THREE-DIMENSIONAL VISUALIZATION DISPLAY DEVICE

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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This research focuses on the design of a device used for presenting three-dimensional images. The machine was built with the purpose of performing two particular tasks. The first task was to be able to adjust an image on a computer screen and have a physical display mirror that image. The second task was to be able to adjust a physical display and have the computer screen mirror the image. Such a device would be useful for rapid prototyping, virtual modeling, topography, measurement, and touch-screens.

The device was built with the hope of escaping the limitations typically involved with virtually creating an object and the time typically involved in physically creating an object. This device utilizes three main components: a computer, a control box, and a physical display. The physical display uses a grid of parallel pins that can be moved in a common direction to create a "moving wall." Some of the key issues in designing such apparatus include minimizing the power consumption, packing the pins as tightly as possible, overall use of space, and the accuracy of images.

CHAPTER 1
INTRODUCTION

In this age of information, society has placed great value upon methods for transferring large amounts of information as quickly and tightly packed as possible. One of the best ways to instantly transmit a lot of information is to deliver an image. A three-dimensional visualization is an ideal way of presenting every aspect of an object in a single, complete image. One of the most popular methods of 3-D visualization is through computer graphics displays. Many of these machines can lead to problems where the user is required to wear bulky headgear and only one user can view the image at a time. In 2001, Jeremy Mayer attempted to solve this problem by creating a machine that completed the following three objectives (Mayer 2001):

1. Presents a three-dimensional representation of the object being displayed
2. Does not require the user to wear any special glasses or head mounted tracking system
3. Allows multiple users to simultaneously view the same object. Such a device will greatly aid an operator (or team of operators) in tele-operation and tele-supervision operations.

Mayer's project aimed to create three-dimensional images out of a "moving wall" where the "moving wall" was composed of thin parallel pins that could be moved up and down individually. He successfully created a prototype display device that moved eight parallel pins up and down. It was the desire of this project to create a machine that would improve the capabilities of the prototype design while being more efficient with its use of size, power, and cost.

Such a machine could be of use in the following areas:

- Rapid Prototyping: An instant three-dimensional model could be made for an object designed on a CAD program. This would allow a designer to quickly provide others with a model of a product that they can view and walk around.

- Measurement: An object could be pressed into the pins and its dimensions would be recorded in the process of making a virtual image. These dimensions would be easily accessible for the user.

- Virtual Modeling: Virtual models could be made of real life objects. Awkwardly shaped containers and objects could be virtually rendered after being pressed against the pins. Then a computer could be used to solve premium packing situations.

- Topography: The display could be used to show large areas of land. Such a device could be useful to anyone from engineers deciding where to place a bridge to military officers deciding where to position their men. To get such a tool currently, these people need to have a model sculpted from hand. This device would pair well with a new technology that allows an airplane to reflect radar over a section of land and a computer program uses the reading to render a CAD image of the land. This image would then be easily transferred to the physical display.

- Picture: This would be a new way for friends and families to send one another images. A grandmother could see the three-dimensional hand print of her newborn grandchild that is hundreds of miles away.

- Touch-Screen: The display could be adjusted into a grid of buttons and when the user presses a button, the device would be able to detect the adjustment. An image could be shown down upon the display to help aid in the visual, as well. This would allow for various interactions between user and machine that would be useful in such devices as ATMs or Information Kiosks.

Mayer’s 3-D Display Device

Jeremy Mayer’s machine, seen in Figure 1-1, moved eight pins that were aligned in a row. Depending upon the user’s desire, the pins could be moved manually and a computer image could imitate the pattern, or the computer image could be altered and the pins would imitate the image’s pattern. This is represented in Figure 1-2. The device’s actions were controlled by a graphical user interface (GUI) where the user could adjust the virtual image of pins and tell physical display which task to run. The physical pins rested upon push-pull cables, which were allowed and prevented from moving by solenoid-controlled swivels. The push-pull cables were composed of a metal wire held within a plastic sleeve by friction. The top end of each sleeve was attached to a stable plate, which the physical pins rose out of. The bottom of each sleeve was attached to a plate, which could be moved vertically, where the metal wire hung out loosely. To create a physical pattern of pins, the pins began at their bottom position while all the swivels were activated and pinched the metal wires into a stable position. The moving table could then be lowered by a stepper motor, causing the sleeve to lower, but not the metal wire; in turn, the pins would be raised. When a pin reaches its desired height, the corresponding solenoid is deactivated. This rotates the swivel and the pin is held in place by the friction of the push-pull cable.

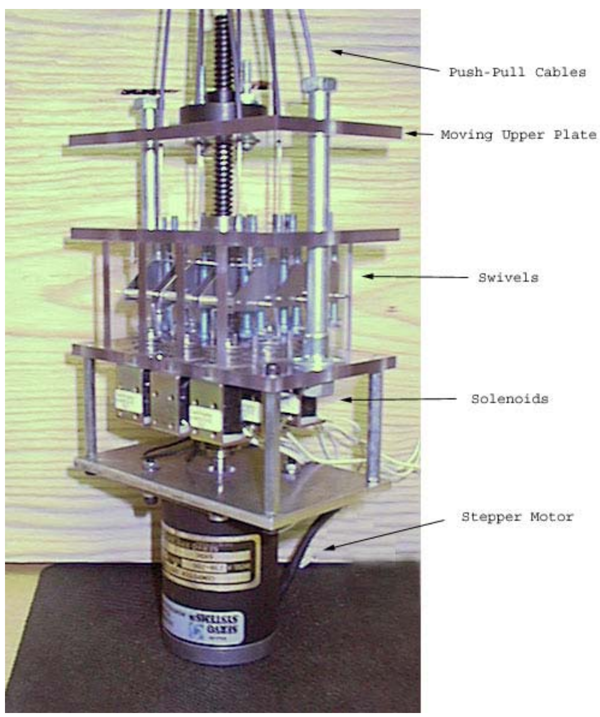


Figure 1-1. Jeremy Mayer’s 3-D display device (translating pins not shown)

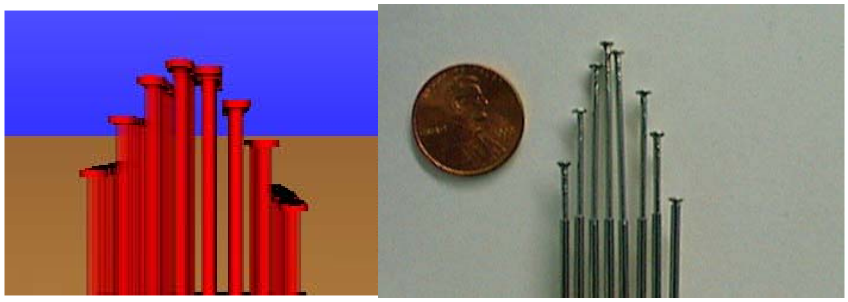


Figure 1-2. Mayer's 3-D display device had eight physical pins and eight virtual pins that could mirror one another

To create a virtual pattern of pins to mirror a physical arrangement, the pins are moved to their highest positions and the swivels are opened. The user can physically adjust the pins and the friction of the push-pull cables will hold them in place. Each hanging metal wire is then gently pressed against an individual switch by the spring-loaded solenoid. The moving plate is translated upward by the stepper motor and the hanging metal wires are pulled up. Eventually, each hanging metal wire will be pulled above the swivel and the spring-loaded solenoid will push the swivel into the switch. The switch will be activated and the relative location of moving plate will tell the controlling computer where the pin was located. The GUI will do the conversions and render a mirror image of pins.

Similar Projects

Research was invested into finding similar projects and inventions in existence. Understanding the designs, successes, and failures from these works could help set an efficient path for the next generation display and prevent previous errors from being repeated. The following are some of the most similar and practical related machines that were found:

The LeviTABLE, seen in Figure 1-3, is being worked on at MIT (Kelliher et al. 2001). This apparatus is an "electromagnetic topographical display" which basically means that it uses electromagnets to create a physical, three-dimensional feature. The device contains a 6.5"×6.5" actuation platform with an array of electromagnets placed in an 8×8 formation. Above the actuation platform is a table system containing 64 drinking straws, also arranged in an 8×8 pattern. The straws, eight inches from top to bottom, move freely in the vertical direction and contain neodymium magnets within them. Varying the strength and polarity of each of the electromagnets in the actuation platform allows one to conform the grid of straws into desirable topographical displays. The display can be changed as quickly as the desired magnetic states can be relayed to the electromagnets and the footprint remains equivalent to the space taken by the grid of straws. However, the straws are limited to 1.5" of movement. The project's most blatant flaw is that although a theoretical movement tolerance of 1.0 mm is claimed, the creators have not yet been able to implement any more than a movement of the straws from one extreme position to the other. Furthermore, the machine requires a continuous supply of energy for all times of use, and the thickness of the straws along with the spacing distances do not allow for a very "tight" image.

Figure 1-3. The LeviTABLE

A Harvard project resulted in the creation of a tactile shape display using RC servomotors, seen in Figure 1-4, with the purpose of “conveying small-scale force and shape information to the tip of the finger” (Wagner et al. 2002). The device is a 6×6 pin display, with 2mm maximum displacement and is an "attempt to realistically simulate skin deformations that occur when interacting with real objects by transmitting small-scale shape information to the fingertip." RC servomotors (small, high-performance ball bearing servos) actuate the mechanical pins as seen in Figure 1-5. Positive features include a low parts cost, simple construction, and the ability to move in time to a specific height. However, the machine also has limited movement and scales in size poorly when an increased number of pins are desired. Also, servos rotate so the pin is being moved in two directions, but since the movement is so small in comparison to the pin size the developers might be thinking the pin crookedness is negligible; however, this will be detrimental if the pin movement is made greater.

Figure 1-4. Tactile shape display using RC servomotors

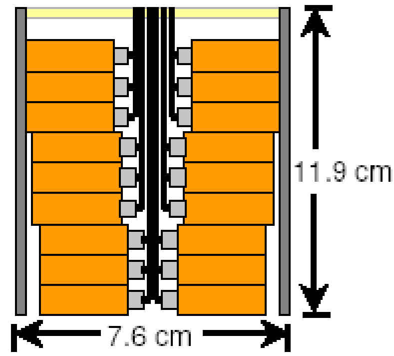


Figure 1-5. Servomotor positioning

The University of Tsukuba's FEELEX Project aims to combine haptic sensation with computer graphics (Iwata et al. 2001). Basically, the shape and image of an object will change as a result of outside forces on the object. The basic system is comprised of an array of actuators beneath a flexible screen. A projector (720×420) shines a two-dimensional image down onto the screen, which in turn becomes three-dimensional when the actuators deform the screen. Sensors on the actuators can determine the force applied against the screen by an outside source. The readings can be used to determine a response in the shape of screen. Two prototypes for this system structure were created.

FEELEX 1, shown in Figure 1-6, was "designed to enable double-handed interaction using the whole of the palms." The flexible screen (composed of a 3 mm thick rubber plate and a white nylon cloth) is 24cm × 24cm in size with a 6×6 linear actuator array beneath it. Each actuator is made of a screw mechanism driven by a DC motor. The machine is PC controlled with two strain gauges atop each actuator acting as force sensors. The apparatus moves in time, is structurally durable, and has a linear ratio between grid size and footprint size. Unfortunately, the machine has a high power requirement, poor resolution of shape, and there are shape limitations, as sharp edges cannot be created.

Figure 1-6. The FEELEX 1

FEELEX 2, shown in Figure 1-7, was created with the intention of improving the resolution of the previous design so that interaction can occur with the fingers. This system has a 50mm × 50mm screen with a desired resolution of 8mm. Because the servomotors used are much larger than the desired resolution a piston-crank system was used to move an array of rods (six inches in diameter) that change the shape of the screen. Force is measured by reading the electric current going into each servomotor. This machines best feature is its tight resolution. Its drawbacks are that the piston-crank system creates size of footprint difficulties for pin expansion, it requires a high-energy intake, and (like the FEELEX 1) there are shape limitations, as sharp edges cannot be created.

The "high density tactile display," created at John Hopkins University and presented in Figure 1-8, is intended for use in neurophysiological and psychophysical experimentation (Pawluk et al. 1998). It contains a 20 × 20 square array of pins. There is 0.5 mm between each pin. The pins are moved by linear motors stacked in layers of 100

Figure 1-7. The FEELEX 2

motors above the array. Each 100 motor layer controls a 10 × 10 section of the pins. The pins can be moved 2.5 mm lengthwise. The machine has the ability to move the pins in time to any desired position as well as maintain a desired pressure from the pins. This design makes it spatially difficult to scale to a larger number of pins (as shown in Figure 1-8), is limiting on the available length of pin movement, requires large supply of power, and is considerably expensive.

Figure 1-8. High Density Tactile Display

Refreshable Braille Displays, pictured in Figure 1-9, were the last similar device that was discovered during the literature search (Gallagher). These devices can be purchased commercially from various vendors. These machines are commonly used by the blind for the purpose of reading text that would be displayed by a computer monitor. The Refreshable Braille Display has a row of "soft cells." Each cell has 8 holes filled with linearly actuated pins. The pins can be moved up or down (using either miniature solenoids or piezo-electric outputs) so that each cell contains a Braille character. The user can scroll through lines of text changing the character displays instantly. The pin movement is limited as they can only be located at one of two positions (up or down). The machines are also expensive, as an average, commercially sold displays run in the tens of thousands of dollars.

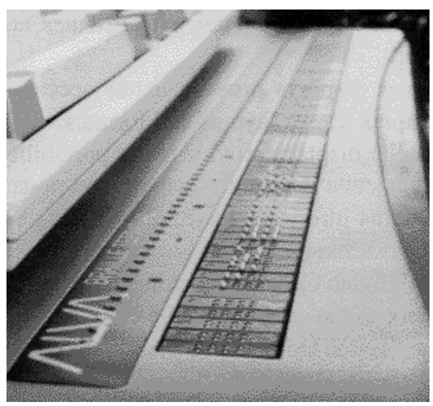


Figure 1-9. Refreshable Braille Display

CHAPTER 2
PROJECT APPROACH AND OUTLINE

The knowledge of other work performed on similar three-dimensional displays helped create guidelines to steer this project. It was important that past errors not be repeated and as much improvement be made as possible. This chapter reviews the project's initial aims to its final product.

Objective

This project began with and was always governed by the three main goals that were created and used by Mayer in his project:

1. Presents a three-dimensional representation of the object being displayed
2. Does not require the user to wear any special glasses or head mounted tracking system
3. Allows multiple users to simultaneously view the same object. Such a device will greatly aid an operator (or team of operators) in tele-operation and tele-supervision operations.

Goals

Evolution

For the next generation display, a new set of subsidiary goals had to be created that would make the display more effective and more efficient while still maintaining the original three objectives as the top priorities. A set of secondary objectives inspired by the experiences and achievements of the previous machine were created. These goals were not set in stone, but merely guidelines meant to help provide direction and an ambitious aim for the project. What follows are the original secondary goals listed in order of importance:

- Pin Pattern: The most vital modification to the new machine is to go from a linear pattern of pins to a 2-D array of pins
- Actions: The apparatus will be capable of displaying the shape of the pins upon the computer screen as well as displaying a computer image physically with the pins
- Pin Grid Size vs. Total Machine Footprint: The device will be designed so that adding additional pins will increase the pin grid size the same amount that it will increase the overall machine footprint.
- Number of Pins: The minimum number of pins will be twenty-five; however, the pin count will ideally be in the thousands
- Spacing of Pins: The pins have a diameter of 0.045”. They will be kept within 2 mm (center to center) of one another.
- Power Allotment: No more than 1.5 Watts will be allotted to the actuation of each pin.
- Height: The top of the machine will be less than 3 feet high so that a person of average height could look down upon the display.
- Footprint: The machine will be within a footprint of 2’×2’ so that it can be easily moved through average size doorways.

Reevaluation

Next it was important to evaluate the existing 8-pin machine. An analysis was performed to decide which of the current features should be altered in order to achieve the desired goals for the next machine and alleviate the difficulties from the first one. The following is a list and description of those decisions:

- Actuation System: Renovating this feature is the most vital action of the project. While the moving table system worked well in the 8-pin display, the push-pull cables caused a number of problems. It wasn’t always reliable as changes in friction occasionally occurred with movement, resulting in display inaccuracies. The rotational solenoids (which supplied far more pressure then was necessary) used for clamping were too large and required too much power to be practical for a machine with an expanded grid of pins. These actuators will have to be replaced with something smaller, cheaper, and less energy draining.
- Power Supply and Control: Having hundreds of pins where each pin needed to be actuated individually would require a more conservative system that requires less power per pin. A new wiring system will also have to be implemented where the

outputs from the controllers will be activating multiple actuators, so as to minimize the number of necessary outputs.

- Sensors: The current sensors are contact sensors that provide acceptable values; however, using something more precise, such as optical sensors, could provide more exact readings of the pins and reduce measurement errors.
- Interface: The interface can be improved with the addition of location axis and data tables giving the exact location of each pin. The tables could be used for both reading where the pin is located and writing where the pin's next desired location is. It would be convenient to give the display an option so that the heads of the pins are seen as a single skin and a section of a CAD drawing could be transposed onto the physical pin display.

Resulting Machine

System Architecture and Overview of 3 Systems

Figure 2-1 shows a picture of the resulting machine. It is composed of three main systems, which can be broken down into the system architecture that is shown in Figure 2-2. The three main components of the setup are the computer, the control box, and the display device. The Computer contains the Graphical User Interface (GUI), the path planner, and the digital input/outputs. The GUI is a display that will appear on the computer monitor and allow the user to interact with the rest of the machine. The data distributor is a program code that translates data instructions between the GUI and the digital I/O. The digital I/O is a PCI card that sends and receives multiple electric signals from the computer to the control box.

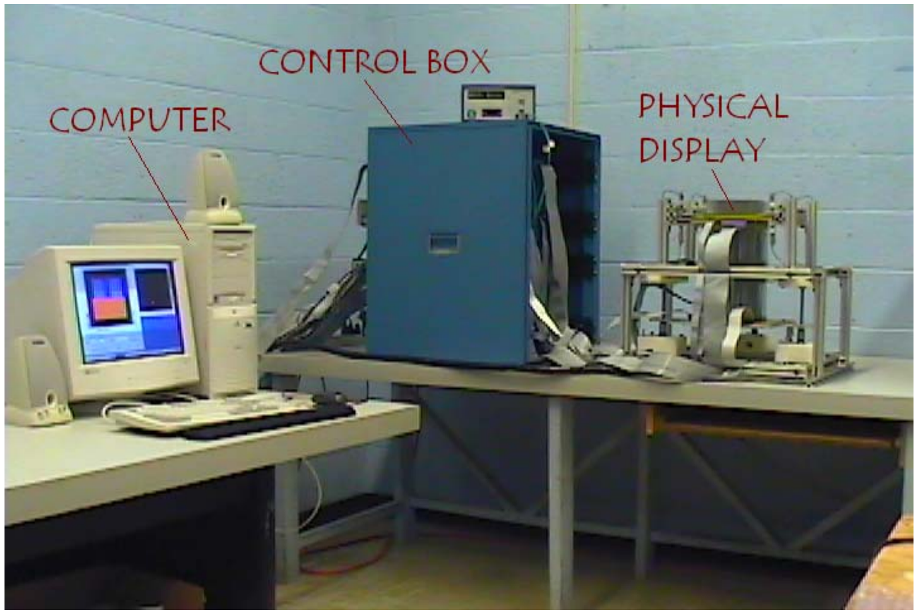


Figure 2-1. The 3-D visualization device

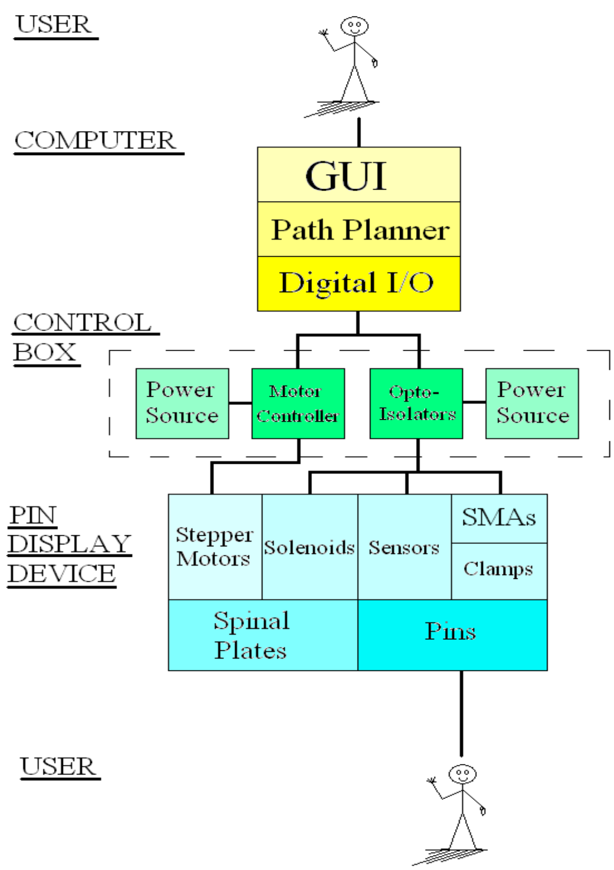


Figure 2-2. System architecture

The control box, shown in Figure 2-3, is made up of opto-isolators, power sources and motor controllers, as well as the numerous wires, cables and terminal boards tying everything together. The motor controllers will regulate the speed and position of the stepper motors. The opto-isolators will regulate when specific sections of the display device receive power.

Figure 2-3. Control Box

The display device, pictured in Figure 2-4, uses parallel pins to form a three-dimensional image that is visible to the user. The pins are moved and monitored using hard plastic plates, clamps, and sensors. The plates are moved by solenoids and stepper motors. The clamps are toggled by shape memory alloy (SMA) wires. The following three chapters will go into the details of the research and development for each of these sections, as well as how they work.

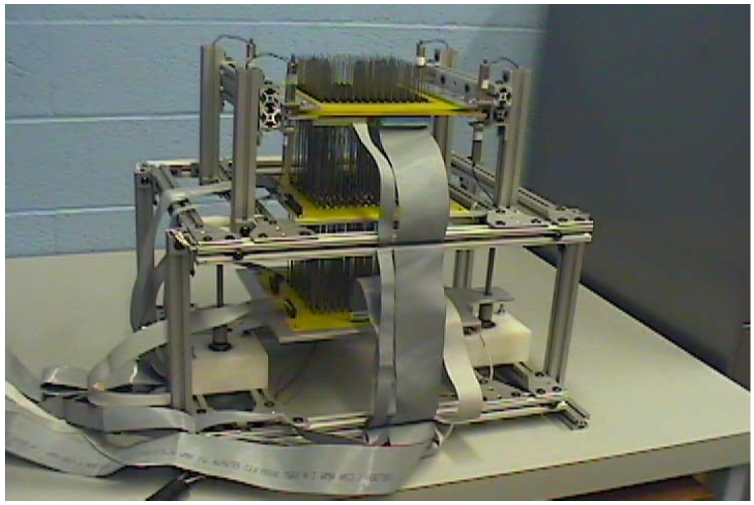


Figure 2-4. Physical display

How It Works

The machine performs two main tasks. One is that it can be provided a virtual arrangement of pins through the computer and then arrange the pins symmetrically on the physical display. The other task is that the pins on the physical display can be arranged into a particular pattern and the computer will render a mirrored pattern of pins. The first task of physical visualization is performed in the following manner.

Employing the GUI shown in Figure 2-5, the user will arrange the pins to their desired locations. This can be done by clicking on the rendered pins with the mouse and dragging them, by typing in the exact height of each pin, or by loading a pre-written file with all the pin heights in it. Once happy with the arrangement, the user will click on the "Send" button of the GUI. At this point the pins will be raised to their top positions by the sensor table and the solenoids will open and release clamps in order to loosen their grips on the pins. Next a new window will appear on the GUI asking if the clamps need to be opened again. If any clamps are still preventing movement of any pins, then the user will continue to click the "yes" button until all the pins are loose. Once all the pins are loose, the user clicks the “no” button. Next, the table that the pins are resting on will lower all the pins to the location of the height of the highest pin. At this location, the table will pause while actuators are activated to hold all of the pins that have that desired height into place. Once activated, the table will lower the pins to the next highest pin location. The pins with activated actuators will be held at their previous locations and new actuators will be activated to hold new pins at the new location. This pattern of lowering, pausing, and activating actuators will be repeated until all the pins have been moved to their desired positions and the table is at its lowest location. The user can then leave the pins at the current configuration or perform another task.

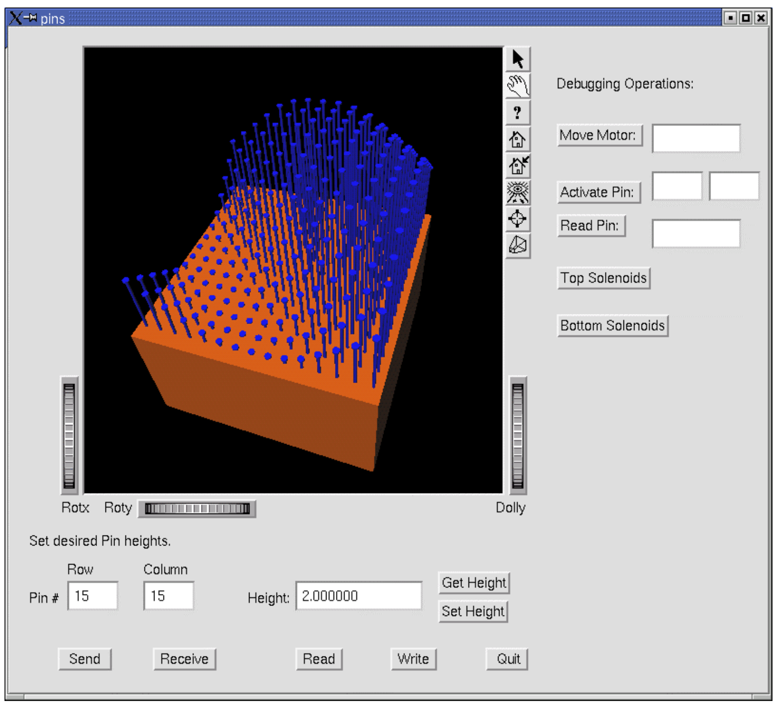


Figure 2-5. Graphical User Interface

The second task of *virtual visualization* is performed in the following manner:

The user will click the “Receive” button on the GUI. The sensor table will move the pins to their highest possible position, the clamps will be toggled into a locking position by the solenoids, and the table will move back to its lowest possible position. The pins will remain held at their highest position and a window will appear on the GUI asking the user to adjust the pins to their desired positions. At this point, the user will physically move the pins into the arrangement he or she wants displayed. Next, the user will click the “OK” button on the new window. This will trigger the sensor board to start moving upward again. The board will move to its top position in a single slow and smooth motion, moving each pin it comes in contact with upward with it. When the board stops, all the pins will be back at their top positions and the GUI will show a rendered image of the user’s arrangement of the pins. The user then has the choice of leaving the machine in its current configuration, recording the pin arrangement into a *.pins file, or performing another task.

Further details on how to use the GUI with detailed flowcharts of the task processes are presented in Chapter 5.

CHAPTER 3
PHYSICAL DISPLAY

The Physical Display is the most complicated of the three main components found within the System architecture. This system is a display device that accomplishes the three main goals of the project. The display contains a grid of movable pins that can be adjusted to create a desired image. The pins can reach their desired positions as a result of two methods: the display will receive position commands from the computer and adjust the pins itself or the user will manually adjust the pins so that the display can detect the positions of the pins and an image of the pin positions can be rendered on the computer screen. This chapter details the components of the physical display, how they were designed, and how they work.

Skeletal Design

The design of the physical display essentially began after a thorough evaluation of Mayer's project and related work. With a guiding set of goals in place, it was decided that the display device would have the basic design that is shown in Figure 3-1. The pins would pass through a device that would be capable of preventing their motion and rest upon a movable plate. Both tasks would begin with the pins at their highest position. For physical visualization, the plate would lower and the pins would follow until the motion of each pin was prevented. For virtual visualization, the motion would be prevented, the table would lower out of the way, the user would adjust the pins positions, and a separate system would detect the positions of the pins. This meant that three systems had to be designed: a system for preventing motion of the pins, a system for moving the table, and a system for sensing the position of the pins.

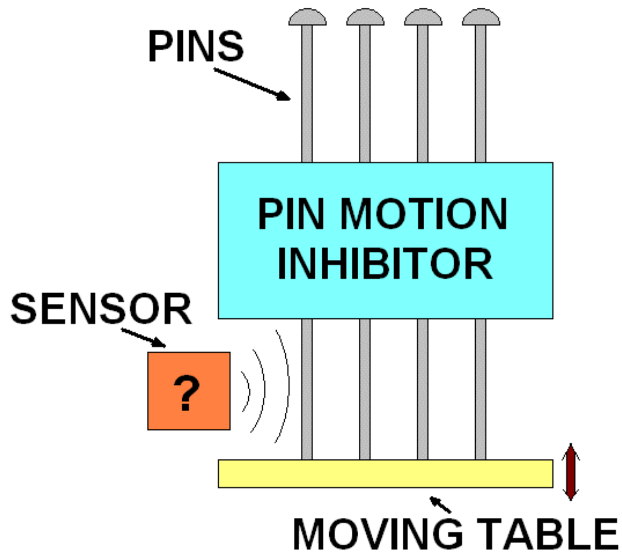


Figure 3-1. The initial skeletal design

Pin Motion Inhibitors

Possible Actuators

The entire design of the physical display revolved around the fact that some form of actuator was going to be necessary to either push, pull, or pinch the movable pins in the display. The type of actuator used would have a direct outcome on the display device's pin-to-footprint-size ratio and its power drainage. The following methods of actuation were initially analyzed and compared in order to find the best method of actuation.

Miniature rotational solenoid

A miniature rotational solenoid, such as the one in Figure 3-2, could have been used to pinch the pins in the same fashion as the actuators in Mayer's design except less space would be necessary for the actuators and only 0.3 Watts would be used per actuator as opposed to the 5 Watts per actuator used by his machine. The worries with this actuation were that as the number of pins was increased, they might be too expensive and still consume too much space. This was a tempting option because the solenoid greatly decreased necessary power and was proven to work quite effectively with Mayer's design.

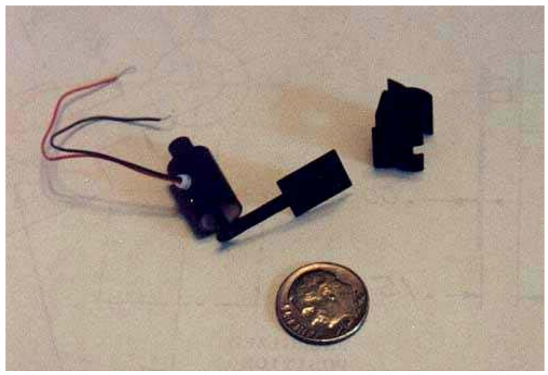


Figure 3-2. A miniature rotational solenoid

Magnetorheological dampening

This method would have had the cables moving through a magnetorheological fluid. When a magnetic field is applied to the fluid, the fluid hardens and grips the pin and when the field is removed, the pin is released. This method could not only have been messy, but it could have lead to corrosion and electrical problems. A system using this method could not be thought up where either the movement of pins or the physical well being of the machine would not be harmed.

Shape memory alloy tubes

This method would have had the pins passing through a shape memory alloy tube. A shape memory alloy (SMA) is a metallic material that holds a specific shape but can be stretched or bent into another shape. As seen in Figure 3-3, when the temperature of the material is changed above or below a specific temperature (this temperature can be hot or cold and depends on how the SMA was manufactured), the material returns to its original shape. In this case, when the tube is heated with an electrical current, it shrinks and grips the cables. When the current is stopped the tube returns to its original state, allowing free movement of the cables. It uses little power (1.2Watts) and takes up little space. The worries were that the SMAs may take a while to react to the current as well as to reset themselves. There was also the possibility that heat from an SMA with current running through it might affect the SMAs nearby.

Figure 3-3. The SMA tubing is bent and then returns to its original shape

Because of its economical cost and structural simplicity, the SMA tubing actuation initially appeared to be the best method available; therefore, work was begun to design and create model that would implement it. The design that was created used three stable plates stacked on one another. The top and bottom plates would have grids of holes just big enough for the pins to move through freely; however, the middle plate would have thicker holes to hold miniature SMA tubes. A current could be passed from the top plate to the bottom plate to heat the tubes. So basically, the pins would be going through the triple-plate stack, able to move freely, but resting on a fourth plate. The fourth plate would begin lowering and each time a pin reached its desired location, its SMA tube would be heated, thus gripping it and stopping the pin's motion. This would continue until all pins could no longer be lowered.

This plan had to quickly be abandoned, when an attempt to build a model proved that the SMA tubes were very difficult to cut. Each attempt to cut the tubes reliably resulted in chipping, cracking, and irreversible bending, as shown in Figure 3-4. Because pre-cut tubing was too expensive, a new method had to be sought out.

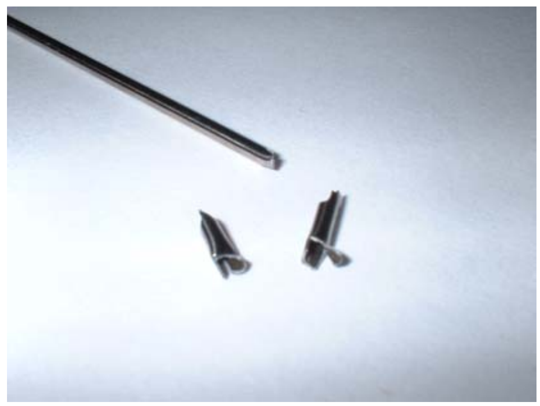


Figure 3-4. Attempts at cutting SMA tubing resulted in irreversible damage

Shape memory alloy wires

While the SMA tubing was a disappointment, the best route still appeared to be to use SMA material. Shape memory alloy wires have the ability to be stretched to a certain length and then heating or cooling makes them return to their original length (Gilbertson 1994). An initial method of actuation was devised using this material. Figure 3-5 presents that method which would be the beginnings of the final method. Basically, the pins would pass through a clamp and cylinder. When left alone, the clamp would prevent any movement of the pin; however, when the cylinder, which allows the pin to pass through freely, is pressed into the clamp, the clamp opens and the pin can move freely. The cylinder could be removed from the clamp when an SMA, attached to the cylinder on one end and a stable plate on the other, is heated; thus, contracting the SMA and pulling on the cylinder. All the cylinders could be pushed back into their respective clamps when a moving plate, with holes allowing the pins and SMAs to pass through, pushes them into the clamps and re-stretches the SMAs.

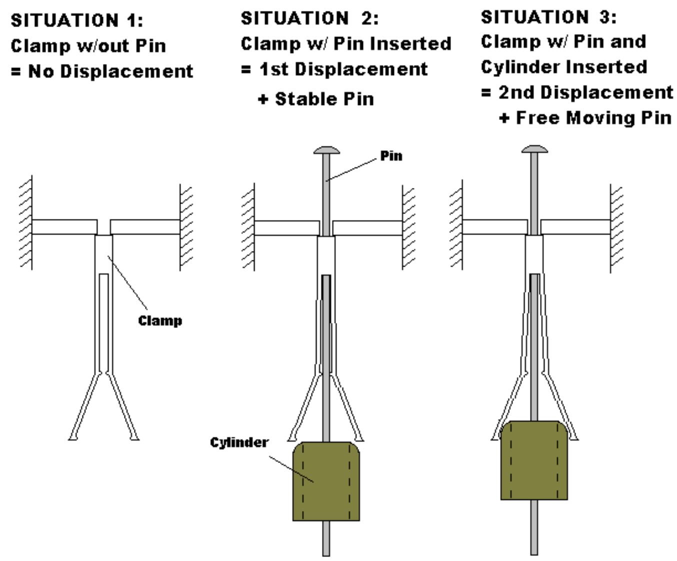


Figure 3-5. The clamping process

Clamp Creation

Home design

With a basic structure for the actuation process established by the SMA wire method, it was necessary to create a more detailed design of the clamp. It was initially decided that the clamps would be designed from scratch and manufactured in-house. Figure 3-6 shows the prototype shape that was created for the clamp.

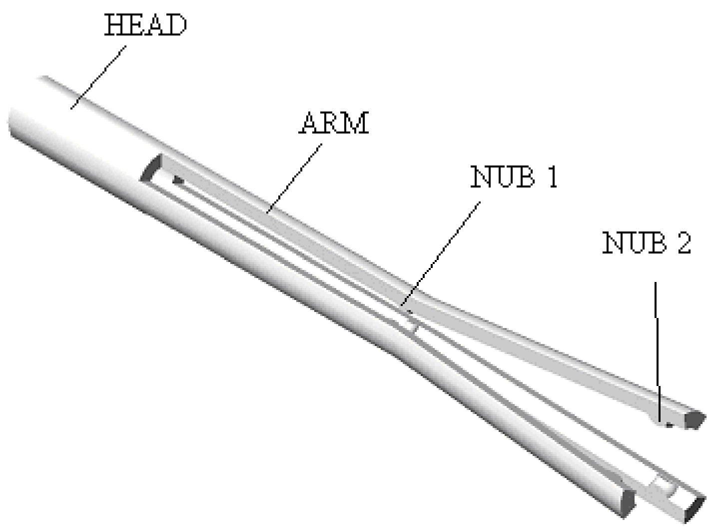


Figure 3-6. Initial clamp shape

A finite element analysis (FEA) was performed using the Ideas software to find ideal clamp dimensions that would create the most effective and long-lasting clamp. This analysis helped determine the clamps dimensions, shape, and material. Figure 3-7 shows an example of one of the analyses.

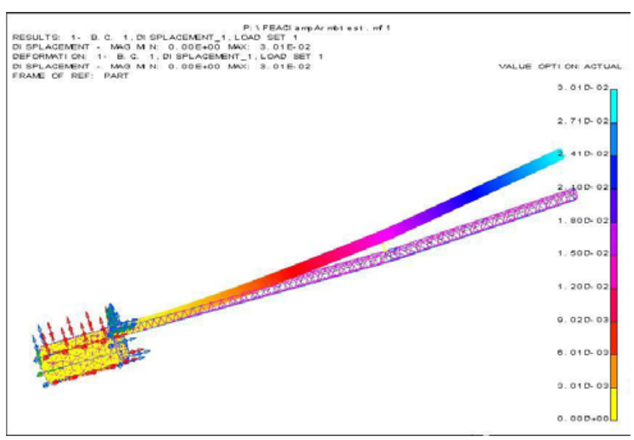


Figure 3-7. FEA analysis for material choice

Next, a complicated manufacturing process was developed for actually creating physical clamps and several prototypes were made, as seen in Figure 3-8. Appendix A has the full detailed report on the shape design, the FEA analysis and the manufacturing process.

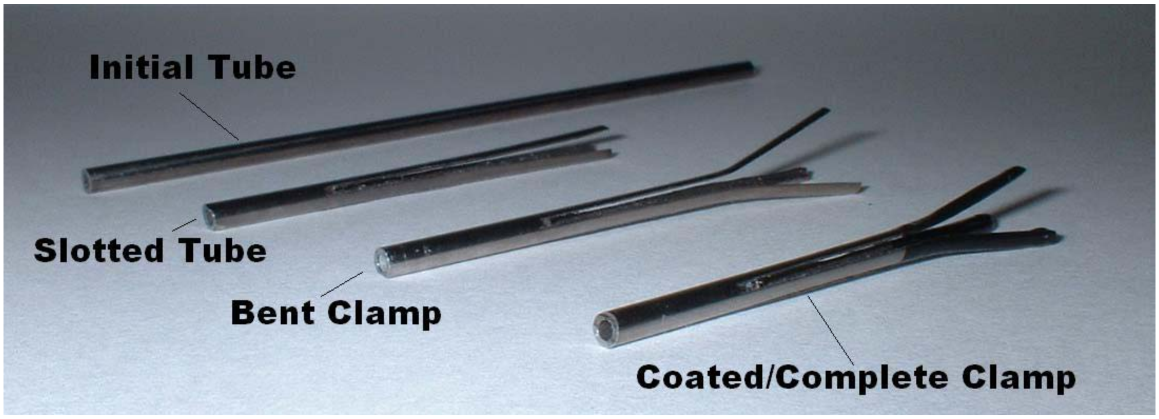


Figure 3-8. Manufacturing of a clamp

Pencil clamps

After refining the manufacturing process for clamp production, it was determined that if clamps were being produced every single day at eight hours per day, it would still take anywhere from five months to a year to produce the desired one thousand clamps. Because that was a longer time investment than was desired, the next best option was to use an out-of-house machinist who possessed more powerful tools. When no machinists were willing to take the job, it was decided to explore further areas for clamp production. It was observed that a majority of commercially sold mechanical pencils are composed of clamps, presented in Figure 3-9, with similar size and shape.

Figure 3-9. Example clamps from mechanical pencils

Pencil clamps that hold 1.3 mm lead were found to provide the results desired from the original clamp; however, the pencil clamps use a system mechanically reversed to the original design. The pencil clamps place the hollowed cylinder on the outside of the clamp while the original design had the cylinder moving inside the clamp (as shown in Figure 3-10). It was decided to proceed by replacing the original design with the pencil clamp system.

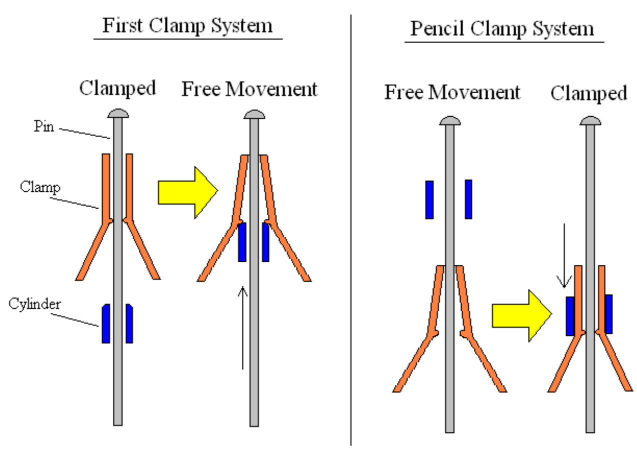


Figure 3-10. Two clamp systems

Evolution of Design

Now that a clamp design was complete and a basic setup existed, tests were begun in order to evolve the clamp system design. A one-pin model, shown in Figure 3-11, was created to test the method of using clamps from a mechanical pencil to hold a pin in place. This test allowed for design concepts to be confirmed, tinkered with, and refined. It proved that the 3.5" SMA wire could comfortably pull the cylinder the desired distance while the keeping the clamp closed with the desired pressure. It also provided helpful guidance related to spacing issues.

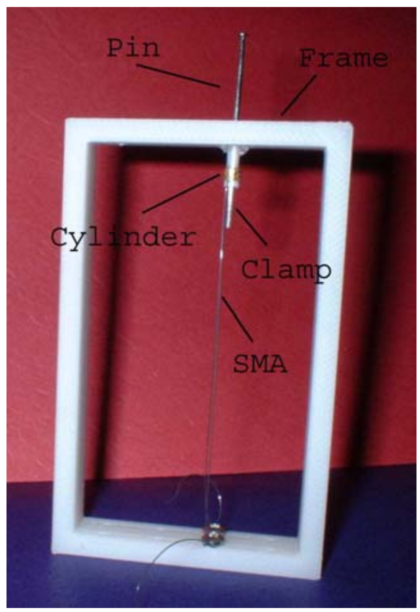


Figure 3-11. Clamp actuation testing model

The next step would be a complicated design process to decide upon a hole pattern. The goal was to maximize the density of pins without sacrificing the structural integrity of the plates and corresponding parts. Figure 3-12 shows the pattern that was chosen and Appendix C contains details of the analysis.

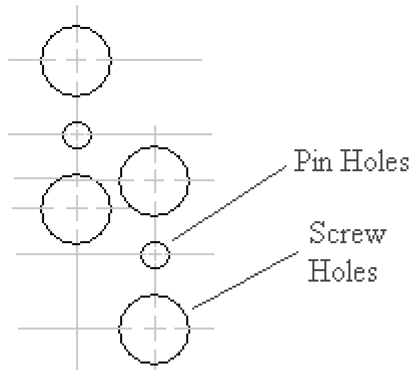


Figure 3-12. The first hole pattern

It was desired to use vented screws to attach the SMA wires to the board as shown in Figure 3-13. Because off-the-shelf vented screws were too expensive, two alternate vented screws were designed that better met the needs of the system. The thought behind this was that it would be cheaper to have a manufacturer produce a large quantity of one of the two designs. Appendix C recounts the design of these screws.

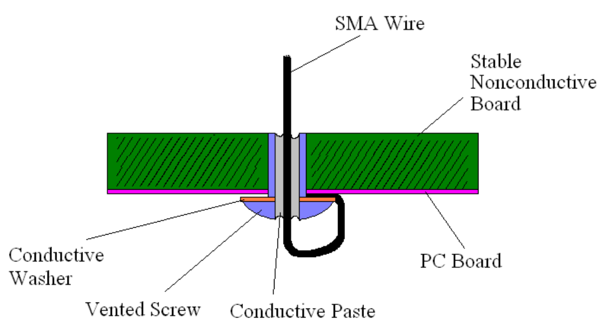


Figure 3-13. Close up of electrical connection

An extra level of four plates would be added to the machine so that the number of necessary holes for vented screws would be cut in half on each plate. Figure 3-14 shows how the refinements evolved the system's design.

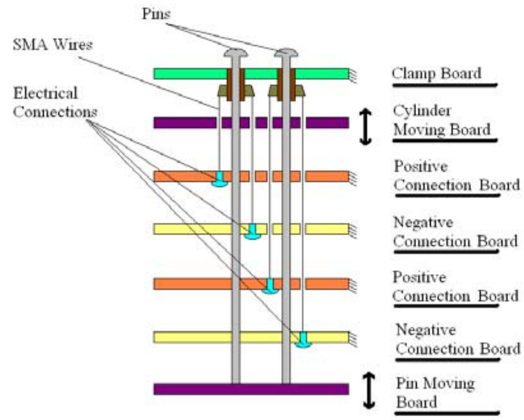


Figure 3-14. Plate arrangement

The five types of plates in the design were as follows:

1. Clamp-holders: These plates have the clamps press-fit into their holes. These will prevent and allow for motion of the pins.

2. Clamp-openers: These plates will open all the clamps and allow the pins and the SMA to pass through without contact, but not the cylinders around the clamps. When the solenoids beneath these plates push them up, the cylinders will be pushed up, the clamps will open, and the pins will be able to move freely.

3. Power-suppliers: These plates will contain the vented screws that supply power to the SMA wires.

4. Grounds-providers: These plates will contain the vented screws that provide a ground to the SMA wires.

5. Pin-mover: This plate will have no holes, but will have sensors attached. The pins will rest on it and be moved by it.

At this point, trying to move forward became very difficult as multiple problems started surfacing. It was realized that creating the various hole configurations necessary for the multiple plates of the machine would be highly difficult if not impossible to create with the University facilities (*especially* those that required electrical traces). Therefore, it was decided to seek help from professional machine shops. Several redesigns of the plates were created to match the capabilities of the different machine shops. It was found that the plate design was going to have to be compromised or the plate creation would cost significantly higher than would have been desired. Shortly after it was found that making the vented screws would be too expensive as well.

BioMetal Micro Helixes

The build up of difficulty led to the system's design taking a step back in order to be capable of moving forward. Problems with board and screw creation led to a reevaluation of the pin clamping actuation design. Discovery of a spring-shaped SMA opened the way for new, more efficient designs. Several new designs using this material were brainstormed and compared in detail. These analyses can be read in Appendix C.

Some of the better designs were prototyped and tested using BioMetal Micro Helixes, shown in Figure 3-15. The micro helixes are an improvement on the SMA wire because they require less power, take up less space, move a greater distance than wire strands of the same length, and are easier to attach.

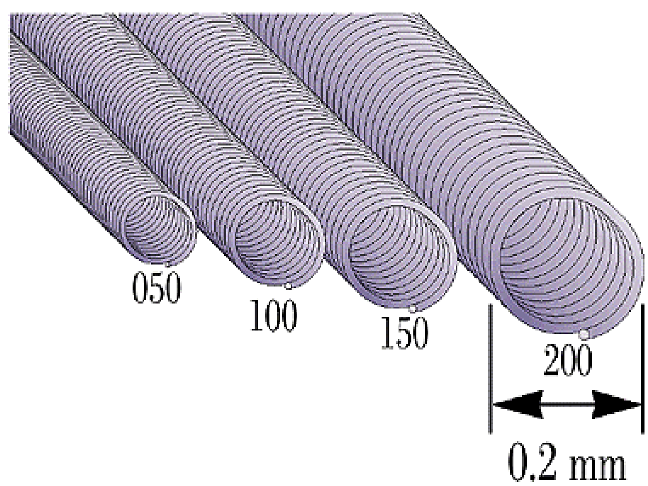


Figure 3-15. BioMetal micro helixes

The most effective of the designs using the micro helix models is seen in Figure 3-3-16. The idea here was similar to the initial design in that the clamp was still held by a stable plate and there was a stable power giving plate and another ground plate. However, the micro helix was so small that it could be attached to the power and ground plates with a normal wire which could be soldered or wound for any attachment type desired. Also, the ground plate could double as a moving plate for opening the clamp. This model performed the gripping actions better than the previous design, was easier to assemble and created far less clutter.

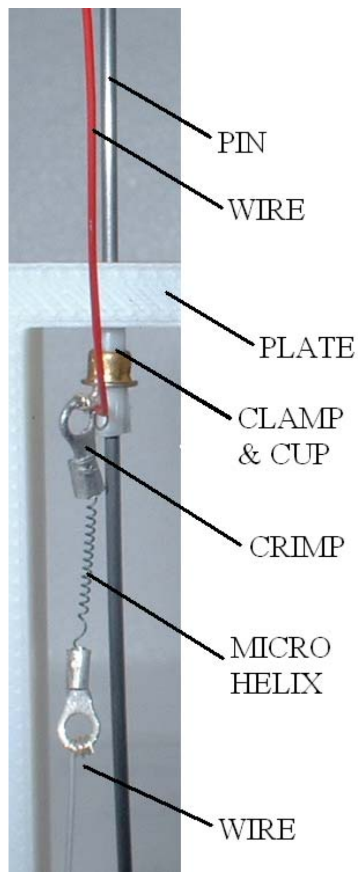


Figure 3-16. Helix model 2

Unfortunately, the micro helix design proved to be too costly for this project and focus had to be returned to the SMA wire design that was originally in place. Even so, the micro helix design was very helpful in evolving the SMA wire design. Figure 3-17 shows the three different designs together. With the new design, one end of a strand of SMA wire is attached to a plate below the clamp and the other is attached to the cup and a regular wire. The other end of the regular wire is attached to a plate above the clamp. Power and ground are supplied from the two plates and when heated the cup is pulled down and the clamp is tightened. The upper plate can move upward and pull on the regular wire, which in turn lifts the cup and releases the clamps grip on the pin.

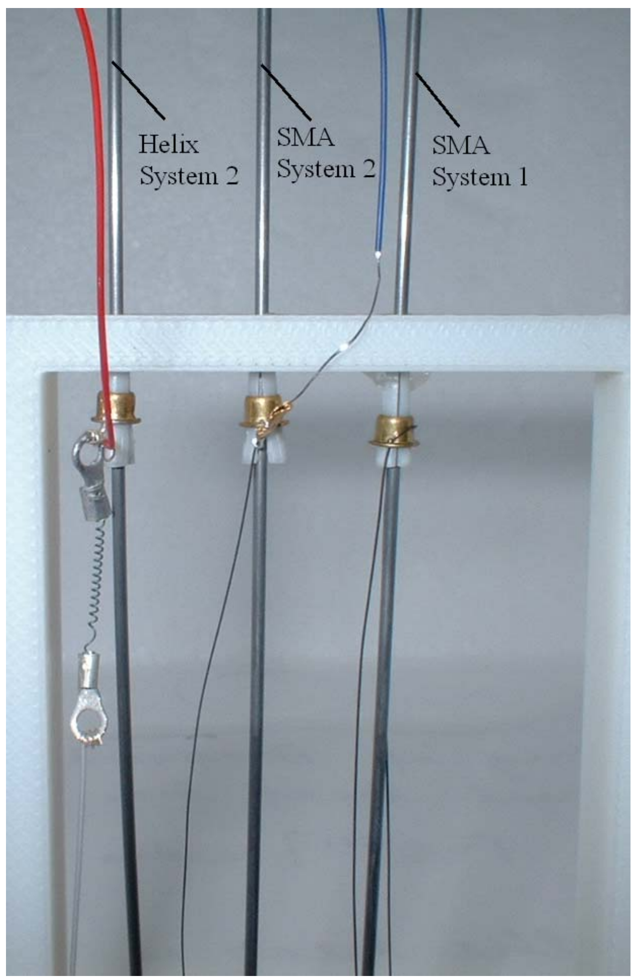


Figure 3-17. Multiple pin clamping model

While the model proved this system to be reliably functional for a single pin, prototyping a system with multiple pins and clamps within an accurate environment lead to several new problems. There were numerous locations where short circuits occurred, hand assembly was difficult, and several connections were structurally unreliable.

Updating to the design shown in Figure 3-18 reduced the severities of the problems. This final design allowed for the system to be assembled in a more convenient step-by-step process and minimized the chance of short circuits.

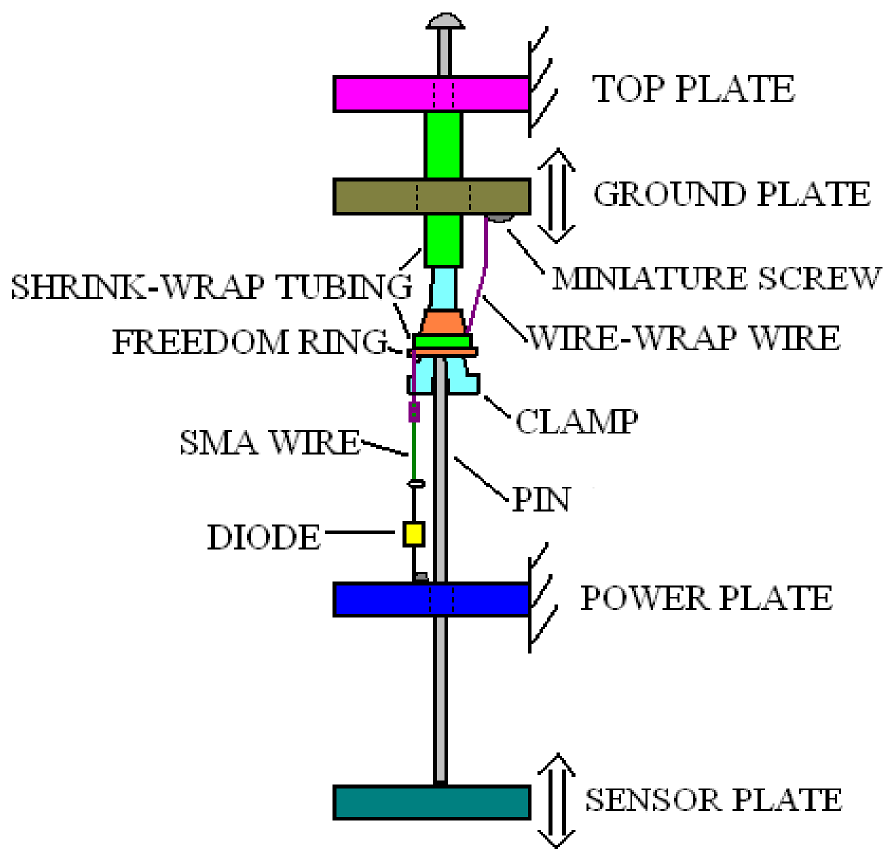


Figure 3-18. Final pin-clamp system design

The use of the shrink-wrap tubing eliminated most current shorting difficulties and actually allowed for a smoother flow of the pin. Using looped and curled wire ends eliminated the need for crimps and allowed for a simpler assembly and a better situation for maintenance.

Hole Pattern

With the changing of the design the screw holes were eliminated and it was decided to do a simple row offset pattern in a 30×30 array. When it was found that additional space was necessary for assembly, every other hole was skipped and the hole pattern became square.

Pin Sensors

In order to read the position of the pins, the bottom plate needed to be lined with sensors. The sensors needed to require a minimal amount of power and take up a minimal amount of space. Most sensors looked at were either too big or not precise enough. The first sensor seriously considered was a hall-effect sensor.

Hall-Effect Sensors

Miniature Hall effect sensors, shown in Figure 3-19, were ordered and tested for use in the machine. The idea was that, during virtual visualization, actual pins would be arranged in a specific manner above the bottom plate of sensors. The plate would be raised and the sensors would detect when each pin comes in contact with the plate. Knowing the contact time and the location of the table at all times will result in the knowledge of all the pin placements.

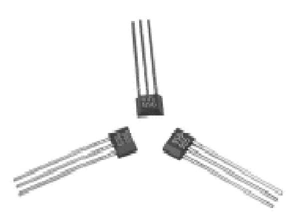


Figure 3-19. Hall-effect sensors

Extensive testing was performed in trying to find the best manner to use the sensors to detect the pins. A successful setup was found where miniature magnets would be placed on the bottoms of the pins, and their presence when within a desired distance would change the magnetical field enough to alter the output of the sensor.

Unfortunately, while tests showed that the miniature hall-effect sensors were capable of sensing when individual pins came into contact with the moving plate, several other difficulties were discovered. The detection signals, which the sensors output, were so small that a complicated interpretation system would have been necessary for the computer to notice them. More importantly, the process of actually attaching 900 of the sensors appeared to be both difficult and time consuming, if not impossible. As a result, this method was abandoned for a more simple design.

Contact Traces and Steel Wool

The new design maintained the concept of detecting when the pins made contact with the moving board; however, the difference involved tracing a sensor circuit in copper onto the moving plate. Below each pin would be two copper pads (each connects to a separate line on the computer). When the metal pin contacts the two pads, the lines get shorted and the computer detects a pin contact. It was found that the sensors were most efficient when the bottoms of the pins were lined with steel wool. The steel wool provides a wide, cushioned contact bumper for the sensor, which allows for imprecise contacts and rough impacts. The steel wool was easily attached to the bottom of all the pins with heat-shrink tubing as shown in Figure 3-20.

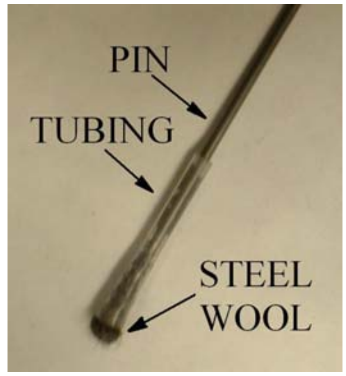


Figure 3-20. Steel wool attached to the bottom of a pin

Trace Pattern and Board Creation

Once there were definite designs for the clamp and sensor systems, it was possible to design and create the plates for the physical display. The five plates from the machine were designed in Protel 99SE and created through an out-of-house manufacturer. Each plate was made from a yellow 9” × 9” × 0.062” sheet of G10/FR-4 glass epoxy. While a greater thickness would have been preferable for the boards, anything thicker would have cost significantly more than the project budget would have allowed for. Figure 3-21 shows the Protel drawing for the mentioned bottom sensor. As described, this board will be used to raise and lower pins as well as detect their positions. Two 50-pin ribbon cables will attach to the board delivering thirty output currents to the board. Two other 50-pin ribbon cables will attach to the board, probing thirty input lines for pin contacts.

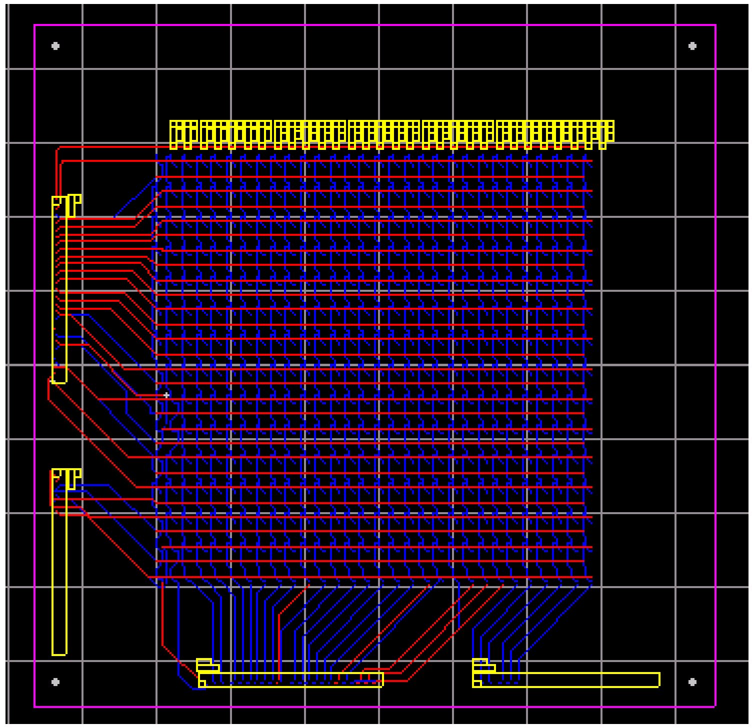


Figure 3-21. Digital bottom plate

Figure 3-22 shows the Protel design for the ground plate that is just above the sensor plate. This board allows the pins to pass through it freely. While the bottom of the SMA wires will be attached to it, the ground board will remain stable and supply grounds to the thirty rows of SMA wires. The grounds will come from the two 50-pin cable ribbon connections.

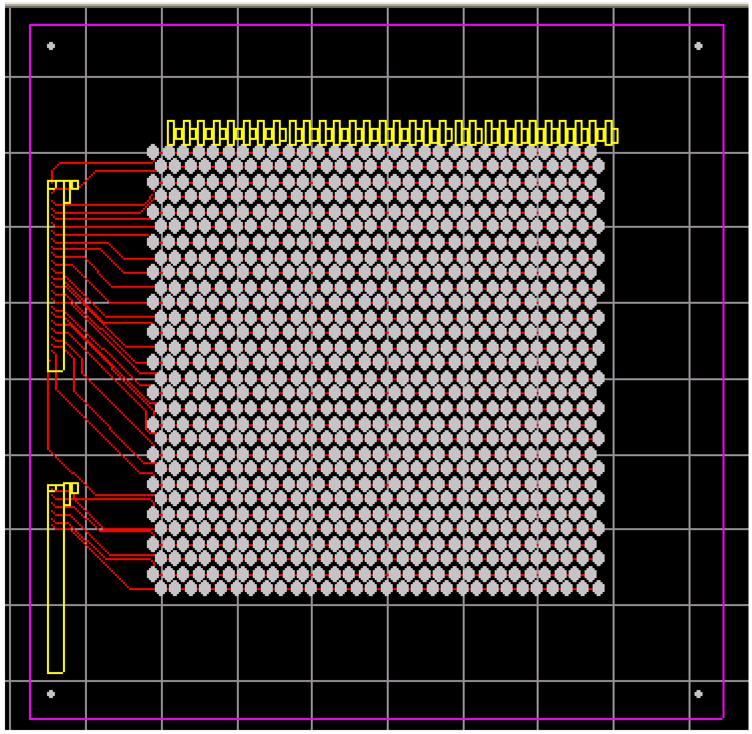


Figure 3-22. Digital ground plate

The power board, seen in Figure 3-23, supplies current to the attached wires which, in turn, pass the current on to the SMA wires. The power is once against supplied from two 50-pin ribbon cable connections to thirty rows of wires. The board is attached to eight push solenoids and can be moved up and down. Moving the plate up will stretch out the SMA wire and release the clamp's grip on the pin. Moving the plate down will help maintain the clamp's grip on the pins when there might be additional outside forces upon them.

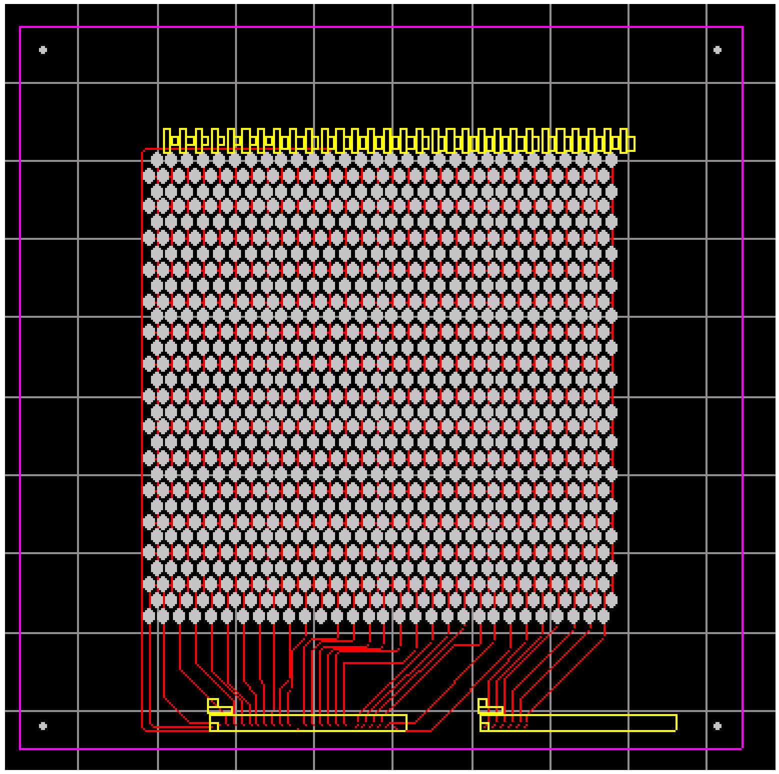


Figure 3-23. Digital power plate

The support plates, shown in Figure 3-24 will be attached to the ground and power plates. These plates will be used to help keep the wires in place by pinching them in between the boards and the support boards will add strength to prevent deformation of the ground and power plates.

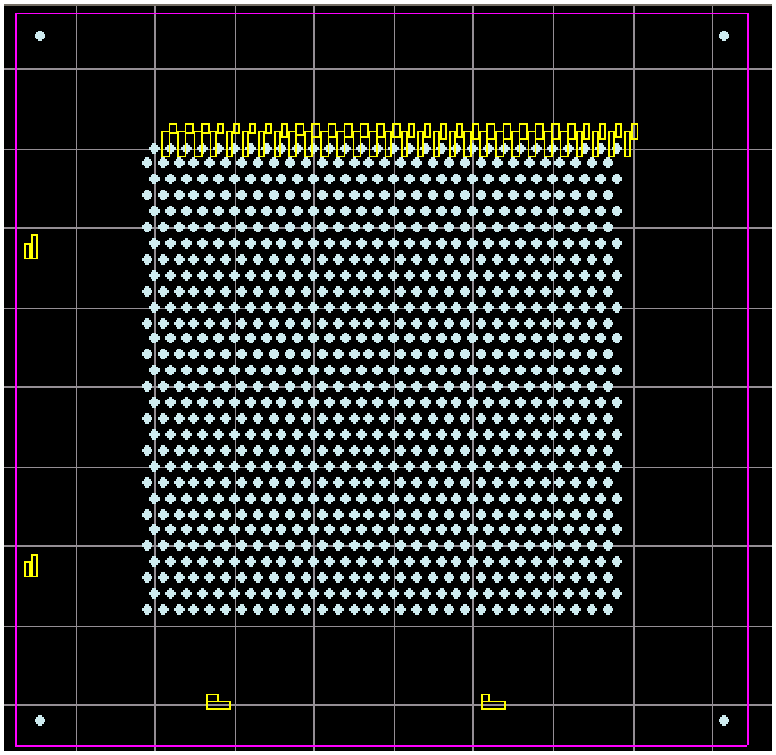


Figure 3-24. Digital support plate

The top board, displayed in Figure 3-25, will be what the user sees from above. It will be held stable by the surrounding skeletal structure and the clamps will be attached to the board. The pinheads will be wider than the holes in the top board and will not be able to move below it.

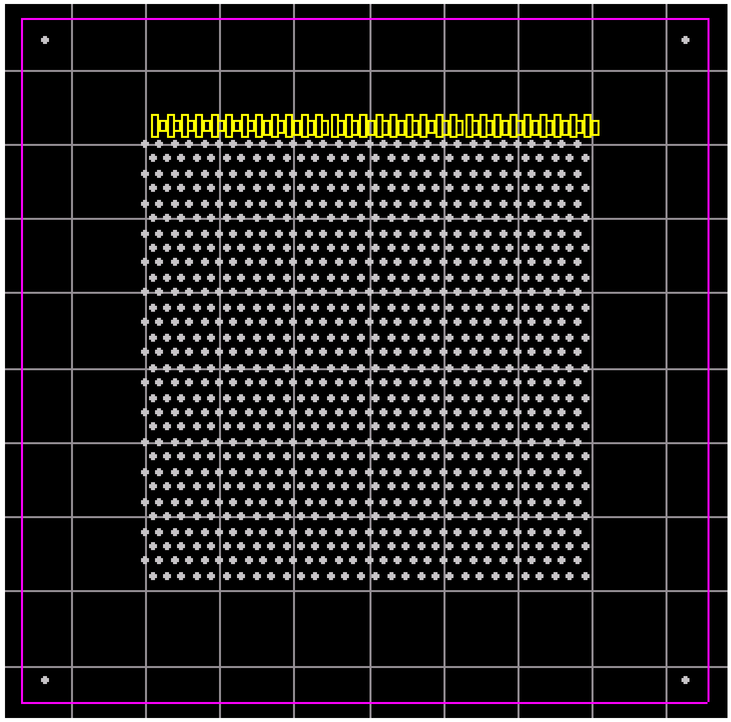


Figure 3-25. Digital top plate

Pin Movement System and Frame

The pin movement system and frame had fewer restrictions on their creation and therefore, were basically designed by working around the other two systems. First, it had to be decided which type stepper motor and solenoid would be used. This was necessary because these pieces needed to be ordered from a manufacturer and the connecting pieces would need to be designed to fit around them.

Motor Selection

Because the plate moving the pins has to make strict, easily controlled movements, it was decided that three uniformly placed stepper motors would be best for shifting the plate up and down (Histand et al. 1999). The most economical motor that met all the desired specifications was the Thompson 55M048D1B Bipolar Stepper Motor, as shown in Figure 3-26.

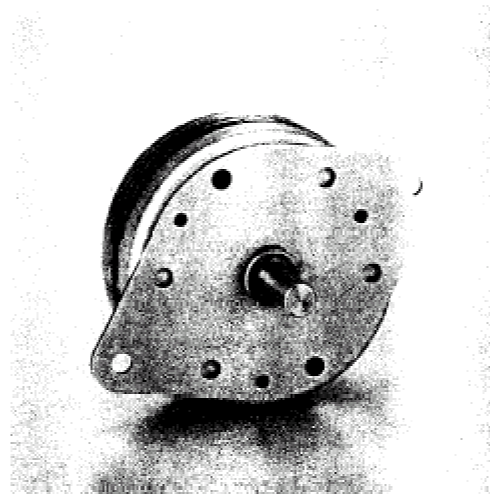


Figure 3-26. Thompson 55M048D1B Bipolar Stepper Motor

It was not important what type of screws would be used to move the sensor board up and down; therefore, it was decided to use some 3/8” round screws that were conveniently already in-house. To decide on the stepper motor that would be used, it was necessary to find the torque required to turn the screws that so that they would smoothly move the sensor board with the pin resting upon it vertically. The necessary torque to be used by each screw, T_u, could be calculated by using Equation 1 and the free body diagram shown in Figure 3-27, where F is the downward force on the screw, f is the coefficient of friction for the metal screw against the plastic nut, L is the lead and D_p is the pitch diameter (Mott 1999).

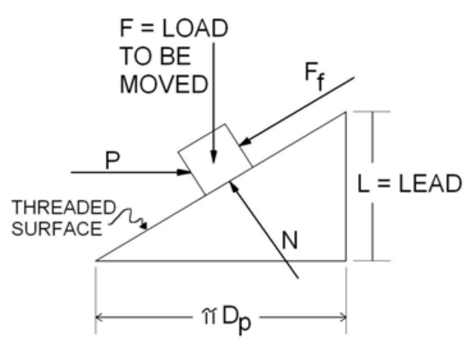


Figure 3-27. Free body diagram of forces on the screw

$$T_u = \frac{F \cdot D_p}{2}\left[\frac{L + \pi \cdot f \cdot D_p}{\pi \cdot D_p - f \cdot L}\right] \qquad (1)$$

The downward force, F, could be found using Equation 2 where m_{pin} is the mass a single pin, n is the number of pins, and W_{plate} is the weight of the sensor board and the bracket it is attached to.

$$F = n \cdot m_{pin} \cdot g + W_{plate} \qquad (2)$$

The mass of an individual pin was measured at 2.92g on an electric scale, the weight of the sensor board and bracket was approximated at 5lb, and at the time of the calculation an n of 900-pins was used. An F of about 11lbs was calculated. Substituting that into Equation 1 along with a D_p, of 0.5", an L of 0.25", and a worst-case f of 0.5, T_u was calculated to be 1.68 lb-in. To find the desirable amount of torque that each stepper motor would provide, Equation 3 was used with a safety factor, SF, of 3, and a stepper motor total, n_{SM} of 3.

$$T_{desired} = \frac{SF \cdot T_u}{n_{SM}} \qquad (3)$$

After converting the units the desired torque was found to be 31.5 oz-in per stepper motor. The Thompson 55M048D1B Bipolar Stepper Motor was chosen for use because it could provide 33.5 oz-in and was an economical purchase.

Solenoid Selection

In order to re-stretch the SMA after having been heated and condensed, the clamp sleeve (which is attached to the SMA) will be moved by one of the spinal plates. It was decided that the plate will be moved by a three Magnet-Schultz DC voltage cylindrical push solenoids, as displayed in Figure 3-28. Moving the plate will move the sleeve and in turn stretch the SMA.

Figure 3-28. Magnet-Schultz DC Voltage Cylindrical Push Solenoid

Because the motion required to move the ground board up and down was a discrete action, it was decided that a solenoid would perform this task best. In order to decide upon an exact solenoid it was necessary to decide how much force (F_{max}) each solenoid was going to be required to apply. The majority of the force used from the solenoids would be used to push the freedom ring over the clamp, everything else could be considered negligible. The maximum force (F_1) required to stretch out a single SMA was calculated using Equation 4, where m_{MAX} is the maximum amount of mass required to pull the freedom ring over the clamp and g is the acceleration of mass due to earth's gravity.

$$F_1 = m_{MAX} \cdot g \tag{4}$$

Tests with an electronic scale showed m_{MAX} to be approximately 10 grams. F_{max} was then calculated using Equation 5 where n is the number of freedom rings being pulled down and N is the number of solenoids being employed.

$$F_{\max} = \frac{n \cdot F_1}{N} \tag{5}$$

It was decided that the operation would be most balanced if a solenoid were employed at each corner of the board, thus making N equal 4. At the time it was believed that there would be 900 pins, thus making n equal 900. Calculated out F_{max} was found to be 353 oz. The Magnet-Schultz DC voltage cylindrical push solenoid was capable of supplying 515 oz of force and was most economical for its capabilities and therefore became the solenoid that was implemented. When n decreased as the design evolved, the force calculated was still sufficient because the additional force could only be beneficial.

Shaft Selection

The shaft system that moves the bottom sensor plate up and down was designed and drawn up in Mechanical Desktop, as seen in Figure 3-29. The stepper motor spins a 3/8” screw to move a nut up and down, and the bottom plate is attached to the nut. The stepper motor will be attached to the screw with a flexible coupling. The ends of the screw will be supported by single-row angular contact ball bearings which will protect the screw from axial and radials loads.

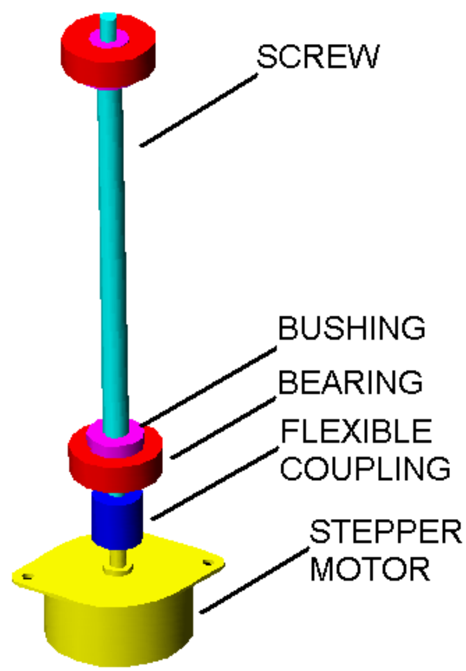


Figure 3-29. Shaft / motor system

The design of the shaft system began with an assessment of what was available, what was necessary, and what was desired. The following facts were known:

- Three 3/8” in diameter screws would serve as the shaft

- The 3 screws would need to be connected to three stepper motors having shafts of 0.25” diameter and 0.375” length
- 4 to 6 inches of plate movement were desired from the shaft
- Bearings would be necessary to hold the screws in place and prevent damage to the steppers (to isolate)

Flexible couplings were bought to connect the screw shaft to the stepper motor shaft. It was decided that the couplings would be flexible so as to prevent damage for the likely situation that the two shafts would not be perfectly aligned. It was decided that the ends of the screws would be worked down to a quarter inch in diameter so as to match the stepper motor shaft and make it easier to find a functional coupling. Because bearings could not be found that would exactly fit the ends of the screws, bushings were created. In order to design the bushings, decide the exact screw length, and make certain that everything would fit together, all the pieces for the system were drawn two-dimensionally in AutoCAD, as shown in Figure 3-30, and aligned properly.

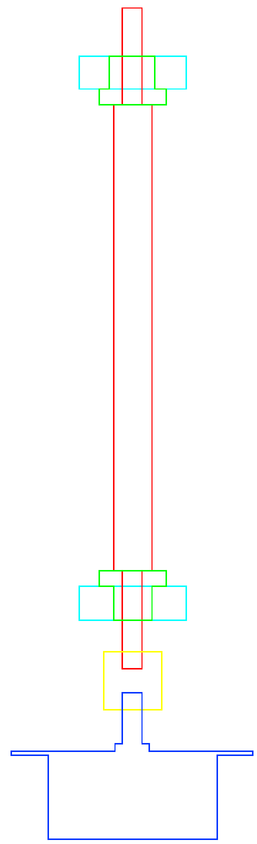


Figure 3-30. Two-dimensional drawing of the shaft/ motor system alignment

With the shaft system and the plates designed, it was possible to create the surrounding structure, which is shown in Figure 3-31. The structure was designed in Mechanical Desktop and is approximately 24” × 20” × 27” in size. The openness of the design allows for easy viewing and accessibility to the machine’s many parts within the structure.

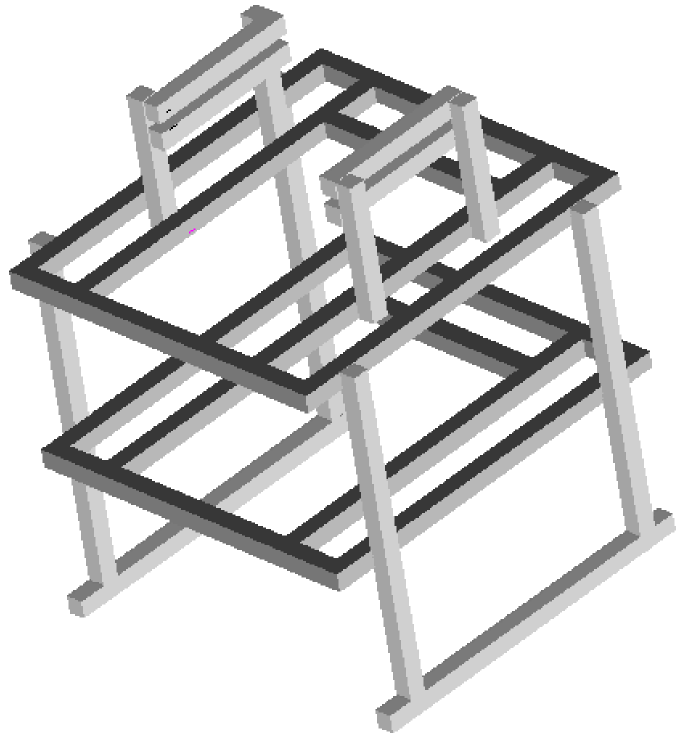


Figure 3-31. Skeletal structure of 80/20

The frame was designed with the purpose of being capable of holding together all of the display's working parts, bearing the weight and forces from the display's actions, and still being open for easy viewing and maintenance. It was made from extruded aluminum and connected using groove-fitted screws and nuts. Figure 3-32 shows the assembled frame with the cooling fan attached.

Figure 3-32. Assembled 3-D display frame with fan

Next, additional mounts had to be designed to connect all the pieces. The “motor mount,” seen in Figure 3-33, serves as an important hub between the shaft system and the machine structure. Made from delrin, this mount braces one of the single-row angular contact ball bearings attached to the shaft while also holding the stepper motor on the bottom. The flexible coupling is sheltered in the center of the mount, but still easily accessible for tightening through two side holes.

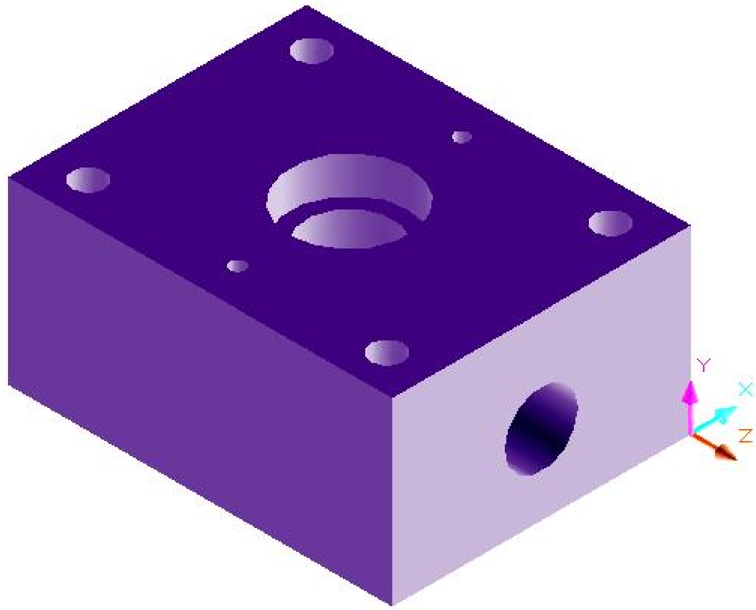


Figure 3-33. Motor mount

The “upper bearing mount” braces the contact ball bearing on the top of the shaft and connects it to the 80/20. Shown in Figure 3-34 and made from delrin, this bearing is aligned in the z-axis with the motor mount to complete the shaft system. The three shaft systems are used to move the bottom plate up and down.

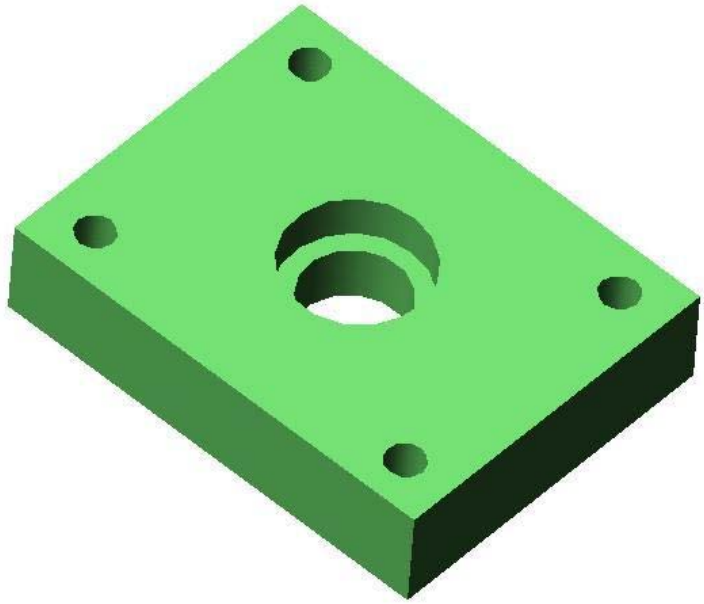


Figure 3-34. Upper bearing mount

The “solenoid mount,” seen in Figure 3-35, has one push solenoid screwed into its top socket and another screwed into its bottom socket. The moving pins in the solenoids are pointing towards one another with the power plate in between them. There is a solenoid system attached to each corner of the power plate. The bottom solenoids are able to push the plate up with the purpose of stretching the SMA wires and releasing the clamps’ grips on the pins. The top solenoids push down on the power board in order to maintain the clamps’ grips on the pins. When neither solenoid is active, the plate is held in its desired place by springs resting around the pushing pins inside the solenoids.

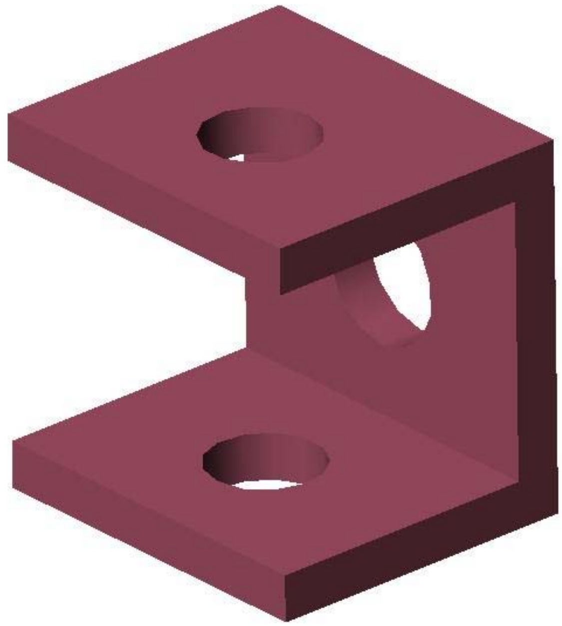


Figure 3-35. Push solenoid mount

Figure 3-36 shows a preliminary drawing of the machine assembled without the pins, clamping systems, or plate attachments. The drawing shows the relative placements of the three shaft systems, four push solenoid systems, and plates with respect to the aluminum structure.

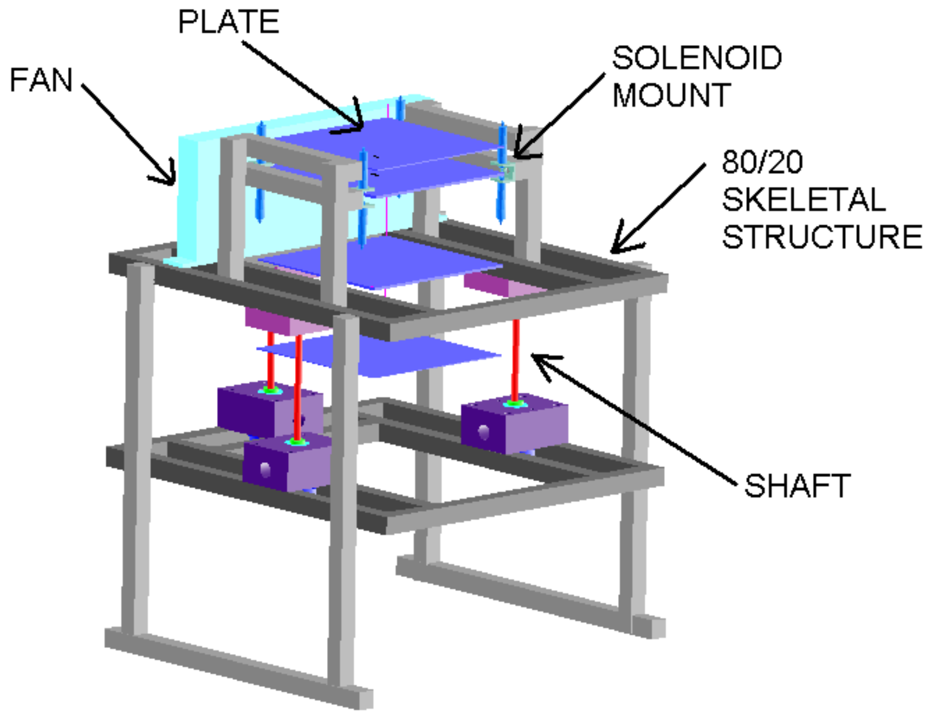


Figure 3-36. Preliminary assembly drawing

Brackets were designed to attach the various plates to the to the machine frame. Each design took into consideration the fit of the parts around it, the actions it would be making, and the forces that it would have to withstand. It was decided that making the brackets from steel would be structurally sound while still being economically efficient. Figure 3-37 shows a detailed dimensioned drawing of the bracket for the top plate. Two of the L-shaped brackets attached to opposing ends of the top plate. The top plate was screwed to one section of the “L” and the top plank of 80/20 extruded aluminum was screwed to the other section. These brackets hold the top board rigid while allowing for free movement of the solenoids (which move the ground plate) around the brackets.

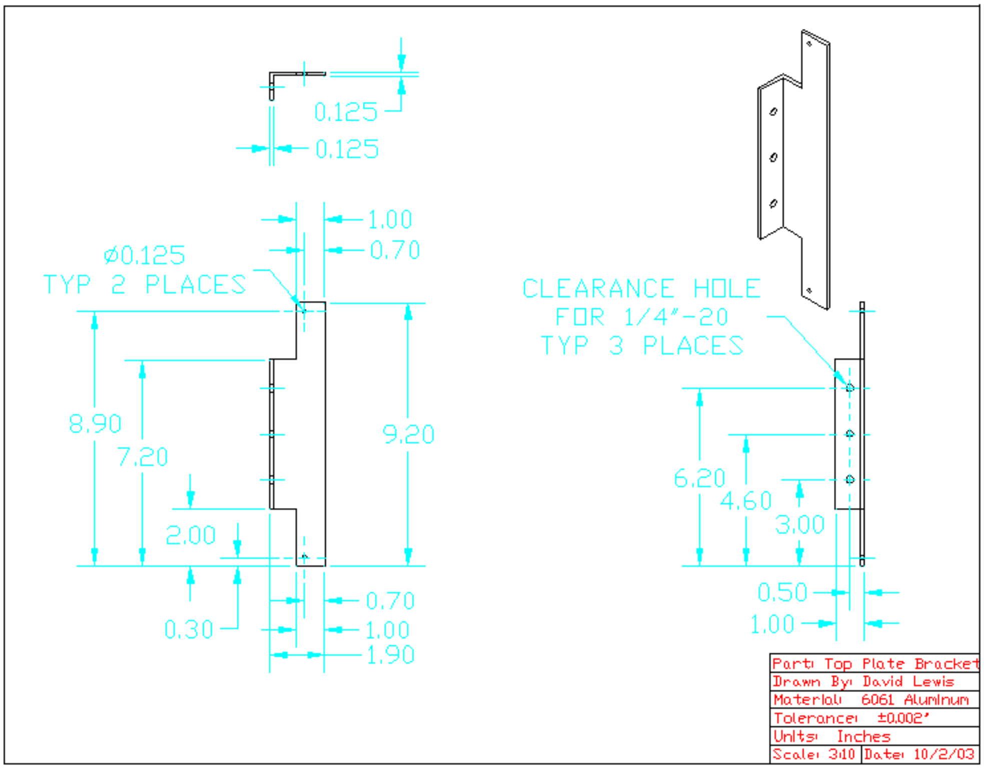


Figure 3-37. Top plate bracket

Figure 3-38 shows the detailed dimensioned drawing of the brackets for the ground plate. These brackets were screwed to the opposing ends of the ground board for a rigid attachment. The other ends of the brackets were attached to four push solenoids each. Two solenoids were inserted into opposing ends of each hole in the brackets. Pushing from the solenoids on the brackets leads to a corresponding movement of the ground plate.

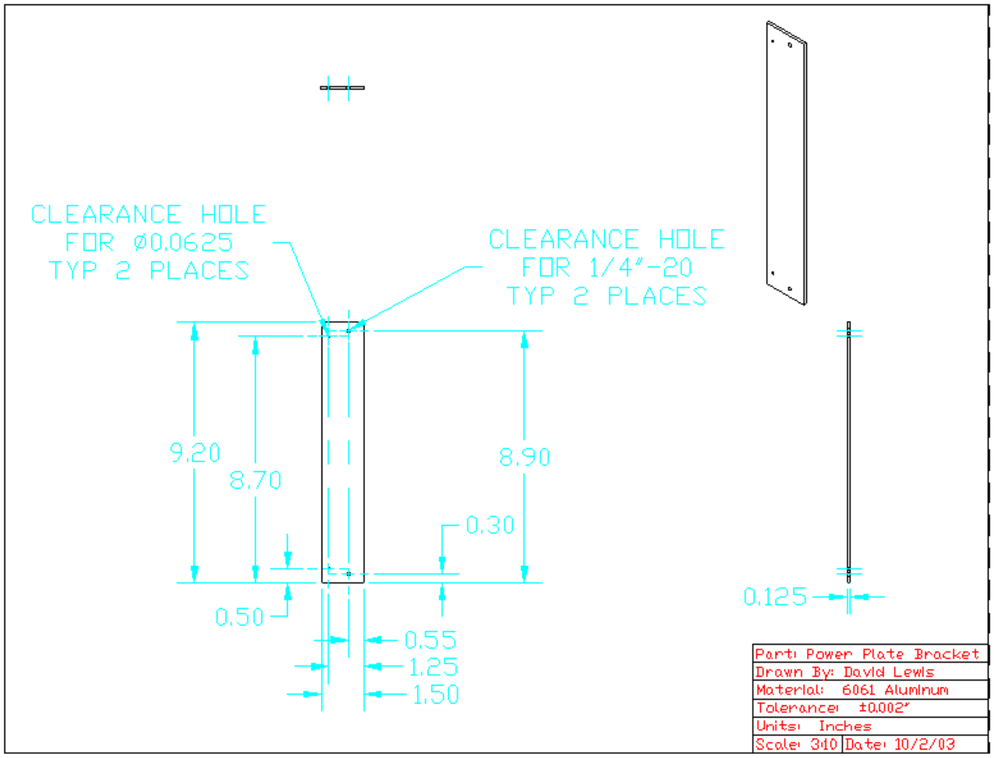


Figure 3-38. Ground plate bracket

Figure 3-39 shows the detailed dimensioned drawing of the brackets for the power plate. Opposing ends of the power plate were screwed to the inside on the longest section of these two C-shaped brackets. The two smaller symmetric sections of the brackets are two planks of 80/20 on the level of the frame that is third from the top. These brackets hold the power plate rigid even when the attached SMA wires are pulling on it.

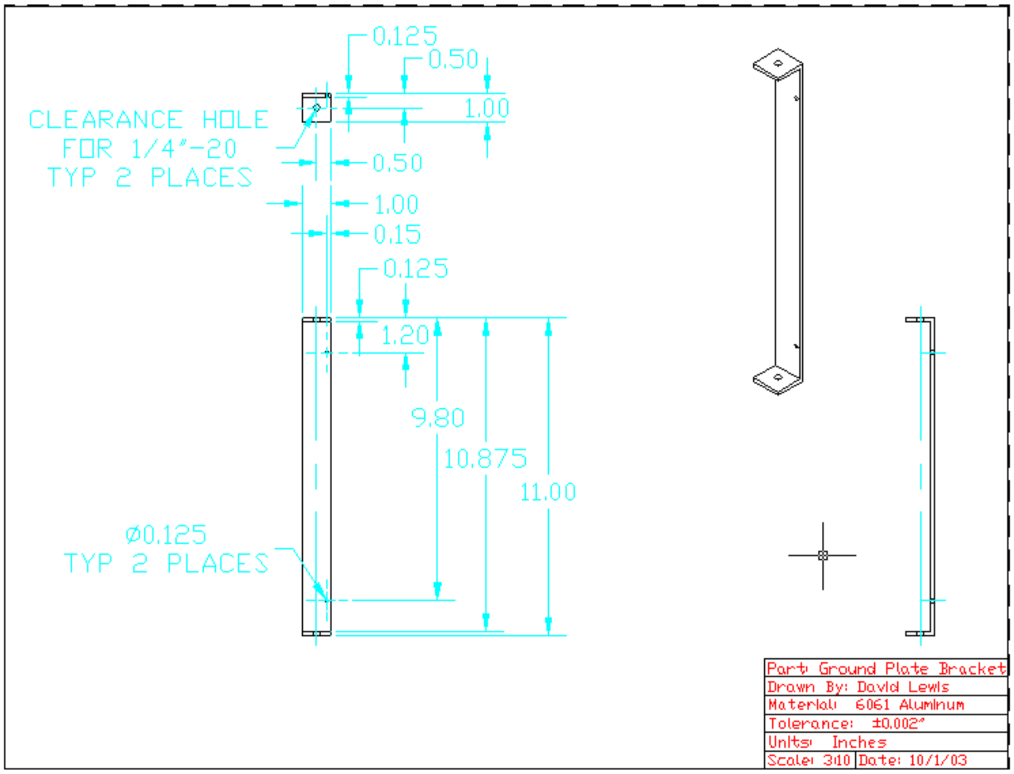


Figure 3-39. Power plate bracket

Figure 3-40 shows the detailed dimensioned drawing of the bracket for the sensor plate. The sensor plate is screwed to this singular piece for a rigid attachment. The three arms of the bracket are screwed to the nuts on the three motor / shaft assemblies. Turning the shafts in unison result in a symmetric movement of the nuts. This, in turn, moves the bracket and sensor plate up and down (lowering the sensor plate allows for movement of the pins).

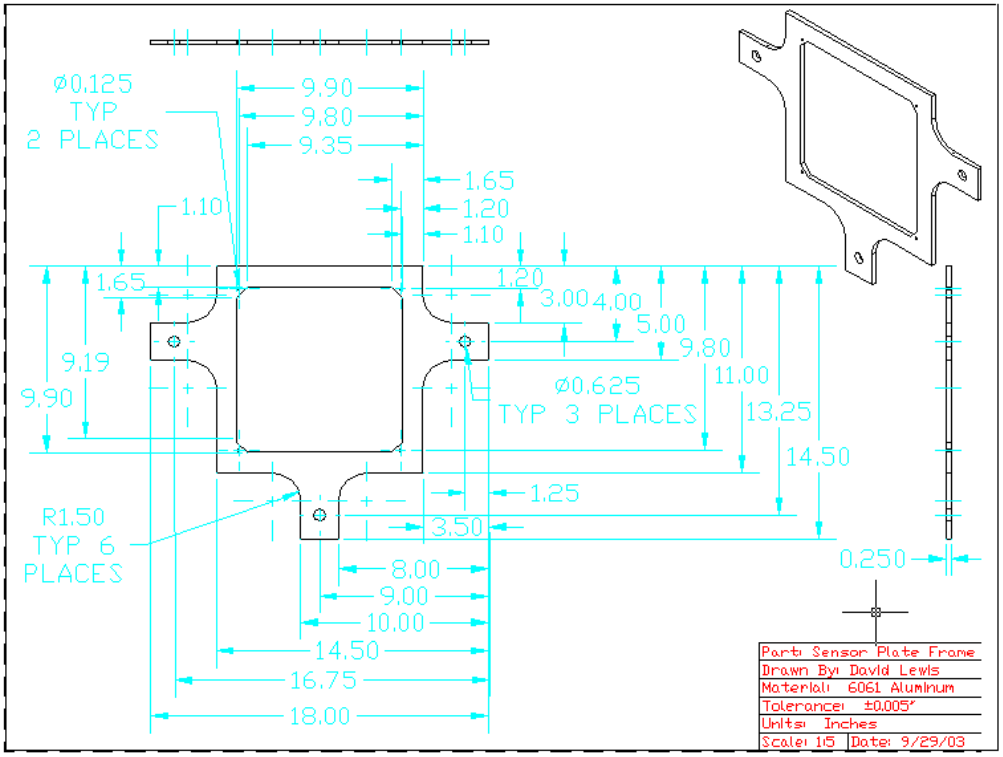


Figure 3-40. Sensor plate bracket

All the parts that were designed specifically for the display device were manufactured. The following parts were all created in the UF machine shop:

Two Top Plate Brackets
Two Ground Plate Brackets
Two Power Plate Brackets
Three Upper Bearing Mounts
Three Motor Mounts
Four Solenoid Mounts
Six Bushings
Six Screw Shafts

To make the top plate bracket, a precise milling machine was required; because this was not available in the UF shop, the piece was created by an out-of-house manufacturer. The pieces were press-fit together as with their associated parts.

Figure 3-41 shows a picture of the finalized physical display, having been fully assembled.

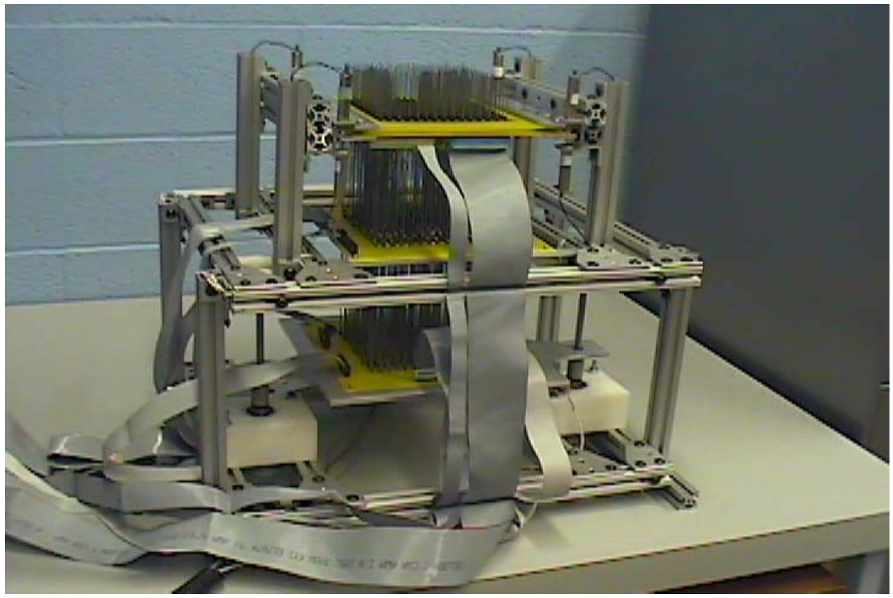


Figure 3-41. The fully assembled physical display

CHAPTER 4
CONTROL BOX

Where the computer serves as the brains of the machine, the control box works as the circulatory system. Control signals are delivered from the computer to the box where they are processed, re-routed and the appropriate signals are sent to the display device. This system contains numerous terminal boards, power sources, controllers and thousands of wires that are vital to the transportation of electrical signal through the machine. This chapter will detail the processes used by the control box, how it is organized, and parts that make it up.

Raster Scanning

As a result of having hundreds of pins, the 3-D Visualization Device has hundreds of actuators and hundreds of sensors that need power. It was an important task that the amount of power being distributed be as minimized as possible. The solution that was implemented was a process known as *raster scanning*. This process only works for grids of electrical devices where the number of columns is equal to the number rows, which was conveniently the case at hand. The benefit of raster scanning is that it decreases to the total number power lines needed to $2\sqrt{N}$, where N is the total number of electrical devices. The negative is that only a single column of devices can be activated at any single moment. The simple solution to this problem is that each column is activated in a pattern of quick sequential bursts. The result is visually the same as activating everything at once. The setup for a raster scan is basically that each column of devices is receiving a common ground line and each row devices is receiving a common power line. This can be reversed, as the important part is that the columns are all receiving one type of power and the rows are receiving another type of power. Figure 4-1 diagrams an example setup for a three by three setup of actuators.

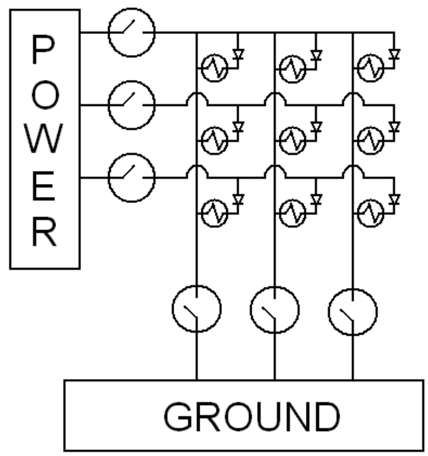


Figure 4-1. An example 3x3 grid of actuators in a raster scanning sequence

The diodes in the setup keep current from flowing in an undesired direction. For a of grid actuators, the columns would output power until it is desired to begin actuation. At that point, the first column will output a ground, and the rows will send power only to the rows that are to be actuated. Next, the first column outputs a power again. Then, the second column quickly outputs a ground and the row outputs change to give power to the actuators being activated in that column. This pattern is repeated for the remaining columns and continues for the remaining time of activation. To the human eye it appears that the actuators are all being activated once.

For the sensors, such as in Figure 4-2, the process is a similar process with polling. The columns are only powered one at a time, while all the rows are read. The rows use a pull down resistor, trying to draw a current. If a current is read, then the sensor at that row and column has been contacted. The polling of columns can be done so quickly that the off time for each column is negligible.

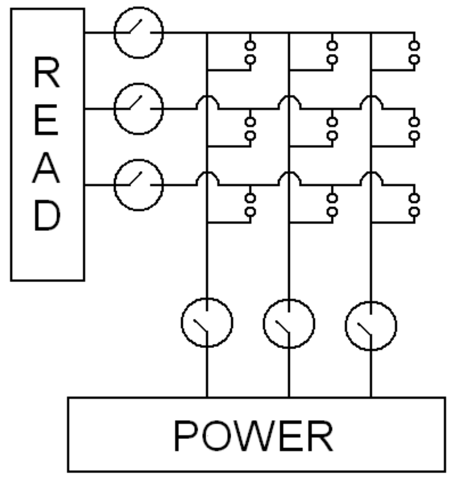


Figure 4-2. An example 3×3 grid of sensors in a raster scanning sequence

Mapping

The control box can initially be looked at as a black box, as show in Figure 4-3. Six 50-pin cable ribbons come out of the computer and connect to their own individual terminal boards. Each ribbon contains 24 actual signals, which are each broken down into an individual wire through the terminal board. Appendix D details the mapping of where each cable ribbon pin goes and what it does. After being processed, the various signals are processed and enter eight more terminal boards, which send information to the display device through eight more ribbon cables.

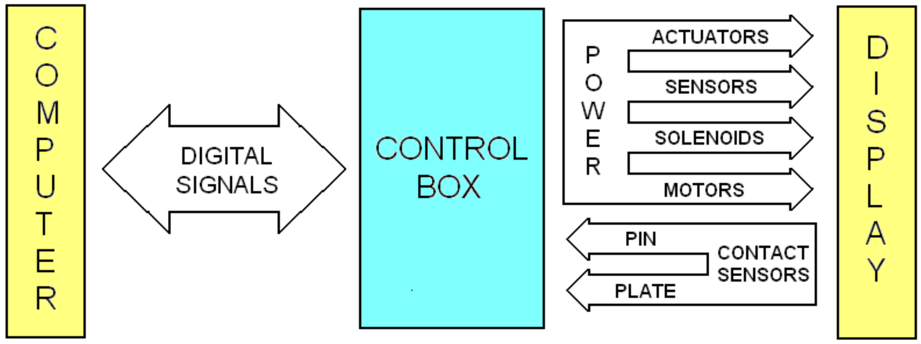


Figure 4-3. Direction of signals through the control box

Figure 4-4 shows a basic mapping of how the control box is connected within and to the surrounding components. Sixty-three of the signals are used to control sixty-three opto-isolators. These opto-isolators act as switches controlling the flow of current too high for the computer to handle. Fifteen opto-isolators control the flow of power to the power board. Fifteen opto-isolators control the deliveries of ground flows from the ground board. Fifteen opto-isolators control the flow of current to the sensor board and fifteen opto-isolators control the reception of current from the sensor board back to the computer. One opto-isolator is used to control the flow of power to the four solenoids, which push the ground plate down, and another opto is used to control the flow of power to the four solenoids pushing the plate up. Another opto receives signals from the sensor on the display device that reads when the sensor plate is completely down. A stepper motor driver inside the box is used to control the timing, speed, and direction of the three stepper motors in the display device. Two power supplies are used to power all the components of the display device. A MAP130-1024 Power-One DC power supply sends 24 Volts to the eight solenoids on the display, and another 24 Volts that are used to power the stepper motor driver. An L&C Inc. switch power supply sends 12 Volts to the columns of the sensor board, and 5.25 Volts to the power board.

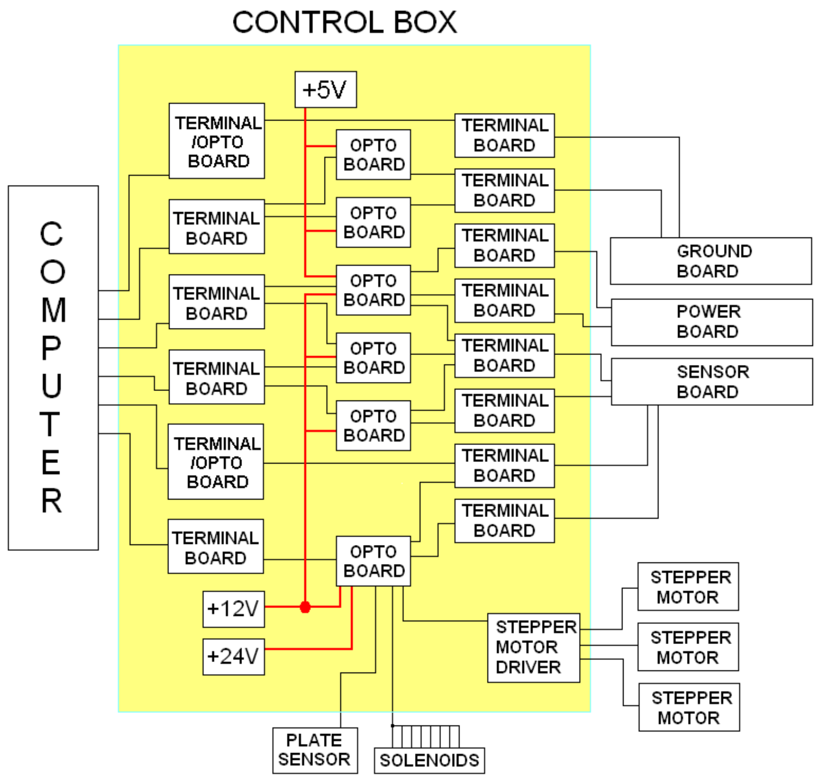


Figure 4-4. Basic mapping of the control box

CHAPTER 5
COMPUTER

The computer serves as both the brain of the machine and a way for the user to communicate with the display devices. Its three main components are the Graphical User Interface (GUI), the path planner, and the Digital I/O. This chapter details how those components work and what they do.

Overview

The computer was setup for controlling the machine, as seen in Figure 5-1. A *Linux* operating system was installed and *Motif* and *Open Inventor* were installed for running the graphical user interface (Brain 1992, Wernecke 1995). Hardware programs were installed to run the digital I/Os and motor controllers.

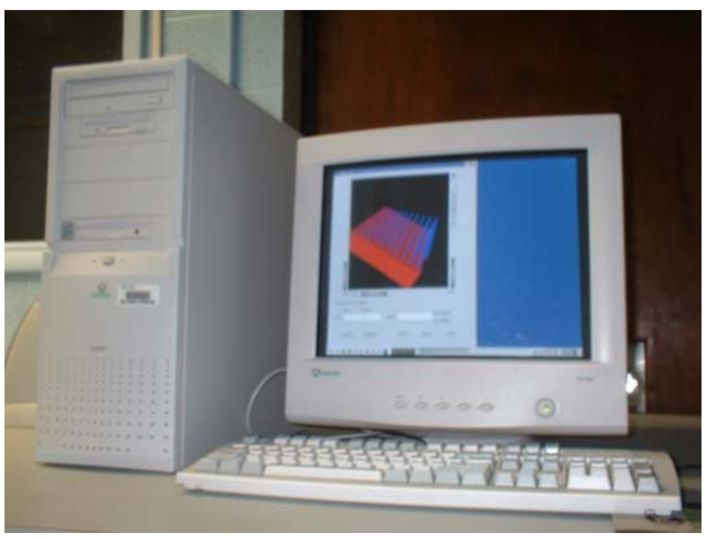
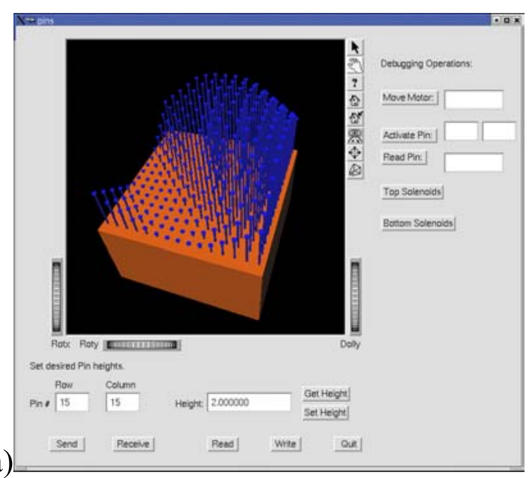


Figure 5-1. Computer setup

Graphical User Interface

In order for the user to be able to control the machine from a computer, a Graphical User Interface (GUI) was created using *Motif* and *Open Inventor*. This interface is used to both tell the physical display how to position itself and present a rendered representation of the current physical display. Figure 5-2a shows the GUI that was created to control the three-dimensional visualization machine. The user can read the current positions of the pins in the drawing by entering the row and column numbers of the desired pin and clicking on a “Get Height” button. It is important to note that the rows and columns are labeled “1” through “15”. Entering a row, column and height and pressing the “Set Height” button will change the height of a pin. As shown in Figure 5-2b, an entire positioning set for the pins can be read from or saved to a file using the “Read” and “Write” buttons. To send the pin positions to the physical display, the “Send” button must be clicked. To display the current pin positions from the physical display, the “Receive” button must be pressed. Also, the display view can be adjusted by dragging the rotating wheels and using the icons alongside the display.

(a) 

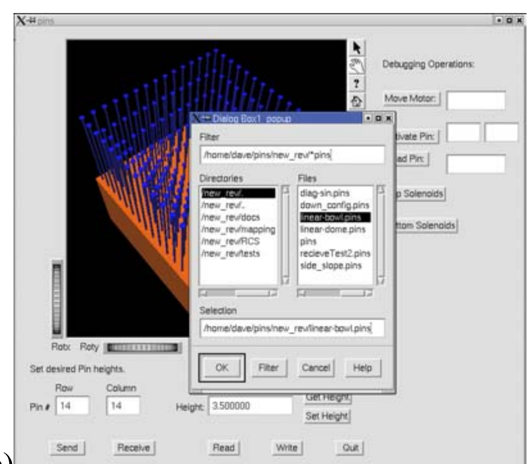
(b) 

Figure 5-2. Graphical user interface (a) Example GUI display, (b) GUI reading a file

The GUI also, has a series of buttons on the right side that can be used for testing the various sections of the physical display. The “Bottom Solenoids” button is used to make the solenoids push the power plate up and the “Top Solenoids” button has them push the plate down. The “Move Motor” button can be used to move the sensor plate up and down. The user places a desired height for the pins in the corresponding text box, then left-clicks the button and the pins are moved to that height. The pins and plate will remain at that position until another command is made. The “Activate Pin” button can be used to trigger a specific pin actuator. The user writes the row and then the column, respectively, of the pin to be actuated in the corresponding text boxes. After the button is clicked, the SMA will be heated and the pin will be clamped. The “Read Pin” button can be used to test the sensor board. The user enters the row and column of the pin to be tested in the text boxes used for the “Activate Pin” button and clicks the “Read Pin” button. Next, the test field next to the “Read Pin” button will say whether or not the pin at the specified position is engaged with the sensor.

Path Planner

In order for the user’s input to reach the pin display device, a “path planner” program was created in C++ that interprets the inputs from the user interface and executes them through the digital I/O. This program executes all major actions such as plate movement, pin sensing, pin clamping, and SMA stretching. It was decided that the program could use an open loop system to move the pins up and down because sensors will allow the program to rediscover the bottom plate’s location at the end of every display process and any location errors that could occur in between would be so negligible that the human eye would not be able to notice them.

The path planner program utilizes the following algorithm for physical visualizations (The terms from the code can be interpreted by using Appendix E):

1. 'Send' button sendPhysical(), sendPhysical2() (MakeItReal.c++)
-------- sendCB() (main.c++)

2. If machine is not busy, lock machine and call sendPhysical(); else, stop.
--------- sendPhysical() (MakeItReal.c++)

3. Load all pins into a priority queue, sort by height (tallest first).

4. Set sensor board speed to fastest setting.

5. Move board to top.
-------- popup_routine() (MakeItReal.c++)

6. Popup dialog asking if user wants to unlock pins by activating solenoids.

7. Continue prompting until user answers, "No, continue."
-------- sendPhysical2() (MakeItReal.c++)

8. Set sensor board speed to slowest setting.

9. Pop front pin off of priority queue and descend to its height.

10. If that height is greater than zero, fire the pin.

11. Reset sensor board speed to fastest.

12. Unlock machine.

In turn, for virtual visualization, the program uses the following algorithm:

1. 'Receive' button receivePhysical(), receivePhysical2() (CompDisplay.c++)
-------- receiveCB (main.c++)

2. If machine is not busy, lock machine and call receivePhysical(); else, stop.
-------- receivePhysical (CompDisplay.c++)

3. Set sensor board speed to fastest.

4. Move board to top.

5. Activate and hold solenoids to lock clamps.

6. Move board to bottom.

7. Popup dialog allowing user to adjust pins. receivePhysical2() when clicked.
-------- receivePhysical2() (CompDisplay.c++)

8. Set sensor board speed to slowest.

9. Move board up and at each click check all pins to see if engaged.

10. Record the lowest height at which a pin was engaged (in 'pinsArea').

11. Unlock the solenoids.

12. Reset sensor board speed to fastest.

13. Unlock machine.

Digital I/O

Two PCI-7296 digital I/O cards, seen in Figure 5-3, were installed into the computer. Each card has 96 entries capable of sending or receiving data signals. They are used for the following functions:

- 30 outputs for clamp control
- 15 outputs for running sensors
- 15 inputs for reading sensors
- 3 outputs for running motor controllers
- 2 outputs for controlling solenoids
- 1 input for sensing the bottom placement of the bottom plate

Figure 5-3. PCI 7296 digital I/O card

CHAPTER 6
ASSEMBLY

The assembly process of this project was complicated, difficult, and greatly time-consuming. While a majority of the design and testing occurred before the assembly process began, the design and testing processes became mixed into the assembly process as well. The physical display had to be restructured several times in order to be accessible for hand assembly as well as to solve unexpected problems. Multiple design questions could only be answered by performing tests as the device was being assembled. As this was a prototype machine, many decisions had to be made on the fly and the process took up a pattern of assemble, test, re-design, and repeat. This was the step of the project where a *don't-look-back* approach had to be taken at times. If a problem occurred, it was corrected to the best degree possible without having to start over again. Now that the machine is completed, it would be recommended to perform some assembly processes differently with some redesign changes. Those recommendations are presented in Chapter 8. This chapter details exactly how this machine was assembled and how to recreate it.

Control Box

The control box was basically assembled by attaching the electrical controls to four perforated shelves. The shelves have rails on them, which were inserted into rails inside a large metal box. The seven opto-isolator boards, the two power sources, and the stepper motor driver were screwed into the perforations in the shelves. The terminal boards had no holes for such attachments, so they were connected to the shelves with snap ties and Velcro was added for additional support. The ports were then wired together following the previously mentioned mapping of Appendix D. Multiple colors of wire were used in order to distinguish separate sections of the mapping.

Pre-Clamp Physical Display

Because the pin clamp systems were delicate and permanent, it was necessary to have everything else on the physical display assembled and working correctly first.

Frame

The first part of the physical display to be assembled was the frame. It is composed from the following parts:

- Four 20" long extruded aluminum strips
- Four 16" long extruded aluminum strips
- Four 11.5" long extruded aluminum strips
- One 11" long extruded aluminum strips
- Four 10" long extruded aluminum strips
- Four 9" long extruded aluminum strips
- Four "T"-brackets
- Fifty-Six "L"-brackets

Because the frame could not be assembled all at once, it had to be made in sections. Figure 6-1 shows what the assembled frame sections would look like without any other attachments.

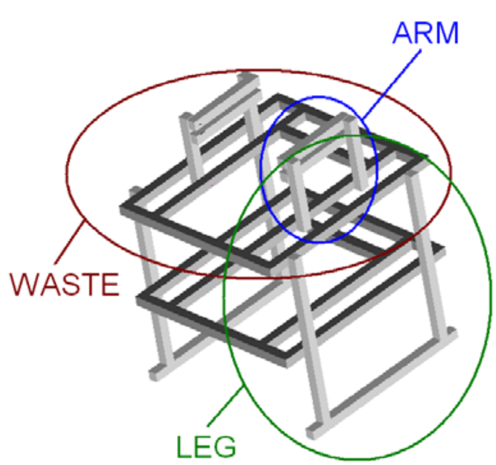


Figure 6-1. The sections of the frame where the red circle encompasses a waste section, the blue circle encompasses an arm section, and the green circle encompasses a leg section

All the strips of aluminum were joined by placing T-nuts inside the aluminum extrusions and screwing the hinges to them. What follows are the three types of frame sections that were created:

- Two waists were made by joining the aluminum strips into the pattern shown in Figure 6-2.

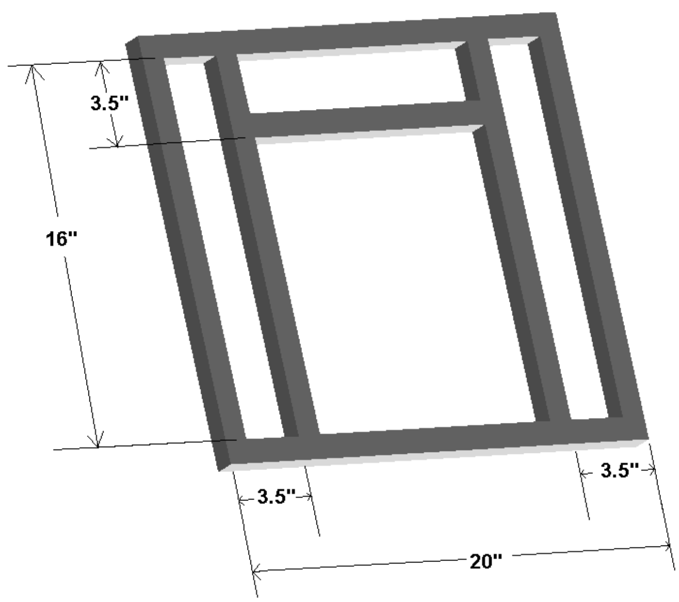


Figure 6-2. Waist section of the frame

- Two legs are used to support the entire display. Joining the aluminum strips in the pattern displayed by Figure 6-3 can create a leg.

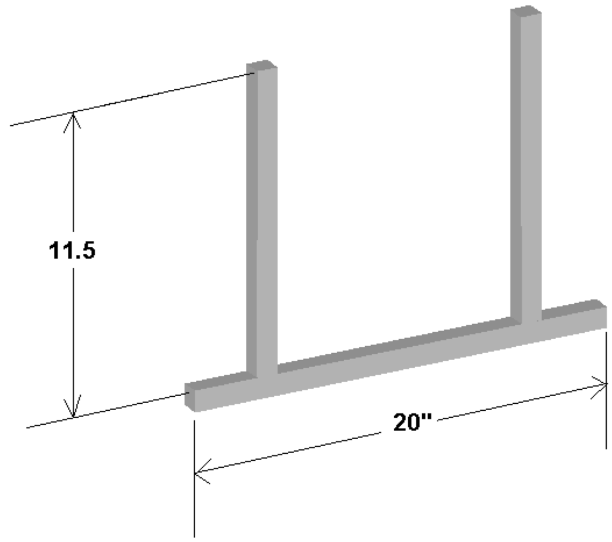


Figure 6-3. Legs section of the frame

- Two arms are used to hold the top two plates. Figure 6-4 shows the aluminum strip assembly pattern

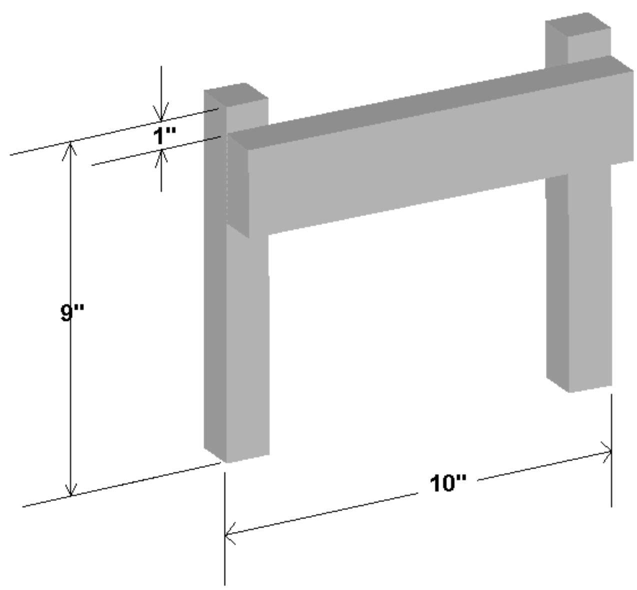


Figure 6-4. Arms section of the frame

The remainder of the assembly was matter of carrying out the following specific procedure:

Motor/Shaft Systems

1. Press fit a bearing into each of the three motor mounts.

2. Press fit a bearing into each of the three upper bearing mounts.

3. Press a single bushing onto each of the three shafts so that the widest end of the bushing is flush against the widest end of the shaft.

4. Tighten the screw on the bushing so as to tighten their grip on the shafts.

5. Insert a flexible coupling into the center of each of the three motor mounts so that the coupling's center hole is facing the top and bottom of the mount.

6. Insert a stepper motor shaft into the bottom of each motor mount and into center hole of the flexible coupling within.

7. Screw the three stepper motors on.

8. Insert the end of a screw shaft that hangs out of the bushing into the top of the motor mount and into the top end of the flexible coupling until the bushing is flush against the bearing.

9. Screw the nuts onto the screw-shaft so that the threads on the nut are at the top

10. Screw the three nuts onto the sensor board bracket and move the bracket to the lowest possible location.

11. Screw the three motor mounts onto one of the waste sections of the frame so that the corners of the bracket are symmetric with the section.

12. Screw the three upper bearing mounts to the other waste section of the frame (make certain to leave the screw loose enough that the mounts can slide on the frame section.

13. Place a bushing on the top of each of the screws so that the widest end of the bushing is flush against the widest end of the screw.

14. Tighten the screws on the bearings.

15. Place the second waste section of the frame on top of the other by inserting the ends of the screws coming out of the bushings into the bearings in the upper bearing mounts until the bushings are flush against the bearings.

16. Adjust the placement of the upper bearing mounts so that the screw-shafts are perfectly upright and the two waste sections of the frame are symmetric with one another.

17. Tighten the screws on the upper bearing mounts.

18. Screw the leg sections of the frame onto the waste sections (the exact placement that they are attached isn't as important as making certain that the waste sections of the frame are level.

Brackets

1. Screw a top plate bracket onto each arm section of the frame.
2. Screw the power plate brackets onto the top waste section of the frame.
3. Screw the ground plate brackets onto the ground plate.

Plates

1. Screw the sensor plate onto the sensor plate bracket.
2. Screw the power plate onto the ground plate brackets.
3. Screw the top plate onto the top plate brackets.
4. Screw the arms loosely onto the top waste section of the frame.
5. Align the top plate with the power plate and tighten the arm attachments.

Solenoids

1. Screw two solenoids into each of the four push solenoid mounts.

2. Screw the solenoid mounts loosely onto the four corners of the arms.

3. Place a solenoid shaft through each of the four top solenoids and tighten a collet around each shaft so that about 1/8" of the shaft hangs out of the collet.

4. Place a solenoid shaft through each of the four bottom solenoids, place a spring around each shaft, and tighten a collet around each shaft so that about 1/8" of the shaft hangs out of the collet.

5. Slide the ground plate into its proper position and insert the eight solenoid shafts into the four ground plate bracket holes so that each hole has a shaft entering it from each end.

6. Re-adjust the collets on the solenoid shafts so that they are flush against the ground plate bracket.

Pin-Clamp Systems

The pin-clamp systems were the most tedious and time-consuming work of the entire project. Most sections of the system had to be shaped, created, or assembled by hand. The time involved in creating the parts was a large reason that the number of pins was lowered from 900 to 225. The difficulty involved in the hand assembly was why the spacing of the pins was increased. Each section was created in mass before creating the next section and each unit assembly followed a carefully structured course of action. It is also important to note that the number of units created for each section outnumbered the number of units needed. This was important because many units were broken in during assembly and testing, and it saved time to have the additional units made. The following assembly procedures detail how to make each section of the system and how to install them into the machine:

Mechanical Pencil Disassembling

Each of the moving pins on the physical display device required a working clamp with a freedom ring to lock its position. Each clamp and freedom ring needed to be removed from a single Pentel Crayz 1.3 mm mechanical pencil. When it was still planned to have 900 pins, 996 pencils were ordered and stripped down to the clamp, spring and freedom ring. Because of the large number pencils, the stripping process was broken down into five specific steps.

1. Disassembly: All parts of the mechanical pencil that were capable of being removed by hand were detached and collected. The detached parts included the eraser cap, eraser, two sticks of lead, the pencil cap, and the cone cover.

2. Shell Removal: The clamp was attached to a long cylindrical, semi-rigid plastic sleeve. A much harder plastic shell surrounds all this, which is what the user grips when writing with the pencil. The hard shell could only be removed by being broken off. The pencil was placed in a vice and when the vice increased the pressure, the shell would fracture linearly and could be peeled off.

3. Sleeve Slicing: The semi-rigid plastic sleeve holds the clamp in place and an increase in the sleeve’s diameter holds the freedom ring and spring over the clamp. A dremel with circular blade was use to slice the sleeve through its smaller diameter where it starts to cover the clamp. This removed all of sleeve except for a thin ring, and, it allowed for the following step.

4. Spring Removal: Without the sleeve to hold it in place, the springs could be removed from around the clamp and placed and bin where they would be used later.

5. Sleeve Dissection: In order to remove the remaining ring from the plastic sleeve around the clamp, the dremel with the circular blade was used to carefully slice through the ring on two sides. The ring was, in turn, dissected into two pieces that would just fall off. Because the clamp was made of a harder plastic than the sleeve, the dremel could be set at a low enough spinning rate that it would cut easily through the sleeve and cause a negligible amount of damage to the clamp. Once the sleeve was removed the freedom ring could be pulled off and the clamp and ring could be stored in their associated bins, as seen in Figure 6-5.

Figure 6-5. Bins of separated materials

Brass Cup and Wire Wrap

Each brass cup needed to be attached to a wire-wrap wire. This process needed to be performed in a precise manner and units that did not meet the desired specifications had to be scrapped of everything except the brass ring. Because the wire-wrap can be delicate when bent, it was necessary to make an additional 75 functional units. What follows is the procedure used to create them.

- Step 1: Cut 300 0.125” lengths of 3/16” in diameter heat-shrink tubing.

- Step 2: Place the bottom of a drill bit in vice so that the bit stands vertical.
- Step 3: Place brass freedom cup around the top of the drill bit so that the rim of the cup is closest to the ground.
- Step 4: Hold a 3" long length of wire-wrap wire along side the freedom cup so that the wire is parallel to the bit and its center is against the cup.
- Step 5: Slide a length of heat-shrink tubing around the wire-wrap and freedom cup so that bottom of the tubing pushes against the rim of the cup.
- Step 6: Heat the tubing so that it shrinks completely around the cup and wire.
- Step 7: Let cool.
- Step 8: Repeat steps 3-7 another 299 times.

Diode Curling

The diodes, shown in Figure 6-6, were necessary to prevent electricity from flowing in the wrong direction. The outgoing wire needed to have a loop that the SMA wire could connect to and the incoming wire needed to have an arm that could be attached to the trace on the power board. Following is how each diode was structured:

- Step 1: Curl the outgoing end of a diode into a spiral.
- Step 2: Cut off the excess wire after the second curl.
- Step 3: Curl the ingoing end of the diode into an L-shape.
- Step 4: Cut off the excess wire so that both brackets of the L-shape are approximately 0.25".
- Step 5: Repeat steps 1-4 another 249 times.

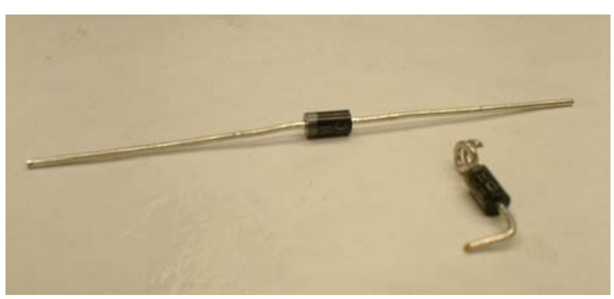


Figure 6-6. A diode before assembly and a diode after assembly

Guide Tubes

The black guide tubes, seen in Figure 6-7, hold the pin clamps in a solid position and provide directional guidance for the pins. Following is the process for making them:

- Step 1: Cut out 275 1.25” long strips of black 3/16” in diameter heat-shrink tubing.
- Step 2: Cut out 275 0.25” long strips of clear 3/16” in diameter plastic tubing.
- Step 3: Clamp one end of a steel rod into a horizontal position so that it is untouched everywhere else.
- Step 4: Place a strip of plastic tubing around the rod.
- Step 5: Place a strip of heat-shrink tubing around the plastic tubing so that one end overhangs the plastic tubing by about 0.25”.
- Step 6: Shrink the tubing with a hot air.
- Step 7: Let cool.
- Step 8: Repeat steps 4-7 another 274 times.

Figure 6-7. On the top-left is the heat-shrink tubing, towards the center is the clear tubing, and on the right is the assembled guide tube

Steel Wool Attachment

Steel wool was attached to the bottom of each pin for the purpose of contact with the sensors. The amount of steel wool used for each pin was arbitrary and not very important as long as it was not so much that it would contact the next sensor over and not so little that it could not flew when it rested on the sensor board.

- Step 1: Cut out 250 0.5-inch lengths of 3/32" in diameter heat-shrink tubing.
- Step 2: Rip out a dime-sized amount of steel wool.
- Step 3: Wrap the steel wool around the end of a music wire. Roll the steel wool between fingers and squish the length down until the steel is about a half inch in length and has a football shape.
- Step 4: Place heat-shrink tubing around opposite end of wire and move down until most of steel wool is cover with a small ball of wool still hanging out (make certain the wire still goes to the end of the heat-shrink tubing.
- Step 5: Heat the tubing until it shrinks completely.
- Step 6: Let cool.
- Step 7: Repeat steps 2-6 249 more times.

SMA System Assembly

The connection of SMA wire to the diode and the wire-wrap wire needed to be done carefully for two reasons. Bending or over-stretching the SMA wire could render it useless without any visible problems until after being installed into the display device. Accidental bending of the wire-wrap wire could make it weak and lead to wire breaking during the later assembly. The pieces were attached to one another in the following manner:

- Step 1: Bend an SMA wire approximately 1" from its end.
- Step 2: Loop the bend and place the closest end through the loop, so as to create a loop that is approximately 0.25" in diameter.
- Step 3: Place the same end through the same hole in order to maintain the stability of the knot.
- Step 4: Bend the SMA 3.5" from the loop.
- Step 5: Cut the SMA 4.5" from the loop.
- Step 6: Repeat Steps 2&3 on the opposite end of the wire.

- Step 7: Bend the wire-wrap wire on a brass cup assembly piece so that when the SMA is completely straight and the wire-wrap wire is straight, the rim of the cup will be 4” from the furthest loop on the SMA wire.

- Step 8: Place the wire-wrap wire through the closest loop on the SMA wire and wrap around the loop so that the bend in the wire-wrap wire is around the very top of the SMA wire.

- Step 9: Wrap the excess wire-wrap wire around the SMA loop and down about another half-inch and back up again.

- Step 10: Swivel the unused SMA loop around the curled end of a shaped-diode and clamp into place with pliers.

- Step 11: Repeat steps 1-9 another 249 times.

Final Attachment Process

The installation of the clamping systems was easily the most difficult part of the assembly process. It required poise, patience, and awkward use of the hands. It is virtually impossible to perform this assembly by hand to a degree of precision that is necessary for perfect results. The following steps were taken to perform the attachment:

- Step 1: Place the threaded end of a 4-40 socket head cap screw through a hole in the ground board to the front-left of the hole where the Pin 1,1 will be placed so that the threaded end comes out on top.

- Step 2: Screw a 4-40 small pattern machine screw nut onto the screw and tighten it so that the screw can not move (if the screw is not secure, it may loosen and fall off later due to shaking of the board).

- Step 3: Repeat steps 1-2 for the remaining 224 pin holes, respectively.

- Step 4: Place a 4-40 socket head cap screw through the hole in the power board (so that the threaded end comes out from the bottom of the board) that is directly below the screw for Pin 1,1 in the ground board.

- Step 5: Screw a 4-40 small pattern machine screw nut loosely onto the screw.

- Step 6: Select an SMA system assembly and pinch the bottom wire of the “L” shaped diode wire between the head of the screw and the copper tracing beneath (it may help to curl the bottom stretch of wire with a pair of pliers so that it fits more snugly around the screw).

- Step 7: Tighten the nut on the screw so that it cannot move.
- Step 8: Loosen the screw directly above.
- Step 9: Wrap the wire-wrap wire around the loosened screw (between the nut and the copper tracing on the ground board) so that the SMA system assembly is taught.
- Step 10: Tighten the screw so that it cannot move.
- Step 11: Place a guide tube through the hole in the top board where Pin 1,1 will be placed.
- Step 12: Trim the guide tube.
- Step 13: Place a pencil spring around the guide tube and a pencil clamp through the freedom ring on the SMA and into the guide tube so that it is tight.
- Step 14: Thread the thin end of an assembled pin through the bottom of the power board, into the clamp and out the top of the guide tube.
- Step 15: Test the system to make certain it works ("C" shaped tubing can be wrapped around the guide tube to tighten the pencil spring and hot glue can be used to tighten the wire-wrap wire.

Elimination of the Fan

Originally, the final step of the assembly called for the attachment of a fan to be attached in line with the pin-clamp systems as shown in Figure 6-8. However, when the machine reached that stage, there was worry that the system was too fragile to handle the fan. Also, because only one SMA was being heated at a time, there really wasn't much chance of the heat in that area being any hotter then the rest of the room; thus, making the fan unnecessary anyhow and therefore, the fan was never attached. Once the machine was run it was obvious that the fan was not necessary.

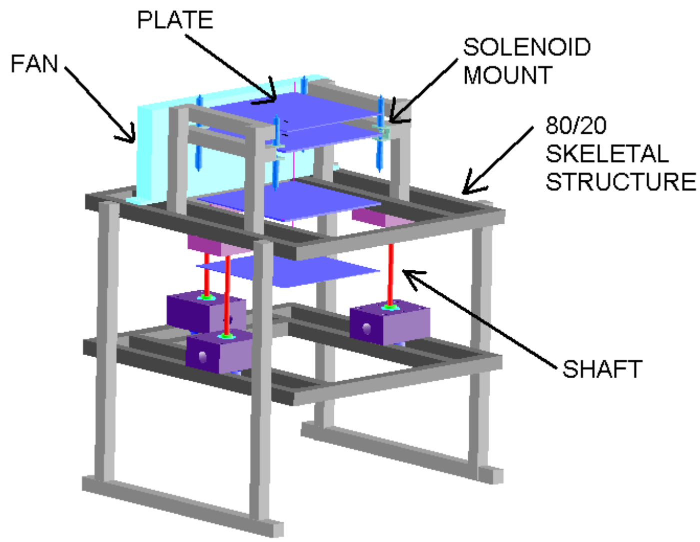


Figure 6-8. Physical display with fan

CHAPTER 7
TESTING AND RESULTS

As discussed in the previous chapter, testing was a vital process in the progression of the design of the 3D virtualization device. Each concept needed to be implemented into a smaller scale prototype before it was assimilated into the final design. This process was used from the time the first design concepts were thought up until the final tinkering of the finished product. This chapter further details the tests used to prove or disprove concepts, their results, and the adjustments that they led to.

Tests

Clamp System Tests

First SMA test

When an initial clamp design was complete and a basic setup existed, tests were run in order to evolve the clamp system design. A one-pin model, shown in Figure 7-1, was created to test the clamping process that will be vital to the visualization machine. The model tested the method of using clamps from a mechanical pencil to hold a pin in place. Pulling a cylindrical collar over the clamp closes it and locks the pin in place. The collar is pulled down though use of SMA wires. These wires contract when heated with an electrical current. Several methods of attaching the wire to the collar had to be tested. The most successful tests came by drilling holes through a thin rim on the collar, threading the wire through the holes and attaching the two ends to the bottom of the model frame. The ends of the wire were where the power attachments were made. The frame was designed on a CAD program and then created in a rapid prototyping machine.

The clamp was attached to the frame by being press-fit, and hot glue was used to hold it in position.

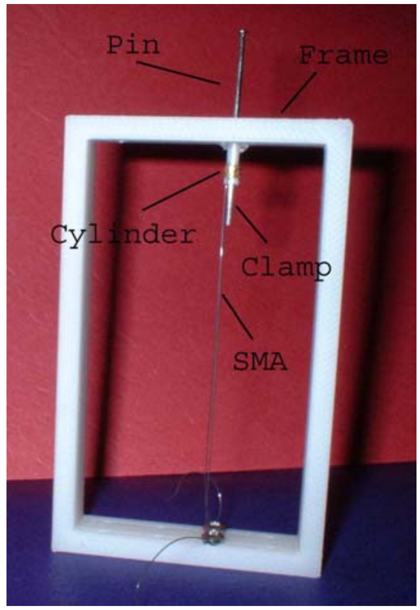


Figure 7-1. Clamp actuation testing model

This test officially proved that the SMA wire could be used to pull the freedom cup over the clamp and provide the necessary force to hold the pin in place. It also showed that the length of wire between the cylinder and electrical connection could be minimized to 3.5”. In the initial system, the wire was run to the cylinder and back again because there was no convenient way to place an electrical connection at the cylinder. It was found that the system remained functional when one of the sections of wire run from the cylinder to the electrical connection was replaced with a normal wire. This cut the amount of SMA wire needed in half.

Micro helix tests

Two Models were made to test the BioMetal Micro Helix in clamp actuation. Figure 7-2a shows the first model. The idea here was that the cup would be held stable in the plate and the micro helix would pull the clamp down into the cup, thus preventing movement of the pin. The second model shown in Figure 7-2b turned the clamp upside-down and held it stable within the plate. This time the micro helix pulled the cup down to tighten the clamp and prevent movement of the pin. While both actuators accomplished the desired task, the second model proved to be more reliable. Leaving the clamp loose, as it was in the first model, made the pin shakier. Also, when the pin was moved, the clamp maintained a better grip when it was positioned as it was in the second model.

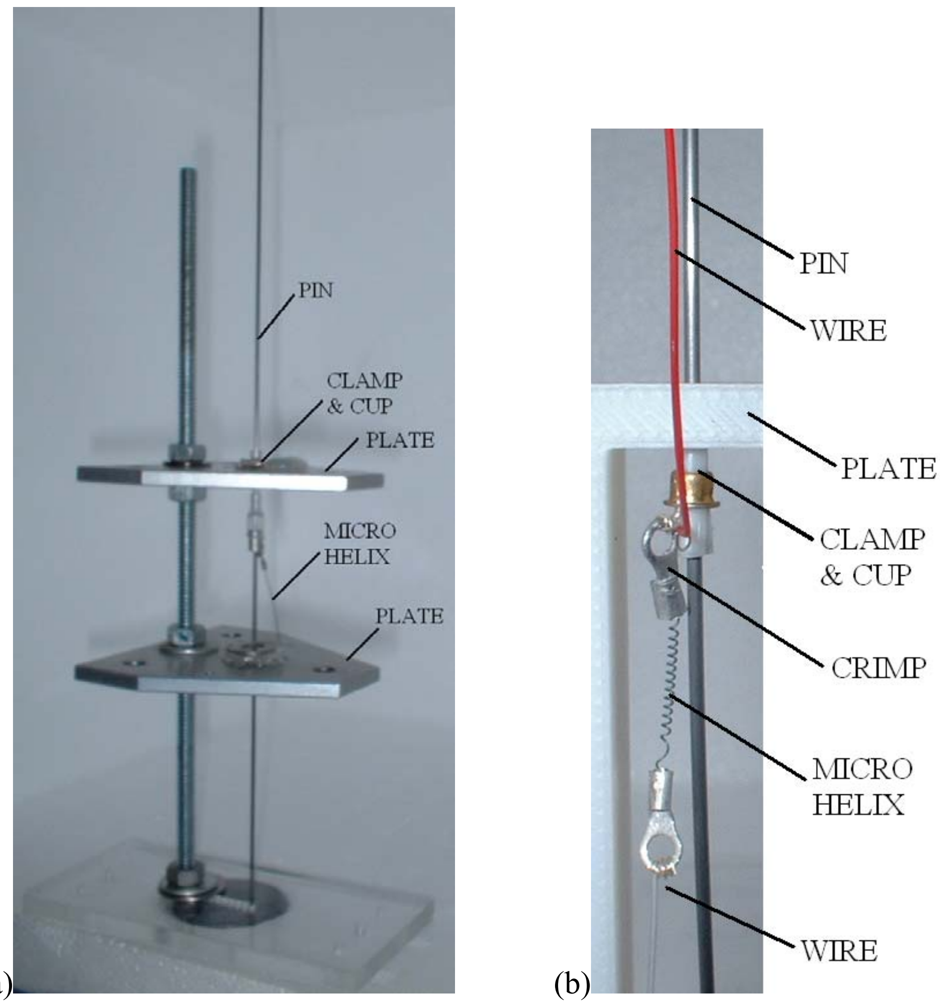


Figure 7-2. Micro helix tests (a) Helix model 1, (b) Helix model 2

Unfortunately, the micro helix design proved to be too costly for this project and focus had to be returned to the SMA wire design that was originally in place.

Electrical Tests

Raster Scan Test

A test was created in order to prove that the raster scan test would be capable of controlling the clamp and to make certain that some of the parts being used would fit the system properly. Figure 7-3 shows the setup for the test. Basically, a 3×3 grid of LEDs, each in series with a resistor, was used to represent the SMA's. The LEDs were wired to a power source in the pre-described raster scan method. The power source was wired to the grid through a board of opto-isolators that would actually be used in the finally machine. The opto-isolators were controlled by PICmicro 16F627 micro-controller. A keypad that was wired to the micro-controller could be used to make a specific pattern of LEDs light up. The micro-controller would determine what button was pushed, the corresponding pattern that went with it, and would control the flow of current so as to create the desired pattern.

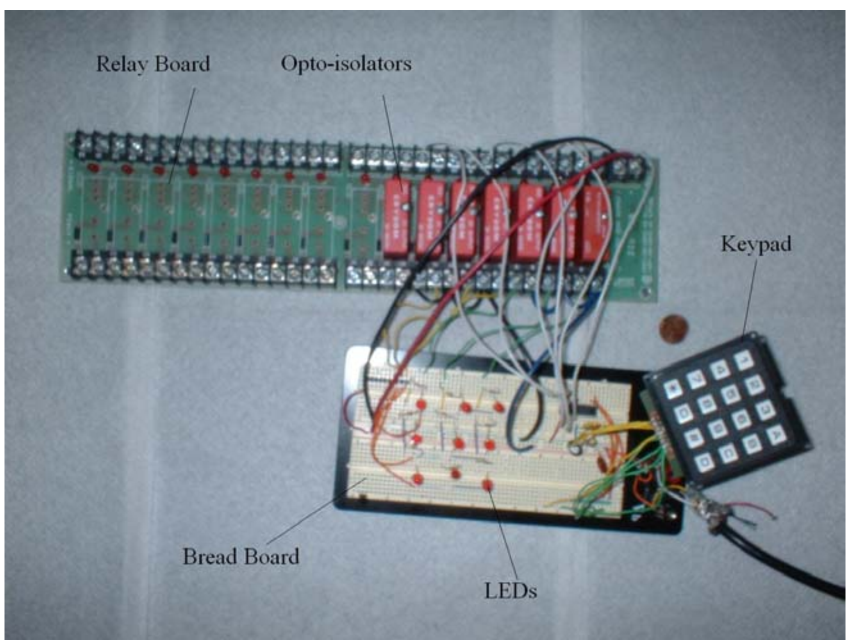


Figure 7-3. The raster scan test setup

The test provided to be a helpful lesson in using the parts system and setting it up. It proved that the system would work successfully. It also showed that many of the available opto-isolators either did not work in this type of system or just did not work at all.

Sensor Tests

Hall Effect

With initial plans of detecting pin positions with hall-effect sensors, an effort was made to find the best way to use the sensors. Two methods of pin sensing, based on the fact that hall-effect sensors detect a change in the surrounding magnetic field, were devised and tested, as seen in Figure 7-4. Five sensors were arranged on a proto plate in a manner similar to how they would be arranged on the bottom plate of the machine. The first and most convenient detection method involved placing a magnet on each sensor. When a metal pin was lowered in front of the magnet, the magnetic field would change and the sensor output would show the change had occurred. The second method involved placing the magnets on the bottoms of the pins. When the magnet would get near the sensor, the field change would be detected. The tests monitored how all the sensors reacted to the pins being at various locations, and how different magnet shapes, thicknesses, and locations affected them. A method had to be found that would have the most reliable outputs from the detecting sensor while not interfering with the surrounding sensors.

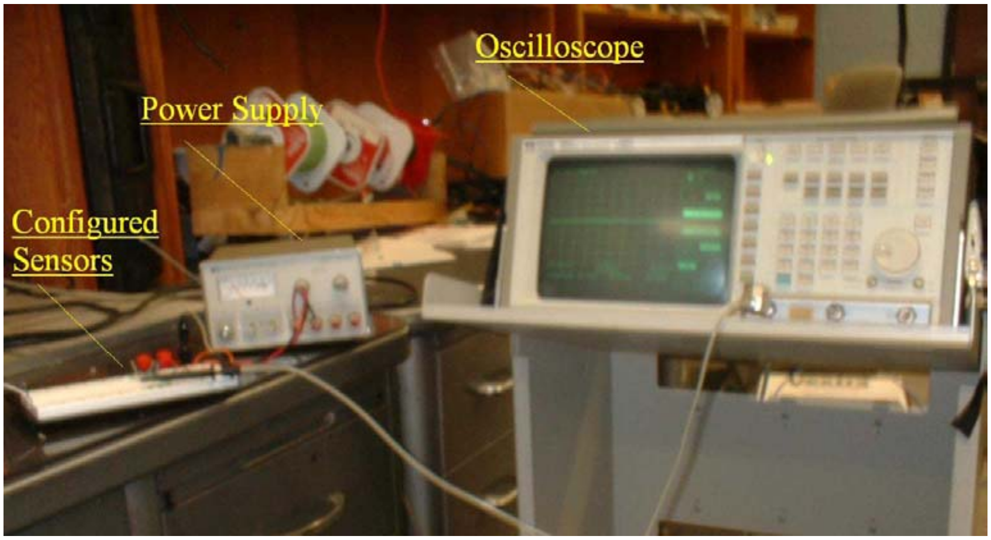


Figure 7-4. Sensor test setup

For the first method, while the sensor outputs did relay the field change, they did so weakly. This made it difficult to distinguish pin appearances from common noise in the room. With the machine requiring 900 sensors, the inability to distinguish noise from actual pin contact could lead to many problems. The second method worked perfectly. The presence of a thin rubber magnet was strongly detected by the significant sensor from a short distance and no other sensors were noticeably affected. It was decided that the second method would be used and 1/32" thick magnetic tape would be used on the bottom of the pins. Unfortunately, difficulties with attachment to the board and detection by the digital I/O led to changing the type of sensor used.

Contact Sensors

The contact sensor method was easily tested by using the GUI's sensor test button. The board was hooked up to the digital I/O with a ribbon cable and the test was run for several seconds. Different types of metal were touched to the various sensor contact points on the sensor plate and the GUI would say which sensor was reading contact. This test showed that solid pieces of metal were very unreliable when used to contact the sensors. Something more flexible was necessary and the steel wool proved perfect.

Testing the Steppers, Drivers, and Digital I/O

In the process of interfacing the computer with the machine, several tests were run to make sure parts were running correctly and more efficiently. The stepper motor used to move the bottom plate up and down was wired to a stepper motor driver, as seen in Figure 7-5, which was wired to the digital I/O, which was plugged into the computer. The motor's abilities (direction, speed, torque, step angle) were tested and modefied until it was running most efficiently. It was decided that the motor would be used with a step angle 7.5 degrees and would turn a shaft at 2/3 rev/s. A simple program was made for running the motor at its desired rates that would be called by the path planner.

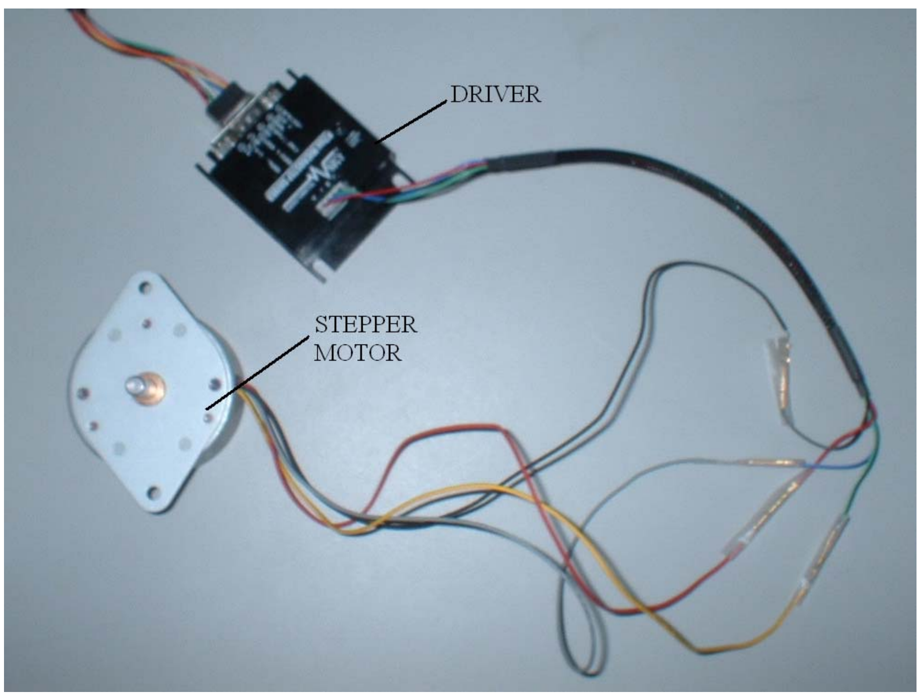


Figure 7-5. Stepper motor wired to a driver

The part of the path planner program that tells the pin display device how to shape itself was tested using the setup shown in Figure 7-6. A display was chosen on the GUI and when the "send" button was clicked, the stepper motor was run when the bottom plate was to be moving and an array of LEDs were lit to represent individual clamps being activated. The same setup was also used for testing the method of detecting pin placement on the pin display device and making the computer show the image. The stepper motor was run when the bottom plate would be moving and switches could be thrown to mock pins making contact with the sensors. A set of LEDs was used in series with the switches in order verify the flowing currents.

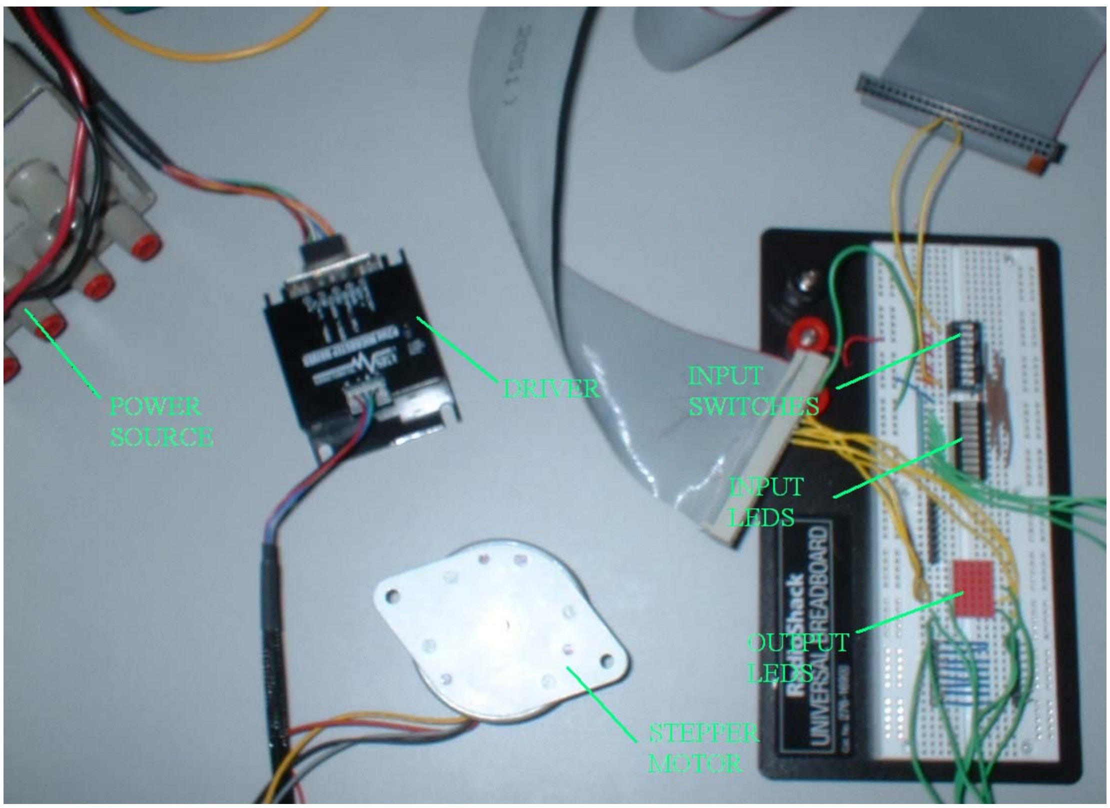


Figure 7-6. Path planner test setup

Final Results

During its assembly, the physical display, at best, could only be test in segments of the tasks that it would need to perform. It was not until the absolute completion of the device's assembly that either of the two main tasks could be run in their entirety. As expected, both the physical virtualization and virtual visualization tasks did not perform exactly as desired on their first runs, but both had correctable problems that were dealt with in the most efficient manner possible.

Physical Visualization

Because of the delicacy of the pin systems and the difficulty of putting them together precisely, it was expected that some of the pins systems would not function when physical visualization was performed. When the first tests were run far more pins malfunctioned than expected. Several varied shapes were attempted for physical visualization and only about 20 to 30 pins would work properly on each run. Some of the malfunctions were that the pins got stuck in a position height above where they were supposed to be, but an overwhelming majority of the malfunctions were that the pins were slipping and falling down to their lowest positions. Often the pins would visibly hold to their desired positions for a few seconds before falling loose. There are several reasons for this slipping:

- Pencil Clamps: The main cause of the slipping is the pencil clamps. While the clamps perform ideally as far as holding the pins when closed and letting the pins move freely when open, they are weak at toggling between the two and staying toggled. There is no real snap to hold the freedom cup into place when it has been pulled down to close the clamp. In all preliminary tests the cup reliably held clamps shut, yet the combination of actual tasks going on in the final assembly of the physical display reliably allow the clamps to reopen.

- SMA Wires: The delay in clamp release was congruent with the amount of time it took the SMA wire to cool off. Many of the pins could be seen dropping right after the SMA wire returned to its original length. It’s possible that the minor stretching of the SMA wire caused just enough force to be pushed on the freedom rings that they came loose. It’s also possible that rings just came loose more easily once the SMA wires were no longer pulling them down.

- Stepper Motor/ Shaft Systems: Pulsing the stepper motors caused a vibration of the physical display. It is possible the intensity of the vibration may be a result of the shafts not all being perfectly aligned.

- Friction Prevention: The prevalent problem that occurred in all the preliminary tests for the clamping system was difficulty of movement by the pins because of friction. As a result, there was an over compensation in the assembly of the physical display making a strong attempt to prevent friction problems. Such adjustments included shortening of the pin guides and using thinner boards. The thinner boards were too flexible. Each clamp system attached pulled on a board above it and a board below it. As the systems were installed, the forces on the boards changed and because they were flexible, their shapes changed as well. This would explain why the systems that were installed last seemed to work best.

- Diodes: In order to compensate for the lack of precision involved in the hand assembly of the clamp systems, each diode was bent to a relative degree to make each system taught. Why this worked well at first, many diodes slowly were unbent with each successive pulling of the SMA on each run.

Quick Fixes

Assembling the physical display was both expensive and time consuming. Making a major change to correct the pin slipping problems would have taken an impractical amount or more time and money. However, a number of *quick fixes* were thought up and applied to the machine with the intention of making the physical visualization work as best as was possible.

- Heat: It was thought that if the room temperature of that the SMA wire was kept at was made a little hotter, the wire wouldn't relax so much when it was deactivated and the freedom cup wouldn't be pushed loose so easily. Bright spotlights that generated a good deal of heat were placed around the display and some tests were run. The lights were not seen to have any affect on the wires or the display.

- Surface Roughening: An attempt was made to increase the friction between the pins and clamps. First starch was sprayed on a pin from an aerosol can and a test was run. No changes were noticed. Next hairspray was sprayed on a couple pins and a test was run. This time there was a noticeable increase in friction. Unfortunately, there was too much friction and the pins would get randomly stuck. Also, it was not possible to spray the entire pins, which had already been installed, so some parts of the pin were too loose and others too tight. It was also noticed that occasional sparks occurred on the sensor board and it would be a bad idea to be using an aerosol around sparks. Therefore, this idea was not taken any further.

- Activation Time: The time that current was supplied to each SMA wire was increased from 2 seconds to 3 and 2.5 seconds for several tests. The hope was that the increased time would tighten the freedom cup on the clamp and prevent easy loosening. There appeared to be a very minor increase in functioning pins, which may or may not have been a result of the increase. Therefore, the activation time was left at 2.5 seconds.

- Stepper Motor Speed: When the test was first run, the stepper motors were run at their fastest speeds for the entire test. The process was changed so that the motors ran at their slowest speeds when the pins were capable of being knocked loose (when the table was going down). The decrease in step size decreased the vibration intensity and appeared to double the number of functioning pins.

- Fidgeting: The crudest fix used was to fidget with each of the diodes that could be reached so that those clamps systems remained taught. This appeared to have a minor.

Figure 7-7 shows the result of a physical visualization test attempting to create a bowl shape with the pins. While a large percentage of the physical pins have fallen down by the end of the test, a slope towards the center of the grid is still noticeable. It is also noticeable that the number of functional pins per row increases with how recently that row was installed.

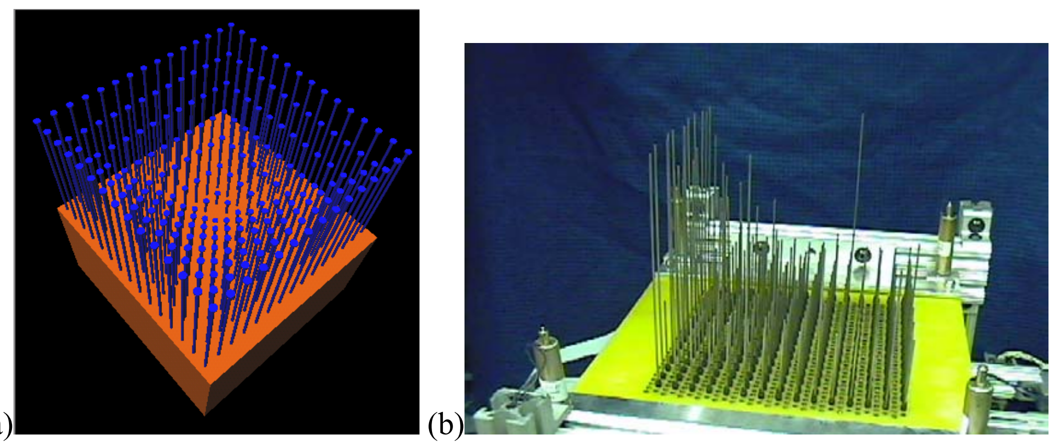
(a)  (b)

Figure 7-7. Results of a physical visualization test where (a) is desired product that was formed on the GUI and (b) is the final product produced by the physical display

Virtual Visualization

When the virtual visualization tests were first performed, there were two obvious problems observed. The first problem was that about half the pins were not being held in place while display read the positions of the pins. This was easily explained. Using a thinner ground board had again caused a problem. The board was being pushed down by the solenoids on its four corners and was bending in an upside down bowl shape. The pins closest to the corners were being held best, but the pins closest to the center were the loosest. This problem was exaggerated by the fact that the solenoids were too weak to push the ground board as much as desired. The second problem was far more difficult to solve. The patterns displayed on the GUI were far different from the patterns created on the physical display device. This was made more inexplicable by the fact that the sensing process had worked in all previous tests. It had worked for tests involving individual pins and multiple pins; however, it turned out that there was a particular arrangement of pins that confused the sensors, which by chance had not been tested. When any three pins that are touching the sensor board form an “L-pattern” (one pin shares the same row of a second pin and the column of a third pin where the second and third pin have different rows and columns) the computer will sense a fourth pin at the column of the second pin and row of the third pin. This is a special case in the raster scanning process where the arrangement of pins allows a current to slip to a line where it should not be. It can occur in the four patterns displayed in Figure 7-8. The sensing process involves the pins maintaining contact with the sensors from first contact until the end of the process and therefore this special case arrangement is destined to occur for every single time this task is run.

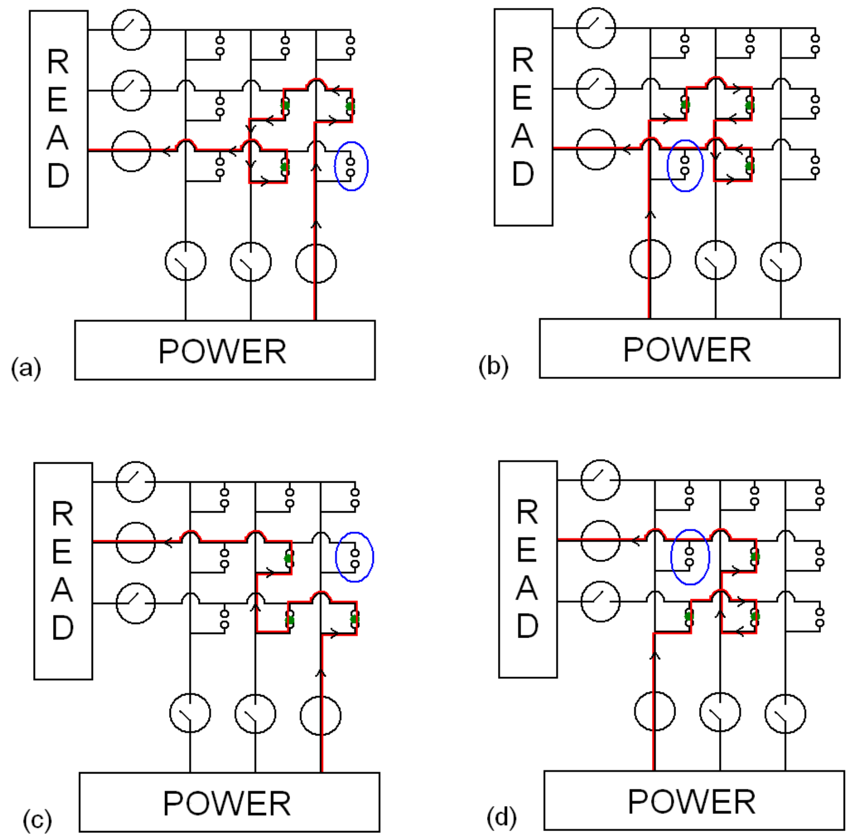
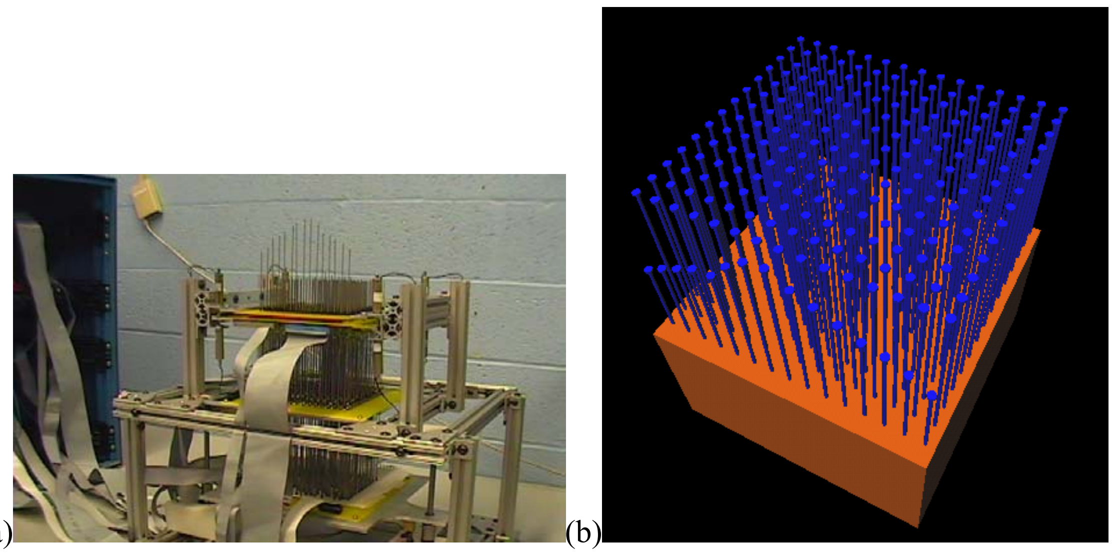


Figure 7-8. The four possible arrangements for incorrect sensor readings where the red line is the path of the current, the arrow heads are the direction of the current, the green dots are where the pins contact the sensor board, and the blue circle encompasses the surface that will be read as having pin contact when there is none

The pin hold process could easily be fixed by placing a wedge in between the top board and the ground board so that the ground board is pushed down and the pins are held for the entire time the task is run. The stepping angle of the stepper motors was also decreased to its smallest possible amount in order to increase the strength of the motors and decrease the speed, which in turn decreased the vibration of the system. This kept loose pins from falling and allowed the sensing board to move the tightest pins with more ease. Unfortunately, the special case for the sensing process could not be completely fixed. Because the problem does not occur when only scanning a single row, it was decided that the test of virtual visualization would only test the front row in order to prove that everything else works. The sensors of all the rows except the front were covered with a sheet of paper and thereby rendered ineffective. Tests were then run for just the front row. These tests provided reliably identical images between the pattern of pins on the physical display and the GUI, as shown in Figure 7-9. Occasionally, one or two pins would go undetected due to those pins not lining up correctly with their assigned sensor on that run, but most tests were reliable.



(a) (b)

Figure 7-9. The results of a virtual visualization test where only the front row was tested; (a) shows the initial arrangement of the physical pins and (b) shows the virtual results (there is a difference in the pins behind the front row because the sensors for those pins were turned off and the computer assumed that those pins were at their highest positions)

CHAPTER 8
FUTURE WORK

This chapter presents possible solutions for previously mentioned problems, methods for improvements that could help the design, and general advice for future work on similar three-dimensional displays.

General Changes

If this machine was to be remade there are some very basic changes that would improve it a good deal.

- Use stronger stepper motors with smaller step angles. The smaller step angles would allow for smoother motion and decrease the vibration of the system. Increasing the strength would prevent jamming of the shaft system.

- Use stronger solenoids. While the solenoids that were used provided the desired force for minimal movement, the movement that was needed was greater than expected. Because the solenoids shafts get weaker as they get further from the shell, they provided insufficient force at times.

- Use thicker boards, especially for the ground and power boards. It is recommended that the current thickness of 0.062” be tripled or quadrupled. It was seen that the worries of pin friction were overcompensated for and the additional thickness would result in a significant increase in stiffness that would prevent bending.

- Lessen the wiring. The control box was initially wired to control 900 pins and 900 sensors, but is now only used for 225 pins and 225 sensors; however, because the wiring was still functional and there was no reason to fix something that wasn’t broken, nothing in the control box was changed. This means that there is more space and parts being used than is necessary. A second machine could use a smaller control box with less terminal boards, opto-isolator boards, ribbon cables and wires. Also, one of the digital I/Os could be eliminated.

- Use a pin made from a grittier material. The pins were too loose and a pin with a rougher surface likely would have had more surface friction with the clamp and held its position better. Another option would be to lightly spray all the pins with a lacquer or hair spray before installation.

Major Changes

While this project delivered a lot of important information in the creation of a 3D Visualization Display, it is unlikely that the current machine (even in perfect working order with all the general changes added) could properly serve the purposes that it has been created for. There are still improvements that need to be made within the physical display that will make the machine more exact, reliable, and efficient. These are some ways to upgrade the display and methods that may make those upgrades possible.

Clamping

The most necessary change for future work would be to evolve the clamps. Future devices need clamps that have a more definitive toggle. Some type of snap or bump-to-groove setup would probably work well. The pre-designed clamps mentioned in Appendix A would probably be sufficient. Whatever clamp is put into use, it is necessary that it remain tightly in the position it has been toggled to until toggled again.

Early in the assembly process, another possible clamp system was developed. At the time, it seemed far more complicated and was discarded; however, after the complications of assembly, it seems that it may be less complicated and has a more effective toggling action. The idea was that one could actuate an entire row at once and an entire column at once with pulleys. To lock a pin at position *(i,j)*, the following is performed:

1. Actuate every pin in row i.
2. Actuate every pin in column j
3. De-actuate row i and column j

Figure 8-1 exemplifies this procedure, where it is important to note that the left block moves with the pins' rows and the right block moves with the pins' columns. Before the procedure begins, all the pins look like *(a)* in the figure; there is slack on the pulley. After step one, all the pins in row *i* are taut like *(b)* while everything else still looks like *(a)*. After step two, most of row *i* hasn't changed and most of column *j* goes taut like *(c)*; however, the pin at *(i,j)*, which was already taut, pulls the pulley and collar down into the locked position to look like *(d)*. After step three, all pins return to *(a)* except for pin *(i,j)*; it goes slack, but it is locked until all the pins get reset. As for resetting, it could still be done in the same fashion currently being employed.

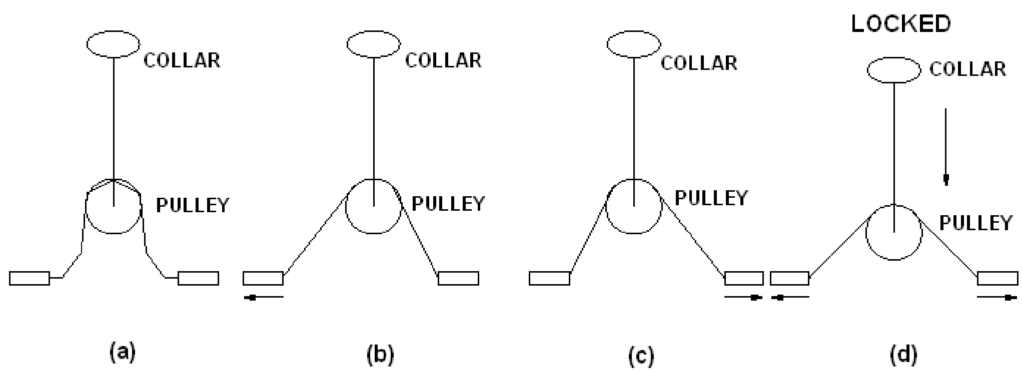


Figure 8-1. Pulley system of clamp actuation where the left block moves with the pins' rows and the right block moves with the pins' columns

Sensing

A possible solution for the special case that prevents sensing the pin positions correctly involves rebuilding the system as follows. The physical display would only change in that the sensing board would basically be split into two boards, a board for pushing the pins and a board for sensing them. The pushing board would be identical to the current sensing board but would have no sensors (basically is would be just a plain flat plastic board). The new sensing board would have holes where the sensors are on the current sensing board so that the pins can pass through. The sensors on this board would be along the side of the holes or possibly in the form of brushes that would not impede the passing of the pins through the holes. Both boards would be able to move up and down the same distance that the current sensing board moves. The new sensing board would merely rest upon the pushing board any time that the pushing board would be in use. When sensing is to occur, the pushing board would remain at its lowest position and the sensing board could be raised up by itself. This would improve the system in that the physical display of pins would not be destroyed during sensing as it is in the current device. The major change would be that each pin would have two points that would get read as opposed to the current design where each pin has only one. The read points could be made by adding a magnet, steel wool, or whatever material the sensor in use is capable of detecting. Each pin would get read at its lowest point and a specified higher point. In the current design, the sensing board reads one column at a time. The special case occurs when a pin is sensed at an incorrect row in that column. Therefore, the new design would have the second read points placed at equal distances from the first read point on the columns but different distances on the rows, as shown in Figure 8-2. This setup will allow contact to occur at specific points in time rather than for the remaining amount of time. The computer will know that there need to be a specific amount of time between contacts and should it experience more than two contacts, the correct two had a specific amount of time between them. The pin would be place at the first of those two. This will make it far less likely that the special case will occur and on the rare occasion when it does, it will not be able to occur at the second reading because of the different heights.

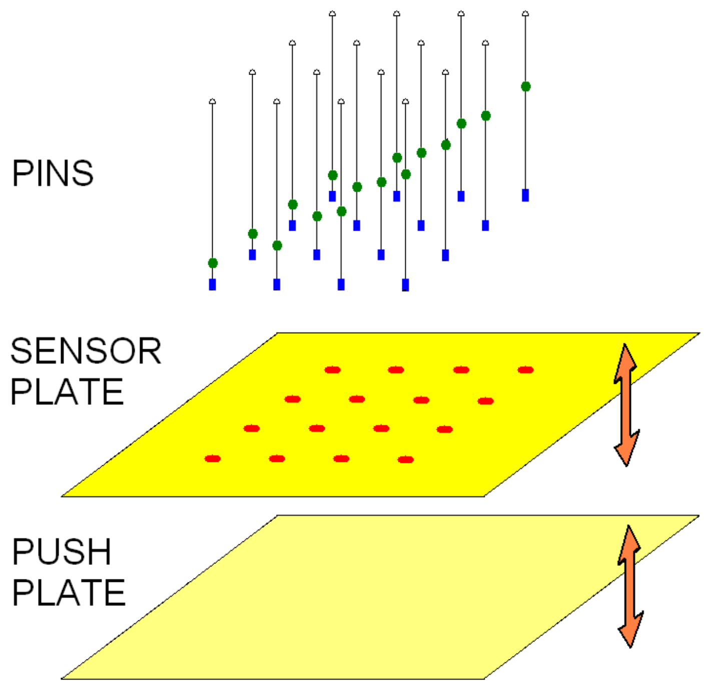


Figure 8-2. A two-level sensor reading system in a raster scan arrangement where the red ovals represent sensor holes, the blue squares represent the single-level first read points, and the green dots represent the multi-level set of second read points

Conclusions

The following conclusions can be made as a result of this development project:

- Shape memory alloy wires were capable of working a clamp system for a grid of closely spaces pins
- The speed of the physical visualization process was most dependent on the time it took to activate the SMA wires which was about two seconds per wire
- The speed of the virtual visualization process was most dependent on how fast the stepper motors could move the sensor plate from its lowest position to its highest position
- The clamps used were capable of holding the pins with the necessary amount of friction
- The toggling system used by the clamps was completely inefficient as the brass freedom cup slipped far too easily on the clamp

- A single level of contact sensors could not be used to reliably detect a grid of objects when wired in a raster scan arrangement (while a second level of sensors might correct that problem)
- The sensor arrangement was capable of detecting a single row of pins with at least 80% accuracy at a reliable rate
- The computer driven by the GUI and path planner programs was capable of directing all the parts being controlled (motors, solenoids, sensors, opto-isolators) as fast as was necessary

Opinions and Personal Advice

The clamping system requires far too much precision to be assembled by hand and provide reliable results. Finding a more mechanical method of assembly (perhaps from another machine) would not only provide a more effective device, but also allow for a tighter packing of the pins. In fact, the miniature scale of parts being dealt with in this project is so small that an argument could be made that the best route of design would be through use of microfabrication.

The greatest possible improvement that could be made to this device would be to make the clamping systems modular. The machine would simply be far more efficient in assembly, repair, and maintenance if the clamping system could be plucked in and out of the display at any given time without affecting the surrounding parts.

APPENDIX A
DEVELOPMENT OF THE FIRST PIN CLAMP

This section of the appendix describes the creation of a clamp from design to actual creation. The design was eventually scrapped for the use of a pre-made mechanical pencil clamp.

Home design

With a basic structure for the actuation process established it was necessary to create a more detailed design of the clamp. The top cylindrical section of the clamp design, pictured in Figure A-1, known as the “head”, serves as the attachment that will ground the clamp to the top table. This piece will be pressed into the table and will be the only part of the clamp that does not move. The pin will go through the hole in the center of the head. The hole will be large enough that the pin will be able to move freely through it.

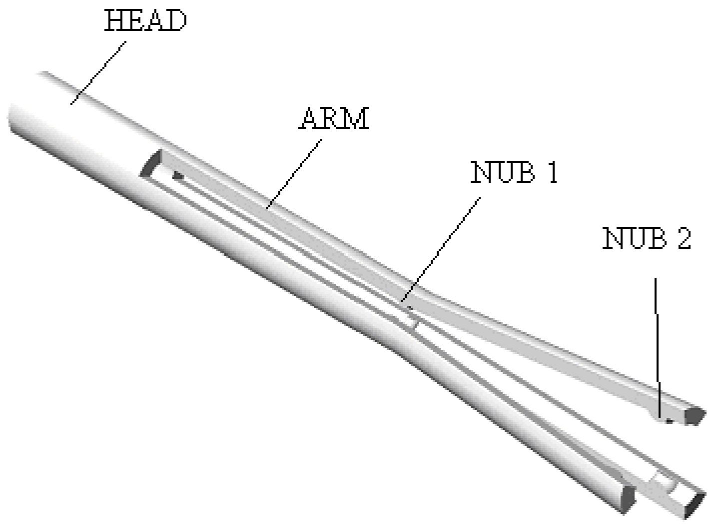


Figure A-1. Initial clamp design

Extending from the head are the clamp's "arms." These perform the actual clamping action and are where all the actual bending will be occurring. In deciding the number of arms necessary, it was realized that having two arms would allow for slipping of the pin in some directions tangent to the axis while having three or more arms would keep the pin on a single path. In order to keep manufacturing time and complexity to a minimum, it was decided to have three arms.

Each of the arms has two bumps extruding toward the center (where Nub 1 is the top bump, and Nub 2 is the bottom bump). At steady state the diameter of the free space in-between the three Nub 1's is smaller than the diameter of the pin. Therefore, when the pin is inserted into the clamp, Nub 1 on each of the three arms will be pressing against the pin, preventing it from moving.

When the collar is pressed in between the circle of Nub 2's, the arms will be extended further in an outward direction. The second set of nubs will hold the collar in place so that the arms remain open. The first set of nubs will have been pulled far enough from the center that the pin will move freely. Heating a SMA that is attached to the collar will cause the collar to be pulled from the clamp and return the clamp to its previous state.

Therefore, pressing the collar into the clamp allows for free motion of the pin, and pulling the collar out of the clamp prevents motion of the pin.

Finite Element Analysis

The initial design was given dimensions that were convenient for use in the parent design while still realistic for manufacturing. With the basic shape of the pin clamps decided, an FEA analysis could be used to parameterize the dimensions. The results would be used to derive the final design dimensions. The dimensions analyzed revolved around the initial dimensions.

Test 1

The first decision that needed to be made was what material the clamps would be made from. For manufacturing purposes, it seemed most practical to make the clamps either out of a plastic or a metal. Therefore, an analysis using the initial clamp dimension was performed on a clamp made from each material where delrin was the plastic used and general isotropic steel, shown in Figure A-2, was the metal used. The analysis determined the amount of force that the clamp would return when the nubs were displaced a common amount (0.025”). The analysis showed that the plastic returned a force unacceptably small force while the steel return a more suitable force value that was 80 times greater than the plastic. This made steel the definitive choice for material.

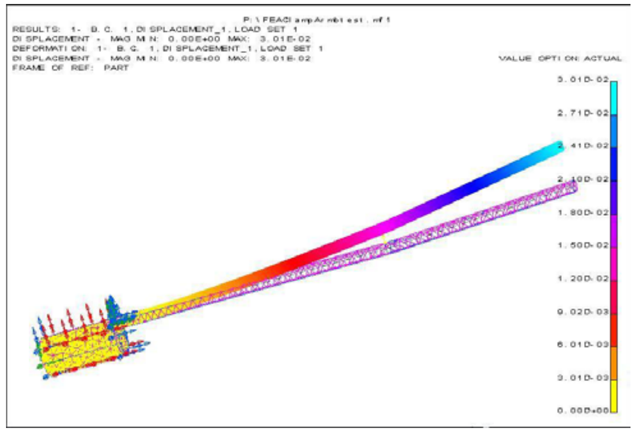


Figure A-2. FEA analysis for material choice

Test 2

The next analysis was performed in order to determine the size and placement location of Nub 1 on each clamp arm. This test used a constant beam cross-section while varying the location of the nub. A beam analysis was performed on each of eight possible locations for Nub 1. The tested locations, or nodes, were spaced 0.125" apart, as presented in Figure A-3, where Nub 1 is at the head of the clamp. The analysis was performed by varying the force input to each nub location, then, in turn the maximum stress and displacement of the nub was output. The best location would have the greatest nub displacement, while the max stress was under 29,000psi (the stress level when fatigue begins to set in) and the force from each arm was about 1/3 to 1/9 lb. The best placement proved to be 0.75" from Node 1 at the start of the arm.

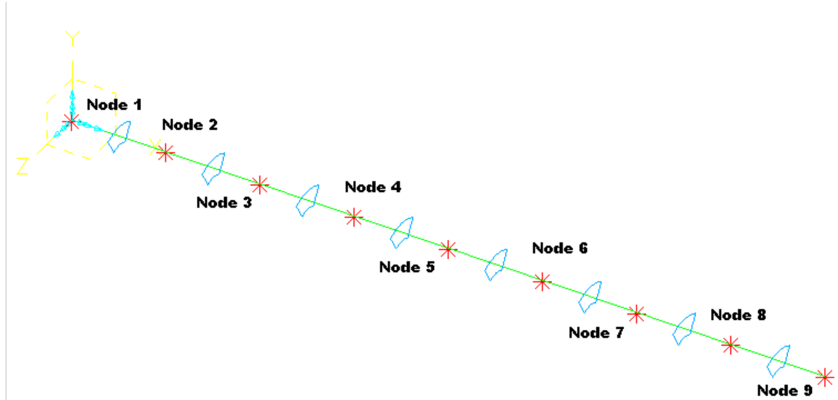


Figure A-3. Node placement on beam analysis for Nub 1 placement

Test 3

Thirdly, a test was performed to see the effects of increasing the cross-section. While increasing the cross-section would be detrimental to the parent design (because the pins would have to be spaced further apart from one another), this analysis would show if the benefits of increasing the cross-sectional area would outweigh the negatives. The cross-sectional area was enlarged by increasing the outer diameter of the clamp arm only. Like the previous analyses, this analysis was performed by inputting different forces at Nub 1 and outputting the maximum stress and the nub displacement. Using the previous analysis as a starting point, nub locations tested were placed around 0.75". The analysis showed that increasing the outer diameter actually had negative results and increased the max stress. This made sense as the extra material would make the arms stiffer and thus create greater difficulty in reaching the desired displacements.

Test 4

When it was realized that the cross-sectional shape would be inconvenient for the manufacturing process, the cross sectional shape was changed from a tube with triangular slices removed to a tube with rectangular sections removed. This new cross-section could easily be achieved by slotting the tube axially with a saw blade. Test 2 was repeated on the new cross-section, however, the previous results allowed the testing points to be narrowed to the most successful points of the previous analysis. The results provided the same peak points while showing the design would be more helpful to the overall needs of the design.

Test 5

When it was realized that the steel rod was most commonly found in fractional units rather than decimal the outer diameter was changed from 0.1" to 3/32". Test 4 was repeated and surprisingly, the results were almost identical to those of Test 2; therefore, Nub 1 was placed at Node 7 (0.75" from the head of the clamp).

Test 6

The final decision was the placement of Nub 2. An analysis was performed using the same process followed in the previous five tests on a beam with the same cross-section as that of Test 5 where a fifteen-degree outward bend occurs at Node 7. Points were tested at four nodes placed 0.125", 0.25", 0.5", and 0.75" from Node 7 as shown in Figure 16. It was decided to place Nub 2 a distance of 0.5" from Node 7 based on four concerns:

1. Make certain the max stress is under 29,000psi
2. Try to have force of about 1/3lb or more on the cylinder
3. Make certain the displacement at Node 7 (location of first nub) can be greater than 1.25E-2"
4. Location of the second nub will provide adequate room for the cylinder to fit between while still not touching the pin

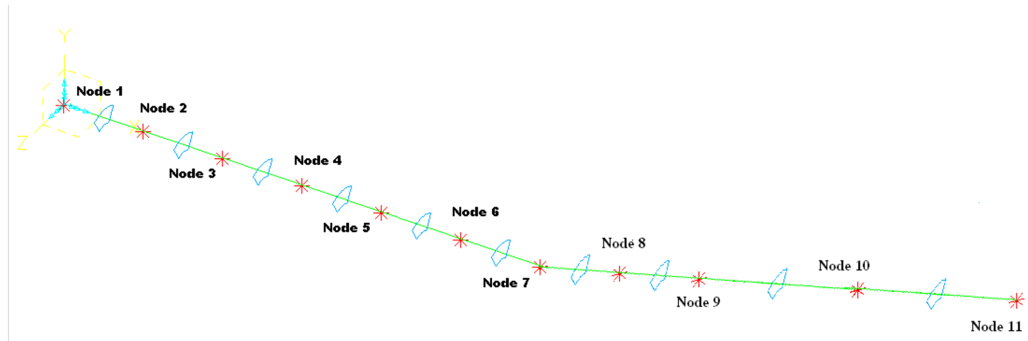


Figure A-4. Node placement on beam analysis for Nub 2 placement

The Clamp Manufacturing Process

The initial idea for the manufacturing of the clamps was to make it out of a steel rod. While it was preferable to start with an already hollow tube, no tube mills could be found that made steel tubes with the exact desired dimensions (OD=3/32" and ID=0.05"). In fact, it was difficult to find a steel rod with an outer diameter as small as 3/32". The softest most manufacturable steel rod that could found at the desired size was drill rod made of type A-1 steel. The drill rod was hollowed out with a drill bit (OD = 0.0492") in a lathe.

Next the three arms could be cut out of the hollow drill rod by placing three slots along the centerline of the rod in 120-degree increments. The hollow rod would be slotted through use of a computer numerically controlled (CNC) Mini-mill. Attached to the mill's moving x-y plate was an indexable fixture with a collet in it. The collet would hold one end of the hollow rod and the fixture would allow for rotation of the rod after each slot. The other end of the rod would be held in a metal block that was also attached to the moving x-y plate. The end of the rod would be placed in a hole in the metal block. The placement would not prevent movement in the direction of the cut feed (that was done by the collet), but it would prevent motion in the directions that would allow for bending of the rod.

However, it was discovered that the bit used to hollow out the rod could only clear out a depth of about 3/4" on each end of the rod (1.5" total). The slotting process required a hollow rod with 1.25" for cutting and 1/2" at each end for clamp-to-blade clearance. This meant that the drill rod could not be used for slotting.

The best solution was to use stainless steel tubing for the slotting. The inner diameter was larger than would have been preferred (ID=0.538") and the stainless steel (90 Brunell hardness) was much harder than the drill rod.

In case this method did not work, another method would be using the drill rod. Rather than hollowing out the rod, a center hole would result from the intersection of the three slots placed on the mini mill. The method is less preferable because the three arms would have flat inner faces opposed to the curved faces resulting in the previous method. Having curved faces gives the clamps a greater contact area with the pins.

Fortunately, the stainless steel tubing could be slotted by the CNC machine; however, a slow federate had to be used. Three-inch slots were placed along the sides of 3.5” long tubes. The slotted tubes could then be cut in half for the creation of two clamps. A mandrill was designed so that the slotted tubes could be given the desired bends. The mandrill was rapid prototyped using a FDM prototyping process. It functioned as a plastic shell where the slotted tube was placed inside the mandrill and when pressed in a vice, the tubing was bend. The dipping process was performed successfully. This involved dipping part of the clamp in a primer, and once dry, dipping the primed portion in a plastic. It was found that to get the desired thickness of plastic, it is best to dip the clamp in plastic multiple times. Figure A-5 shows the first completed clamp prototypes. Figure A-6 shows the evolution of the manufacturing process in the creation of the clamp

Figure A-5. Completed clamps

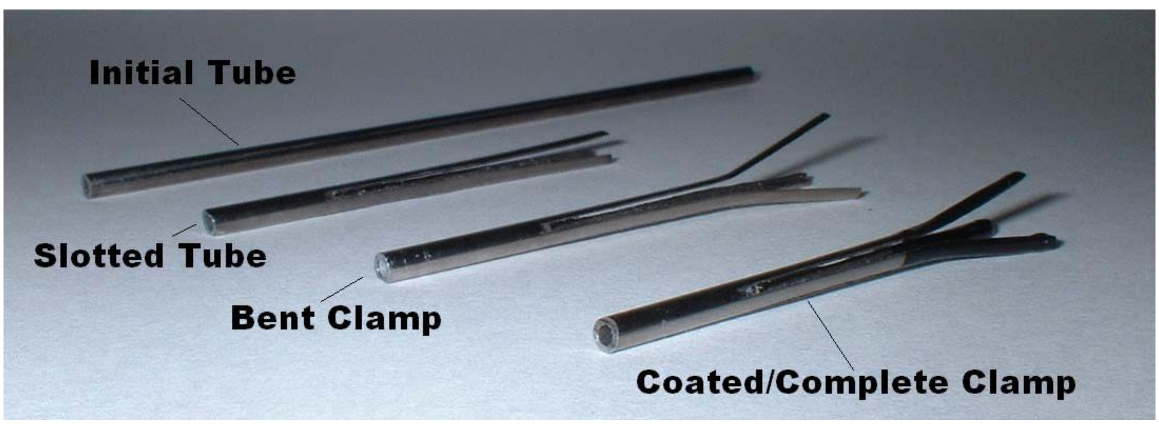


Figure A-6. Evolution of clamp creation

Sample clamps were made in order verify this process. The first step involved slotting the tubes so that they had arms. The arms were then stamped over a mandrill, which bent the arms into the desired shapes. Finally the arms were dipped in a coat of plastic so that they had the desired grip.

For the stamping process, a mandrill was designed and rapid prototyped using a FDM prototyping process. While the plastic mandrill was proven to be capable of performing the desired bends on the slotted tube, it began falling apart after four uses.

The dipping process involved dipping part of the clamp in a primer, and once dry, dipping the primed portion in a plastic. It was found that to get the desired thickness of plastic, it is best to dip the clamp in plastic multiple times. Figure A-7a shows the first completed clamp prototypes. Figure A-7b shows the evolution of the stainless steel tubing into a completed clamp.

(a)

(b)

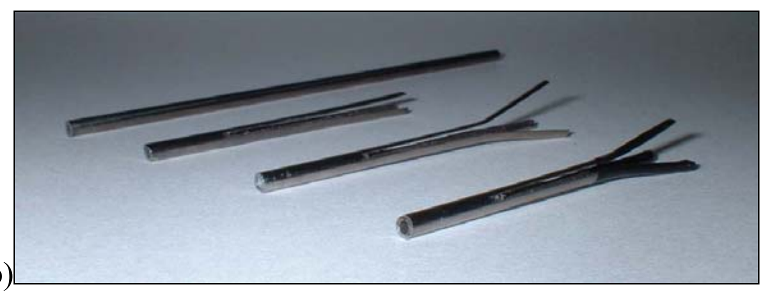


Figure A-7. Manufactured clamps (a) Completed clamps, (b) Clamp changes through production

APPENDIX B
THE RASTER SCAN TEST REPORT

It was decided that the number of controller outputs could be minimized by wiring the actuators with a raster scanning technique, which will be explained in further detail later in the report. This form of wiring would require the use of opto-isolators. Combining the fact that the relay-boards that were on hand held a maximum of sixteen isolators with the desired size of the pin array, it was decided that the next machine would have a 30x30 grid of pins with the remaining isolators left open for other necessary connections. Therefore, it would be necessary to have a circuit that would control a 30 x 30 array of Shape Memory Alloy (SMA) wires. This decision was followed by a project where a scaled down model (3 x 3) was created in order to verify the circuit design for the actual machine was acceptable.

The system was modeled with a 3 x 3 array of LED's where LED's acted as the SMAs. A keypad was used to tell which lights to light up. Figure B-1 shows the position of the lights and their labels. The keypad contained keys with the numbers one through nine. Pressing Button One would result in L1 lighting up. Pressing Button Two would cause L1 and L2 to light up, and so on, until pressing Button Nine lights up L1 through L9 (all the LED's).

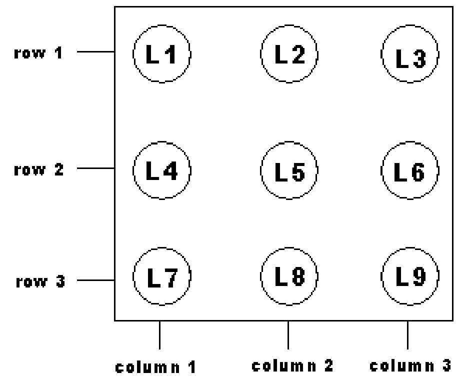


Figure B-1. Configuration of LED's

The raster scanning technique makes it so that only 2n controller outputs are needed for any nxn array of actuators. In this case, nine LED's were capable of being lit by six controller outputs. The system was created by configuring the circuit so that each LED was in series with all the other LED's in the same row and column. This configuration meant that only 6 outputs were needed for the model (3 grounds for the columns and 3 voltage sources for the rows). In order to make certain the desired LED display occurred, only one column could be lit up at one time; however, the lighting of each column would occur so quickly that the human eye would perceive all the columns as being lit up at once. Only one ground would be given to any column at any time, thus allowing for only one column to be lit up at any time. The process would begin by the first column of lights being given a ground and current being sent to the appropriate rows. The ground would then be shifted to the second column and its appropriate rows would be given current. Finally, the third column would be given the ground and once again the desired rows would be given power. The process would occur so quickly that it would need to be repeated hundreds of times before a human eye would notice any light, and at that point it would appear that all the lights were being lit simultaneously. Figure B-2 shows the wiring diagram.

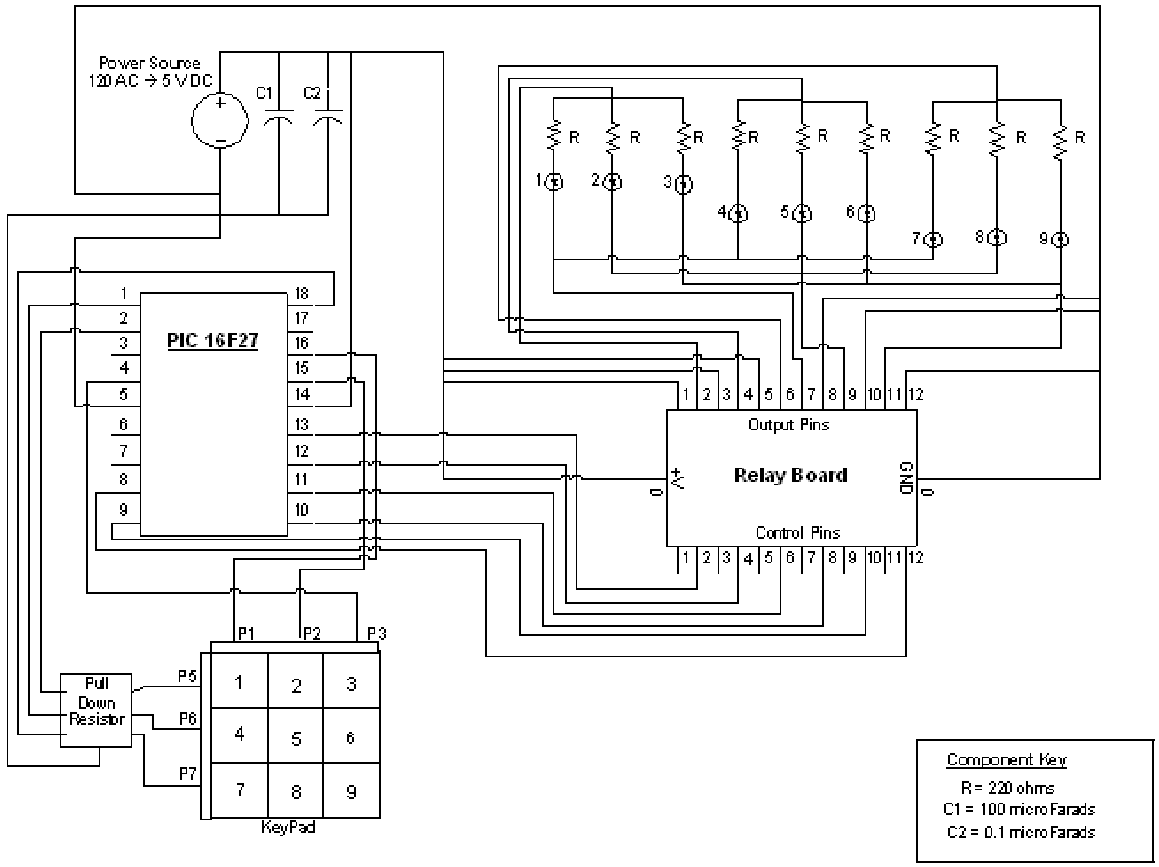


Figure B-2. The Wiring Diagram For the LED Display

The System, displayed in Figure B-3, was powered by an <u>APX Technologies Inc. class 2 power supply</u> and composed of the following items.

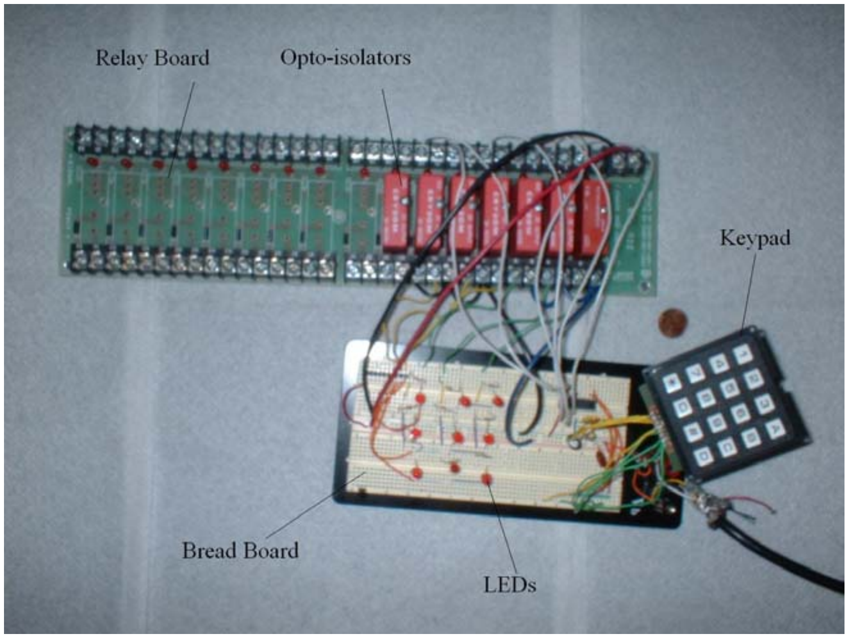


Figure B-3. The Assembled Electrical System

The supply sent a line of five volts and a line of ground to a JAMECO JE24 breadboard. The breadboard contained the LED display, the microprocessor, and the keypad.

The Velleman Matrix Type Keypad had six lines: a line to each of the 3 columns, and a line to each of the three rows. Pressing a button created a short circuit between the wire connected to that row and the wire connected to that column. Finding which button has been pressed was accomplished by performing a polling technique. The column lines of the keypad were attached to output pins of the microprocessor and the three row lines were attached to three input pins of the microprocessor. When a current was sent to the column of a button when it was pressed, the input pin attached to the button's row read a high value; otherwise, the pin read a low value because a pull-down resistor was attached to all the input/row lines. The pull-down resistor prevented floating and kept the input/row lines low when no button was pushed. The processor performed a button-by-button search in order to find which had been pushed. First a high output would be sent to the column being checked. Then row inputs were read. If a high voltage were found entering a pin, the processor would know that the button at that row and column had been pressed and the LED display was configured appropriately. Then the processor would continue polling the columns until a button is pushed again.

The Potter and Brumfield relay board along with six CRYDOM ODC5 opto-isolators were used in order to keep the system as close to the 30 x 30 system as possible. Attaching the items together created a six-relay system. The system ran on five volts drawn from the breadboard. Six output pins from the microprocessor were attached to six control pins on the relay board. The relay board had six outputs; each attached to an input to the LED display. Three of the relay board's outputs were in series with grounds and the other three outputs were in series with a voltage source (the ground and five volt source were drawn from the breadboard, but this will be different for the case of the 30 x 30 array of SMAs). However, a current could only flow between the relay board output and the attached ground or voltage source when the attached opto-isolator had been activated. When the microprocessor wanted to activate an output on the relay board, it would send a low output to a particular control. This would in turn activate the attached opto-isolator, which in turn would allow current to flow between the attached output and ground/voltage source. Ground outputs were connected to the columns in the LED display and voltage outputs were attached to rows of the LED display. When the microprocessor triggered a ground output and voltage output on the relay board, a light on the LED display would light up at the corresponding row and column.

The PICmicro 16F627 was used to control all actions in the system. Six outputs from Port B were connected to the relay board and used to control the LED display. Three outputs and three inputs from Port A were used to poll the keypad.

The microprocessor found the button pushed and created the LED display as desired on each test as shown in Figure B-4 and Figure B-5. The system design and coding algorithms used on the model allow for easy conversion to an n x n system of actuators, where n is the number of rows in the array (n is also equal to the number of columns).

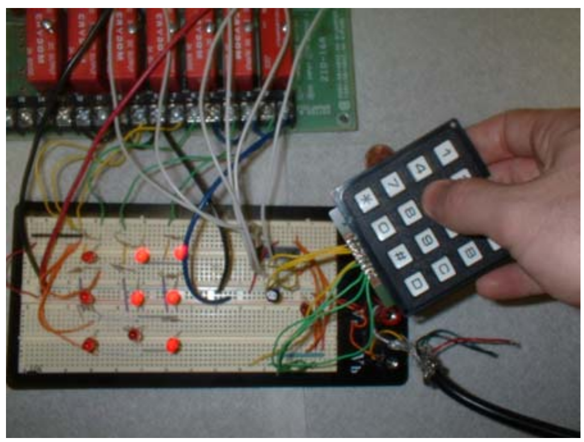


Figure B-4. Five LEDs Being Lit

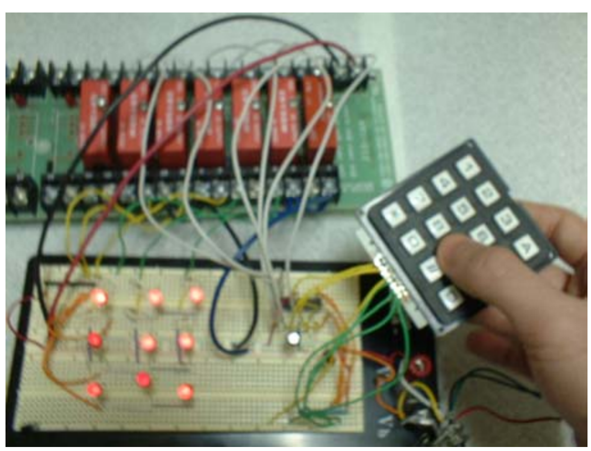


Figure B-5. Nine LEDs Being Lit

One major concern that arose in the testing of the system model was that current was going through LEDs that should not have been receiving any. It could be seen that any column or row that had at least one LED lit up would result in all the LEDs in that column or row emitting some amount of light. The light from the “misfiring” LEDs could be decreased to nearly undetectable levels by adding delays to the code when a column is lit up and/or turning off all the LEDs before displaying the following column configuration. Adding a delay to the time that the lights remained off between column displays also decreased the amount of undesired emitted light. A pull-up resistor was also added to the inputs of the LED columns, but this failed to have any effect on the system. The reason for this undesired light was not clear but the following are possible:

1. The opto-isolators could not switch as quickly as desired.
2. The quick change of outputs created a leak from one display to another on the column outputs.
3. Some item in the breadboards allowed for a slight amount of grounding to occur in the columns at all times.

Some other important occurrences and observances noted for future work include the following:

1. Some opto-isolators never worked.
2. The opto-isolators only allow current to flow in one direction through the output lines.
3. Continuity never occurs between the opto-isolator outputs

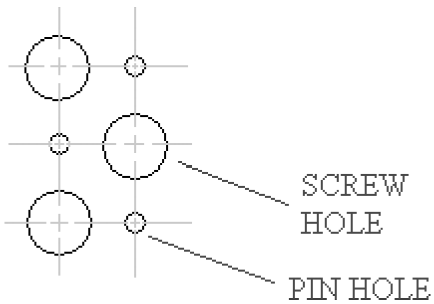
APPENDIX C
ODDS AND ENDS

Hole Pattern

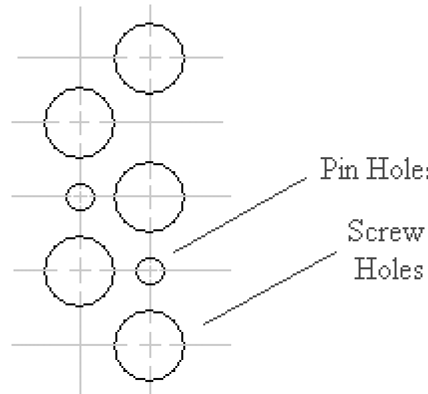
The design of the hole pattern began while the clamp design still involved using a V-shaped strand of SMA wire that would be attached on opposing ends of the pin. In order to form an idea of the machine's shape and the placement of its parts, an initial decision needed to be made on the hole patterns for the pins that would pass through the spinal plates. The patterns had to be made based on the following desires:

1. There can be no overlapping parts
2. Have pins as densely packed as possible,
3. Use a symmetric hole pattern,
4. Allow as much open space as possible for convenience during assembly and maintenance, and
5. Remove as little as possible from the plates to prevent bending, fracturing, and breaking.

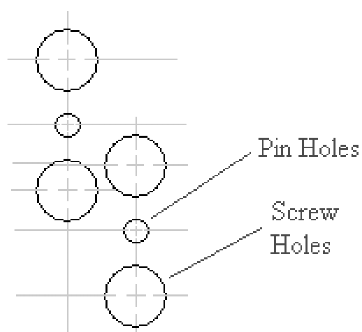
Three hole patterns were created and evaluated. In looking at the parts inserted into the plates, preventing overlapping between the pins and the heads of the vented screws would prevent all possible overlapping. Therefore, the pin patterns were created with the placement of each pin and the two, vented screws that were assigned to each pin in mind. The first and densest design pattern, shown in Figure 2.1b-17, was so close to overlapping that it seemed certain the addition of any form of tolerance error or incorrect dimension would lead to assembly problems. The second design, seen in Figure 2.1b-18 eliminated all overlapping worries but there was still worry about the structural integrity of the plates with the holes so close. The third and most space consuming design, displayed in Figure C-1, provided the greatest factor of safety while not sacrificing much in the way of pin separation.



(a)



(b)



(c)

Figure C-1. The three hole patterns that were analyzed

It was decided to use the third design, but an extra level of four plates would be added to the machine so that the number of necessary holes for vented screws would be cut in half on each plate. With the changing of the design, the screw holes were eliminated and it was decided to do a simple row offset pattern in a 30x30 set. When it was found that additional space was necessary for assembly, every other hole was skipped and the hole pattern became square.

Wiring Scheme

With the aim of keeping the physical display aesthetically pleasing and safely arranged, its wiring was weaved through the extruded aluminum frame. Wires moving vertical were threaded down the center of the extruded aluminum bars. Wires moving horizontal were held in the side grooves of the bars with specially made plugs.

SMA Attachments

A method for attaching the ends of the Shape Memory Alloy (SMA) wires to electrical connections was designed. Figure C-2 shows the basic machine setup as far as plate arrangement and pin module design. The method has each end of the SMA pass through the center of a vented screw as seen in the close-up cross-section view in Figure C-3. The vented screws have been inserted into the bottom of a nonconductive stable board. The bottom of the board will be attached to a pc board with wire traces etched into it. The end of the SMA will come out through the head of the screw and be tucked under a washer against the tightened screw head. The wire will be held in place between the washer and a part of the board containing the end of a wire trace. One board will allow the current to enter the SMA and the other will allow the current to leave the SMA.

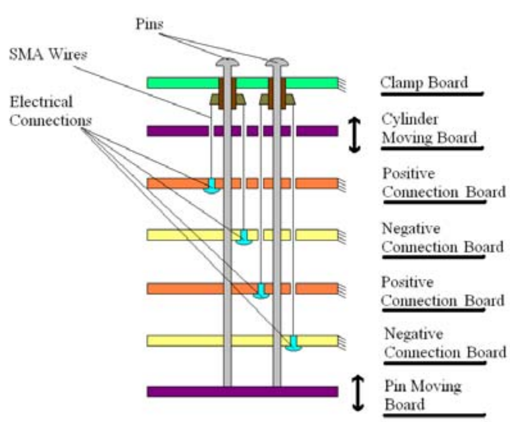


Figure C-2. Table Arrangement

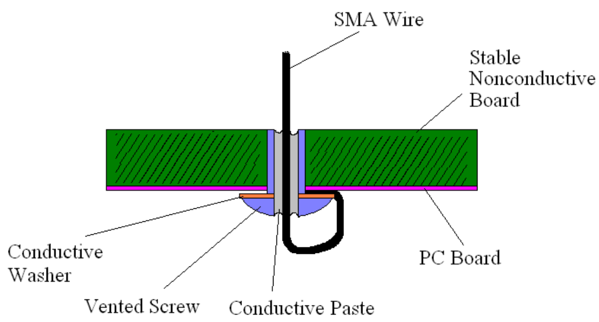


Figure C-3. Close-up of electrical connection

It was realized that the miniature vented screws to be used for connecting the SMA wires to the Electrical board would be difficult to attach through common means. The screws were intended to be attached by inserting an Allen wrench into the head cap; however, because the SMA wire would be passing through the head cap, the insertion is not possible. Also, because the head cap is cylindrical, it could not be gripped by a hex-wrench. Two new screw designs were created and sent to small parts manufacturers for price quotes. The first and most useful design is shown in Figures C-4 and C-5. The screw is identical to the original design except that it has a hole just below the head cap. With this design, the SMA wire could be pulled out of the hole before passing through the head cap. This would allow for insertion of the Allen wrench into the head cap and the bonus result would have the SMA wire already under the head cap, so the task of looping the SMA would be eliminated.

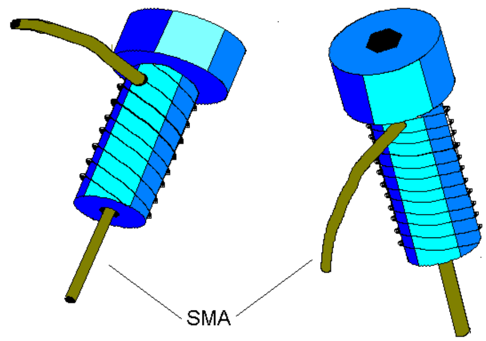


Figure C-4. Design 1 concept drawing

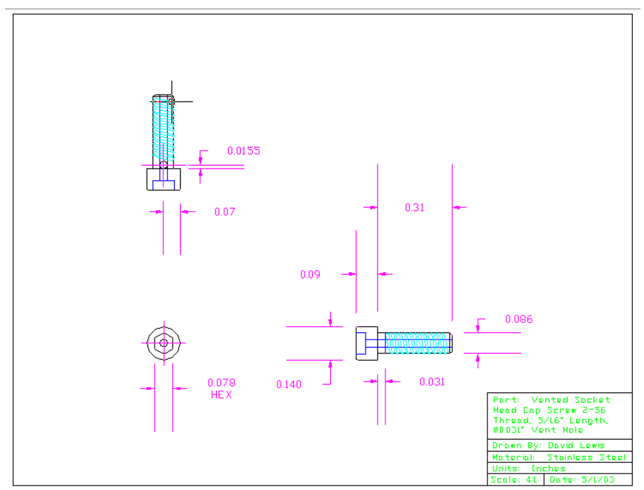


Figure C-5. Design 1 detail drawing

The more basic second design, displayed in Figure C-6 and C-7, differs from the original screw design in that the head cap has been changed from a circular shape to a hex shape and the counter bore for the Allen wrench insertion has been eliminated. The result would make the head cap more easily gripped from the outside by a wrench.

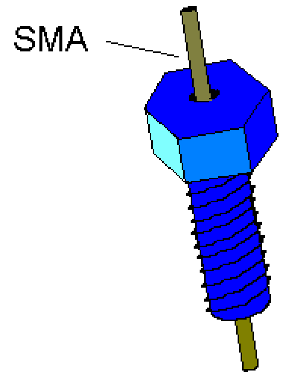


Figure C-6. Design 2 concept drawing

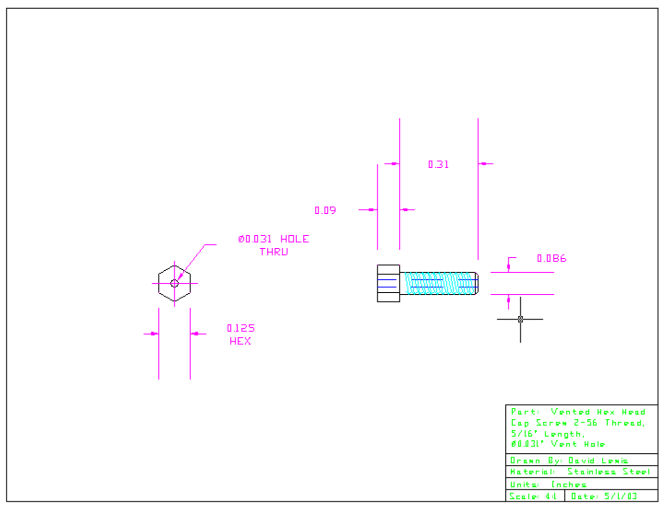


Figure C-7. Design 2 detail drawing

The manufacturing of both designs proved to be far more expensive than would have been desired, so they were scrapped. In an effort to prevent from losing any more time on this problem, it was decided that the screws would have to be turned by inserting an Allen wrench that was a couple sizes smaller than the insert hole into the head cap. If this method proved to be too harmful to the SMA wires, then the screws would be turned by gripping the head caps with a pair of pliers. If this method proved to be ineffective as well, then a special tool would have to be created

SMA Spring Designs

Discovery of a spring-shaped SMA opened the way for new, more efficient designs (Huettl et al. 2000). This material, depending on the type, can either be stretched or compressed, and when heated will return to its original shape. The SMA spring can replace the SMA wire in the original design as shown in Figure C-8. An inelastic band will be threaded around the brass cup, as the SMA wire would have been. Instead of being connected to the board, the ends will be connected to a ring that loosely encompasses the pin. The ring will then be attached to the board with the SMA spring. As in the original design, heating the SMA will pull the brass cup down and clamp the pin. Also like the previous design, all the clamps will be opened and the SMA will be stretched by pushing the brass cup upwards with a moving plate. This method cuts the number of boards with electrical traces in half and lowers the number of holes in each board to one hole per pin.

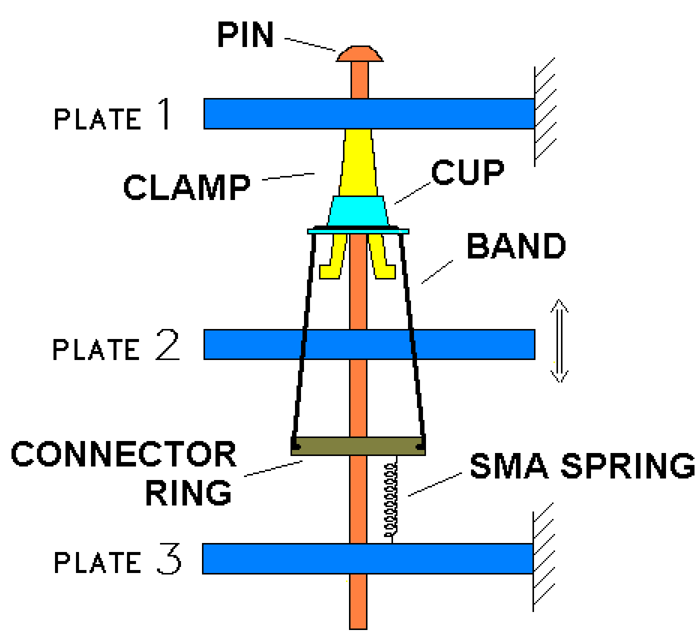


Figure C-8. SMA spring actuation with inelastic band

The most ideal design comes from the arrangement displayed in Figure C-9. This design utilizes an SMA that expands when heated. The SMA is attatched to the bottom of the top board and wraps around the pin. The other end is attached to a ring that holds the brass cup. When the SMA receives a current from the top board, it expands and pushes the cup over the clamp and the pin is gripped. As with the original design, a moving plate lifts the cup and resets the SMA. This design has the following benefits:

1. Less Perforated Boards: The design goes from needing eight perforated boards with four containing electrical traces to two perforated boards with one needing electrical traces.

2. Fewer holes: Each bored only needs one hole per pin.

3. Eliminates need for miniature vented screws

4. Easier assembly: There are fewer parts and attachments aren't as complicated. The boards are no longer connected

5. Easier maintenance: Having less parts and taking up less space, there will be less possibilities for parts breaking and it will be easier to make adjustments.

6. Eliminates size limitations: In the original design, the spacing of the pin separation was governed by the bulkiness of the actuation setup. With SMA springs having coil diameters as small as 0.20 mm, the size limitations are now governed by how small the clamps and pins can be made.

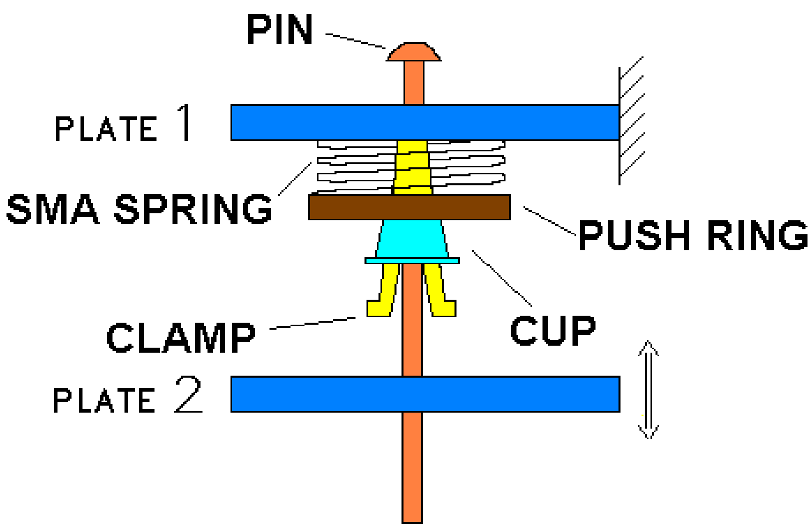


Figure C-9. Ideal spring SMA actuation design

Because SMA springs that compress when heated are more common than those that expand, a design was created using the more common SMA spring, as shown by Figure C-10. Once again the SMA is wrapped around the pin and connected to the top board, which supplies the necessary current. However, in this case, the other end of the SMA is attached to the clamp instead of the brass cup. Heating the SMA pulls the clamp upwards into a stable perforated plated, causing the clamp to close and the pin to be gripped. A moving plate resets the SMA by pushing the clamp downward and out of the stable perforated board. For Virtualization, a moving plate can be moved upward to hold the clamp inside the stable perforated board in order to keep the pins gripped when they are being adjusted. This design maintains all the benefits of the previous design, except to a lesser degree in some cases.

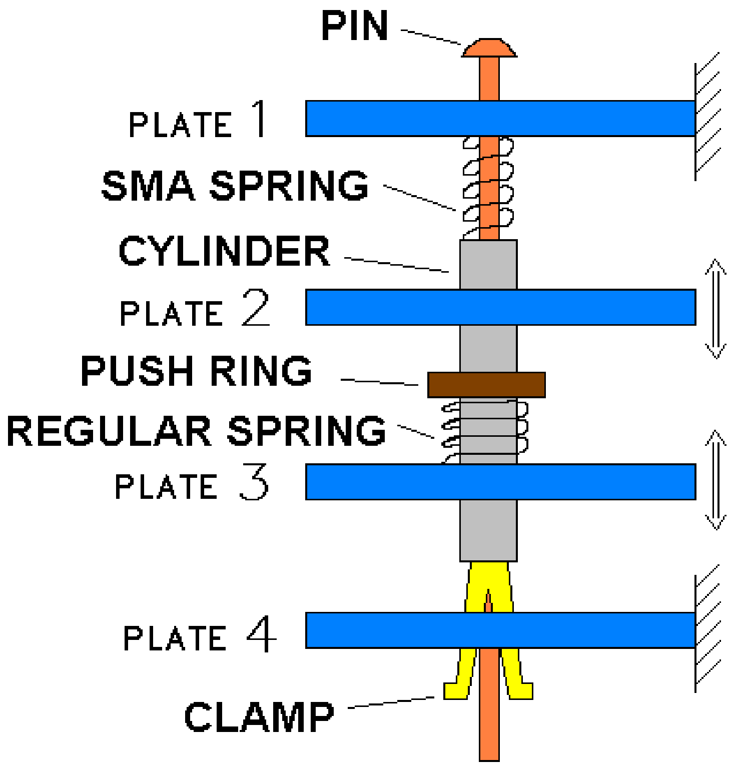


Figure C-10. Compressing SMA spring actuation design

The only SMA springs that could be found in mass production were either significantly larger in diameter than the pins or significantly smaller. This led to the design shown in Figure C-11. The only difference in this design from the previous one is that the SMA location has been moved from being around the pin to being beside it. This may increase the space between pins from that of the previous design, but because the SMA is so thin, it is considered a negligible change.

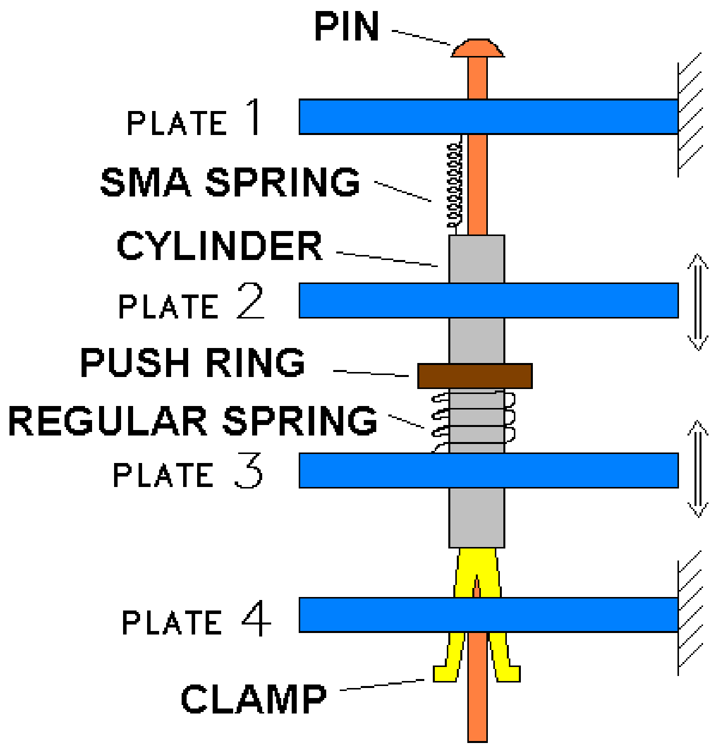


Figure C-11. Miniature compressing SMA spring actuation design

APPENDIX D
SPECIFICS OF WIRING

Pin Assignment Table

Table D-1 maps each pin on the digital I/Os. It details the specific pin names, the connected ribbon cables, and which board inputs and outputs are controlled.

Table D-1. Pin assignments of the digital I/Os

	Digital I/O to Ribbon Cable Labels						Power Board		Ground Board		Sensor Board			
							Output		Output		Input		Input	
Variable #		n = 1 2 3 4	x = a b c	b = 0-7		Ribbon	Power		Ground		Power		(Read)	
Program Call Name	Card	Ribbon # on Card	Port	Pin	Ribbon	Pins	Rows	2nd	Cols	2nd	Rows	2nd	Cols	2nd
out_row_power	0	2	c	7	2	1	1							
out_row_power	0	2	c	6	2	3	2							
out_row_power	0	2	c	5	2	5	3							
out_row_power	0	2	c	4	2	7	4							
out_row_power	0	2	c	3	2	9	5							
out_row_power	0	2	c	2	2	11	6							
out_row_power	0	2	c	1	2	13	7							
out_row_power	0	2	c	0	2	15	8							
out_row_power	0	2	b	7	2	17	9							
out_row_power	0	2	b	6	2	19	10							
out_row_power	0	2	b	5	2	21	11							
out_row_power	0	2	b	4	2	23	12							
out_row_power	0	2	b	3	2	25	13							
out_row_power	0	2	b	2	2	27	14							
out_row_power	0	2	b	1	2	29	15							
out_row_power	0	2	b	0	2	31	16							
out_row_power	0	2	a	7	2	33	17							
out_row_power	0	2	a	6	2	35	18							
out_row_power	0	2	a	5	2	37	19							
out_row_power	0	2	a	4	2	39	20							
out_row_power	0	2	a	3	2	41	21							
out_row_power	0	2	a	2	2	43	22							
out_row_power	0	2	a	1	2	45	23							
out_row_power	0	2	a	0	2	47	24							
out_col_ground	0	3	c	7	3	1			30					
out_col_ground	0	3	c	6	3	3			29					
out_col_ground	0	3	c	5	3	5			28					
out_col_ground	0	3	c	4	3	7			27					

out_col_ground	0	3	c	3	3	9			26					
out_col_ground	0	3	c	2	3	11			25					
out_col_ground	0	3	c	1	3	13			24					
out_col_ground	0	3	c	0	3	15			23					
out_col_ground	0	3	b	7	3	17			22					
out_col_ground	0	3	b	6	3	19			21					
out_col_ground	0	3	b	5	3	21			20					
out_col_ground	0	3	b	4	3	23			19					
out_col_ground	0	3	b	3	3	25			18					
out_col_ground	0	3	b	2	3	27			17					
out_col_ground	0	3	b	1	3	29			16					
out_col_ground	0	3	b	0	3	31			15					
out_col_ground	0	3	a	7	3	33			14					
out_col_ground	0	3	a	6	3	35			13					
out_col_ground	0	3	a	5	3	37			12					
out_col_ground	0	3	a	4	3	39			11					
out_col_ground	0	3	a	3	3	41			10					
out_col_ground	0	3	a	2	3	43			9					
out_col_ground	0	3	a	1	3	45			8					
out_col_ground	0	3	a	0	3	47			7					
out_row_power	0	4	c	7	4	1		25						
out_row_power	0	4	c	6	4	3		26						
out_row_power	0	4	c	5	4	5		27						
out_row_power	0	4	c	4	4	7		28						
out_row_power	0	4	c	3	4	9		29						
out_row_power	0	4	c	2	4	11		30						
out_col_ground	0	4	c	1	4	13				6				
out_col_ground	0	4	c	0	4	15				5				
out_col_ground	0	4	b	7	4	17				4				
out_col_ground	0	4	b	6	4	19				3				
out_col_ground	0	4	b	5	4	21				2				
out_col_ground	0	4	b	4	4	23				1				
in_row_power	0	4	b	3	4	25					1			
in_row_power	0	4	b	2	4	27					2			
in_row_power	0	4	b	1	4	29					3			
in_row_power	0	4	b	0	4	31					4			
in_row_power	0	4	a	7	4	33					5			
in_row_power	0	4	a	6	4	35					6			
in_row_power	0	4	a	5	4	37					7			
in_row_power	0	4	a	4	4	39					8			
in_row_power	0	4	a	3	4	41					9			
in_row_power	0	4	a	2	4	43					10			
in_row_power	0	4	a	1	4	45					11			
in_row_power	0	4	a	0	4	47					12			
in_row_power	1	1	c	7	5	1					13			
in_row_power	1	1	c	6	5	3					14			
in_row_power	1	1	c	5	5	5					15			
in_row_power	1	1	c	4	5	7					16			

in_row_power	1	1	c	3	5	9					17			
in_row_power	1	1	c	2	5	11					18			
in_row_power	1	1	c	1	5	13					19			
in_row_power	1	1	c	0	5	15					20			
in_row_power	1	1	b	7	5	17					21			
in_row_power	1	1	b	6	5	19					22			
in_row_power	1	1	b	5	5	21					23			
in_row_power	1	1	b	4	5	23					24			
in_row_power	1	1	b	3	5	25					25			
in_row_power	1	1	b	2	5	27					26			
in_row_power	1	1	b	1	5	29						27		
in_row_power	1	1	b	0	5	31						28		
in_row_power	1	1	a	7	5	33						29		
in_row_power	1	1	a	6	5	35						30		
EMPTY	1	1	a	5	5	37								
EMPTY	1	1	a	4	5	39								
EMPTY	1	1	a	3	5	41								
EMPTY	1	1	a	2	5	43								
EMPTY	1	1	a	1	5	45								
EMPTY	1	1	a	0	5	47								
in_col_read	1	2	c	7	6	1							1	
in_col_read	1	2	c	6	6	3							2	
in_col_read	1	2	c	5	6	5							3	
in_col_read	1	2	c	4	6	7							4	
in_col_read	1	2	c	3	6	9							5	
in_col_read	1	2	c	2	6	11							6	
in_col_read	1	2	c	1	6	13							7	
in_col_read	1	2	c	0	6	15							8	
in_col_read	1	2	b	7	6	17							9	
in_col_read	1	2	b	6	6	19							10	
in_col_read	1	2	b	5	6	21							11	
in_col_read	1	2	b	4	6	23							12	
in_col_read	1	2	b	3	6	25							13	
in_col_read	1	2	b	2	6	27							14	
in_col_read	1	2	b	1	6	29							15	
in_col_read	1	2	b	0	6	31							16	
in_col_read	1	2	a	7	6	33							17	
in_col_read	1	2	a	6	6	35							18	
in_col_read	1	2	a	5	6	37							19	
in_col_read	1	2	a	4	6	39							20	
in_col_read	1	2	a	3	6	41							21	
in_col_read	1	2	a	2	6	43							22	
in_col_read	1	2	a	1	6	45							23	
in_col_read	1	2	a	0	6	47							24	
in_col_read	0	1	c	7	1	1							25	
in_col_read	0	1	c	6	1	3							26	
in_col_read	0	1	c	5	1	5								27
in_col_read	0	1	c	4	1	7								28

in_col_read	0	1	c	3	1	9								29
in_col_read	0	1	c	2	1	11								30
board_switch	0	1	c	1	1	13								
EMPTY	0	1	c	0	1	15								
step	0	1	b	7	1	17								
direction	0	1	b	6	1	19								
EMPTY	0	1	b	5	1	21								
EMPTY	0	1	b	4	1	23								
EMPTY	0	1	b	3	1	25								
step_res_con_1	0	1	b	2	1	27								
step_res_con_2	0	1	b	1	1	29								
EMPTY	0	1	b	0	1	31								
solenoid_up	0	1	a	7	1	33								
solenoid_dn	0	1	a	6	1	35								
dumb	0	1	a	5	1	37								
dumb	0	1	a	4	1	39								
dumb	0	1	a	3	1	41								
dumb	0	1	a	2	1	43								
fan_switch	0	1	a	1	1	45								
EMPTY	0	1	a	0	1	47								

APPENDIX E
PROGRAM CODE

Guide to Code

- clicks.c++

Global variable describing the length of a pin in inches ('pinLength') and utilities to convert between inches and 'clicks' of the stepper motor.

  - double pinLength = 4.1; // In inches.
  - int step_fraction_inv = 1; // In clicks.

  The stepper motor can operate at several different speeds. At the fastest speed, one step corresponds to one click of which there are 48 per revolution. At the slowest speed one click corresponds to eight steps. This variable contains the number of steps per click.

  - double clicksToGUI(int clicks);

  This function converts the number of clicks to the real, physical inches. It depends on the speed of the motor.

  - int GUIToClicks(double inches);

  Inverse of above.

  - int MAX_CLICKS = GUIToClicks(pinLength);

  Total number of clicks to go from bottom to top, to traverse `pinLength` inches.

- CompDisplay.c++

Function to read pin heights from the machine.

  - long delay_nsec = 6000000;

  Time in nanoseconds to pause when changing which row gets power.
  We need this because it takes time for the power on a row to set up and to power down. If this is set too low, multiple rows will receive power at once and when we see that a column also has power, we won't know from which row it received its power.

  - void wait(long nsec);

  This will sleep for 'nsec' nanoseconds. We cannot use the system call 'usleep' because it lacks the necessary resolution. E.g., if we ask it to sleep for one milisecond, it might sleep for as much as 20 milliseconds. Please keep nsec < 1e9.

- bool isPinEngaged(int row, int col);

Returns 'true' if the pin at (row,col) is engaged. 'row' and 'col' indexed from zero.

- void receivePhysical();

Operate machine and read in the pin heights. Update the display with the new heights. This function moves the board to the bottom, then puts up a prompt to allow the user to adjust the heights of the pins. Clicking off the prompt calls 'receivePhysical2.'

- void receivePhysical2();

This function moves the board up and polls the pins as it moves, recording the height at which a pin first engages the board.

- main.c++

GUI and main.

- PinViewer *pinsArea;

Main data structure holding pin heights.

- Widget myBB;

Main GUI widget.

- int machine_busy_flag = 0;
- void machine_lock(); { machine_busy_flag = 1; }
- void machine_unlock(); { machine_busy_flag = 0; }
- bool is_machine_busy(); { return machine_busy_flag; }

This variable and these functions prevent multiple requests from going to the machine at once. When the user begins an operation, the operation locks the machine and if the user should try to initiate another operation before his first terminates (and releases its lock), the second operation will quit upon seeing that the machine is locked.

- void motorCB(Widget w, XtPointer client_data, void *call_data);
- void acpinCB(Widget w, XtPointer client_data, void *call_data);
- void readpCB(Widget w, XtPointer client_data, void *call_data);
- void solupCB(Widget w, XtPointer client_data, void *call_data);
- void soldnCB(Widget w, XtPointer client_data, void *call_data);

When the user presses the 'Debugging ops' buttons on the right side of the GUI, he calls these functions. They respectively move the motor, activate a pin, read the status of a pin, activate the upper solenoids, and activate the lower solenoids.

- void sendCB(Widget w, XtPointer client_data, void *call_data);
- void receiveCB(Widget w, XtPointer client_data, void *call_data);

These callbacks call sendPhysical and receivePhysical respectively. Pressing the 'Send' or 'Receive' button calls them.

- float getMotorInputField();
- int getIntFromInputField(Widget text_field);
- int getRowInputField();
- int getColInputField();
- float getHeightInputField();
- void setRowInput(int row);
- void setColInput(int col);
- void setHeightInput(float pHeight);

These functions access/modify the GUI text fields.

- void setPinHeight(Widget w, XtPointer client_data, void *call_data);
- void getPinHeight(Widget w, XtPointer client_data, void *call_data);

Called by clicking 'set/get height' buttons.

- Widget makeLabel(Widget parent, char *s);
- Widget makeButton(Widget parent, char *s, XtCallbackProc cb);
- void setOnBoardPos(Widget w, int x, int y);
- void setOnBoardPos(SoXtComponent *c, int x, int y);
- void setWidgetSize(Widget w, int x, int y);

Convenience functions.

- void main(int argc, char **argv);

Main function. Initializes GUI, jumps into GUI event loop.

- MakeItReal.c++

Writes pin heights to the physical system.

- int pin_burn_time_usec = 2500000;

Time (in microseconds) for which to activate each SMA.

- void wait_until_height(height_t desiredHeight);

// Move sensor board down to 'desiredHeight'

- void activate_pin(const Pin &p);

// interfaces to digital I/O in order to activate pin.
// Fire SMAs for time in pin_burn_time_usec.

- void sendPhysical();

// Called from main.
// Move the sensor board and activate the pins to lock them in place.
Move board to the top; then popup a dialog, allowing user to unlock pins.
Continuing through dialog calls sendPhysical2.

  - void sendPhysical2();

    Lowers board, pausing to lock each pin at appropriate height.

- mapping.c++

Reads file 'pin_map.table' maps logical addresses to I/O card. This is the lowest level interface with the digital I/O cards. Must call read_mapping() before using any of the functions. read_mapping() insures it will only be called once. read_mapping() calls init_cards() and initializes the instance 'board' of the class 'SensorBoard.'

- PinViewer.c++

Draws 3D representation of pin array.

- SensorBoard.c++

Controls movement of the sensor board up and down.

- StepperMotor.c++

Used inside SensorBoard.c++ to activate the clicks of the motor.

- waitDialog.c++

Creates the pause that occurs between executing sendPhysical() and sendPhysical2(), as well as receivePhysical() and receivePhysical2().

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BIOGRAPHICAL SKETCH

David Lewis was born in Hollywood, Florida, on Valentine's Day of 1979. He followed in his parents' footsteps by attending the University of Florida and followed in his grandfather's footsteps by receiving a Bachelor of Science degree in Mechanical Engineering. He decided to stay at UF for his Master of Science degree.