DESIGN PROJECT FINAL REPORT
ME 450 WINTER 2006

Section 4 – Professor R. Brent Gillespie

Apparatus for Testing the
Persistence of Haptic Memory

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TABLE OF CONTENTS

1.0 EXECUTIVE SUMMARY

The human brain uses at least three types of stimuli to acquire information: auditory, visual, and haptic. A great deal of research has been completed in the study of visual and auditory memory, allowing researchers to understand the abilities and limitations of these types of memory. Researchers have investigated the human brain's ability to remember and recognize haptic patterns, but little has been done to verify the persistence of short-term haptic memory, the memory created based on touch or feel. The purpose of this project was to create an apparatus that could be used to test the short-term persistence of haptic memory. This device works in a manner similar to the Simon-Says game in that various types of cues will be given to a test subject in a particular order and the subject will then attempt to recall the sequence.

Important factors in the design of this apparatus include: a computer interface for programming cues and recording data; complete programmability of the buttons; reproducibility of each cue type; and production of all three types of cues (auditory, visual, and haptic) by each button. The haptic cues will be delivered to each button through vibrations from a motor, in a manner controlled by the researcher. A speaker connected to a computer with a sound card will provide auditory cues, and visual cues will be supplied by different colored LEDs. The computer interface will allow a researcher to program the type and order of the cues and record responses. The size of the apparatus is not of great importance since it is meant primarily for research, but it should easily fit on a tabletop. It also should not appear intimidating in case children are tested.

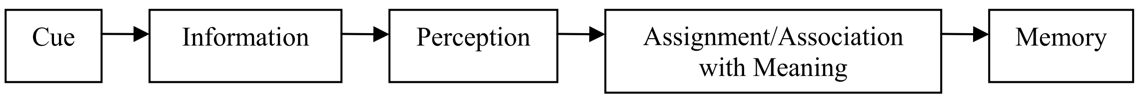
In designing this apparatus we considered several types of motors, position sensors, and button layouts. To select the concepts used for our prototype, we created a selection matrix for each concept category (motor, sensor, and layout). Our selected concepts were a rotary voice coil motor, a linear optical encoder, and a flat faceplate design. There are two faceplates, per our sponsor's request, with different button arrangements: radial and circular. The majority of the device will be constructed from Plexiglas using a laser cutter.

By analyzing each component of our final design, we were able to ensure that the dimensions, shapes, and materials selected would result in a fully functional prototype. The main difference between our prototype and the final design is its lack of a computer interface. Rather than a using a computer, our prototype will make use of potentiometers and switches to provide various cues. After completing construction of our prototype, we are able to conclude that it meets all of our basic requirements. Using our control circuit, we can provide distinct visual cues by altering the current through the LEDs to produce hundreds of colors. Our button motors are more than capable of lifting a test subject's finger and can be held up by providing a constant current to the voice coils. This ensures that our device can be used to produce distinct haptic cues once it is computer-interfaced. The entire device fits easily on a tabletop, and the button arrangement can be changed by simply switching the face and mounting plates.

2.0 INTRODUCTION

There are three basic types of memory that will be studied in this project: auditory, visual, and haptic. While auditory and visual memory are well researched and understood, haptic memory (memory related to touch and feel) has not been researched to the same degree, and little is known about the human mind's ability to perceive and remember haptic cues. A theory of how haptic memory functions is depicted in Figure 1. The goal of this project was to design an apparatus for testing the persistence of haptic memory in comparison to auditory and visual memory. The apparatus is a Simon-Says type game with a computer interface so researchers may control the type and sequence of cues given to the test subject, while also recording the subject's response.

Figure 1: Theory behind how haptic memory works



3.0 INFORMATION SOURCES

3.1 Haptic Memory Studies

There have been many studies on the subject of haptic memory. One study investigated the interaction of colors on haptic memory, more specifically how color presentation mode affects human haptic memory for rough surfaces. Information presented visually can alter haptic perception. The colors used in the study could be the same or vary. The results indicated that haptic recognition memory performance for rough surfaces is very sensitive to color presentation mode. For example, showing objects first in red and then gray increased performance (of haptic memory), while showing them first in green and then in gray worsened performance [1].

Another study explored the role of haptics in immersive telecommunications applications, questioning if all senses are equally important for "generating a sense of presence." It was found that "assigning meaning to sensory patterns requires that haptic patterns are stored in memory and recognized in new situations." In addition, "research on neurology of haptics shows that haptic patterns are memorized and recognized even if the haptic experience itself is not remembered." Resonance is vital. If a cue is random or inconsistent, it is confusing. If the cues are not recognizable but repeat, they can be learned and memorized [2].

In a test by Stadtlander, Murdoch, and Heiser, subjects were presented with sequences of seventeen items at a rate of one every ten seconds and then asked to write down in order as many as they could remember. In the control trials, seventeen high-imagery nouns were read to each subject, and in the vision-only trials, subjects were shown seventeen common household items. The subjects were given seventeen items to hold and visually examine in the vision-and-haptic trials, and finally in the haptic-only trials, the subjects were blindfolded and allowed to hold each object. The results showed that recall for real objects were better than recall for high-imagery nouns. The vision-and-haptic trials had better performance than the vision-only trials, which demonstrates that the touching of an object improves a subject's recall [3].

Tan, Durlach, Reed, and Rabinowitz conducted a test in which subjects were asked to rest their thumb, index, and middle finger on separate one-degree-of-freedom actuators (the "Tactuator"), which provided vibrating stimuli of varying amplitude, frequency, and waveform. They were able to feel the difference between slow motion (up to 6 Hz), fluttering motion (10-70 Hz), and smooth vibration (above 150 Hz) in 500 msec tests. The subjects were tested with stimuli durations of 500 msec, 250 msec, and 125 msec and asked to select the waveform they had just experienced from pictures of all the waveforms being simulated. They also had to select which finger had experienced the stimulus. The subjects' responses were all over 90% correct [4].

Another test by Tan, along with Gray, Young, and Traylor, measured the effectiveness of haptic cues in directing a subject's visual-spatial attention. In this test, haptic cues were applied to different areas of a subject's back, and they were then asked to detect a change between two similar visual scenes. Results showed that reaction time decreased by an average of 41% when the location of the haptic cue coincided with the changing area of the visual scene, and reaction time increased by about 19% when the two did not coincide [5].

Although several tests on haptic memory have been conducted with functional Magnetic Resonance Imaging, none of the tests found in our research used fMRI in conjunction with a Simon-Says type of device.

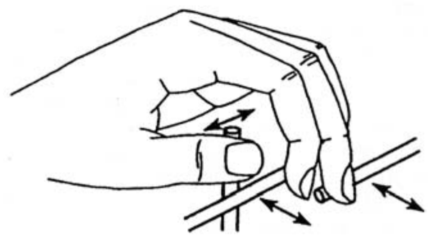
3.2 Benchmark Evaluations

Because we are designing a research tool, there are no products that will directly compete with our apparatus. However, the toy "Simon^2" operates in a similar way using only combined visual and auditory cues. It has four buttons that each have a particular color and sound, and these buttons light up and sound a tone simultaneously in random sequences. The user then responds by pressing the buttons in the same order and proceeds on to a longer cue sequence if correct. "Simon^2" is shown below in Figure 2.

Figure 2: "Simon^2" tests visual and auditory memory.

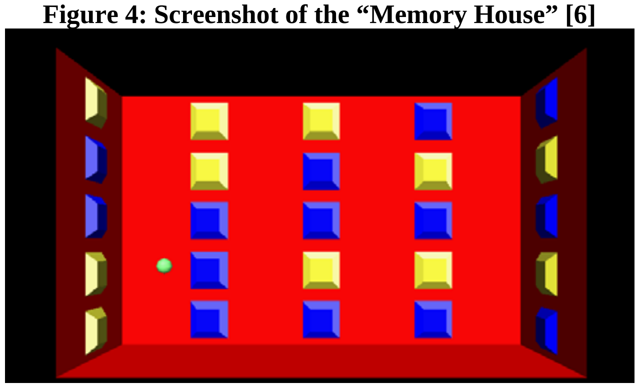
There is also a haptic memory-testing device called the "Tactuator" that was designed by Hong Tan, but it does not test the visual or auditory modes of memory. The "Tactuator" (Figure 3) is made up of three rods that the user's thumb, middle, and index finger rest on in a natural hand configuration. These rods provide stimuli of waveforms with varying amplitude and frequency, and the user is asked to identify the waveform felt, as well as the finger that experienced it. Each rod of the "Tactuator" is operated by a disk-drive head-positioning motor and is equipped with angular position feedback [4].

Figure 3: The "Tactuator" provides only haptic cues.



"The Memory House" (see Figure 4 below) is a computer game used as a test for haptic interface objects. The user has to find pairs of sounds that are played when he or she pushes different buttons. Using the program helped the researchers to gain information about how blind people can use haptics to establish "inner pictures" of complex systems. The researchers plan to use this information to find out how to build a computer operating system or other haptic programs that will work well for people with poor vision. Tests were performed with blind subjects using "the Memory House" and subjects with good vision using a game with the same layout but based on vision rather than haptics. The haptic interface had the same layout as the graphical interface and both programs worked the same except for the way of interacting with the user, so it was possible to compare the results of the blind users to the results of the sighted users. The blind users were given about an hour of experience with the "Memory House" before testing was started. Results indicated that blind users could complete the task almost as well as sighted users, and did so with confidence, but they generally needed more time [6].

Figure 4: Screenshot of the "Memory House" [6]



3.3 Existing Patents

A patent search turned up an existing patent that fits several of the requirements for this project. Patent # 6697044, submitted by Immersion Corporation of San Jose, California, describes a device that both provides haptic stimulation and records user input. The patent claims at least one button to be operated by a finger. This button will be driven by a motor along a degree of freedom, and includes a displacement sensor to record feedback from a user for use of manipulating a graphical object on a graphical display.

The patent also covers the use of multiple buttons and buttons with more than one degree of freedom. This patent is geared towards creating a game controller capable of force feedback and does not mention the use of this device for testing of the persistence of haptic memory.

3.4 Auditory Research

The characteristics of sound are frequency, wavelength, amplitude, and velocity. Changing these values affects the loudness, pitch, quality, and type of sound. Sound is audible to humans in a frequency range between 20 and 20,000 Hz. This can vary person to person. Varying the wavelength and waveform (such as sinusoidal, saw-tooth, square, and triangle) changes the type of sound produced. The amplitude is referred to as sound pressure level and is measured in decibels. The decibel is used as a measure of the loudness of sound. The normal range of human hearing extends from about 0 dB to 140 dB. Sound levels above 85 dB are harmful, while levels above 150 dB can cause damage to the ear. A "comfortable" loudness is around 50 dB, which is considered as the level inside a quiet to moderately quiet restaurant or office [7].

3.5 Visual Research

Colors can be quantified by their wavelength and brightness. Wavelengths that fall within the human visual light spectrum range from approximately 380 nm to 740 nm. The brightness of a light can be measured in lumens, which is a rate of energy flow from the light. This means the brightness of each light in our apparatus can be measured by the amount of power it absorbs because power also measures the rate of energy flow [7, 8].

Our team plans to use light-emitting diodes (LEDs) to produce visual color cues because they provide many advantages over a typical incandescent or fluorescent light. Most importantly, LEDs are small, so it will be easy to fit many of them on our testing apparatus. In addition, LEDs produce light in a particular color without the use of a color filter, and they have an extremely long life span and give off less heat than incandescent light bulbs. Finally, LEDs are insensitive to vibration and shocks, and their solid cases make them hard to break and very durable [7]. When using LEDs, we must be sure to power them with a constant current source because if a voltage source is used, each LED may not receive the same amount of current [9].

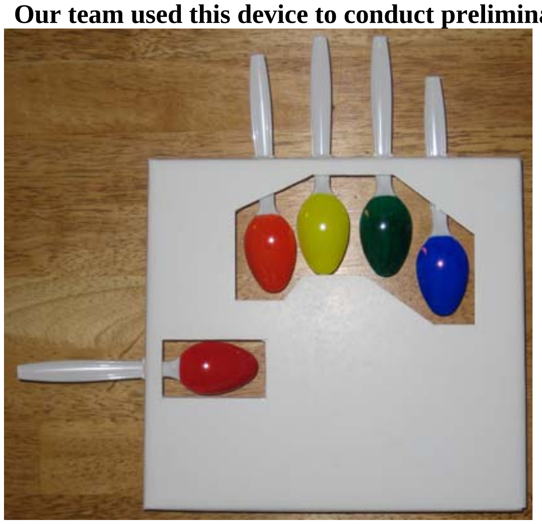
3.6 Haptic Research

Haptic cues can be quantified by amplitude, frequency, force, shape, and duration, but there are some limits to what a human subject is able to perceive. In a study of the detection thresholds of haptic cues, Jesse Dosher found that the minimum detectable force for a sinusoidal cue was about 60 mN. The minimum detectable force for a saw-tooth cue was about 30 mN [10]. In addition, the human hand is unable to sense small amplitude vibrations at frequencies less than 20 Hz [11].

3.7 Preliminary Experiment

Before building our prototype, we felt it would be helpful to conduct an experiment similar to that for which our apparatus is intended. To accomplish this, we constructed a simple testing device out of Foamcore and plastic spoons. We mounted five spoons in a configuration that a subject could comfortably rest their fingertips on, and we left the ends of the spoons exposed. This way, the "researcher" could easily input haptic cues by pressing the ends of the spoons. To create a control condition, we colored each of the spoons a different color and created corresponding flashcards to use as cues. A photo of our testing device is shown in Figure 5.

Figure 5: Our team used this device to conduct preliminary tests.



3.7.1 Control Test

In our control tests, the subject was shown a colored flashcard and asked to press the spoon of the same color. We began our control tests using a format similar to that of the Simon-Says game; the subject was asked to recall an increasingly long sequence until making an error. This task was not difficult for the subject, and an average sequence length of ten cues was reached before any errors were made. Our team felt the built-up sequence used in a Simon-Says game was not challenging enough, so we also tried varying sequences of five cues. This was easy for our test subject, and no errors were made in recalling the five-cue sequences.

3.7.2 Haptic Test

For our haptic tests, the subject was blindfolded with their fingertips resting on the spoons, and the "researcher" pressed the ends of the spoons to provide haptic cues in random sequences of five. The subject was asked to respond by pressing the spoons down in the correct order. This was very difficult for the subject, and three-fourths of our subjects failed on their first attempt.

3.7.3 Findings

After conducting our haptic tests, it was apparent that many factors affected the subjects' ability to recall the given sequence. When the haptic sequence was pressed more quickly on the spoons, it became more difficult for the subjects to recall the pattern correctly. At times when one of the spoons would get stuck or move inconsistently, the subjects were also more likely to respond incorrectly. Finally, if the "researcher" were to tap a spoon twice by accident, the subjects recalled the cue more accurately. This could be due to reinforcing, the distinctness of the cue, or the extended length of the cue.

By interviewing our subjects after they were tested, we were able to gain some insight into why their response accuracy varied. Many of the subjects remembered the cues by recognizing the finger that had moved and memorizing the finger names (such as "pinkie" or "index") in order. So when the haptic sequence was given more quickly, they had inadequate time to go through this mental process. When the finger names were not remembered, the subjects attempted to recall cues simply by their spatial location, which led to errors of pressing the spoon adjacent to the correct one. In addition, the subjects noted that cues of larger amplitude had been easier for them to remember.

3.7.4 Implications
Our simple experiment provided some insight into what will be necessary in our final apparatus design. The device must be capable of producing cues of different amplitudes and lengths, and the speed at which these cues are given must be variable. These three factors all affected the subject's ability to remember haptic cues in our preliminary tests. Our experiment also gave an indication that subjects may perform better in tests of the visual persistence of memory than in haptic tests.

4.0 CUSTOMER REQUIREMENTS

Professor Gillespie plans to use our project to test a hypothesis, so it is most important that the device we design fits his research expectations. He intends to test the persistence of human memory for haptic, visual, or auditory information, as well as any combination of the three. Our apparatus must be capable of providing haptic, visual, and auditory cues, and be capable of being computer-interfaced and completely programmable. This will allow the researcher to select the type and order of cues given, and it will also provide a means for receiving and recording subjects' responses.

There are different quantities associated with the three different modes: visual, auditory, and haptic. The visual and auditory quantities can be measured, for instance, we can measure the wavelength of an LED light or the loudness or frequency of a musical note. However, there are some things that we cannot measure but want to; for instance, perception. We cannot "measure" how a cue is perceived by a test subject; we can only infer based on him or her describing how it felt.

In order to produce valid results, each cue must be distinct. The colors given as visual cues must all be of the same brightness and differ equally in hue. Auditory cues must all be given at the same volume and sound as distinctly different as the colors appear different. Because this apparatus will be used in research studies, it must be simple and built to precise specifications to allow for reproduction. It is also preferred that the device be built entirely of non-ferrous materials, so it can be used in conjunction with fMRI machines.

During research, the subjects will have to place their hand on the apparatus in order to receive haptic cues. For this reason, it would be most useful for the device to have five buttons spaced appropriately for the subject's fingers and thumb to rest comfortably on. In case children are used as test subjects, the apparatus should be non-intimidating and adjust to fit multiple hand sizes.

5.0 QUALITY FUNCTION DEPLOYMENT (QFD)

The customer requirements are vital to this project. The device is going to be built for research purposes and to test a particular theory; therefore it must meet all of the requirements specified by the sponsor. The customer requirements were translated into engineering specifications using a Quality Function Deployment (QFD) chart (see Appendix, section 19.3). First, we ranked the importance of our customer requirements by considering the type of research that would be conducted with our apparatus. The requirements that would affect the validity of the research were given the highest relative importance, and other requirements relating to comfort and ease of use were given lower rankings. Secondly, the QFD chart was used to benchmark the competition against our specific customer requirements. The "Simon[2]" game and the "Tactuator" were used as benchmarks because they both provide cues that must then be recalled by the user, which is a major goal of our design. Next, our quantifiable engineering specifications were added to the QFD chart and correlated to the customer requirements. Finally, after cross-correlating the engineering specifications, we were able to assess our benchmarks against them and set our own engineering target values.

6.0 ENGINEERING SPECIFICATIONS

We have obtained all of the engineering specifications in detail. Our preliminary engineering specifications were confirmed based on research and verification with our project sponsor.

6.1 Research Specifications

For research purposes, our apparatus must be capable of being computer-interfaced using a LabVIEW system. This will enable the researcher to design and select haptic cues and multiple-cue sequences. Computer interfacing also allows the subject's responses to be input to the computer and recorded. We have selected the LabVIEW program in particular because it is readily available to us, and Professor Gillespie is accustomed to using it. This will make it easier for him to begin his research with our apparatus. Our apparatus must also operate on 110 V, so it can be plugged into a typical electrical outlet without any special requirements.

6.2 Comfort Specifications

To make our device comfortable for the human subjects tested, we would like the buttons to be arranged in a typical hand configuration. There will be five buttons total; one for each finger and thumb on a single hand. Ideally, each button will be wedge-shaped: narrow near the palm and wider at the fingertip. This will allow children with smaller hands to use the apparatus as easily as adults. The device must fit easily on a tabletop to simplify the research setup and avoid frightening young subjects, so we would like it to be no larger than 2 ft^2. We would also like to keep the subject's wrist angle under 10º to prevent strain and fatigue.

6.3 Auditory Cue Specifications

Since the apparatus will be programmable by computer, there will be thousands of different sounds that can be produced. Our group will need to ensure that the device is capable of producing such a wide variety of sounds. Connecting a computer with a sound card to a speaker would be satisfactory for this project. Per our sponsor, our prototype will not need to incorporate the sound aspect, but the final design will. So eventually, the programmer of the device will need to be concerned with the "acceptable" sound levels in order to prevent injury or discomfort to the test subject, which means sound levels should not exceed 60 dB.

6.4 Visual Cue Specifications

Our team will use various colors provided by light-emitting diodes (LEDs) to test the persistence of visual memory. Each color cue must be distinct, so we would like the colors to differ in wavelength by at least 40 nm. In order to allow one color for each finger resting on our apparatus, we will likely use blue (470 nm), green (530 nm), yellow (580 nm), orange (620 nm), and red (700 nm) LEDs, as well as white for control tests [7]. Our LEDs will have to be powered by a constant current source to ensure that each absorbs the same amount of power, so every LED color is the same brightness [8, 9].

6.5 Haptic Cue Specifications

The amplitude, frequency, force, shape, and duration of haptic cues should be fully programmable by the scientist, but we have established some limits based on human senses and motor specifications. The maximum amplitude of the vibration will be 0.5 in. We have chosen this value so that a small force is required from the motor. Thus, we can choose smaller motors and magnets, which adhere to our size constraints, are easier on our budget, and are less intimidating to the test subject. Furthermore, this choice of maximum amplitude will provide a comfortable range of motion for the hand. Also, if the scientist wishes to use frequencies of 20 Hz or less, 0.5 inches is a large enough range of motion that the movement of the button will be easily detected.

The frequency of the vibration cue is important for two reasons. The test subject must be able to feel the vibrations and differentiate between them (depending on the scope of the test). The selected range of frequencies is 0.5 to 1000 Hz with the stipulation that any frequency less than 20 Hz must have amplitude of at least 0.25 inches.

The minimum programmable force for a cue is 100 mN. Since we want the subjects to feel all of the cues, we chose a value that is well within the range of detectable forces. The selection of the duration and shape of the haptic cues will be left up to the scientist.

7.0 CONCEPT GENERATION

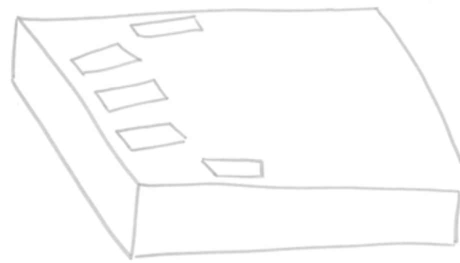
Our project team brainstormed to generate various concept designs. These designs revolved around the apparatus as a whole, as well as individual components such as the buttons, motors, and position sensors.

7.1 Layout of Apparatus

7.1.1 Flat

This concept is a very simple design, shown in Figure 6. The apparatus will resemble a small box with all six buttons (four fingers plus two for thumbs) on the top face. There are six buttons so that right- or left-handed subjects can use the apparatus. Also, the buttons are elongated to accommodate different hand sizes.

Figure 6: Our most simple layout concept was this flat design.



7.1.2 Curved

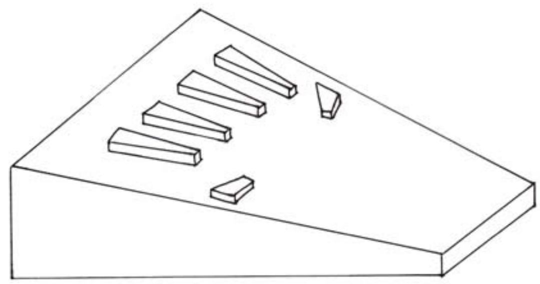
A sketch of another layout concept is shown in Figure 7. This concept is similar to the shape of a computer mouse. It is contoured so that a hand may rest comfortably on its surface during long test sessions. In addition, the thumb of a rested hand does not lie in the same plane as the fingertips; therefore the thumb button is slightly angled from the face with the other four buttons.

Figure 7: A curved apparatus may be more comfortable for the subject.

7.1.3 Pie-Shaped

A third layout concept is shown in Figure 8. This concept will have the appearance of a wedge. This design will be able to accommodate different hand sizes due to the elongation of the buttons. There will be six buttons: one for each finger and two for the thumb so either the right or left hand can be used in testing.

Figure 8: Pie-shaped layout. This layout will be easier to manufacture, and more comfortable for the hand than the flat layout.

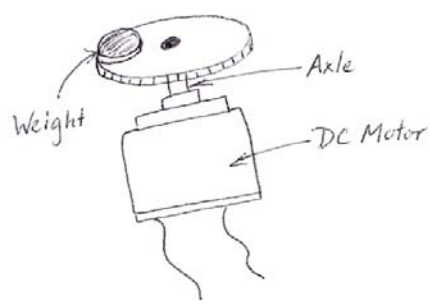


7.2 Motors

7.2.1 Proof Mass Motor

A simple vibration motor causes vibrations by rotating an eccentric mass with the drive shaft of the motor. Rotating this off-balance mass causes the motor, and anything to which the motor is mounted, to vibrate. A sketch of this mechanism is shown below in Figure 9.

Figure 9: Vibration motor concept. This motor creates vibrations by rotating a mass.

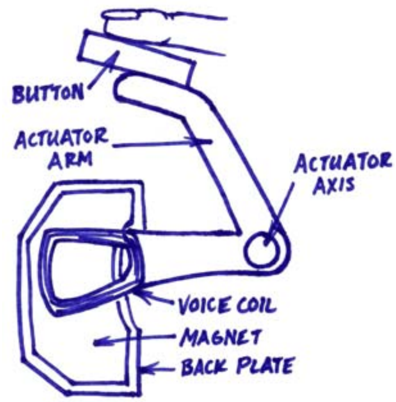


7.2.2 Disk Drive Motor

The disk drive motor, better known as a rotary voice coil motor (see Figure 10 below), consists of a magnet, a coil of wire, and a voltage source, which can be either DC or AC. When current flows through the coil, a magnetic field is induced which reacts with the magnetic field of the permanent magnet. This produces a torque about the actuator axis, causing the arm of the motor to move. This type of motor achieves a limited rotary motion of the arm fixed to the coil. In Figure 11, a sketch can be seen relating this concept to our project.

Figure 10: A partially-disassembled disk drive motor. Magnet is moved to expose the wire coil. [12]

Figure 11: Voice coil concept. A rotary voice coil motor could be placed underneath each button.



7.2.3 Speaker Motor

Another type of voice coil motor uses a magnetic core that is surrounded by the voice coil. A common example of this type is the standard audio speaker. When a current is passed through the voice coil, it induces a magnetic field perpendicular to the plane of the coil. This induced magnetic field reacts with the existing magnetic field of the magnetic core to cause a linear displacement of the coil. A speaker motor is shown in Figure 12.

The speaker motor is a simple design. Since all force is transmitted to the button through magnetic fields, there are very few moving parts. Constraining the button is more complicated. The simplest way would be to suspend the button on a membrane, but this does not guarantee one-dimensional movement of the button. Further, the stiffness and damping properties of the membrane material could cause difficulty in controlling the exact button movement. We could use a linear bearing system, but it would be more complicated and difficult to build. Another problem that may occur with this type of motor is the size of the magnet needed. To drive the button, a large magnet may be necessary to produce the required force. Thus it would be hard to position the motors beneath the buttons. A simple sketch of the speaker motor concept is shown in Figure 13.

Figure 12: Speaker motor

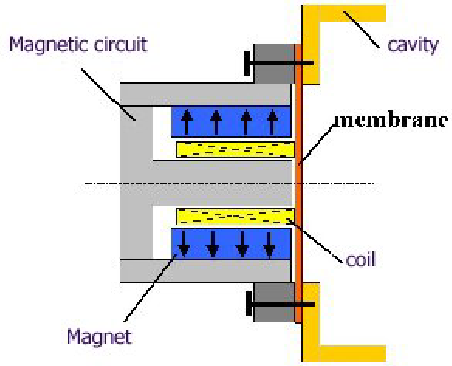
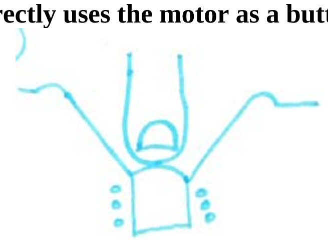


Figure 13: Speaker motor concept. This concept directly uses the motor as a button.



7.2.4 Stepper Motor

A stepper motor is an electromagnetic device that uses digital pulses to electronically switch a magnetic field. This produces the movement of a magnet, which is attached to a mechanical shaft [13]. A stepper motor is shown in Figure 14.

For our purposes, the stepper motor would be used in the following manner. It would be attached to the end of a lever opposite from the button, and would sit directly under the lever. Then, using a computer, the desired vibrations can be translated to the button. This mechanism is seen in Figure 15.

Figure 14: Linear stepper motors creates motion by altering the magnetic field around a magnet [13].

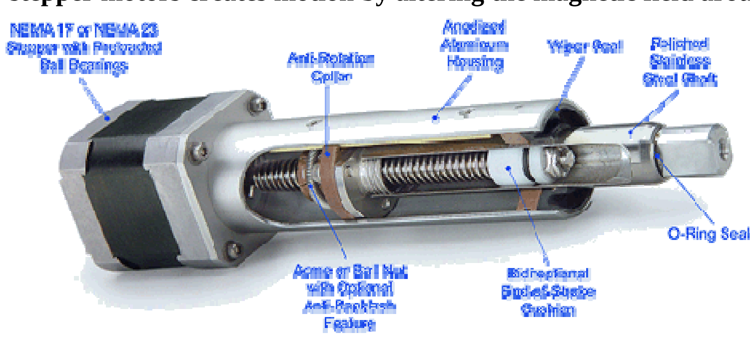
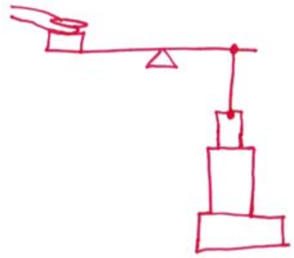


Figure 15: Stepper motor concept. The stepper motor is attached to the lever arm that controls the position of the button.



7.2.5 Tactors

Tactors are small vibrating motors, similar to those used in cellular phones. Currently there are two types available: pneumatic and electromagnetic (see Figure 16). The pneumatic tactor is made of plastic and latex, and produces a tapping sensation in the finger by pulsing air through the latex bladder. The electromagnetic tactors utilize a magnet and electrical coil to produce a tapping sensation in the finger [14, 15].

Tactors have a binary output, which means that the amplitude of the haptic cues cannot be varied. However, the frequency of the cue can be varied by changing the amount of power supplied, or by turning it on and off quickly. As many as sixteen Tactors can be controlled through a TactaBoard at once. And, the TactaBoard has a serial computer port [14].

Figure 16: Electromagnetic and pneumatic tactors. Tactors produce a tapping sensation in the finger through vibrations (electromagnetic) or air pulses (pneumatic) [14, 15].

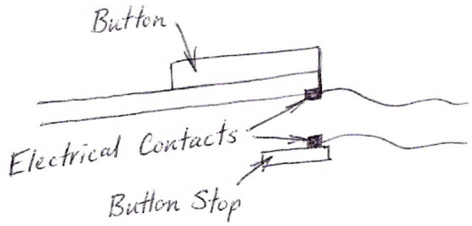
Electromagnetic Tactor *P2S Pneumatic Tactor*

7.3 Position Sensors

7.3.1 Simple Switch

Our first position sensor concept was a simple, switch-like device, which is sketched in Figure 17. This device would have two contacts, one attached to the moving button and the other attached to the base. When the button was pressed down, the two elements would come into contact, completing a circuit and sending a signal to the computer interface.

Figure 17: By pressing the button, the subject would complete a circuit.

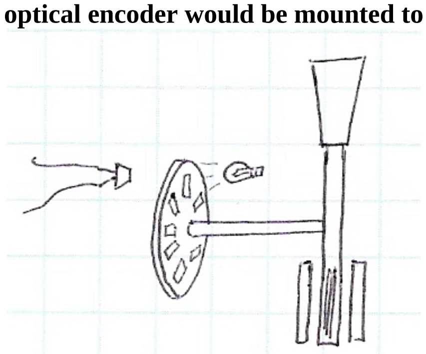


7.3.2 Optical Encoder

Our second position sensor concept was an optical encoder, and it can be seen in a sketch in Figure 18. Optical encoders are linear/angular position sensors that use light and optics to sense motion. A rotary optical encoder consists of a glass disk with equally spaced markings, a light source on one side of the disk, and a photo detector on the other side. The markings on the disk temporarily obscure the passing of light as the disk rotates, which causes the encoder to output a pulse. To measure the position of an object, the output of an encoder can be connected to a counter, which records the pulses generated to determine the position of the object [16].

With an optical encoder attached to each button, we would be able to detect when the button is pressed and record it through our computer interface. This type of sensor would also allow us to examine whether subjects are capable of duplicating a waveform by pressing a button in a particular way.

Figure 18: The optical encoder would be mounted to the button axis.



Variations of the concepts above are included in section 19.1 of the Appendix.

8.0 CONCEPT SELECTION PROCESS

After our brainstorming session, we discussed our ideas and created lists of the advantages and disadvantages of each concept. We then created several scoring matrices, and chose the concepts that best achieved our engineering specifications.

8.1 Layout

The flat, box-shaped concept has a few disadvantages. Although it has long buttons to accommodate different hand sizes, it is not designed for very small hands (i.e., a child's hands). Also, depending on the length of the test, a subject may have to keep their hand flat against the device for long periods of time, so the muscles may become exhausted. However, it has the simplest design, and will be easiest to manufacture.

The curved or computer mouse-shaped concept has the disadvantage of being the most difficult to manufacture since the bottom of the apparatus is the only flat face. But the angle of the thumb is accounted for, making it a more comfortable design.

The pie-shaped concept has the advantage of being easily manufactured, while still being comfortable for the hand.

To help us choose the best design, we created a scoring matrix (Table 1) using the applicable engineering specifications from our QFD and the list of pros and cons for each concept. The matrix shows that the pie-shaped layout is the best choice.

Table 1: Layout Scoring Matrix. This matrix uses our engineering specifications to determine the best layout concept.

Engineering Specification	Layout		
	Flat	Curved	Pie-Shaped
Maximum wrist angle of 10º	-	+	+
Variable age range	-	-	+
5 buttons	+	+	+
Advantages	+1	+1	+1
Disadvantages	-2	-1	0
Total	-2	+1	+4

8.2 Motor

The simple vibration motor is advantageous in the simplicity of the setup. But it lacks control over the amplitude of vibration and it cannot produce step displacements.

The rotary voice coil motor is a good choice because it can be built on our limited budget. However, it is possible to supply too much current, which may cause the Plexiglas that supports the coil to melt.

The speaker motor is a great design because of its simplicity. Since all force from the magnetic fields is transmitted to the button, there are very few moving parts. But constraining the button is complicated. Also, size may be an issue because a large magnet may be needed.

The linear stepper motor would be perfect for this application because of its precise motion control. But six of these actuators would cost an exorbitant amount of money. In addition, stepper motors are very slow and would not be able to produce a wide range of cue frequencies.

Tactors have a few pros and cons. The amplitude of the haptic cues cannot be varied, and the signal must be varied constantly to modulate the frequency. But systems are commercially available that could control all of the Tactors over one serial computer port. Also, the pneumatic tactor could be used for testing with fMRI.

Again, we created a scoring matrix (Table 2) using the applicable engineering specifications from our QFD and the list of pros and cons for each concept. The matrix shows that the disk drive motor is the best choice.

Table 2: Motor Scoring Matrix: This matrix uses our engineering specifications to determine the best motor concept.

Engineering Specification	Motor				
	Simple Vibration	Disk Drive	Speaker	Stepper	Tactor
100% programmable	-	+	+	+	-
Total size less than 2 ft^2	+	+	-	+	+
AC source voltage 110V	-	+	+	+	+
Amplitude range for haptic cues .25 to .5 in	-	+	+	+	-
Minimum force of cues 100 mN	+	+	+	+	+
Frequency range of cues 0.5 to 1000 Hz	-	+	+	+	-
Advantages	+1	+1	+1	0	+2
Disadvantages	-2	-1	-2	-1	-2
Total	-3	+6	+3	+5	0

8.3 Position Sensors

A large disadvantage to the switch sensor concept is that it can only be on or off. If the button is not pressed down completely, a signal will not be recorded. In addition, the possibility of testing whether a subject can duplicate a waveform is eliminated. Simplicity is on the side of the switch sensor, though. We could easily and cheaply create our own switch sensor.

The optical sensor concept offers an accurate reading of any button movement induced by the test subject. It would allow the scientist to test whether the subject can duplicate the waveforms.

Table 3 is another scoring matrix that uses the applicable engineering specifications from our QFD to identify the best choice for the position sensor. Here, again, we have utilized our list of pros and cons for each concept. The matrix shows that the optical encoder is the better choice for a position sensor in our device.

Table 3: Position Sensor Scoring Matrix. This matrix uses our engineering specifications to determine the best sensor concept.

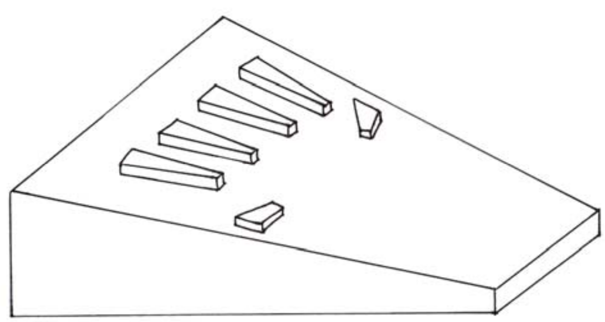
Engineering Specification	Position Sensor	
	Switch	Optical Encoder
100% programmable	-	+
Total size less than 2 ft^2	+	+
Source voltage required 110V	+	+
Advantages	+2	+1
Disadvantages	-2	0
Total	+1	+4

9.0 SELECTED CONCEPT: THE "ALPHA DESIGN"

9.1 Selected Layout

The selected concept will have the appearance of a wedge. This design will be able to accommodate different hand sizes, seen in Figure 19. There will be six total buttons: one for each finger and two thumbs so either the right or left hand can be used in testing. The buttons will need to be spaced appropriately. If the buttons are too closely-spaced, it may be hard for the test subject to distinguish which button actually produced a vibration. Also, we want to have enough room for the internal components to fit inside (motors, sensors, wiring, etc.). In addition, the flat surfaces of this pie-shaped design will make it easy to manufacture.

Figure 19: Pie-shaped layout of selected design



9.2 Selected Motor

After comparing the benefits and drawbacks of each type of motor we decided to use the rotary voice coil motor. This type of motor provides us the most benefits and least drawbacks of all the motors considered.

Since it is a voice coil motor, it is completely programmable by controlling the current supplied to the voice coil. The rotary voice coil can be run on AC current to produce a vibration, or DC current to produce a stepped displacement. Displacement amplitudes are directly correlated to the supplied current, allowing for amplitude control. Vibration motors lacked the ability to easily change displacement amplitude and were incapable of producing stepped displacements.

The motion of the rotary voice coil motor is easy to constrain. Use of a high quality bearing at the pivot point of the assembly constrains all but the necessary degree of freedom with negligible frictional losses. Motion constraint of the linear voice coil motor would be much more difficult because of the need for more complicated linear bearings. Suspending the button via a rubberized membrane was also considered for the linear voice coil motor, but ultimately rejected, as this would only constrain lateral motion and not necessarily rotational motion.

The rotary voice coil motor also fits well within our space constraints. Several motors can be stacked horizontally which saves space and allows the motors to share magnets. Placement of linear voice coil motors in our apparatus would have been more difficult as these motors are usually wider and cannot be stacked in the same manner.

The model in Figure 20 below represents a possible configuration of the apparatus buttons and motors. One key feature of this setup is that the motor coils are lined up next to each other while the buttons are more spread out. This allows for a more efficient use of magnets between the motors while maintaining the ability of the setup to work with different hand sizes. The model is also shown in other orientations in Figures 21 and 22.

Figure 20: This CAD rendering gives an example layout of four buttons mounted on rotary voice coils.

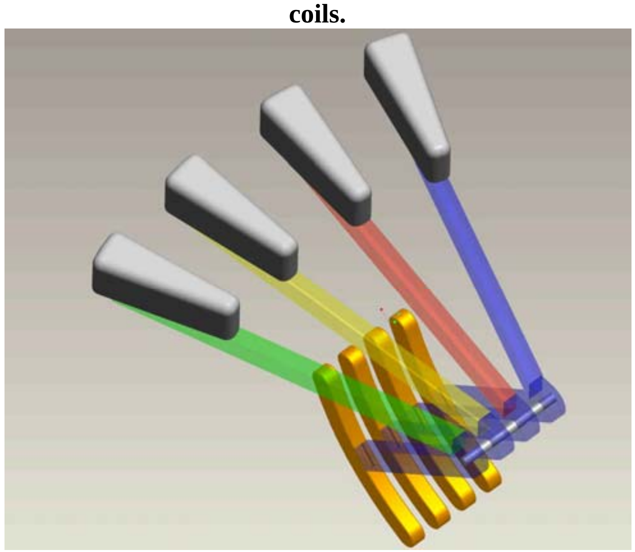


Figure 21: A view of the CAD model looking down from the fingertips

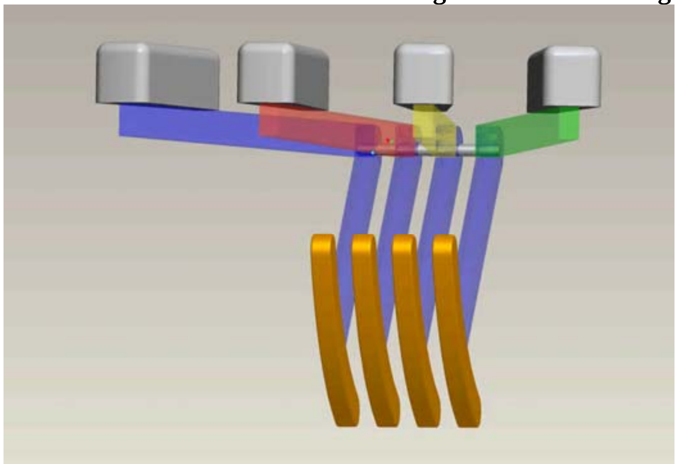
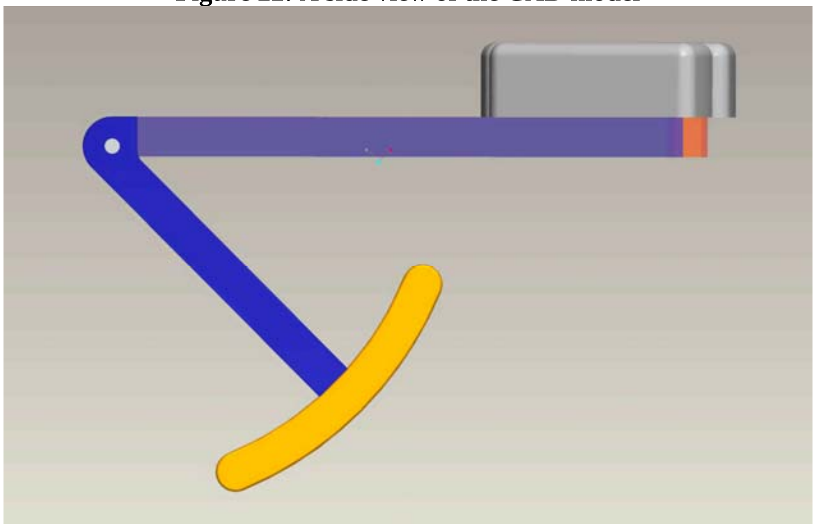


Figure 22: A side view of the CAD model



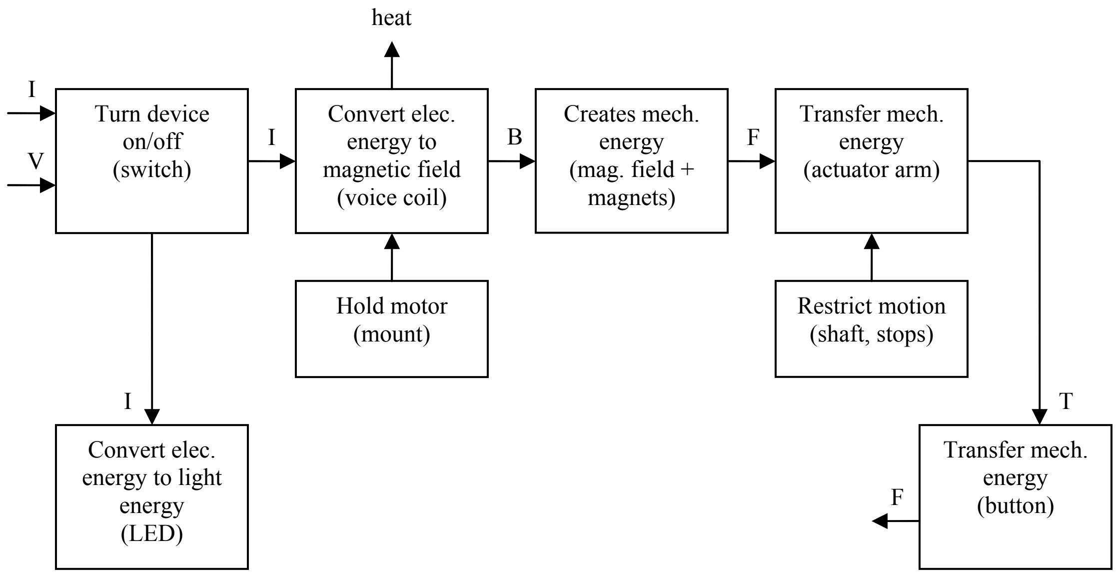
9.3 Selected Position Sensor

Our team has chosen to use optical encoders as our position sensors. An optical encoder will be attached to each button along the axis to allow its angular position to be recorded. This type of sensor provides an opportunity for more detailed research. In addition to recording whether a button has been pressed, it can also record how the button was pressed. For example, this enables the researcher to test a subject's ability to reproduce the haptic cues they have felt.

9.4 Functional Decomposition

A basic functional decomposition of the selected concept is shown below. The purpose of the functional decomposition is to break down the entire device into several main functions that describe what the device does. Dividing the device into finer functional detail helps to better understand the design problem.

Figure 23: Functional Decomposition. The functional decomposition breaks the device down into its main functions.



10.0 ENGINEERING DESIGN PARAMETER ANALYSIS

10.1 Use of Plexiglas

Our team initially wanted to use Plexiglas for many different components of the device. But before choosing Plexiglas as the definite material, we needed to research some of its material properties and determine if it would indeed be suitable. From past experience and research, we know that Plexiglas is readily available, both break- and impact-resistant, not easily deformed or shattered, easy to work with using a laser cutter and appropriate CAD tools, easily bonded, rather lightweight, and it does not have an extremely low melting temperature. Various properties of Plexiglas, listed in Table 4, verify that Plexiglas is lightweight, strong, and not easily melted. Reviewing the properties and manufacturability of Plexiglas, it is a simple yet very effective material for use in our project.

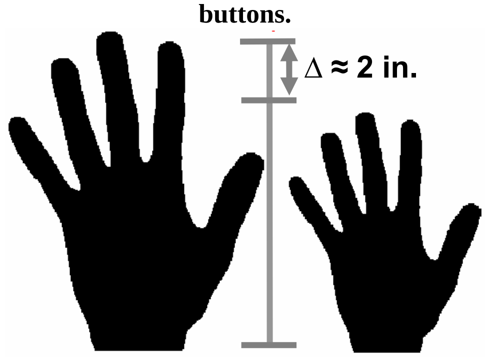
Table 4: Properties of Plexiglas [7,17,18]

PROPERTY	VALUE
Density (g/cm^3)	1.19
Tensile Strength @ Room Temperature (MPa)	70
Yield Strength (MPa)	105
Compressive Strength (MPa)	124
Melting Temperature (^oC)	135

10.2 Buttons

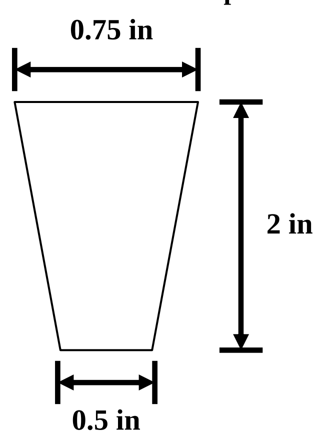
The buttons on our testing apparatus are an important aspect of our design because they will be the primary component interacting with the human subject. We needed to determine the size and shape of the buttons. Per our engineering specifications, the device must be able to be used by both children and adults, so the buttons must be adaptable to different hand sizes. To obtain the button length required to achieve this, we measured the difference in length between small and large adult hand sizes. We found this difference in length to be 2 in. (see Figure 24).

Figure 24: Measuring the difference in length between small and large adult hands helped us design buttons.



One of the faceplate designs will have a radial arrangement of the buttons, and the buttons will be placed fairly close together. To allow for this design, we chose to make the buttons a trapezoidal shape (Figure 25). (More information on the radial faceplate can be seen in section 11.2.)

Figure 25: Dimensions of trapezoidal buttons



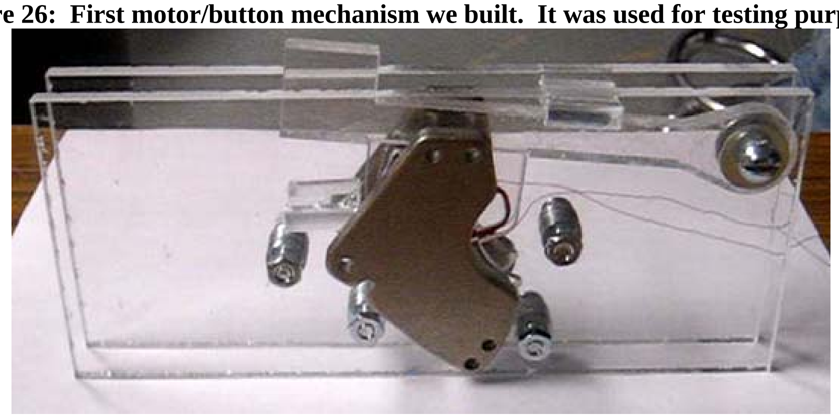
Finally, we would like to make the buttons out of Plexiglas using the laser cutter, so they will be easily integrated into the rest of the apparatus. This material choice demands that our buttons have a flat, smooth surface.

10.3 Motors

Our team will use rotary voice coil motors to move each button in our apparatus, and we will be making these motors ourselves. We initially built one motor/button mechanism

(Figure 26) and used it for testing purposes. The operation of a voice coil motor is based on the concept that a magnetic field exerts a force on a current-carrying wire placed in the magnetic field. This force will be translated into a torque, which will produce the rotary motion of our buttons.

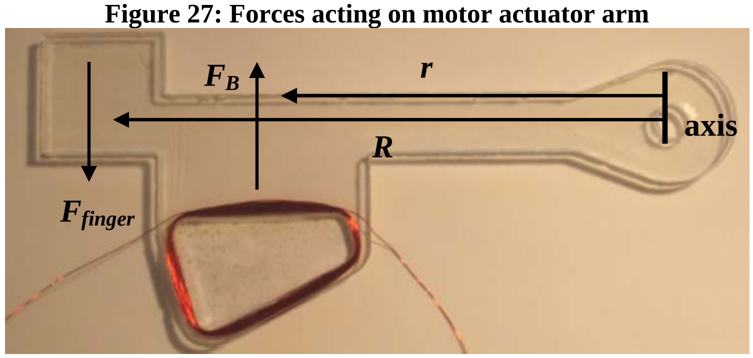
Figure 26: First motor/button mechanism we built. It was used for testing purposes.



10.3.1 Motor Force

Our team had to determine the design parameters of our voice coil motor. We first needed to establish the minimum force required to move each button when a human subject's finger is resting on it. A large range of forces will be used for testing purposes (to vary the frequency and amplitude of vibrations), thus we wanted to have a rough idea of what motor forces to aim for. To do this, we first used a fish scale attached to a string wrapped around a finger to obtain an estimate for how much force a finger would exert. We determined the length of each motor's actuator arm based on the maximum button displacement needed, and performed a moment balance about the arm axis to determine the minimum force, $F_{B,min}$, required from the motor (see Figure 27 and related equations).

Figure 27: Forces acting on motor actuator arm



F_{finger} = force by finger
R = motor actuator arm length ≈ 4.5 in.
F_B = force by motor
r = distance from axis to coil center ≈ 3.223 in.

$$\Sigma M = F_{finger} \cdot R - F_B \cdot r = 0 \quad \rightarrow \quad F_{B,\min} = \frac{F_{finger} \cdot R}{r}$$

10.3.2 Motor Current Related to Force

The force, F_B, acting on the wire coil in our motor will be equal to the amount of current traveling through the wire, i, multiplied by the length of the wire, L, and the magnitude of the magnetic field which the wire coil is submerged in, B (Eqn. 1) [7]. This relationship is valid as long as the magnetic field is perpendicular to the wire coil.

Equation 1: Equating the force produced in a voice coil motor [7].

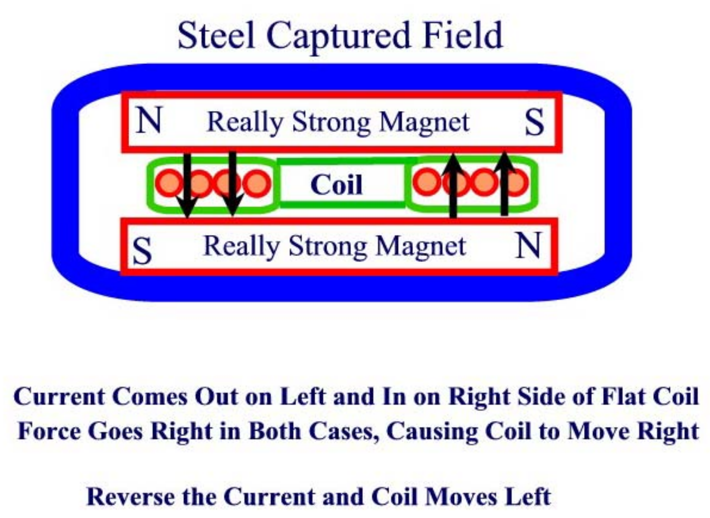
$$F_B = iLB$$

We needed to ensure that our motors would produce the necessary amount of force, so our team had to determine the required values for i, L, and B. The magnets we are using to create the magnetic field have a particular rating, which gives us the magnitude of the magnetic field. The amount of current can be varied to produce a particular force output. We knew the length of the wire, the amount of current being supplied to the motor, and the minimum force needed to move a button; however we did not know the rating of the magnets. To determine what levels of currents we needed to produce the desired forces, we had to run "trial and error" tests with the prototype motor we built. This essentially allowed us to develop a table of force outputs for current inputs that the researcher can use in testing. The results of these tests can be seen in section 13.

10.3.3 Importance of Coil Shape

Another concern relating to our motor design was the shape of the wire coil. Our team saw several other rotary voice coil motors and most of them had a wire coil shaped like a curved trapezoid. We discovered this is due to the fact that it is important to have two long, straight sections in the wire coil. The wire coil will be sandwiched between two magnets, with the permanent magnetic field pointed in opposite directions at the two ends of the magnets due to their polarity. This phenomenon is shown Figure 28 [19].

Figure 28: Interaction of current and magnetic fields in a voice coil motor to produce movement [19].



10.5 Faceplate and Frame

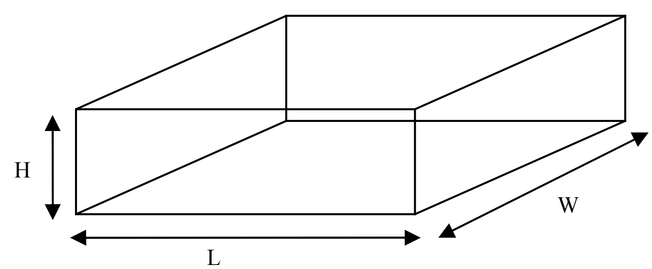
The final faceplate and frame dimensions were determined following final spacing and dimensioning of the buttons, voice coil motors, stops, and motor mounts.

After we determined the spacing of the motors and button mechanisms, we designed the final button layouts. The design of the faceplates (radial and circular, see section 11.2) was simple to draw in BobCAD, and the base was the same as area LW in Figure 29. We did, however, have a faceplate size restriction (area LW) of less than 2 ft^2 to satisfy the engineering specifications.

The frame was the simplest component of the entire device. All faces of the frame are flat and it resembles a small box (Figure 29). It was designed to make the entire device as small as possible. To construct the frame, we simply had to determine the dimensions L, W, and H (Figure 29), draw the rectangular faces in BobCAD, cut the Plexiglas with a laser cutter, and glue the pieces together. Our sponsor wanted to keep the appearance of the device as simple as possible, and this design was the simplest model that still met the engineering specifications.

Both the faceplate and frame were made of Plexiglas. Reasoning behind this decision is described in section 10.1.

Figure 29: Dimensions and shape of the frame; length L, width W, height H



10.6 Optical Encoder Selection

Our team had several specific requirements for the optical encoders we used in our design. To allow for precise position measurements, we wanted to make use of a linear rather than a rotary encoder. A rotary encoder would have to be mounted to the actuator axis, which only rotates a small amount as the button is moved, making it difficult to obtain precise measurements. The linear strip of a linear encoder can be mounted directly to the moving button support, so our position measurements will be as exact as possible. We also wanted our linear optical encoders to have the highest standard resolution available.

10.7 LED Selection

The LEDs used on our apparatus had to fulfill several requirements. First of all, they must be capable of producing at least five distinctly different colors. We preferred to accomplish this through the use of just one LED light per button to prevent the human subjects from associating a spatial location with a particular color. The LEDs used must also have a fairly wide viewing angle to allow test subjects to view them from various heights and positions.

10.8 Design for Manufacturability/Assembly

Our haptic memory project is a one-of-a-kind device that will be used to research the persistence of haptic memory. It was designed in a specific way for a specific purpose. The design will not need to be mass-produced, thus the time for assembly is not of large importance.

We decided to use Plexiglas for many of the components of the device because it is easy to design and manufacture the pieces using an appropriate CAD program and laser cutter. If the researcher decides to change the dimensions or shape of certain components, it can be done easily and quickly. And since this device is one-of-a-kind, making small alterations over time will not pose a problem.

10.9 Failure and Safety

Our team used DesignSafe 3.0 software to analyze the safety issues and risks associated with our prototype design. We strived to determine all risks associated to the use of the device and rank them appropriately according to severity and probability of each. We analyzed mechanical, electrical, and ergonomic risks to both the test subjects of varying ages and the researcher. As we had assumed, the most significant risk to the user is associated with the electrical components of the device.

All risks that we analyzed were classified as either "low" or "negligible", except for the risk of contact with direct parts (the wires and power supply). This was classified as a "high" risk level. Although we only used 9V batteries to power the prototype LEDs and motors, there is still some risk of electrical shock. In the future, the sponsor may decide to use a separate power supply with the potential of supplying more than 9V to the device. This, of course, would pose an even greater risk.

The prototype has many more safety issues and risks than the final design will have. The prototype has exposed wires running from the LEDs and voice coils to the control circuit and batteries. The use of a computer and [possibly] a LabVIEW program with the final design will eliminate many of the wires as well as the control circuit. Overall, the final design will be much safer than the current prototype. But in the meantime, before the final design is produced, we need to eliminate or reduce the risk from the electrical components. The researcher should be well-educated on the proper use of the device, the test subject should only come in contact with the faceplate and buttons of the device, and the circuit should be re-wired to get rid of any exposed wires that a user could come in contact with.

As described in section 10.8, this device is one-of-a-kind. If one component fails, it will not be a problem to remake that component. In addition, the lifetime of the device is not of great importance, either. Parts can be purchased or remade quickly.

A more detailed analysis from DesignSafe 3.0 is available in Appendix 19.5.

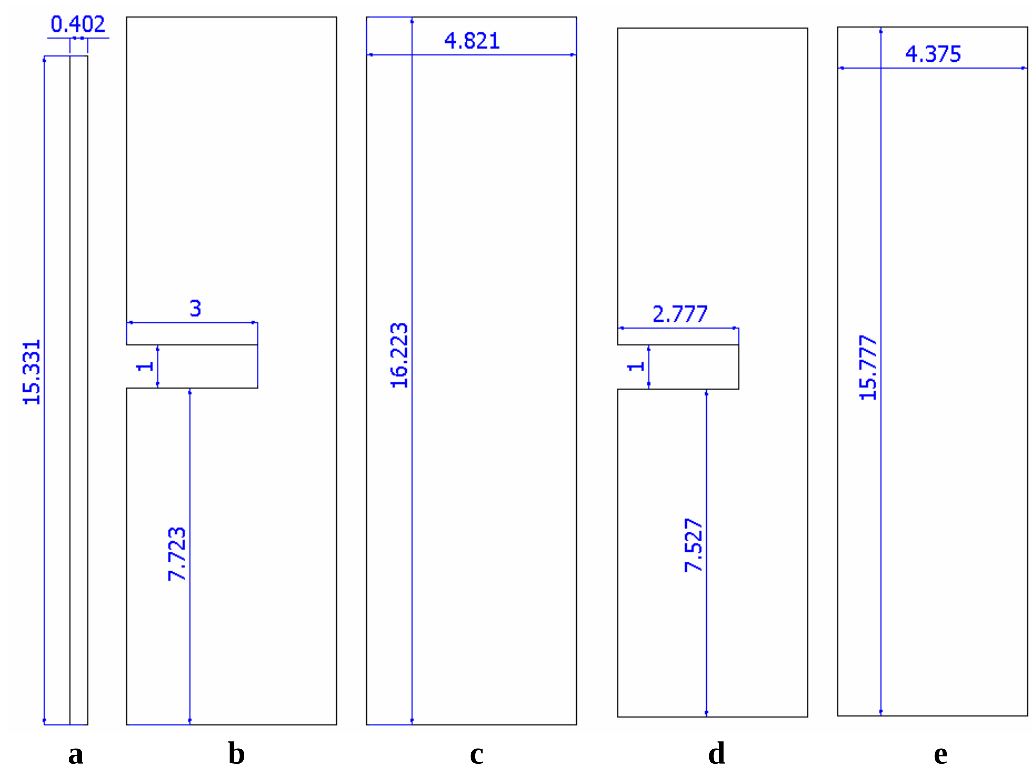
11.0 FINAL PROTOTYPE DESIGN DESCRIPTION

The haptic memory apparatus changed numerous times throughout the whole design process. The following sections describe in detail the final prototype design.

11.1 Device Frame

The base of the frame is a 16 by 16 in. square cut from quarter-inch Plexiglas. The four sides of the frame are rectangles cut from the same Plexiglas, one with a slot for wiring to run through (pieces b and c in Figure 30). The sides were glued to the outside edges of the base of the frame using plastic glue. Next, four slightly smaller rectangles (pieces d and e in Figure 30) were cut and glued along the sides of this structure, creating a small shelf which a 16 by 16 in. faceplate can rest on. Finally, four small rectangular strips (piece a in Figure 30) were made and glued to the inside of the box, forming a second shelf that holds the mounting plate.

Figure 30: Diagram of device frame dimensions (all in inches)



11.2 Faceplate Designs

Our sponsor requested two different faceplates that will be interchangeable and attach to the same frame: a radial design and a circular design. Both have five buttons rather than six, as we had originally designed. The radial design (Figure 31) has the buttons arranged in an arc formation, similar to the shape of a human hand, and the circular design (Figure 32) has the buttons arranged in a circle, similar to the Simon[2] game (Figure 2). The 0.875 in. squares in each faceplate are for the LED mounts.

Figure 31: Radial faceplate design (all in inches, degrees)

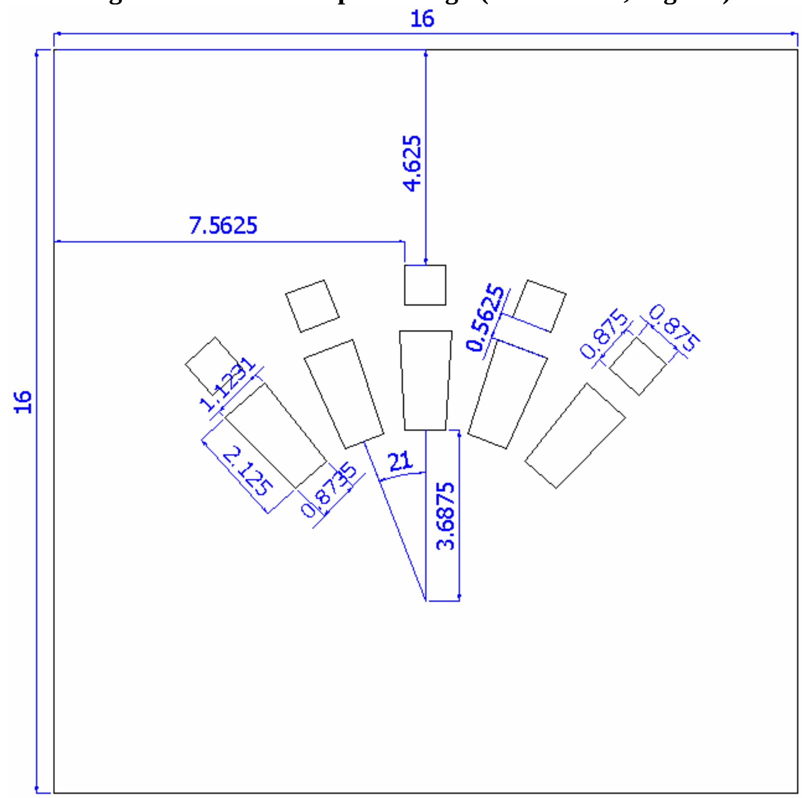
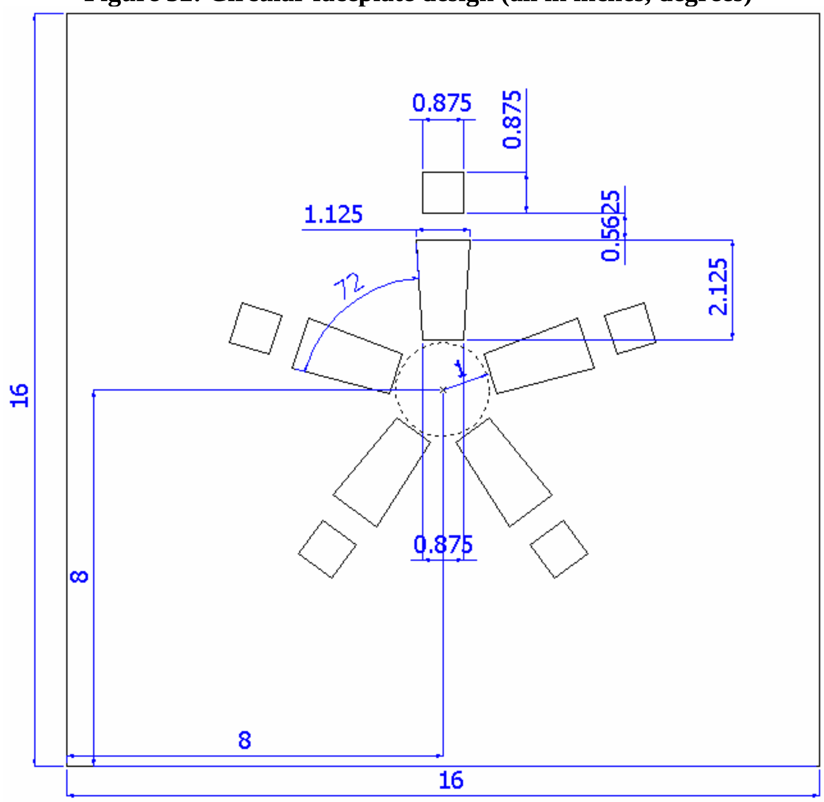


Figure 32: Circular faceplate design (all in inches, degrees)



11.3 Buttons

Each button consists of two pieces: the top piece and the button piece. The bottom piece with the groove (Figure 33b) mounts onto the end of the button arm (see Figures 34a-b) and the top piece (Figure 33a) sits on top of the bottom piece. The top pieces were sandblasted to have a finish different from the faceplates.

Figure 33a: Top button piece

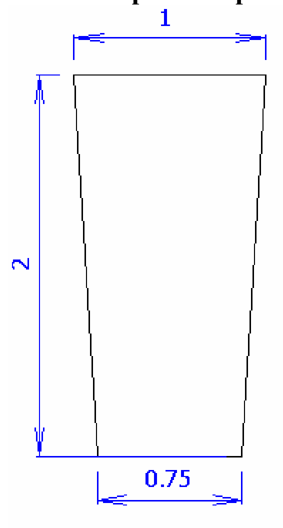
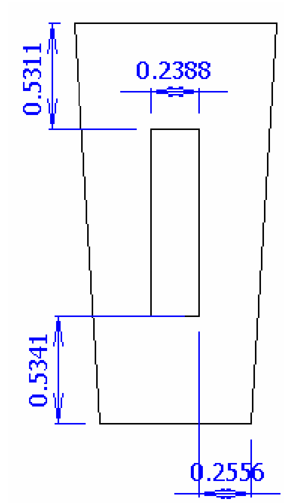


Figure 33b: Bottom button piece (all in inches)



11.4 Modular Button System

Our sponsor specified that he would like to able to easily change the layout of the buttons. In order to accommodate this specification, we developed a modular button system. The use of this system will allow our sponsor to place the buttons in any desired arrangement within the frame of the device. The button module consists of the button arm and motor coil sandwiched between two motor mounts. One LED and one optical encoder are also mounted to each module.

11.4.1 Button Arms

The button arm consists of three pieces: two outside layers (Figure 34a), a middle layer (Figure 34b), and the small piece around which the voice coil is wrapped (Figure 34c).

Figure 34a: Outside layer (x2) of button arm (all in inches)

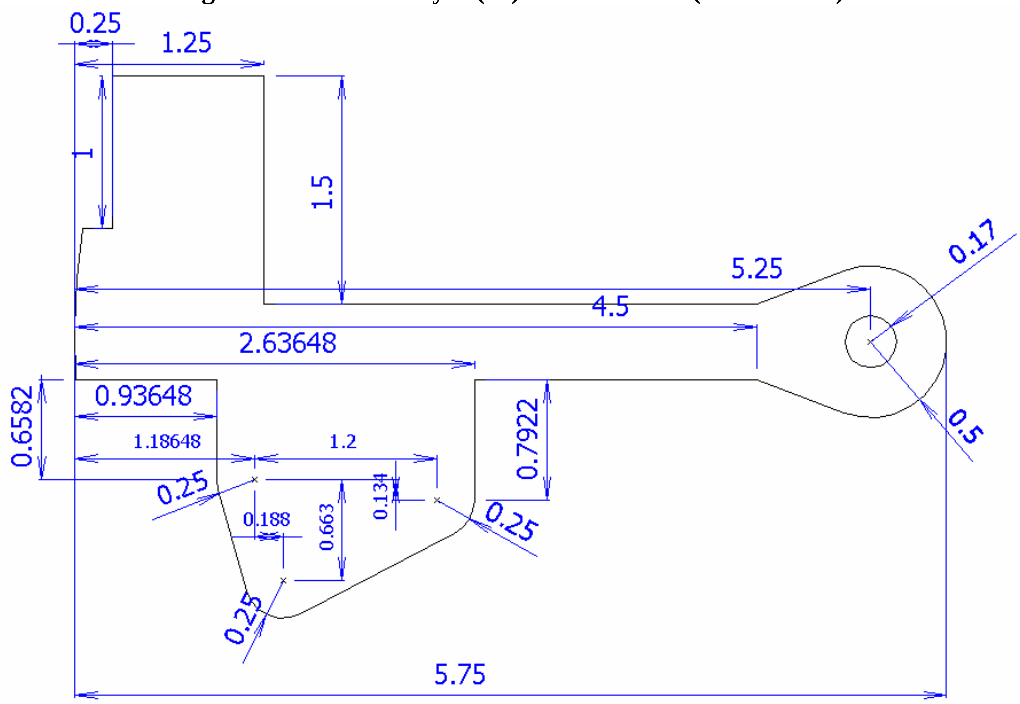


Figure 34b: Middle layer of button arm (all in inches)

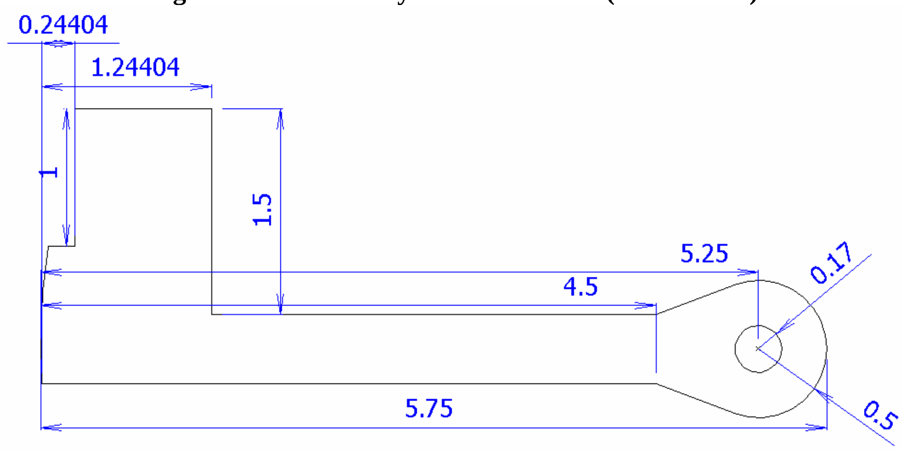
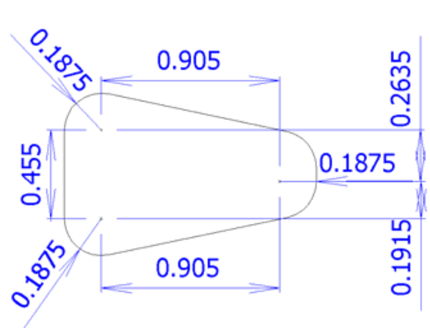


Figure 34c: Center piece around which the voice coil is wrapped (all in inches)



11.4.2 Motor Mounts

Each motor mount consists of two sides: the left-side mount (Figure 35a) and the right-side mount (Figure 35b). They are identical except for the cutout in the right-side to which the encoder mount (Figure 36) is attached. The holes in the encoder mount are slotted to allow for adjustments. One LED is attached to each 0.875 in. square that is cutout from the faceplate. Each of these assemblies (five in total) is placed on top of the motor mounts and aligned with the square holes cut from the faceplate.

Spacers (0.5 in. washers) are used to maintain a uniform gap of 0.4375 in. between the two plates and to prevent deformation when the motor magnets are mounted. The motor magnets are mounted opposite each other and centered over the motor coil. The strength of their magnetic fields is sufficient to hold them in place. The button arm rotates on a 0.25 in. diameter shoulder bolt using a bearing (5/16 in. inner diameter) to ensure smooth movement with minimal friction. Stoppers (with a thin piece of foam attached for padding) are inserted to restrict the movement of the button arm to 0.5 in. total.

Figure 35a: Left-side motor mount (all in inches, degrees)

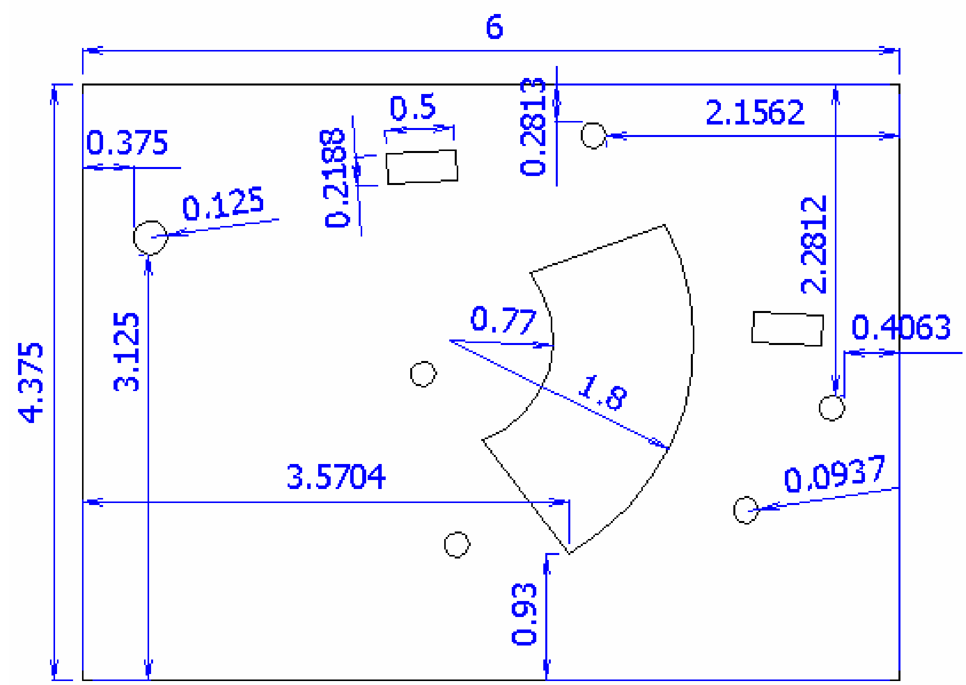


Figure 35b: Right-side motor mount (all in inches, degrees)

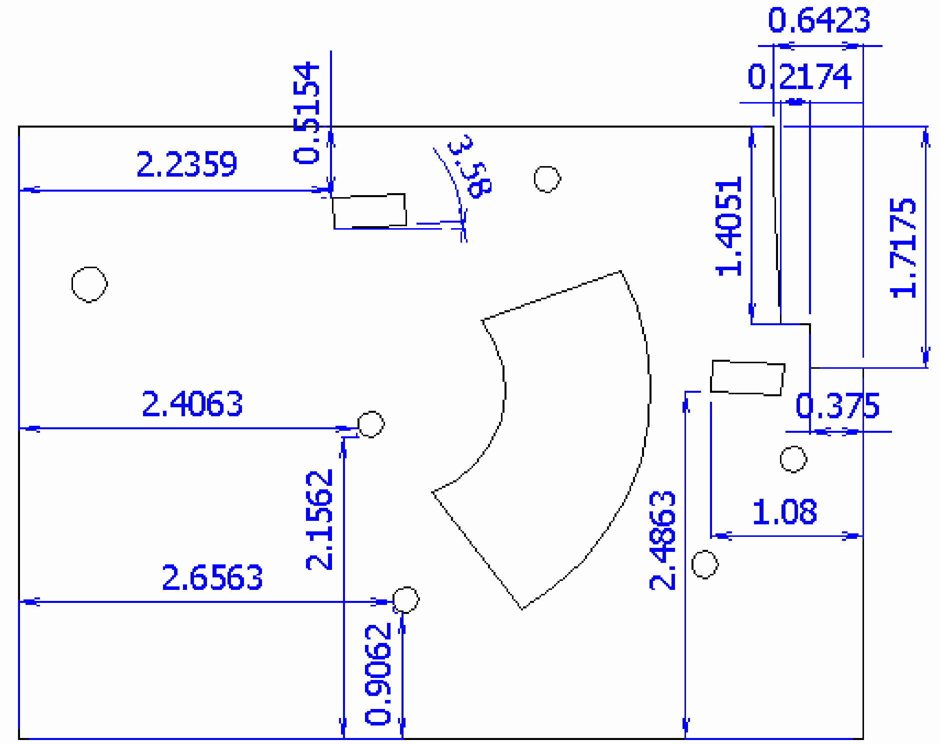
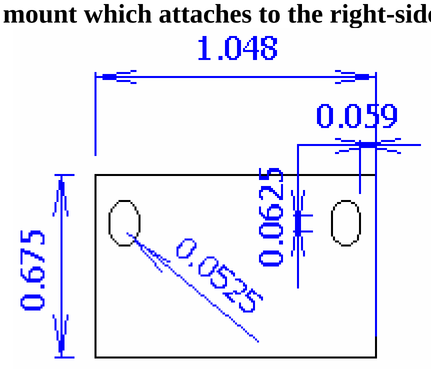


Figure 36: Optical encoder mount which attaches to the right-side motor mount (all in inches)



11.5 Mounting Plates

Since there are two completely different faceplates, we cannot permanently fix the motors to a particular location. We designed mounting plates that will allow the different button arrangements. Each faceplate design has a corresponding mounting plate that holds the motor mounts in place (Figures 37 and 38). The button modules simply drop into the slots on the mounting plates.

Figure 37: Radial mounting plate design (all in inches, degrees)

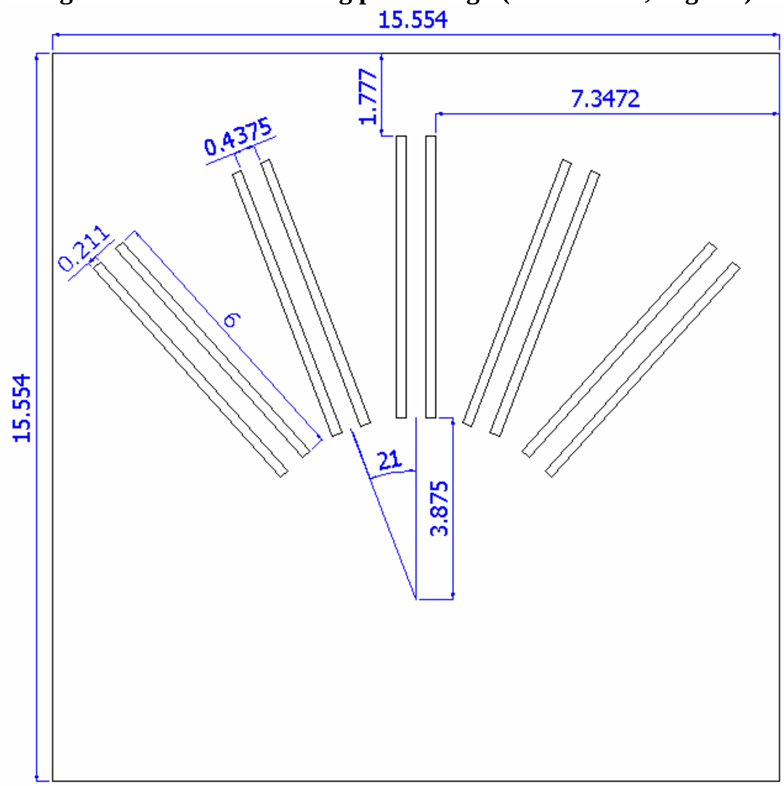
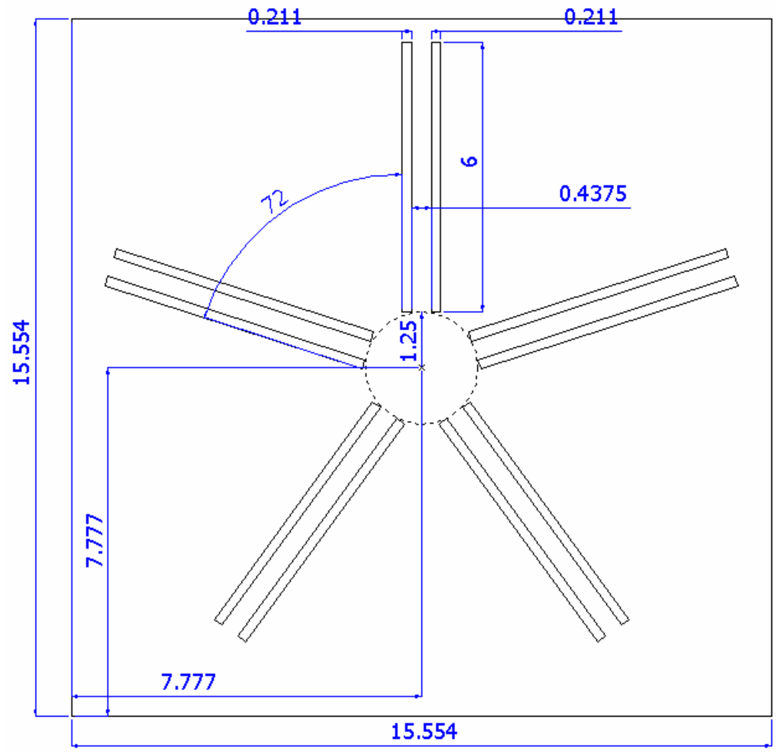


Figure 38: Circular mounting plate design (all in inches, degrees)



11.6 Optical Encoders

Based on the optical encoder requirements given in section 10.6, we have selected the proper encoder for use with our apparatus. We are utilizing a linear optical encoder from US Digital Corporation with a resolution of 360 counts per inch. This encoder module has part number HEDS-9200-360, and its corresponding linear strip has part number LIN-360-2 for a length of 2 inches [20].

11.7 LEDs

Our team is making use of a three-chip LED in our design. The LED we have selected from LEDtronics, Inc. (part number DIS-1024-105A) contains red, green, and blue chips that allow it to produce hundreds of different colors based on the amount of current it receives [21]. This particular LED also has a wide viewing angle of 120 degrees that allows test subjects of varying heights to see it clearly.

11.8 Prototype versus Final Design

The device built by our team is a prototype of the final design. We focused mainly on the mechanical operation of the apparatus, rather than the computer interfacing required for our final design. This is the main difference between our prototype and the final design. Rather than manually operating switches and adjusting potentiometers to select the cue sequences given to the test subject, the researcher will use a computer to control the final apparatus.

In addition to the need for switches, our prototype's lack of computer interfacing affects its operation in a couple other ways. Although the prototype is equipped with optical encoder position sensors, there will be no computer to read out the button positions until the final computer-interfaced design is completed. Also, our prototype does not currently have the capability of providing auditory cues to the test subject. The final design will make use of a computer sound card to produce the auditory cues.

12.0 MANUFACTURING PLAN

We needed to manufacture three types of components for the apparatus: frames, button modules, and motors. The necessary parts, processes, and tools for creating these components are listed in Table 5.

Table 5: Breakdown of manufacturing plan. This table lists the parts, processes, and tools required to manufacture and assemble the components of our apparatus.

Component	Part	Process	Tool
Frame	Plexiglas	Cut Plexiglas parts	Laser Cutter
	Plastic Glue	Assemble Frames	Syringe
	Nuts/Bolts/Washers	Assemble Frames	Screwdriver
Button Modules	Plexiglas	Cut Plexiglas parts	Laser Cutter
	Plastic Glue	Assemble Modules	Syringe
	Bushings	Mount Bushings	3/8" Reamer
	LEDs	Mount LEDs	Soldering Iron
	Optical Encoders	Mount Encoders	Screwdriver; Adhesive
	Power Supply	Mount Power Supply	
	Magnets	Mount Magnets	
Motors	Plexiglas	Cut Plexiglas Parts	Laser Cutter
	Plastic Glue	Assemble Motors	Syringe
	Voice Coil Wire	Wrap Motor Coils	

To use the laser cutter to manufacture our parts, we had to create a BobCAD file of each individual piece. After we drew the components in BobCAD, we used the laser cutter to cut the Plexiglas parts. Then we constructed the button modules, beginning with the button arm.

The button arm was comprised of six parts: the voice coil core, two outer faces, the arm core, and the bushing. Before we could wrap our coils, we needed something to wrap them around, so we glued the coil core and the two outer faces of the arm together. Then we wrapped the wire around the core until we had 110 coils. After the coils were wrapped, we slid the arm core between the two outer faces and glued it in place. To insert the bushing, we reamed the hole until it was just large enough for the bushing then press-fit it into place.

When the button arms were finished, we built the button modules. We glued the encoder mount to the appropriate module side. Then, on one side of a motor mount, we put bolts through all of the spacer holes and the arm mount hole. Washers were placed on all of the bolts to act as spacers to hold the module sides apart, and then the button arm was positioned on its mount. To finish, we placed the other module side on top, put nuts on the ends of all bolts, and placed our magnets in their mounting holes.

After the button modules were constructed, we had to create the frame, faceplates, and mounting plates. The faceplates and mounting plates were simple, we only had to create a BobCAD file and cut them out with the laser cutter. The frame was a bit more complex. We cut out all of the parts, based on our BobCAD file, with the laser cutter. To assemble, we glued the outer sides and the bottom together. When the glue on the outer sides had dried, we glued in the inner sides, making sure that they were placed so that we had a stepped interface at the corners rather than a single seam. When the inner sides were dry, we used the same strategy for a stepped interface to position the mounting plate spacers, and then glued them in place.

When manufacturing these components, we considered several tolerances. The most important of these tolerances was associated with the button holes and modules. We needed to manufacture and position the moving parts so that they would not collide with the frame. This means we had to be sure that the button faces were smaller than their corresponding holes. And, we had to be sure that the mounting holes for the modules were spaced so all of the modules would fit into the frame. We also had to consider the tolerances associated with using the laser cutter, which, as we found out, were larger than expected.

On this apparatus, the critical surfaces were the top and bottom of the frames. We had to be certain that the mounting holes on the bottom of the frame were positioned such that the buttons will not collide with the top of the frame when actuated.

We designed this apparatus with the manufacturing and assembly processes in mind. All of the tools and most of the materials required for this project were available to us through the ME 450 shop at the University of Michigan, Ann Arbor. Thus, a redesign due to problems with manufacturing and assembly was unnecessary.

13.0 TEST RESULTS

In order to determine whether our motors could produce enough force on the button to easily lift a test subject's finger, we conducted tests using gram weights. We placed various amounts of weight on the button surface and ran current through the voice coil to find the current level needed to lift the button and weight. The results of our tests showed that our button motors can easily lift the weight of a human finger when supplied with a relatively small amount of current, and these results are shown below in Table 6.

Table 6: Our motors can produce a button force of 1.962 N when supplied 1.411 A.

Mass (g)	Force (N)	Voltage (V)	Current (mA)
50	0.4905	3.186	482.0
100	0.981	5.259	795.6
200	1.962	9.327	1411.0

Before constructing our circuit, we had to determine the resistance of the coil for each motor. This was done by connecting each motor to a multimeter individually and recording the measured resistance. We found our motor coils to have an average resistance of 6.3 ohms. The complete results are shown in Table 6.

Using the circuit we constructed, we tested our prototype to ensure that it is capable of meeting our customer requirements. By adjusting the current supplied to each motor, we are able to alter the amplitude of the button movements. Also, at maximum amplitude, we can increase the force necessary to press down each button by further increasing the current supplied to the motor. In the same way, by adjusting the current levels through the red, blue, and green chips of each LED, we can successfully change their color. Hundreds of colors are possible, ensuring that our device is capable of producing distinct visual cues.

14.0 DISCUSSION: DESIGN CRITIQUE

We believe our prototype meets the majority of the specifications our sponsor provided. There are also many opportunities for improvement of this design.

The prototype we have developed is capable of providing fully programmable haptic and visual cues to the test subject. It also has the ability to determine the exact position of the button through the use of a linear optical encoder. In conjunction with a computer interface, this can be used to read the test subjects response, or actively control the position of the button through closed loop control. Each LED is capable of a wide range of colors that may also be controlled through computer interface, or by adjusting the current run through each of the leads of the LED. The modular button design allows the experimenter to change the arrangement of the buttons as needed to accommodate different hand sizes or experiment setups. The box is designed to accommodate these different layouts with the use of interchangeable base plates and faceplates. In addition, the prototype was easy to manufacture using a laser cutter and Plexiglas for a majority of the components. Each piece was drawn in a CAD program (BobCAD) and therefore, redesign is easy.

There are several areas in which this prototype could be improved. The current prototype is not computer interfaced. This can be resolved by creating the proper LabVIEW program, as all the other necessary hardware is already in place. Computer-interfacing the final design will eliminate many of wires that are currently running throughout the frame. Computer-interfacing will also solve the current prototype's lack of sound, as auditory cues will be provided through the computer's soundcard. Another issue with the current prototype is the curving of the button arms. We do not know the exact reason why the button arms curve to one side or the other, but likely reasons include initial defect in the stock material, heat induced warping during the laser cutting procedure, or improper seating of the sleeve bearing. This could possibly be fixed through different material selection or manufacturing processes. In addition, the prototype is quite large, so we believe that final design should be smaller. It will be easy to transport and perhaps not as intimidating as the prototype.

15.0 RECOMMENDATIONS

After completing the construction of our prototype, we have several manufacturing recommendations to improve of the quality of future devices that make use of our design.

Due to the type of Plexiglas used in our prototype, we had difficulty aligning the button arms inside the motor mount gaps. Many of the Plexiglas button arms came out curved, causing them to rub against the sides of the mounting pieces. Also, the bushings we press-fit into each button arm were often angled, rather than perpendicular to the arm due to inconsistencies in the Plexiglas and imprecise cuts by the laser cutter. Our team recommends the use of high-quality extruded Plexiglas in the final design to reduce these effects. We also feel the tolerances could be improved by using a well-aligned laser cutter for the final design. Often, we found the laser cutter in the shop to be cutting our material on an angle.

In addition, although the sand blaster created a nice finish on the Plexiglas, we found that the plastic glue reduced the opaqueness of the sandblasted Plexiglas. Because it will be important that test subjects are not able to see through the final apparatus, we recommend the use of colored (preferably black) Plexiglas to ensure opaqueness.

Our team had planned to use spacers rather than washers between the two mount sides on each button module, but we were unable to purchase the necessary size. For the final design, we recommend machining spacers to the appropriate size or special ordering them if possible.

16.0 CONCLUSIONS

The goal of this project is to design and build an apparatus for our sponsor that will be used to test the persistence of haptic memory. There are no devices known to exist that are similar to this project, therefore the basis for the design will be derived solely from requirements given by our sponsor. Our team must design and construct a device that provides distinct visual, auditory, and haptic cues. This apparatus must be capable of being computer-interfaced, so the researcher can program and select cues and record the subject's responses. It must also fit on a tabletop and adjust to different hand sizes.

The design we have developed to satisfy our customer requirements consists of five independent, identical button modules. Each module is equipped with a rotary voice coil motor that produces movement of the button arm when current is supplied to it. There is also a RGB LED to provide visual cues and a linear optical encoder to record button position on each button module. The five button modules will all fit into slots at the bottom of a box and a faceplate will drop over them, which the buttons and LEDs will protrude through. The button modules, box, and faceplates will all be made out of Plexiglas.

Our team has completed construction of a prototype of the final design just described, and our device is fully-functional. Using a circuit with potentiometers to provide variable resistance, we are able to light up all of the LEDs and create hundreds of colors by altering the current supplied to each. This ensures that our apparatus will be able to provide distinct visual cues. Our rotary voice coil button motors are able to provide a force at the button to lift more than 200 grams, so they will be capable of lifting a human subject's finger. We are also able to hold up the buttons by providing a constant current to the voice coils. With the addition of computer-interfacing, it will be possible to program the button movement, allowing for distinct haptic cues. Finally, our complete apparatus fits easily on a tabletop, and its interchangeable faceplates make it simple to change the button configurations.

17.0 ACKNOWLEGEMENTS

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Felix Huang, Graduate Student, University of Michigan Dept. of Mechanical Engineering
Bob Coury, Machine Shop Foreman, University of Michigan Dept. of Mechanical Engineering
Prashanth Gururaja, Franklin Jen, Robert Middleton, and Ho Yeung Shea, Team 1, ME450 Winter 2006, University of Michigan

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19. 0 APPENDIX

19.1 Description of Engineering Changes Since DR#3

Some changes were made to the design after Design Review 3. The prototype retained the same fundamental design. The position sensors and LEDs were incorporated into the button modules, the faceplates were modified to accommodate the LEDs, and the construction of the frame was finalized.

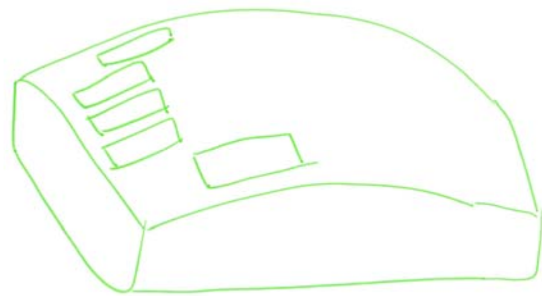
19.1.1 Motor Module Design

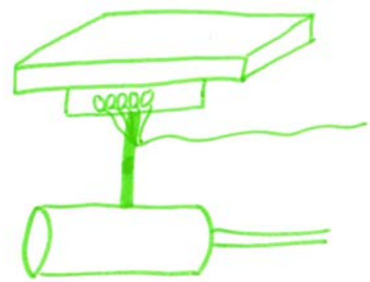
Since Design Review 3 the motor module has been modified to allow the attachment of the linear optical encoder. This involved changing the shape of one side of the motor mount and adding a Plexiglas bracket for mounting the encoder, as well as adding a rounded surface to the end of the button arm with a radius centered at the axis of rotation for mounting the encoder strip. We have also changed our bearing selection. While the selected ball bearings provided the desired ease of movement, they had too much lateral play. We decided to use SAE 841 Bronze sleeve bearings. These provide much better restraint of the button arm laterally. They also cost much less than the ball bearings, at $0.49 each versus $6.25 each for the ball bearings. We have also mounted the LEDs to the motor modules.

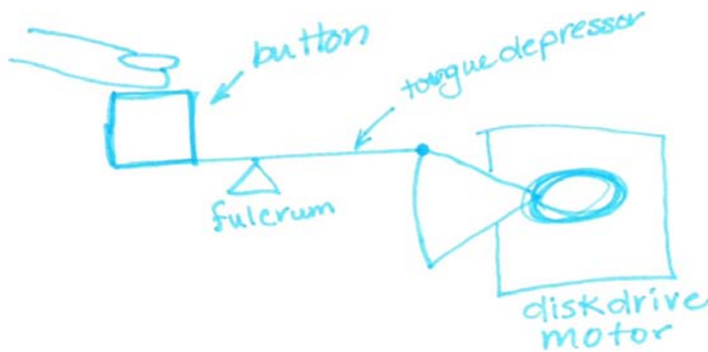
19.1.2 Faceplate and Frame Design

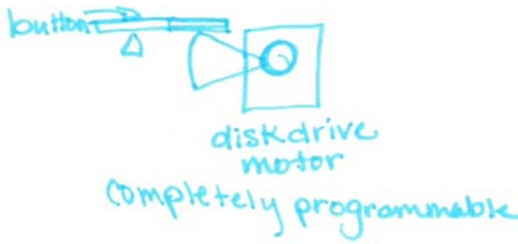
We added cutouts to the faceplates to allow the LEDs to fit through the faceplates and be visible by the test subjects. We also developed mounting plates to hold the button modules in the correct position inside the box. The design of frame was finalized to facilitate easy changing of the button layout. This was accomplished through use of tiered sidewalls inside the frame. The mounting plate sits on the first tier, the faceplate sits on the second tier, and the top of the faceplate is flush with the third tier.

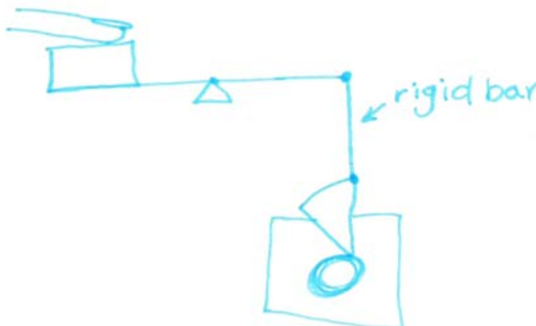
19.2 Additional Concepts

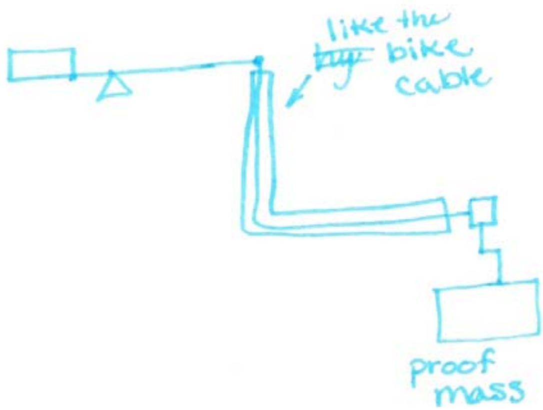




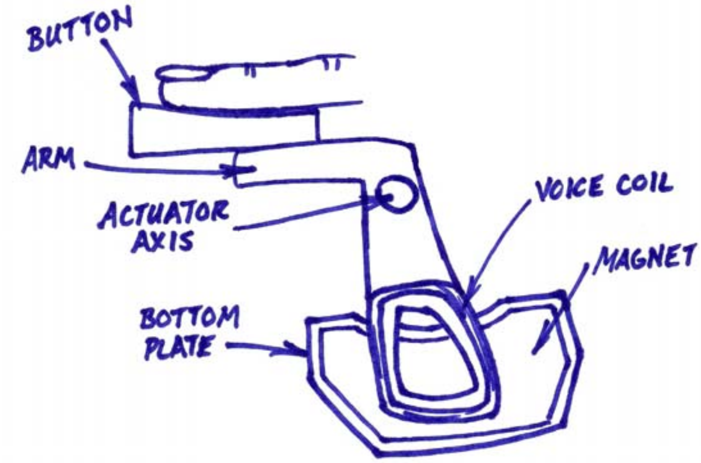


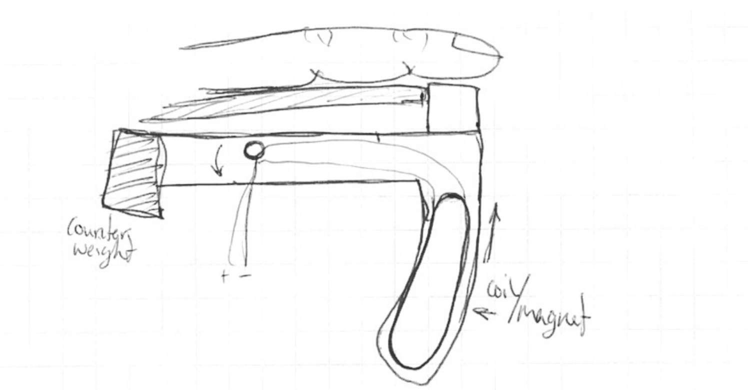

button
diskdrive
motor
completely programmable

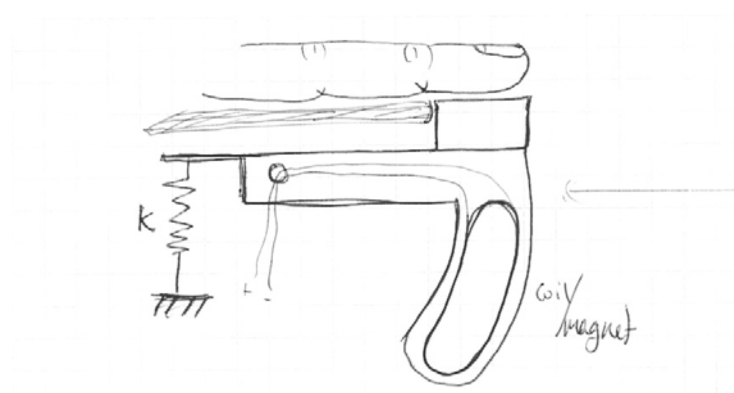

rigid bar


like the
bike
cable
proof
mass

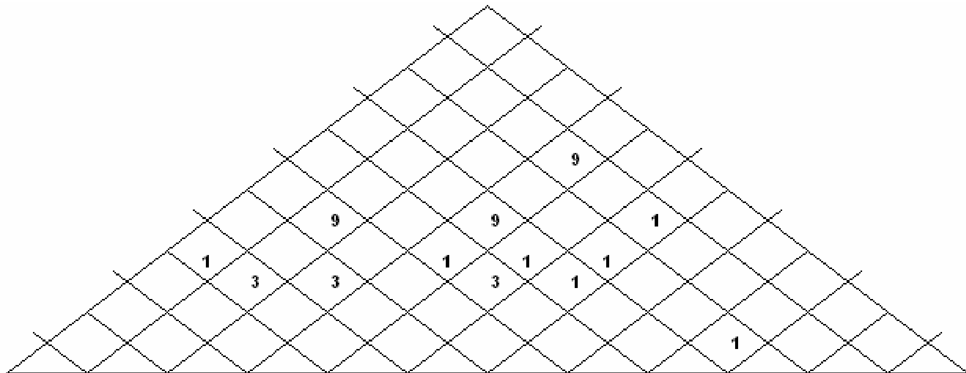

no amplitude
variation


BUTTON
ARM
ACTUATOR AXIS
VOICE COIL
MAGNET
BOTTOM PLATE


counter weight
+ -
coil/magnet


K
+ -
coil/magnet

19.3 QFD Chart



Customer Requirement	Importance	maximum wrist angle (°)	user age range (years of age)	difference in power supplied to LEDs (W)	programmability (%)	size of device (sq. ft)	source voltage required (V)	minimum difference in color wavelengths (nm)	number of buttons (#)	amplitude range of haptic cues (mm)	minimum force applied by haptic cues (mN)	frequency range of haptic cues (Hz)		Simon2	Tactuator
comfortable for hand	4	9	9			1			3	1	1	1		2	4
adjustable for different hand sizes	6	1	9						1					4	4
can be used for research	10		3	9	9	3	1	9	3	3	3	3		2	5
provides haptic cues	9				9		1		3	3	3	3		1	4
provides visual cues	8			3	3		1	9						4	1
allows for different cue combinations	9				9				3	3	3	3		2	2
colors are visually distinct	6			3				9						4	1
haptic cues can be easily sensed	7									9	9	9		1	4
reproducible	9			1	3			3		3	3	3		5	4
table-top size	5					9			1					5	4
plug-in	7						9							1	5
ambidextrous	2				1				9					4	1
Simon2		15	>7	N/A	0	2			4	N/A	N/A	N/A			
Tactuator		10	>5	N/A	100	2		N/A	3	0.0-26.0		0-400			
target		10	>5	0	100	2	110	40	6	4.0-12.0	100	.5-1000			

19.4 Bill of Materials

Item	Qty	Source	Catalog Number	Cost	Contact	Notes
Plexiglas	4	Carpenter Bros. Hardware		$35.56@	Carpenter Bros. Hardware	18" x 32" x 1/4"
Plexiglas	3	Home Depot		$2.19@	Home Depot	11" x 14" x 1/8"
Plastic Glue (Dichloromethane)		ME 450 Shop		free	Bob Coury	
Nuts	30	ME 450 Shop		free	Bob Coury	
Bolts	25	ME 450 Shop		free	Bob Coury	
Shoulder Bolts	5	Stadium Hardware		$1.00@	Stadium Hardware	0.25" diameter, 0.75" length
LEDs	5		DIS-1024-105A	$3.55@		
Optical Encoder Modules	5		HEDS-9200-360	$29.40@		
Linear Strips	5		LIN-360-2	$14.70@		
Duracell 9V batteries	5	Home Depot			Home Depot	
SAE 841 Bronze Sleeve Bearing	7	McMaster-Carr	6391K136		mcmaster.com	1/4" shaft, 3/8" OD, 3/8" Length

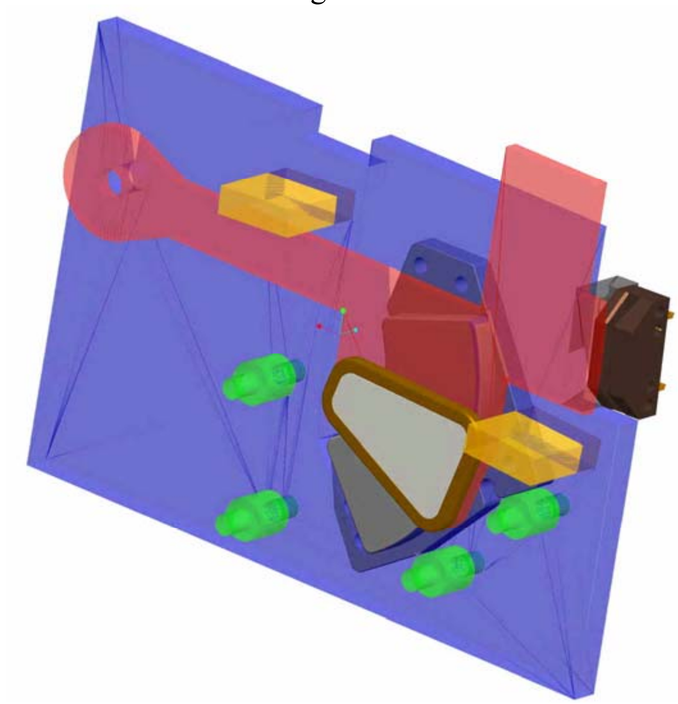
19.5 DesignSafe Analysis

User	Task	Hazard	Failure Mode	Severity	Probability	Risk	Remedy Action
consumers / general public	normal use	cutting / severing	When using the device, the test subject could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
consumers / general public	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
consumers / general public	normal use	normally live parts(direct contact)	The test subject could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
consumers / general public	normal use	overloading	Overloading the control circuit could pose a risk to the test subject.	Slight	Possible	Low	Guard against hazard
consumers / general public	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
consumers / general public	normal use	software errors	The software could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
consumers / general public	normal use	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the test subject.	Minimal	Unlikely	Negligible	Eliminate by design
consumers / general public	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
consumers / general public	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
children	normal use	cutting / severing	When using the device, the test subject could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
children	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
children	normal use	normally live parts(direct contact)	The test subject could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
children	normal use	overloading	Overloading the control circuit could pose a risk to the test subject.	Slight	Possible	Low	Guard against hazard
children	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
children	normal use	software errors	The software could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
children	normal use	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the test subject.	Minimal	Unlikely	Negligible	
children	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
children	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
youth	normal use	cutting / severing	When using the device, the test subject could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
youth	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
youth	normal use	normally live parts(direct contact)	The test subject could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
youth	normal use	overloading	Overloading the control circuit could pose a risk to the test subject.	Slight	Possible	Low	Guard against hazard
youth	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
youth	normal use	software errors	The software could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
youth	normal use	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the test subject.	Minimal	Unlikely	Negligible	
youth	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
youth	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
the elderly	normal use	cutting / severing	When using the device, the test subject could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
the elderly	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
the elderly	normal use	normally live parts(direct contact)	The test subject could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
the elderly	normal use	overloading	Overloading the control circuit could pose a risk to the test subject.	Slight	Possible	Low	Guard against hazard
the elderly	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
the elderly	normal use	software errors	The software could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
the elderly	normal use	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the test subject.	Minimal	Unlikely	Negligible	
the elderly	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
the elderly	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
user w/ physical abilities / limitations	normal use	cutting / severing	When using the device, the test subject could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
user w/ physical abilities / limitations	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
user w/ physical abilities / limitations	normal use	normally live parts(direct contact)	The test subject could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
user w/ physical abilities / limitations	normal use	overloading	Overloading the control circuit could pose a risk to the test subject.	Slight	Possible	Low	Guard against hazard
user w/ physical abilities / limitations	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
user w/ physical abilities / limitations	normal use	software errors	The software could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
user w/ physical abilities / limitations	normal use	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the test subject.	Minimal	Unlikely	Negligible	
user w/ physical abilities / limitations	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
user w/ physical abilities / limitations	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
skilled user (researcher)	normal use	cutting / severing	When using the device, the researcher could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
skilled user (researcher)	normal use	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	normal use	overloading	Overloading the control circuit could pose a risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	normal use	software errors	The software could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	normal use	unfamiliarity with hazards and risk	The researcher should be familiar with how the device works to prevent injury.	Slight	Possible	Low	Train user
skilled user (researcher)	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
skilled user (researcher)	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
skilled user (researcher)	assembly	cutting / severing	The researcher could be cut by sharp edges while assembling the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	assembly	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	assembly	lifting / bending / twisting	The device is quite heavy, and could pose a danger if dropped on a foot, toe, etc.	Minimal	Possible	Negligible	Warn of hazard
skilled user (researcher)	first use / test	cutting / severing	The researcher could be cut by sharp edges while testing the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	first use / test	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Negligible	Negligible	Guard against hazard
skilled user (researcher)	first use / test	overloading	Overloading the control circuit could pose a risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	first use / test	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	first use / test	software errors	The software could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	first use / test	unfamiliarity with hazards and risk	The researcher should be familiar with how the device works to prevent injury.	Slight	Possible	Low	Train user
skilled user (researcher)	first use / test	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
skilled user (researcher)	first use / test	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
skilled user (researcher)	periodic maintenance	cutting / severing	The researcher could be cut by sharp edges while maintaining the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	periodic maintenance	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard

User	Task	Hazard	Failure Mode	Severity	Probability	Risk	Remedy Action
skilled user (researcher)	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
skilled user (researcher)	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
skilled user (researcher)	assembly	cutting / severing	The researcher could be cut by sharp edges while assembling the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	assembly	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	assembly	lifting / bending / twisting	The device is quite heavy, and could pose a danger if dropped on a foot, toe, etc.	Minimal	Possible	Negligible	Warn of hazard
skilled user (researcher)	first use / test	cutting / severing	The researcher could be cut by sharp edges while testing the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	first use / test	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Negligible	Negligible	Guard against hazard
skilled user (researcher)	first use / test	overloading	Overloading the control circuit could pose a risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	first use / test	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	first use / test	software errors	The software could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	first use / test	unfamiliarity with hazards and risk	The researcher should be familiar with how the device works to prevent injury.	Slight	Possible	Low	Train user
skilled user (researcher)	first use / test	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
skilled user (researcher)	first use / test	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
skilled user (researcher)	periodic maintenance	cutting / severing	The researcher could be cut by sharp edges while maintaining the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	periodic maintenance	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	repair tasks	cutting / severing	The researcher could be cut by sharp edges while repairing the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	repair tasks	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	cleaning	cutting / severing	The researcher could be cut by sharp edges while cleaning the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	cleaning	unfamiliarity with hazards and risk	Researcher should know to disconnect power supplies before cleaning. This will prevent injury from electrical components.	Minimal	Negligible	Negligible	Train user
skilled user (researcher)	disassembly	cutting / severing	The researcher could be cut by sharp edges while disassembling the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	disassembly	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	disassembly	poisons	Dead batteries improperly disposed of could leak and poison the environment.	Minimal	Unlikely	Negligible	Guard against hazard
skilled user (researcher)	disassembly	corrosion	Dead batteries improperly disposed of could corrode and poison the environment.	Minimal	Unlikely	Negligible	Guard against hazard
skilled user (researcher)	disassembly	contamination	Dead batteries improperly disposed of could leak and contaminate the water system and soil.	Minimal	Unlikely	Negligible	Guard against hazard
skilled user (researcher)	disassembly	lifting / bending / twisting	The device is quite heavy, and could pose a danger if dropped on a foot, toe, etc.	Minimal	Possible	Negligible	Warn of hazard
skilled user (researcher)	demonstration	cutting / severing	When using the device, the researcher could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	demonstration	wear	The device could wear with excessive use.	Minimal	Possible	Negligible	
skilled user (researcher)	demonstration	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	demonstration	overloading	Overloading the control circuit could pose a risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	demonstration	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	demonstration	software errors	The software could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	demonstration	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the researcher.	Minimal	Unlikely	Negligible	
skilled user (researcher)	demonstration	unfamiliarity with hazards and risk	The researcher should be familiar with how the device works to prevent injury.	Slight	Possible	Low	Train user
skilled user (researcher)	demonstration	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
skilled user (researcher)	demonstration	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
skilled user (researcher)	trouble-shooting / problem solving	cutting / severing	The researcher could be cut by sharp edges while testing the device.	Minimal	Unlikely	Negligible	Eliminate by design
skilled user (researcher)	trouble-shooting / problem solving	normally live parts(direct contact)	The researcher could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
skilled user (researcher)	trouble-shooting / problem solving	overloading	Overloading the control circuit could pose a risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	trouble-shooting / problem solving	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
skilled user (researcher)	trouble-shooting / problem solving	software errors	The software could fail and pose an electrical risk to the researcher.	Slight	Possible	Low	Guard against hazard
unskilled user	normal use	cutting / severing	When using the device, the test subject could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
unskilled user	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
unskilled user	normal use	normally live parts(direct contact)	The test subject could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
unskilled user	normal use	overloading	Overloading the control circuit could pose a risk to the test subject.	Slight	Possible	Low	Guard against hazard
unskilled user	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
unskilled user	normal use	software errors	The software could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
unskilled user	normal use	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the test subject.	Minimal	Unlikely	Negligible	
unskilled user	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
unskilled user	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design
very young (0-7 yrs)	normal use	cutting / severing	When using the device, the test subject could be cut by a sharp edge.	Minimal	Unlikely	Negligible	Eliminate by design
very young (0-7 yrs)	normal use	wear	The device could wear with excessive use.	Minimal	Negligible	Negligible	
very young (0-7 yrs)	normal use	normally live parts(direct contact)	The test subject could be at risk to electrical components of the device.	Serious	Possible	High	Guard against hazard
very young (0-7 yrs)	normal use	overloading	Overloading the control circuit could pose a risk to the test subject.	Slight	Possible	Low	Guard against hazard
very young (0-7 yrs)	normal use	controls / control systems	Control systems related to the computer interface could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
very young (0-7 yrs)	normal use	software errors	The software could fail and pose an electrical risk to the test subject.	Slight	Possible	Low	Guard against hazard
very young (0-7 yrs)	normal use	repetition	During testing, excessive repetition could cause hand or wrist discomfort to the test subject.	Minimal	Unlikely	Negligible	Eliminate by design
very young (0-7 yrs)	normal use	fatigue	Prolonged use of the device could cause some hand or wrist fatigue.	Minimal	Unlikely	Negligible	
very young (0-7 yrs)	normal use	equipment damage	Various components could break off if they cannot tolerate large vibrations.	Minimal	Possible	Negligible	Eliminate by design

19.6 Supplementary Prototype Drawings and Photos

CAD rendering of button module



Side view of an actual button module used in the prototype

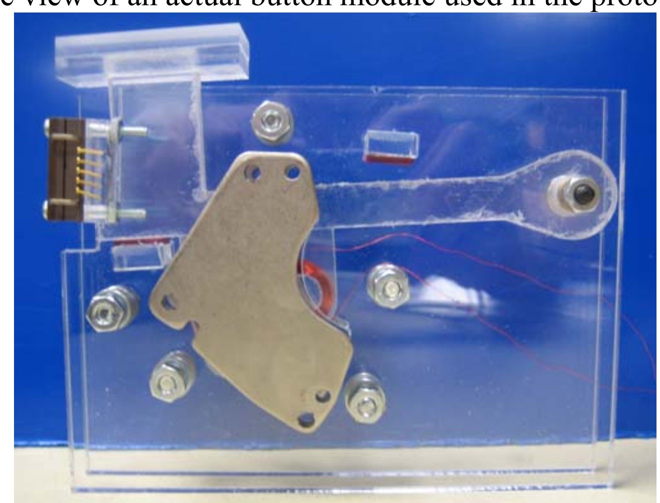


Photo of a corner of the device frame showing inner and outer layers

Photo showing how a motor mount sits in a mounting plate

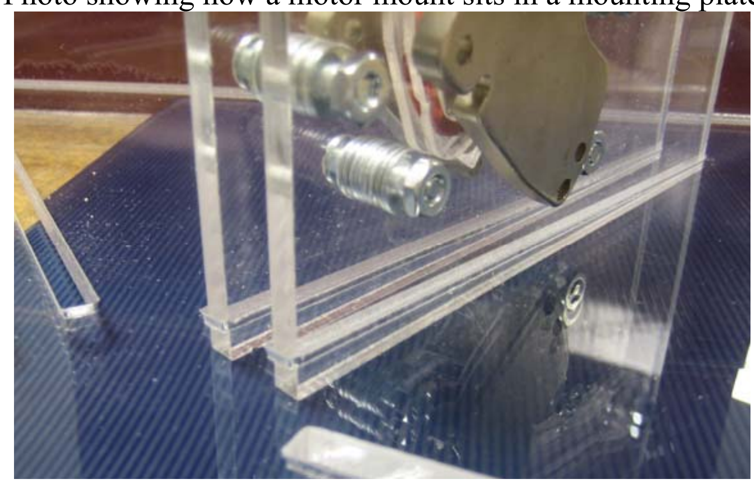
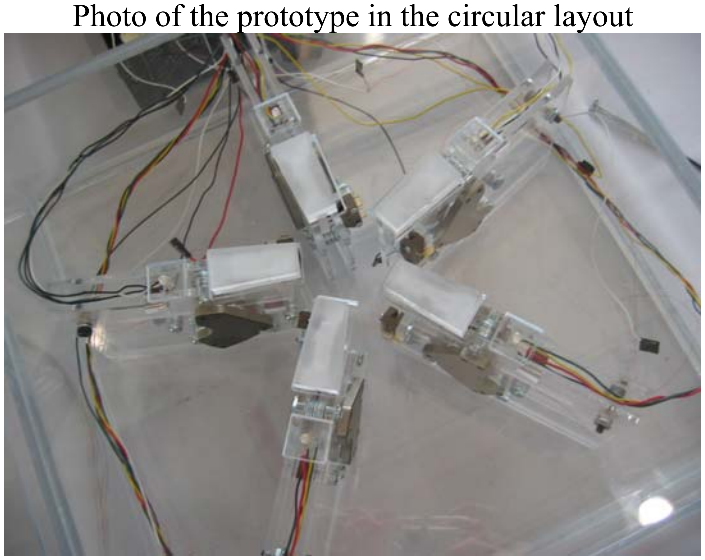


Photo of the prototype in the circular layout



Top view photo of connected prototype and control circuit

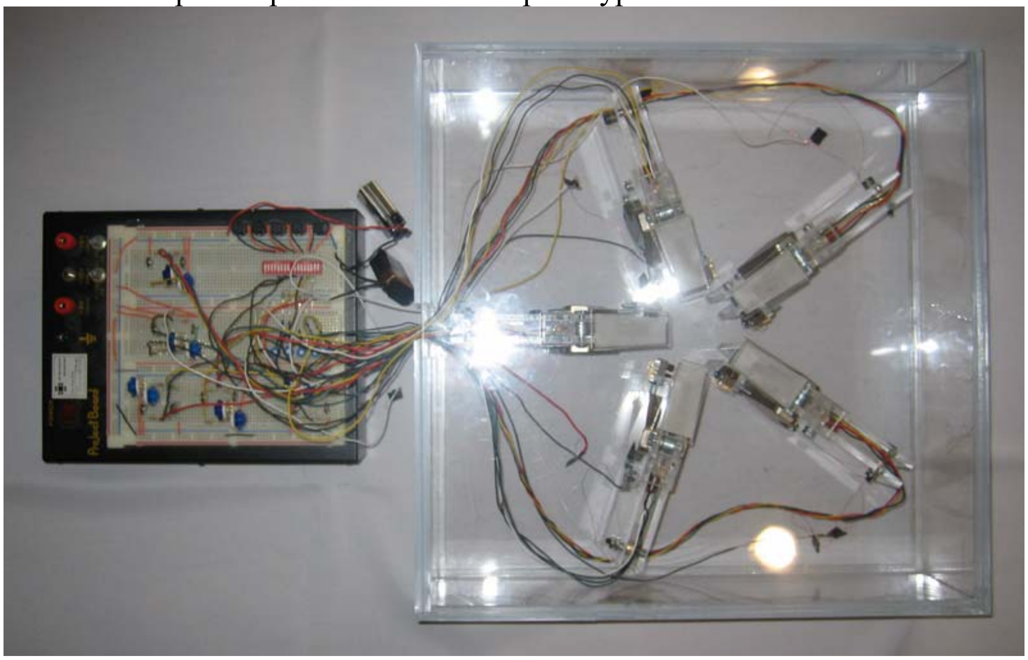
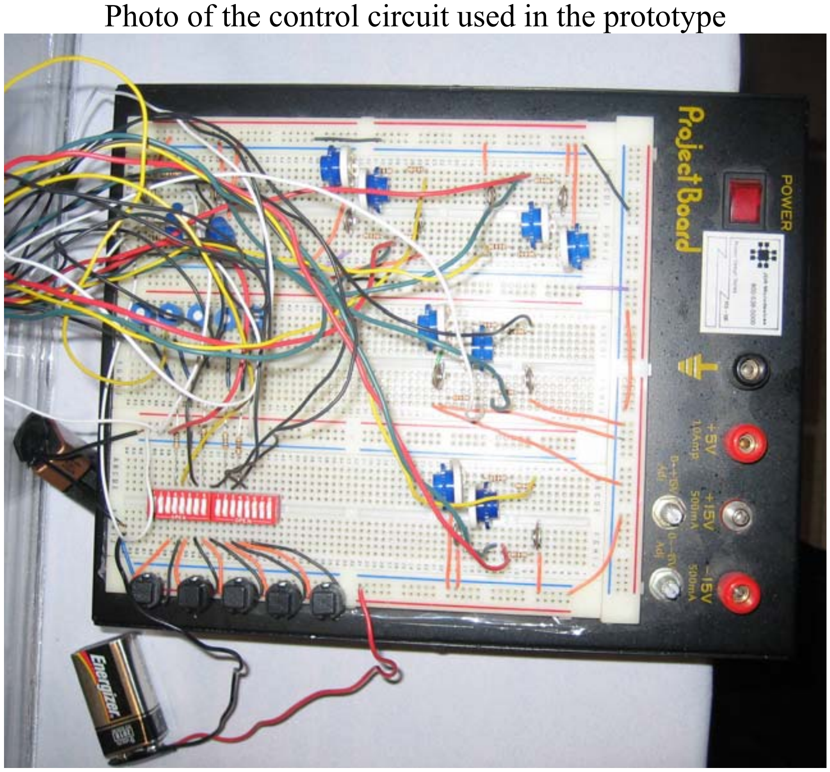


Photo of the control circuit used in the prototype



Schematic diagram of the control circuit