Toccando

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Abstract—**Sophisticated touchscreens for modern day electronic devices have become ubiquitous in our increasingly high-tech lives. However, although the technology of touchscreens has dramatically improved over the past decade, tactile perception has been lost.**

Toccando aims to fill this lack of sensory output by providing tactile feedback in response to user input. Feedback is based on the ultrasonic vibration of piezoelectric speakers attached to a pane of glass. The basic concept uses a one-directional chain of events. First, the location of the user's finger determines whether the device is on or off. Second, this information is sent to a microcontroller that produces a corresponding waveform. The waveform is then amplified to a perceptible level. Finally, the waveform drives the speakers, causing the glass to vibrate and the user to experience a sensation on their fingertip.

Toccando will be a single finger input device aimed at enriching visual maps. It will consist of an Android map application and a hardware casing. The goal is to make smart devices more accessible when visual cues are unavailable or inconvenient. Its significance lies in the potential for improving accessibility and immersion, as well as providing additional support for the visually impaired.

I. Introduction

Touchscreens are an integral part of modern smart devices. These screens allow users to interact with their gadgets, quickly, easily and effectively. Touch is one of the most intuitive mechanisms for transmitting and receiving information and it is currently the leading method of operation for phones, tablets, and other smart devices. Nonetheless, aside from motor-driven vibration of the entire device, there is little to no tactile feedback from these devices. Therefore, due to the prevalence of gadgets that employ touch in their operation, the lack of precise tactile feedback in modern day devices limits the scope and significance of physical and virtual interactions.

There is a need for tactile feedback when visual cues cannot or should not be used. The community of visually impaired have been largely ignored in the advancements of modern technological devices. Those products that exist are expensive, large and bulky, and rely on mechanical movement of pins into place. We have developed Toccando as a proof of concept to demonstrate the ability to display tactile information in a cheap and dynamic, programmable fashion.

Toccando was developed with idea of being an add-on solution to any pre-existing device. This means that unlike other solutions for the visually impaired currently on the market, no specialty device must be purchased. With Toccando simply slide any phone into the case and start the Toccando app. We also thought that many devices were limited in their ability to display visual information dynamically. Because other devices employ a mechanical mechanism, the information that they can display is limited. Our android app is designed to be able to display any standard image format (jpg, png, etc.) and add tactile feedback to any region of the image. Although the technology that we deploy in Toccando has many applications, we focused on displaying letters and shapes.

For visually impaired children it is especially import to be exposed to objects in a tactile manner. The display of letters on our device can be used as an educational tool. While braille is the common language amongst the visually impaired, it important that people with this disability also interact with those who are sighted. In fact, signing documents and papers is important in our society and it is becoming increasingly important to sign onto tablets and phones. Being able to know the contours of letters brings an independence to those who are visually impaired and need to interact by writing.

Toccando uses a technique which ultrasonically vibrates a glass surface with piezo electrics. Ultrasonic surfaces create a tactile impression on a bare finger, by vibrating the surface ultrasonically, reducing surface contact time with the fingertip. This reduction of time in contact with the surface leads to a noticeable decrease in surface friction [1]. The apparent change in surface texture is due to the duplex theory of tactile texture perception, in which vibrations are transduced by rapidly adapting mechanoreceptors in the skin, sending a vibrotactile signal to the brain. Therefore, stemming from the loss of friction, and by virtue of the duplex theory of tactile texture perception, the fingertip, interacts with a seemingly smoother glass surface [4].

We have decided to employ the ultrasonic method of force production in our design, because of the precision it provides, the low cost of the hardware, and the simplicity of construction. The underlying principle behind using ultrasound lies in the *squeeze film effect*. The principle states that when material moves at ultrasonic frequencies close to resonance, the pockets of air between the material and other objects (in our case a finger) are increased, reducing the coefficient of friction. The result is a slipperiness akin to an air hockey table [6-7]. To create the squeeze film effect across a piece of glass and correlate the sensation with a visual image, we have designed Toccando to be a single finger input device. It works by varying the coefficient of friction at controlled intervals to simulate a flat surface. When friction is increased, the finger observes a sticky feeling, approximating the "edge" of an object [2].

The design has five main subsystems (as shown in Figure 1): an Android Application, Microcontrollers, an Amplifier, the Glass and Piezos, and Power. The entire system is contained in a 3d printed case that is small and compact. The electronics fit in the space underneath the glass and the phone. The design is very modular and although a Nexus One device is being used, the case is large enough to accommodate most standard phones. We discuss each of the subsystems in the following subsections respectively: B, C, D, E, and F.

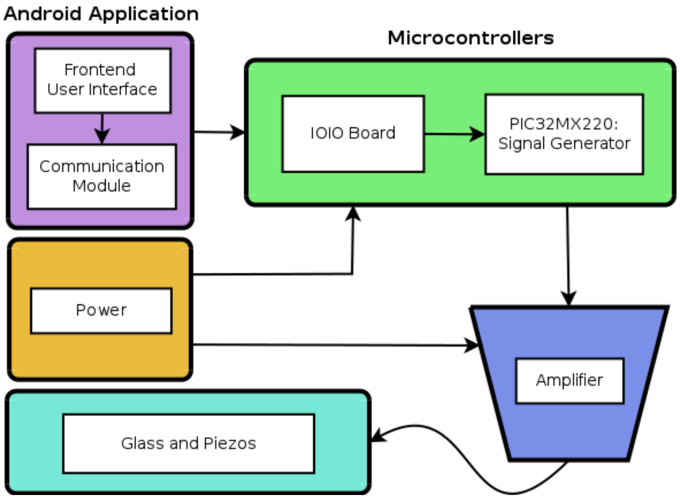

Figure 1. Block Diagram

Additionally, our design meets the following specifications:

Specifications	
Mass	178.6 g
Height	170 mm
Width	140 mm
Depth	70 mm
Response Time	150ms

II. Design

A. Overview

We designed Toccando to rely on a single chain of commands that propagate from the smart phone to the glass and piezos. Sliding your finger across an object displayed on the smart phone screen sends a signal to the IOIO board responsible for switch the rest of the system 'on' or 'off' based on the user's input. When the system is 'on', a PWM signal is driven by the PIC through the amplifier to the piezos. In turn the vibration of these piezos creates changes in the kinetic friction of the glass. Hence, a sensation occurs for the user. One important feature of the device is the fact that it is single touch. The user must pass a single finger across the glass, two finger touches are used to control other functions of the app such as navigating through different images.

The output to the user comes from the glass with piezos attached. In Figure 1, this is represented by the Glass and Piezos block. Several design choices were involved in constructing the touch display. We chose 1.1 mm soda lime glass in order to ensure a lightweight design and guarantee that the finger could still be detected by the phone. To handle the amplitude needed to create a sensation (above 50 V peak-to-peak), a standard piezo buzzer was selected at 35 mm. The size of the round piezos turned out to take up too much space on the glass. Our solution involved trimming the piezos to retain a length of 35mm, leaving a width of only 7 mm. These piezos were glued to a single edge of the glass as seen in Figure 6.

Our amplification system is a switching circuit that uses an inductor wrapped in magnetic wire. The inductor with the magnetic wire coil around it acts as a transformer. The reason a simple transformer did not perform well is the fact that it did not draw enough current. The amplification system draws 200 mA and runs on 5 V, thus the amplifier requires 1 W of power. Using less power results in underwhelming effects that can hardly be detected by the user.

To further enhance the sensation, we engineered the system to vibrate at the resonance frequency of the glass. Experimentation in the lab led us to discover that the resonance of the glass was 37 kHz when using a glass that is 158 mm by 136 mm with four piezos attached. The PIC32MX220 was programed to generate a 37 kHz pwm wave. The duty cycle of the wave is modulated at 200 Hz. Different modulation frequency dictated the intensity and type of sensation. The intensity at a modulation frequency of 200 Hz was pronounced enough that each team member could detect a sensation. Our choice of the PIC was based on its ability to generate a waveform at the high frequency we needed as well as its compactness. The ability to program using C also matched the skills we learned in ECE 353 and ECE 354.

We are using the IOIO Board to communicate with the app. The choice of microcontroller addresses the ability to receive USB signal data. Bluetooth and wireless communication were possibilities that were also considered, however they were deemed too intensive, due to the overhead requirement for receiving messages. The system [needs to provide] a tactile response within 150ms of a user's touch response to avoid the unpleasant 'sticky' feeling associated with longer feedback delays [3]. We went with a cable connection to best address this speed requirement.

The Android Application takes the user input and also does the heavy lifting to determine whether a part of an image should have a sensation or not. Our device makes use of the Nexus One's ability to detect a user's finger using its capacitive touch screen. The 1.1mm glass that is placed on top still allows the phone to detect a user's finger. The app also displays the visual information and correlates the user's touch to pixel color of the image. The app uses a threshold system to determine whether the user should feel a sensation or not. On the backend, the app provides a multithreading interface in order to handle the communication with the IOIO board separately from the frontend user interface.

To summarize, tactile feedback is expected from the design based on the assumption of accurate localization of user input; the interconnectivity of the different components (phone, microcontroller, piezoelectric speakers); and a discernible sensation on the glass surface.

An alternative design that was considered included the use of electrostatic surfaces but was deemed unreasonable due to continuously varying output requirements, and safety concerns related to the high voltages necessary for implementation [5].

B. Android Application

Figure 2. User Interface

The Android Application displays the visual cues such as letters and shapes as well as handling communication with the IOIO board. The application is written in Java and uses the API provided by the IOIO board. The application also makes use of the many built in functions that android development has to offer. Several custom functions were also developed specifically for Toccando.

Since the application can display any image in a png, jpg, jpeg, or bitmap format, we convert all images into a bitmap array in order to more easily access pixel colors. The product is intended to be used on any android device and with varying screen sizes, thus it was important to have the application correlate the finger position with an exact pixel in an image array, otherwise the position would correspond to a pixel but the app automatically scales the image resulting in a disconnect between the response and the image. Color images were converted into weighted grayscale. The following weights were used for RGB: R- 30%, G- 59%, and B- 11%. This allowed us to set a single threshold for whether to send an 'on' or 'off' signal.

The application also handled the number of fingers a user inputs on the screen. A one finger touch corresponded to sending the 'on' or 'off' signal. Two or more fingers were calibrated to change the image. The images are stored with a name and number, for example image_1.png, and we cycle through with a custom gallery function that parses the number from the name of the image and iterates through each image.

The interface to the microcontroller is done using a separate thread. While the main thread sets a global variable to indicate on or off, the thread in charge of the IOIO interface reads this variable. The action performed by this thread must be fast without time delays to prevent the user from experiencing a delay. Setting the pin on the microcontroller to 1 or 0 is incredibly fast and takes only picoseconds. The user then experiences no lag from the time they touch the screen to the time the sensation is perceived.

C. Microcontrollers

We use two microcontrollers: the IOIO board and the PIC32MX220. The IOIO Board was programmed with Java and acts as the communication mechanism to the android phone. It simply switches the system on and off. The wave is generated on a separate microcontroller that is dictated by a separate clock. The system was designed in this manner to prevent delays to the user interface.

The PIC was programmed in C and uses PWM to generate the modulated signal. The signal had a frequency of 37 kHz and was modulated by a 200 Hz frequency sine wave. The sine wave was generated by producing a sine table of 100 values that determined the duty cycle from 2% to 50%. The formula used to digitize the sine is given below:

$$duty\ cycle = 24 * \sin(x) + 26$$

By calculating the duty cycle using this equation we were able to achieve "smooth" transitions between the coefficients of friction.

Figure 3 shows what such a signal looks. Note that this is a recreated image because the oscilloscope was unable to display a steady picture of our modulation.

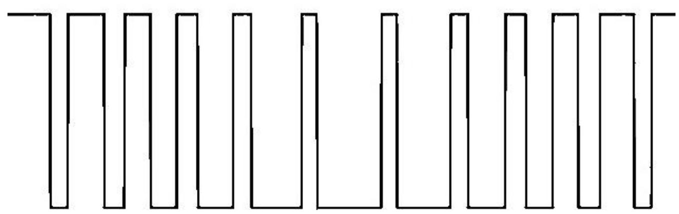

Figure 3. PWM with Duty Cycle Modulation

D. Amplifier

The signal generated by the PIC only has an amplitude of 5 Vpp. In order to feel the vibration we need a peak to peak voltage of 60 V. Our initial approach was to use a transformer. However, the transformer traded current for voltage and the system did not vibrate enough to have any detectable effect. When using a transformer the overall power of the system stays the same. We needed to add power to the system in order to get any effect.

In our correspondence with researcher Joe Mullenbach at Northwestern University, we were informed that in order to create the change in friction, we would need at least 1 W of power. [8] He suggested that we try an audio amplifier. However, the frequency range that is supported by audio amplifiers falls in the normal hearing range of 20 Hz to 20 kHz. The resonant frequency of the glass was

37 kHz, certainly outside the normal human hearing range.

Figure 4. Inductor Wrapped in Magnetic Wire

Therefore, we needed a different solution. Professor Robert Jackson at the University of Massachusetts Amherst suggested using a switching circuit as our amplification system. We developed an amplifier based on this suggestion. The amplifier was composed of a driver, an inductor wrapped in 24 gauge magnetic wire 18 times (as seen in Figure 4), a 7 nF capacitor, and a mosfet. The circuit was able to draw 200 mA and was successful in driving the piezos with enough power to create a change in friction. Figure 5 shows a circuit diagram of the amplifier.

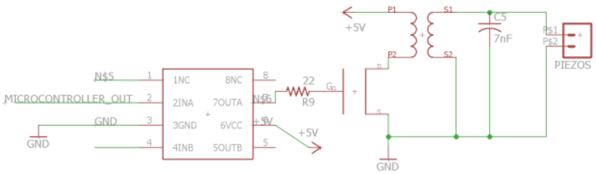

Figure 5. Amplifier Circuit

E. *Glass and Piezos*

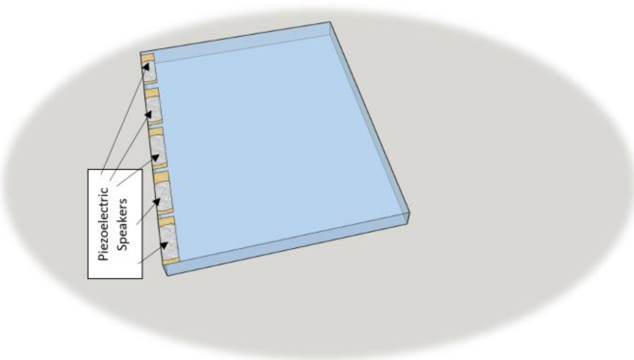

Figure 6. Glass Pane

The interactive piece of Toccando is the glass and piezos. The glass was a piece of soda lime glass at 1.1mm thickness. This thickness was chosen because it enable the phone to be operated through the glass as well as being durable enough to withstand pressure from the user. Four piezos were glued to the edge of the glass. The positioning of the piezo needed to be in a straight line with little gaps between them to ensure that we did not create any “dead” spots. Randomly positioning the piezo creates destructive interference in some places and constructive interference in other places. For the design of Toccando, we needed to have equal sensation uniformly across the glass.

The piezos are wired in parallel and it was import to not only secure the piezos to the glass using superglue but also the wires. If any of the materials near the glass were loose, we experienced a clicking or buzzing sound arising from the object hitting the glass. The positioning of the glass in the case was also important. We suspended the glass from a ledge on the casing using foam tape. The tape was strategically placed only in the four corners of the glass. This suspension technique was developed in response to dampening that occurred if the glass was simply placed on any surface.

F. *Power*

Getting enough power to the system was an ongoing challenge in this project. While many rechargeable battery packs have enough capacity to power our device the amount of current that can be sourced from them is simply not enough. We needed to power the amplifier and both microcontrollers. To solve the problem of sustaining enough amperage to power all systems we customized a power cable to extend out the back of our casing.

The power was then supplied from a laptop externally. Optimally in a consumer product, a custom battery could be developed to source enough current to our system.

III. Challenges

Throughout the project, we faced many technical challenges. Here we describe each challenge and our solution.

A. *Power*

The power system was not providing enough current in order to create the change in friction. To solve this challenge, we used a switching circuit with an inductor wrapped with magnetic wire. This circuit was able to amplify the 5 Vpp output by the PIC to 60 Vpp needed to drive the piezos.

B. *Resonant Frequency*

Finding the resonance frequency was difficult. As we started the project we were unable to get a sensation on the glass. This turned out to be a problem related to the amount of current in the system (see A). Thus we resorted to using a “salt test.” We placed salt on the pane of glass and manually swept through frequencies until we were able to see the salt bounce. The visual effect of the salt bouncing let us find the resonant frequency of the glass. This frequency turned out to be 37 kHz with four piezos in parallel. The frequency differed with the number of piezos attached to the glass. The choice of four piezos corresponded to the amount of piezos that covered the glass from one edge to the other as well as the frequency. 37 kHz is above the normal hearing range of an adult dog. Since dogs are often used as service animals, it was important that the frequency be at a level that does not irritate dogs. In contrast, five piezos yielded a resonant frequency of 33 kHz.

C. *Communication between App and Microcontroller*

Finding a fast, reliable communication system between the phone and the microcontroller proved more challenging than we had first anticipated. For fast communication, we wanted to use a cable connection. However, a phone is usually designed to be an accessory in usb communication protocol. In our case, we wanted to use the phone as the Host and the microcontroller as the accessory.

After researching, phone to microcontroller communication we came up with a solution that included using AOAP (Android Open Accessory Protocol), an OTG cable, and the IOIO board. The IOIO board has the ability to be in accessory mode while the phone is the host using the OTG cable.

D. *Waveform Generation*

For testing, our primary waveform generator had been the function generator in the lab. However, to make our device portable we needed to generate the waveform froma microcontroller.

Unfortunately, generating a wave from the IOIO board caused 1 to 2 second delays. The thread that communicates with the board was preoccupied with generating the wave while in order to detect the user's input, the application needed to switch threads to check the input. Hence, we discovered that the communication with the IOIO board had to be much faster.

Our solution was to move the task of wave generation to a separate microcontroller. We choose the PIC for this task as it could produce the high frequency wave we needed. We previously tried the Atmega32 but needed to use interrupts to create such a high frequency wave, these interrupts ended up making a clicking sound from the piezos. The PIC was able to handle the high frequency output without producing this clicking sound.

IV. Future Work

Toccando does several things well: 1) It changes the kinetic friction of the glass surface, 2) It accommodates single touch, 3) Tactile feedback is binary and depends on the fingers location on the glass. There are several directions future work can be done on this technology.

A. *MultiTouch and Beamforming*

Work by Charles Hudin et al. shows that localized haptic feedback can obtained by randomly spacing the piezos around the perimeter of the glass. The wave that propagates through the glass by one piezo can be calculated and constructive inference can be used in order to create only a single point of vibration. The research can be found in [9]. Note the arrangement of piezos as shown in Figure 6 versus the arrangement shown here in Figure 7.

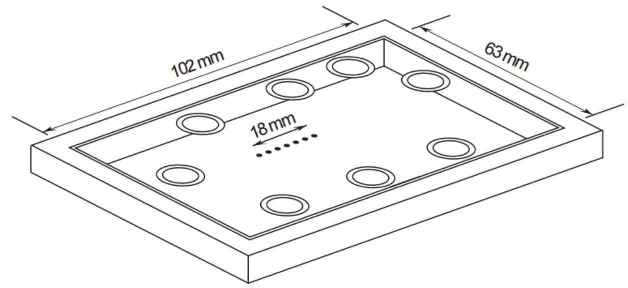

Figure 7. Piezo Arrangement in [9]

This technique would allow multiple touches on the glass, having one finger feel something while another does not. It also unlocks the possibility of creating braille dynamically.

B. *Multiple Feedback Settings*

In the lab, we were able to generate different feelings using the function generator. The sensation could be made to feel "rubbery" vs. "grainy." The intensity could also be controlled by changing the frequency of the modulating signal. In the future, these different sensations could be incorporated to create different sensations for different images or different sensations for different parts of a single image. For example, the intensity of the sensation could be correlated to color on the image.

Another possibility discussed by Xiaowei Dai et al. is the creation of button press sensations. This can be done by adding additional piezos along edges perpendicular to those edges where piezos are already placed. The effect is discussed in [10].

C. *Enhanced Texture*

Our current device gives a subtle sensation. However, work can be done to intensify this sensation. Our system currently uses only 5 V as input, increasing the voltage to the system will create a stronger sensation. We also use PWM as our choice of modulation while frequency modulation tends to give a smoother feel. The choice for PWM was based on it ease of implementation in the digital world, but a frequency modulated signal though harder to create would have a better effect.

V. Project Management

Project management was often inhibited by delayed communication outside of weekly meetings. After MDR the task responsibilities were reassigned and progress went more smoothly. Restructuring task assignments to better accommodate the skills of group members enabled us to produce the final product to functionality at Demo Day.

Every member of the team was fully cooperative, attended weekly meetings, and was present for weekly group meetings. With the exception of the FPR presentation, we were well organized and prepared for presentations. The major problem at FPR was a push for perfection. In retrospect, appearing on time and being professional in a presentation is as important as having a working product. We have all gained experience from the pressure of having to meet deadlines and being faced with technical difficulties.

Our team consisted Ygorsunny Jean (EE), Casey Flanagan (EE), William Young (CSE), and Esther Wolf (CSE). Our team was led by Esther Wolf. The responsibilities of each team member are as follows. Ygorsunny Jean created and built the glass and piezo system. He was also responsible for the power system as well as web content management. Casey Flanagan designed the final case and also debugged hardware. William Young built the amplification system and programmed the PIC. Esther Wolf designed and programmed the android app and interfaced the phone with the IOIO board. Each member was also responsible for many hours of debugging all systems as well as the research that went into finding the appropriate frequencies.

VI. Conclusion

After MDR, we have almost completely redesigned the circuitry of our project. At MDR, we were unable to create a sensation using high frequency waves and resorted to using only low frequency waves. This merely vibrated the glass at a level that was dampened so much by the frame to be virtually undetectable. In our final product, we actually change the frictional coefficient of glass. A major breakthrough happened when we found the desired frequency as well as adding modulation.

Modulation of the wave was key in creating the desired effect. Without modulation, the user does not have a reference point for what the friction of the glass was originally. When modulating, the user notices the changes in the frictional coefficient when passing their finger across the glass. The surprising result was that it did not matter whether what type of modulation we used. Amplitude modulation did the trick but created a humming noise from the piezos. Frequency modulation proved silent and smooth. Pulse Width Modulation was easy to generate digitally from the microcontroller and had minimal humming.

The reason that any type of modulation suffices is the fact that the user must just feel the change in friction. AM achieves this through using enough voltage to change the frictional coefficient and then dropping the voltage low enough to be close to the original frictional coefficient of the glass. FM achieves the effect in a completely differ manner but the end result is similar. FM changes the frequency from one that is in resonance and therefore is able to change the coefficient of friction to one that is far enough away from the resonant frequency that the effect is close to the original friction of the glass. Lastly, PWM achieves the same effect using power. At a duty cycle of 50% there is enough power to have a detectable effect, moving it low enough causes the effect to be close enough to the original glass. The greater the deviation in modulation, the more intense the sensation is to the end user.

The other key to making a working prototype was the power. At MDR, we simply used a transformer to amplify the signal, moving to an amplification system that was able to draw more current made it possible to create a sensation at high frequency.

Some of the more minor changes that have taken place since MDR that contributed to a final closed loop system were the use of two new microcontrollers, namely the IOIO Board for interfacing with the android phone and the PIC32MX220 for generating the waveform.

The project is a functioning prototype which varies the coefficient of kinetic friction of the glass. The effect works best if the user's hands are dry and not cold. People feel the effect in different ways. From feedback given to us by students, faculty, and those who showed up the showcase we have heard the following comments about the sensation. It feels: "resistive", "vibrate-y", "wet", "slippery", "rubbery", and "grainy."

We also took note of those who could easily feel the sensation, those who were hesitant but admitted to feeling it after a few tries, and those who were unable to feel the sensation at all. The table below reports our findings.

Sensation Survey			
	Yes	Maybe	No
Total Number of People	101	11	5
Percentage	86.3%	9.4%	4.2%

The project itself could be taken further to improve the response. We have listed a few of the ways that we might continue the project given more time in Section IV.

Appendix

A. Cost

Part	Price
IOIO Board	$39.95
Piezos (4)	$4.72
M8297-ND (Inductor)	$1.10
IXYS IXDN604PI Driver	$1.80
LE33 Voltage Regulator	$0.75
8 MHz CLK	$1.00
Battery	$25.99
3D Case	$36.83
PIC32MX220F032B	$3.10
IRF52NPBF (MOSFET)	$1.14
Misc. (RC)	$0.40
Total	**$117.00**

B. Case Design

The case was designed with portability and modularity in mind. The case has a ledge on the top from which the glass can be suspended with foam tape to minimize dampening. A platform can pulled out on which to place the phone. This way the user can easily place take their phone in and out of the case. The bottom of the case is cleverly fitted on the bottom to easily pop on and off. This makes accessing the circuit inside easy and convenient.

C. Our Final Product

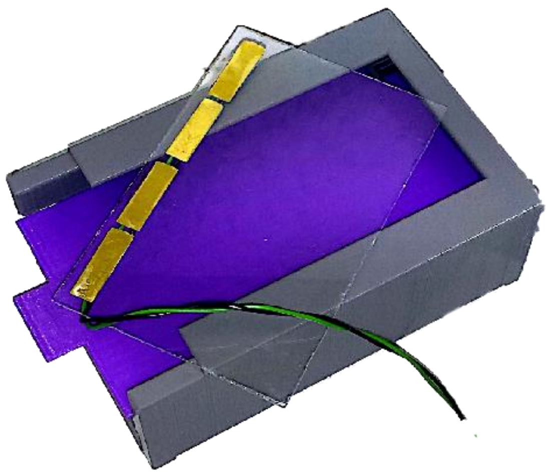

Figure 8. Toccando

ACKNOWLEDGMENT

Team Toccando would like to express our gratitude to Professor Patrick Kelly, for his enthusiastic spirit and extraordinary guidance, through our many hurdles.

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