Boston University

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Senior Capstone

Haptic Feedback Sleeve

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Abstract

Haptic feedback devices provide the user with a tactile response to real world information. Commonly used in medicine, robotics, and virtual reality, HFD's are advancing the way operators interact with their equipment and the world. HFD's are generally designed for and used in specific applications, however the goal of this project is to develop an HFD that can be used in a wide variety of applications, with a focus on restoring senses to those who have lost them. This device will be capable of translating real world data, such as sound, into a tactile signal that the user can learn to associate with the original information. This is accomplished by stimulating the nerves below the skin with an array of electrodes controlled by a microprocessor. These electrodes are controlled independently, allowing for the creation of complex patterns to represent complex data. The entire device is fitted into a sleeve that is worn on the forearm, an area of the body that is sensitive enough to allow for stimulation with low voltages, and is seldom used for other purposes. This project will use the device to translate text entered through a terminal into the corresponding braille patterns mapped to the electrode array. With further development, this device is theoretically capable of translating anything from text messages to engine speeds in real time.

1 Background and Research

1.1 Problem

Living without the use of one or more of the five senses is the unfortunate reality that people who are mute, blind, and deaf face daily. Globally, it is estimated that there are 39 million people who are blind[1], 466 million who are deaf[2], and millions more who have other types of sensory impairment. In light of this, researchers have developed a variety of ways for those with these disabilities to navigate the world.

1.2 Existing Solutions

Sensory Substitution is not a new idea. Those who are blind use Braille and white canes to substitute visual data for a tactile sensation. The deaf substitute sound for hand motions taken in through the visual cortex. Everyone who can read uses sensory substitution by replacing auditory input for visual letters on a page, just as you are now.

David Eagleman is a professor at Stanford University who's research in neuroscience led to the creation of a Versatile Extra-Sensory Transducer, or VEST. This vest feeds information into the brain through the somatic nervous system by means of vibration. Actuators in the VEST press against the back and oscillate in spatial-temporal patterns[1] in response to the received input. This oscillation is felt by the user and learned as a representation of the original information stream. Dr. Eagleman used this technique to teach a deaf person to "hear"[3], as seen in his famous TED Talk[2].

BrainPort[3] is a sensory substitution device created by nueroscientist and researcher Paul Bach-y-Rita. BrainPort consists of an electrode array on a flat plate designed to be pressed against the tongue. A camera mounted to the top of the head analyzes the surrounding environment and sends the corresponding signals to the electrode array. The user feels the stimulation on the tongue and recognizes the pattern as representing an obstacle in the physical world. In effect, it allows a blind person to "see"[4].

2 Methods

Although there are several concepts already in existence for use in HFD, our team narrowed down two potential devices for initial investigation: piezoelectric ceramics and electrodes.

Piezoelectric ceramics are crystals with fixed electric charges relative to the shape of the material. By applying a voltage across the piezo, the crystal structure deforms and macroscopically expands. When voltage is removed, the piezo contracts. By alternately supplying and removing voltages as high as 5V[4] with a square wave, a vibrational effect can be achieved[5]. These vibrations can be used to generate haptic feedback patterns. In order to fit these into a sleeve, the piezos have to be smaller than what is generally

[1]Spatial-Temportal Patterns are patterns that vary in space and time
[2]`https://www.youtube.com/watch?v=4c1lqFXHvqI&t=700s`
[3]`https://www.wicab.com/`
[4]This voltage can vary depending on the crystal being used, reference data sheet for actual voltage

found in household devices. They are available in many shapes and sizes, however, cost increases exponentially as size decreases. Piezos also take time to deform after applying a voltage. These crystals can oscillate at several kHz, thus the delay is on the order of milliseconds. These high frequency oscillations can also be painful to someone who touches them. Piezos are often used in humidifiers to eject water into the air. Anyone who has touched that crystal while the humidifier is running knows it is not an enjoyable sensation.

Electrodes are electrical conductors used to electrically join a circuit to a nonmetallic medium. For medical use, and in the case of the HFD, that medium is the skin. Our electrodes were inexpensively sourced from acupuncturists who use metallic needles to treat their patients. They are designed to be inserted into human skin and happen to be conductive enough for our purposes. Being able to penetrate the skin with electrodes allows us to bypass the electrically insulating outer layer of the skin. This reduces the required voltage for stimulation from roughly 70V to 3.3V. It should be noted that accidentally applying too large a voltage can cause pain[5]. Electrodes are effectively wires and do not require an special signals to operate and have no associated latency. They are also small enough to fit into a sleeve.

A pugh chart summarizing the metrics discussed is shown in reference to motors, which were used in the VEST created by Dr. Eagleman.

Design Criteria	Weight	Motors	Piezos	Electrodes
Price	1		-	+
Power	2	D	+	+
Mechanical Design	3	A	+	+
Electrical Design	3	T	+	+
Size	2	U	+	+
Latency	1	M	+	+
Safety	3		-	-
	+	0	11	12
	0	7	0	0
	-	0	4	3
	Total	**0**	**7**	**9**

Figure 1: Metric Comparison Chart for Piezos vs. Electrodes

A higher weighting was put on the criteria that reduce the difficulty of building the device. Given the time constraint and the facilities we had access too, we wanted to ensure the design and manufacturing process wouldn't be more complex than was necessary. With this weighting system, electrodes came out ahead and were subsequently chosen as the method used in later prototypes.

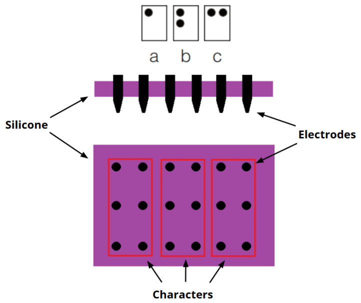
[5] 5V is roughly the upper limit for subdermal electrodes before inducing pain

3 Silicone Prototype

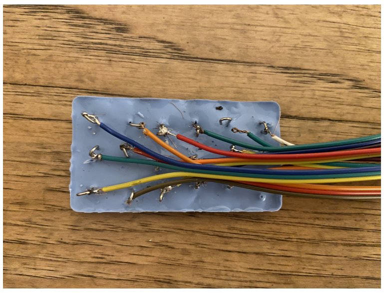
Before developing an entire sleeve, we had to verify that electrodes could provide the stimulation required to make the device work. We also wanted to ensure that it is possible to distinguish multiple electrodes activating in close proximity. This was meant as a proof-of-concept.

3.1 Design

This prototype houses an array of stainless steel kirschner pins[6] encased in a silicone "patch". The patch fixes the k-pins in a uniform 3x6 array, which can accommodate three braille characters simultaneously. Braille is a proven method of converting characters to tactile feedback and uses patterns that are easy to recreate on this array. Using patterns that are already known by prospective beta testers also eliminates the need to learn the significance of the patterns, rather than having to learn custom patterns we create. Each pin is soldered to a jumper wire that connects back to an Arduino microcontroller. The pins are given unique I/O pins on the Arduino, such that the electrodes can be activated independently. This independent excitation is what allows for the creation of complex patterns on the HFD.



(a) Patch side and top view, highlighting components and braille layout



(b) Completed patch top view

Figure 2: Silicone Prototype Design and Final Product

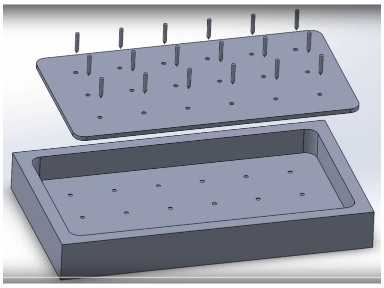
3.2 Manufacturing

The silicone patch was made from a CNCed acrylic mold that consists of a reservoir to hold the liquid silicone and an alignment plate to hold the pins in place during the setting process. Note that the alignment plate fit so well in the reservoir that a hole had to be drilled through the bottom to prevent the formation of a vacuum as the plate is removed.

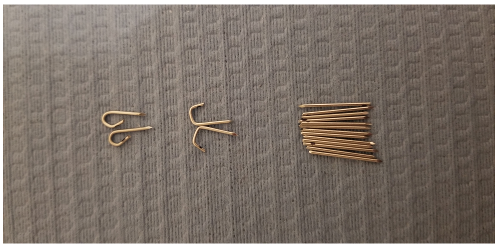
The pins were cut to a 15mm length and bent to form a hook. The hook shape allows the copper jumper wires to wrap around the stainless steel electrodes so that they remain electrically connected when soldered.

The silicone was mixed and poured into the mold until the reservoir was filled to the rim. The pins were inserted into the silicone until they found their corresponding holes

[6]This was created before we sources the acupuncture needles



(a) Acrylic mold for creating the silicone patch



(b) Electrode Pin Bending

Figure 3: Acrylic Mold and Stainless Steel Electrodes

in the bottom of the reservoir. The viscosity of the silicone is sufficient to hold the pins vertically during the setting process. The silicone was left to sit overnight and was pulled from the mold the following morning. The jumper wires were stripped, wrapped around the hook, and soldered in place. The result is a flexible array of electrodes that can be taped down to the skin and controlled with a microcontroller, as seen in Figure 2b.

3.3 Testing

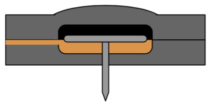
The completed patch was taped to the underside of the forearm and wired to an Arduino. The goal of this prototype was to ensure that each pin could be felt and easily distinguished. It was therefore not necessary to develop software. Instead, each pin was manually connected and disconnected from 5V. The sensation was felt at the onset of the impulse, but faded quickly and was barely noticeable. This prompted for the use of quick pulses and a higher voltage in the proceeding prototype.

4 Textile Prototype

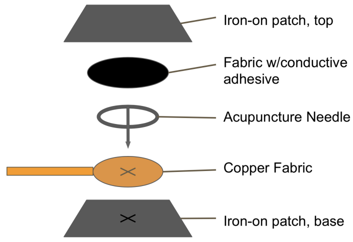
The textile prototype maintains the fundamental ideas of the silicone prototype, but in the finalized form the was envisioned from the start. This prototype is composed of another patch made from conductive and non-conductive textiles, as shown in Figure 4. This was sandwiched between two sleeves, as shown in Figure 6, and is the final prototype of this project.

4.1 Mechanical Design

The acupuncture needles were pressed through a layer of conductive copper fabric that acts as a flexible trace through which we can supply a voltage. The electrodes are held in place by a layer of non-conductive fabric with a conductive adhesive. These layers were then sandwiched between a non-conductive iron-on fabric. This layering allows for each electrode in the array to remain isolated to prevent short circuits and is flexible enough to conform to the forearm.



(a) Textile Layering, Side View



(b) Textile Layering, Exploded View

Figure 4: Textile Layering

4.2 Manufacturing

A 3×2 electrode array was created according to Figure 4. We chose to reduce the size of the array to maintain simplicity and ease of manufacturing, without sacrificing significant functionality. An outline for the individual traces was drawn onto the copper fabric and cut accordingly. The electrodes were then pierced through the copper and secured with the adhesive layer. A heat gun was used to soften the adhesive and fuse the layers together. These were placed between the iron on patches and heated with an iron. Once cool, the patch was fused and the electrodes securely in place. The ends of the traces, which extended beyond the iron-on fabric, were connected to stripped jumper wires with electrical tape[7].

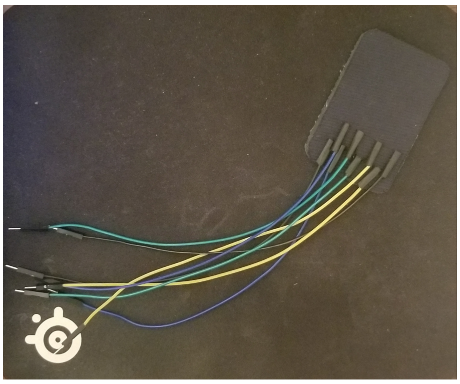


Figure 5: Textile Patch

This patch was fitted into a zipper sleeve to allow it to be easily taken on and off. The sleeve is made of spandex, which provides the tight fit necessary to ensure the patch stays pressed against the skin. With the exception of the input wires protruding out by the elbow, the sleeve is otherwise unsuspecting. It does extend slight beyond the elbow and wrist, making it difficult to flex. In the future, the length of the sleeve would be reduced to avoid this.

[7]The copper cannot be soldered too. In the future, we want to sew the jumper wires into the fabric

Figure 6: Haptic Feedback Sleeve Prototype

4.3 Software Simulation

A simulation created in python shows the activation and deactivation of the electrodes in the array as the braille characters are generated. The characters traverse the array from right to left in order to simulate reading braille off a page. Typically, the finger moves across the braille from left to right; this is relatively the same as the braille moving across the finger from right to left. Similar to how an display works, the electrodes are given the illusion of movement by activating and deactivating in the correct sequence.

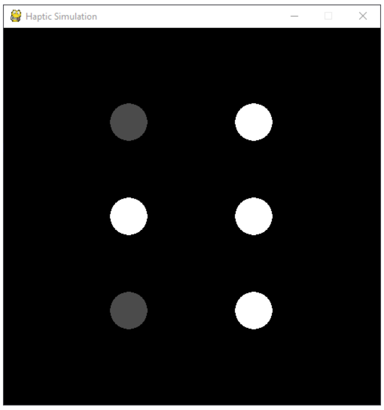


Figure 7: Snapshot of the letter 'w' traversing the simulated electrode array. White and gray dots represent activated and deactivated electrodes, respectively

The simulation is capable of taking an input string and simulating the corresponding braille character. It does so by parsing through the input string, reading into a dictionary that relates English and braille characters, and turning the corresponding circles white or gray through nested for loops. The code is open source and available on github[8].

The intention of this simulator is to show non-users what the device is physically doing. From the outside, it isn't immediately apparent that the device is doing anything. This simulation allows us to demonstrate the functionality to a wider audience[9].

[8]https://github.com/mikepapa98/haptic_simulator

[9]Due to the spread of COVID-19 and University wide shutdown, we have focused on another method of showing device functionality. See section 4.4

```python
import pygame
from haptic_sim import *


def activate(char):
    screen.fill(black)
    for y in range(-1,2):
        deactivate()
        for x in range(len(char)):
            if (pos_x * char[x][0] + pos_x * y >= pos_x and pos_x * char[x][0] + pos_x * y <= screen_width - pos_x):
                pygame.draw.circle(screen,white,(pos_x * 3 - pos_x * char[x][0] - pos_x * y, pos_y * char[x][1]), rad)
                pygame.display.flip()
        pygame.time.delay(delay)
    deactivate()

def deactivate():
    for x in range(1,3):
        for y in range(1,4):
            pygame.draw.circle(screen,gray,(pos_x * x, pos_y * y), rad)
            pygame.display.flip()

def check_quit():
    for event in pygame.event.get():
        if event.type == pygame.QUIT:
            run = False

def get_input():
    phrase = input("Enter a phrase: ")
    return phrase
```

Figure 8: The functions used by the simulation. Methods for turning electrodes white and gray, getting input, and a check for the user quitting the program

4.4 LED Display

Due to the spread of COVID-19 and our lack of ability to personally demonstrate the prototype, we have developed an LED Display that acts as a substitute for the electrode sleeve. The display consists of an array of LED's fitted to a housing. Each anode is connected to an independent GPIO Pin on a Raspberry Pi 3, with the cathodes connected to a common ground through a resistor. This setup is electronically identical to using the bare electrodes. The LED's are a substitution used only to show visually which electrodes are activating and in what order. This allows us to demonstrate the prototype over a video call.

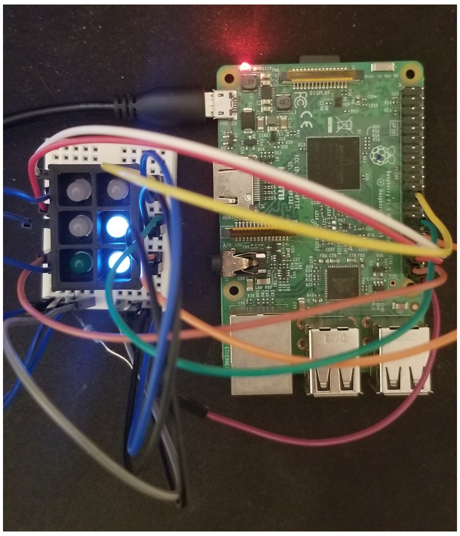


Figure 9: The LED Display (Left) as temporarily wired to the Raspberry Pi (Right)

The LED Display software works nearly identically to the simulation software. Instead of drawing the corresponding circles to the screen, the corresponding GPIO Pins on the Raspberry Pi are powered. This supplies 3.3V to each LED, turning them on and simulating powered electrodes.

5 Future Considerations

5.1 Technical Developments

Due to the electrodes' final position being embedded in the topmost layer of the skin, importance was placed on understanding the implications this could have on users concerning safety and comfort[7]. Beneath the surface of the skin there are many types of receptors found at different depths for sensing temperature, movement, and pain. Because the goal of the device is for it to be felt by the user to the extent that the brain can convert the tactile sensation into whatever necessary response, stimulation of movement receptors was prioritized. Concerning improvements that could be made to the device in the future, prioritization towards the skin's pain receptors should be addressed. Pain receptors, or free nerve endings, are found throughout the skin where they start below the dermis and end in the stratum granulosum (one of the layers of the epidermis)[8]. For this device it would be beneficial for the electrodes to reach a maximum depth which would be above these pain receptors. In order to avoid any contact with the stratum granulosum, and therefore the free nerve endings, our team decided that the needles would not benefit from penetrating deeper than the stratum corneum. Although the thickness of the corneum varies throughout the body, the average thickness found for the forearm (where our device will be used) was 19-20 micrometers[9]. The current HFD version includes acupuncture needles which penetrate roughly 1.5 mm into the skin. Future improvements could be made by decreasing the length that the needles can protrude from the patch according to the thickness of the corneum.

The following figure serves to illustrate the previous discussion of the layers of the skin as well as point out where pain receptors lie.

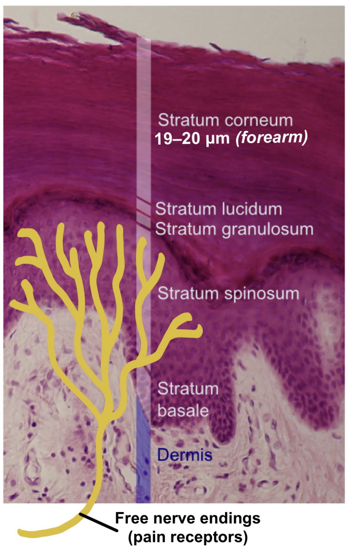


Figure 10: Sideview of Epidermis Showing Depth of Pain Receptors[10]

6 Conclusion

Current international circumstances clearly prohibit us from moving forward with the hardware development of the Haptic Feedback Sleeve. For the time being, we will be relying on the LED Display to demonstrate functionality. Beyond cleaning up the circuit, there is not much we can do without the equipment and facilities we initially planned on having access to. The current situation also makes it impossible to find users to beta test. The plan was to allow someone to spend a minimum of one week with the completed prototype to see how quickly they could learn to interpret the signals. Without that study, we have to rely on prior studies, as cited, to demonstrate the feasibility of sensory substitution. If we are to continue with this project, we do hope that it would become possible to lend the device to a trial user so show definitively that it does work as a sensory substitution device.

References

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