

Embroidered Multi-Modal Sensing Arrays for Tactual Perception

by

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Abstract

Humans possess a peripheral nervous system that gives them the ability to sense and interpret tactile information, normal and shear force, and vibrations. This provides us with the ability to perceive changes in our surroundings and react to them, allowing us to complete complex tasks. Bestowing these sensory modalities to robotic systems would enable them to complete complex manipulation and assembly tasks that are trivial for humans. In this work, we present new types of robotic skins that give robots the ability to sense normal force, shear force, and vibration. Fabricated with a highly-automated manufacturing process, our sensing systems can be inexpensively manufactured. Furthermore, we can capture forces over a high range by employing multi-gain capturing techniques. We demonstrate our sensing systems capabilities by designing and fabricating a set of devices and utilizing them for human wearables and robotics applications.

Thesis Supervisor: Wojciech Matusik
Title: Professor

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Chapter 1

Introduction

Humans rely on multi-modal tactual feedback from their skin’s mechanoreceptors to understand and interact with objects in their surroundings. The different sensing modalities at our disposal help us recognize objects as humans grasp and touch them [20]. Normal and shear force feedback allows us to attain feedback about when we have made contact with an object and if we have a sufficient grasp to hold it. Sensing vibrations is useful for detecting if objects are moving or if an object could be dangerous [16, 25]. Furthermore, humans possess the capability of sensing forces over a wide range of magnitudes, which allows us to complete the manipulation of small objects as well as large ones [15]. Tactile sensing systems with similar performance to humans are important for giving robots similar capabilities. To achieve this, our human skin requires a complex topological structure making it difficult to create cost-effective equivalents for robotics applications.

Recently, many tactile sensing systems have developed novel sensor architectures [31, 26, 22, 4], developed new materials[27, 8], and used new fabrication processes [36, 24]; however, these sensing systems are not able to meet the requirements above. Robotics systems typically have a significant space constraint due to the hundreds of parts needed for their motion systems to function properly [13, 18]. Many of the current tactile sensing systems possess bulky designs and complex manufacturing processes, making them unrealistic to integrate into current robotic systems without significant redesign of the motion systems. By creating tactile sensing systems with

human-like multi-modal sensory ability and the ability to be easily integrated into current designs, we foresee solving a major trade-off of current tactile sensing systems.

In this work, we present a tactile sensing system that integrates a sensor design capable of normal force, shear force, and vibration detection while still being able to be easily integrated into current robotics designs and wearable applications. To make this possible, we harness the capability of machine embroidery, a textile process that allows us to fabricate thin piezoresistive sensing arrays in an automated fashion. Further, we installed a force translator on top of our embroidered tactile sensing array that allows us to sense the directionality of an applied force. We also present a method of reading the sensor that enables sensing vibrations up to 500 Hz and reading forces anywhere from 0.5 N to 6 N. Finally, we present a calibration technique that allows us to calibrate our tactile sensing system’s force readings in an automated manner. We show how this sensing can be used in robotics and wearable device applications alike.

In this thesis, we will give an overview of previous work in tactile sensing, the sensor design and fabrication process we have developed, and finally characterization and sample devices we have fabricated. Chapter 2 introduces the background and previous work. Chapter 3 details the tactile sensing system design and fabrication process we have developed. Chapter 4 gives the results of sensor fabrication and characterization. Finally, chapter 5 summarizes the work and future directions.

Chapter 2

Related Work

Tactile sensor designs have previously been used for identifying objects and monitoring human activity [31, 23]. Furthermore, Others have also utilized tactile sensors in robotics to grasp and manipulate objects [34, 17]. In this section, we will review the different technologies that have been used to produce tactile sensors. Furthermore, we will review the machine embroidery manufacturing process and different functional devices that have been manufactured using this method.

2.1 Tactile Sensing

To measure tactile changes on a surface, tactile sensors will typically measure physical changes that occur in a material. Typically, they will be capacitive, resistive, optical, or changes in charge of a system. We will review the major transduction methods that are currently used.

2.1.1 Piezoresistive Sensors

The piezoresistive effect occurs when a material changes its electrical resistance when a force is applied to it and mechanically deforms. Materials such as force-sensitive polymers, rubbers, and foams exhibit this phenomenon. These materials are mixtures of material that makes up a structural matrix and a conductive polymer that is dis-

persed about that matrix. As the matrix gets compressed, the conductive particle gets closer together and creates conductive traces in the material [33]. Others have previously developed piezoresistive tactile sensing architectures for robotics applications [32, 12, 5].

2.1.2 Capacitive Sensors

Capacitive sensors typically consist of two conductive plates that are separated by a deformable material that keeps the two plates electrically separated. When pressure is applied to the sensor during operation, the deformable layer deforms and brings the two plates closer together, changing the sensor’s capacitance [29, 28, 1, 2]. The advantage of capacitive sensors is that they can be read at a very high frequency compared to other technologies.

2.1.3 Piezoelectric Sensors

Piezoelectric sensors focus on materials that generate a charge when a crystalline material deforms. Typically, a quartz or lead zirconate titanate material are used to generate a charge, but less expensive polymers have also been developed and tested [30]. Others have utilized the piezoelectric effect for sensing tactile signals in robotics [10, 35, 21].

2.1.4 Optical Sensors

Optical sensors focus on measuring changes in a material’s optical properties or geometry through the use of an embedded camera system. These systems can be used to estimate the geometry and force applied to an object that is touching the surface [37, 19]. By placing spatial trackers on the surface of an optical material, measurement of shear force is also possible by using similar optical-based tactile sensors [38].

2.2 Machine Embroidery

Machine Embroidery has been as an automated manufacturing method to fabricate new types of actuators, sensors, and wearable devices. Recently, machine embroidery has been used as a method to fabricate novel pneumatically-driven actuators [9, 6]. Recently, sensors that can measure pressure [3], movement, and power [7] have also been developed. Finally, wearable devices with integrated electronics have also been designed for and fabricated on an embroidery machine [14].

Chapter 3

Sensor Design and Manufacturing

3.1 Multi-modal Tactile Sensing Arrays

We present a new tactile sensor that is able to sense normal force, shear force, and vibrations. The sensor is comprised of three main parts: the embroidered force resistor sensor array, a force translator, and an FPGA-based sensor reading circuit that are shown in Figure 3-1. The embroidered force resistor array is used to capture information about changes in force on the surface of the sensor. The force translator is used to extract the directionality of the applied force. The embroidered force resistive array and force translators are tiled over the entire area of a desired surface. The FPGA-based force is used to capture readings from the sensing array at high-speed.

We manufacture our multi-modal tactile sensors by the use of two highly automated manufacturing processes, which are machine embroidery and 3D printing. Utilizing these manufacturing processes can greatly reduce the manual processing needed to make a sensor, reducing that overall cost. As shown in Figure 3-2, our piezoresistive tactile sensor is manufactured with machine embroidery, and our force translators are manufactured with 3D printing. The two parts are then affixed to each other to create a working sensor.

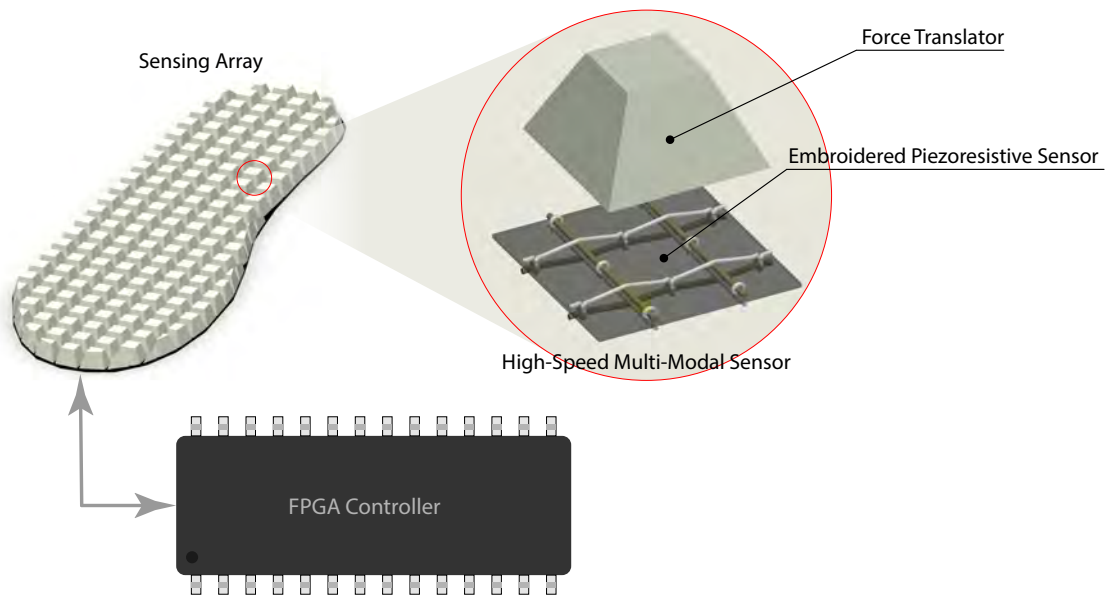


Figure 3-1: Overview of our multi-modal tactile sensing array that is able to measure normal and shear force and vibration.

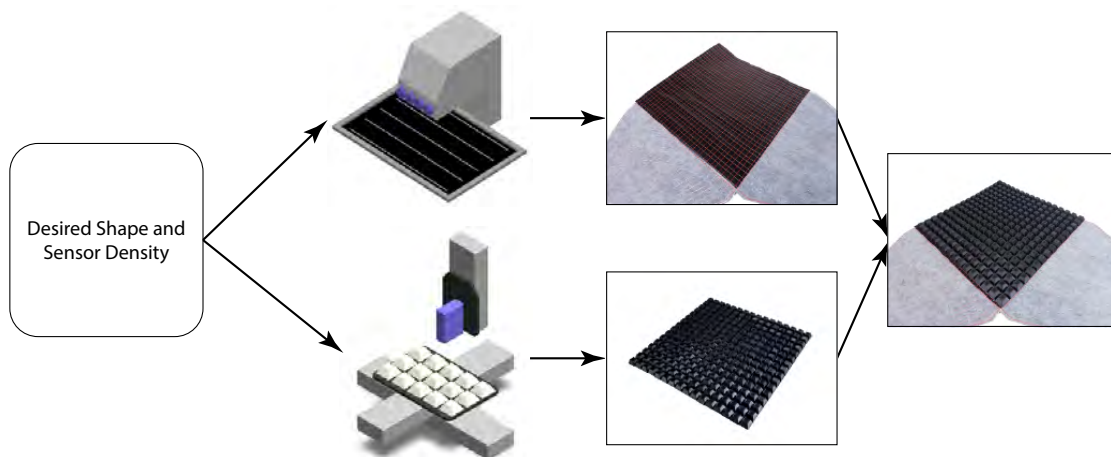


Figure 3-2: Overview of our manufacturing process for our multi-modal tactile sensing arrays.

3.1.1 Embroidered Tactile Sensors

The embroidered force resistor sensor array is comprised of a resistive sheet, an array of electrically conductive threads located on both sides of the sheet, and non-conductive passive threads used to interlock the electrically conductive threads through the sheet, and an electrical connector board that interfaces with sensing electronics. The resistive sheet, electrodes, and the interlocking passive thread is then sandwiched by a non-conductive fabric to protect the sensing array from environmental hazards and shorting. In operation, the electrodes, as shown in Figure 3-3A, are used to measure the resistance of the resistive sheet at the specific point where a pair of top and bottom electrodes intersect. The resistance of the resistive sheet reacts to external changes in force. The electrodes are placed to sense the resistance change at various locations on the resistive sheet and create an electrical connection to a set of connection points that interface with sensing electronics. To place the electrodes, a series of sewing switches are used to affix the electrode to the resistive sheet as shown in Figure 3-3B. During the stitching process, the electrode is interlocked with a thread that is resistive or non-conductive.

Embroidery Materials

Our embroidered sensors have two important functional components, the resistive sheet, and the conductive electrodes. The resistive sheet acts as a force-sensitive resistor where the resistance between the top and bottom of the sheet changes when a force is applied to the sheet. For our embroidered sensors, we utilized a volume-conductive carbon-impregnated polyolefin sheet of thickness of 6 mils (Velostat, Desco, Canton, MA) as shown in Figure 3-4A. The resistive sheets may also be stacked to increase resistance. The conductive electrodes create electrical traces that measure the resistance at a specific point of the resistive sheet. We utilized a silver-plated polyamide thread as a conductive electrode (HC40, Madeira, Freiburg, Germany) as shown in Figure 3-4B.

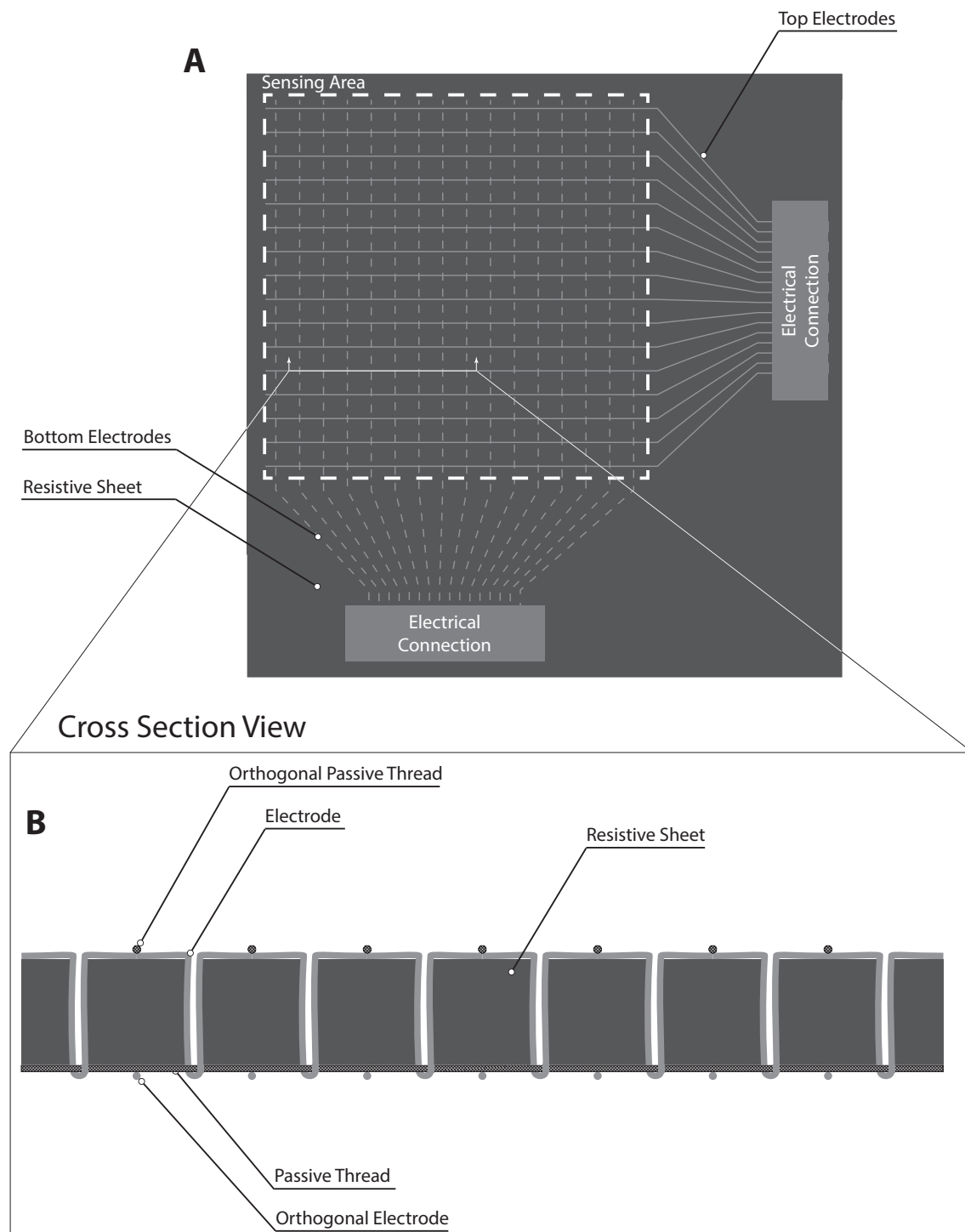


Figure 3-3: (A) An embroidered tactile sensor and all of its main components. (B) A cross-section view of an embroidered tactile sensor.

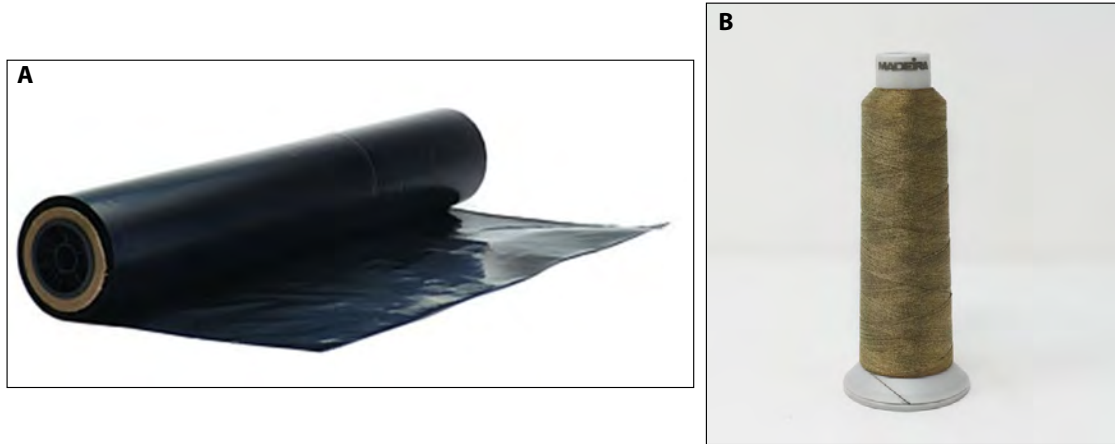


Figure 3-4: (A) Resistive sheet and (B) conductive thread used for embroidered sensors.

Embroidery Process

To manufacture our tactile sensing arrays, we utilize machine embroidery to automate the placement of electrodes. Although previous architectures of force resistive sensing arrays require inexpensive materials, typically, they require manual placement of the electrodes in the correct location which significantly increases the total cost of the sensor and reduces the ease of scalability. By using an automated process to lay the electrodes, we greatly decrease the total cost of our sensors.

Machine Embroidery is a textile manufacturing technique that sews threads onto textiles to create patterns. As shown in Figure 3-5, an embroidery machine is comprised of 2 main parts, a motor-driven stage that moves a sheet in x and y and a sewing head that can affix thread to the sheet using a lock-stitch. During operation, the embroidery machine's stage moves to a set of points that lie on a prescribed path. At each point, the sewing head will create a lock-stitch affixing a thread to the sheet. As the embroidery machine continues to affix the thread, it lays a line of thread along the prescribed path, creating a pattern.

To manufacture our tactile sensors, we utilize an embroidery machine to affix the electrodes to the resistive sheet. First, we install a resistive sheet into the x-y stage. The embroidery machine uses a passive thread as the top thread and conductive

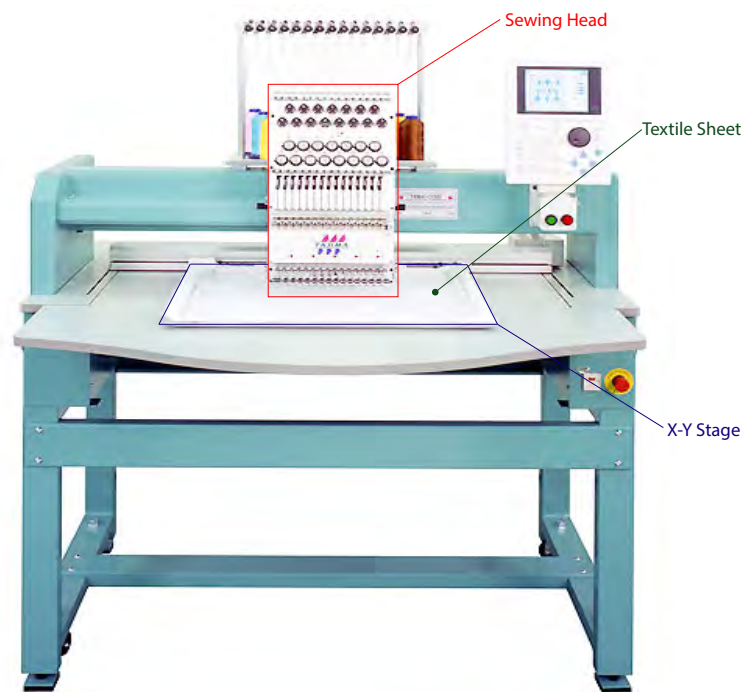


Figure 3-5: An image of an embroidery machine (TFMX-C, Tajima, Kasugai, Japan) and its major parts, the sewing head, and the xy stage.

thread as the bobbin thread. As shown in Figure 3-6, first, the embroidery machine follows a prescribed path to affix one electrode to the resistive sheet. For ease of manufacturing, the set of electrodes is connected together into one serpentine pattern to reduce the number of times the embroidery machine must start and stop a thread. After one side of the sheet is populated with electrodes, the entire sheet is flipped, and the same electrode-laying process is completed. We then sew on insulating sheets in needed places to protect the electrodes from electrically shorting. Finally, electrical connectors are attached to the sheet to interface with the reading electronics.

Sensor Layout

To program the automated embroidery machine, we must give it a sequential list of locations to create stitches. To do this, a user defines the sensing area geometry and the location of the electrical connector with respect to the sensing areas as shown in Figure 3-7. Other parameters, such as the number of sensors and density, are important to predetermine before laying out the electrodes. Within the sensing area, the top and bottom electrodes will orthogonally cross, creating a sensor. Once these parameters are selected, and the sensing area and connector location are known, the sensor locations and the electrode routing area can be determined, and the two vector paths are laid out within those areas. Next, each vector path is converted into an array of equidistant points that lie along that path. To avoid shorts, points are also chosen to be a specified distance from the opposite electrode path. Finally, the set of points is converted into a file format that can be interpreted by the embroidery machine. Separate embroidery files are also created in a similar fashion to affix the insulating fabric to the sensing arrays to protect against shorting.

3.1.2 Force Translator

To extract force direction information from the normal force reading that our embroidered tactile sensing arrays can measure. To do this, we utilize a set of rigid blocks affixed to the top of our tactile sensing arrays, and four sensors sit below each

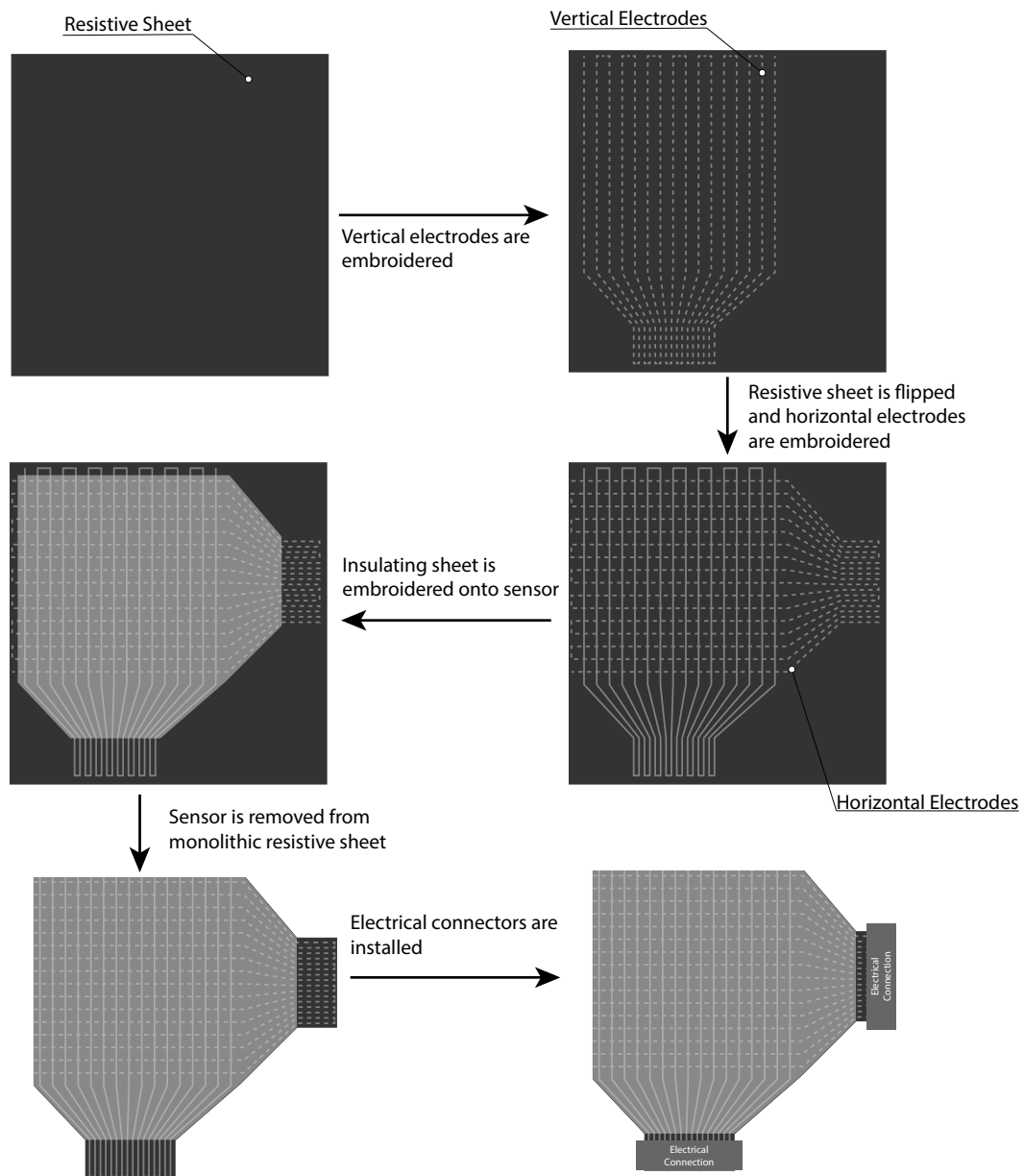


Figure 3-6: The steps of creating a force sensitive tactile sensing array using an embroidery machine.

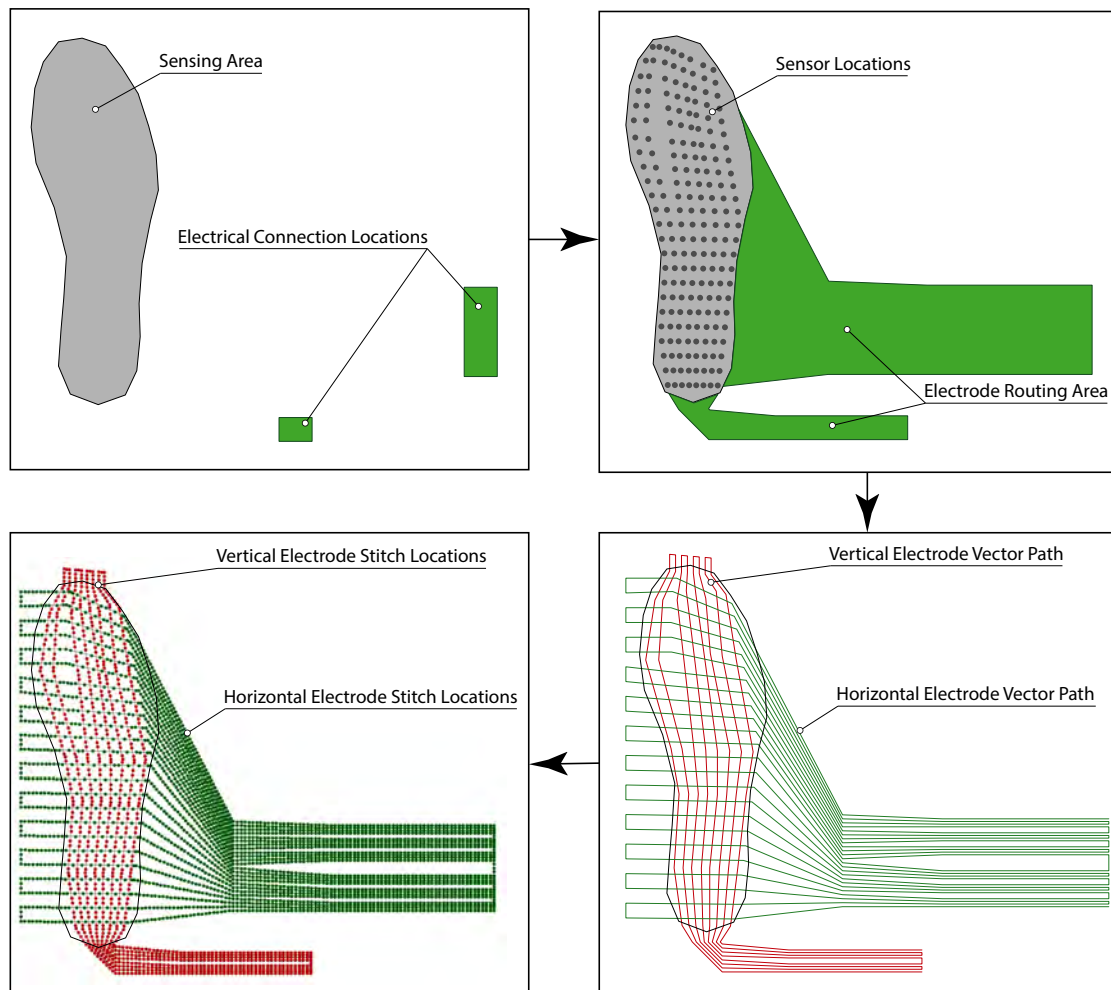


Figure 3-7: The layout process to create the embroidery file for a shoe insole tactile sensor.

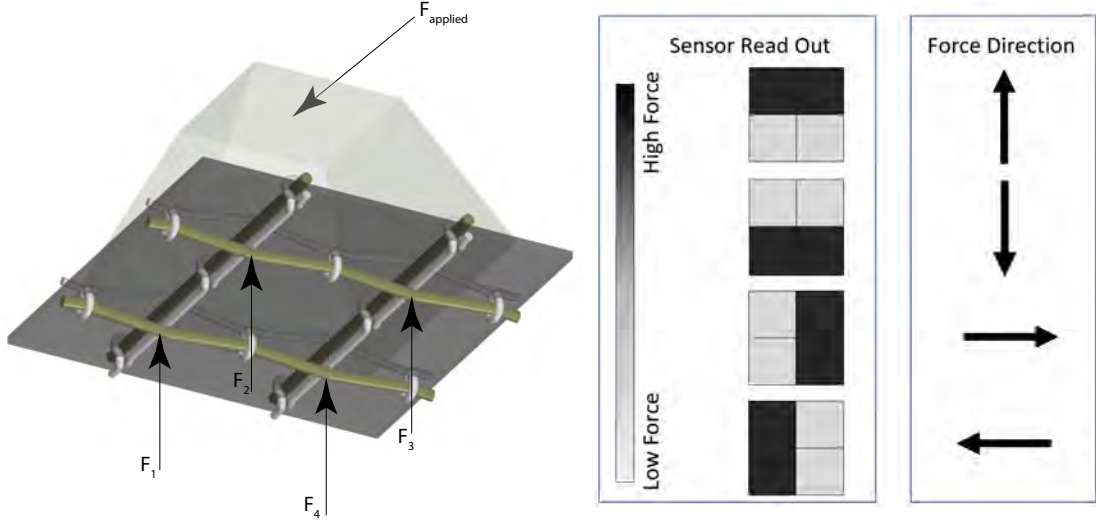


Figure 3-8: (Left) A force applied to a force translator and resulting force readings from four sensors located underneath. (Right) Example readouts from four sensor readings when a force is applied in the upwards, downwards, left, and right directions

block, as shown in Figure 3-8. During operation, a force vector of $F_{applied}$ is applied to the top of the force translator. The three components of the vector F_x, F_y, F_z can be computed from the readings from the four sensors below the force translator. To obtain the normal force F_z the readings from all four sensors can be summed. To obtain the x and y force components, the difference between the left and right, as well as top and down sensors can be taken. A geometric correction factor is applied to adjust for the size and thickness of the force translator. The matrix form of this calculation is shown in equation 3.1.

We manufacture the force translators using a fused filament 3D Printer (Onyx Pro, Markforged, Watertown, MA, USA). The calculations of the force vectors described in equation 3.1 rely on the assumption that the force translator is sufficiently stiff; to ensure this, we manufacture the force translators out of carbon fiber-impregnated nylon (Onyx, Markforged, Watertown, MA, USA). The size and dimensions of the force translator are determined by the overall size of the sensor array being fabricated. The force translators are affixed onto the embroidered tactile sensor by the use of double-sided tape (VHB(c) 4905, 3M, Maplewood, MN, USA).

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ -1 & 1 & -1 & 1 \end{bmatrix} = \begin{bmatrix} F_z \\ F_x \\ F_y \end{bmatrix} \quad (3.1)$$

3.2 Reading Methodology

Our multi-modal tactile sensor is a piezoresistive-based sensor array, meaning that the resistivity of each sensor changes when the applied force changes on that sensor as shown in Figure 3-9 Left. Each sensor is comprised of a force-sensitive film and two orthogonal electrodes. The force is applied to the film and the resistance between the two electrodes changes. This resistance measurement can then be correlated to a known force as shown in Figure 3-9 Right.

To take a reading of this resistance, we utilize a non-inverting operational amplifier circuit shown in Figure 3-10. The circuit uses an operational amplifier with a reference voltage supplied to the positive input of the op-amp. The force-sensitive resistor is connected between the negative input of the op-amp and ground. A gain resistor is attached between the op-amp's output and the negative input and can be changed to adjust the sensitivity of the reading circuit. The voltage is then measured at the output of the op-amp to read the change in the resistance of the force-sensitive resistor.

To create an array of these piezoresistive-based sensors we can create a set of these horizontal and vertical electrodes where as shown in Figure 3-11, the sets of electrodes run parallel to each other. To take a reading of one sensor, we can select the pair of horizontal and vertical electrodes that cross at a desired location. However, due to many other vertical and horizontal electrodes crossing paths with the selected set of electrodes, the resistance reading will include a large number of parallel resistance readings of other sensors, as shown in Figure 3-12. These other paths where current can flow will cause an error in the reading of the resistance of interest. To mitigate the error, we must isolate the parallel resistances from the sensor resistance of interest

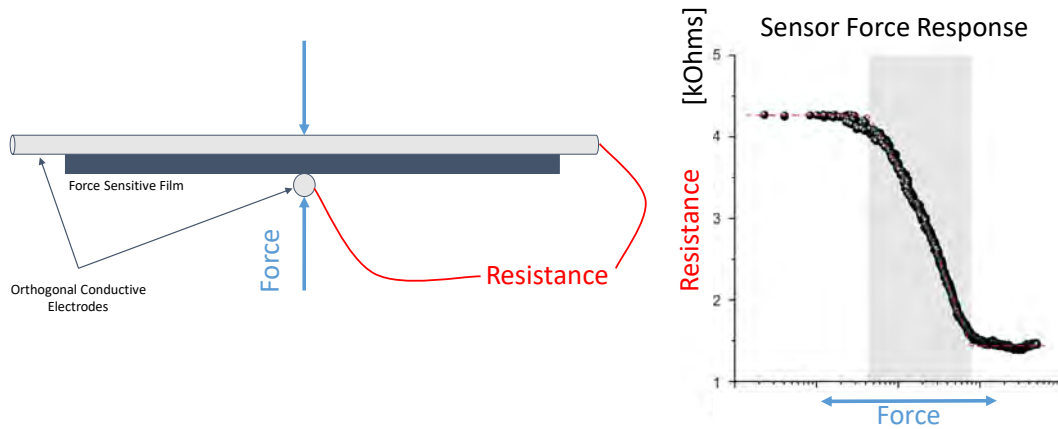


Figure 3-9: (Left) An example piezoresistive sensor. (Right) An example response curve from a piezoresistive sensor when a force is applied.

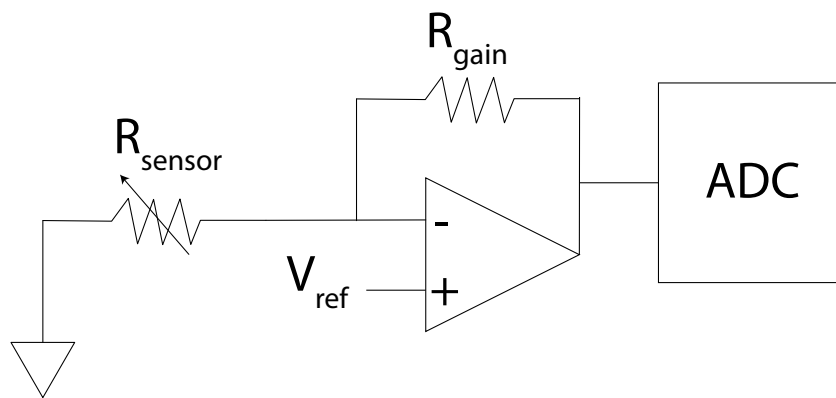


Figure 3-10: A schematic of the reading circuit used to read our piezoresistive sensor.

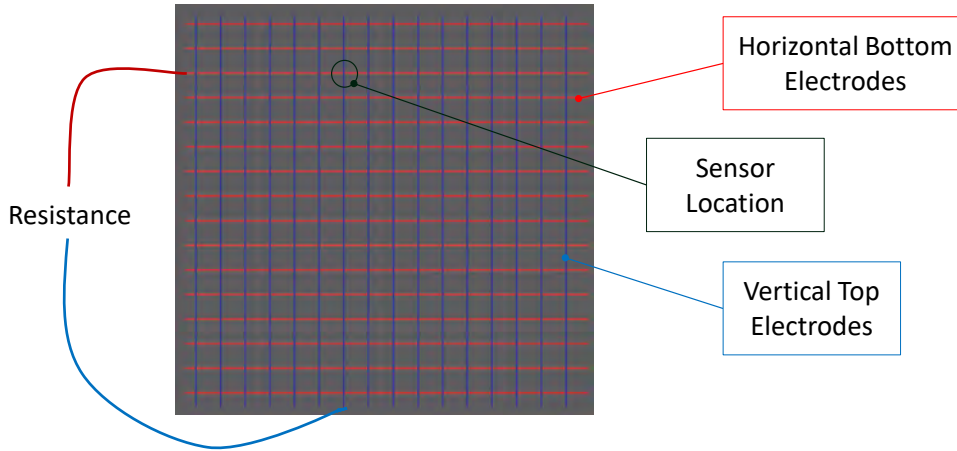


Figure 3-11: An example of how to take a reading from a sensing array.

to reduce the amount of cross-talk current.

We utilize an isolation circuit proposed by Shimojo et al to mitigate the amount of cross-talk current and only take a reading of the resistance of the one sensor of interest ?? . This isolation circuit utilizes a set of two-way switches attached to each horizontal electrode. When one horizontal electrode is used for the reading of a resistor, the switch for that row is set to ground, and all other rows are set to the reference voltage. This allows only the current from the reading circuit to flow through the resistor of interest. This isolates the resistor of interest from all the parallel resistances that cause the error.

3.2.1 High-Speed Readout Circuit

We implement our system based on a flash programmable gain array (FPGA) (Xilinx Kria KR260, San Jose, CA, USA). As shown in Figure 3-13, each column in the signal array has a digital potentiometer to set the gain of the signal, op-amp for signal conditioning, and an ADC. The signals controlling digital potentiometers and ADCs are implemented using the programmable logic (PL) part of the FPGA.

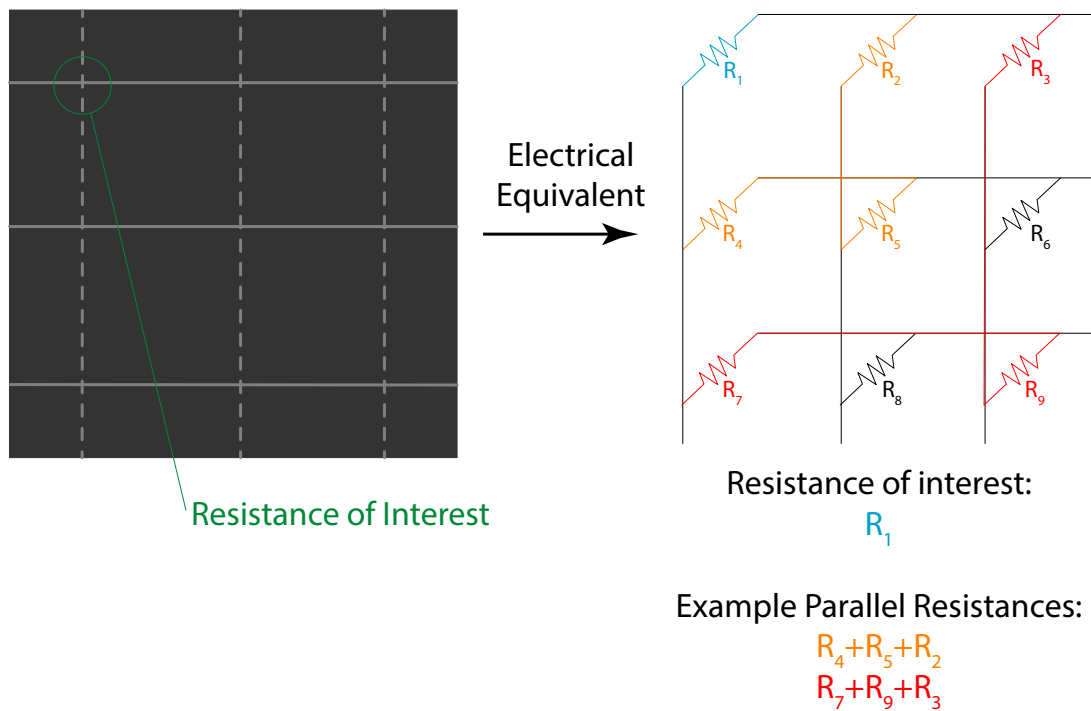


Figure 3-12: An example 3 by 3 piezoresistive sensor array and its equivalent. Blue shows the resistance of the sensor of interest. In yellow and red are example resistance paths that are in parallel with the resistor of interests cross-talk current will flow causing error.

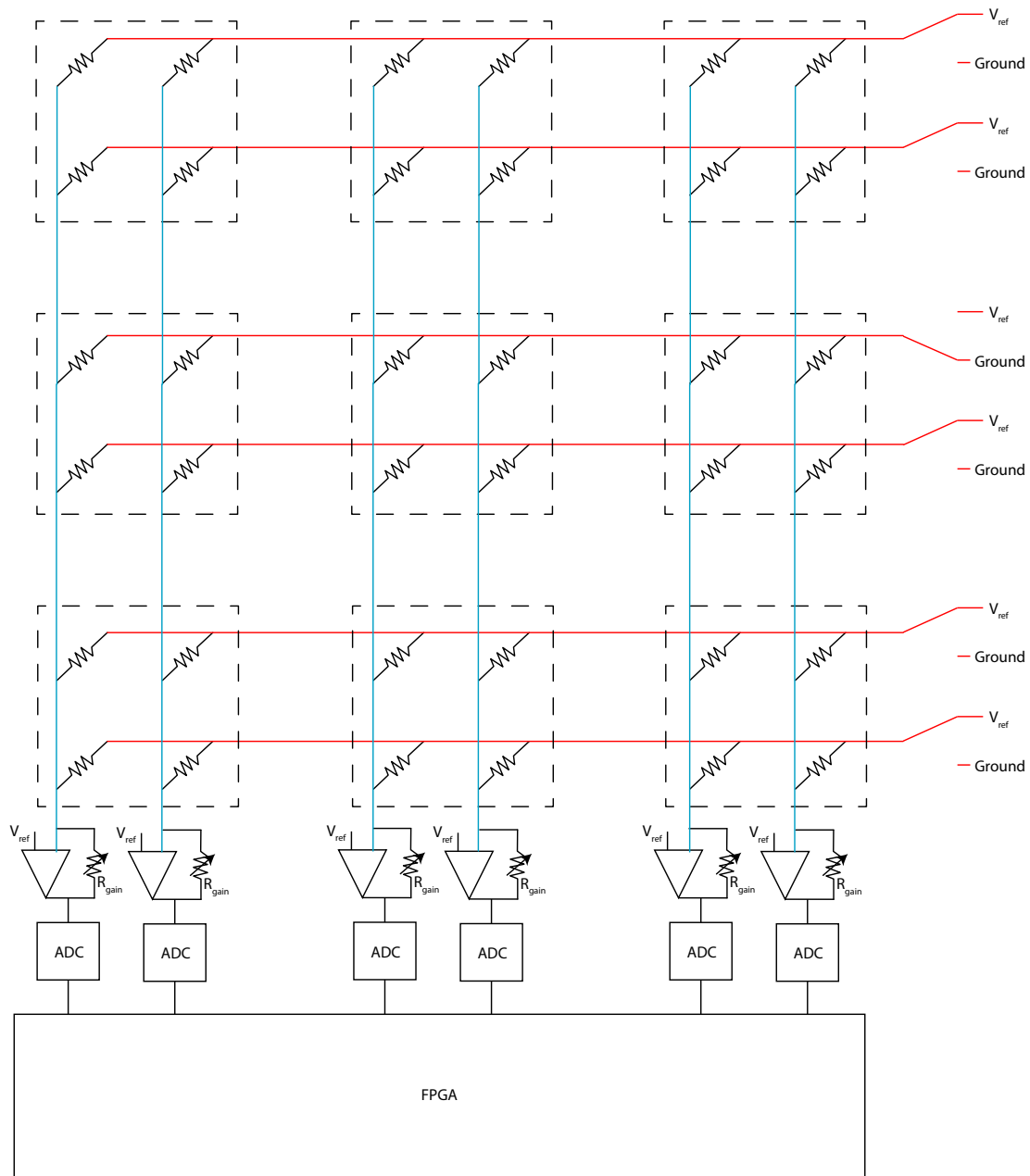


Figure 3-13: Schematic of our high-speed read-out circuit for an example 3 by 3 sensing array.

For each readout, we set the value of the digital potentiometers, select a row, and read the ADC output of all columns simultaneously. We then select another row and repeat the operations until it is finished. The data from ADCs is sent to a DMA controller using AXI-stream. We exposed control registers for setting ADCs sampling time, frame rate, and potentiometers with AXI-Lite. We use the ARM processing system of the FPGA based on Ubuntu for controlling AXI-Lite, DMA, and data capturing to flash memory or through Gigabit Ethernet.

3.2.2 High Dynamic Range Reading

We propose a method for fusing high-dynamic range (HDR) readings from several different tactile sensor arrays. Our method takes as input tactile readings from different [sensitivity] saturation tactile sensor arrays to recover a high-dynamic-range tactile map. As shown in Figure 3-14, to capture multiple readings with different sensitivities, we capture three consecutive sensor readings while changing the potentiometer resistances between each reading. We adopt the Debevec [11] HDR method for recovering the high dynamic range tactile map. Debevec method is originally proposed for reconstructing high dynamic range radiance maps from photographs taken with conventional imaging equipment. It takes as input several photographs with different exposures to compute the imaging response function. With the computed response function, the algorithm uses a weighted objective to fuse the input photographs together to form one high-dynamic-range image.

Directly employing the Debevec algorithm to reconstruct our HDR tactile map can be difficult for several reasons. 1) computing the response curve on tactile reading can be computationally expensive as our tactile readings are in 14-bit, which is much more fine-grained compared to image data which run in 8-bit format 2) it is unclear whether the linear weighting objective proposed in by original Debevec algorithm suits our task and purpose. To solve the first problem, we propose to conduct HDR fusion after calibration. As force magnitude and voltage gain differ per pixel, making the original response curve fitting infeasible. The algorithm directly works with force values and avoids response curve computation by applying HDR fusion after calibration. To

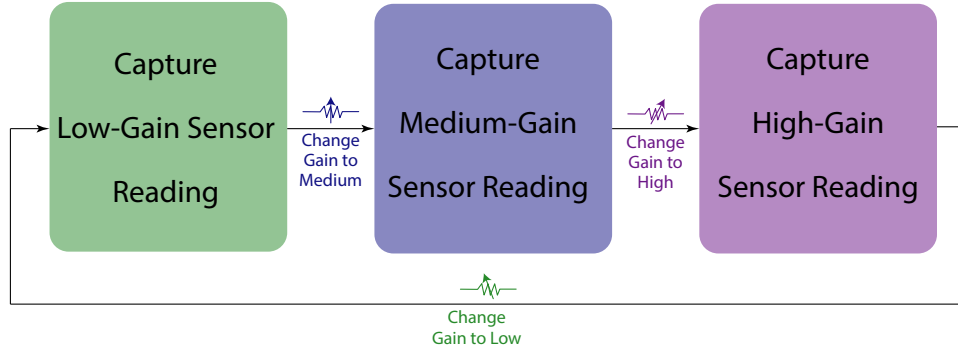


Figure 3-14: High-dynamic range capturing methodology.

encourage fast computation, we use local bin values per frame instead of all 14-bit across all frames, and HDR fusion is conducted per frame and then synchronized across frames. To tackle the second challenge, we experiment with various commonly employed weighting schemes, which shows that the skewed-linear weighting scheme works the best.

Chapter 4

Results

4.1 Sensor Characterization

4.1.1 Sensor Repeatability

To measure the repeatability over a long period of time, we cyclicly tested a single embroidered resistor. The resistance profile of a typical sensor unit is measured by a multi-channel datalogger (BK Precision DAS220, Yorba Linda, CA, USA) under a programmed normal force loading up to 6N at the speed of 2 mm/min (Shimadzu, Kyoto, Japan) with the contact area of 4 mm². A cycle test was performed with 1000 cyclic normal force load-unload (0-20N at speed 5mm/min). Three individual cycle tests are shown over the cycle test in Figure 4-1 Top. Figure 4-1 Bottom shows that over the period of tests, the maximum resistance only varied between 1.8 and 2 kohms.

4.1.2 Shear Sensing Performance

To measure the sensing performance under shear force, sensors attached to the force translator were mounted on the customized 3D-printed stands at angles of 15, 30, 45, and 60 degrees. During characterization, a normal force (up to 6N at the speed of 2 mm/min) was applied in the middle of the force translator, which generated both normal and shear force towards the sensing units. As shown in Figure 4-2, as the

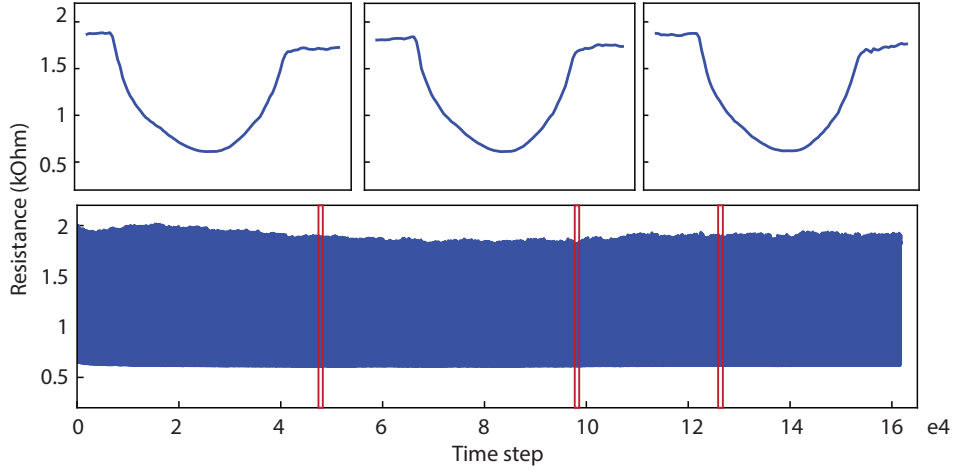


Figure 4-1: (Top) Three plots of resistance of one piezoresistive sensor during a cyclic compression test. (Bottom) Resistance of piezoresistive sensor over a 1000 cycle durations.

angle α increased, the separation between the resistances of s_0 and s_1 and s_2 and s_3 increased.

4.1.3 Vibration Characterization

To measure how well our sensors can measure a vibrating object, we mounted a modal shaker (2060E Modal Shaker, The Modal Shop, Cincinnati, Ohio, USA) on top of a 16 by 16 multi-modal sensing array. The modal shaker applied a vibratory force with a peak sinusoidal force of 60 pounds force that ramped linearly from 0 to 700 Hz over 60 seconds. We measured the piezoresistive sensor array readings using our high-speed readout circuit at a rate of 5000 frames per second. We then utilized the fast Fourier transform algorithm and plotted the spectrogram in Figure 4-3. The frequency can be determined up until 500 Hz.

4.2 Manufactured Sensors

To test the design and fabrication of our multi-modal tactile sensors, we manufactured a set of example devices for wearable and robotics applications. For wearable device

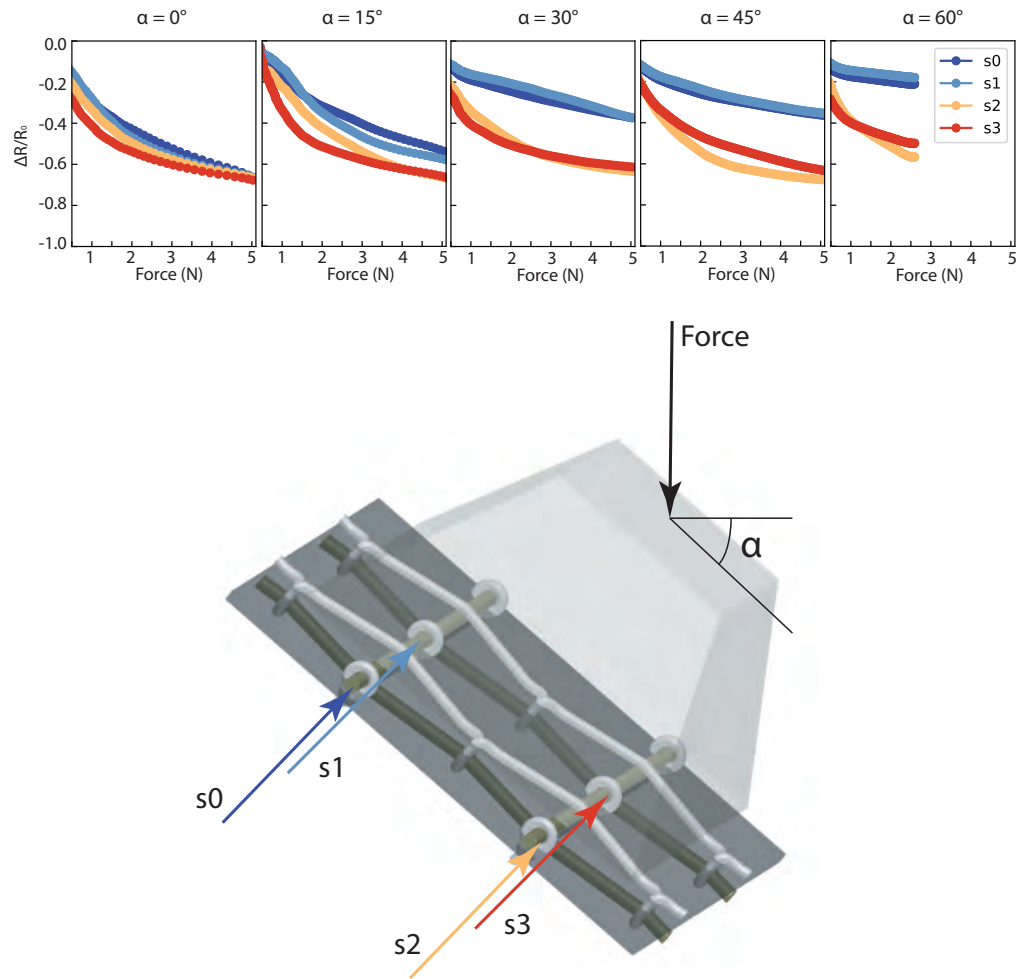


Figure 4-2: Resistance of piezoresistive sensors when force is applied at angles of alpha equal to 0, 15, 30, 45, and 60 degrees.

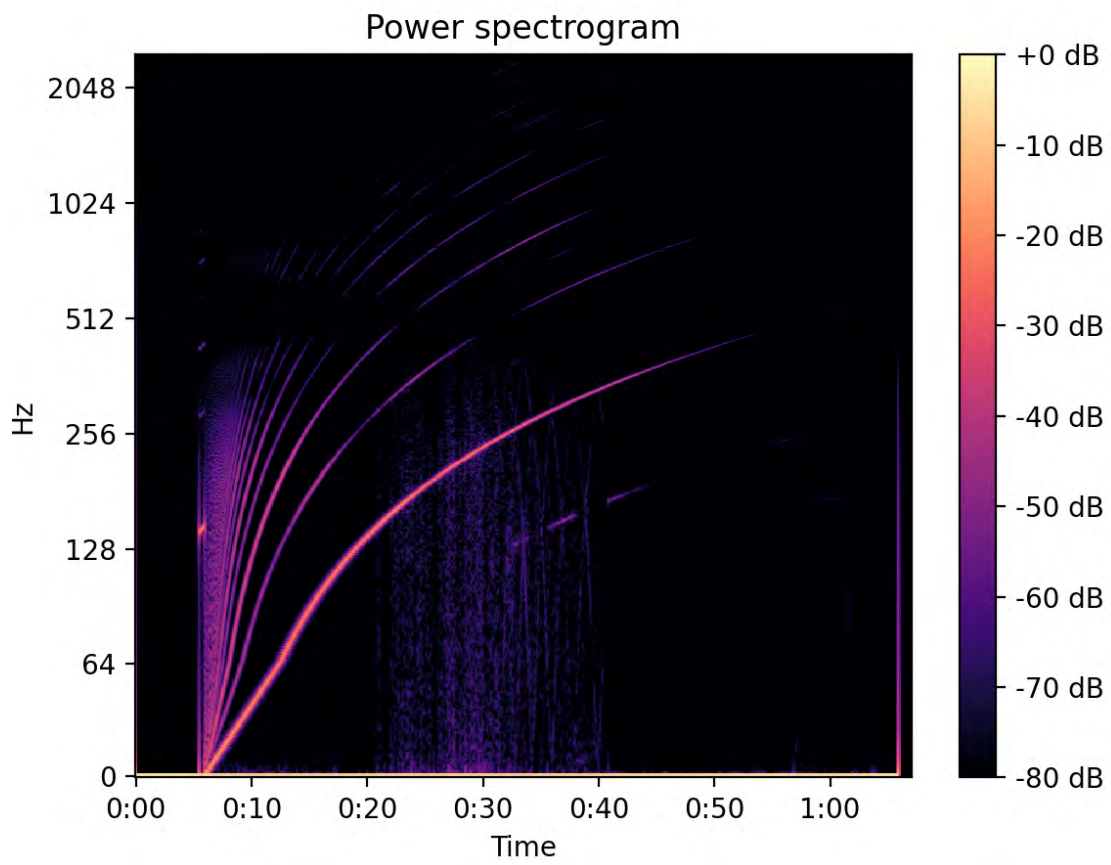


Figure 4-3: Spectrum of frequencies captured using our multi-modal tactile sensing array.

applications, we developed a tactile sensing insole with a form factor that is capable of being worn within a shoe while a user is standing and walking. Furthermore, for a robotics application, we developed tactile sensing grippers for a robotic hand. In the following section, I will describe the design and manufacturing process for each of these designs.

4.2.1 Wearable Insoles

We designed a set of wearable insole sensors that can measure the normal and shear force that a human applies while they stand and walk, as shown in Figure 4-4. The sensor consists of 48 (4x12) multi-modal sensors. The sensors are spread over an area of 55 mm by 280 mm. To design the sensor, we first laid out the sensor locations within the area of an insole that fits within our target shoe, as shown in Figure 4-5. Next, we create an embroidery file that would place the electrodes in the proper location. We also create a set of force translators that cover the entire area of the insole. Designs for the embroidered sensor and force translators are shown in Figure A-1 and A-2 in Appendix B.

4.2.2 Robotics Grippers

We also designed a set of robotic grippers that can measure the normal and shear force when a robot grasps and interacts with objects. We installed two multi-modal tactile sensors to each jaw on a parallel gripper (Robotiq, Levis, Canada) as shown in Figure 4-6. Each gripper is 48 mm by 108 mm and has 36 (4x9) multi-modal sensors on its surface. The sensor was laid out to attain the desired sensor density, and the electrodes were routed to connection points on the back of each gripper. Electrode layouts can be found in Figure A-3 and A-4 in Appendix B.



Figure 4-4: Images of our multi-modal tactile sensing insole.



Figure 4-5: Images of our insole sensor installed into a shoe.

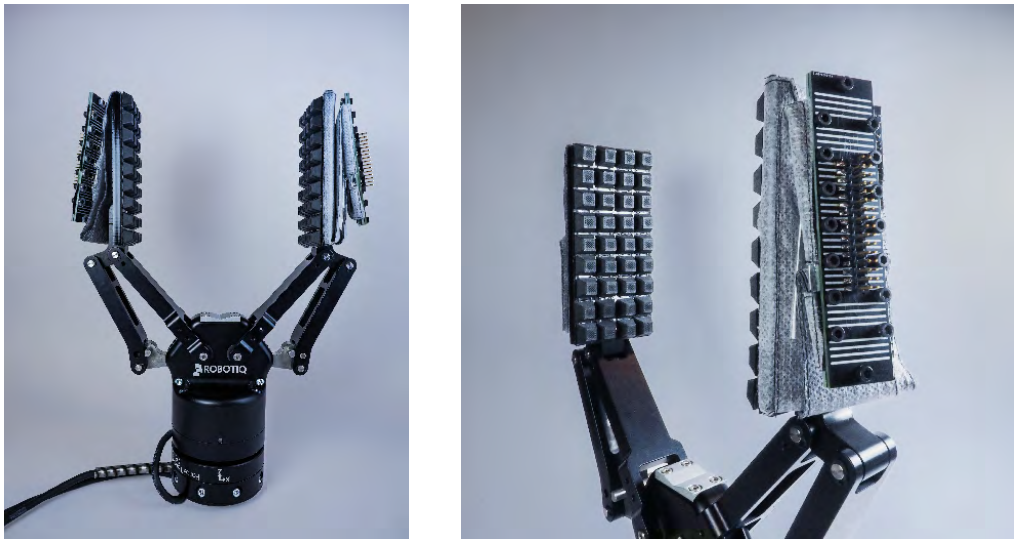


Figure 4-6: Images of our multi-modal tactile sensors attached to parallel grippers.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

This work presents a new multi-modal sensing array architecture that can be utilized to sense normal and shear forces. We also present a manufacturing process that is able to produce our multi-modal sensing arrays in a highly-automated and inexpensive fashion. Finally, we present a sensor reading methodology that enables high-speed reading that is capable of sensing vibrations and can also sense a wide range of forces. Finally, we demonstrate how these sensors can be used in wearable devices and robotics applications.

5.2 Future Work

There are a number of directions that could be taken to further improve the usability and performance of our sensors.

- We look further to improve our spatial resolution of multi-modal sensing systems. We foresee this giving us the capability to do small object classification. We plan to find modifications to our manufacturing process or look into other manufacturing processes that can attain higher spatial resolution.
- Currently, our sensors cannot cover surfaces with complex geometries, like hu-

man hands or other surfaces with double curvature. We plan to investigate other methods to cover more complex surfaces in the future.

- Humans also have the ability to sense other functionalities like temperature, surface texture, and moisture. By including other resistive films that are reactive to these environmental changes, we can include these modalities in our design. In the future, we plan to develop and test new materials that are capable of incorporating these sensor modalities.

Appendix A

Figures

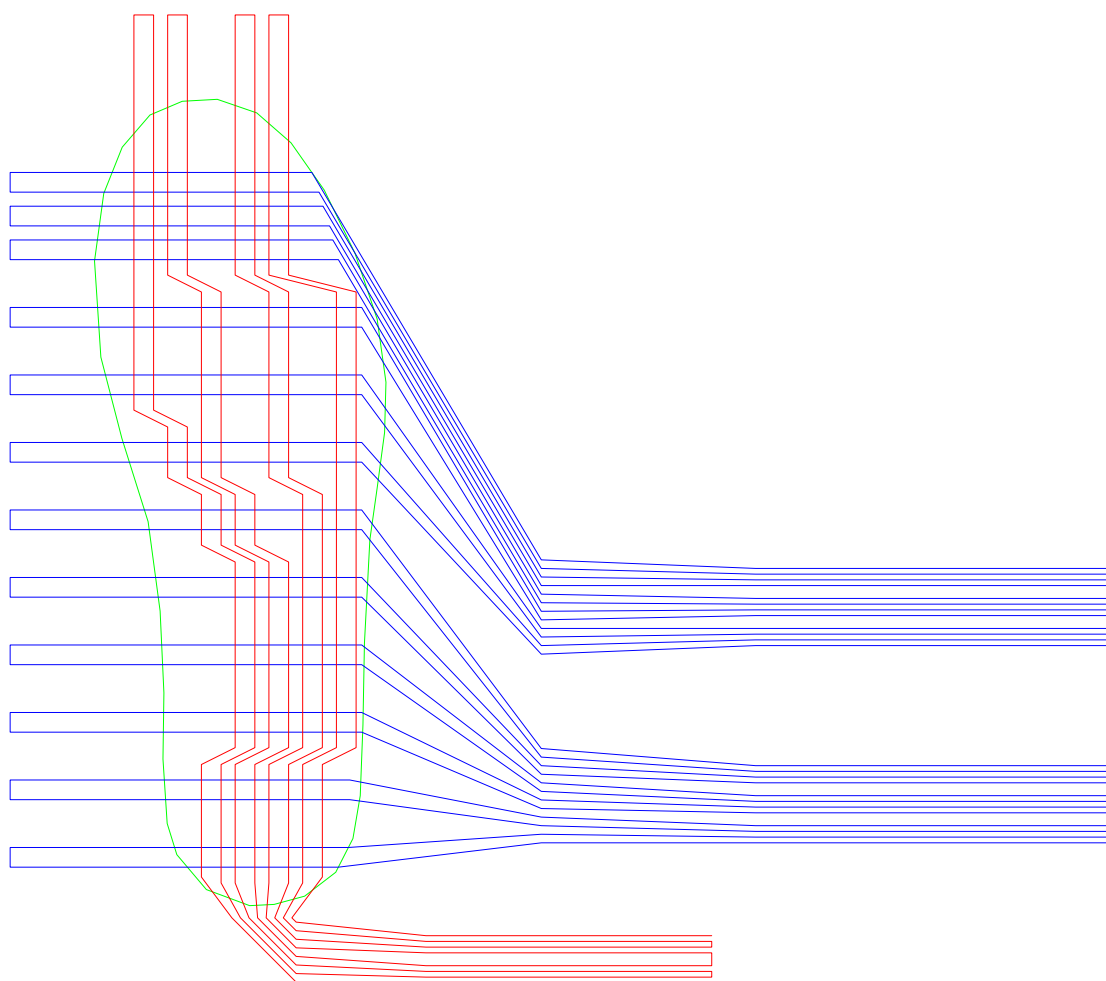


Figure A-1: Vertical (red) and horizontal (blue) electrodes of the insole sensor.

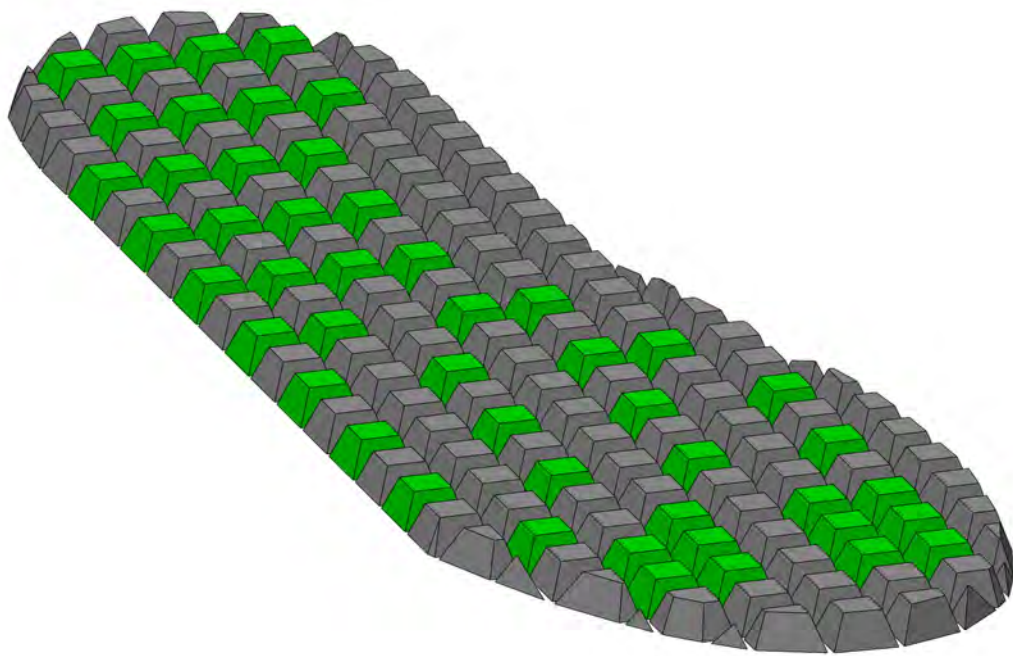


Figure A-2: Force Translator model for the tactile sensing insole. Force translators with active sensors are shown in green

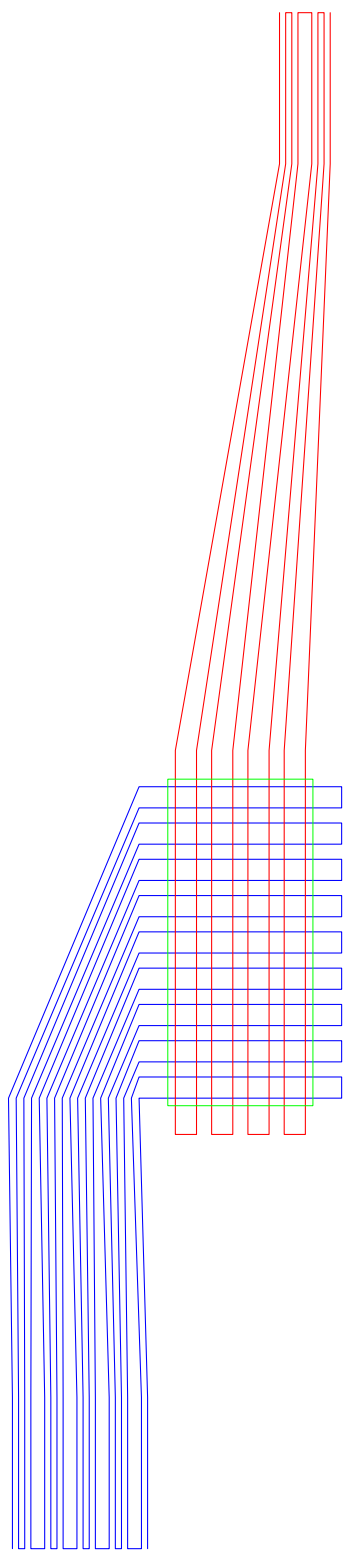


Figure A-3: Vertical (red) and horizontal (blue) electrodes of the gripper sensor.

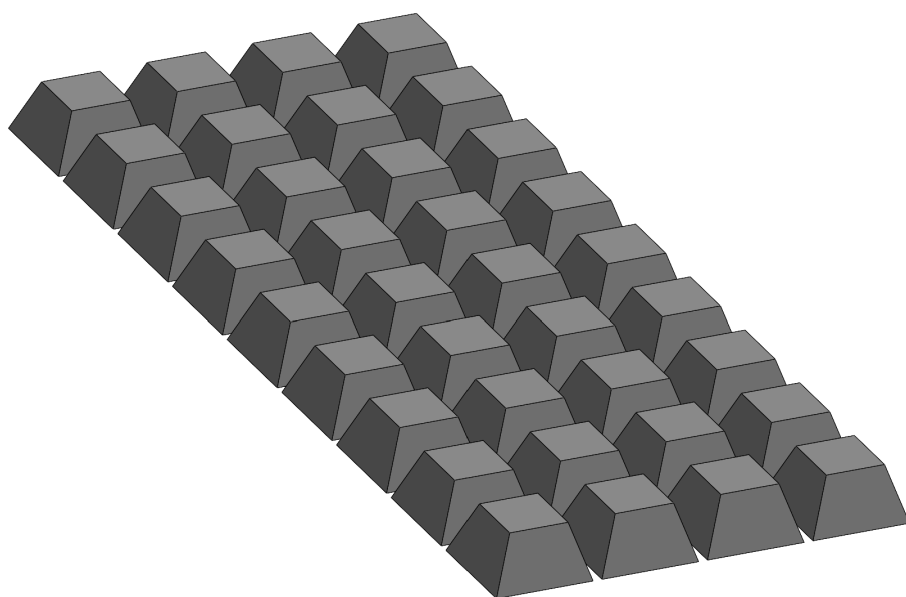


Figure A-4: Force Translator model for the tactile sensing gripper.

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