Trace to Touch: Eliciting Gestures from Capacitive Touch Electrodes

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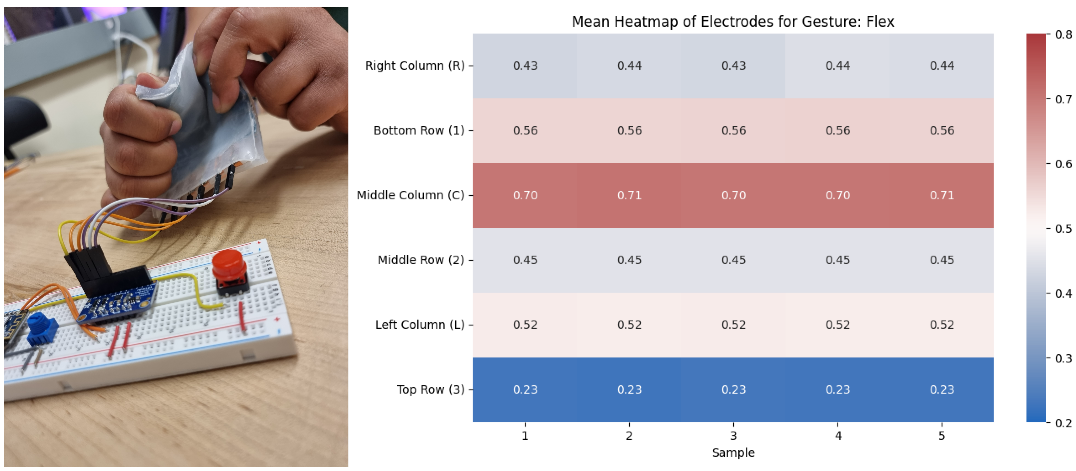

Figure 1: Flexing gesture performed on a capacitive touch sensor made with conductive yarn arranged in a grid pattern and encapsulated in silicone with the corresponding heatmap of mean sensor values over time.

ABSTRACT

Capacitive touch relies on electrodes to detect and interpret touch gestures. These electrodes are conventionally designed as rigid, grid-like structures, optimized for manufacturing efficiency. However, the advent of diverse conductive materials opens new avenues for enhancing the way electrodes are designed. In this paper, we develop a textile-silicone sensor composite using embedded conductive yarn as a capacitive touch electrode. By deviating from the grid pattern, we explore how alternative patterns can inspire novel, playful, and expressive gestures. We describe our design process for conceptualizing gestures from electrode design principles and iteratively test gesture detection using an off-the-shelf CNN model. Our approach in developing a textile-silicone sensor with unique electrode designs enables the development of creative, comfortable and customizable haptic interfaces.

CCS CONCEPTS

• **Human-centered computing** **Human computer interaction (HCI)**; *Haptic devices*; User studies.

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1 INTRODUCTION

Frank Lloyd Wright's work explores organic architectures and sustainability, and one of the principles from his mentor that inspired his work was "Form Follows Function". [9] Due to its manufacturing ease, typical electrode design is confined in a rigid grid structure limiting the "form" to express new innovative gestures. What if electrode designs were more creative? Can the electrode design motivate new gesture expressions? To tackle this challenge, we propose a layered composite sensor utilizing capacitive touch that allows flexibility to create unique electrode designs. We develop a data collection system that allows us to iteratively design and evaluate new gestures. Previously, we have seen capacitive touch implemented in touch screen devices such as smartphones, tablets, and touch-enabled tablets. We also observe them in our daily environment from the touch buttons on a microwave to a washing machine. Our work introduces a novel approach to capacitive touch interfaces that can inspire new gestures. Additionally, we investigate how electrode designs support the gestures we perform by analyzing patterns in our data. A system where "Function follows Form" opens the potential for new creative ways to make gestures outside of ones limited to grid designs.

2 RELATED WORK

In this section, we explore innovations in sensor design. One area of special interest is the use of textiles and embroidery. We compare their design choices and techniques with ours, and take inspiration from their techniques.

2.1 Silicone in Sensor Design

Quitemeyer, et al., discuss the practice of embedding electronics in plastic and distinguishing between large-scale and small-scale fabrication. To eliminate several difficult fabrication steps, small-scale fabricators may embed electronics directly in silicone rather than taking steps such as encasing the electronics in plastic to protect the electronic components as is done for industrial uses. Our method allows us to take advantage of the benefits of embedding sensors in silicone while ensuring the security of the electronic components [6]. When it comes to haptic-based interfaces that involve physically stimulating the interface, one such study by Hoggan et al. utilized a pressure-based haptic communication system to design ForcePhone. ForcePhone allows users to squeeze the sides of their phones and send vibrations of varying intensity to the receiver. In this research, they allow the users to come up with ways to display nonverbal communication using these "Pressages". Their pressure sensor was developed by augmenting a Nokia Phone with a Force-Sensing Resistor. Their design is without any additional hardware and covered with a silicone case to allow the user experience to reflect the interaction method. [3] TIMMi compacts sensor design by creating a "textile input device" that understands multimodal inputs by stitching conductive threads at different locations and painting on a conductive elastomer on nylon-spandex fabric. The analog readings are transmitted to a microprocessor through a fabric connector and the data is transferred through Bluetooth, keeping the sensor design comfortable to wear and flexible. [11]

2.2 Textiles and Embroidery in Sensor Design

Several researchers have used textiles and embroidery in their sensor designs. Enokibori et al. created an e-textile-based sensor with conductive fibers woven in a checkered pattern using a weaving machine. The machine detects changes in pressure using a capacitance measurement measured and converted to pressure [1]. Skinergy is a wearable, self-powered sensor that combines silicone, embroidery, and electronics. They create a unique design by embroidering a design into the sensor with an embroidering machine and casting the embroidered design in silicone. This sensor was then tested via a user study with the following gestures: rest, single tap, double tap, pinch, spread, swipe right, swipe left, swipe down, swipe up, clockwise right, and counterclockwise left. The authors of this paper combat the large cost of embroidery software with a software converter that takes an SVG file created using vector graphic design software as input and outputs both a model for 3D printing and embroidery instructions. We take this one step further in our paper using simpler stitching techniques that further lower the costs of production. [12]. Tapis Magique is another innovative sensor. This piezo-resistive e-textile masterfully joins music, dance, and textiles into an original and engaging experience. Inspired by traditions from traditional cultures such as Japanese and Balinese gamelan, and Maharashtra folk dance, they carefully select meaningful patterns to stitch into their fabric. They map music notes onto a grid so that the location and pressure of the dancer's feet inspire the music that is created [10].

3 SENSOR DESIGN AND SETUP

3.1 Sensor Design

This sensor can be adapted for use with a variety of designs and configurations. As part of our research, we propose two designs: **Spiral** and **Grid**. The Grid design is an adapted version of the grid-like pattern that is often found in electrode design. When gestures are performed on it, they can be mapped to traditional rectangular quadrants. The Spiral design, however, uses quadrants that can better be described through polar coordinates. These differences in locations of points of intersection and configuration means that both patterns lend themselves to different sets of gestures and create interesting results.

3.1.1 *Materials.*

- A 3D Printed Mold of desired dimensions
- A piece of fabric of the same length and width as that of the 3D Printed Mold
- Several lengths of conductive thread slightly longer than required to create the design
- A spool of non-conductive thread.

3.1.2 *Creating the Conductive Thread Pattern.*

- *Fabric and Electrode Embroidery.* We chose a sturdy, canvas-like fabric as the electrode substrate to prevent tearing or puckering from the tension of different embroidery stitches. After marking out the path of the threads on both sides of the fabric (Figure 2), we secured the conductive yarn onto the substrate with couching stitches at even intervals (Figure 2). These stitches secure the thread in place without affecting the functioning of the sensor due to the non-conductive nature of the securing thread. Once the layered composite is complete, the result is two layers of conductive yarn separated by fabric. So, when the sensor is pressed, both layers are activated while remaining isolated.
- *Breakout Board Fabrication.* This layered composite was next connected to an acrylic breakout board to make the routing of the conductive yarn easier and more compact. The board was fabricated with holes for each of the conductive threads. In order to make this connection conductive, copper tape was applied across the top of each hole and new holes were cut into the tape. Each piece of yarn was wrapped around the holes in the board and secured with two to three even coats of nail polish. This kept the conductive thread in place and had a faster drying time than other methods of securing it, such as glue [8]. In order to connect the breakout board to the Arduino board used to collect data, we soldered 6 male-to-male jumper wires using a soldering wire of a thickness of 0.8mm at 550 degrees F.
- *Silicone Encapsulation.* Once the sensor was fabricated, it was encased in silicone to make it durable and resistant to wear and tear. In order to fabricate the silicone sheets, we mixed together equal parts of EcoFlex 00-50 Part A and Part

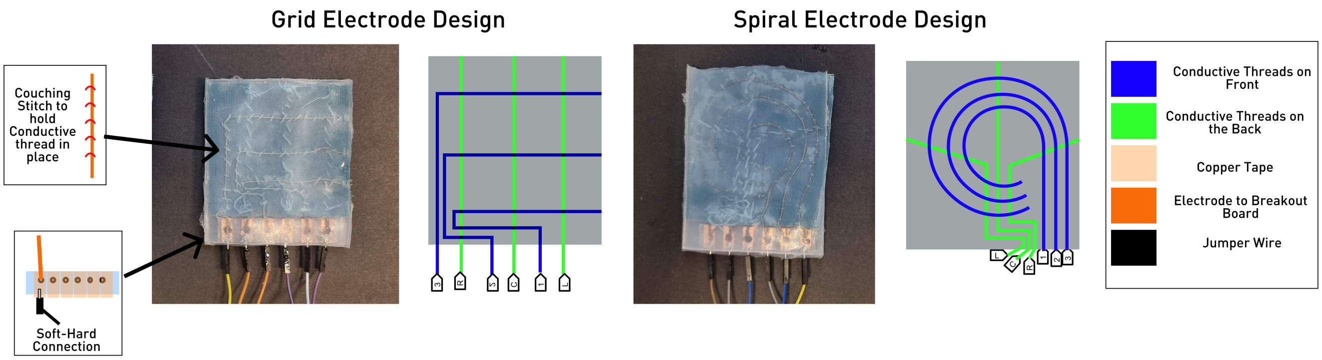

Figure 2: Grid vs. Spiral Electrode Design. Our two proposed layered composite sensors with Grid and Spiral Electrode Designs. Additional zoomed in portions of the image clarify how the couching stitch and soft-hard connections were performed.

B fluids: 5g each for the top layer of silicone and 10g each for the bottom layer. Once the silicone mixture was thoroughly mixed, it was degassed in a vacuum chamber at -100 kPa (-30 inHg) to remove the air bubbles created during the mixing process. Additionally, the silicone was cured in an incubator at 57 °C (135 °F) for 10 minutes for the top, thinner sheet, and about 20 minutes for the bottom, thicker layer. The mold for the casting was created by 3D printing a dam or well and attaching it to a piece of acrylic with double sided tape.

It is important to note that when the layered composite and breakout board are created, this board is significantly taller than the composite. In order to ensure that they sit at the same height when cast, a well was created in the bottom layer of silicone to hold the board. A very thin layer of silicone was poured evenly across the base, and an an unused 3D printed breakout board was placed on top, after which we poured silicone around it until it reached the height of the PCB Board. Once the silicone was cured, the board was removed, leaving behind a well in which the board could sit. We then applied a thin layer of uncured silicone on top of this surface with a paintbrush and placed the completed sensor and breakout board on top to stick the layers together. After that, we applied another layer of uncured silicone onto the top sheet of silicone and placed it face down on the sensor. This was then cured.

3.2 Data Collection

3.2.1 Virtual Configuration. In order to collect data from the sensor, we used the Adafruit MPR 121 Microcontroller. In the C++ file, we set the MPR 121 Config 1 value to 0x4C which is 12A and the MPR 121 Config Value to 0x40 which is 1 μs.

3.2.2 Physical Configuration. To Configure the Arduino,

(1) Place a push button in the location shown in Figure 3. This button changes its reading to 1 when pressed and to 0 when released. As this reading of 1 will only be displayed as long as the button is being pressed, we can push it when an action is being made on the sensor. This allows us to eliminate readings that are not related to the action and precisely clean our data.

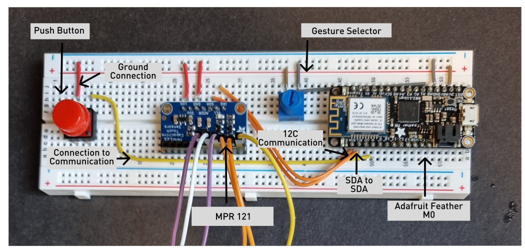

Figure 3: Bread Board Set-up for our Data Collection System. Arduino Set-up with the MPR 121, Gesture Collector, Push Button, and Electric Circuit Board.

(2) Place a rotary knob-shaped potentiometer at the location shown in Figure 3. The readings from the potentiometer are divided into eight sections allowing us to perform up to eight different gestures on our sensor and use those as labels when training our model, simply by turning the knob to the number we assigned to the gesture before collecting data for it.
(3) Remaining components placed onto Arduino as seen in Figure 3.

3.2.3 Gesture Selection. For our sensors, we decided to test a total of 7 gestures to understand which gestures are most aligned with our electrode design. To have a baseline and validate that our sensor is not producing any noise, we included recordings from the sensor when it was left undisturbed, without performing any gestures. We decided to also include conventional gestures that are typically made on touch-based devices such as smartphones that are Top-Right Tap, Three-finger tap, Bottom-Up swipe, and Left-Right swipe. Inspired by the spiral design of our sensor, we tested circular motion to understand if the spiral sensor would capture the gesture better than the grid sensor. Finally, since the sensors are made from silicone and fabric it allows for flexibility so we tested a flex gesture.

3.2.4 CNN Training. We tested our 7 different gestures on each sensor. The data collected is saved as a CSV file with each row containing 500ms of readings per electrode. We collect about 1 minute's worth of data per gesture. This is then converted into a Pandas dataframe, and all readings without any actions performed are dropped. The gesture column is used as the label and the six electrode values are merged into one single column. This was done so that we could treat the electrode values as a 6 x 5 image, where six is the number of electrodes and 5 is the number of readings per electrode. We trained a simple Convolutional Neural Network (CNN) with Adam optimizer and the loss function as cross-categorical entropy. We trained for 100 epochs and implemented early stopping.

4 RESULTS

The CNN had an accuracy score of 97.04% for the Grid design and 99.45% for the Spiral design. Accuracy tells us the ratio of correctly predicted observations over the total number of observations, providing us with an overall understanding of the performance of our model. Furthermore, we compare the mean heatmaps of the traditional Grid Design with the Spiral Design. For our Control, our results are consistent across all electrodes for both designs. For the Circular Motion Gesture, the Spiral Design has a precision score of 1.00, while the Grid Design has a precision score of 0.92. The precision score is the ratio of correctly predicted positive observations over the total predicted positives. This variation in precision could be due to the result of the Circular electrode being consistently activated throughout the gesture, allowing precise data. However, the Grid Design has a slightly higher precision score of 0.95 for Top-Right Tap as compared to 0.92 for the Spiral Design. This could be attributed to the even spacing of electrodes for the Grid structure whereas the Spiral Design creates more opportunities to accidentally activate other electrodes due to its compact design. Both designs had a precision of 1 for Flex, and as observed in Figure 4 the mean electrode readings dropped the lowest for the Flex gesture. This can be credited to the flexibility of the sensor allowing for more pressure when flexing the sensor.

5 DISCUSSION

5.1 Applications

Steer et al. investigated how people relate colors, graphical design, and physical shapes to the surface stiffness of deformable surfaces. Our research has the potential to adapt their findings to create applications with different colours of conductive thread and shapes of the sensors allowing users to apply force based on their perception of surface stiffness. [7] This can motivate purposeful pinching, flexing, or stretching movements on our sensors. Our research has the potential to fall into the field of Crossmodal Correspondences (CCs). CCs refer to the idea where people relate certain attributes or features across multiple sensory modalities. Lin et al. conducted a user study to assign colors and emotional categories to 3D-printed objects with varying degrees of angularity and complexity [5]. This research can be implemented to create silicone sensors of varying thicknesses, shapes, and colors of conductive threads. Hoggan et al. manipulated the angle, direction, distance, and position of two-finger pinch gestures. Their results investigate how we can allow for faster pinch gestures and avoid difficult pinch tasks. [2]. The layering and design of our electrodes can be customized to motivate new gestures and can aid in making easier and quicker pinching gestures. TaSSt, which is a wearable tactile sleeve for social touch, leverages different types of touch such as rub, squeeze, push, etc. to communicate between two people and can be adapted to utilize different electrode designs to inspire creativity and potentially introduce new ways of communicating between two people. [4]

5.2 Limitations

The smooth silicone texture can provide unnecessary friction that disrupts the motion of the finger. This can be eliminated by applying corn starch or exploring micro-textured silicone that can guide seamless movement. Another limitation to be addressed is the limited number of electrode designs and gestures that were explored. Based on our findings for flex, there are future opportunities to test bending, pinching, and rolling gestures that stray outside the realm of conventional UI Gestures. Furthermore, the dataset includes gestures collected from one participant but for future studies, it is crucial to conduct a user study and collect data from multiple participants to observe if the model can classify those gestures. For our future work, conducting a qualitative analysis via a user study would help explore potential applications and constraints of our proposed sensor.

6 CONCLUSION

Our results show robust accuracy scores across different designs from our Convolutional Neural Network (CNN), with slight differences in precision noted for various gestures across designs. The results display that our sensors showed the most change in electrode readings for the flex gesture encouraging gestures that go beyond the surface-level. The flexibility of our layered composite sensor along with brainstorming new gestures based on electrode designs allows us to explore creative applications of our sensor. This approach allows us to look past the predefined functionalities of rigid electrode designs and elicit gestures that have the potential to be adapted for performing new shear gestures in applications ranging from comfortable wearables to immersive gaming experiences.

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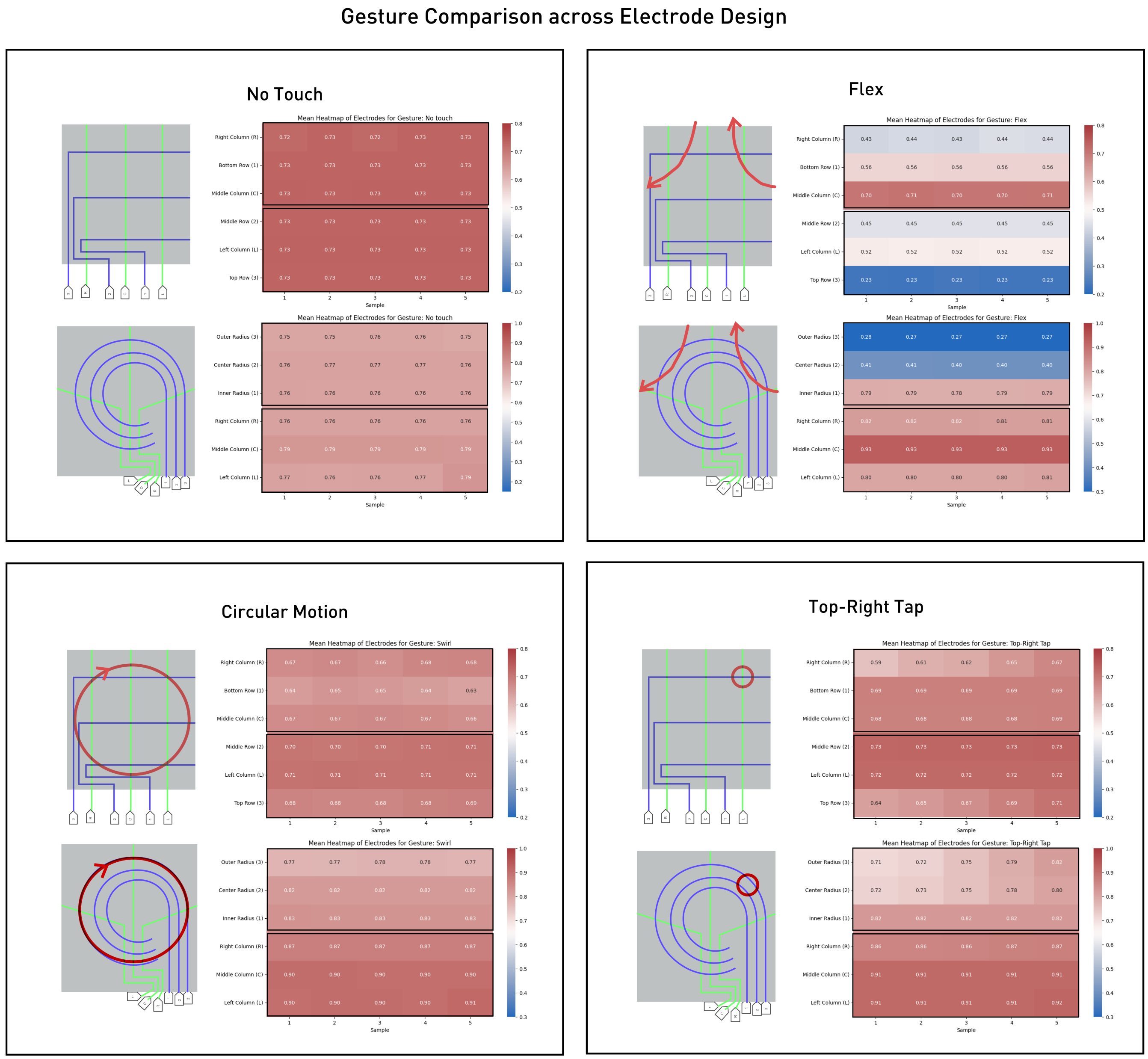

Figure 4: Mean Heatmaps for Four Different Gestures across Grid Design and Spiral Design. A) No touch gesture when each sensor is left undisturbed. B) Both sensors are flexed or twisted with force applied in opposite directions. C) Touch is applied in circular motion for both sensors. D) A tap is performed at the top-right corner of each sensor.

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