Touch-FX

Final Report

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EXECUTIVE SUMMARY

Our current design challenge is to create a device to generate knowledge about the psychophysics of vibrotactile perception. This knowledge may be useful in establishing the effectiveness of vibrotactile devices for interpersonal communication. In particular, our device will be used determine the ability of vibrations to induce tactile saltation for use in communication devices.

The customer specifications for our design require the excitation of individual or multiple actuators as well as the variability of the vibration amplitude and frequency, and spacing between active actuators. The specifications for our design were based on questions regarding how humans would interface with a vibrotactile communication device. For instance, the ability to vary parameters such as vibration amplitude and frequency will help determine the best conditions to induce tactile saltation with vibrotactile actuators. These questions came from literature on haptic communication, our peers, and from discussions with our sponsor. The ability to control variables such as vibration frequency and amplitude could also later be used to determine the type of information that can be transmitted through the tactile channel (ie, rhythm, mood, texture). Additionally, the engineering specifications for each component of our device were derived from their individual functions. For example, the substrate that the vibrotactile actuators will be mounted on must have a high yield strength so it will not tear. Other engineering specifications included the cost of each component, the manufacturability of the device, etc.

The required functions of our device were based on the customer and engineering specifications. Then, through a process of functional decomposition, we generated design concepts for each function of the device. We brainstormed ideas to vary the spacing between actuators, considered different materials to interface the device to the body, and examined programmable hardware options to control the vibration amplitude and frequency, and to activate specific actuators individually or simultaneously.

The final design was primarily chosen for its easy and fast attachment method to a substrate. In particular, we wanted to create a vibration motor unit that could easily attach and detach from the substrate without unsoldering wires. The physical part of the final design, the vibration motor unit, consists of four subcomponents: a pager motor, a 3/8"-16 x 1/2" nylon wrench hex nut, a 3/8"-9/16" nylon acorn nut, and a 3/8"-16 nylon threaded rod cut down to 1" length. A thru hole was machined into the threaded rod and a vibration motor was press-fit into the rod. The hex nut was threaded onto the end of the rod with the leads of the pager motor sticking out. The assembly was then passed through a hole in pre-fabricated substrate and an acorn nut was fastened onto the other end of the rod. The hex nut was hand-tightened until the substrate was secured firmly between the mating surfaces of the acorn nut and the hex nut. The hexagonal array of 38 vibration motor units was assembled on a substrate. The final design also includes a printed circuit board (PCB) that holds the circuitry needed for 38 vibration motors. The PCB also connects the array to the computer using ribbon cables. Both the PCB and ribbon cables manage and organize the circuitry for our device. Finally, the vibration motors are controlled by the user through a LabVIEW program specifically designed for the device. The program utilizes user inputs through the keyboard and mouse, pulse width modulation, and timing loops to activate specific motors, control the vibration intensity, and program patterns.

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INTRODUCTION

The original objective of our project was to create a haptic interpersonal communication device using vibrotactile actuators. We considered a few existing tactile languages, such as Braille and Morse Code, that could be used with a tactile device. However, after we surveyed our peers, we learned that the most important feature of such a device is a short learning curve. Thus we began to consider a device that could communicate using the standard written alphabet by tracing it onto the user's skin. In order to create an effective communication device that would utilize the sense of touch, we began to research the touch perception of different locations on the body. We came across the phenomenon of tactile saltation (also known as the "cutaneous rabbit"), which describes how the brain interprets the locations of successive and discrete taps felt on the skin. Previous research on saltation has determined that varying parameters such as vibration intensity, vibration frequency, time duration, and the time between successive tactors affects the way the brain perceives the location of the discrete taps on the skin. For instance, a study conducted by the Cutaneous Communication Laboratory at Princeton University found that by reducing the time interval between successive taps, the location of the first tap seemed closer to the location of the second tap [1]. We hoped to use the phenomenon of tactile saltation to produce a sensation that could be perceived by the brain as an almost smooth trace on the skin with vibrotactile actuators. If we could achieve this sensation, then one person could communicate remotely with another by tracing a message onto a touch pad and the recipient would feel the message as if it is being written directly on him or her. Unfortunately, there is limited information about tactile saltation induced through vibrations as opposed to taps. Thus, the objective of our project changed from creating a haptic interpersonal communication device to creating a device that will help generate knowledge about the psychophysics of vibrotactile saltation. With our device, the user will be able to control the vibration frequency/intensity, time duration, and location of vibratory stimuli by manipulating parameters in a computer program specifically created for the device. Using these same variables, the user could also test for the two-point discrimination threshold (TPDT) and the optimum vibration frequency for different locations on the body such as the forearm and back. With this device, we hope to generate knowledge about the psychophysics of vibrotactile perception.

INFORMATION SOURCES

Our team researched a variety of topics including psychophysical studies in tactile perception, haptic interfaces, and electrical components that are applicable to our project.

Academic Research

We began our research by interviewing our sponsor. During this interview we learned a number of technical terms such as “haptics,” “vibrotactile actuators,” “saltation effect,” and “kinesthesia.” Using these terms to begin our literature search, we utilized the University of Michigan Library and explored several scientific journals and papers. We came across a number of articles on human perception and haptics. These articles led us to begin our own investigations of haptics through experimentation. By conducting rudimentary testing on our peers, were able to investigate the range of touch sensitivity for different areas of the body.

The main focus of our research has been on sensory saltation also known as saltation effect, saltatory illusion, or specifically known to haptics as the "cutaneous rabbit". The "rabbit" was discovered accidently in an experiment involving three equally spaced mechanical tactors placed along the length of a forearm. The tactors were stimulated successively with each tactor receiving three short pulses. The subject reported that instead of feeling localized taps at each of the three sites, the taps seemed to be spatially distributed between the location of the first and last tactor. Furthermore, it was observed that the apparent location of the first tactor felt closer to the second tactor when the time between successive stimulations was reduced. [2, 3].

We encountered an article describing how the perception of touch can improve with training and practice. It included a section specifically relating to the study of Braille for adults, "[There is] a 5-step process which moves from simple to complex, beginning with awareness and attention to tactile details, moving through recognition of structure and shape, part-to-whole relationships, then abstracted graphic representations and finally the learning of Braille symbols." [4] We hypothesize that these same concepts for learning Braille could one day help someone with even a limited haptic perception communicate using a vibrotactile device.

This same article had a section relating to potential difficulties in designing a device for an unfamiliar modality like touch. Specifically the article points out the difficulty in determining how programmed sensations in a computer relate to actual sensations felt by the user. Also, a device that operates using haptics is difficult to compare experimentally to a device that uses a different modality (i.e. sight or sound) because these two devices tend to differ in more ways than one, thus making comparative analysis null. Moreover, with an unfamiliar modality like touch, the learning curve with a device will ~~be~~ requir~~ing~~e lengthy and expensive surveying methods. Lastly, there is limited vocabulary for describing sensations felt during an experiment. [4]

Competitor Benchmarking

To generate some ideas for a tactile communication device, we looked up current haptic technology. From this market research, we found haptic tools for communication; however, they relied greatly on vision [5, 6, 7]. We did come across an article on a device that was entirely haptic, the HandJive [8]. Nonetheless, this device was only a toy and could not transmit meaning. We have numerically evaluated each competitor's device against the customer specifications in a Quality Function Deployment (QFD) chart [Appendix E] on a scale from 0 to 5 (0 = does not satisfy requirements to 5 = satisfies all requirement). If there was not enough information to determine a number, we put an "X" in place of the ranking.

Electrical Component Research

We used Sparkfun.com, an electronics wholesale website, to research different vibrotactile actuators and different touchpads. We have also researched reprogrammable circuit boards to handle all the digital logic to make our device portable and separate from a computer. One of the circuit boards we came across was not only small and reprogrammable, but also flexible and water-resistant.

Information Gaps

There is currently limited information regarding the use and effectiveness of vibrotactile actuators for interpersonal communication. The purpose of our device is to be used in experiments that are designed to fill those information gaps.

REQUIREMENTS AND TARGETS

The project requirements and technical priorities were established by determining the customer and engineering specifications. Both of these types of specifications were established by team brainstorming, discussions with our sponsor, research, questions generated by our peers, and benchmarking of current communication devices as well as other haptic technology.

Customer Specifications

In order to evaluate the effectiveness of vibrotactile actuators to induce tactile saltation, the user must be able to control different variables simultaneously. These variables include the vibration amplitude, time duration, vibration frequency, active actuator spacing for array resolution, and the ability to actuate multiple actuators simultaneously as well as individually. We also determined specifications for individual components of the design. The specifications for a reconfigurable array were determined by considering the user of our device and methods for performing meaningful experiments. The specifications consist of

- an easy method to attach the actuators to the substrate
- a durable attachment method
- an easy way to manage and organize wires
- versatile tactor spacing
- maximum skin-to-tactor contact
- minimal vibration damping
- precision of the attachment method for experiment repeatability

Specifications for the substrate mainly consider the comfort of the test subject. The substrate should be

- thin
- easy to sew and alter
- waterproof/sweat-proof
- easy to clean
- stain resistant
- breathable
- comfortable against the skin
- capable of minimal vibration damping

In addition to the hardware, we considered customer specifications for the software needed to conduct the experiments. These specifications facilitate the ease of experimentation and include

- a graphical user interface (GUI)
- an easy input/output set-up
- the ability to program different patterns and schemes
- the ability to easily change variables such tactor spacing, vibration intensity, and time duration

Finally, the specifications for the vibrotactile actuators consist of

- a small contact area with the skin
- an enclosed packaging
- a modular assembly (standardized dimensions to allow easy interchange and repositioning of each motor)

Engineering Specifications

The engineering specifications include the cost for all the components, the manufacturability of the reconfigurable array and substrate, and durability of the overall device. For the substrate, we must also consider using a material with a high tensile strength to avoid tearing the fabric. However, the substrate must also be inelastic because when it is adjusted to conform around a test subject, it cannot stretch and affect the precision of the actuator spacing.

Determining the Engineering Targets

We used a binary ranking system to compare the importance of the specifications in relation to one another. For a reconfigurable actuator scheme, our primary targets are to create a scheme with minimal vibration damping, direct skin-to-tactor contact, and versatile actuator spacing. For our substrate we must choose a fabric that will also minimize vibration damping, have a high tensile strength while resisting deformation, and be easy to sew or alter.

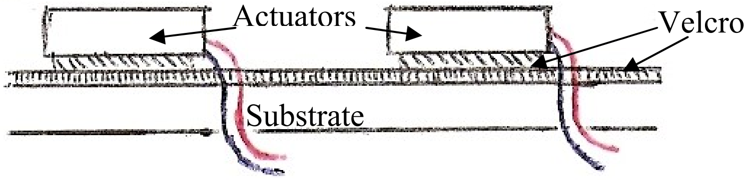
CONCEPT GENERATION

To maximize the variability of our device, we decided to make the array modular, so it could be used with several different patterns and substrates.

Unfixed Array

The first concept for a reconfigurable array was to build an array by attaching individual actuators onto a substrate with Velcro. The substrate would have Velcro sewn onto it while the opposite mating surface of the Velcro would be attached to the back of each tactor (Figure 1). The greatest advantage of this concept was the ability to create different spatial layouts for the array because the actuators could be moved independently of one another. Additional advantages include the ease of attachment and the durability of the attachment. Some disadvantages of this concept included the inability to manage and organize the wires from the actuators and the imprecision of the attachment method for experimental repetition.

Figure 1: Side View of Velcro Attachment Method



Fixed Array

A second concept we generated consisted of using an expandable fence-like attachment. As shown in Figure 2a, the actuators would be fixed .between intersections of the attachment. Each intersection would rotate about a pivot. Expanding the fence-like attachment in one direction would collapse the attachment in another direction (Figure 2b). The fence-like attachment would be fabricated from an inexpensive plastic. Some of the advantages of this concept include the low cost, the variety of spatial layouts, and direct skin-to-actuator contact. The disadvantages of this concept include the difficulty to manufacture and assemble the fence-like structure and the poor durability of the actuator attachment to the structure. In addition, despite the variety of spatial layouts for the vibrotactile actuators, the versatility for spacing is limited because actuators can only follow a prescribed path as the structure expands or collapses.

Figure 2a: Expanded Fence-like Attachment

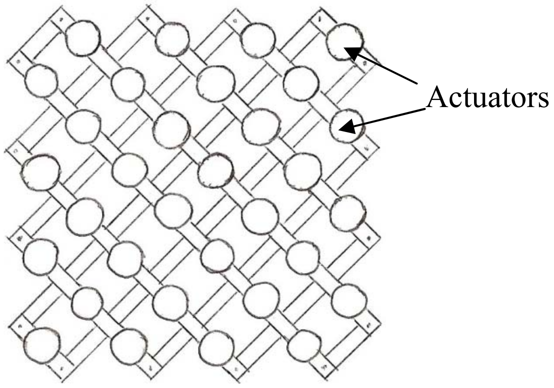
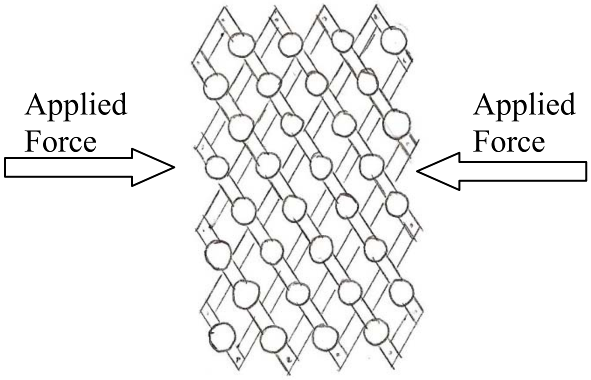


Figure 2b: Compressed Fence-like Attachment



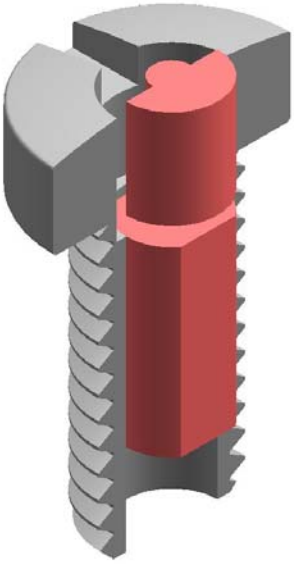
Rigid Attachment

For our final coin motor concept, we would buy 38 coin motors with an adhesive backing and rigidly attach them to the substrate in a hexagonal pattern. The leads for each motor would be threaded through one substrate layer, soldering long wires to the leads. There will also be a plastic mesh around the perimeter of the array to keep the motors from moving with respect to one other. There will also be a second substrate layer sewn on top which will keep the wires organized.

Fixed Pager Motors

We planned to purchase nylon 6/6 bolts and hex nuts for each motor. We would then press a motor, with wires already soldered to the leads, into the bolt, that would have a through hole and a counterbore at the head, with the eccentric weight at the bolt head. See Figure 3 (p. 9) for a cross-section view. Additionally, we would have 38 holes cut in a hexagonal pattern for two layers of our substrate with a plastic mesh around the perimeter of the array and between the substrate layers. We would then insert each motor unit to the substrate and screw a hex nut to the opposite side with the wires connected to a circuit board via a ribbon cable.

Figure 3: Cross section view of a fixed pager motor concept



Modular Pager Motors

Another attachment scheme consisted of purchasing threaded rod, hex nuts and acorn nuts for each motor. We would face, drill, ream, and counterbore 1” segments of the treaded rod and press a motor, with wires already soldered to the leads, into the threaded rod with the eccentric weight at in the counterbore. See Figure 4 for a CAD Drawing. Additionally, we would have 38 holes cut in a hexagonal pattern for two layers of our substrate. We would then screw the hex hut onto the threaded rod, insert each motor unit to the substrate, and screw the acorn nut onto the other side of the substrate to hold it in place. See Figure 5 for an assembled view.

Figure 4: Assembled view of a modular pager motor unit

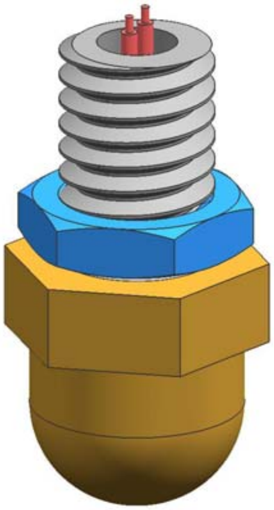
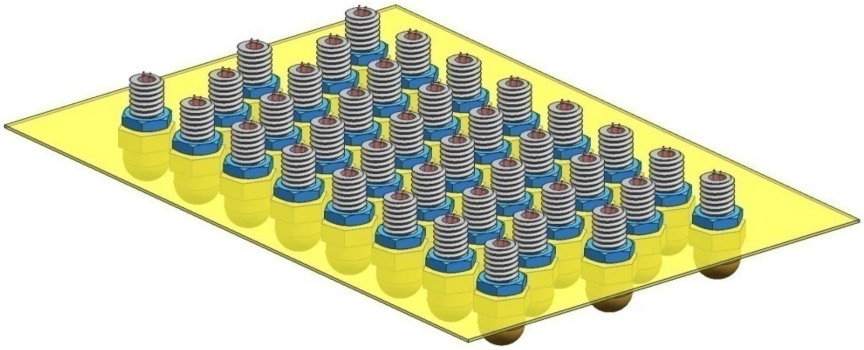


Figure 5: Assembled view of motor unit array



CONCEPT SELECTION

We selected the modular pager motor design to be used with different substrate patterns and materials. The selection process was done in a logical manner rather than a calculated one.

Coin motors are small and nicely packaged, which would have allowed us to have a very dense array and increase our spacing options. However, these motors have the least amount of variability when it comes to spacing. To keep precision, the motors would not be able to change locations on the substrate or chance the substrate itself. In order to change the position of the motors easily, precision is sacrificed because with Velcro, expanding fence, or another method described in Appendix D, it would be unlikely that the motors would be placed in the exact locations used in previous tests. Also, coin motors would have cost $11.01 apiece including shipping, and extra materials to create the array would only increase the cost.

With fixed pager motors, we saw the price per unit drop to around $2.__, and the motor units could be relocated and retain the same position used in previous tests. However, this would force us to spread the motor units farther apart due to the size of the hex nut because contact between different motor units could lead to inaccurate results. Additionally, changing substrate patterns or materials would involve unsoldering and then re-soldering both leads to all 38 motors.

Using the modular attachment scheme meant that it would take more time to manufacture each motor unit and we would have to increase the spacing on the substrate because of the size of the acorn nut. However, this method was also cost efficient, being only $2.30. Also, only the acorn nut would need to be removed in order to use different substrates.

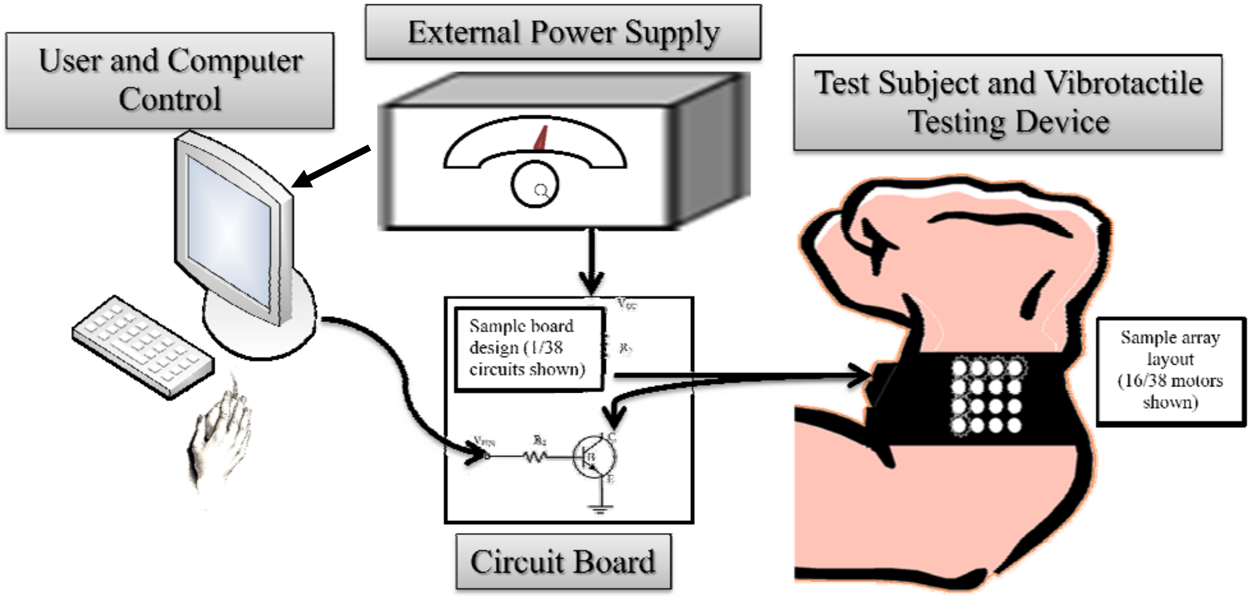
Programming

A few of the options we considered for programming and controlling our device included a programmable circuit board, LabVIEW, and cRIO. Since our device will be used for experimentation purposes, we decided to use LabVIEW to control the experiments and collect data. Both the programmable circuit board and cRIO do not have the ability to display a graphical user interface and would be difficult to reprogram. The user of our device would be able to control variables such as vibration frequency, amplitude, and time duration through the graphical user interface in LabVIEW.

CONCEPT DESCRIPTION

Our device has three main subsystems—computer with LabVIEW software, printed circuit board with electrical components, and the vibrotactile testing device with 38 vibrotactile motors—as is shown below in Figure 6 (p.11). The user controls the entire system using a mouse and the control software on the computer. The computer outputs corresponding control signals of high and low to each of 38 motor circuits based on the sequence of control switches actuated by the user on the graphical user interface (GUI). The external power supply is required to amplify the control voltages from the computer because the original signals from the computer are not high enough to run 38 motors. For a more detailed description of the subsystems, see section “Final Design.”

Figure 6: Schematic of subsystems



PARAMETER ANALYSIS

The purpose of this section is to describe the parameters that shaped the design of each sub- component of our device.

Vibration Motor Selection and Design

Table 1: Vibration motor unit subcomponent cost

Component	Cost per component
Vibration Motor	$1.52
Nylon 6/6 acorn nuts (3/8"-16 x 9/16" wrench)	$0.27
Nylon 6/6 hex nuts (3/8"-16 x 1/2" wrench)	$0.22
Nylon 6/6 threaded rod (3/8"-16 x 6' long)	$0.29 (per inch)

We decided to use Nylon 6/6 acorn nuts, hex nuts, and threaded rods because the material is cheap, easy to manufacture, lightweight, and has a sufficient strength for our application. Additionally, the size of the acorn nuts, hex nuts, and threaded rod were chosen based on the size of the pager motor and its eccentric weight.

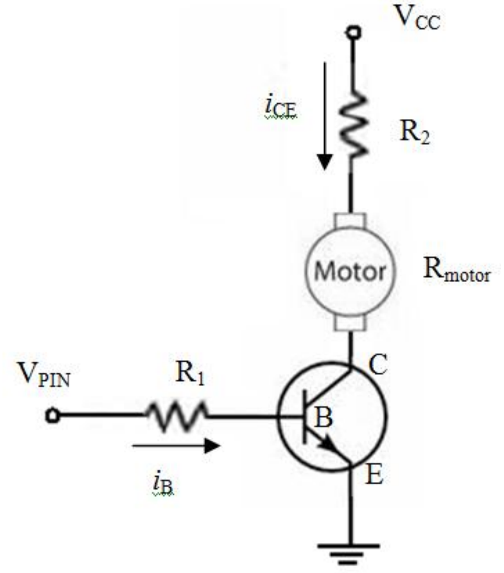
Printed Circuit Board

We have chosen to design and purchase a printed circuit board to organize and manage the wires required for our design. The spacing of components on this board and the sizing of the traces was originally cost driven. We placed all the components as close together as possible to gain the best value. However, after consulting our sponsor, we have since spaced the components at least a tenth of an inch apart and increased the size of the high voltage traces to twice their original width. The increased spacing between the electrical components will help dissipate any heat generated during the operation of our device

Electrical Components

The circuitry for our project is designed to be used with a National Instruments PCI-DIO-96 data acquisition card (DAQ). Each channel of the DAQ can only output up to 2.5 mA, which will not provide enough power to run the motor at desired frequencies. Therefore, we will use an external power source to drive the motors. Since the DAQ provides digital output, we will use a PN2222A NPN transistor as a switch to turn on and off the motors. The motors will turn on when the switch completes the circuit between the external power supply (V_{cc}) and ground. In addition, we will use two resistors to limit the current through the circuitry. The transistor will amplify the current through the motor by a factor of β=100 (Eq. 1, p.8). Using Kirchhoff's Voltage Law (Eq. 2 and 3, p.8), we determined the maximum resistances needed to create the voltage drops $V_{CE,\ SAT}$ and $V_{BE,\ SAT}$. However, we decided that we wanted V_{CE} and V_{BE} to be at least 1 V each to sure that the transistor will always worked like two forward-biased diodes. If the maximum current output from the DAQ is 2.5 mA, we determined that the first resistor should be 680 Ω and the second resistor should be 5 Ω. The first resistor will placed between the DAQ pin and the transistor. The second resistor will be placed between the external power supply and the motor. Please see Figure 7 for a schematic of each motor circuit. The calculations to determine the required resistances can be found in Appendix F.

Figure 7: Motor control schematic



$$\text{Eq. } 1: \beta i_B = i_{CE}$$

$$\text{Eq. } 2: V_{CC} - i_{CE}R_2 - i_{CE}R_{Motor} - V_{CE} = 0$$

$$\text{Eq. } 3: V_{PIN} - i_B R_1 - V_{BE} = 0$$

$$\text{Eq. } 4: i_B < i_{SOURCE}$$

Dynamic Modeling

As the eccentric weight rotates, the motor unit creates a lateral force against the skin. These forces are shown in the free body diagram (Figure 8, p. 13). There are forces in the x and y direction (lateral) due to both the skin and the substrate, as well as the vertical force of the substrate forcing the units onto the skin, a normal force due to the skin, and a vertical force due to the wires. We can assume that the maximum forces in the x and y direction (lateral) are equal. This can be modeled as a 1-D mass-spring-damper (Figure 9, p. 13) with spring constants and damping coefficients for the skin and substrate (k_{skin}, k_{fabric}, b_{skin}, b_{fabric}). We can also assume that the respective *k* and *b* values are equal in the lateral directions.

Using general relationships for rotational and lateral motion, we were able to determine the acceleration of eccentric weight and model an equation for the input force or each unit (Eq 5, p. 10). We also used the mass-spring-damper model in Figure 9 (p. 13) and modeled the springs and dampers in parallel on one side of the mass (Figure G.4, p. 38). This relationship allowed us to model the system as a 2nd order Ordinary Differential Equation (*ODE*) given by Eq. 6 (p.10). Simplifications and equations can be found in Appendix G.

Figure 8: Free Body Diagram of Bolt Assembly

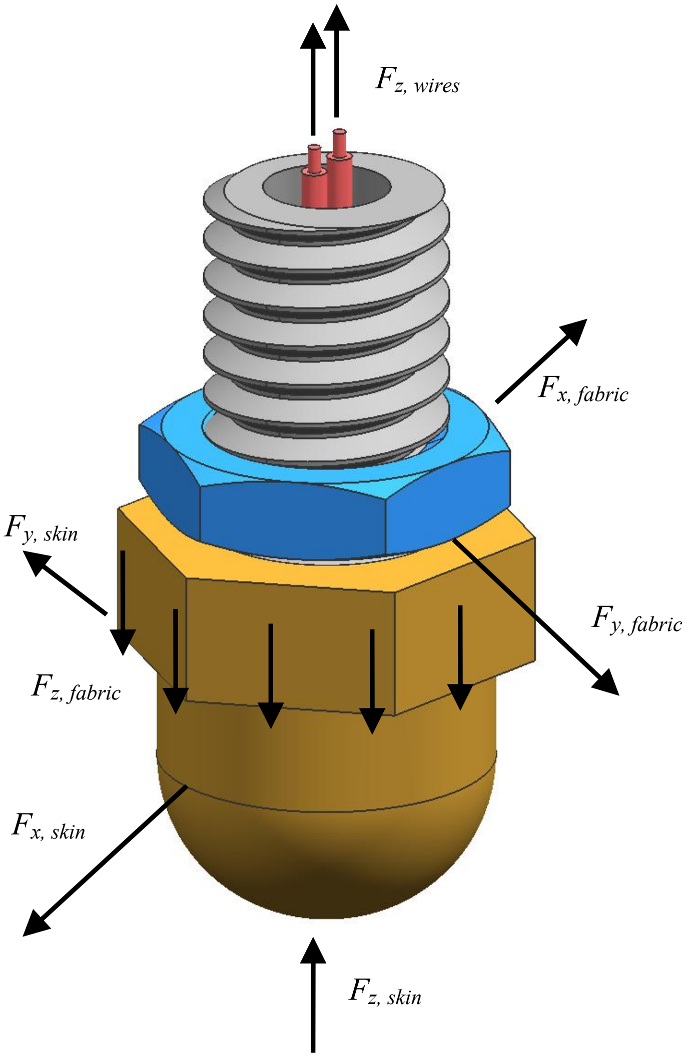
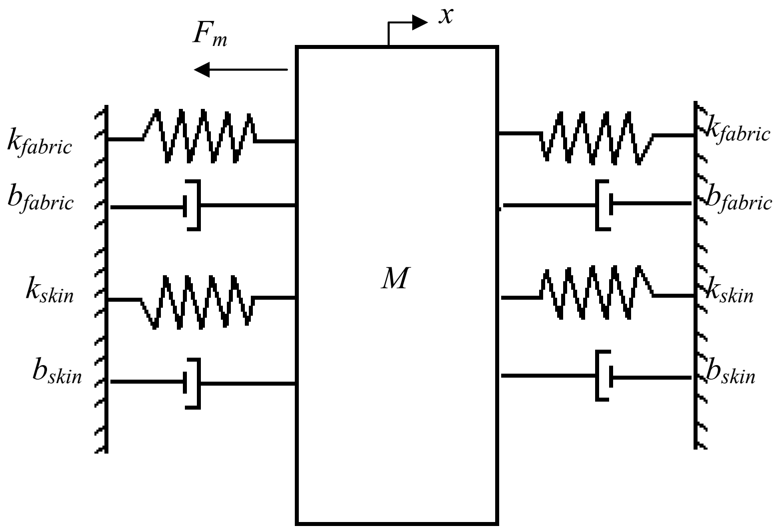


Figure 9: Mass-spring-damper model



$$\text{Eq. 5}: \; F_{Motor} = Ma = M\sqrt{(\alpha r_{CM})^2 + (\omega^2 r_{CM})^2}$$

$$\text{Eq. 6}: \; F_{Motor} = M\ddot{x} + \frac{1}{2} b_{skin}\dot{x}_{skin} + \frac{1}{2} b_{fabric}\dot{x}_{fabric} + \frac{1}{2} k_{skin} x_{skin} + \frac{1}{2} k_{fabric} x_{fabric}$$

PROTOTYPE DESCRIPTION

The final design will consist of a hexagonally spaced array of 38 vibration motor units attached to a substrate. There will be three rows of eight units and two rows of seven units (Figures 10 & 11). The vibration motor units will consist of a pager motor press-fitted into a drilled, reamed, and bored Nylon 6/6 threaded rod. To attach the vibration motors to the substrate and construct our grid, we will first cut out a hexagonal array of 0.3125" holes in the substrate. The holes will be spaced 0.6" from center to center. The motor units will be attached by passing the rods through the holes in the substrate and fixing them in place with acorn nuts on one side of the substrate and hex nuts on the other. The test subject's skin will be in contact with the acorn nuts. The eccentric weight inside the rod will face the end with the acorn nut. The leads of the pager motor will be exposed at the other end of the rod. The acorn nut will be of size 0.5675" with 3/8"-16 threads. The hex nut will be 0.5" with 3/8"-16 threads. The design of the motor housing and attachment scheme will give the user the flexibility to quickly and easily test different array configurations and substrates.

Figure 10: Top view of assembled device

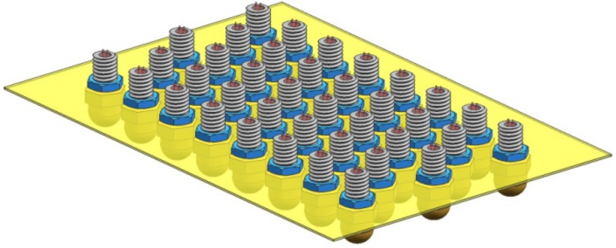
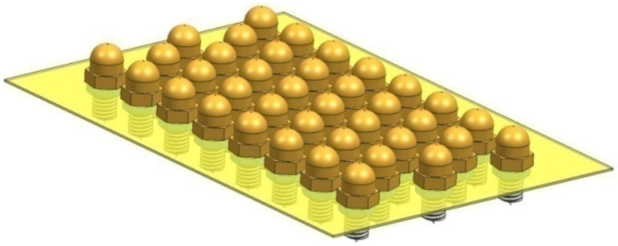


Figure 11: Bottom view of assembled device



The motors will be controlled via a specifically designed LabVIEW graphical user interface (GUI). The program will in turn activate and deactivate motors as well as control the vibration frequency/intensity and time duration. Using pulse width modulation (PWM), we will vary the frequency and duty cycle in order to achieve variable vibration frequency/intensity. Additionally, we will use timing loops to control the time duration of the vibrations and time interval between vibrations. The program will also be able to read position input from a mouse and data input from a keyboard. The control signals will be sent to the motors via a National Instruments PCI-DIO-96 data acquisition device (DAQ).

We will be using a printed circuit board (PCB) to organize and manage the circuitry and wires needed to connect 38 vibration motors to the computer. The PCB board will hold all the electrical components required for 38 motors. Using PN2222A NPN transistors as switches, we will turn the motors on and off using digital output. In addition, the circuitry will also include two current limiting resistors. The first resistor will be 680 ohms and the second will be 20 ohms. Please see figure 7 (p. 12) for a schematic of each motor circuit. The calculations to determine the required resistances can be found in the Parameter Analysis section.

Each motor will have two wires connected to its leads with each wire connected to one (of two) ribbon cables leading to corresponding headers on the PCB. An SCB-100 Shielded Connector Block will also be soldered to the PCB and will be connected to the DAQ and computer via a two meter SH100-100-FLEX cable.

We have yet to decide upon a substrate material because we have assumed the substrate will be an independent variable in experimentation. For our prototype, we will using a 35% cotton/ 65% polyester blend. We will sew a vinyl into the substrate around the perimeter of our array. The vinyl weave will be rigid in both compression and tension. However, it will give in bending so that it can contour to the body without compromising the spacing between the tactors.

We have included a bill of materials in Appendix A.

FINAL DESIGN DESCRIPTION

The final design consists of 38 individual vibration motors units arranged in a hexagonal array on a prefabricated substrate. Using a laser cutter, we created the hexagonal array that consists of three rows of eight holes and two rows of seven holes. The holes are 0.3125" in diameter and spaced 0.875" from center to center (Figure G.5, p. 40 & G.9, p. 42). Each vibration motor unit includes an acorn nut that is 0.5675" across, between parallel faces, with 3/8"-16 threads, a hex nut that is 0.5" with 3/8"-16 threads, a 1" long drilled, reamed, and bored threaded rod, and a pager motor. The nuts and threaded rods are made of Nylon 6/6. The motor unit is created by press-fitting a pager motor into a 1" long drilled, reamed, and bored threaded rod. Each pager and threaded rod assembly are passed through a hole in the substrate and fastened in place with a acorn nut on one side of the substrate and a hex nut on the other (Figures 10 and 11, p. 14). The acorn nut is fastened to the end of the rod closet to the eccentric weight of the pager motor and makes contact with the skin. The leads of the motor are exposed at the other end of the rod (Figure G.1, p.37). The design of the vibration motor unit and its associated attachment method gives the user the flexibility to quickly and easily build different array configurations on different substrates.

The motors are controlled via a custom built LabVIEW graphical user interface (GUI). The user has control over the sequence in which motors are actuated by clicking switches that correspond to motors on the sleeve. The program stores the motor sequence in an array. The motors will vibrate in the selected sequence when the user presses the “Start” button. In addition, the user controls the vibration intensity, vibration time, and pause time between vibrations for each of the motors by entering numeric values with the keyboard. Due to the constraint of digital I/O, the vibration intensity is controlled using pulse width modulation (PWM). In the software, we use case structures with timing controls to set the duration of the vibrations and the time interval between vibrations. The control signals are sent to the motors via a National Instruments PCI-DIO-96 data acquisition device (DAQ). Please see Appendix J for a detailed explanation of the LabVIEW code.

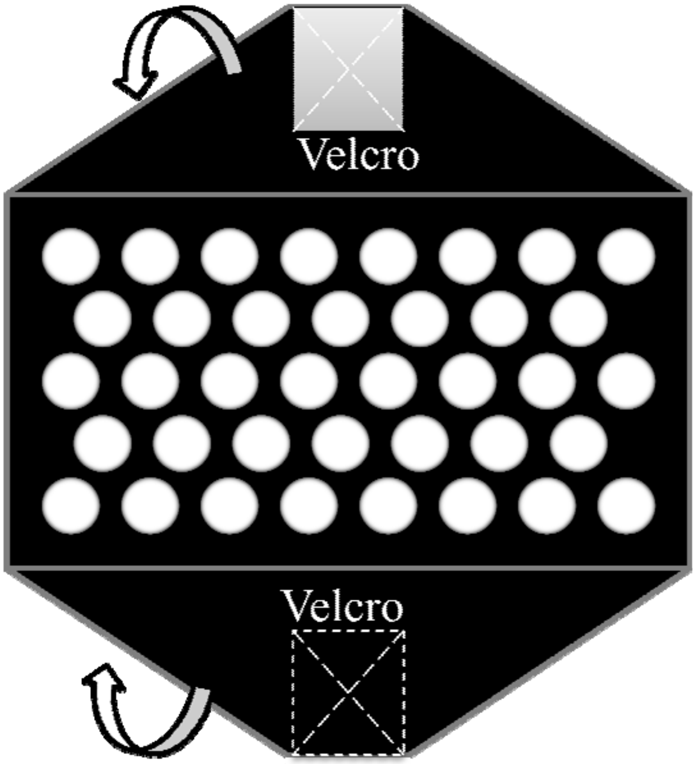
A custom printed circuit board (PCB) organizes and manages the circuitry and wires needed to connect 38 vibration motors to the computer and an external power supply. The PCB board, which is 4.35" by 11.8", holds all the electrical components required for each motor. Using a simple switch circuit with a PN2222A NPN transistor acting as the switch, the motors turn on and off using digital output from the DAQ. In addition, the circuitry also includes two current limiting resistors. The first resistor (R_1) is 680 ohms and the second (R_2) is 5 ohms. Please see figure 7 (p. 12) for a schematic of each motor circuit. The calculations to determine the required resistances can be found in the Parameter Analysis section.

The leads of each motor connect to two wires on one (of two) ribbon cables. The ribbon cables connect the motors to the PCB by plugging into a header that is soldered onto the board. An SCB-100 Shielded Connector Block is also soldered to the PCB and connects to the DAQ and computer via a two meter SH100-100-FLEX cable.

The choice in substrate material is an independent variable in experimentation. However, for our prototype we created an armband out of canvas. The armband consists of two rectangular layers of canvas with the cutout hexagonal pattern of holes attached to two trapezoidal canvas “wings” (Figure 12, p. 16).

A “X” square of Velcro is sewn to one side a trapezoidal wing. The mating square of Velcro is sewn to the opposite side of the second trapezoidal wing.

Figure 12: Array attachment to arm



FABRICATION PLAN

The initial fabrication plan for our device includes a description of the required machining processes, assembly processes, and locations of manufacturing and assembly.

Machining Processes

Our motor assembly will consist of a pager motor that is press-fitted into a through hole down the longitudinal axis of a piece of nylon threaded rod. Then the rod/motor assembly will be passed through the fabric layer. On one end of the rod, an acorn nut will be tightened to the deepest point its threads will allow. Then, a hex nut will be tightened down from the other side. The faying surfaces of acorn and hex nuts will compress the fabric to retain the assembly's position in the fabric matrix.

The threaded rod pieces must be cut to length from the 6.0' length it comes in. Each piece of rod will be cut to slightly longer than 1.0" using a band saw. The pieces will be cut slightly longer so that each end will be faced on a lathe so that the ends each piece will be square. This will improve aesthetics and allow for better fit with other components.

In order to perform the turning operations, a fixture must first be made so that the chuck of the lathe can hold a piece of threaded rod during operation. The fixture will be made from a piece of aluminum alloy round stock 1.00" or 0.50" in diameter and 2.0" in length. The stock will be cut slightly longer than the dimension listed above so that the ends may be faced. It will not be necessary to turn down the outside diameter of the stock. The fixture will be drilled from the tailstock leaving behind a through hole. This will allow for the chips created during drilling and reaming to pass through the fixture. Drilling will be done at 3000-6000rpm with a 0.3125" (5/16"). Lastly, the through hole will be hand-tapped with 3/8"-16 tap only about 0.75" deep. This will create a stop for the threads of the rod during the turning processes.

After the fixture has been made, it will be placed into the chuck of the lathe so a piece of threaded rod may be held fast without crushing the soft, nylon threads. A piece of threaded rod will be turned tightly into the fixture. The first turning operation will be to face both ends of the rod. Following this, the rod will be drilled at 1000rpm with 0.1935" (#10 Drill) resulting in a through hole using the tailstock as previously. Then the hole will be reamed with a 0.1960" (#9 Drill). Lastly, a counterbore will be made that is 0.25" deep by 0.25" in diameter.

Tolerances must be used to ensure consistency in manufacturing. The desired tolerance for facing is ±0.005". The facing tolerance is only required for a flush fit into the acorn nut and for aesthetics at the other end. The overall length of the rod is not overly critical, but it is desired to have a consistent length for all rods. The desired tolerances for drilling and reaming are ±0.001". The diameter of the bores are more critical because the motors will be press-fitted into them. The tolerances for the holes in the fabric must be of ±0.005".

Assembly Processes

Our fabric must be fabricated prior to any other assembling. A pattern will be created and transferred to the fabric to ensure proper spacing. The arrangement of the motors will be in a hexagonal shape, similar to that of a honeycomb. Then, at each point of attachment for the motors, a small, circular incision will be made using a small pair of scissors. The hole diameter must be 0.3125". The center-to-center distance between adjacent holes will be 0.60". Each hole will allow a rod/motor assembly to pass through the fabric. Another possibility for making the pattern is to do it with a laser cutter. Attachment of 3.00" long wire leads to each pager motor must be done next. The wire leads will be attached by soldering. Then, a pager motor will be compression-fitted into each rod. The motors will be gently pressed in using the Machine Shop's arbor press. The leads will have to be passed through the bore of the rods prior to pressing. Care must be taken not to harm them during pressing. The motors will be pressed in only far enough to have their eccentric weight past the end of the rod and still within the counterbored area. Each rod/motor assembly will then be passed through a hole in the fabric. After this, an acorn nut will be put on the end of the rod that is counterbored. It will be turned as tight and deeply as the threads allow. Next, the leads of each motor will be passed through the hex nut and will then be turned onto the threads of each rod. This hex nut will be hand-tightened against the acorn nut. This will compress and hold the fabric between the faying surfaces of the nuts.

The next process will be to assemble the printed circuit board (PCB). The layout of the PCB was created using a CAD software called ExpressPCB. The PCB is then ordered from the CAD vendor, www.ExpressPCB.com. ExpressPCB will make the PCB to the CAD model designed. ExpressPCB cuts the board to size and also the holes through the board and makes all of the desired traces on the board. Then the components (transistors, resistors, angle connector, etc.) of the PCB must be soldered on by us. A ribbon cable will be soldered to the circuit board. The other end of the ribbon cable will be soldered to each of the wire leads of the motors. Every component must be precisely matched so each motor is operated correctly.

Locations of Manufacturing and Assembly

Manufacturing of the components will be carried out in various locations. The turning of components will be done on the lathes and cutting will be done using the band saw in the Machine Shop in the G.G. Brown Building. The soldering of electrical components will be carried out in the X50 Laboratory in G.G. Brown Building. Assembly of the components will be completed in both the X50 Lab and the Machine Shop.

VALIDATION TESTING

Most of the haptic research papers we examined used measurements in units of cycles per second (Hz) to describe their experimentation set-ups. Since the frequency of our actual motors is unknown, we suggest running a test with a Hall Effect sensor connected to LabVIEW to create a calibration curve relating the user input "duty cycle" to the angular velocity of the eccentric weight. The calibration results of this test give us the ability replicate previously performed haptics experiments. And in replicating previously performed tests, we will be able to validate our device by comparing their results with ours. The calibration curves will also give us a way to check if any motor needs individual calibration. Additionally, we can compare calibration curves for individual motors over time, to see if any specific motor needs replacing.

Since our device is meant for testing and any comes with an associated error. We have devised a series of tests to determine the accuracy and precision of our device.

In order to test for precision of tactor spacing, measure distance between motors placed into a substrate using calipers. Take out all the tactors and place them back into the substrate. Assuming the spacing changes, use the difference in spacing as +/- error.

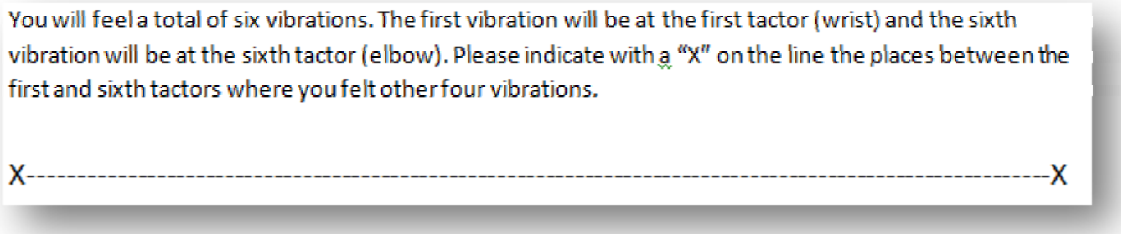
We expect that each substrate material will have a different factor of stretch when tightened around an arm or any other part of the body. In order to compare the tactor spacing of one material to another, the amount of stretch per distance must be measured and added into any tactor spacing measurements.
As the substrate wraps around the body, the spacing between tactors will decrease based on the curvature of the arm or any other body part where the device is worn. A rough measurement for change in tactor spacing should be included as a +/- error or a function can be derived to describe how much distance is lost between tactors as the device based on the curvature of the skin.

In our own testing, we noted a timing issue for in the logic based timing. Specifically when total time (pulse duration + pause) is equal to elapsed time, the while loop is supposed to quit looping. However, it didn't ever stop looping until we changed the Boolean logic block "is equal to" to a "less than or equal to". The reason for this is that the computer isn't fast enough to process the digital logic on the ms scale. We noted that the timing errors were on the order of 10-20 milliseconds.

TESTING RESULTS

We ran a rudimentary test during the Design Expo to determine whether test subjects could distinguish between the tactile saltation effect and a control case. The testing device was affixed to the test subject's right arm with Velcro. Two separate vibration sequences—control and test—were administered and the test subjects were asked to mark X's on a line indicating where they felt the vibrotactile stimulation for each of the two tests. A total of six stimulations were delivered per test and we marked the first and last vibrations for the test subject so as to avoid any issue with scaling. The test subject was asked to indicate the other four X's. A sample sheet is indicated below (Figure 13, p. 19). The sheets were double-sided and coded with a random letter written on each side. The side with the letter closer to the beginning of alphabet was the control case and the other side was the test. The control case consisted of actuating six tactors in a row down the sleeve. The test case consisted of skipping every other tactor where two vibrations were given per tactor. In both cases, the duration of the vibration was 100 milliseconds with a 120 millisecond pause in between each.

Figure 13: Sample sheet used for validation testing during the design expo



You will feel a total of six vibrations. The first vibration will be at the first tactor (wrist) and the sixth vibration will be at the sixth tactor (elbow). Please indicate with a “X” on the line the places between the first and sixth tactors where you felt other four vibrations.

X--X

Based on the data collected from a sample size of eleven test subjects, we were able to reveal some interesting statistics. We found that 60% of all test subjects indicated similar spacings for the vibrations in the test and control case although the spacings did vary person to person. Additionally, 50% of test subjects who could correctly identify the control case, were mislead by the saltation effect into believing there were more tactors being actuated in the test case.

PROJECT PLAN

Since Design Review 1, we have shifted our focus to designing a device that will be used to test the saltation effect. This change required us to do more research on the saltation effect as well as haptics in general. During this time, we also generated concepts and made our selection based on input from our sponsor as well as using functional decomposition for the three main areas of the device: array, substrate, and programming. A demonstration prototype was also made during this time for use during the presentation at Design Review 2.

Since Design Review 2, we have ordered some of the components needed for testing and fabrication. In addition, we have been programming the LabVIEW interface. We ordered and received the PCI-DIO-96 DAQ that we will use for our device. Both its hardware and software have been installed on a computer in 1089 G.G. Brown (X50 Lab). A fabrication plan has also been developed in this time. Dynamic modeling of the device’s motor assemblies has been completed, as well as the designing of motor control circuitry. During this time, we also crafted a prototype for the presentation at Design Review 3.

Following Design Review 3, the first thing we will do is the ordering of our electrical components, such as the printed circuit board and its components (i.e. transistors and resistors). Then, we will fabricate the motor assemblies and continue programming in LabVIEW. We will then be assembling our device and begin carrying out testing. Based on feedback and test results from Design Review 3, we will make modifications and present the alpha prototype at Design Review 4. Then we will be able to make the final modifications to the alpha prototype and present it at the Design Expo.

LOGISTICAL AND SPECIAL CHALLENGES

Manufacturing

We worry that while pressing the motor into the threaded rod the wire leads could be damaged beyond repair. Additionally, we worry that if the motor is pressed too far into the rod the eccentric weight would come into hard contact with the bore. The eccentric weight of the motor would be prevented from spinning. We could prevent this situation by using calipers to measure the depth that the motor has been pressed. In the event of such failures, new motor assemblies will be quickly manufactured for replacement.

Anticipated challenges relating to circuitry and programming

We spaced and sized the printed circuit board components and trace on the fly. Since we have never designed a circuit board before, we worry that the components may not fit the board's holes. Once we identify which holes and spacing were wrong, we fix the CAD and have a new circuit board within days. However, we double-checked many of our calculations and reread all component specification sheets in hopes that everything fits the first time.

Additionally, we placed many of the through holes for soldering on the PCB relatively close to one another. Although all team members have experience soldering, given the number of solder joints we will have to make to complete the board fabrication, there is a good chance of a bad connection. We believe this cannot be prevented. However, if we make a quick LabVIEW program which turns on all the motors, it won't be hard to pinpoint the bad solders joints.

With regards to LabVIEW programming, we are all relative new to the software. Much of what we have learned so far is comes from programs written by others. In fact, our progress is almost directly proportional to the number of programs we can reverse engineer. We worry that unless we find a program with all the features we require, we will be at a loss for how to move forward in programming. However, we plan to meet with Tom Bress to learn about other function blocks in LabVIEW that will help us achieve our desired functionality.

DISCUSSION AND RECOMMENDATIONS

The purpose of this section is to critique the final design and to recommend improvements.

Vibration Motor Units

The final design for the vibration motor unit serves to house the pager motor and to provide an attachment method to a substrate. The final design allows the user to change the size of the tactor. The vibration motor units use an acorn nut to secure a motor to the substrate and create contact with the skin. However, any nut or bolt that fits the threaded rod may also be used. In addition, the design is modular which gives the user the flexibility to vary the physical spacing of tactors and move tactors from substrate to substrate easily. The user can simply unscrew the acorn nut and remove the rest of the assembly from the substrate then reattach the vibration motor to another substrate. Although the motor units can be moved around easily, the initial assembly of motor units to the circuitry requires soldering the leads of the pager motor to the ribbon cable. To improve the modularity of the vibration motor unit, we could design female connectors for the ends of the ribbon cables. The connectors would have two holes that the leads of the vibration motors would plug into. Inside the connectors, the leads would make contact with the wires connected the printed circuit board. Using a connector would eliminate the need to solder the leads of the vibration motors directly to the ribbon cable wires. In the event that a vibration motor unit stops working, it can be replaced quickly without unsoldering wires. Additionally, one output channel could be used to send signals to more than one motor. A limited number of output channels may be used to power the same number of motors for different tactor layouts. For instance, the first eight output channels could power eight vibration motor units arranged in a circle and then the wires could be unplugged using the connectors. The wires could then be plugged into eight different motor units arranged in a line.

The entire vibration motor unit could also be redesigned using coin motors instead of pager motors. A housing similar to the current housing for the vibration motor unit could be designed to create a modular motor unit. The moment created by the wires that connect the motor to the circuit board would be smaller than the moment on the current motor unit since coin motors are much smaller in length than pager motors.

Software

The current device is controlled through a graphical user interface (GUI) that was created using a LabVIEW code. The user can control the sequence which motors vibrate and specify the vibration intensity, vibration time, and time interval between vibrations. Although the code allows the user to vibrate the motors for time interval on the order of milliseconds, LabVIEW is only accurate up to tens of milliseconds. Due to the nature of human perception experimentation, vibration times for the motors need to be accurate on the order of milliseconds and ideally the code should run accurately up to tenths of microseconds. Additionally, the computer's processor is only capable of running accurately up to milliseconds. Thus, using different programming software and a computer with a faster processor will improve the accuracy of the timing schemes required for experimentation. Alternatively, we could use an embedded system that could devote its CPU to running the program. The current code could be improved by replacing several of the express VIs used to create the functionality of the device. Express VIs tend to slow down the signals since they are cable performing several tasks that may be unnecessary for the functionality the device may be trying to achieve.

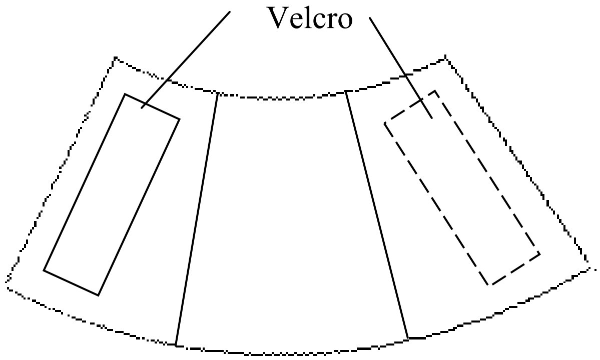
Substrate Design

We recommend using a laser-cutter with a CAD package to create a desired array of holes. The array can be designed in the CAD package and then accurately cut out using the laser-cutter. In addition to the accuracy of the holes, the laser-cutter will cauterize the fabric and keep it from fraying around the edges.

Interfacing the Device to the Formarm

The armband we used to create our device consists of a rectangular section that holds the array of tactors with two trapezoidal wings on either side. A “X" square of Velcro is stitched to one side of one of the wings. The mating square of Velcro is stitched to the other side of the other wing. The device is fastened by wrapping the wings around the forearm and securing it in place with the Velcro. Due to the tapered shape of the forearm, simple geometric shapes may not create a tailored fit. Instead, the entire armband should look like the area between two concentric arcs when it is laid out (Figure 14). The large wings would distribute the stress on the sides of the array more evenly than the trapezoidal wings.

Figure 14: Suggested redesign or armband



CONCLUSIONS

Our project was to create a device that will be used for experimentation on the effectiveness of vibrotactile interpersonal communication. The main goal for experimentation was to determine if it is possible to incite tactile saltation through the use of vibrations. After a literature review of haptics and discussion with our sponsor and peers, we identified customer and engineering specifications. We generated concepts to meet these specifications and then determined our alpha design using a selection process. A fabrication plan for the device has been created. Based on many concepts, we have created a device which allows the user to digitally control vibration intensity, time duration of vibration, pause time. In hardware, the user is able to quickly easily change the spacing and locations of the tactors on the substrate. We have completed the dynamic modeling of the device. We have also created the motor control circuitry and control software using LabVIEW. After the device was assembled, we ran a rudimentary experiment and determined that 50% of users that could correctly identify the control case were fooled by the salutatory illusion. We find this number a success and hope further experimentation with the different parameters will continue to increase that percentage.

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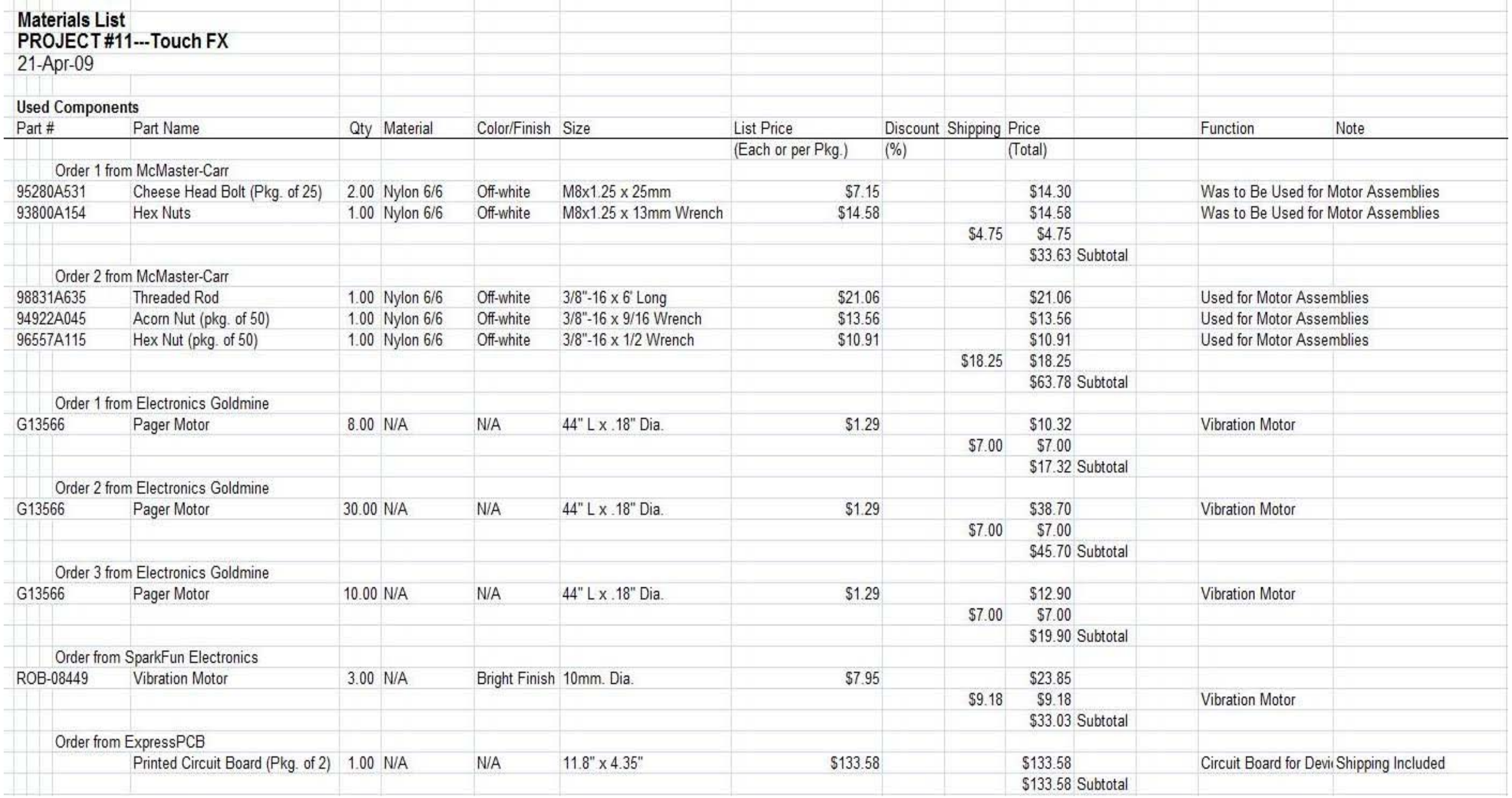
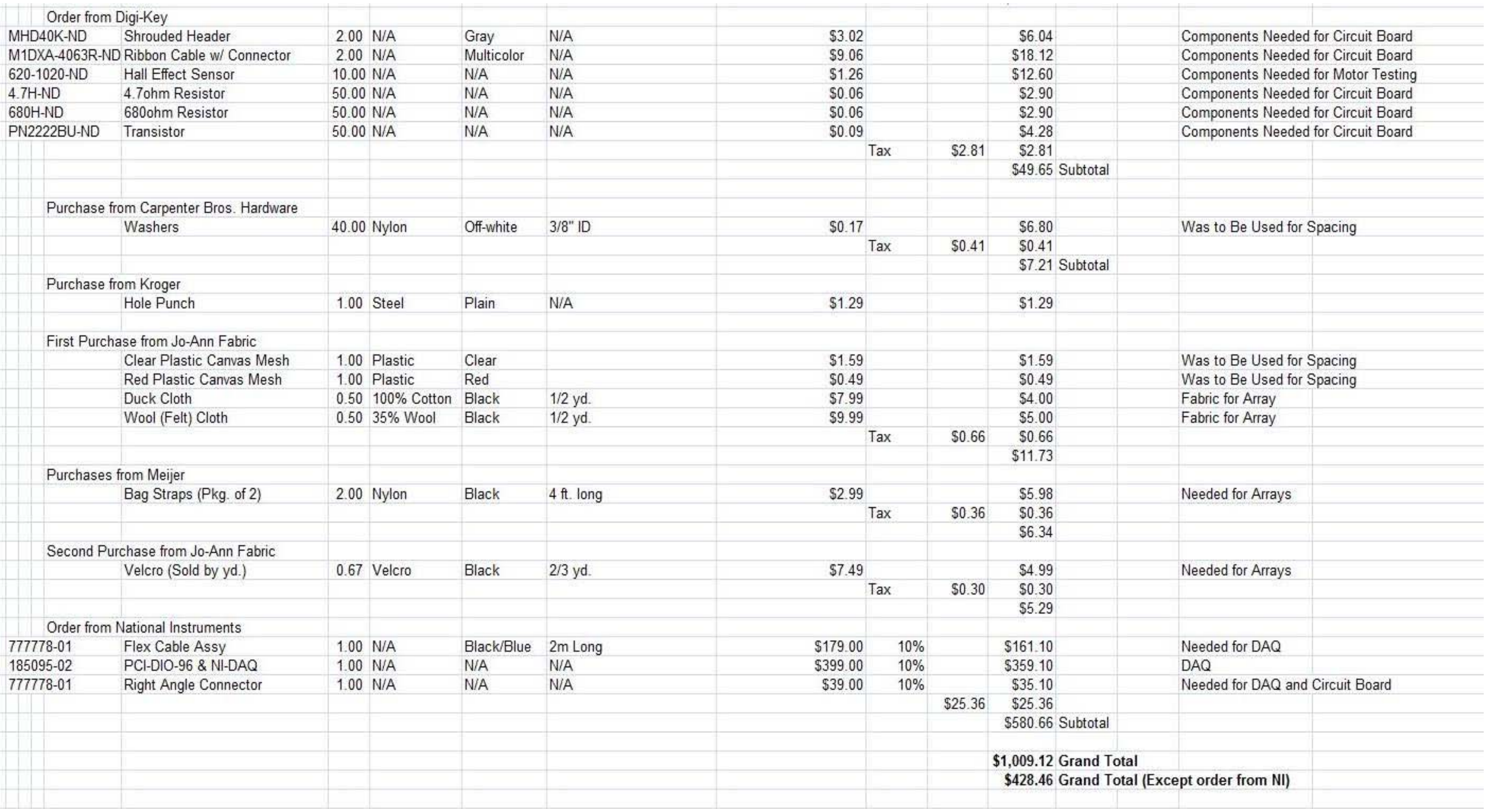
APPENDIX A: BILL OF MATERIALS



Materials List
PROJECT #11---Touch FX
21-Apr-09

Used Components

Part #	Part Name	Qty	Material	Color/Finish	Size	List Price	Discount	Shipping	Price		Function	Note
						(Each or per Pkg.)	(%)		(Total)			
Order 1 from McMaster-Carr												
95280A531	Cheese Head Bolt (Pkg. of 25)	2.00	Nylon 6/6	Off-white	M8x1.25 x 25mm	$7.15			$14.30		Was to Be Used for Motor Assemblies	
93800A154	Hex Nuts	1.00	Nylon 6/6	Off-white	M8x1.25 x 13mm Wrench	$14.58			$14.58		Was to Be Used for Motor Assemblies	
								$4.75	$4.75			
									$33.63	Subtotal		
Order 2 from McMaster-Carr												
98831A635	Threaded Rod	1.00	Nylon 6/6	Off-white	3/8"-16 x 6' Long	$21.06			$21.06		Used for Motor Assemblies	
94922A045	Acorn Nut (pkg. of 50)	1.00	Nylon 6/6	Off-white	3/8"-16 x 9/16 Wrench	$13.56			$13.56		Used for Motor Assemblies	
96557A115	Hex Nut (pkg. of 50)	1.00	Nylon 6/6	Off-white	3/8"-16 x 1/2 Wrench	$10.91			$10.91		Used for Motor Assemblies	
								$18.25	$18.25			
									$63.78	Subtotal		
Order 1 from Electronics Goldmine												
G13566	Pager Motor	8.00	N/A	N/A	44" L x .18" Dia.	$1.29			$10.32		Vibration Motor	
								$7.00	$7.00			
									$17.32	Subtotal		
Order 2 from Electronics Goldmine												
G13566	Pager Motor	30.00	N/A	N/A	44" L x .18" Dia.	$1.29			$38.70		Vibration Motor	
								$7.00	$7.00			
									$45.70	Subtotal		
Order 3 from Electronics Goldmine												
G13566	Pager Motor	10.00	N/A	N/A	44" L x .18" Dia.	$1.29			$12.90		Vibration Motor	
								$7.00	$7.00			
									$19.90	Subtotal		
Order from SparkFun Electronics												
ROB-08449	Vibration Motor	3.00	N/A	Bright Finish	10mm. Dia.	$7.95			$23.85			
								$9.18	$9.18		Vibration Motor	
									$33.03	Subtotal		
Order from ExpressPCB												
	Printed Circuit Board (Pkg. of 2)	1.00	N/A	N/A	11.8" x 4.35"	$133.58			$133.58		Circuit Board for Devi	Shipping Included
									$133.58	Subtotal		



Order from Digi-Key											
MHD40K-ND	Shrouded Header	2.00	N/A	Gray	N/A	$3.02			$6.04		Components Needed for Circuit Board
M1DXA-4063R-ND	Ribbon Cable w/ Connector	2.00	N/A	Multicolor	N/A	$9.06			$18.12		Components Needed for Circuit Board
620-1020-ND	Hall Effect Sensor	10.00	N/A	N/A	N/A	$1.26			$12.60		Components Needed for Motor Testing
4.7H-ND	4.7ohm Resistor	50.00	N/A	N/A	N/A	$0.06			$2.90		Components Needed for Circuit Board
680H-ND	680ohm Resistor	50.00	N/A	N/A	N/A	$0.06			$2.90		Components Needed for Circuit Board
PN2222BU-ND	Transistor	50.00	N/A	N/A	N/A	$0.09			$4.28		Components Needed for Circuit Board
							Tax	$2.81	$2.81		
									$49.65	Subtotal	
Purchase from Carpenter Bros. Hardware											
	Washers	40.00	Nylon	Off-white	3/8" ID	$0.17			$6.80		Was to Be Used for Spacing
							Tax	$0.41	$0.41		
									$7.21	Subtotal	
Purchase from Kroger											
	Hole Punch	1.00	Steel	Plain	N/A	$1.29			$1.29		
First Purchase from Jo-Ann Fabric											
	Clear Plastic Canvas Mesh	1.00	Plastic	Clear		$1.59			$1.59		Was to Be Used for Spacing
	Red Plastic Canvas Mesh	1.00	Plastic	Red		$0.49			$0.49		Was to Be Used for Spacing
	Duck Cloth	0.50	100% Cotton	Black	1/2 yd.	$7.99			$4.00		Fabric for Array
	Wool (Felt) Cloth	0.50	35% Wool	Black	1/2 yd.	$9.99			$5.00		Fabric for Array
							Tax	$0.66	$0.66		
									$11.73		
Purchases from Meijer											
	Bag Straps (Pkg. of 2)	2.00	Nylon	Black	4 ft. long	$2.99			$5.98		Needed for Arrays
							Tax	$0.36	$0.36		
									$6.34		
Second Purchase from Jo-Ann Fabric											
	Velcro (Sold by yd.)	0.67	Velcro	Black	2/3 yd.	$7.49			$4.99		Needed for Arrays
							Tax	$0.30	$0.30		
									$5.29		
Order from National Instruments											
777778-01	Flex Cable Assy	1.00	N/A	Black/Blue	2m Long	$179.00	10%		$161.10		Needed for DAQ
185095-02	PCI-DIO-96 & NI-DAQ	1.00	N/A	N/A	N/A	$399.00	10%		$359.10		DAQ
777778-01	Right Angle Connector	1.00	N/A	N/A	N/A	$39.00	10%		$35.10		Needed for DAQ and Circuit Board
								$25.36	$25.36		
									$580.66	Subtotal	
									$1,009.12	**Grand Total**	
									$428.46	**Grand Total (Except order from NI)**	

APPENDIX B: DESCRIPTION OF ENGINEERING CHANGES SINCE DESIGN REVIEW #3

Since DR#3, we only made a few small changes. The acorn nuts were larger than we expected, so we increased the spacing of each motor unit in the hexagonal array from 0.6” to 7/8”, which lead to a larger array. We also chose substrate materials such as felt and duck cloth to use in addition to the polyester-cotton blend. We cut our hexagonal pattern in the duck cloth to use as our primary substrate material, and cut different patterns in the felt.

We also needed a way to attach the substrate to a person’s arm, which we had not previously discussed. Nylon straps were one method that we had used, however it was too difficult to securely attach the device. We then sewed “flaps” on the side of the substrate and used a Velcro attachment.

Finally, we were not able to completed our LabVIEW code until we had our finalized circuit board. This was because we had to test the which pin on DAQ corresponded to which specific motor. We also created a diagnostic program that turned on motors with switches. This also doubled as a proof that we could actuate multiple motors at once.

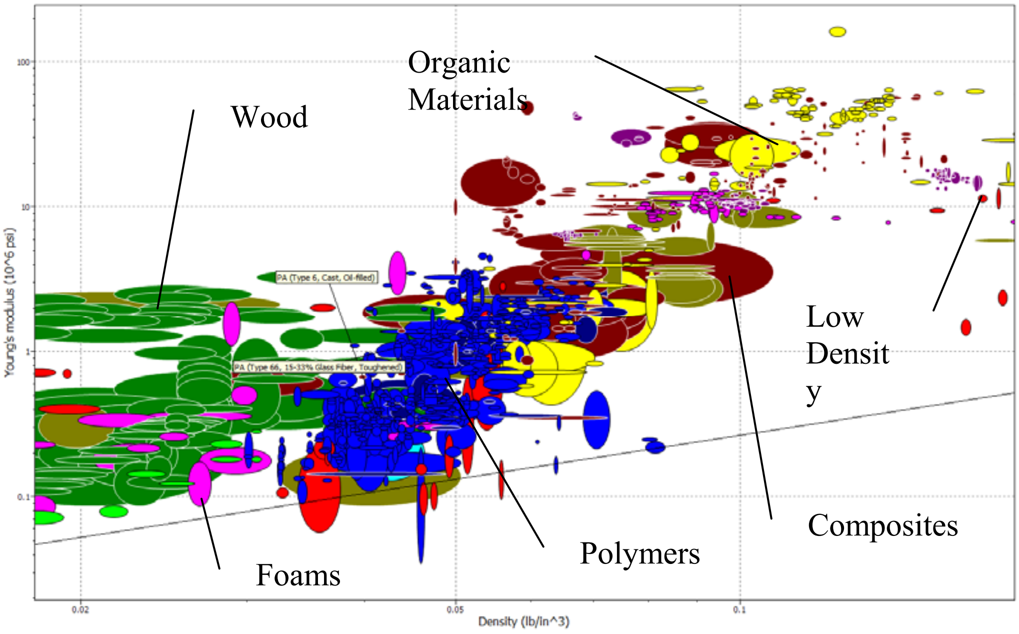
APPENDIX C: Design Analysis

Material selection: Functional Performance

The threaded rod is the major component of the vibration motor unit. Our design uses 38 motor units to build a hexagonal array worn on the body; therefore the threaded rod should have a low density. Additionally, since the threaded rod houses the pager motor, it must be easy to machine and stiff enough to transmit vibrations. The threaded rod must also be electrically non-conductive for the safety of the test subject. Finally, it was desirable that the threaded rod was inexpensive. From these derived material specifications, we decided to a polymer. Next, we looked up what materials the threaded rods come in. After applying our material and size constraints, our selection was narrowed down to threaded rods made of nylon 6/6.

We justified using nylon 6/6 with Cambridge Engineering Selector (CES). First, we used our material specifications to set limits on the material properties. We searched for materials with a low density (0.001 - 0.072 lb/in^3) and low thermal conductivity (0.013 – 29 BTU·ft/hr·ft^2·F) [X, X]. After setting these constraints, metals were eliminated from our material options. In addition, we were particularly interested in the density and stiffness of the material because we wanted a lightweight material that could transmit the vibrations of the pager motor. Since the rod can be considered a bending beam, we used a material index of E/ρ. We created a graph of our results with the density (ρ) on the x-axis and Young's modulus (E) on the y-axis and plotted a line with a slope of 1. The results show a range of materials that include different types of woods, foams, ceramics, polymers, and some low density metals. We were able to eliminate woods, organic materials, and ceramics because these materials would be difficult to machine. We were also able to eliminate foams because they may damp vibrations. Also, since composites are expensive, we decided against using them for our applications. Thus, we narrowed our material options to polymers and low density metals. Different types of nylon with similar material properties to nylon 6/6 were amongst the results produced by CES (Figure C.1).

Figure C.1: Several types of nylon recommended by CES software



Material selection: Environmental Performance

This section covers the environmental impact that the material selection process yields for the threaded rod that was to be used for motor housings. The two materials that we selected to use are nylon 6/6 and the aluminum alloy 6061. However, the database in SimaPro does not include data for Al 6061, so we elected to use the closest material offered, Al 6060. We chose to use Al 6060 because it is a type of 6000-series aluminum alloy with a similar composition to Al 6061.

Before using SimaPro to analyze the environmental impact of our housings, we must first find the mass needed for them using nylon 6/6. Ten fully-machined housings were measured for mass to find an average. The average mass was 0.99g. We needed to utilize a total of 38 housings for the final device, so the total mass of nylon 6/6 was 43.54g. For comparison, we needed to determine the volume nylon 6/6 used by calculation of known mass and density. The density of nylon 6/6 is 1.14 g/cm^3. Using this method, the volume per housing is calculated to be 0.866cm^3. To find the mass of identically sized housings made of Al 6061, we multiplied this volume by the density of Al 6061. The density of Al 6061 is 2.70g/cm^3. By calculation, the total mass of aluminum needed for 38 fully-machined motor housings is 88.89g.

Using SimaPro, it is found that more emissions (in grams) are released in the manufacturing of nylon 6/6 components as opposed to that of Al 6060. This can be seen in Figure C.2. This is due to the raw materials involved in the manufacture of nylon 6/6.

When looking at environmental impact compared to one another, it is easily seen that Al 6060 is more impactful than nylon 6/6. As seen in Figure C.3, Al 6060 is more impactful in every category than nylon 6/6. In only one impact category is nylon more than half as impactful as Al 6060. This category is respiratory organics and nylon 6/6 has only 90% of the impact that Al 6060. The only category that neither material has any impact on is radiation. The remaining categories have nylon 6/6 impact rates between 0 and 31% that of Al 6060. From this figure, it can be seen that nylon 6/6 has no impact on land use and minerals and minimal impact on the release of carcinogens (cancer-causing substances).

When the subdivisions of impact are normalized together, it can be seen in Figure C.4 that nylon has a minimal impact on the environment. Both materials perform well on their impacts on human health and ecotoxicity. Where they differ is in the use of resources. The production of Al 6060 is very mineral- and land use-intensive. For this reason, it can be seen that nylon 6/6 will have less of an impact on the environment.

Finally, in the points-scoring section of SimaPro's impact assessment, it can be seen that nylon 6/6 has less of an impact on the environment than Al 6060. As seen in Figure C.5, the point scores of nylon 6/6 and Al 6060 are about 8mPt and 265mPt. Thus, nylon 6/6 is better for the environment

Upon reviewing this, we believe that the choice of using nylon 6/6 was the better one. It has less of an impact on the environment. As discussed previously in the report, we chose nylon 6/6 over Al 6061 because of the insulative properties of nylon 6/6. It is an added benefit that nylon 6/6 is also better for the environment.

Figure C.2: Total Mass Emissions of Nylon 6/6 and Al 6060

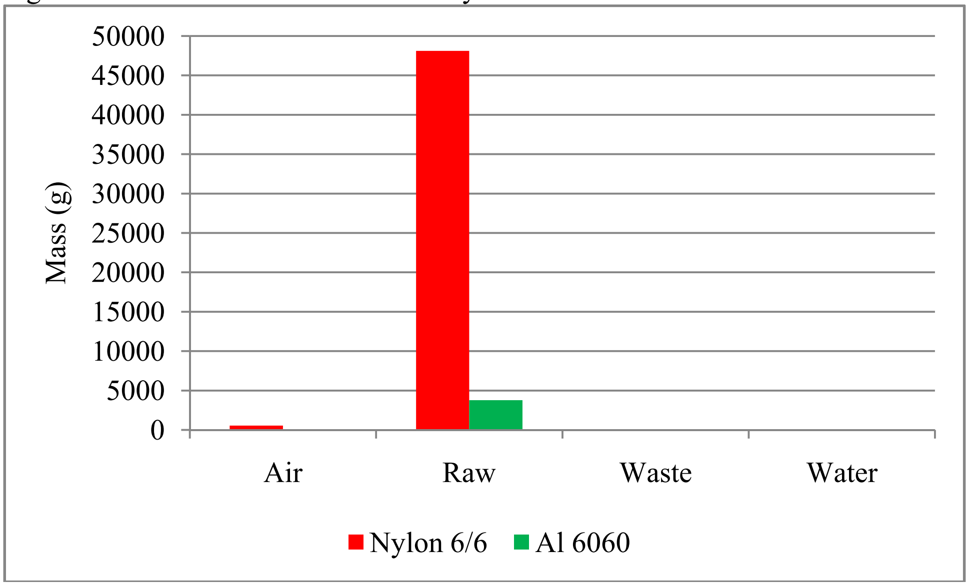
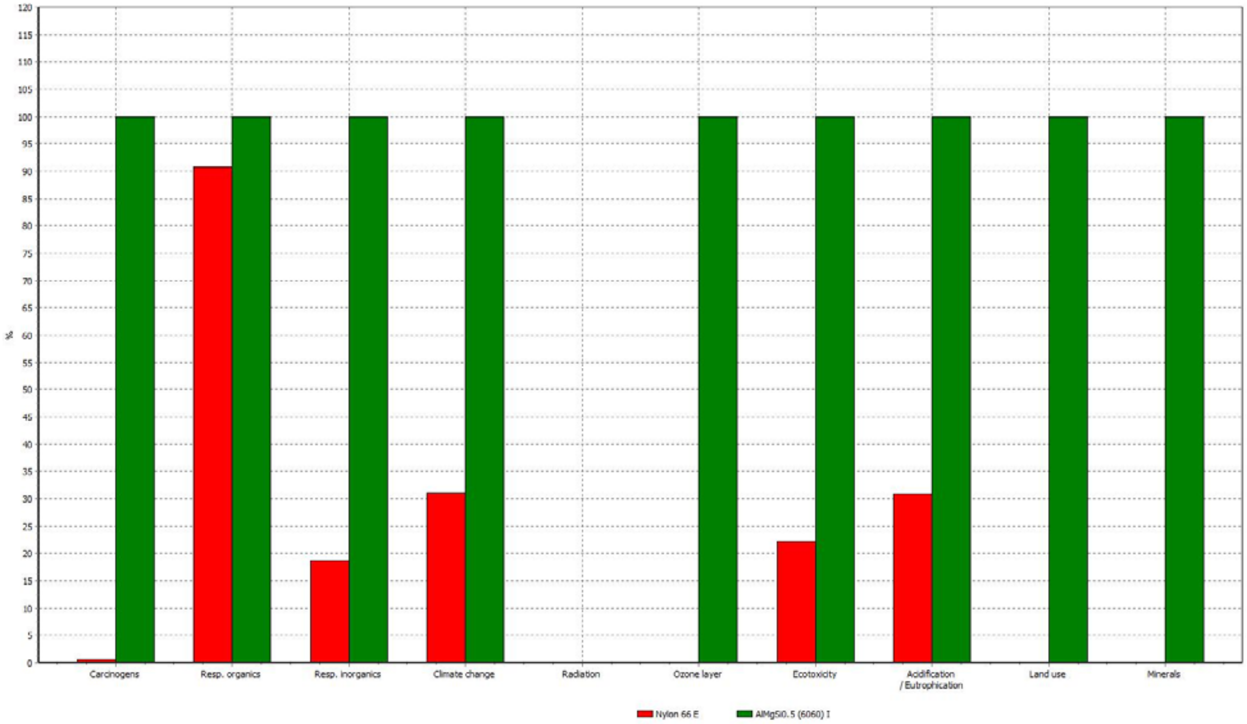
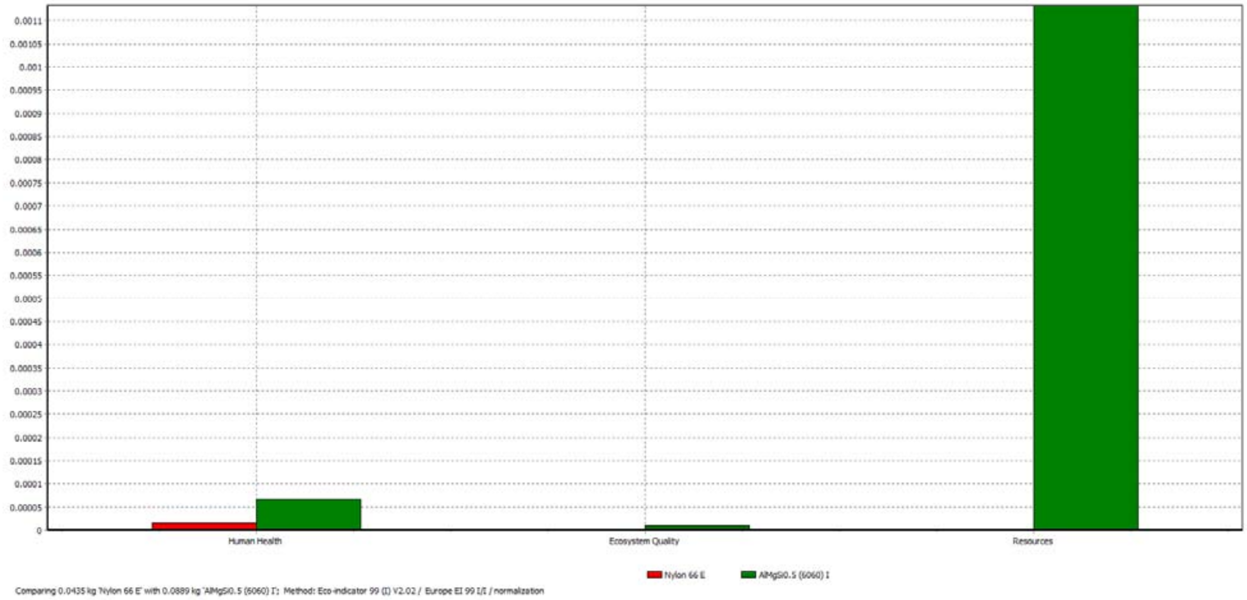


Figure C.3: Characterization of Nylon 6/6 vs. Al 6060



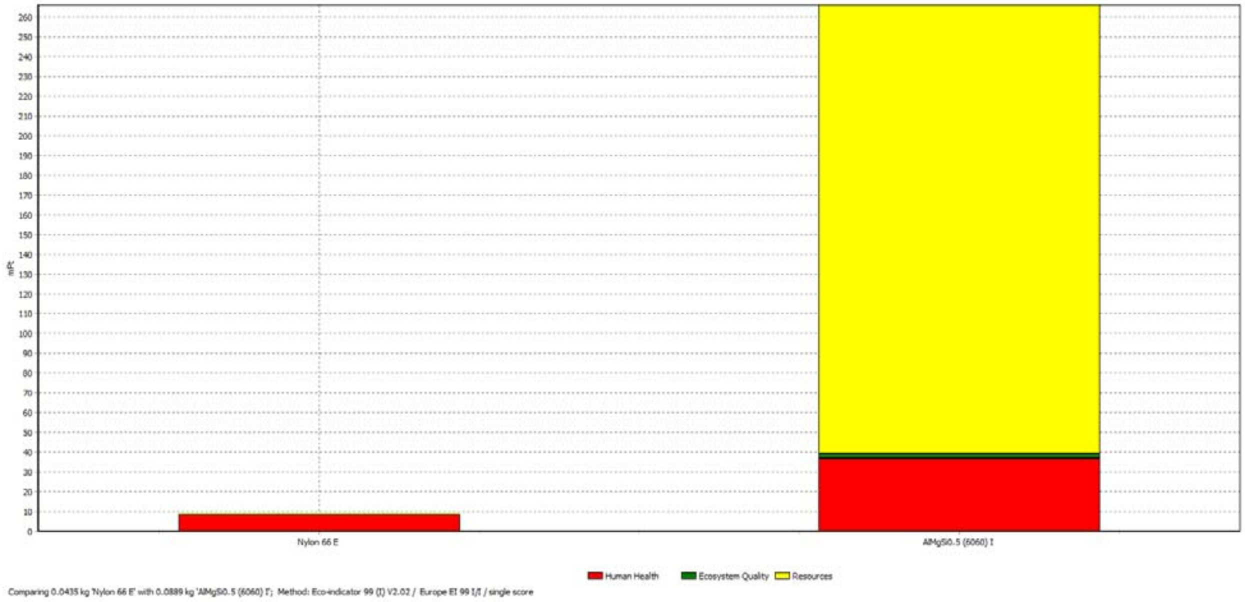
Comparing 0.0435 kg 'Nylon 66 E' with 0.0889 kg 'AlMgSi0.5 (6060) I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / characterization

Figure C.4: Normalization of Nylon 6/6 vs. Al 6060



Comparing 0.0435 kg 'Nylon 66 E' with 0.0889 kg 'AlMgSi0.5 (6060) I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / normalization

Figure C.5: Single Score of Nylon 6/6 vs. Al 6060



Comparing 0.0435 kg 'Nylon 66 E' with 0.0889 kg 'AlMgSi0.5 (6060) I'; Method: Eco-indicator 99 (I) V2.02 / Europe EI 99 I/I / single score

Manufacturing Process Selection

If our device were to have duplicates made in their likeness, we would assume that perhaps 100 would be made. This production number has been selected because the device is going to be used for academic research here at the University of Michigan. We realize that researchers at other universities and institutions, as well as some at companies and corporations may be interested in using a device such as ours.

As discussed previously, several of our electrical components, such as pager motors and angle connectors, are ordered from independent suppliers and the task of making these would be left to them and would continued to be purchased from them. As for hardware, such as hex nuts and threaded rod, we would suggest continuing ordering these from independent suppliers as well. Utilizing CES Materials Selector we have found that nylon 6/6 and aluminum alloy Al 6061 are the most ideal materials to make the housings from and for the hardware.

Considering that our device utilizes 38 motor housings with a production number of 100, this totals 3800 housings to be made. With relatively few components needing to be turned, the largest factor for manufacturing technique will be dictated by cost.

If we were to craft housings of Al 6061, we have a few options of manufacture. The first option is to make them in the same fashion as we have done for this device. Another option is to turn the components on a CNC lathe. This would be a more hands off approach for machining; however, time is lost during tool changes and worker operations of switching component orientation. Yet another option is to turn the components on a multiple-spindle bar automatic machine (automatic screw machine) or a Swiss-style CNC lathe using the same processes as described for the manufacture of our device. These last two machines are very efficient for mass production of turned components; however, these machines are very expensive with some at costs of in excess of $100,000. The traditional CNC lathe may be used but given that turning on this doesn't save much time as opposed to using a traditional lathe. For these reasons, we would recommend using the same method of manufacture using a traditional lathe for 100 devices as was used to craft the one in our report. It should be noted that for all of these processes, dimensional tolerances can be kept accurately.

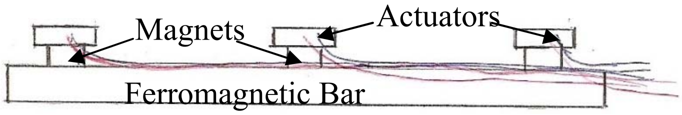
If we were to craft our motor housings of nylon 6/6, our options for manufacture are the same as for Al 6061 plus one more. The additional option for manufacture in this case is to use injection molding. This can be done because nylon 6/6 is a thermoplastic plastic, which quite suitable for injection molding. The components could be made if the proper tooling was fabricated and an injection molding machine was available. If they were made using this method, the costs would be quite high. An injection molding machine can be just as expensive to purchase as the automatic bar or the Swiss-style CNC lathe. In addition to the machine, the tooling for injection molded products costs in excess of $10,000. With these considerations, we believe that for manufacturing the housings made of nylon 6/6 it is best to utilize the method described previously in the report using a traditional lathe.

In summary, the manufacturing method that was done for our project is the best method for manufacture, given the relatively few devices that may be actually produced. The cost of manufacture is the largest factor to consider. Our decision is justified by the reasons stated above.

APPENDIX D: Concept Generation
CONCEPT GENERATION: ARRAY

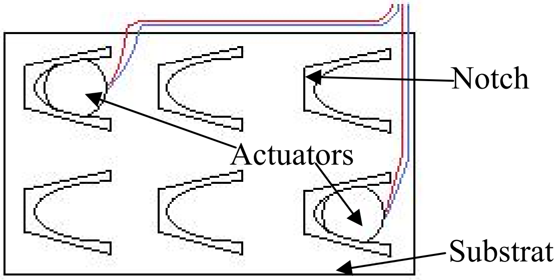
Another concept was to build a reconfigurable array by attaching the vibrotactile actuators with magnets. The concept consists of a thin ferromagnetic bars embedded in the substrate. A magnet would be attached to the back of each actuator. Then, the actuators would be attached to the substrate using the magnets (Figure D.1). Like the first concept, one major advantage is the variety of spatial layouts that can be created. This concept would also allow for direct skin-to-actuator contact and is relatively inexpensive. However, the disadvantages of this concept also include the imprecision of the attachment method for experimental repetition. The magnetic fields may also adversely affect the current to the actuators. Finally, we're concerned that the ferromagnetic bar may unintentionally transmit vibrations from one location to another because of its density and length.

Figure D.1: Side View of Magnet Attachment Method



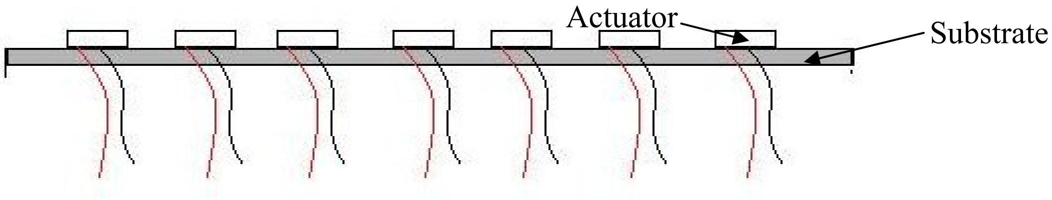
The next concept we considered was building an array using a substrate with prefabricated notches that the actuators would slip in and out of (Figure D.2). The advantages of this concept include the durability of the attachment between the actuators and the substrate, the ease of the attachment, and the precision of the attachment for experimental precision. However, the disadvantages of this concept include the difficulty to manage and organize wires and the difficulty to manufacture the notches on the substrate.

Figure D.2: Substrate with Prefabricated Notches



We also considered a concept using an array of actuators fixed to a substrate. However, the array would be reconfigurable using a programming scheme run by a computer (Figure D.3). For instance, to test the effect of different distances between actuators, a computer program could stimulate every actuator in a row or be programmed to stimulate every other actuator in the row. The advantages of this concept include a durable attachment between the actuators and the substrate, a precise method of attachment for experimental repetition, and an easy way to manage and organize wires. A disadvantage of this concept is the large number of actuators needed to create versatile computer controlled spatial layouts.

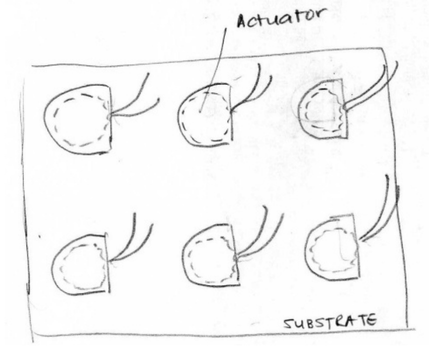
Figure D.3: Computer Controlled Fixed Array



Substrate with Prefabricated Pockets or Notches

One concept for attaching unfixed actuators was creating a substrate with a prefabricated array of evenly distributed pockets or notches (Figure D.2, p _, Figure D.4). The actuators would slip easily into the pockets or notches and be held snugly in place. These methods would facilitate the easy of attachment and have good precision for experimental repetition. However, they have poor versatility for spacing, management of wires, durability of attachment, and manufacturability. The additional material to create the pockets or notches would also dampen vibrations, reduce skin-to-actuator contact, and increase the cost of the device.

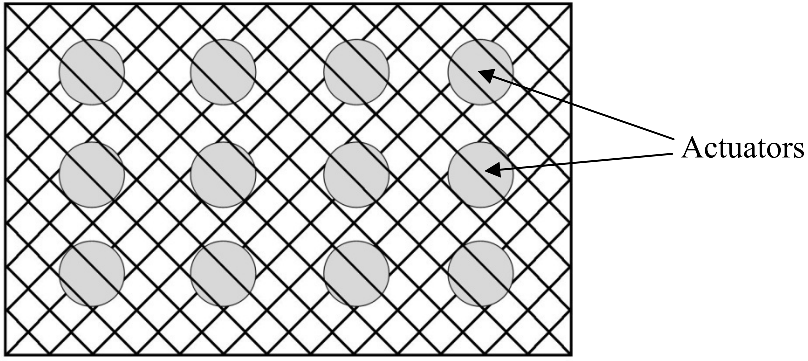
Figure D.4: Substrate with Prefabricated Pockets



Mesh Weave

We considered creating a rigid frame and tightly stringing a dense weave from one side of the frame to the other. The actuators would be placed at the in between intersections of the weave (Figure D.5). Although, this concept offers an easy actuator attachment and versatility for spacing, it does not offer a durable attachment method for the actuators. This concept would poorly manage of wires, reduce skin-to-actuator contact, dampen vibrations, and offer poor precision for experimental repetition. The cost to create a mesh weave would be comparable to the cost to create the reference.

Figure D.5: Mesh Weave



Porous Substrate-Thread Tactor Wires

Another concept we considered was threading the wires of the actuators through a porous substrate (such as cross-stitching material) (Figures D.6a, D.6b). Actuators would be positioned by rethreading the wires through holes in different locations. The attractive features of this concept included low vibration dampening and the direct skin-to-tactor contact. Additionally, the versatility for spacing, manufacturability, and cost were similar to the reference. However, this concept was not selected due to the inconvenient attachment method and the poor durability of the actuators to the substrate.

Figure D.6a: Top View of Porous Substrate
Thread Tactor Wires

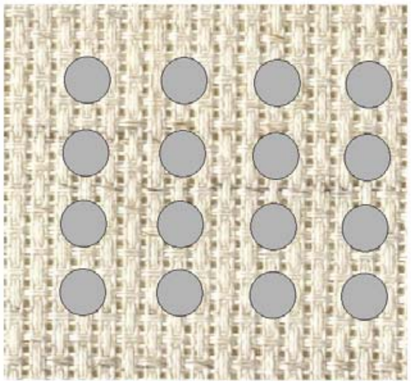


Figure D.6b: Side View of Porous Substrate
Thread Tactor Wires

Rigid Channel of Actuators

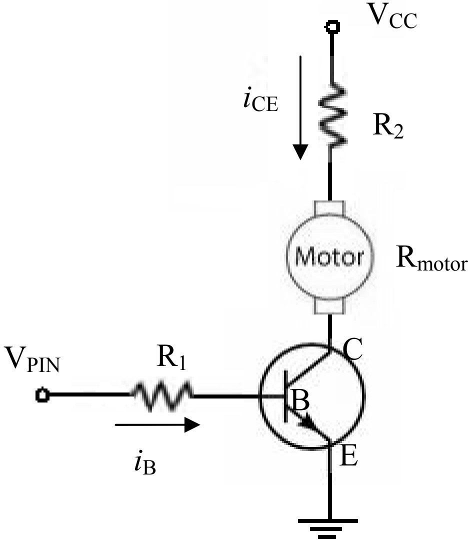
Another concept that we had was to place several actuators in a fabricated channel of fixed length that could easily be attached to the substrate. Each channel would have a slot that the actuator wires would thread through. The actuators would be able to move within the channel. The channel would be attached to any spot on the substrate with Velcro. The substrate would be made of the mating surface of Velcro. This concept offers versatility in spacing. However, this concept is highly unfeasible because the attachment scheme to the substrate is difficult and not durable. This concept is also difficult to manufacture, dampens vibrations, reduces skin-to-actuator contact, and offers poor management of wires.

APPENDIX E: Quality Function Deployment (QFD) Chart

			Engineering Specifications										Competitors			
		Weight	Number of Components	Manufacturability	Cost	Low Power Consumption	Durability/Robustness	Size (Portability/Weight)	Isolated/Simulataneous actuators	Bidirectional	Asynchronous/Asymmetric	Continuous	Lumi Touch	Hand Jive	TactaPad	Billow
Customer Specifications	Aesthetically pleasing	4.72		3	3		9	9					5	3	5	x
	Repositionable with customizable fit (can be worn on arm, back, leg, etc)	4.74	3	9	9		9	9					x	x	2	x
	Fun to use	4.85		3	3	1			3	9	1	9	5	5	5	3
	Stealth (not distracting to others)	5.15		1	9		3	9					3	4	1	1
	Ability to receive/playback message at own rate	6.03	3		3				9	9	9	9	4	1	x	1
	Ability to multitask while using device	6.95				1			9	9	9	9	1	5	5	1
	Durable (water-, sweat-, shock-, etc, resistent)	7.38	3	9	9		9	3					x	3	x	3
	Compatible with other communication devices (cell phones, computers, etc)	7.69	9	1	3	3		1		9	9	9	3	2	3	1
	Compact/lightweight (small surface area)	8.15	9	3	9	3	9	9					3	1	1	2
	Long Battery Life	8.67	3		9	9		3	9	9	9	3	x	x	x	x
	Comfortable to use and wear	8.82	1	1	3		9	9	3				x	3	4	4
	Quick transfer time between devices (send/receive messages quickly)	8.87				3			1	9	3	9	5	x	5	5
	Easy to learn how to use the device-quick learning device	8.97			1				3	3	9	9	5	1	5	x
	Technical Priorities		231.84	183.9	412.11	163.96	319.74	340.06	271.64	414.45	376.25	416.25				

APPENDIX F: Equations and Calculations

Figure F.1: Motor control schematic



$V_{CC} = 5$ V

$i_{SOURCE} = 2.5$ mA (max); *obtained from Spec Sheet for NI PC-DIO-96

$i_B = ?$

$i_{CE} = ?$

$\beta = 100$;

$R_{motor} = 11\ \Omega$

$V_{PIN} = 2.7$ V

$V_{BE,\,SAT} = 0.6$ V

$V_{CE,\,SAT} = 0.3$ V

$$\beta i_B = i_{CE} \qquad \text{Eq. F.1}$$

$$V_{CC} - i_{CE}R_2 - i_{CE}R_{motor} - V_{CE} = 0 \qquad \text{Eq. F.2}$$

$$V_{PIN} - i_B R_1 - V_{BE} = 0 \qquad \text{Eq. F.3}$$

$$i_B < i_{SOURCE} \qquad \text{Eq. F.4}$$

If we assume that $i_B = 2.0$ mA:

$$i_{CE} = \beta i_B = 100 \times 2.0 \text{ mA} = 200 \text{ mA}$$

then the most R_2 can be to ensure V_{CE} will be large enough to make diode CB forward biased is:

$$R_{2,max} = \frac{V_{CC} - V_{CE,SAT} - i_{CE}R_{motor}}{i_{CE}} = \frac{5\text{ V} - 0.3\text{ V} - 200\text{ mA} \times 11\ \Omega}{200\text{ mA}} = 12.5\ \Omega$$

Similarly, $R_{1,\,max}$ to ensure V_{BE} is large enough to make diode BE forward biased is:

$$R_{1,max} = \frac{V_{PIN} - V_{BE,SAT}}{i_B} = \frac{2.7\text{ V} - 0.6\text{ V}}{2\text{ mA}} = 1050\ \Omega$$

If we assume that $i_B = 2.5$ mA:

$$i_{CE} = \beta i_B = 100 \times 2.5 \text{ mA} = 250 \text{ mA}$$

then the most R_2 can be is to ensure V_{CE} will be large enough to make diode CB forward biased is:

$$\mathrm{R_{2,max}} = \frac{\mathrm{V_{CC}} - \mathrm{V_{CE,SAT}} - \mathrm{i_{CE}R_{motor}}}{\mathrm{i_{CE}}} = \frac{5\ \mathrm{V} - 0.3\ \mathrm{V} - 250\ \mathrm{mA} \times 11\ \Omega}{250\ \mathrm{mA}} = 7.8\ \Omega$$

Similarly, $R_{1,\ max}$ to ensure V_{BE} is large enough to make diode BE forward biased is:

$$\mathrm{R_{1,max}} = \frac{\mathrm{V_{PIN}} - \mathrm{V_{BE,SAT}}}{\mathrm{i_B}} = \frac{2.7\ \mathrm{V} - 0.6\ \mathrm{V}}{2.5\ \mathrm{mA}} = 840\ \Omega$$

Just to make sure V_{CE} and V_{BE} are bigger than $V_{CE,\ SAT}$ and $V_{BE,\ SAT}$, choose R_1 and R_2 so that V_{CE} and V_{BE} are 1 V:

For i_B = 2 mA:

$$\mathrm{R_1} = \frac{\mathrm{V_{PIN}} - \mathrm{V_{BE}}}{\mathrm{i_B}} = \frac{2.7\ \mathrm{V} - 1\ \mathrm{V}}{2\ \mathrm{mA}} = 850\ \Omega$$

$$\mathrm{R_2} = \frac{\mathrm{V_{CC}} - \mathrm{V_{CE}} - \mathrm{i_{CE}R_{motor}}}{\mathrm{i_{CE}}} = \frac{5\ \mathrm{V} - 1\ \mathrm{V} - 200\ \mathrm{mA} \times 11\ \Omega}{200\ \mathrm{mA}} = 9\ \Omega$$

For i_B = 2.5 mA:

$$\mathrm{R_1} = \frac{\mathrm{V_{PIN}} - \mathrm{V_{BE}}}{\mathrm{i_B}} = \frac{2.7\ \mathrm{V} - 1\ \mathrm{V}}{2.5\ \mathrm{mA}} = 680\ \Omega$$

$$\mathrm{R_2} = \frac{\mathrm{V_{CC}} - \mathrm{V_{CE}} - \mathrm{i_{CE}R_{motor}}}{\mathrm{i_{CE}}} = \frac{5\ \mathrm{V} - 1\ \mathrm{V} - 250\ \mathrm{mA} \times 11\ \Omega}{250\ \mathrm{mA}} = 5\ \Omega$$

Specs

For i_B = 2.0 mA

$R_{1,\ max}$	1050 Ω
$R_{2,\ max}$	12.5 Ω
R_1	850 Ω
R_2	9 Ω

For i_B = 2.5 mA

$R_{1,\ max}$	840 Ω
$R_{2,\ max}$	7.8 Ω
R_1	680 Ω
R_2	5 Ω

APPENDIX G: Mechanical Components

Figure G.1: Cross Sectional View of Motor and Bolt Assembly

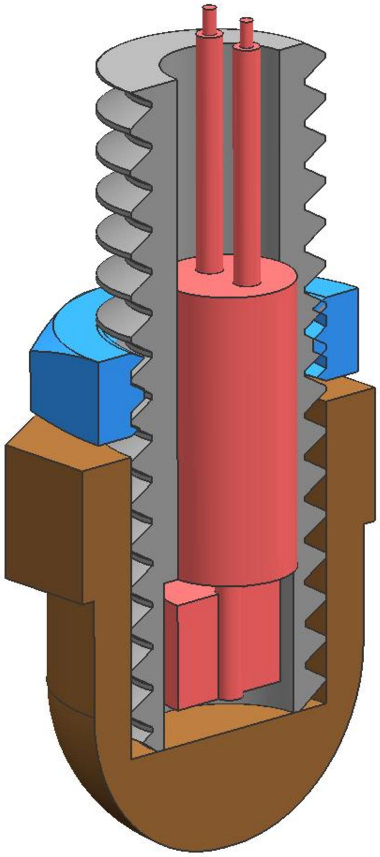


Figure G.2: Free Body Diagram of Bolt Assembly

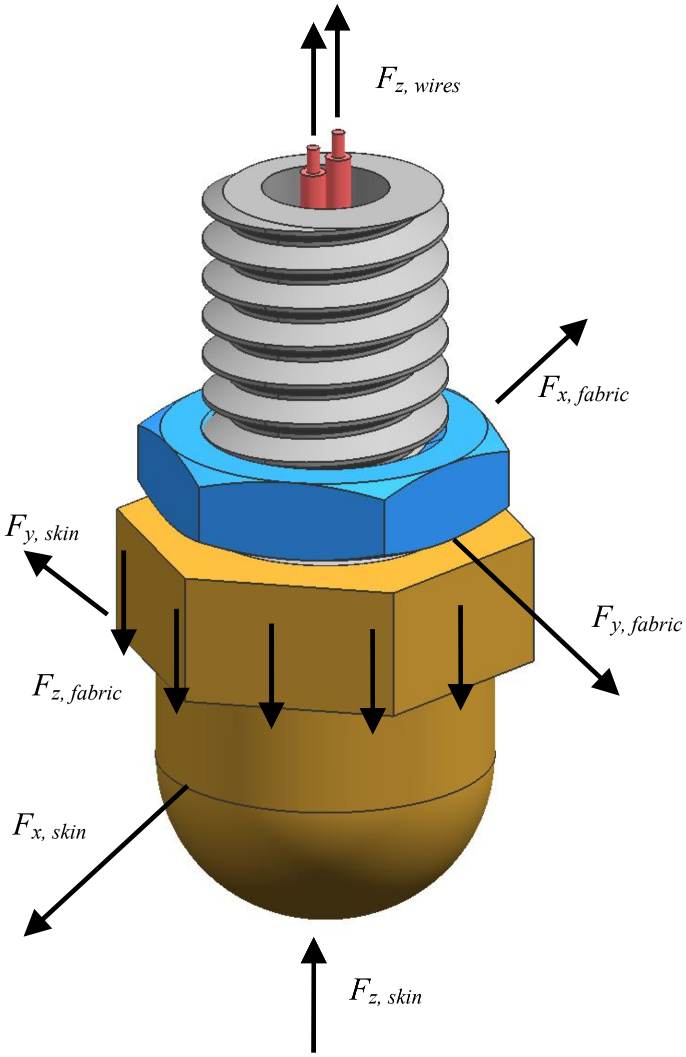


Figure G.3: Mass-spring-damper model

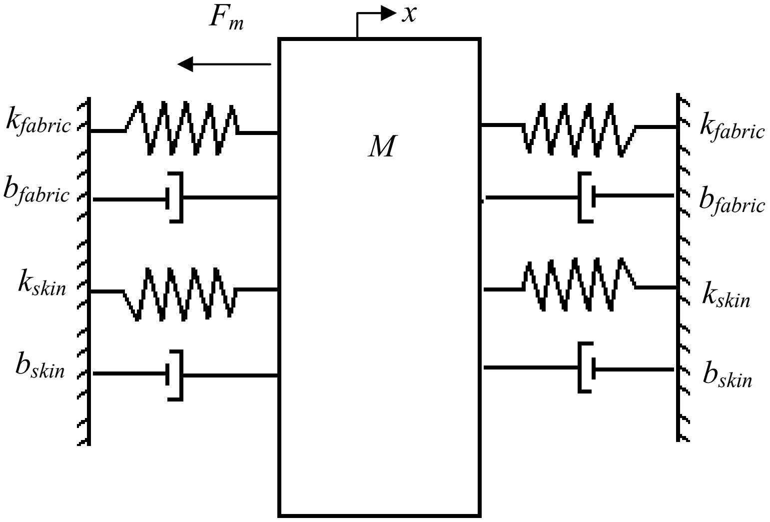


Figure G.4a: Simplified mass-spring-damper model

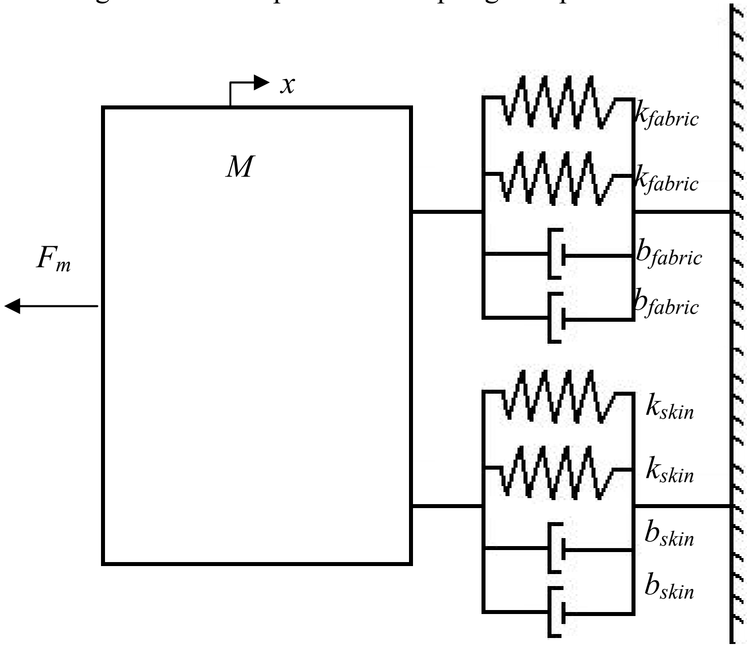
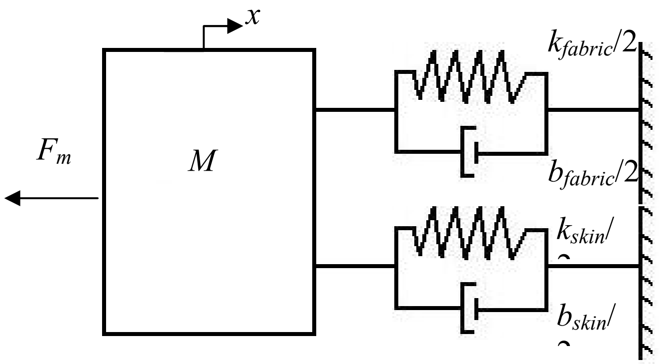


Figure G.4b: Simplified mass-spring-damper model



r_H: radius of head, r_T: radius of threads, r: radius of eccentric weight,

r_{CM}: radial location of the center of mass ($r_{CM} = \frac{4r}{3\pi}$)

k_{skin} = __ b_{skin} = __k_{fabric} = __ b_{fabric} = __

$$\dot{x} = v = r_{CM}\omega \qquad \ddot{x} = a = (\alpha r_{CM})\hat{i} + (\omega^2 r_{CM})\hat{j} = \sqrt{(\alpha r_{CM})^2 + (\omega^2 r_{CM})^2}$$

$$F_{Motor} = Ma = M\sqrt{(\alpha r_{CM})^2 + (\omega^2 r_{CM})^2}$$

$$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2} \Rightarrow k_{eq} = \frac{1}{\frac{1}{k_1} + \frac{1}{k_2}} \Rightarrow k_{eq} = \frac{k_1 k_2}{k_1 + k_2} = \frac{k^2}{2k} = \frac{k}{2}$$

$$\frac{1}{b_{eq}} = \frac{1}{b_1} + \frac{1}{b_2} \Rightarrow b_{eq} = \frac{1}{\frac{1}{b_1} + \frac{1}{b_2}} \Rightarrow b_{eq} = \frac{b_1 b_2}{b_1 + b_2} = \frac{b^2}{2b} = \frac{b}{2}$$

$$F_{Motor} = Ma = M\sqrt{(\alpha r_{CM})^2 + (\omega^2 r_{CM})^2} = M\ddot{x} + \frac{1}{2}b_{skin}\dot{x}_{skin} + \frac{1}{2}b_{fabric}\dot{x}_{fabric} + \frac{1}{2}k_{skin}x_{skin} + \frac{1}{2}k_{fabric}x_{fabric}$$

$$F_{Motor} = M\ddot{x} + \frac{1}{2}b_{skin}\dot{x}_{skin} + \frac{1}{2}b_{fabric}\dot{x}_{fabric} + \frac{1}{2}k_{skin}x_{skin} + \frac{1}{2}k_{fabric}x_{fabric}$$

Figure G.5: Substrate model

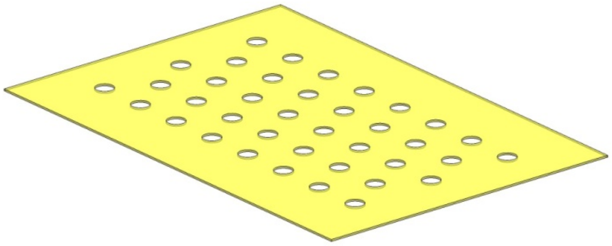


Figure G.6: Top view of device assembly

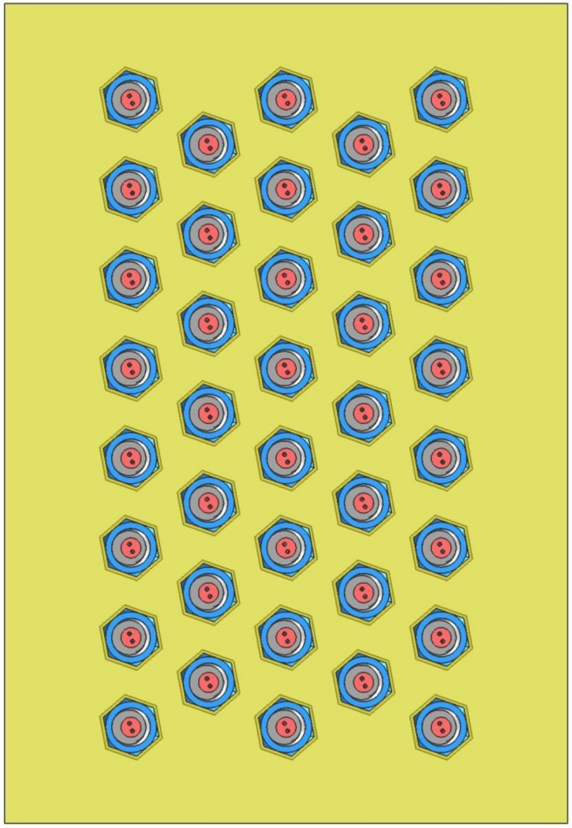


Figure G.7: Bottom view of device assembly

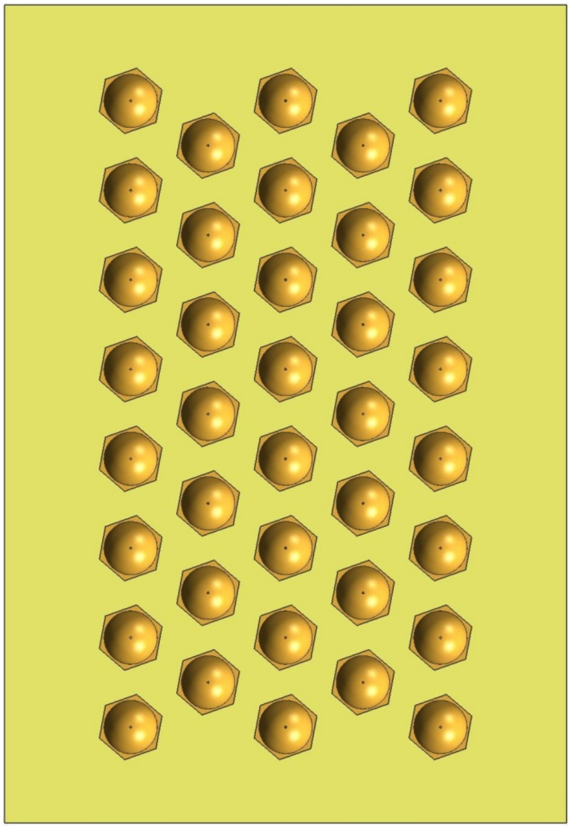


Figure G.8: Engineering drawing of assembled motor-bolt unit

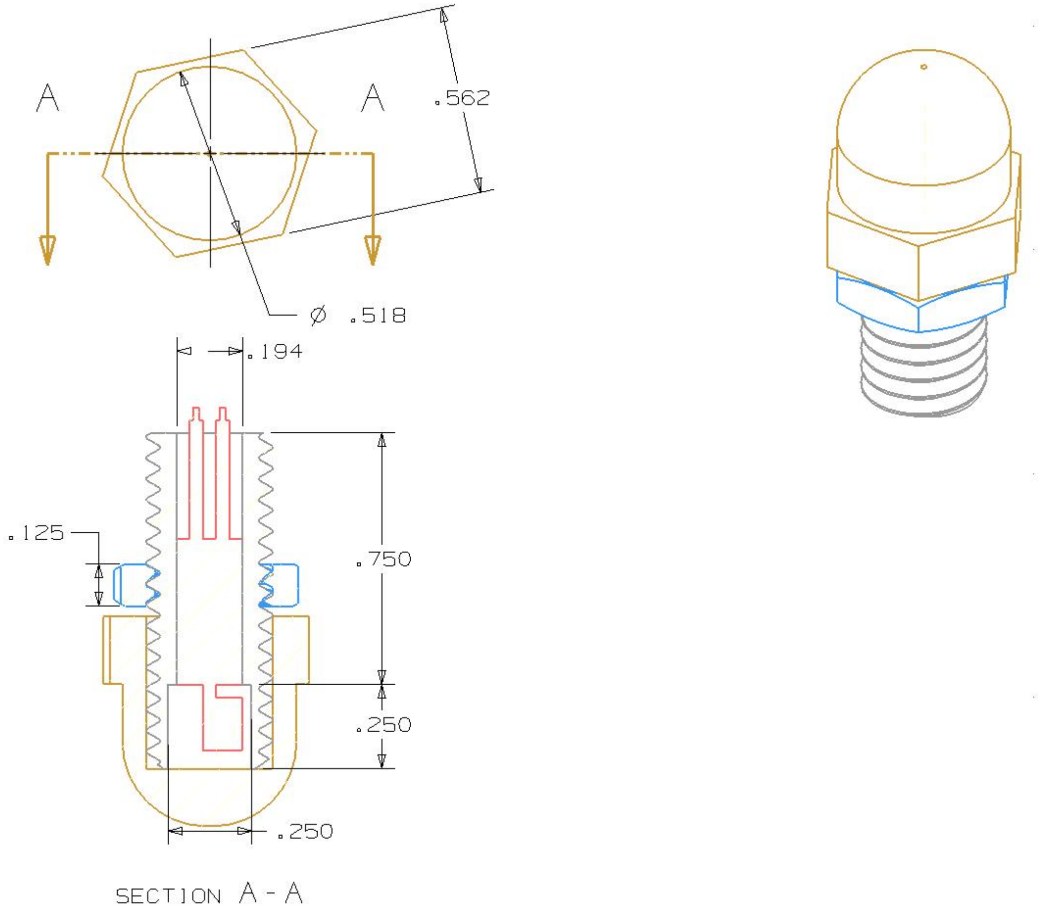
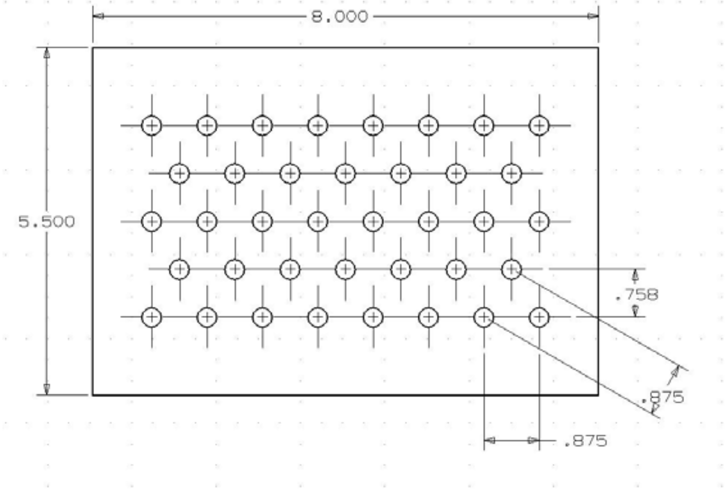
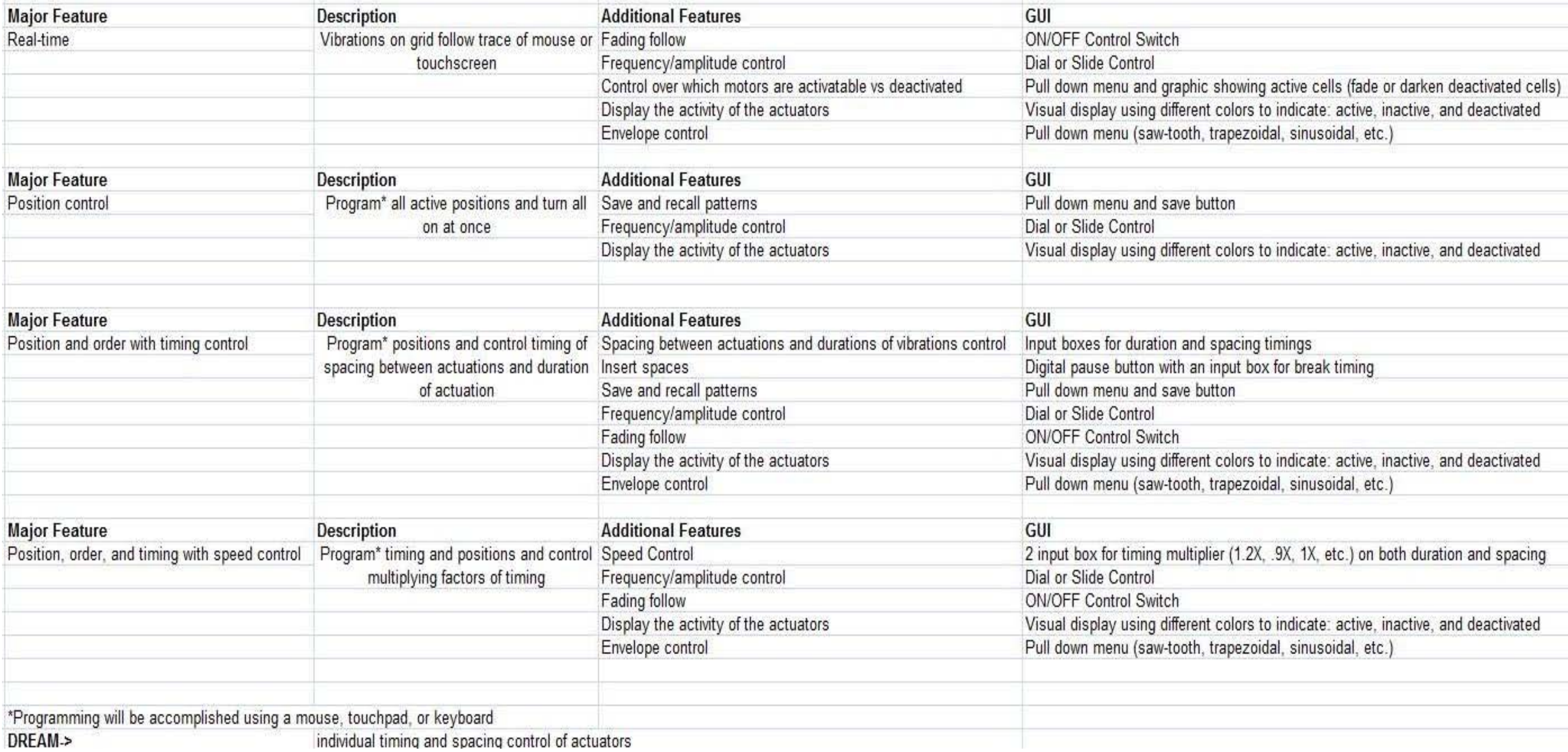


Figure G.9: Engineering drawing of substrate,



APPENDIX H: LABVIEW CODE

Figure H.1 Desired functionality of LabVIEW Code



Major Feature	**Description**	**Additional Features**	**GUI**
Real-time	Vibrations on grid follow trace of mouse or touchscreen	Fading follow	ON/OFF Control Switch
		Frequency/amplitude control	Dial or Slide Control
		Control over which motors are activatable vs deactivated	Pull down menu and graphic showing active cells (fade or darken deactivated cells)
		Display the activity of the actuators	Visual display using different colors to indicate: active, inactive, and deactivated
		Envelope control	Pull down menu (saw-tooth, trapezoidal, sinusoidal, etc.)
Major Feature	**Description**	**Additional Features**	**GUI**
Position control	Program* all active positions and turn all on at once	Save and recall patterns	Pull down menu and save button
		Frequency/amplitude control	Dial or Slide Control
		Display the activity of the actuators	Visual display using different colors to indicate: active, inactive, and deactivated
Major Feature	**Description**	**Additional Features**	**GUI**
Position and order with timing control	Program* positions and control timing of spacing between actuations and duration of actuation	Spacing between actuations and durations of vibrations control	Input boxes for duration and spacing timings
		Insert spaces	Digital pause button with an input box for break timing
		Save and recall patterns	Pull down menu and save button
		Frequency/amplitude control	Dial or Slide Control
		Fading follow	ON/OFF Control Switch
		Display the activity of the actuators	Visual display using different colors to indicate: active, inactive, and deactivated
		Envelope control	Pull down menu (saw-tooth, trapezoidal, sinusoidal, etc.)
Major Feature	**Description**	**Additional Features**	**GUI**
Position, order, and timing with speed control	Program* timing and positions and control multiplying factors of timing	Speed Control	2 input box for timing multiplier (1.2X, .9X, 1X, etc.) on both duration and spacing
		Frequency/amplitude control	Dial or Slide Control
		Fading follow	ON/OFF Control Switch
		Display the activity of the actuators	Visual display using different colors to indicate: active, inactive, and deactivated
		Envelope control	Pull down menu (saw-tooth, trapezoidal, sinusoidal, etc.)
*Programming will be accomplished using a mouse, touchpad, or keyboard			
DREAM->	individual timing and spacing control of actuators		

APPENDIX I: LabVIEW Graphical User Interface (GUI)

1a) User varies the duty cycle and frequency of the duty cycle to control the vibration intensity.

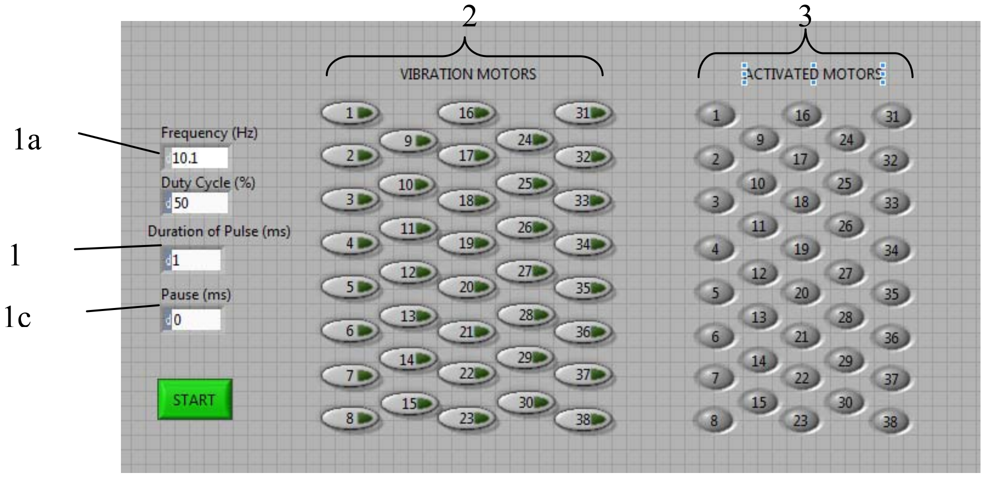
1b) User specifies the time duration of vibration in milliseconds.

1c) User specifies the pause time between vibrations in milliseconds.

2) Each motor is represented in the GUI with a push button with a “Latch when Released” mechanical action. Each push button has a corresponding on/off value within the LabVIEW code (Figure I.1).

3) When a motor is vibrating, the corresponding indicator lights up.

Figure I.1: User controlled LabVIEW GUI



Frequency (Hz) 10.1
Duty Cycle (%) 50
Duration of Pulse (ms) 1
Pause (ms) 0

APPENDIX J: LabVIEW Code

1a) User varies the duty cycle and frequency of the duty cycle to control the vibration intensity in GUI.

1b) User specifies the time duration of vibration in milliseconds in GUI.

1c) User specifies the pause time between vibrations in milliseconds in GUI.

2) Each push button on the GUI outputs a boolean value indicating if the switch is on or off.

3) Individual control over each motor was achieved using an event structure with 39 events. When a motor is selected in the GUI, the corresponding boolean value changes. The event case for the motor recognizes the value change and appends the number of the motor to a 1-D array.

4) When the user hits the "Start" button (by default) the 39th event in the event structure recognizes the value change, appends a "0" to the array, and exits the while loop.

5) The 1-D array stores the order that the motors were selected.

6) The array is fed into a for loop that contains a case structure with 38 cases. The for loop compares the value of each element in the array, except for the last element, with each of the 38 cases.

7) The case structure matches the value of the element with a corresponding case.

8) Each case contains a while loop that constantly updates the elapsed time.

9) The elapsed time is compared with the specified vibration time.

10) The elapsed time is compared with the sum of the specified vibration time and pause time.

11) Keeps track of the start time for the vibration.

12) Keeps track of the elapsed time for the vibration.

13) When the elapsed time is less than the vibration time, a square wave signal that controls the digital output voltage is generated and fed to a specific digital output channel on a National Instruments PCI-DIO-96 data acquisition device (DAQ). When the elapsed time is greater than the vibration time, no signal is sent to the output channel. If the elapsed time is greater than the sum of the vibration time and time between vibrations, the program exits the while loop and reads the value of the next element in the array.

14) Generates the square wave used for pulse width modulation (PWM).

15) Case structure that converts values of "1" and "-1" from the square wave into boolean values.

16) "And" gate makes sure DAQ outputs no signal when the time duration ends regardless of the value of the square wave when the while loop finishes.

17) Outputs to specified DAQ channel.

Figure J.1:Block diagram of LabVIEW code