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Vibrotactile Device for Optimizing Skin Response to Vibration

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Abstract

It is important to understand stochastic resonance on the hands in order to prove how it effectively enhances vibrosensory perception. To do this, an MR-compatible tactor is needed to provide a vibration stimulus to the hand during an MRI of the brain. The key design requirements of the device are that it must run at a frequency range of 30-300 Hz, and be small enough to fit on the subject's finger while maintaining a 1 mm thickness. In order to achieve these requirements, three design options were evaluated: solenoid, piezoelectric, and pneumatic. Of these three options, the piezoelectric device was determined to be the best suited design. Future work will be conducted to determine optimal materials for the tactor, as well as the required circuitry needed to drive the system.

1 Introduction

1.1 Problem Statement

Falling from ladders or scaffolds is of the leading causes of workplace injuries and fatalities. A device must be developed to improve the workers' response time by stimulating their sense of touch through vibrations in their hands. The device must be MR-compatible in order to analyze brain activity during the stimulus to the hand. The overall goal is to prove that a continuous stimulus on the hand can improve the range of sensory frequency perception.

1.2 Background

According to previous studies, the skin sensation of hand is believed to be the first available sensory cue for workers to detect and react to the fall initiation. On average, healthy young people took about 100 ms to arrest and stabilize their bodies when sudden forces were applied to the ladder [4]. Out of the 100 ms period, approximately 40 ms was because of the delay in the brain cortical reflex loop, while the other 60 ms was mainly from the delay of hand skin receptors to detect the change in contact force [4]. If this 60 ms time period could be reduced by decreasing the amount of time skin receptors used for detecting the change in force, then the person's ability to rescue the fall could be greatly enhanced [4].

The pacinian corpuscle is the main nerve center in the hand for receiving signals from vibrations [15]. The pacinian corpuscle is a part of the somatic sensory system; it is located in the hypodermis, which is the inner-most layer of the skin. When a vibration occurs, it travels through the skin and to the hypodermis, causing the cell membranes of the pacinian corpuscle neurons will be displaced [16]. These neurons are mechanoreceptors, meaning that they will convert this mechanical displacement into electrical impulses, or signals. The electrical signals are sent to the central nervous system (spinal cord and brain) via peripheral nerve pathways. Vibration signals sent by the pacinian corpuscle are rapid pulses, similar to sine waves. Like all nerves in the body, the pacinian corpuscle has a designed threshold that a vibration stimulus must overcome in order to trigger a signal to the brain [15]. If a vibration is not strong enough to cause the pacinian corpuscle to reach threshold, the brain will not sense the vibration, and the body will not respond. In the case of falling from ladders or scaffolds, there will be an early vibration on the hands that is too weak to reach the threshold of the pacinian corpuscle, and the vibration is not sensed by the brain. This precedes a large vibration that can cause the person to lose their grip and fall. If the body were able to sense the early vibrations in the ladder or scaffold, they would be able to respond by gripping the ladder tighter before the large vibration causes them to fall. In order to allow the pacinian corpuscle to sense these small vibrations, it may be possible to increase the amplitude of small vibrations above threshold by introducing an additional noise signal.

Stochastic resonance (SR) is a phenomenon that occurs when a sub-threshold signal is enhanced by the presence of noise [5]. As shown in Figure 1, SR can assist a sensing system in detecting a signal by adding a predetermined amount of noise. This noise has the same modality as the signal, but does not contain significant information to the system, or is sub-threshold. When adequate noise is added to the signal, it increases the amplitude of the signal, which can bring it above threshold as shown in Figure 1b. In most cases, it is preferred to eliminate noise from a signal; however, in the case of sensing small vibrations, an outside noise is helpful for bringing the signal above threshold and allowing the body to sense the small vibrations.

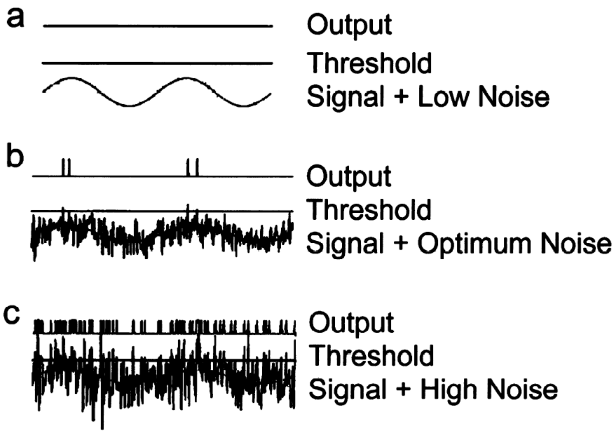

Figure 1. Example of stochastic resonance. (a) When the signal and noise is low and does not exceed the threshold, the system won't produce any output. (b) When optimal amount of noise is added to the signal, the signal and noise cross the threshold whenever the signal reaches its peak. (c) Excess of noise is added to signal; the threshold crossings do not reflect the phase of the signal (because it is greatly affected by noise) [5].

In order to reduce the amount of time for skin receptors to detect the vibrations from a ladder or scaffold, a vibrotactile device can be used to add the additional noise for Stochastic Resonance to occur. This will enhance the response of skin receptors by allowing sub-threshold signals to gain amplitude and reach threshold. The vibrotactile device would produce small amounts of vibration at a high frequency (optimum noise) so that the small vibrations generated in a ladder or scaffold prior to fall initiation can be detected by the skin receptors. Such a device has already been shown to enhance skin sensation in young and old healthy people, as well as reduce the walking gait variability in elderly fallers [5, 6]. However, the vibrotactile devices used in these experiments were designed for the foot and would be too bulky to fit between the hand and rung/scaffold.

The results from experiments performed to determine the most sensitive regions of the hand are showed in Figure 2 [7]. According to Figure 2, the most sensitive regions of hand are fingertips and the middle of palm because the amount of voltage required (for the vibrotactile device to vibrate) is the smallest. This means that the ideal spots to place the vibrotactile device are at fingertips and palm. Also, the experiments indicated that a frequency range of roughly 30 Hz to 300 Hz is most sensitive to the hand skin receptors. Different stimuli (such as force, temperature etc.) will affect different receptors in the hand. The receptors related to this project are Meissner corpuscles and Pacinian corpuscles, which are both rapid adapting receptors. Meissner corpuscles cover about 40% of the tactile receptors in hand and they serve as velocity sensors to provide feedback on grip and grasping function. They mainly work at frequency range of 3 to 40 Hz. Conversely, Pacinian corpuscles cover about 13% and are sensitive at 200 Hz to 350 Hz [7]. As a result, a vibrotactile device that is designed for hand stimulation should have an adjustable range of frequency from roughly 30 Hz to 300 Hz.

Color	Amplitude range [V]
Blue	0.3 → 0.6
Red	0.6 → 0.9
Purple	0.6 → 1.2
Yellow	1.2 → 2.1
Green	2.1 → 2.9
Gray	3

Figure 2: Map of hand sensitivities based on applied tactor voltage: Notice that there is an increased sensitivity a the tips of the fingers [7].

2 Motivation

The motivation behind this project is the high number of falls from ladders and scaffolds in the workplace. These falls are usually started due to destabilization of the ladder/scaffold, and it is believed that by using the SR phenomenon, the reaction time to these destabilizations can be significantly reduced. A tactile stimulator that can be used in an MRI would allow observation of brain activity during the stimulus, and examination of the effects of SR on the sensory threshold. The brain activity study may help the researchers to verify and obtain direct evidence that vibrotactile stimulation can reduce reaction time and further prevent falling accident at workplace.

3 Original Design Specification

The purpose for designing this vibrotactile device is to reduce the amount of lag time between vibration stimulus and reaction. In order for researchers to study the brain activities during tactile stimulation, the device needs to be MR-compatible. The MRI scanner applies extreme magnetic fields, rapidly changing magnetic field gradients, and radiofrequency pulses to create images for area of interest [8]. As a result, an MR-compatible device must be composed of nonmagnetic and non-conductive materials, or be heavily shielded, in order to not interfere with the imaging process. The tactor design for this project should aim for dimensions of less than 1mm in thickness and 1cm in diameter so it may be placed on palmar side of the hand. If it is placed on the dorsal side of the hand, the size may be up to 2mm in thickness and 2cm in diameter. The vibrotactile device has to operate at a random frequency output, changing in a range of 30 Hz to 300 Hz and the output vibration should be sub-threshold (meaning the subject won't consciously feel the vibration). Refer to the Appendix for detailed design specifications.

4 Vibration Method Chosen

Based on the above design criteria, a piezoelectric system for vibration was chosen to provide adequate noise for stochastic resonance. When a mechanical force is applied to some solid materials, an electrical charge will form as a result. This is known as piezoelectricity [9]. There are a variety of ceramic and crystalline materials that are piezoelectric. The specific properties of the materials that create the piezoelectric effect are dipolar crystal patterns. When the material is stressed, the dipoles are displaced, which redistributes the ions of the material, causing an electrical charge to form. This charge is directly related to the amount of force applied, and can be easily measured.

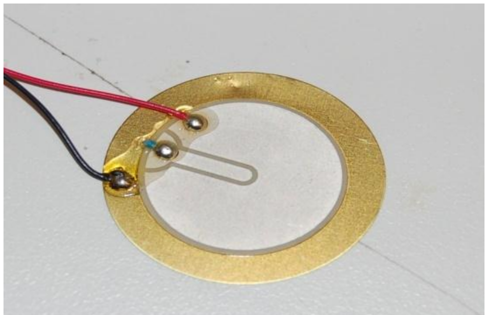

Figure 3: Piezoelectric vibrator [10]

The property of piezoelectricity can be reversed by applying an electrical charge to a piezoelectric material, which causes a mechanical force or vibration directly proportional to the amount of charge applied. The system would require a voltage source, wiring to connect the voltage source to the piezoelectric vibrator, and the piezoelectric material itself as shown in Figure 3. The voltage source is used to apply a charge to the piezoelectric material through the wiring. The frequency of vibration is dependent on the amplitude of the charge, so increasing or decreasing the charge will have the same effect on the vibration frequency, making the system easily adjustable [11].

A piezoelectric vibrator system is advantageous because it can be made with non-ferrous materials. Piezoelectric parts are also relatively inexpensive, and the vibrator itself would cost approximately $50 [12]. Another benefit of such a system is that the frequency would be easily adjustable based on the voltage applied. Piezoelectric systems run at a wide range of frequencies, and for the purposes of the tactile stimulator it could be adjustable from 30-300 Hz.

The main limitation of a piezoelectric system for use in an MRI is the fact that the system would require wiring inside the MRI tube to lead from the vibrator to the voltage source. It would be possible to use non-ferrous wiring in the system; however, the materials are not the only determining factor in MR-compatibility. Any wires in the system that have a charge running through them will create a changing electrical current that will create an competing magnetic field, interfering with the MRI. Another limiting factor of the wiring system would be that the strong magnetic field of the MRI would induce its own current to the wires. The system could possibly be designed to compensate for the MRI current, but if the current is too strong it may cripple the system and make it impossible to achieve the correct charge for vibration. The wires would require heavy shielding in order to prevent any interaction between the wires and the magnetic field of the MRI.

5 Fall 2011 Design

Based on the evaluation of each design and the scoring from the design matrix, the Piezoelectric Tactor was chosen. In order to drive the piezoelectric system, as shown in Figure 4, three components are need: a voltage source, a driving circuit, and the piezoelectric tactor itself.

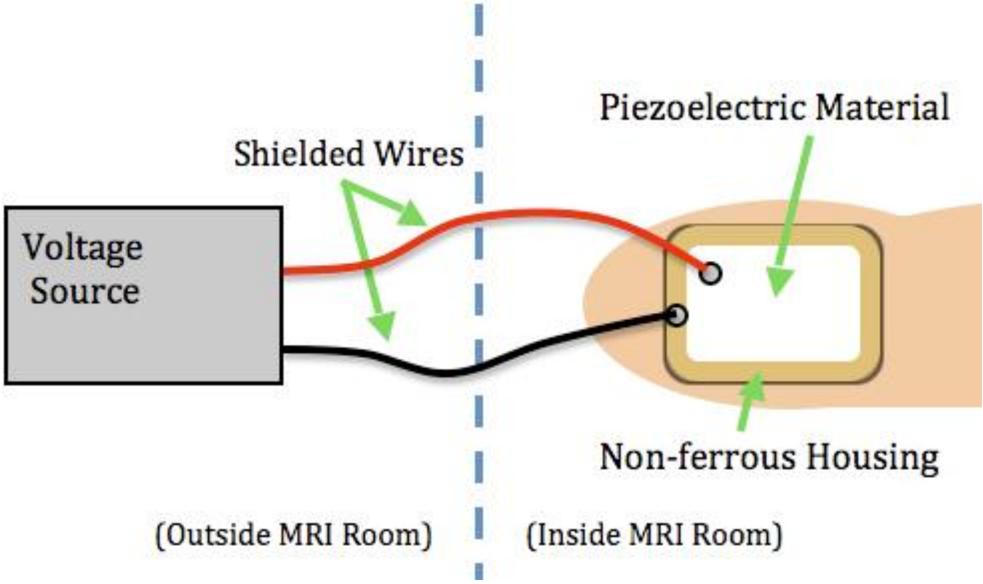

Figure 4. Diagram of the Piezoelectric system: Shows the connection of the outside voltage source to the piezoelectric tactor inside the MRI room.

In order to avoid extra complications due to the MR-compatibility requirement, the system will be set up so that the voltage source and the driving circuit will be located outside of the MRI room, with shield wires running into the MRI room. The piezoelectric system operates by using a DC voltage source to power the circuit element. The circuit then converts the DC source to AC with the desired frequency. The driving circuit then powers the piezoelectric tactor using frequency and displacement parameters set by the user. Each component is described in detail below.

5.1 The Voltage Source

Since the voltage source will be located outside of the MRI room, a standard ferrous voltage source can be used. Due to the nature of the piezoelectric tactor that was chosen for the system, and the circuitry that was build around it, only a 9-volt battery is required. Two of the benefits from reducing the voltage source to a 9-volt battery are that the system will be easily transportable, and the overall cost will be greatly reduced. The value of 9 V was chosen mainly because it is the recommended operating value for the 555 chip and because 9 V falls in the voltage range required for the LT3469 chip.

5.2 The Driving Circuit

In order to properly drive the piezoelectric tactor, a circuit is needed that can change the DC input volt to an AC output at variable frequencies, as well as have the ability to drive a capacitive load. In order to achieve these two requirements, the circuit can be broken down into two sub-circuits. The component that changes input DC to an AC output uses a 555 timer, while the component for driving the capacitive load uses a 3469 amplifier.

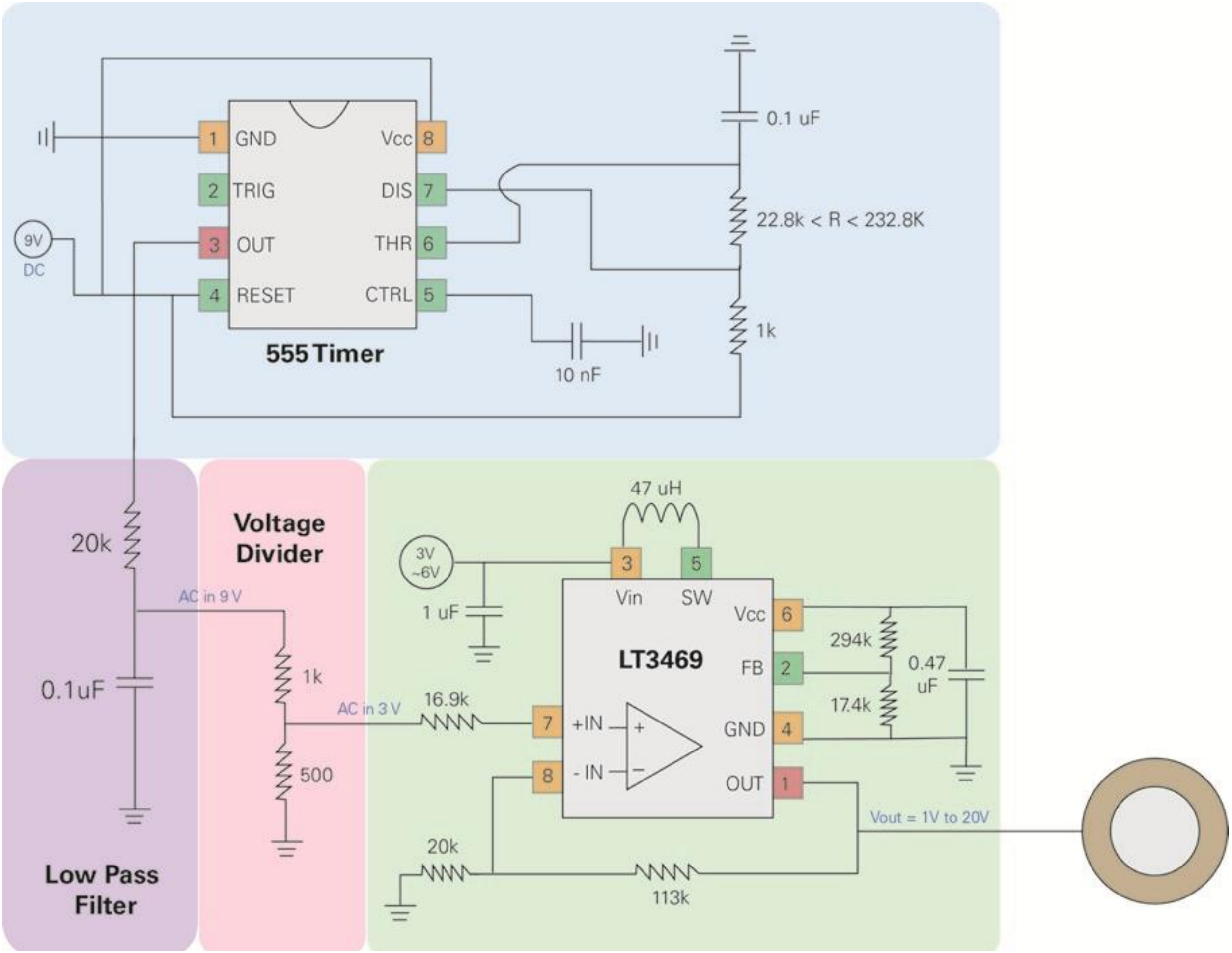

Figure 5: Driving circuit with power source and attached piezoelectric tactor. Shows the: 555 timer (Blue), Low-pass filter (Purple), Voltage divider (Pink), 3496 amplifier (Green).

5.2.1 The 555 Timer

$f = 1 / [\ln(2)*C*(R_1 + 2R_2)]$ $T_m = 0.7*(R_1 + R_2)*C$ $T_s = 0.7*(R_2)*C$ $R_2 = 0.7 / (f*C)$

The circuit diagram for the 555 timer can be seen in Blue section of Figure 5. This circuit is powered by the 9-volt DC and outputs a ~9 V_{pp} square wave. Since the output frequency needs to be able to be variable in the range of 30 Hz to 300 Hz, a potentiometer (pot) is used. Using the equations listed below, the necessary capacitor and resistor values were calculated to give a duty cycle close to 50 percent. For simplicity, a value of 0.1μF was chosen for the capacitor, and an arbitrary resistor value of 1000 Ω was chosen for the first resistor and the pot was used for second resistor. Using the equation for R_2, the range of resistance needed for the 30 Hz to 300 Hz range was calculated as $22.8\ k\Omega \le R_2 \le 232.8\ k\Omega$. To meet this frequency range, the circuit uses a 500 kΩ pot was used (a 250 kΩ pot would have worked, but there was a 500 kΩ pot available).

After some testing it was discovered that because of operating frequency range of the piezoelectric tactor, audible noise is produced when using a square wave input. To remedy this problem, the square wave is passed through a low-pass filter so that the square wave can be converted into a sine-like wave. The low-pass filter uses a 20 kΩ pot so that the cut-off frequency can be modified based in the square wave's frequency. It is possible to avoid using the low-pass filter by modifying the 555 timer to produce a sine wave. The reason that we did not do is was primarily because it requires a transducers which was unavailable due to time constrictions that did not allow for ordering more parts.

5.2.2 The LT-3469 Amplifier

The circuit diagram for the LT-3469 amplifier can be seen in the Green section of Figure 5. This circuit takes in the waveform, amplifies the voltage, and improves the current's ability to drive a capacitive load such as the piezoelectric tactor.

Along with allowing for driving a capacitive load, this portion of the circuit is also responsible for varying the voltage output. Because this is the sub-circuit that amplifies the voltage going to the piezoelectric tactor, a pot can be inserted into the circuit (at the location of the 113 kΩ resistor) to control the voltage output. By changing the resistance value of this pot, the gain from the amplifier can be adjusted. Taking advantage of this adjustability, and the LT-3469 chips ability to give a 1 V to 20 V output range, control over the volt input to the piezoelectric tactor can be achieved. The reason this control is necessary is so that the magnitude of displacement for the piezoelectric tactor can be controlled.

Notice that between the low-pass filter and the LT-3469 amplifier, there is a voltage divider. The reason for this is because the input signal for the amplifier must be between 0 V_{pp} and 3 V_{pp}. As mentioned previously, the 555 timer's output has a magnitude of ~9 V_{pp}. In order to require only one voltage source, it is necessary to insert a voltage divider.

5.3 The Piezoelectric Tactor

In choosing the piezoelectric tactor that could meet the frequency and the displacement requirements, the size requirements suffered. Because the resonance frequency of piezoelectric crystal is dependent on physical size of the crystal, a piezo with a diameter larger than 10 mm is or a stack of piezos with thickness of greater than 1 mm is needed. Alone with the frequency constrains, in order to get a displacement in the range of 10 μm to 500 μm would require and driving voltage in the kilovolts range if a small piezoelectric element was used. This large voltage brings up the safety concern of using the system in close contact with living subjects. Considering this information, as well as discussing the important aspects of the device, it was determined that size could be sacrificed for frequency and displacement.

With this in mind, a piezoelectric buzzer sold by CUI inc. was found. The piezoelectric buzzer (CEB-44D06) has a resonance frequency of 600 Hz with a maximum input voltage of 20 V_{pp}. The 600 Hz resonance frequency allows for the piezoelectric buzz to operate effectively in the 30 Hz to 300 Hz range and the input voltage is low enough that safety is not a concern. Since the max operating voltage is only 20 V_{pp}, the piezoelectric buzzer can be used safely around living subjects, and does not require a large voltage source. Another good aspect of this piezoelectric buzz is that the size was not overly compromised. Since the piezoelectric element has a 25 mm diameter, it is still small enough that it would match size with a thick finger. For more details on the piezoelectric buzzer, refer to its data sheet.

Since the piezoelectric buzzer needs to be free to vibrate, it cannot be directly attached to the subject's finger. Therefore, a housing unit was built (Figure 6). The prototype housing unit sandwiches the piezoelectric buzzer's non-ferrous outer layer as to not disrupt the vibrations. A semi-circular piece of PVC tubing is attached with a strip of elastic to allow for adjustment for a thicker finger. Padding was then inserted into the concave section of the PVC for comfort as well as added adjustability for varying finger thicknesses.

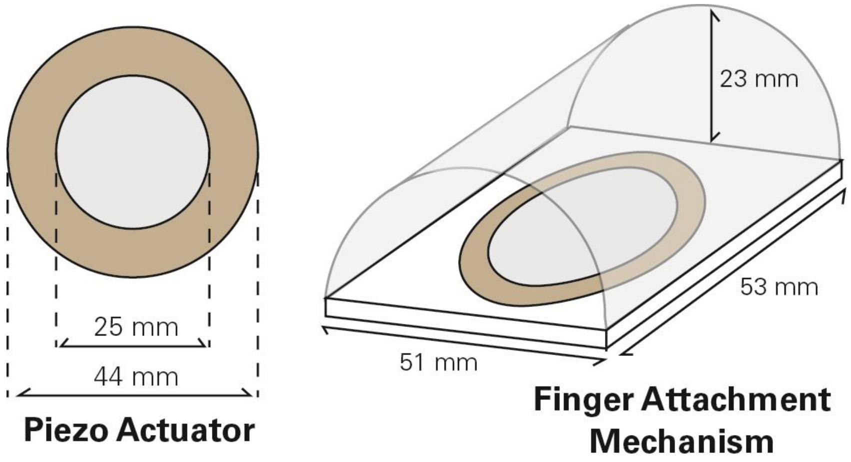

Figure 6: The piezoelectric buzzer's housing unit: The Piezo Actuator (left) is shown in the housing unit (right).

6 Client Discussion and Modifications from Fall 2011

6.1 Client Meeting at UW-Milwaukee

The team was able to drive to Milwaukee to meet Professor Seo, her associate Pilwon Hur, and the rest of the Hand Rehabilitation Laboratory at UW-Milwaukee. The purpose of the meeting was to learn more about the lab, and give them a presentation of the piezoelectric device from last semester, because they were not able to come to Madison to see it and observe its function during the semester. The team learned about all of the testing done in the lab, with the main concern being the portion of their research that is directly related to stochastic resonance, which was useful for the design of the piezoelectric device. The key testing mechanism used was a hanging bar, which the user would grab onto. Embedded into the bar was a solenoid device that produced the random vibration for stochastic resonance. The random frequency varies from 30 to 300 Hz, which is a design feature that we were previously unaware of. This changing frequency is generated by an audio file, which drives the solenoid device. The test subject grabs the bar and the bar is quickly pulled away from the subject; tests of reaction time are conducted by recording the subject's ability to maintain their grip on the bar with the actuator powered on and off. Their testing had not been fully completed at the time, but it had been shown that the stochastic resonance from the vibrator improved the subject's reaction time.

After observing the Hand Rehabilitation's application of stochastic resonance, we showed them our piezoelectric device. Professor Seo and Pilwon were able to give some recommendations for future work, including the implementation of the random frequency from the audio file used in their lab. They were satisfied with the in-progress prototype, and are looking forward to a finished prototype that they can use in the spring semester.

6.2 General Modification of Specifications from Fall 2011

There were a number of problems with the design from last semester that required modification in order to produce a workable prototype for the client to test in an MRI. The most significant change to the design was the incorporation of a random, changing frequency for the actuator. This was a design feature that the group was unaware of because of a miscommunication with the client. Professor Seo and her group in Milwaukee use an audio signal with a changing frequency to drive an actuator at randomly changing frequencies. In order for the piezoelectric device to operate at the random frequencies that the client wants, it was determined that the simplest way to drive the piezoelectric actuator is to use the same audio signal from the other device. As a result, the circuit for the piezoelectric device must be modified to run with the input being an audio signal. Modifications must be made for the voltage input, because it is assumed that the audio signal will have a different voltage than the 3 to 6 volts from the original power source (described in Section 6.2).

The actual circuit from last semester must also be modified to include the LT3469 driver chip, which was backordered and not received before the end of the semester. We received the chip over winter break, and discovered that it had a SOT23-8 pin package; this will make the chip very hard to incorporate in our circuit because the tiny pins will not fit into a breadboard for testing. There are a number of options for converting the package to fit into the breadboard, but for simplicity it was decided to look for a converter chip that would connect the smaller package to a set of DIP-8 SMT pins that will fit into the breadboard.

Other modifications to the final design will be mainly aesthetic, and have the purpose of making the prototype easier to operate for Professor Seo and her group in Milwaukee. The first modification will be to make a finger attachment mechanism that is not made from scrap parts, and makes it easy for the actuator to be attached to the finger. It may also be possible to look into smaller piezoelectric actuators, because the client originally wanted an actuator that was small enough to fit on a person's fingertip. It has been thought that a smaller piezoelectric device would not work for this application because smaller piezoelectric devices have resonant frequencies that are much higher than the 300 Hz, but testing of the 300-600 Hz piezo actuator showed that the resonance frequency did not mean that the device could not run at lower frequencies. Therefore, it could be possible to use a smaller piezoelectric device, regardless of its resonant frequency.

7 Design Modifications

After meeting with Professor Seo at her UW-Milwaukee lab, the design team was presented with some new information about stochastic resonance. In order for stochastic resonance to work, the sub threshold wave needs to be constantly changing between 30 Hz and 300 Hz, not just able to be adjusted to provide a constant frequency between 30 Hz and 300 Hz. In order to achieve this randomly changing frequency, it was decided that the best course of action would be to use an MP3 file to feed the waveform into the piezoelectric buzzer. Due to this change, the circuit from the previous final design was modified.

7.1 MP3 waveform source

In order to take the waveform from the computer use it to drive the piezoelectric buzzer, a 3.5mm mono male to stripped end, shielded, audio cable was used. The 3.5mm end is the standard end for computer, MP3 players, and smartphone audio ports. The MP3 file that will be used was created by Pilwon Herr (Post-Doctorial in Professor Seo's lab). Along with producing the randomly changing frequency, the use of an MP3 file allows for easy adjustment of the strength of the waveform (and therefore the input voltage driving the piezoelectric buzzer) simply by changing the volume on the device playing the MP3 file.

7.2 Circuit Modifications

With the addition of the MP3 waveform source, certain parts of the pervious circuitry became unnecessary. Along with removing the unneeded components, two different circuits are being considered to best drive the piezoelectric buzzer.

7.2.1 LT3469 Option

The first option uses the LT3469 driver circuit that was shown in the previous final design, along with a voltage stepper circuit (Figure 7). The voltage stepper circuit shifts the waveform up by 1.5 V so that all of the wave peeks are positive in value. This is needed because the LT3469 chip requires 0 V to 3 V for an input. This circuit requires 1 LT3469 chip ($2.45), 3 capacitors ($2.49), 7 resistors ($0.91), 1 inductor ($1.44), and 1 SOT23-8 to

DIP-8 SMT Adapter ($2.99). This gives a total component cost of $10.28 for this circuit option (note voltage sources not included).

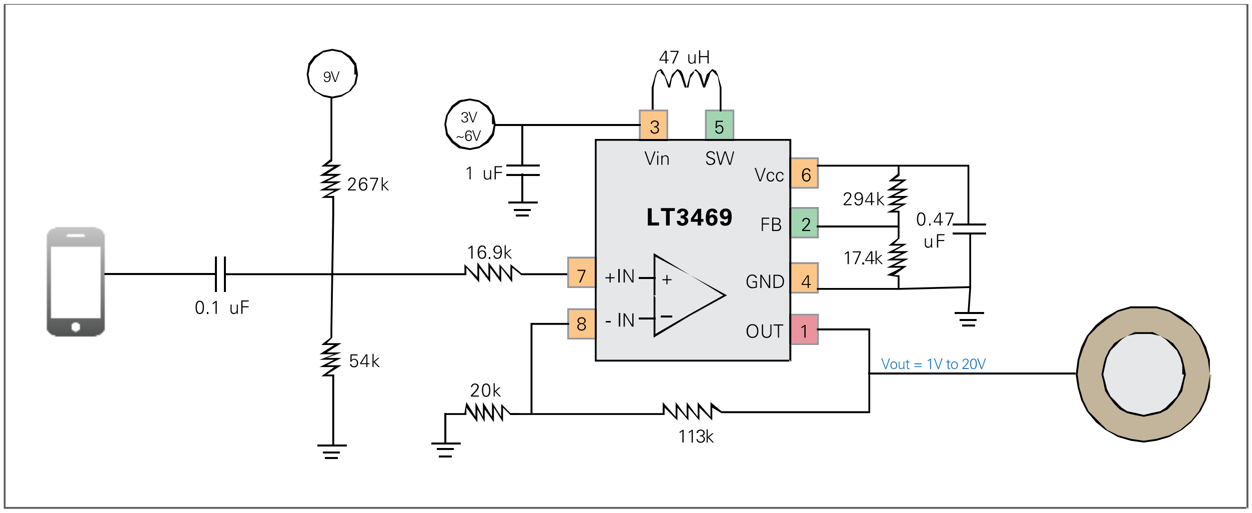

Figure 7: Circuit design for using the LT3469 driver chip to amplify the audio input.

7.2.2 741-Op Amp Option

The second circuit option simply uses a 741-Op Amp (Figure 8) to amplify the waveform. The op amp uses two 9 V batteries to power the op amp and give a gain of 11. This circuit requires 2 resistors ($0.26) and 1 741 chip (~$0.75). This gives a total component cost of ~$1.01) for this circuit option (note voltage sources not included).

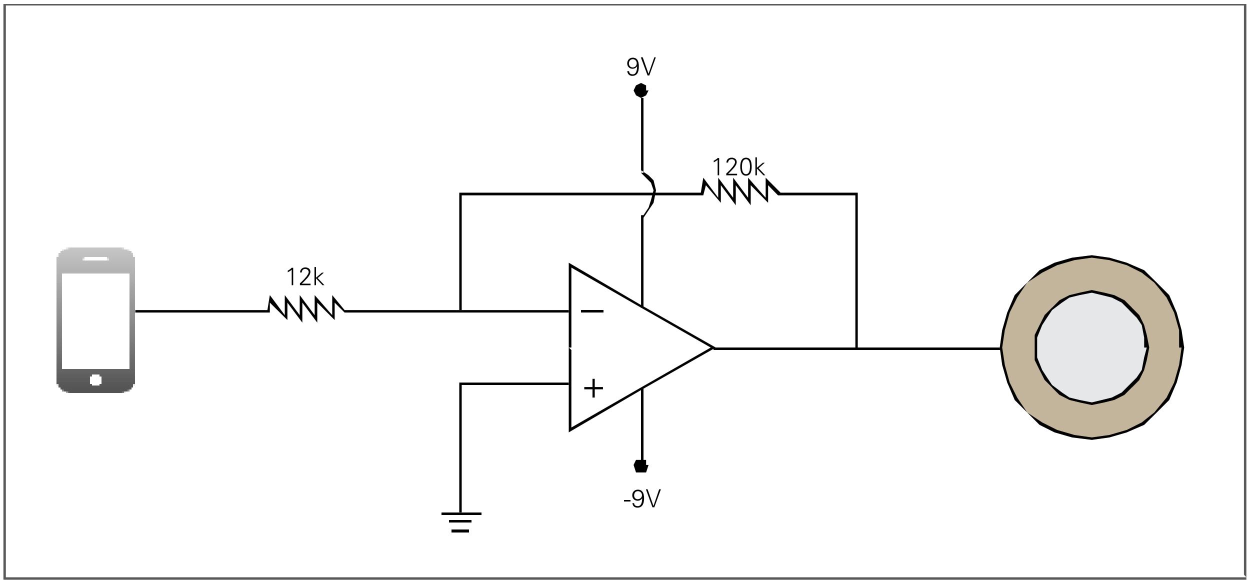

Figure 8: Circuit design for using the 741 operational amplifier to drive the piezo.

7.2.3 Circuit Comparison

Each of the above circuits has benefits and drawbacks as seen in Table 1 below. The 741-Op Amp as simple circuit with only 3 components, while the LT3469 driver is more complex and uses 12 components. Because of the extra components, the LT3469 driver circuit is significantly more expensive (although still relatively cheap) than the 741-Op Amp. However, the 741-Op Amp's simplicity is what causes its drawbacks. The 741 only has the ability to amplify to a certain voltage. After this voltage is reached, the wave saturates, causing the wave to take on square wave properties. This saturation occurs around 16 V for this circuit, which is an acceptable voltage for the CEB-44D06 Piezoelectric Buzzer (15 V_{pp} suggested input), but may not be sufficient for small, high voltage demanding buzzers. In comparison to the 741-Op Amp, the LT3469 should not saturate, but should be capable of outputting 20 V for the circuit shown in Figure ? above. The LT3469 only require one 9 V source (with the addition of a voltage divider so it can be used to power the chip itself) while the 741 requires two 9 V sources (since it needs both a positive and negative input to power the chip). This additional power source slightly increases the cost of the 741, but not to the extent of becoming more expensive than the LT3469.

Table 1: LT3469 versus 741

	LT3469	**OpAmp 741**
Circuit	Complex	Simple
Cost	higher	lower
Voltage Range	Ideal	Acceptable
Voltage Source	Smaller	Larger

8 Final Design

Out of the modifications that were discussed in the previous section, the final design implements the MP3 waveform source, but there has not been a decision on which circuit will be implemented. The reason this has not been decided is due to circuit debugging problems. Due to either at bad LT3469 chip, or bad circuit design, the waveform is not being amplified. Instead, the circuit is seemingly outputting 21 V with just a 3 V power source powering the chip and no waveform input. Once the waveform with 2 V_{pp} is input, the output drops to 1.8 V_{pp}. This will be discussed more in the Testing and Future work sections.

Because of the problems that have been occurring with the LT3469 circuit, the current plan is to use the acceptable 741-Op Amp to drive the piezoelectric buzzer. This way, our client can begin preliminary testing (i.e. make sure the device is in fact MR compatible and provides the needed stimulation affects) while the design team continues to work on circuit debugging. Based on the client's results with the 741-Op Amp, it will be determined which circuit will be used.

9 Testing

Due to the fact that our design uses waveform generated from the audio file provided by the client, it is important to determine the output voltage of the device that is playing the audio file. Since the client might use different devices to run the audio file, the output voltage could vary between each device. Regardless of the circuit design (OpAmp or LT3469 circuit) eventually used in the final design, the voltage feeds into the circuit should be carefully regulated to ensure our design works properly. As a result, the team surveyed several devices including Dell Optiplex 980 desktop, Apple's MacBook Pro, iPhone 4, and iPod Touch 4th generation about the voltage output from their audio jacks.

To test the voltage output from various devices, the team used a tuning audio file posted on YouTube [14], which plays constant frequency (523.25 Hz) at maximum volume, and measured the output voltage of each device's audio jack. 15 samples were taken for each device to see the consistency of output voltage, and the data were shown in Figure 9. The averages and standard deviations of the maximum voltage outputs were calculated and plotted in Figure 10. From Figure 10, it clearly indicated that different devices had different amount of output voltages even when playing the same audio file. This means that the current circuit design might need some further fine-tuned in order to accommodate the wide range of output voltage from different audio-playing devices.

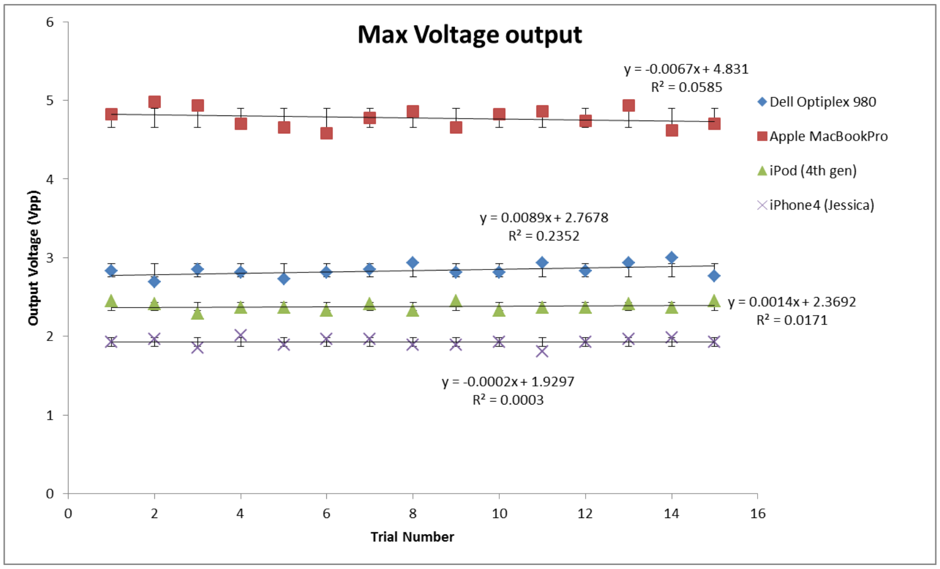

Figure 9: Graph of maximum V_{pp} throughout 15 tests using the random-frequency signal from different audio sources.

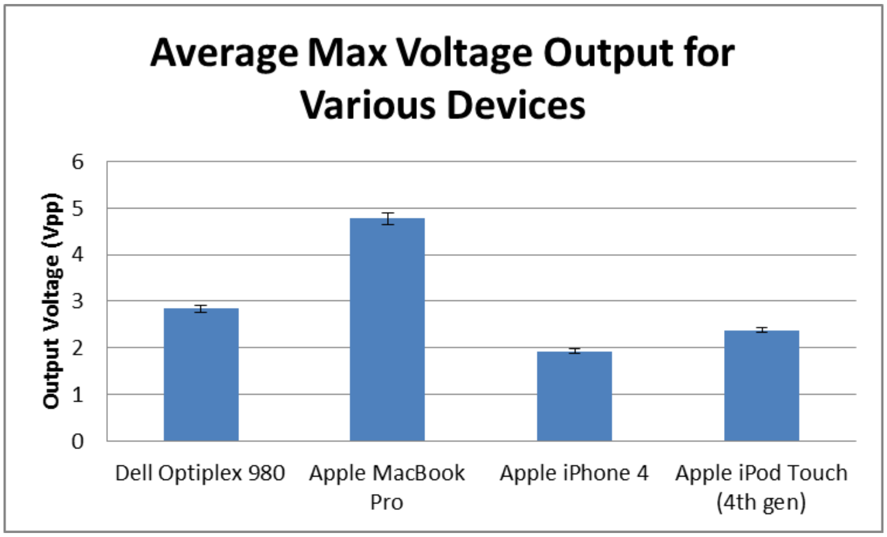

Figure 10: Average values for maximum output V_{pp} for each of the tested audio sources.

Although the use of LT3469 chip has better voltage range, the current design for the LT3469 circuit still needs some major adjustments in order to make it functions. For now, the LT3469 circuit can do some level of amplification of the original waveform, but the output waveform contains a lot of noises, as shown in Figure 11. The exact cause of the noises still remains unclear, and more investigations are needed for improvement of this circuit. Possible solutions include applying a filter or amplifying the input voltage to within the optimal range of voltage for the LT3469 chip. However, more testing should be carry out to verify if these proposed solutions could resolve the noise problem.

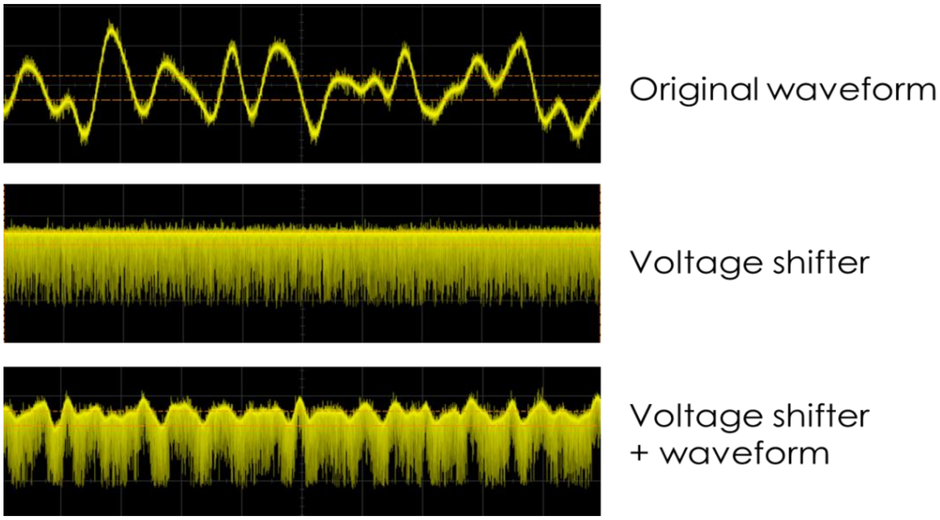

Figure 11: Oscilloscope display from the unmodified audio signal waveform (Top), voltage shifter only (Middle) and the waveform of the audio signal after passing through the voltage shifter (Bottom).

10 Future Work

10.1 Finalization of Driving Circuits

Up to this point there are still two options left to choose for the piezo driving circuits – LT3469 and OpAmp 741. Theoretically, the LT3469 chip is designed specifically for the piezo actuator used in current model. It provides a larger range of voltage outputs, which can adopt a wider range of vibration displacement for further adjustment of the sub-threshold. Currently the LT3469 circuitry does not deliver the corrected signal to the piezo actuator and therefore the vibration does not occur. However, when a regular OpAmp 741 replaces the LT3469 circuitry, the piezo would vibrate normally. Debugging is certainly necessary since LT3469 is still a better solution.

Moreover, after confirming the frequency source that the client prefers to use, different values of the circuitry elements (resistance and capacitance) may be modified due to the different output voltages from various frequency sources, including desktop, MacBook Pro, or iPhone. It is also ideal for the circuit to be a stand-alone system, and the final circuit will be put on a perfboard, rather than a breadboard after testing has concluded.

10.2 Size Reduction

The current piezo actuator is larger than the desired dimension. Two smaller piezo buzzers have been purchased. A 1.3 kHz corresponds to a piece with 44 mm in diameter, while a 2 kHz corresponds to another with 20 mm in diameter. Theoretically, the size of the piezo is inversely proportional to its running frequency, meaning that the smaller the piezo is, the higher the frequency it runs at. Testing is needed if those smaller piezo buzzers can still vibrate properly at a lower frequency range, 30 to 300 Hz. If a smaller piezo can be incorporated into the final design, the finger attachment mechanism will need to be remodeled to fit a smaller piezo. A new attachment mechanism can also be designed for better contact between subject's finger and the piezo. The finger should not apply additional compression force to the piezo during stimulation to prevent inaccuracy.

10.3 MR-compatibility

One of the major design requirements is to make the device MR-compatible in order to serve as a research tool to monitor brain activity. Although ideally the designed power source should be separated from the MRI room when performing the test, the extended regular wires connected to the piezo actuator will be an issue to induce the undesired current and interfere the MRI system. As a result, shielding of the wires or finding MR-compatible cables is required in order to be used in the MRI system. Coaxial cables might be an option but further modification of the cables is needed since the coaxial cables are too thick. Research on other possible MR-compatible conductive wire will be one of the future tasks for the team. The length of the wire also needs to be acquired from the client based on the MRI room layout in order to purchase and install into the circuit system. In addition, the voltage output should be tested again to confirm that the shielded wire would not affect its performance.

10.4 Testing

Once the fabrication of the prototype is completed, two major testing should be performed. First of all, the measurement of vibration displacement should be collected in order to obtain the relationship with the voltage input. Since the LT3469 piezoelectric actuator driving circuit is incorporated, the vibrational displacement of the actuator can be adjusted. The displacement of the actuator depends on the voltage provided. Because the piezoelectric buzzer obtained from CUI Inc. did not provide the information on voltage to displacement, the relation need to be determined via displacement testing. To measure the displacement of the actuator, a laser vibrometer setup at the Mechanical Engineering department (University of Wisconsin – Madison) can be used. The vibrometer uses light scattering to detect the displacement of piezoelectric actuator, and the target displacement is between 10 to 500 microns. The team planned to find out the relationship between voltage and displacement to ensure the displacement remains in the desired range with a random frequency.

After completing the constructions and the improvement for the design, the device should be tested inside the MRI system. The device should be first tested and proven that it is MR-compatible before entering the MRI room. Once the MR-compatibility is confirmed, the concept of stochastic resonance can be studied and the brain activity can be monitored using the device in the MRI system.

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Appendix A

Product Design Specifications

Tactile Stimulator
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March 14, 2012

Problem Statement

Falling from ladders or scaffolds is of the leading causes of workplace injuries and fatalities. A device must be developed to improve the workers' response time by stimulating their sense of touch through vibrations in their hands. The device must be MR-compatible in order to analyze brain activity during the stimulus to the hand. The overall goal is to prove that a continuous stimulus on the hand can improve the range of sensory frequency perception.

Client Requirements

- The device must reduce the 60 ms lag time between stimulus and reaction
- Does not obstruct the user's grip while holding onto a ladder or scaffold
- Small enough to fit on the palmar side of the user's fingers
- MR-compatibility for testing purposes
- The frequency must be randomly changing, and operate between 30-300 Hz

Design Requirements

1. Physical and Operational Characteristics
   - *a.* *Stimulation:* The device must stimulate the Pacinian corpuscle, with a randomly changing frequency of 30-300 Hz.
   - *b.* *Size:* Stimulators on the palmar side of the hand cannot exceed 1 mm in thickness and 1 cm diameter; stimulators on the dorsal side of the hand should not exceed 2 mm thickness and 2 cm diameter.
   - *c.* *Operating environment:* The device must function in a Magnetic Resonance Imager in order to analyze brain activity during stimulus.
   - d. *Versatility:* Must accommodate a range of hand sizes. Also should be easily sterilized for repeated use.
   - e. *Sensitivity:* The patient must not consciously feel the vibrations, and the device must accommodate a range of nerve sensitivities in patients.
   - f. *Life in Service:* The device should remain fully functional for a minimum of one year under normal work conditions.

2. Production Characteristics
   - *a.* *Quantity:* One working prototype (for a single hand) must be fabricated for MRI testing purposes.
   - *b.* *Target Production Cost:* (Will establish with client after creating list of parts needed.)

3. Miscellaneous
   - *a.* *Customer:* Researchers observing the effects of vibration stimuli to the hand.
   - b. *Competition:* None.

Appendix B

Estimated Cost of Parts

Elements in Prototype	**Quantity**	**Price (USD)**
CEB-44D06 Piezoelectric Actuator	1	2.21
LT3469 Transconducance Amplifier	1	2.45
Adapter	1	2.99
wire	1	4.99
Resistors	8	.13
Capacitors	5	.83
Inductor	1	1.44
Finger Attachment Mechanism	1	0
Total Price		**$19.76**

Complete Parts Summary	**Quantity**	**Price (USD)**
CEB-44D06 Piezoelectric Actuator	5	2.21
LT3469 Transconducance Amplifier	4	2.45
adapter	1	2.99
wire	1	4.99
668-1017-ND	1	1.68
668-1004-ND	1	1.02
Resistors	20	.13
Capacitors	8	.83
Inductors	4	1.44
555 Timer Chip	1	FREE (BME Lab)
Finger Attachment Mechanism	1	FREE (COE Shop Scraps)
Shipping	2*	~10.53
Total Amount Spent		**$54.36**

*We will not be able to order all the parts from one company

Appendix C

Work time spent on project:

Team Member	**Hours Spent on Project**
John	5.25
Alan	11.0
Jessica	11.75
Albert	7.75
Total group meeting time	6.5