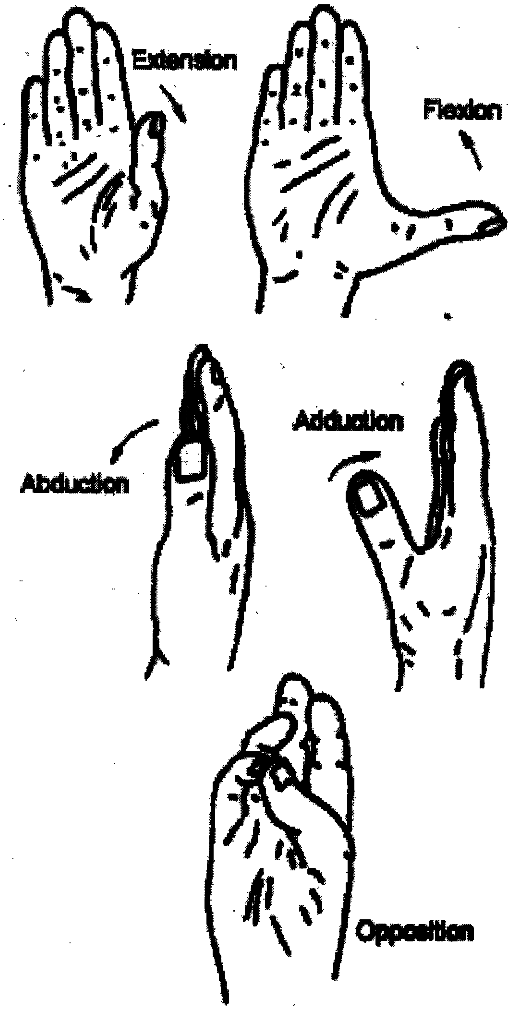


Figure 3.4: Degrees of freedom in the CMC joint of the thumb [6].

Also of interest is the wrist, which has two degrees of freedom.

3.2. Grasps

Using the multiple degrees of freedom allowed by the joints, a person can employ any number of different grasps. In rehabilitation of stroke patients, several common grips are tested and used. One set of grasps commonly used in rehabilitation is Brunnstrom's movement therapy [7].

The hook grasp involves utilizing all the fingers in flexion, creating a hook in the fingers.

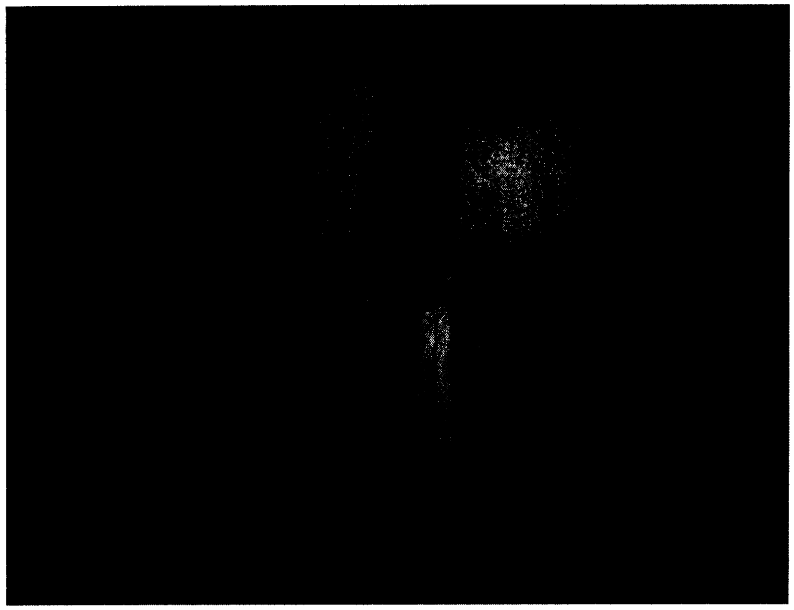


Figure 3.5: An example of a hook grasp.

Lateral prehension brings the thumb to the side of the index finger in order to grasp something between them.

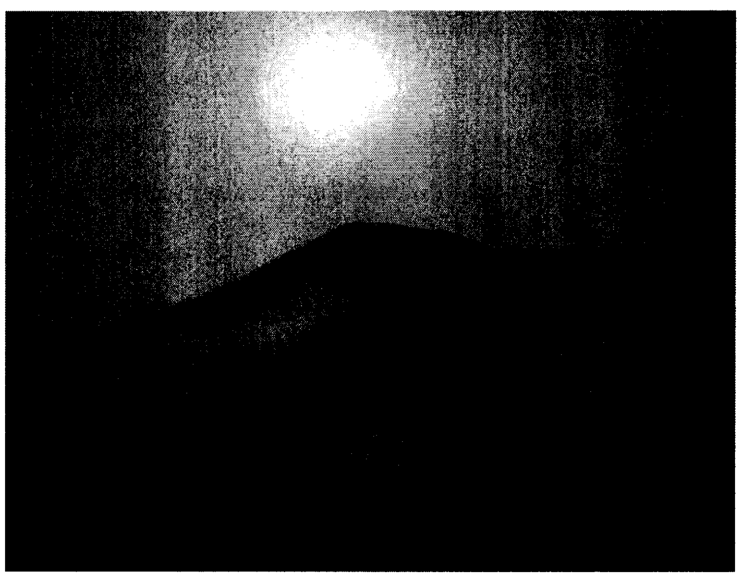


Figure 3.6: An example of lateral prehension.

Palmar prehension brings the finger pad of the thumb to the finger pad of the first one or two fingers. This is also known as a pincer grasp.

Figure 3.7: An example of almar prehension

The cylincrical grasp is used to pick up an object such as a can or jar than fits in the palm of the hand, held there by the fingers and the thumb.

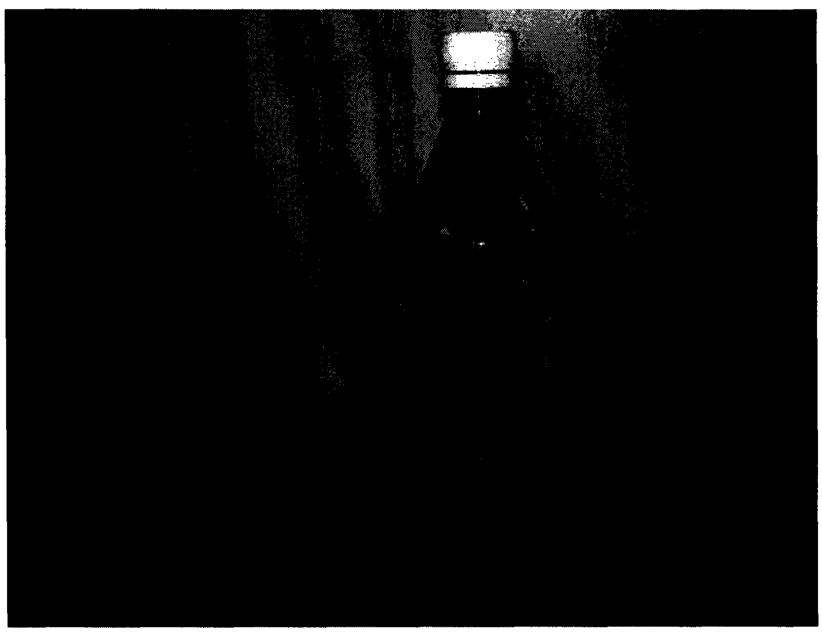


Figure 3.8: An example of a cylindrical grasp.

A spherical grasp is used to pick up a round object in the palm using the fingers and the thumb.

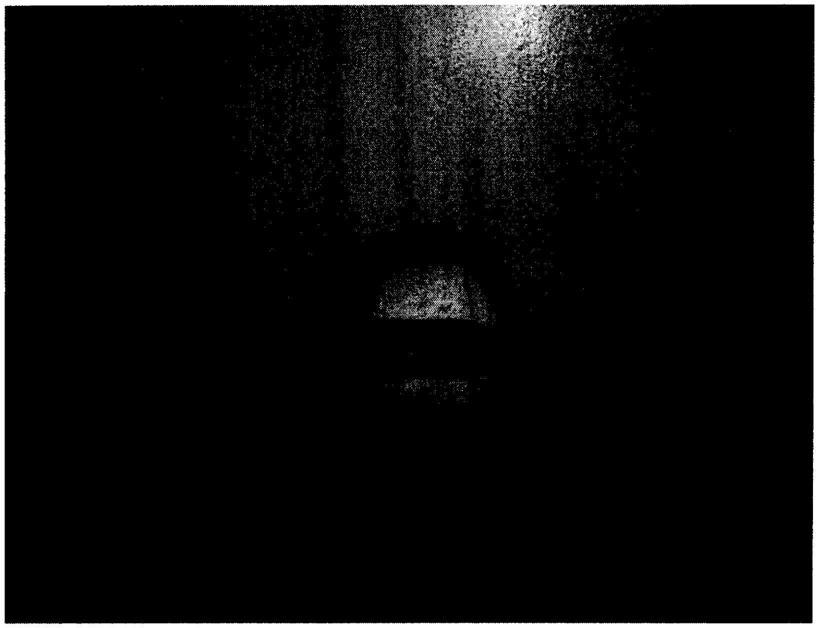


Figure 3.9: An example of a spherical grasp.

In addition to these common grasps, tasks such as opposition and movement of the thumb are also used.

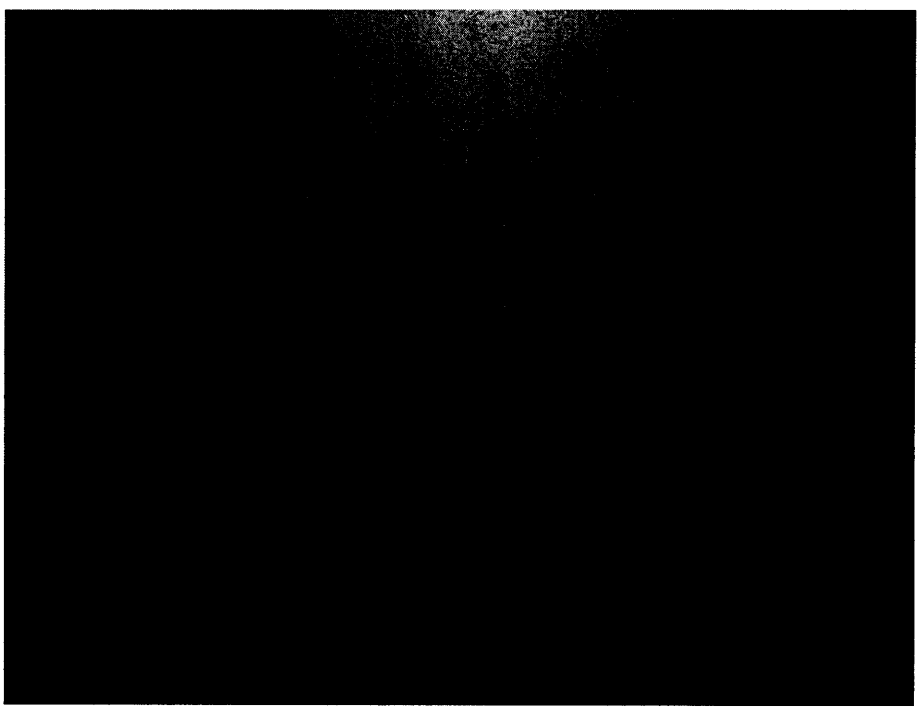


Figure 3.10: An example of opposition.

4. Functional Requirements

4.1. *Grasps*

Though the tracking of every grasp and motion possible would be ideal, in order to simplify the project in or to fit time, cost, and size restraints, it was necessary to narrow down the grasps that would able to be tracked. Because this apparatus would be used on the functional hand, grasps that are commonly used in bimanual tasks were first considered. This included the cylindrical grasp which is used in such tasks as opening a jar. In addition, other simple tasks usable for testing the usability of the system were also taken into account, such holding and turning a key and holding a pencil. These would involve lateral prehension and palmar prehension.

4.2. *Joints*

Once the desired grasps were determined, it was then necessary to determine which joints must be tracked in order to properly identify the grasp without overburdening the system with too many joints to be tracked. For simplicity, only the index finger and thumb were the only fingers to be tracked, in addition to the wrist. Based on the grasps which were to be tracked, the degrees of freedom which were to be tracked were decided. The DIP and IP joints on the index finger and thumb were not tracked because they are rarely actuated independently. In addition, abduction in the index finger and wrist were not found to be necessary in tracking the previously determined grasps. However, maintaining freedom to move in this direction in important in the design. Though tracking the PIP and MP joints would be desirable, there are not critical, and were left out of this design. Finally, the wrist was included to allow characterization of basic hand movement This left four degrees of freedom to be tracked in the hand:

- Flexion/extension in the MCP joint of the index finger
- Flexion/extension of the wrist
- Adduction/abduction of the CMC joint in the thumb
- Flexion/extension of the CMC joint in the thumb

4.3. *Other desired parameters*

4.3.1. Size, weight and forces

The apparatus should be able to fit comfortably onto a patient's hand with minimal interference. Thus, size and weight should be minimal while still providing the desired function. Overall weight of the hand apparatus should be no more than 100g, while requiring less than .1N force to move it.

4.3.2. User interaction

The device must be able to fit a variety of patient's hand sizes, and be able to be used on either the right or left hands. In addition, it should be easy to put on and remove, taking no longer than a minute to adjust to a particular user's size and a minute to attach comfortably to the hand. The apparatus must also be comfortable, avoiding irritation and discomfort to the user.

4.3.3. Cost

A primary motivation for this project is create something that is low cost for the lab. Currently on the market is the Cyber Glove, which retails at approximately $9800. The goal is to create a device that performs a similar function for a fraction of the cost. The target material cost will be $600. Manufacturing can be done in house, which is useful in reducing costs substantially.

5. Design

5.1. Design considerations

Several design options where considered when deciding what direction to pursue. These included optical sensing, strain gauge sensing, cable actuation, and linkage sensing.

5.1.1. Prior art

There currently exists several similar items on the market today. The most prominent one being the CyberGlove by the Immersion Corporation. The glove uses thin resistive bend sensors that provide little bending resistance. These are implanted into a glove that is then worn by the user.

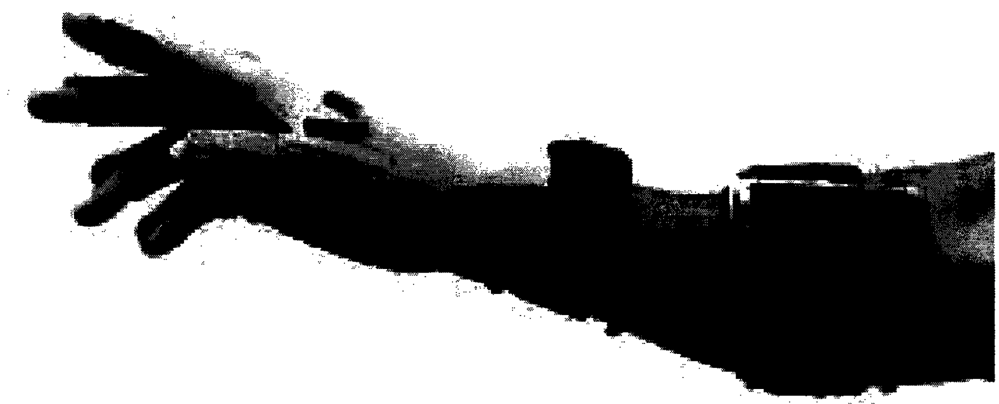


Figure 5.1: CyberGlove by Immersion Corporation [8].

Unfortunately, a glove-like device was ruled out because it reduces the sensation felt by the user and can make it difficult to grab or grasp objects. In addition, it is difficult to create an appropriate glove size that will accommodate most users. Patients may also suffer from arthritic joints, making putting on a glove difficult. Finally, using a glove would dictate that a right handed and a left handed set both be made, doubling the cost of the project.

5.1.2. Optical sensing

One option that was considered was to use optical sensing to track finger and hand movements and location. This would involve placing distinctive marks such as adhesive dots on various points on the subject's hands, and using cameras to track the user's movements. A computer would then locate and track the dots, translating their location into hand position and location. This option would be lightweight and very unobtrusive for the user as it eliminates any need to wear a mechanical apparatus on the hand. However, implementation would be prohibitively expensive. In order to track motion in three dimensions, multiple cameras would be required, and an intensive software package would have to be purchased. In addition, substantial computing power would be needed to quickly and accurately process the video image and translate to hand positions. Because of the high costs associated with optical sensing, this option was eliminated.

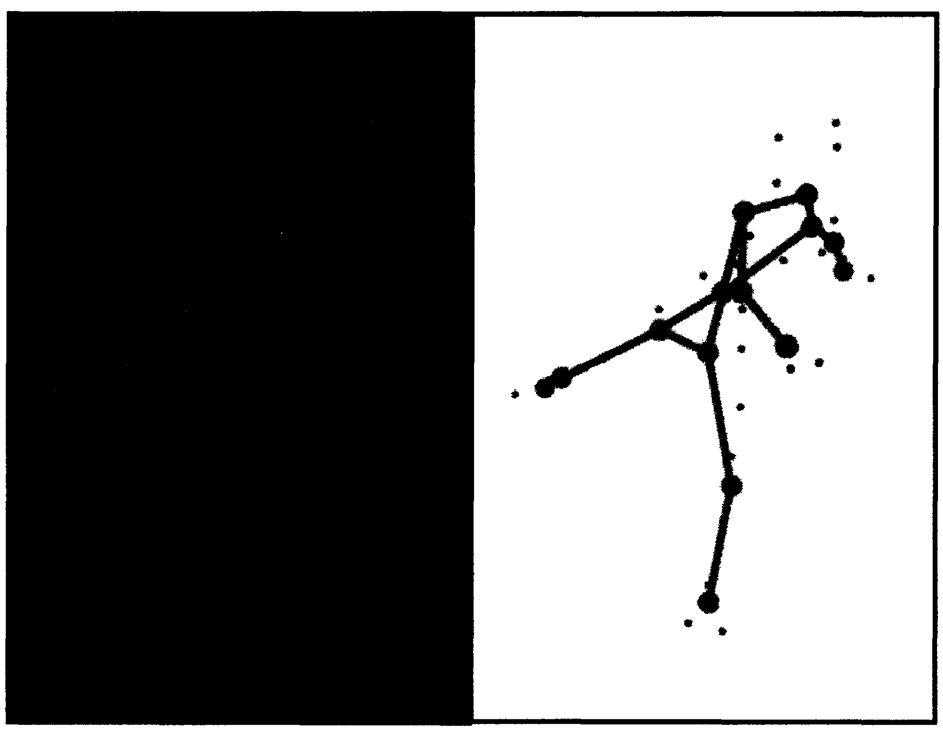


Figure 5.2: A user wearing optical sensors that is then picked up by cameras and translated to a computer [9].

5.1.3. Strain gage

Another option was to use strain gauges attached to the joints that will stretch when the joint is bent. The apparatus would be relatively small, as strain gauges are thin, small, and light. In addition, it can measure small displacements relatively easily. However, it would require a measurable force in order to create strain in the strain gauges, which is undesired. Additionally, signal output is a low level voltage which requires a high level of sensitivity in the measurement equipment, as well as leaves it easily susceptible to interference and noise.

5.1.4. Cable actuation

Cable actuation was also considered. In this system, a cable is pulled around the joint when the joint is bent, and the displacement of the cable is measured. However, a restoring force is necessary in order to pull back the cable after it has been pulled out. This creates an impeding force when the device is in use.

5.1.5. Linkage sensing

The linkage design concept uses two linkages attached by a pin joint in the middle, with the two free ends attached to plates though pin joints that strap on to the hand and arm. The wrist acts as a fourth joint, effectively creating a four bar linkage, where the angle of middle joint is dependent on the angle at which the wrist is actuated. This concept was bulkier than the others, but it could be designed to not interfere with the user's movements. There would be no force to overcome except for the friction in the system and the force required to actuate the sensor.

5.2. Material consideration

The functional requirements require that cost, strength, and weight be important parameters when considering materials. In addition, for ease of manufacturability, the machinability of the material was also considered. These considerations led to the decision to use standard 6061-T6 aluminum for the hand and wrist plates, as well as the linkages. Aluminum is relatively cheap, light and strong for a metal. For the brackets, delrin was chosen because of it use as a bearing surface, low cost, and in particular, its ease of machinibility.

5.3. Sensors

When deciding what sort of sensors to use to read the joint angle, two options were considered: optical encoders and potentiometers.

5.3.1. Optical encoder

Optical rotary encoders use a pattern of light and dark areas on a disk to determine its angle, providing absolute or incremental measurements. They provide very accurate, repeatable measurements, often with 1000 point per revolution resolution. They typically output a waveform that must be read by a digital counter card. However, small optical encoders are still relatively large—3/4" or larger in diameter. In addition, they are also much more expensive than other options.

5.3.2. Potentiometer

Potentiometers are variable resistors, whose resistance varies according to the amount of which the output shaft is turned. Resistance can very linearly or logarithmically, with linearity usually within 1-20%. Compared to optical encoders, they are much more low cost, and easily obtainable. In addition, they also tend to be smaller and lighter than optical encoders. A DC input voltage must be applied and the output voltage is measured though a analog to digital converter which takes the output voltage and converts it to a digital reading.

5.4. General linkage design

For the hand tracker, the general linkage concept was kept, with a few critical adjustments. In order to minimize the forces needed to actuate the system, the sensor was moved from the junction between the two linkages to the junction between the base plate and one of the linkages. While this provides less overall displacement, and thus a possibly less accurate reading, it reduces the load on the user but not requiring an addition force to move the linkages up and down with the weight of the potentiometer on it.

In order to maximize the range of motion of the linkages in order to get the most accurate readings, it is necessary to choose linkage lengths as short as possible, while still allowing a full range of motion for the largest hands that we expect to encounter. If the linkages are too long, the relative angle change will be small and it will be difficult to determine a precise joint angle. If the linkages are too small, the hand will not be able to fully close.

Pin joints are used to allow one degree of freedom in each joint.

5.4.1. Index finger

Data suggests that the first phalange of the index finger is on average 1.792 inches. The first link will attach to the middle of the first phalange of the index finger and the second will reach attach to a point on the hand in line with the finger and similarly spaced from the joint. Allowing for larger hand sizes, a linkage size of 1in was chosen.

5.4.2. Wrist

The male palm length is 4.3in while the female palm length is 3.78in [6]. The first link will attach to the back of the hand via a plate that will strap on. Placing the link at the midpoint of the hand and the second link equally spaced on the wrist, and allowing for a 30 degree bend in the wrist, the linkage size of 2.5in was chosen.

5.5. Thumb linkage design

Designing a method for tracking the thumb required multiple sensors because of the multiple degrees of freedom involved. The CMC joint has three degrees of freedom. Although only two are of interest for the purposes of this device, flexion and abduction, the third must still be left to freely move so as not to impede the user. In addition, the CMC joint is located near the wrist, and the thumb does not extend from the hand until after the IP joint. Thus a linear potentiometer is used to measure the abduction of the thumb as it extends from the hand. In addition, a rotary potentiometer is used to track flexion. At the thumb, pin joints are used at the point where the linear potentiometer attaches to the thumb in order to maintain rotational freedom in the thumb.

5.6. Base design

The base is used to give absolute position and angle of the hand. This requires 3 sensors to measure 3 degrees of freedom: x, y, and z coordinates, as well as allowing rotation around the x, y and z axes. In order to accomplish this, the first degree of freedom is rotation about the base. Two linkages provide two other degrees of freedom, allowing the end point to reach any point in space within range.

In order to provide rotational degrees of freedom, a universal joint was designed, using two small joints that allow one degree of freedom each. The final degree of freedom was hand to rotate around the axis of the end joint.

5.7. Design for adjustability

In order to fit the widest range of users comfortably, it is necessary to make the device adjustable not only for size, but for orientation so that it can be used with either hand. The hand plate needs to be adjustable not only so that it fits a wide range of hands comfortably, but also to align the index finger linkage with the index finger. Doing this also brings the thumb assembly closer to the thumb. In order to make it size adjustable, the hand plate is slid open to make it wider, with a bolt to tighten it to the desired width. In order to make it both left and right handed, the thumb and index finger subassemblies can be unscrewed from the hand plate and reattached in the desired position.

5.8. Design for manufacture

In order to make the device easily manufacturable, several design and materials choices were made. First, the hand and wrist plates were made out of aluminum sheet metal, which could be easily cut using the waterjet. In addition, the linkages were all made using 1/8" thick aluminum and were also cut using the waterjet.

5.9. Patient interaction

The device attaches to the user's hand, wrist, and fingers using Velcro, which can be easily attached and is easily adjustable for a wide range of sizes. In addition, to aid in patient comfort, the hand and wrist plates are lined with rubber lessen irritation with the skin, as well as to avoid any sharp edges.

6. Manufacture

6.1. Sketch model

A sketch model was first made using cardboard, brads, hot glue, and a glove as a proof of concept. It showed the idea was feasible, though also brought up the difficulty in tracking the thumb.

6.2. Mockup

A mockup was made with aluminum parts. Several issues came up during the design and manufacture of the mockup. Initially, the brackets were designed to be only .125in thick, and attach to the hand plates using 0-80 screws. However, this proved difficult to manufacture due to the small size of the drill bits necessary. In addition, the narrow diameter of the screws did not provide adequate lateral support for the brackets. However, it demonstrated the viability of using a linear potentiometer and rotary potentiometer to track the thumb, but it was evident that a linear potentiometer with wider range was necessary. Finally, a more secure attachment to the thumb was also necessary in order to prevent the bracket from sliding.

6.3. Prototype

The final prototype was built using the design improvements from the first two iterations. New brackets were made from delrin, and 4-40 screws were used to secure pieces. In addition, the final prototype was made to be adjustable for both hand size as well as orientation. The base was also built. Wires were wound and routed along the base in order to minimize interference.

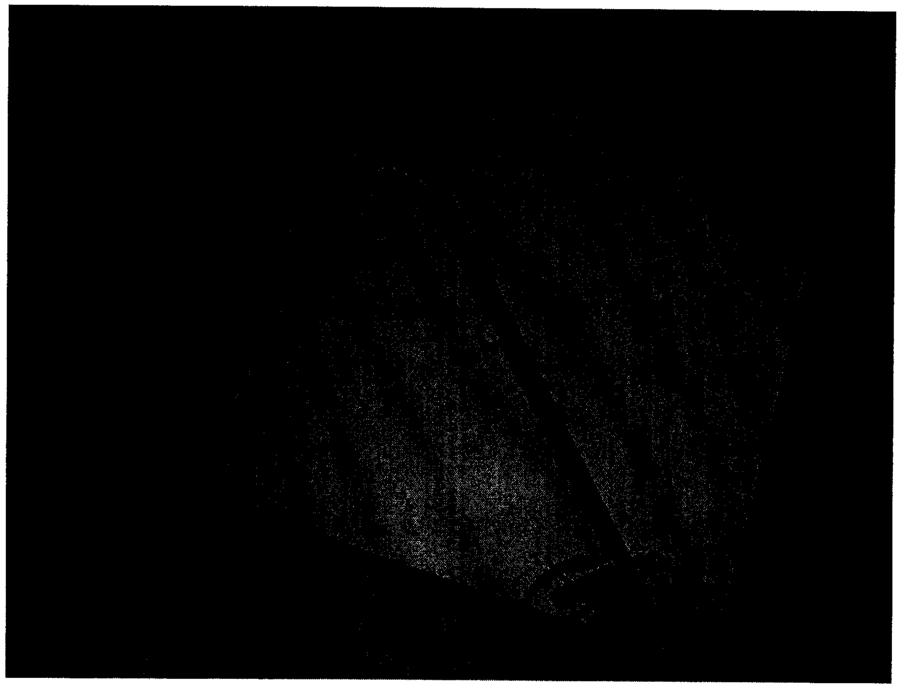


Figure 6.1: Completed base assembly.

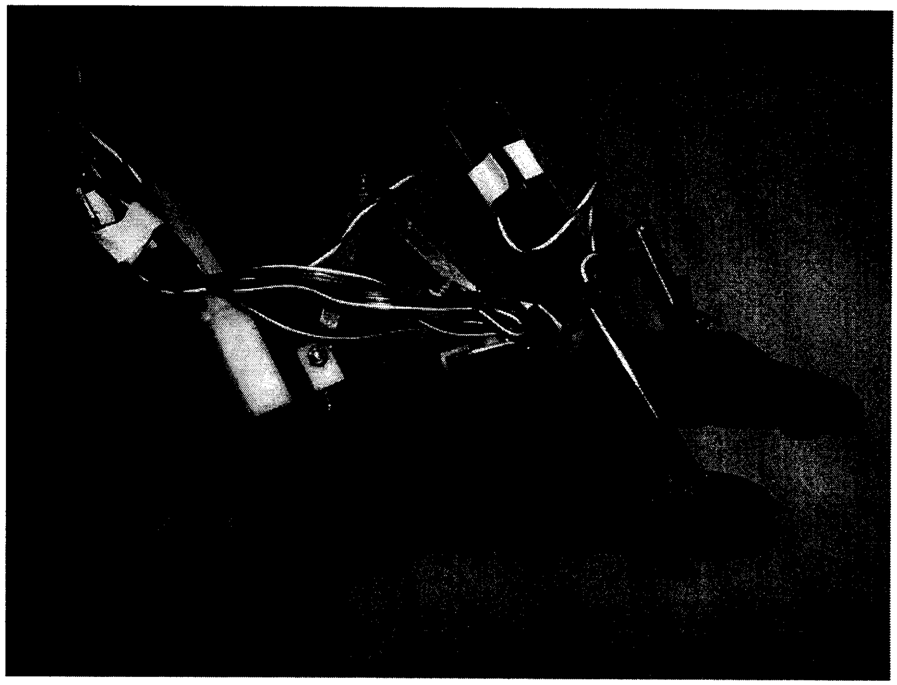


Figure 6.2: Completed hand assembly with and open hand.

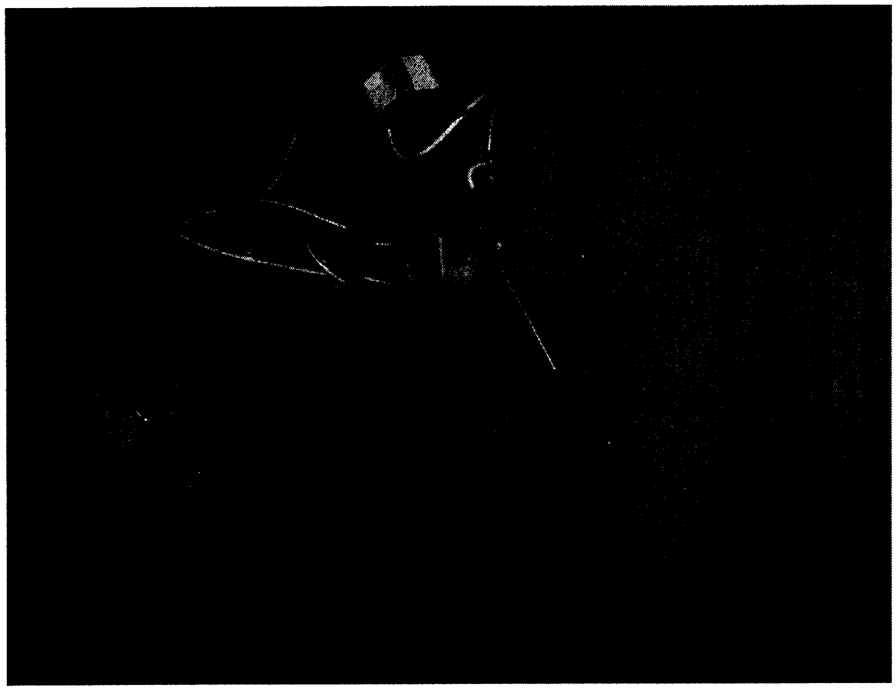


Figure 6.3: Hand making a closed fist while wearing hand assembly.

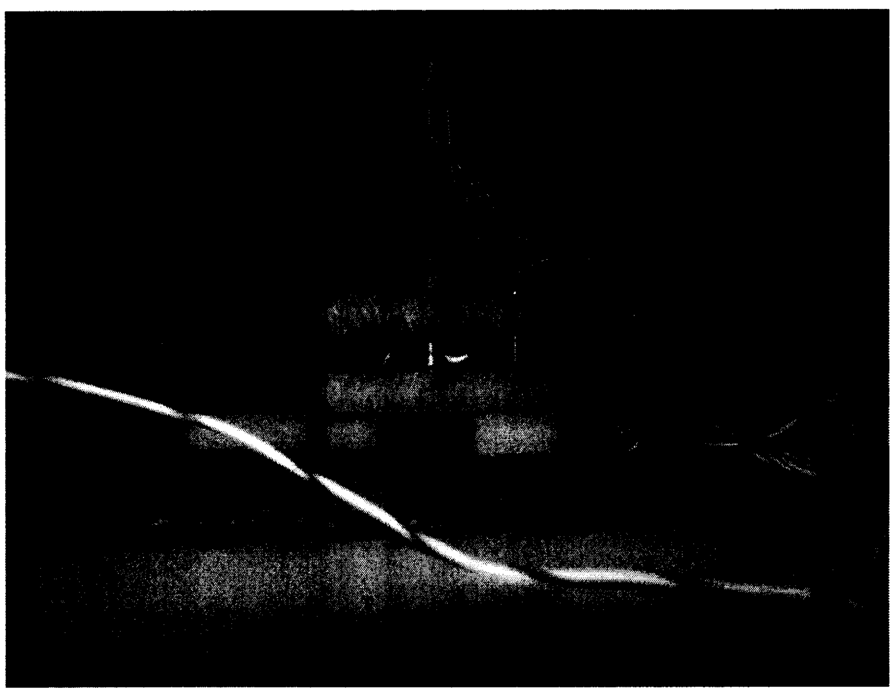


Figure 6.4: Completed base lower assembly.

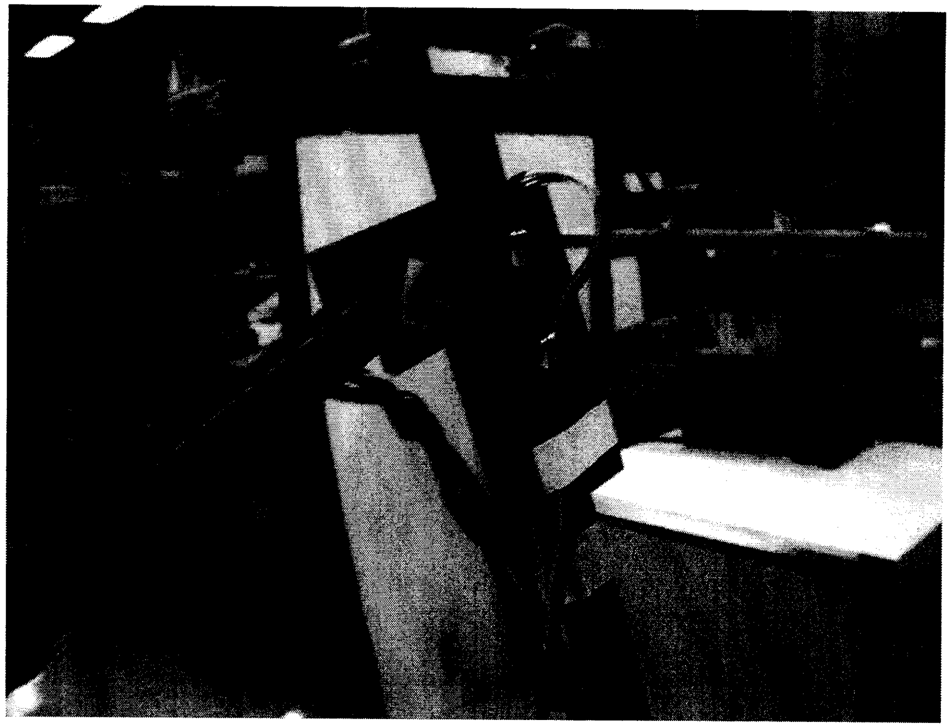


Figure 6.5: Base arm joint.

7. Analysis and Software

7.1. Computer interaction

The apparatus constructed utilizes a Real Time (RT) Linux environment, which allows for uninterrupted data input and output. The hand tracker connects to the computer though a data input card, which reads up to 8 inputs though coaxial cables.

7.2. Angle translation

The flow of information from the hand to the computer is seen in figure 7.1.

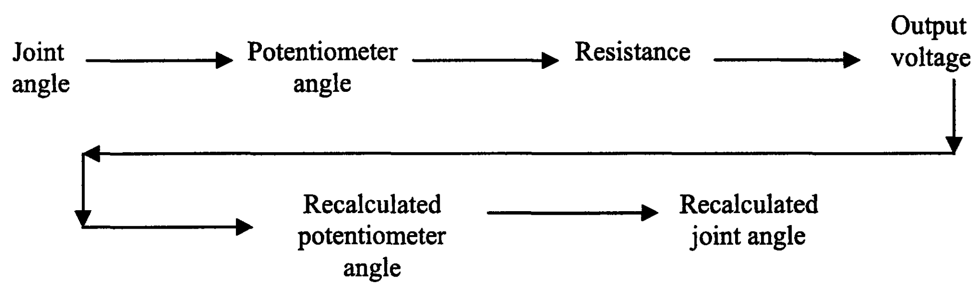


Figure 7.1: Block diagram of information flow.

The movement of the joint influences the angle between the hand/finger and the linkage. This angle is sensed by the potentiometer which then changes its internal resistance and thus varies the output voltage. This voltage is then read by the computer and then once again translated to the linkage angle and then the joint angle.

The joints are tracked using potentiometers as described in section 5.3.2. Potentiometers are given an input voltage, and as the angle of rotation changes, the resistance changes, thus the output voltage also varies such that

$$V_{out} = \frac{R_{var}}{R_{tot}} V_{in}$$

where R_{tot} is the total resistance value of the potentiometer, 10KOhms. V_{in} is the input voltage given by a power supply, 5V, and R_{var} is the variable resistance that changes with the angle of rotation of the potentiometer.

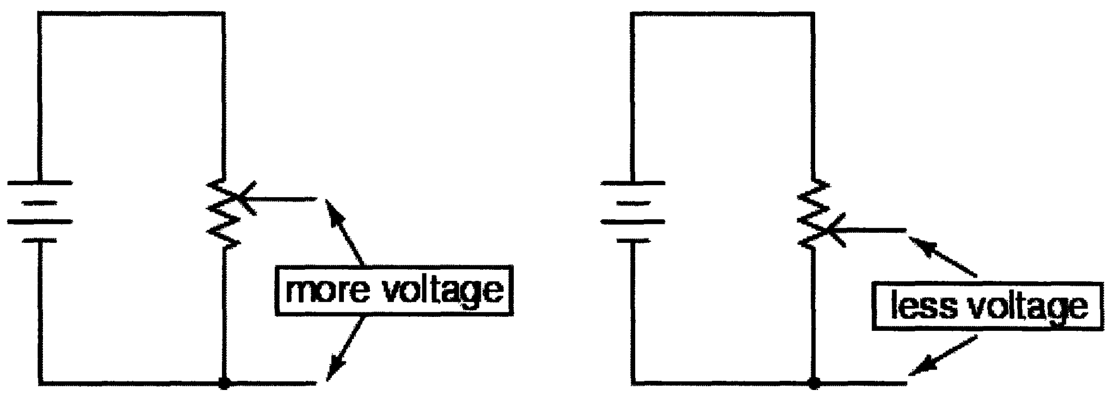


Figure 7.2: Schematic of a potentiometer acting as a voltage divider.

To find the angle that corresponds to the output voltage, each potentiometer is calibrated independently by finding the voltage output at two known angles and linearly interpolating to find the relationship, which results in the form y = mx + b.

Where the wrist and MCP joint are tracked though linkages, in order to find the relationship between the potentiometer angle and the actual joint angle, the system can be modeled as a four bar linkage. The two linkages act as two bars while the hand and finger act as the other two effective bars. It is also assumed that the ends of the two linkages are placed such that the joint is centered between them.

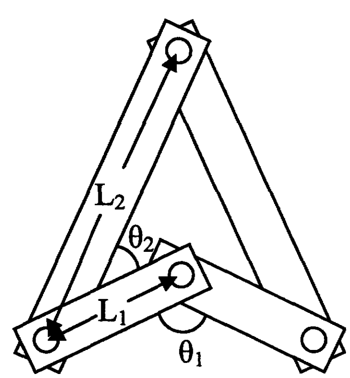


Figure 7.3: Four bar linkage.

Using this model, the relationship between the joint angle and the potentiometer angle is found to be

$$\theta_2 = \cos^{-1}\left[\frac{L_1}{L_2}\cos\left(\frac{\pi-\theta_1}{2}\right)\right] - \frac{\pi-\theta_1}{2}.$$

7.3. Position tracking

The base is modeled as a system of linkages as joints as seen in figure 7.4.The first angle, θ_1, is the rotational angle of the base. The second angle, θ_2, measures the angle from horizontal of the first linkage, while θ_3 measures the angle between the second and third linkages.

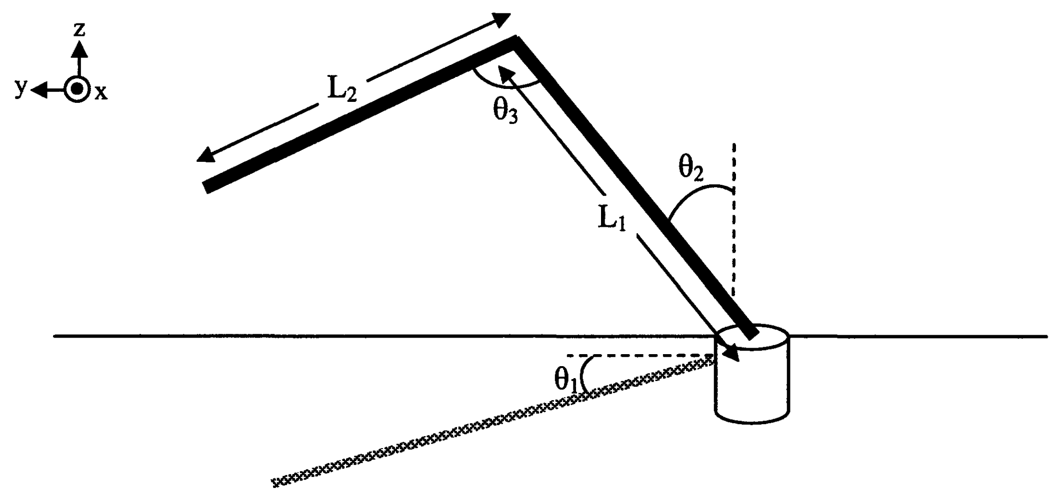


Figure 7.4: Base setup.

The x, y, and z position of the end of the base, where the hand is located is as follows:

$$x = \sin(\theta_1)\cdot\left(L_1\sin(\theta_2) + L_2\sin(\theta_3-\theta_2)\right)$$

$$y = \cos(\theta_1)\cdot\left(L_1\sin(\theta_2) + L_2\sin(\theta_3-\theta_2)\right)$$

$$z = L_1\cos(\theta_2) - L_2\cos(\theta_3-\theta_2).$$

7.4. Hand and finger position tracking

Once the joint angles of the wrist and MCP joint are determined, the end points of the hand and finger can be found. Simplifying the hand and index finger into single lines yields figure 7.5.

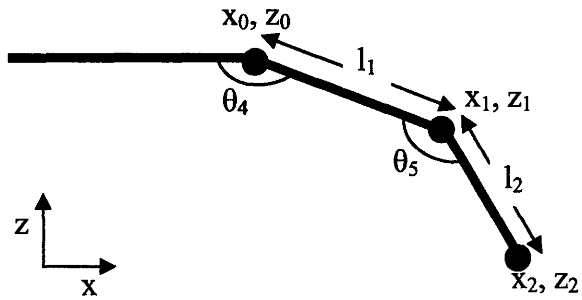


Figure 7.5: Simplified model of the hand and index finger in the x-z plane.

Using this model, the positions of the end points can be found:

$$x_1 = l_1 \cos(\pi - \theta_4) + x_0$$

$$z_1 = -l_1 \sin(\pi - \theta_4) + z_0$$

$$x_2 = l_2 \cos(\frac{5\pi}{2} - \theta_5 - \theta_4) + x_1, \text{ and}$$

$$z_2 = -l_2 \sin(\frac{5\pi}{2} - \theta_5 - \theta_4) + z_1$$

.

7.5. Thumb tracking

Tracking the thumb is more difficult because the thumb can move in all three dimensions, as seen in figure 7.6.

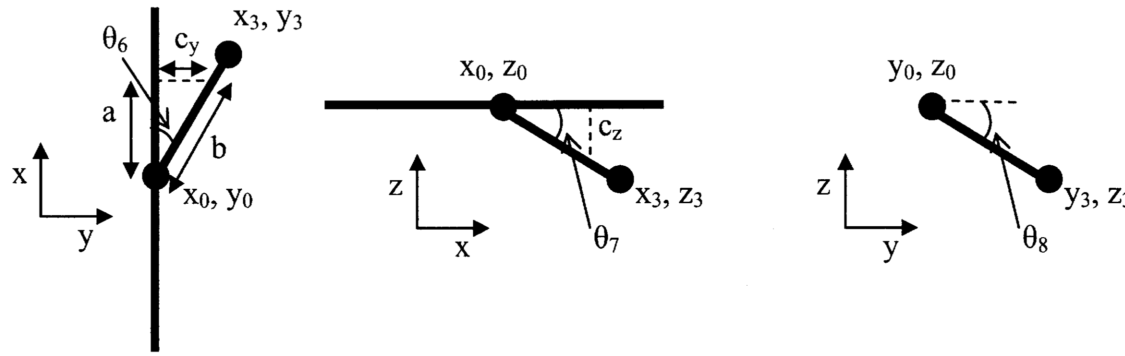


Figure 7.6: Model of the thumb in x-y and x-z planes.

In this model, c is the distance measured by the linear potentiometer, a is the distance from the joint to the linear potentiometer along the hand, and b is the distance between the joint and the end of the potentiometer along the thumb. The angle θ_6 is the angle between in the thumb and forefinger in the x-y plane, while θ_7 is the angle between the thumb and forefinger in the x-z plane. A potentiometer output gives the angle for θ_8, while the overall length c is found using the linear potentiometer. These two pieces of information can give values for c_y and c_z:

$$c_y = c\cos(\theta_8)$$

$$c_z = c\sin(\theta_8).$$

With a, b, and c_x known, θ_6 can be found using the law of cosines:

$$\theta_6 = \cos^{-1}\left(\frac{c_x^{\,2} - a^2 - b^2}{-2ab}\right).$$

Similarly,

$$\theta_7 = \cos^{-1}\left(\frac{c_z^{\,2} - a^2 - b^2}{-2ab}\right).$$

With this, the end points of the thumb can then be found:

$$x_3 = b\cos\theta_6 + x_0$$

$$y_3 = b\sin\theta_6 + y_0\text{, and}$$

$$z_3 = -b\sin\theta_7 + z_0 .$$

7.6. Software

A simple program was written in TCL/TK to test the functionality of the hand tracker. As the computer read the input signals from the potentiometers, these signals are then translated into angles, and then into positions of the hand and fingers. This is then displayed on the screen, as the computer mimics what the hand is doing. Because there are no 3D drawing capabilities in TCL/TK, the hand position is drawn using x-y and x-z planes.

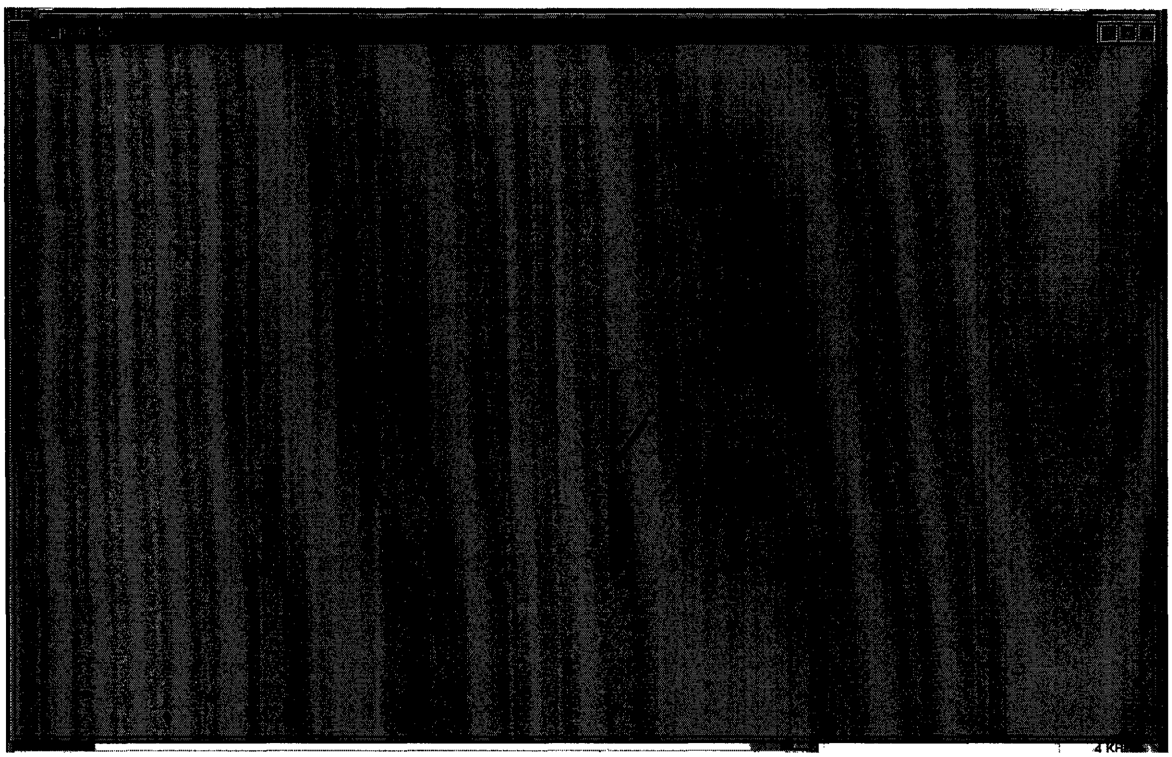


Figure 7.7: Screen shot of x-y plane simulation.

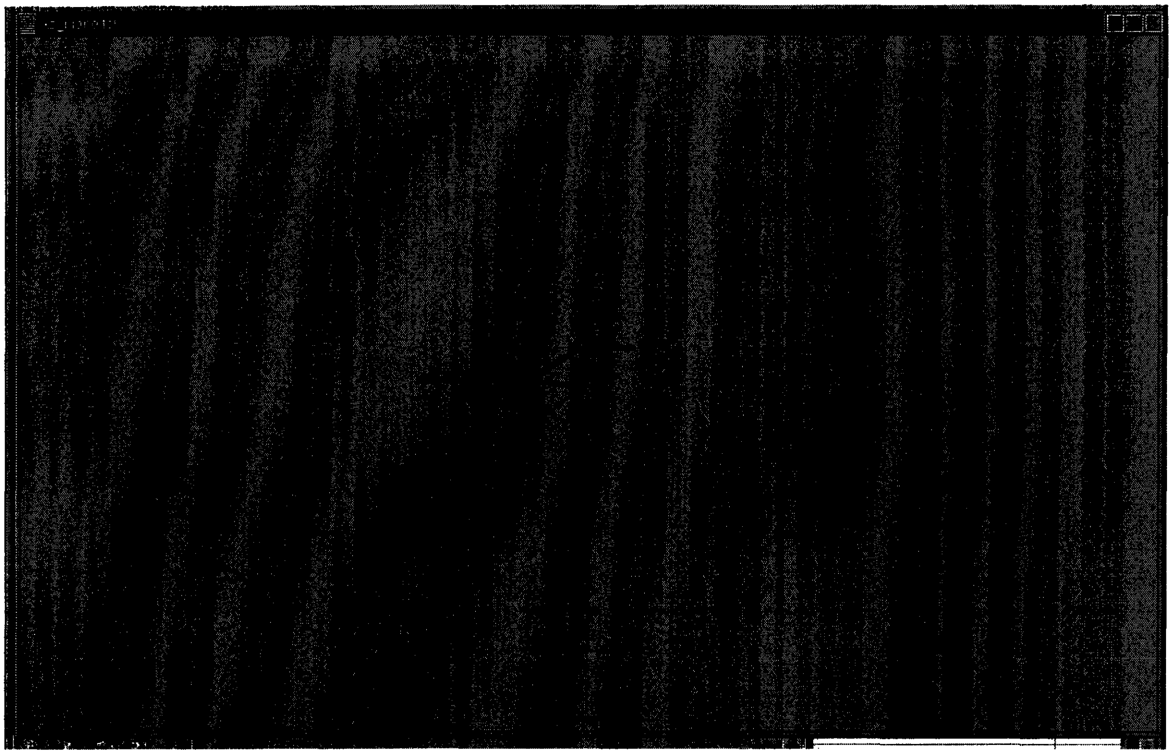


Figure 7.8: Screenshot of x-z plane simulation.

Figure 7.9: Program imitating the hand in the x-y plane.

Figure 7.10: Program imitating the hand in the x-z plane.

8. Conclusion

8.1. Achievements

For this thesis project, I was able to design a novel hand tracker that can monitor several joints in the hand and wrist. The design allowed for free movement of the hand while maintaining the ability to perform function tasks. It was also adjustable for various hand sizes, and configurable for both the right and left hand. This design was manufactured using a variety of tools, including a computer numerical control (CNC) mill, lathe, and waterjet. In addition, a simple software program was created that allowed for the simple tracking of the hand.

8.2. Proposed Improvements

There are several possible improvements for this project. The first proposed improvement is to reduce the weight of the base. The current base structure is constructed from steel extrusion, and its weight creates a high inertia to overcome when it is moved. The base could be reconstructed with aluminum extrusions, and if possible, the wall thickness of the extrusion could be reduced in order to further reduce the weight. In addition, the base can also be counter balanced using springs to reduce the effective weight borne by the user, so that it rests in the center of the workspace.

The current wiring system that connects the apparatus to the computer involves a series of coaxial cables that must be plugged in individually before the system can be used. This is a cumbersome and time consuming process, with a high possibility of error if two or more cables are plugged in incorrectly. A possible improvement would be to utilize an alterative data input interface, such as a USB cable or a multi-pin plug.

This project can also be improved by increasing the number of sensors used in the hand tracker. This will give a more thorough model of the hand and thus be more useful in research and analysis.

Finally, the robustness of the hand tracker can also be improved upon. The current brackets are attached to the hand and wrist plates using 4-40 screws that screw directly into the bracket. However, as the brackets swivel around pivot point, the screw tends to come loose. This issue was addressed in several of the brackets with a thread fastener, however, this option is not useful for the brackets for the linkages that attach to the thumb and the finger, as these should be easily removable for reconfiguration. One possible solution is to create a base that is secured to the hand plate using screws and wing nuts, with a bracket that rotates around this base. Thus, the piece is easily removable by unscrewing the wing nuts but still allowing the bracket to rotate freely.

8.3. Future Work

This project was created with the goal of being used in laboratory tests with the MIT MANUS project. In order for this to occur, the design improvements discussed above should be implemented in order to create a simpler, more robust apparatus. In addition, more software needs to be developed that combines the data collected by both this hand tracker as well as the MIT MANUS robot and creates simple challenges for the patients to accomplish.

References

[1] Mayo Clinic, *Stroke.* http://www.mayoclinic.com/health/stroke/DS00150

[2] D. Wood, *Stroke.* http://www.massgeneral.org/vascularcenter/page.asp?id=stroke

[3] http://www.strokehelp.com/newsletters/t-05-02.htm

[4] K. A. Jugenheimer, "A Robot for Hand Rehabilitation," M.S. thesis, Massachusetts Institute of Technology, Cambridge, MA, 1999

[5] http://www.drfoot.co.uk/wrist_pain/wrist_anatomy.htm

[6] Derek, Field, Nigel, Palastanga and Roger Soames. *Articulations Within the Hand,* pages 244-75. Butterworth-Heinemann, Boston, 2 edition, 1994.

[7] Katheryn Sawyer and Jeanne LaVigne, *Burnnstrom's Movement Therapy in Hemipelgia: A Neurological Approach.* J B Lippincott Co., Philiadelphia, 2 edition, 1992.

[8] http://www.metamotion.com/hardware/motion-capture-hardware-gloves-Cybergloves.htm

[9] A. Kirk, J. O'Brien, and D. Forsyth, *Skeletal Parameter Estimation from Optical Motion Capture Data,* From the proceding of IEEE Conf. on Computer Vision and Pattern Recognition (CVPR) 2005.

Appendix A:
Data Sheets

THIS DOCUMENT CONTAINS PROPRIETARY DATA OF POLARIS INDUSTRIAL ENTERPRISES,INC. NO DISCLOSURE, REPRODUCTION, OR USE OF ANY PART THERE OF MAY BE MADE EXCEPT BY WRITTEN PERMISSION.	REV.	BY	DATE	APPRVL.	REV. NOTE:	P/N LCP12
	M	BT	03/27/00		ADDED NOTE:	

SPECIFICATIONS

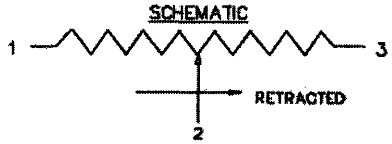
RESOLUTION ------------------- INFINITE
OUTPUT SMOOTHNESS ----------- LESS THAN 0.1% INPUT VOLTAGE
CONTACT RESIST. VARIATION----- LESS THAN 2%
DIELECTRIC STRENGTH ---------- 500 VAC MIN.
INSULATION RESISTANCE -------- 1000 MEGOHMS AT 500 VDC MIN.
FRICTION ---------------------- 1.8 oz. (3.6 oz FOR LCP12-100)
STOP STRENGTH ---------------- 20 OZ. MIN..
RESISTANCE TEMPCO ----------- ±400 PPM/°C
WEIGHT ----------------------- 10 TO 35 GRAMS
LIFE EXPECTANCY -------------- 20 MILLION STROKES

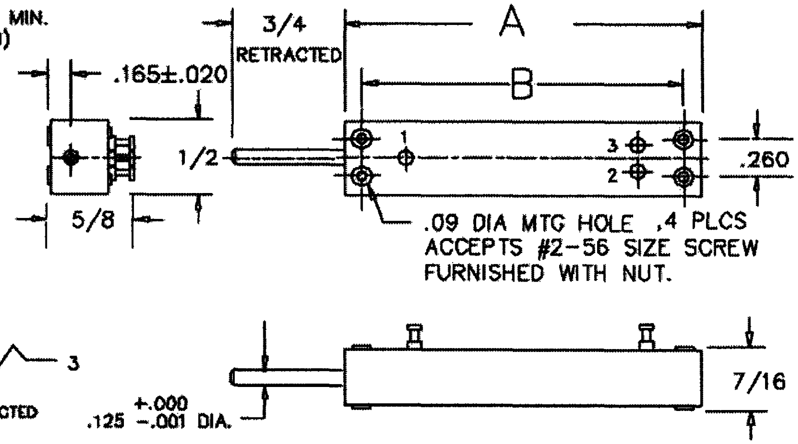
MATERIALS

BODY ------------------------- ALUMINUM(BLACK ANODIZE)
LID --------------------------- HIGH TEMP. PLASTIC
SHAFT ------------------------ STAINLESS STEEL
TERMINALS -------------------- BRASS GOLD PLATED
RESISTANCE ELEMENT ----------- CONDUCTIVE PLASTIC

OPTIONS AVAILABLE

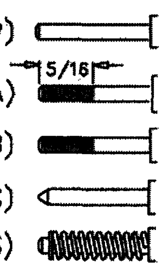
SPECIAL ENDED SHAFTS
SPECIAL RESISTANCE VALUES
SPECIAL LINEARITY
NON STANDARD STROKES
SPRING RETURNS





MODEL NO.	LCP12-12	LCP12-25	LCP12-50	LCP12-76	LCP12-100
STD.RESIS.VALUES	500,1K,2K 5K,10K	500,1K,2K 5K,10K	500,1K,2K 5K,10K,20K	1K,2K,5K 10K,20K	1K,2K,5K 10K,20K
RESISTANCE TOL. LINEARITY (IND.)	±20% ±1.5%	±20% ±1.0%	±20% ±0.7%	±20% ±0.5%	±20% ±0.5%
POWER RATING	0.2 WATT	0.4 WATT	0.7 WATT	1.2 WATT	1.2 WATT
STROKE MECH+.1-.0 STROKE ELECT ±.02	1/2"	1"	2"	3"	4"
'A' DIM ±0.04	1.50	2.00	3.00	4.00	5.00
'B' DIM ±0.02	1.26	1.77	2.75	3.76	4.76

MODEL NO'S. / SHAFT STYLES



MODEL NO'S.	SHAFT STYLES	
LCP12P-(STROKE)-(RES.)	(P)	PLAIN
LCP12A - " "	(A)	#4-40 THREAD
LCP12B - " "	(B)	#5-40 THREAD
LCP12C - " "	(C)	CHAMFERED 0.030"DIA. X 45°
LCP12S - " "	(S)	SPRING RETURN

LCP12S-76 OR -100 (RES) RETRACTED LENGTH OF SHAFT TO BE 1 1/4" FOR 3" & 4" STROKE SPRING RETURN.

NOTE: FOR SPRING RETURN WITH THREAD, SEE DWG. LCP12ST

TOLERANCES
XX = +/- .010" FRACT. = +/- 1/64"
XXX= +/- .005" ANGLES = +/- 1/2"
ALL SPECIFICATIONS SUBJECT TO CHANGE WITHOUT NOTICE.

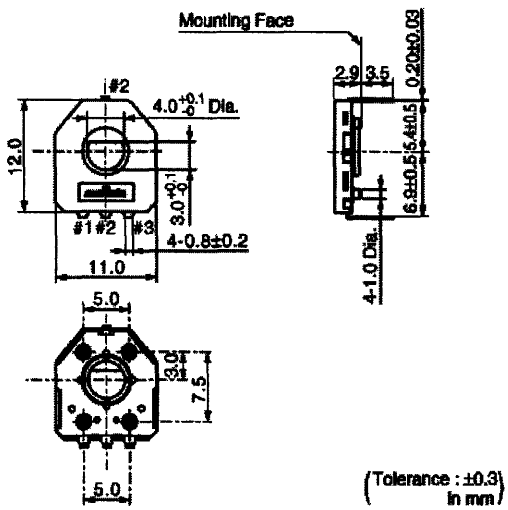
SCALE	DATE: 3-29-88
	BY
NONE	APPRV'D BT
CODE IDENT: 19477	

ETI SYSTEMS
ETI SYSTEMS CARLSBAD CALIFORNIA

TITLE
LINEAR MOTION POTENTIOMETER

PART NO.
LCP12

Home > Search Engine > SV01L103AEA11T00: Dimensions



Resistors > Trimmer Potentiometers > SMD Dust Proof Type 12mm Size
Sensors > Rotary Position Sensors >

Specification

Global Part Number	SV01L103AEA11T00
Previous Part Number	PVS1L103A03T00
Total Resistance Value	10k ohm ±30%
Rated Voltage	5Vdc
Dielectric Strength	250Vac, 1 min., Leakage current 50 micro A max.
Insulation Resistance	100M ohm min. (250Vdc)
Linearity	±2%
Effective Rotational Angle	333.3° (Ref.)
Torque	2mN.m (Ref.:21gf.cm) max.
TCR	±500ppm/°C
Rotational Life	1M cycles
Operating Temperature Range	
Soldering Method	Flow/Soldering Iron
Weight	0.38g

Details

- Part Numbering
- Appearance
- Dimensions
- Features_and_Applicatio
- Spec.
- Construction
- Mounting_Holes
- Notice_(Storage_and_operating_cor
- Notice_(Soldering_and_r
- Notice_(Handling)
- Notice_(Other)
- Soldering_Profile

Minimum Quantity

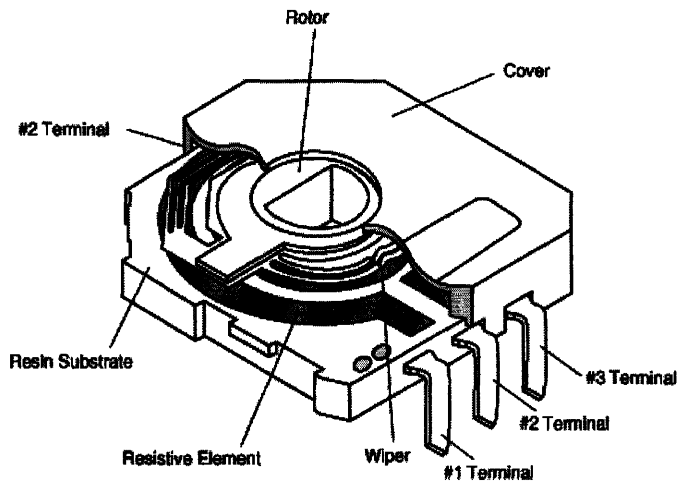
180mm Paper Tape	
180mm Embossed Tape	
330mm Paper Tape	
330mm Embossed Tape	
Bulk Case	
Bulk(Bag)	
Ammo Pack	

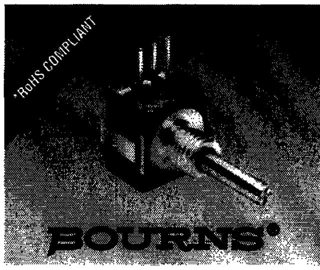
320Reel	
Magazine	
Box	1000

Product specifications in this catalog are as of March 2007,
and are subject to change or obsolescence without notice.
Please approve our product specifications or transact the approval sheet before orderi
Please read rating and !Cautions first.

Temperature Cycle (Thermal Shock)	ΔTR	±20%
	Linearity	±3%
Humidity	ΔTR	±20%
	Linearity	±3%
Vibration	ΔTR	±10%
	Linearity	±3%
Shock (20G)	ΔTR	±10%
	Linearity	±3%
Humidity Load Life	ΔTR	±20%
	Linearity	±3%
High Temperature Exposure	ΔTR	+5/-30%
	Linearity	±3%
Low Temperature Exposure	ΔTR	±20%
	Linearity	±3%
Rotational Life (1M cycles)	ΔTR	±20%
	Linearity	±3%

ΔTR: Total Resistance Change


Rotor
Cover
#2 Terminal
Resin Substrate
#3 Terminal
#2 Terminal
Resistive Element
Wiper
#1 Terminal



Features

- RoHS compliant*
- Conductive plastic or cermet
- Linear and audio tapers
- PC board and bushing mount
- Gangable
- Metal bushing and shaft
- Sealed for board washing

51/53 - Sealed 1/2 " (12.5 mm) Square Control

Standard Resistance Range		
Linear	1 K ohms to 1 megohm	150 ohms to 1 megohm
Audio	1 K ohms to 1 megohm	1 K ohms to 1 megohm
Total Resistance Tolerance		
Linear Tapers	±10 % or ±20 %	±10 % or ±5 %
Audio Tapers	±10 % or ±20 %	±10 %
Independent Linearity	±5 %	±5 %
Absolute Minimum Resistance	2 ohms maximum	2 ohms maximum
Effective Electrical Angle	270 ° ±5 °	270 ° ±5 °
Contact Resistance Variation	2 %	2 %
Dielectric Withstanding Voltage (MIL-STD-202 – Method 301)		
Sea Level	1,500 VAC minimum	1,500 VAC minimum
70,000	500 VAC minimum	500 VAC minimum
Insulation Resistance	1,000 megohms minimum	1,000 megohms minimum
Power Rating At 70 °C (Derate To 0 At 125 °C)		
(Voltage Limited By Power Dissipation or 350 VAC, Whichever Is Less)		
Linear Tapers	0.5 watt	1.0 watt
Audio Tapers	0.25 watt	0.5 watt
Theoretical Resolution	Essentially infinite	Essentially infinite

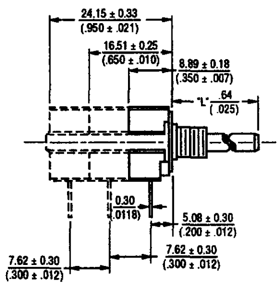
Operating Temperature Range	+1 °C to +125 °C	+1 °C to +125 °C
Storage Temperature Range	-55 °C to +125 °C	-55 °C to +125 °C
Temperature Coefficient Over Storage Temperature Range	±1,000 ppm/°C	±150 ppm/°C
Vibration (Single Section)	15 G	15 G
Total Resistance Shift	±2 % maximum	±2 % maximum
Voltage Ratio Shift	±5 % maximum	±5 % maximum
Shock (Single Section)	30 G	30 G
Total Resistance Shift	+2 % maximum	±2 % maximum
Voltage Ratio Shift	±5 % maximum	±5 % maximum
Load Life	1,000 hours	1,000 hours
Total Resistance Shift	±10 % TRS maximum	±5 % TRS maximum
Rotational Life (No Load)	50,000 cycles	25,000 cycles
Total Resistance Shift	±10 % TRS maximum	±10 % TRS maximum
Contact Resistance Variation @ 25,000 Cycles	±2 %	±4 %
Moisture Resistance (MIL-STD-303, Method 103, Condition B)		
Total Resistance Shift	±10 % TRS	±5 % TRS
IP Rating	IP 64	IP 64

Stop Strength	56 N-cm (5 lb.-in.)
Mechanical Angle	290 ° ±5 °
Torque	
Starting (All Sections)	Running torque +0.35 N-cm (+0.5 oz.-in.) maximum
Running (Single Section)	0.15 to 1.4 N-cm (0.2 to 2.0 oz.-in.)
Running (Dual or Triple Section)	0.35 to 1.8 N-cm (0.5 to 2.5 oz.-in.)
Mounting (Torque on Bushing)	1.7 to 2.0 N-m (15 to 18 lb.-in.) maximum
Weight (Single Section)	5.5 grams
(Each Additional Section)	3.0 grams
Terminals	PC pin or solder lug
Soldering Condition	Recommended hand soldering using Sn95/Ag5 no clean solder, 0.025 " wire diameter. Maximum temperature 399 °C (750 °F) for 3 seconds. No wash process to be used with no clean flux. Part can be wave soldered at 260 °C (500 °F) for 5 seconds, no wash process with no clean flux.
Marking	Manufacturer's trademark, part number, resistance value and date code.
Ganging (Multiple Section Potentiometers)	6 cups maximum
Hardware	One lockwasher and one mounting nut is shipped with each potentiometer, except where noted in the part number.

[1]At room ambient: +25 °C nominal and 50 % relative humidity nominal, except as noted.

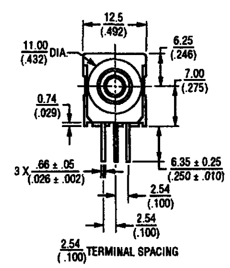
*RoHS Directive 2002/95/EC Jan 27 2003 including Annex
Specifications are subject to change without notice.
Customers should verify actual device performance in their specific applications.

PACKAGE DIMENSIONS

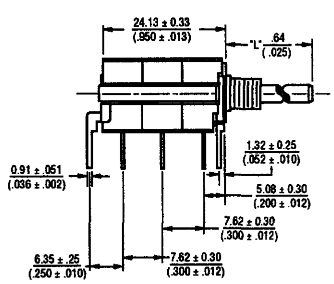


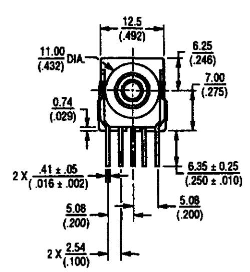
(SINGLE, DUAL AND TRIPLE MODULE SHOWN)
AVAILABLE IN 1 THROUGH 6 MODULE VERSIONS.

MODEL 51



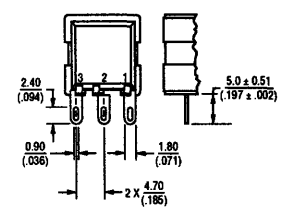
PACKAGE DIMENSIONS PCB MOUNTING BRACKET



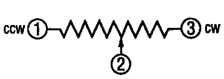


AVAILABLE IN 1 THROUGH 6 MODULE VERSIONS.

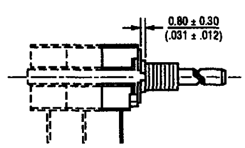
SOLDER LUG TERMINALS
MODEL 53

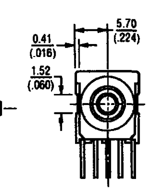


ELECTRICAL SCHEMATIC



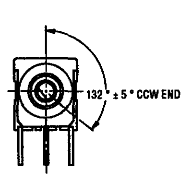
ANTI-ROTATION LUG
(Style "A", 90 CW Shown)



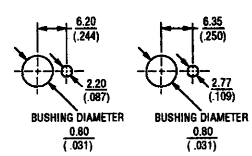


DIMENSIONS ARE: $\frac{\text{MM}}{\text{(INCHES)}}$

SHAFT FLAT
ORIENTATION



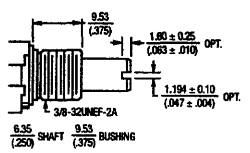
SUGGESTED PANEL LAYOUTS
The Model 50 can be used with either of the two panel layouts shown below.



FOR TOLERANCES SHOWN: .XX = ± $\frac{.25}{(.010)}$
.XXX = ± $\frac{.13}{(.005)}$
SHAFT DIMENSIONS ± $\frac{.80}{(1/32)}$

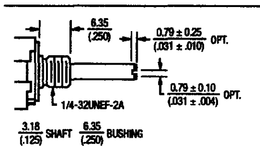
Specifications are subject to change without notice.
Customers should verify actual device performance in their specific applications.

A Style Bushing



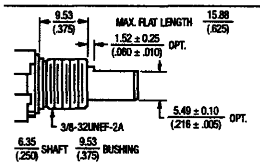
STD. LENGTH 'L'
.500 (12.7)
.625 (15.88)
.750 (19.05)
.875 (22.23)
1.000 (25.4)

C Style Bushing



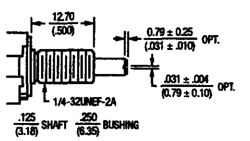
STD. LENGTH 'L'
.375 (9.53)
.500 (12.7)
.625 (15.88)
.750 (19.05)
.875 (22.23)
1.000 (25.4)

A Style Bushing - Flatted Shaft



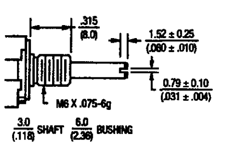
STD. LENGTH 'L'
.625 (15.88)
.750 (19.05)
.875 (22.23)
1.000 (25.4)

F Style Bushing



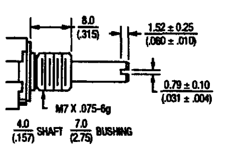
STD. LENGTH 'L'
.625 (15.88)
.750 (19.05)
.875 (22.23)
1.000 (25.4)

S Style Bushing



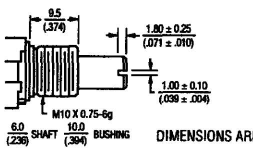
STD. LENGTH 'L'
.394 (10.0)
.512 (13.0)
.630 (16.0)
.866 (22.0)
.984 (25.0)

U Style Bushing



STD. LENGTH 'L'
.394 (10.0)
.512 (13.0)
.630 (16.0)
.866 (22.0)
.984 (25.0)

R Style Bushing



STD. LENGTH 'L'
.512 (13.0)
.630 (16.0)
.866 (22.0)
.984 (25.0)

DIMENSIONS ARE: MM / (INCHES)

51	A	A	D	-	B	28	-	A	15	L

RoHS IDENTIFIER	
Code	**Description**
L	**Compliant**

MOUNTING BRACKET/ ANTI-ROTATION LUG	
Code	**Description**
A	**AR Lug 90 °CW**
C	AR Lug 270 °CW
D	**No AR Lug or Bracket**
L	Front Bracket
M	Rear Bracket
N	Front and Rear Bracket

# SECTIONS/DETENTS	
Code	**Description**
A	**Single No Detent**
B	Double No Detent
C	Triple No Detent
D	Quad No Detent
E	Single w/Center Detent
F	Double w/Center Detent
G	Triple w/Center Detent
H	Quad w/Center Detent
J	Five Section
K	Six Section
L	Five Section w/Detent
M	Six Section w/Detent

BUSHING CONFIGURATION	
Code	**Description**
A	**3/8 "D x 3/8 "L**
C	**1/4 "D x 1/4 "L**
F	1/4 "D x 1/2 "L
R	**10 mmD x 9.5 mmL**
S	**6 mmD x 8 mmL**
U	**7 mmD x 8 mmL**

MODEL	
Code	**Description**
51	**PC Pins (.100 " centers)**
53	**Solder Lugs**

ELEMENT TAPER TYPE/TOLERANCE		RESISTANCE (CODE)	
Code	**Description**	**VALUE IN OHMS**	
(A) (H)	**Linear Cermet ±10 %** Linear Cermet ±5 %	(28) – 150 (06) – 200 (07) – 250 (08) – 500 (09) – 750 **(10) 1 K** (29) – 1.5 K (11) – 2 K (12) – 2.5 K **(13) 5 K**	(14) – 7.5 K **(15) 10 K** (30) – 15 K (16) – 20 K (17) – 25 K **(18) 50 K** (19) – 75 K **(20) 100 K** (23) – 500 K (25) – 1 M
(B) (E)	**Linear C-P ±20 %** Linear C-P ±10 %	**(10) 1 K** (12) – 2.5 K **(13) 5 K** **(15) 10 K** (16) – 20 K (17) – 25 K	**(18) 50 K** **(20) 100 K** (22) – 250 K (23) – 500 K (25) – 1 M
(C) (F)	CW Audio Cermet ±10 % CCW Audio Cermet ±10 %	(10) – 1 K (12) – 2.5 K (13) – 5 K (15) – 10 K (17) – 25 K	(18) – 50 K (20) – 100 K (23) – 500 K (25) – 1 M
(D) (S)	**CW Audio C-P ±20 %** CW Audio C-P ±10 %	**(10) 1 K** (12) – 2.5 K **(13) 5 K** **(15) 10 K** (17) – 25 K	**(18) 50 K** **(20) 100 K** (22) – 250 K (23) – 500 K (25) – 1 M
(G) (T)	CCW Audio C-P ±20 % CCW Audio C-P ±10 %	(10) – 1 K (12) – 2.5 K (13) – 5 K (15) – 10 K (17) – 25 K	(18) – 50 K (20) – 100 K (22) – 250 K (23) – 500 K (25) – 1 M
(Y)	CW Dual Audio Taper C-P ±20 %	(10) – 1 K (12) – 2.5 K (13) – 5 K (15) – 10 K (17) – 25 K	(18) – 50 K (20) – 100 K (22) – 250 K (23) – 500 K (25) – 1 M

SHAFT TYPE		AVAILABLE ONLY IN	
		BUSHINGS	**LENGTHS**
Code	**Description**	**Code**	**Description**
A	Single Plain 1/4 "D	A	20,24,28,32
B	**Single Slotted 1/4 "D**	**A**	12,16,20,**24**,**28**,32
C	Single Flatted 1/4 "D	A	20,24,28,32
D	Single Plain 1/8 "D	C, F	16,20,24,28,32
E	**Single Slotted 1/8 "D**	**C, F**	12,16,20,**24**,**28**,32
R	**Single Slotted 6 mmD**	**R**	10,13,16,22,**25**
T	**Single Slotted 4 mmD**	**U**	10,13,16,22,**25**
U	**Single Slotted 3 mmD**	**S**	10,13,**16**,22,25

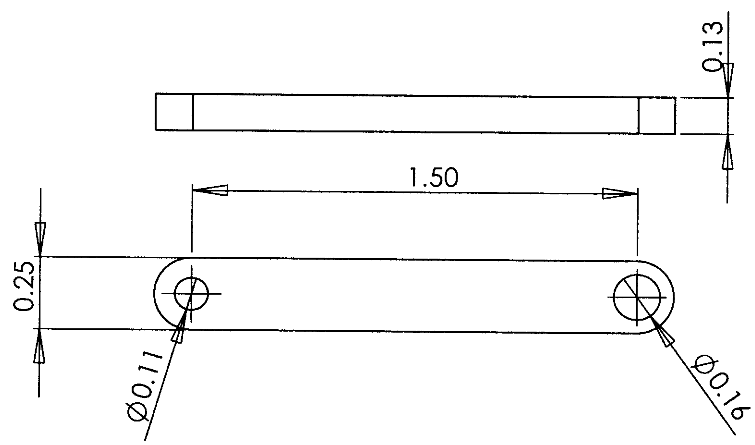
SHAFT LENGTH (FMS)		AVAILABLE ONLY IN BUSHING
Code	**Description**	**Code**
12	3/8 "	B, C
16	1/2 "	A, C
20	5/8 "	A, C, F
24	**3/4 "**	**A, C, F**
28	**7/8 "**	**A, C, F**
32	1 "	A, C, F
Metric		
10	10 mm	R, S, U, T
13	13 mm	R, S, U, T
16	**16 mm**	**R, S, U, T**
22	22 mm	R, S, U, T
25	**25 mm**	**R, S, U, T**

Boldface features are Bourns standard options. All others are available with higher minimum order quantities.

REV. 12/11/06

Specifications are subject to change without notice.
Customers should verify actual device performance in their specific applications.

Appendix B:
Part Drawings

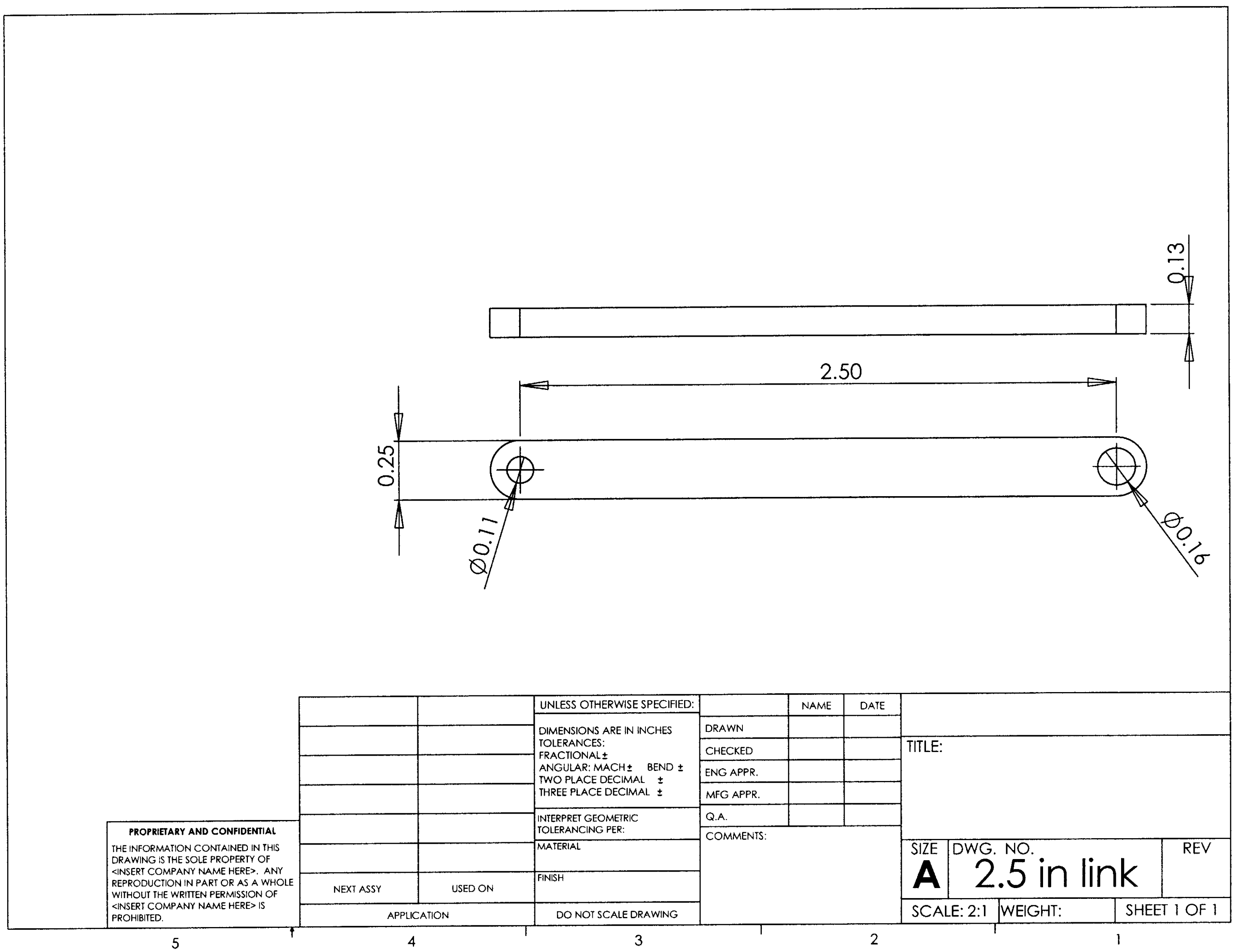


UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN			
	CHECKED			TITLE:
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
MATERIAL	COMMENTS:			SIZE A | DWG. NO. 1.5 in link | REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

5 4 3 2 1


0.13
2.50
0.25
Ø0.11
Ø0.16
PROPRIETARY AND CONFIDENTIAL
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APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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DO NOT SCALE DRAWING
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CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
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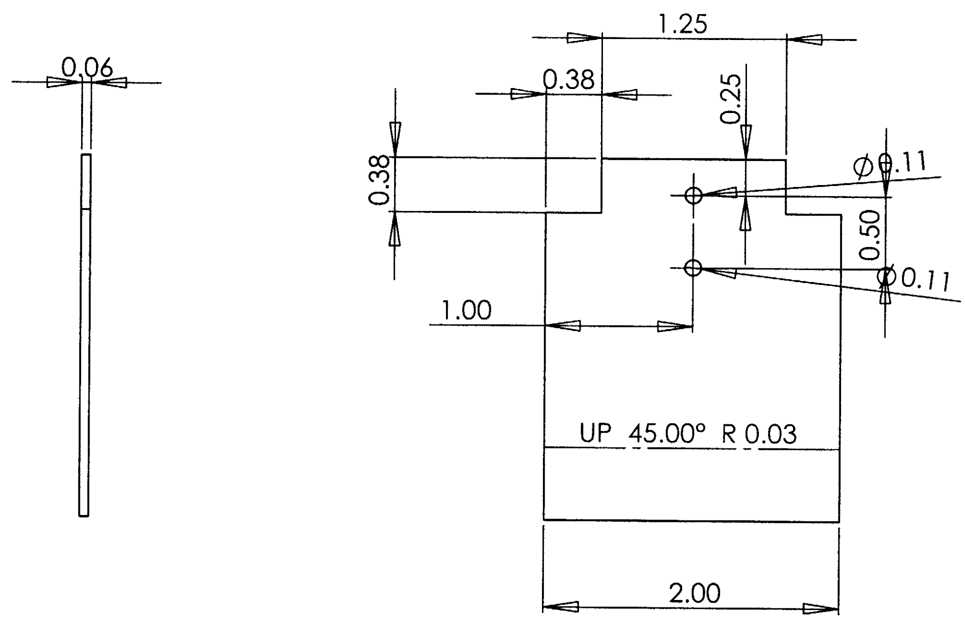
DWG. NO.
2.5 in link
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

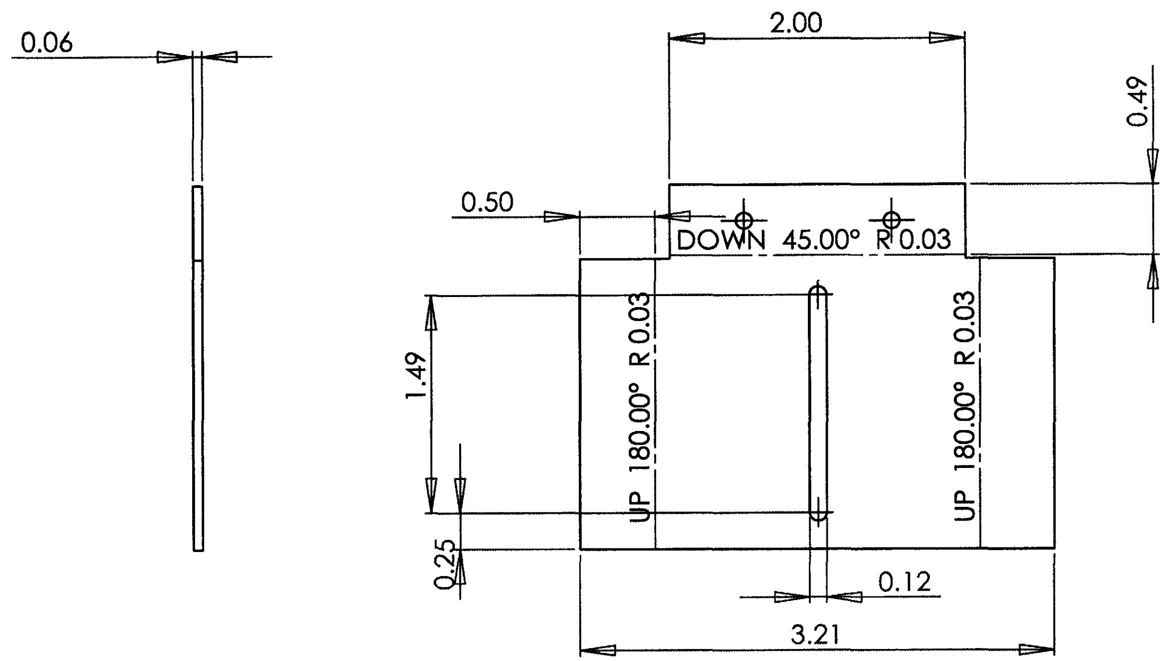
COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	wrist plate 1	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



PROPRIETARY AND CONFIDENTIAL

NEXT ASSY	USED ON
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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

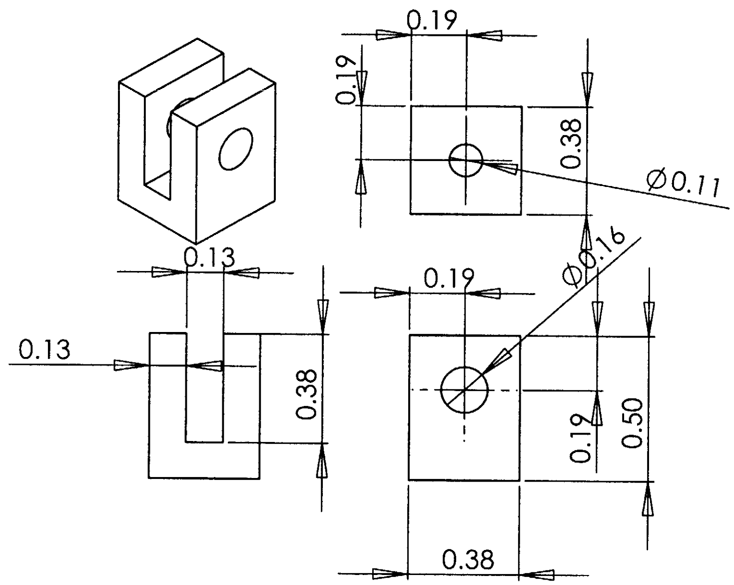
COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	wrist plate 2	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

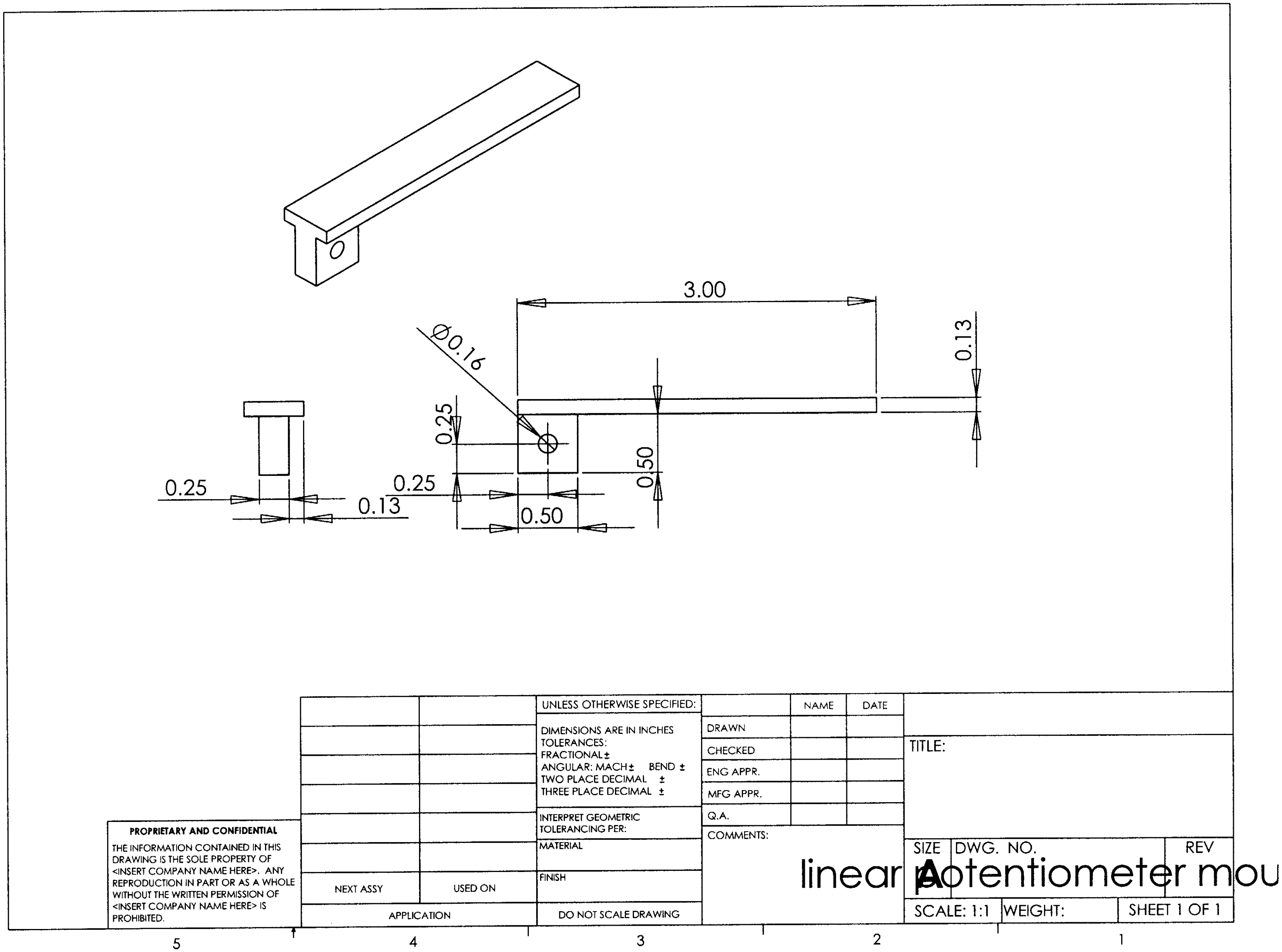
NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE A | DWG. NO. bracket | REV

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1


3.00
Ø0.16
0.13
0.25
0.50
0.25
0.13
0.25
0.50
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
A
linear potentiometer mou
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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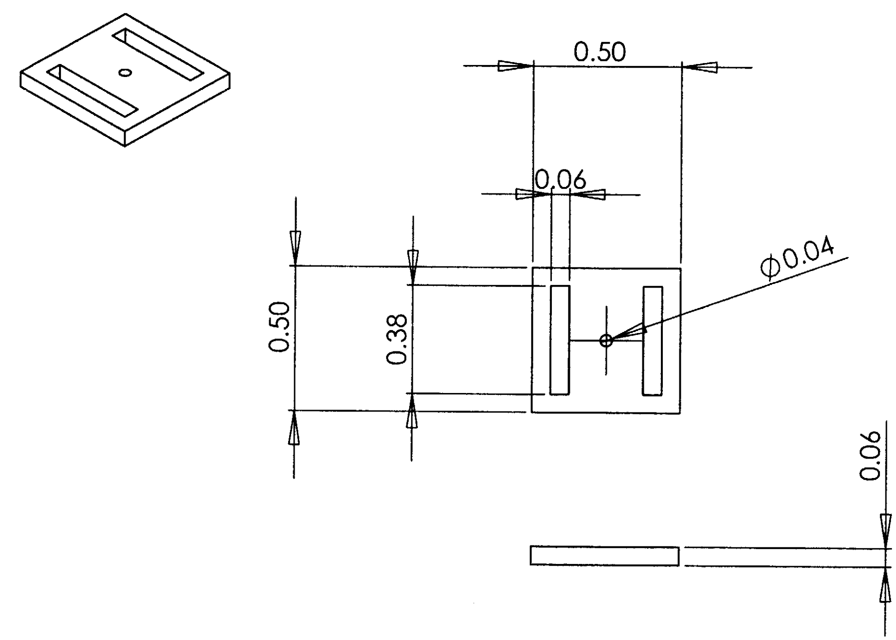
5
4
3
2
1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

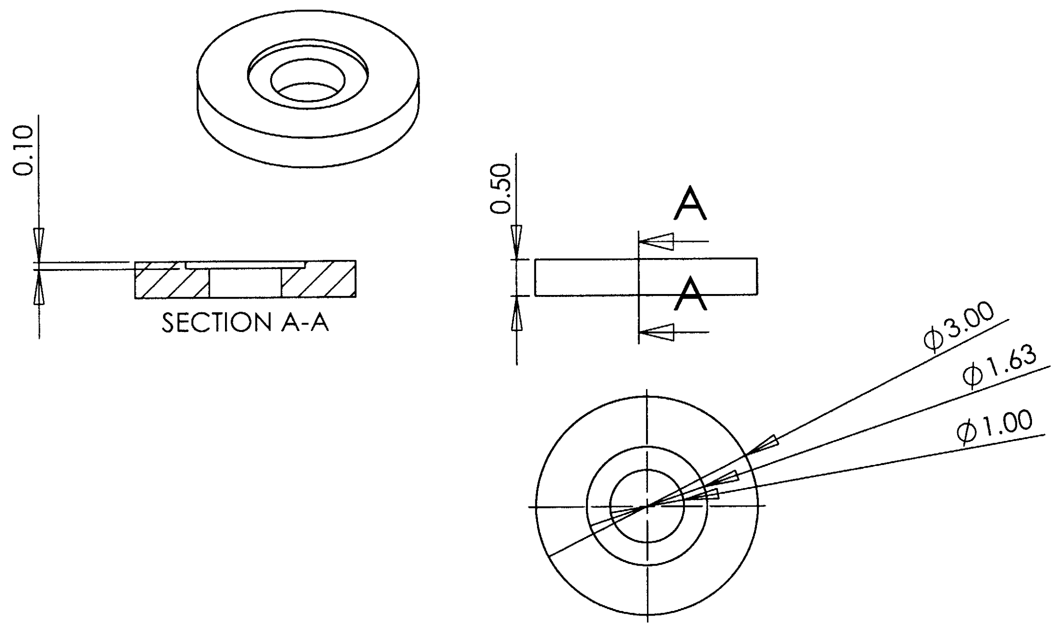
COMMENTS:

TITLE:

SIZE A | DWG. NO. finger mount | REV

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

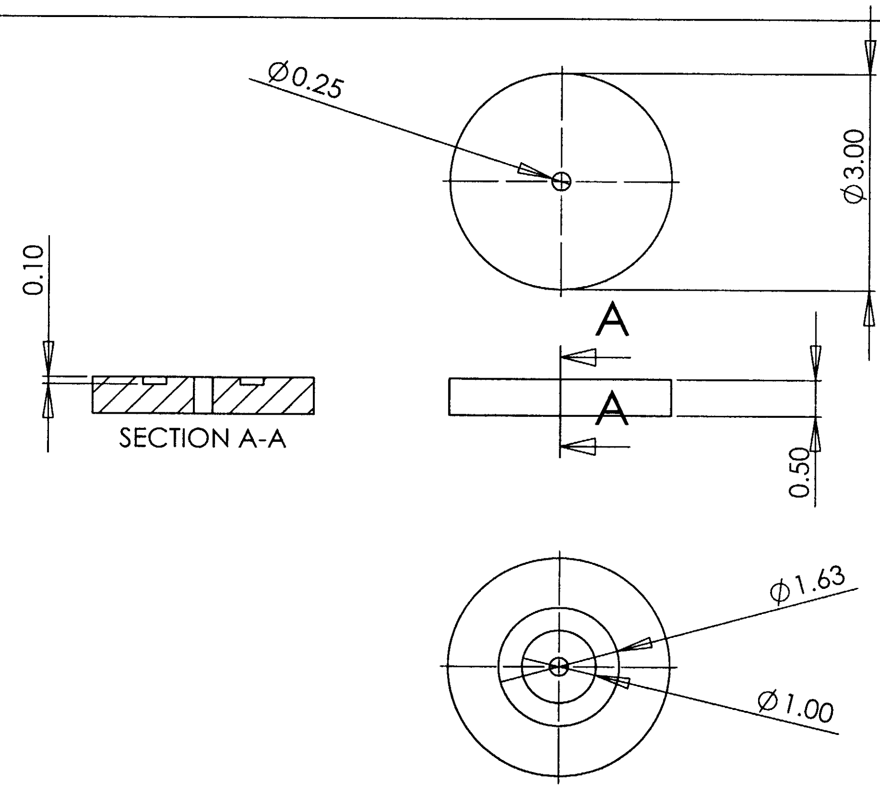
COMMENTS:

TITLE:

SIZE **A** DWG. NO. upper base REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

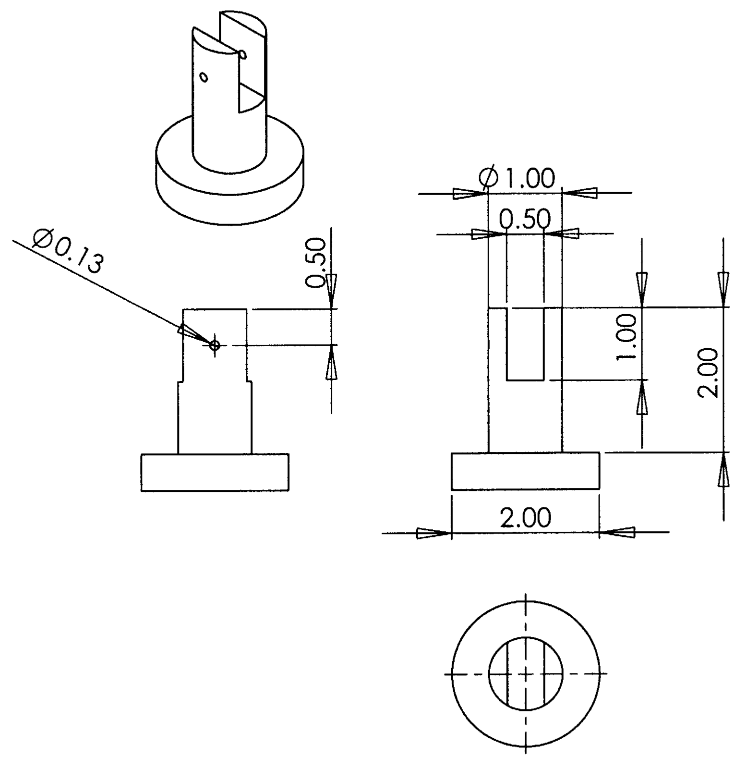
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	lower base	
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

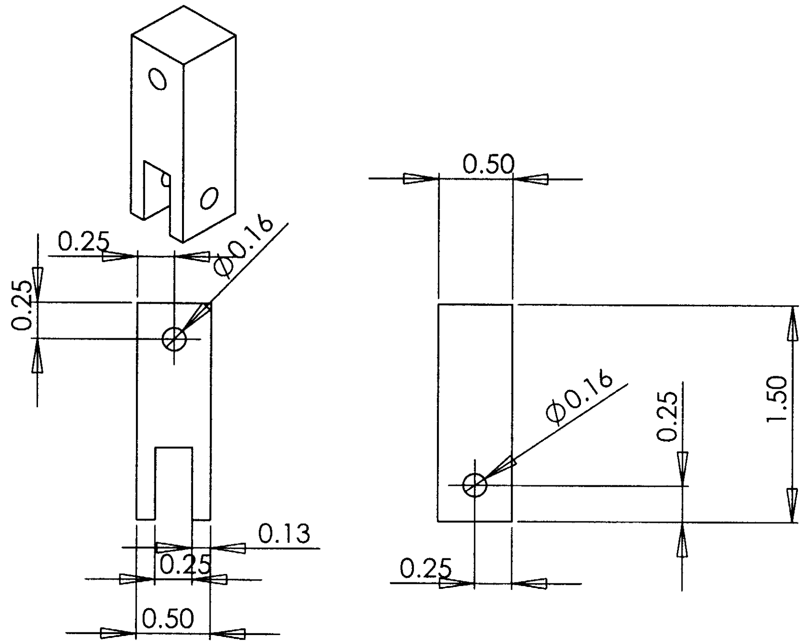
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

SIZE	DWG. NO.	REV
A	swivel arm	
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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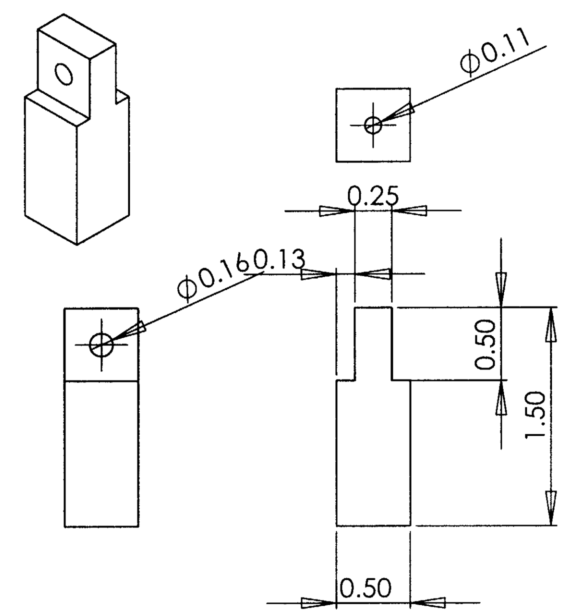
NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED:		NAME	DATE
APPLICATION		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
		FINISH			
		DO NOT SCALE DRAWING			

TITLE:

SIZE	DWG. NO.	REV
A	niversal joint	1
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

TITLE:

SIZE	DWG. NO.	REV
A	universal joint	2

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1

Appendix C:
TCL/TK Programs

```
#!  /usr/bin/wish

# this is a sample program that draws a simplified hand model on the screen
# (adjusted from drawfn_Shelly.tcl)

package require Tk

source shm.tcl

bind . <Key-q> done
bind . <Key-g> domove

start_rtl

# do body every ms milliseconds
# info level 0 : the stack level of the current procedure is global

proc every {ms body} {eval $body; after $ms [info level 0]}

proc getcurxy {w} {

# NT 5/5/07 - edited for hand tracker
        set pi 3.14159
        set scalar 1

        # r4 and r5 are the ratio of linkage length to hand location (11/12)
        set r4a .05
        set r4b .04
        set r5 .5

        # a1 and a2 are the lengths of the base arms in meters
        set a1 100
        set a2 100

        # l01, l12, l03 are the lengths of the hand, finger, and thumb
        set l01 50
        set l12 50
        set l03 50

        # a7 is the distance of linear pot from base of hand
        set d7a .05
        set d7b .05

        # get input voltates from potiometers (pot 7 is linear pot)
        set pot1 [rshm adcvolts 8]
        set pot2 [rshm adcvolts 9]
        set pot3 [rshm adcvolts 10]
        set pot4 [rshm adcvolts 11]
        set pot5 [rshm adcvolts 12]
        set pot6 [rshm adcvolts 13]
        set pot7 [rshm adcvolts 14]

        # convert potentiometer voltages to joint angles

        set ang1 [expr {-1.17*($pot1-1.97)}]
        set ang2 [expr {-1.2*($pot2-2.41)}]
        set ang3 [expr {1.17*($pot3-1.73)}]

        #pang is the potentiometer angle, ang is the hand joint angle
        set pang4 [expr {-1.113*($pot4-3.34)}]
        set ang4 [expr {2*$pang4 + $pi/2}]

        set pang5 [expr {-1.076*($pot5-3.57)}]
```

```
                                        xy_plane
        set ang5 [expr {2*$pang5 + $pi/2 + $ang4 - 3*$pi/2}]

        #ang6 measures the angle between the thumb and forefinger in the x-z plane
        set ang6 [expr {4.133*($pot6-1.51)}]
        #d7 is the linear  poteniometer distance
        set d7 [expr {.103*($pot7-.58)}]
        #ang7 is the angle between the thumb and forefinger in x-y plane
        set ang7 [expr {acos( (pow($d7,2)-pow($d7a,2)-pow($d7b,2)) / (-2*$d7a*$d7b)
)}]

        # get x, y, and z coordinates

        # x0, y0, z0 are the points where the base of the hand is located
        set x0 [expr {-cos($ang1) * ($a1*sin($ang2) + $a2*sin($ang3 - $ang2))}]
        set y0 [expr {sin($ang1) * ($a1*sin($ang2) + $a2*sin($ang3 - $ang2))}]
        set z0 [expr {-$a1*cos($ang2) + $a2*cos($ang3 - $ang2)}]

        # x00, y00, z00 is the base of the arm
        set x00 [expr {-100 + $x0}]
        set y00 $y0
        set z00 $z0

        # x1, y1, z1 are the points of the first knuckle of the index finger
        set x1 [expr {($l01*cos($pi - $ang4) + $x0)}]
        set y1 $y0
        set z1 [expr {($l01*sin($pi - $ang4) + $z0)}]

        # x2, y2, z2 are the points of the second knuckle of the index finger
        set x2 [expr {($l12*sin($pi - $ang5) + $x1)}]
        set y2 $y1
        set z2 [expr {(-$l12*cos($pi - $ang5) + $z1)}]

        # x3, y3, z3 are the points of the end of the thumb
        set x3 [expr {$l03*cos($ang6)*cos($ang7)+$x0}]
        set y3 [expr {$l03*cos($ang6)*sin($ang7)+$y0}]
        set z3 [expr {$l03*sin($ang6)+$z0}]

        list $x00 $y00 $z00 $x0 $y0 $z0 $x1 $y1 $z1 $x2 $y2 $z2 $x3 $y3 $z3


 }

proc done {} {
        stop_rtl
        exit
}

# make a canvas, pack it, and create a cursor

canvas .c -width 1000 -height 800
pack .c

.c config -scrollregion [list -500 -500 500 500]

# called 20x per second.
every 5 {

        # NT 5/5/07

        .c delete line

        foreach {x00 y00 z00 x0 y0 z0 x1 y1 z1 x2 y2 z2 x3 y3 z3 ang4} [getcurxy .c]
```

```
break

        # draw lines

        # quadrant 1: x,y
        # positive x is defined as up, which is negative in TCL/TK terms, so must
make x values negative
        set x00 [expr {$x00*-1}]
        set x0 [expr {$x0*-1}]
        set x1 [expr {$x1*-1}]
        set x2 [expr {$x2*-1}]
        set x3 [expr {$x3*-1}]

        .c create line $y00 $x00 $y0 $x0 -width 5 -tag line
        .c create line $y0 $x0 $y1 $x1 -width 5 -tag line
        .c create line $y1 $x1 $y2 $x2 -width 5 -tag line
        .c create line $y0 $x0 $y3 $x3 -width 5 -tag line

}
```

```
#!  /usr/bin/wish

# this is a sample program that displays the hand position on the screen
# (adjusted from drawfn_Shelley.tcl)


package require Tk

source shm.tcl

bind . <Key-q> done
bind . <Key-g> domove

start_rtl

proc every {ms body} {eval $body; after $ms [info level 0]}


# returns the x and y cursor position with 0,0 at the upper-left
# edge of the canvas window
# w specifies which widget

proc getcurxy {w} {

# NT 5/5/07 - edited for hand tracker
         set pi 3.14159
         set scalar 100

         # r4 and r5 are the ratio of linkage length to hand location (l1/l2)
         set r4a .05
         set r4b .04
         set r5 .5

         # a1 and a2 are the lengths of the base arms in meters, multiplied by a
scalar for on screen viewing
         set a1 [expr {1*$scalar}]
         set a2 [expr {1*$scalar}]

         # l01, l12, l03 are the lengths of the hand, finger, and thumb on screen,
in pixels
         set l01 50
         set l12 50
         set l03 50

         # a7 is the distance of linear pot from base of hand (actual, in m)
         set d7a .05
         set d7b .05

         # get input voltates from potiometers (pot 7 is linear pot)
         set pot1 [rshm adcvolts 8]
         set pot2 [rshm adcvolts 9]
         set pot3 [rshm adcvolts 10]
         set pot4 [rshm adcvolts 11]
         set pot5 [rshm adcvolts 12]
         set pot6 [rshm adcvolts 13]
         set pot7 [rshm adcvolts 14]

         # convert potentiometer voltages to joint angles
         #
         set ang1 [expr {-1.17*($pot1-1.97)}]
         set ang2 [expr {-1.2*($pot2-2.41)}]
         set ang3 [expr {1.17*($pot3-1.73)}]
```

```
        #pang is the potiometer angle, ang is the finger joint angle
        set pang4 [expr {-1.113*($pot4-3.34)}]
        set ang4 [expr {2*$pang4 + $pi/2}]

        set pang5 [expr {-1.076*($pot5-3.57)}]
        set ang5 [expr {2*$pang5 + $pi/2 + $ang4 - 3*$pi/2}]

        # ang6 is the angle of the thumb from the forefinger in x-z plane
        set ang6 [expr {4.133*($pot6-1.51)}]
        #d7 is the distance of the linear potiometer
        set d7 [expr {.103*($pot7-.58)}]
        #ang7 is the angle of the thumb from the forefinger in x-y plane
        set ang7 [expr {acos( (pow($d7,2)-pow($d7a,2)-pow($d7b,2)) / (-2*$d7a*$d7b)
)}]

        # get x, y, and z coordinates


        # x0, y0, z0 are the points where the base of the hand is located
        set x0 [expr {-cos($ang1) * ($a1*sin($ang2) + $a2*sin($ang3 - $ang2))}]
        set y0 [expr {sin($ang1) * ($a1*sin($ang2) + $a2*sin($ang3 - $ang2))}]
        set z0 [expr {-$a1*cos($ang2) + $a2*cos($ang3 - $ang2)}]

        # x00, y00, z00 is the base of the arm
        set x00 [expr {-100 + $x0}]
        set y00 $y0
        set z00 $z0

        # x1, y1, z1 are the points of the first knuckle of the index finger
        set x1 [expr {($l01*cos($pi - $ang4) + $x0)}]
        set y1 $y0
        set z1 [expr {($l01*sin($pi - $ang4) + $z0)}]

        # x2, y2, z2 are the points of the second knuckle of the index finger
        set x2 [expr {($l12*sin($pi - $ang5) + $x1)}]
        set y2 $y1
        set z2 [expr {(-$l12*cos($pi - $ang5) + $z1)}]

        # x3, y3, z3 are the points of the end of the thumb
        set x3 [expr {$l03*cos($ang6)*cos($ang7)+$x0}]
        set y3 [expr {$l03*cos($ang6)*sin($ang7)+$y0}]
        set z3 [expr {$l03*sin($ang6)+$z0}]

        list $x00 $y00 $z00 $x0 $y0 $z0 $x1 $y1 $z1 $x2 $y2 $z2 $x3 $y3 $z3


 }

proc done {} {
        stop_rtl
        exit
}

# make a canvas, pack it

canvas .c -width 1000 -height 800
pack .c


# scrollregion Specifies a list with four coordinates describing the
# left, top, right, and bottom coordinates of a rectangular region.
# This region is used for scrolling purposes and is considered to be
```

```
# the boundary of the information in the canvas

.c config -scrollregion [list -500 -500 500 500]


# called 20x per second.
every 5 {

        # NT 5/5/07

# deletes previous lines
        .c delete line

#NT 5/7/07
        foreach {x00 y00 z00 x0 y0 z0 x1 y1 z1 x2 y2 z2 x3 y3 z3} [getcurxy .c]
break

        # draw lines

        #  x,z plane

          .c create line $x00 $z00 $x0 $z0 -width 5 -tag line
          .c create line $x0 $z0 $x1 $z1 -width 5 -tag line
          .c create line $x1 $z1 $x2 $z2 -width 5 -tag line
          .c create line $x0 $z0 $x3 $z3 -width 5 -tag line

}
```