AC 2011-2535: DESIGNING DEVICES TO HELP THE DISABLED

Saeed B. Niku, California Polytechnic State University

Professor of Mechanical Engineering at Cal Poly since 1983, author of many papers in robotics, design, engineering eduaction and others, author of two textbooks, 1) Introduction to Robotics: Analysis, Control, Applications”, Second Edition, Joh Wiley and Sons, 2011, 2) Creative Design of Products and Systems”, John Wiley and Sons, 2009. Two patents on Flexible Fasteners.

Ross James Miller

Designing Devices to Help the Disabled: Artificial Skin Tactile Sensor for Prosthetic and Robotic Applications

Abstract

A number of devices have been designed and developed to help disabled individuals. In one case an artificial skin tactile sensor, a stretchable, deformable substrate populated with tens of piezoelectric sensors, was developed to aid in the design of prosthetic devices and robots. A circuit, including multiplexers and a controller, sequentially reads the signals from the piezoelectric sensors and plots or reports them. These signals may be used in prosthetic and robotic applications. An immediate application of the skin sensor is in the design of artificial hands and limbs, helping injured veterans.

Introduction

Prosthetic devices, robots, and even toys are commonly integrated with simple touch and tactile sensors of varying degrees of sophistication. An ultimate prosthetic device should function like a human limb, with sensory input that allows the user to perceive touch, the force exerted, and the shape and the feel of the object (temperature, texture, weight, and so on). The device may be physiologically integrated with the central nervous system through nerve endings and communicate directly with the brain. However, in the current state of the art, this is not easily achievable. Therefore, a sensor that can be integrated with the device that functions as a skin sensor may be very useful. The sensor may be shaped to mimic the human skin with its texture, color, and exact shape. If the skin is populated with a large array of touch sensors, a flexible tactile skin sensor can be developed. Although this sensor does not communicate with the brain or the central nervous system, nonetheless the information it provides can be used in a variety of forms to aid the user.

Similarly, a tactile sensor that provides almost-continuous information about an object, forces involved, and shapes, can be used in many robotic applications, including haptics and animatronics applications. This can be extended to advanced toys that can react to human touch and behave accordingly.

In this project, stretchable, deformable, tactile sensors were developed to provide a large array of sensory information that may be used by a microprocessor for other applications. The skin can be formed into any shape and size, from a human finger or hand to the skin of a teddy bear to an artificial robotic hand (Figure 1). The prototypes contain a large array of sensors that read the force exerted on each sensor sequentially and report back to a microprocessor. The skin can be stretched, bent, shaped, or cast into any shape. A large number of sensors can be integrated into the system as well. In this project, piezoelectric sensors were used, although other sensors may be integrated into the system in a similar manner.

Figure 1: A cast human thumb skin sensor. (Courtesy of Dr. Robert Erb. Made from vacuum-forming 7 layers of silicone foam with detailed painting between coats to match human skin.)

The Educational Objectives

This project was performed as a Masters thesis, and therefore, it was assessed through a written thesis[1] and an oral defense. It was deemed appropriate for this purpose due to its complexity and the need to research methods for construction of the sensors and the substrate, and to develop the design. However, with the accumulated knowledge, it is possible to use this idea for further development as a senior project, individual projects, group projects, or in-class projects.

In senior design classes where each group works on a different project, the artificial skin idea may be assigned to one group of students to further develop and test varied designs of this system. New methods, sensors, and material may be used.

In classes where all teams work on the same idea, the artificial skin project may be assigned to all teams and the results may be assessed competitively. In this case, each team competes for the best results, and therefore, must keep its designs confidential until revealed at the end. Cross pollination of ideas will not occur, but it simulates the real-world relationship between competitive businesses.

The artificial skin idea may also be used for individual projects, extra-curricular projects, or in conjunction with other projects such as robotics, biomechanics, and many others.

And finally, the idea may be applicable to class projects in instrumentation labs. This may occur at different levels, depending on the type and the level of the lab. For example, the project may be a full-term project, with the following tasks divided into individual labs: the development of the skin substrate; the manufacture of the sensors; integration of the sensors and the skin; construction of the required circuitry; integration of the microprocessor control with the controller and the sensors; development of computer interface; and the testing of the system. Alternately, each part of the project may be assigned to a different team, having to work with each other and communicate their required specifications, deadlines, and results.

The following sections describe the different elements of the system.

The Skin Substrate

A material called Dragon Skin® that is a high-performance platinum cure silicone rubber was chosen as the substrate. This two-part silicone rubber material can be cast, brushed, thickened, and shaped to almost any desirable shape. Mixing an equal ratio by volume of parts A and B creates a material with a Shore A Hardness of 10, tear strength of 102 pounds per linear inch and a possible elongation of up to 1000%[2].

By adding a third equal part of Slacker® Tactile Mutator, a silicone rubber can be made which is softer and more "flesh-like," with rebound properties. Additionally, by adding a small quantity of Fleshtone Silc Pig® Silicone Pigment, a very realistic flesh-colored specimen can be made.

In most cases, a prosthetic device may be made of a highly durable yet soft silicone rubber which is designed for prolonged use under normal conditions. The prosthesis is capable of simulating both the texture and the look of human skin. It can feature both major and minor wrinkles (including fingerprints), be hand-painted and tinted to differing shades of skin pigmentation in order to blend with the surrounding anatomy, and can even be implanted with hair[3].

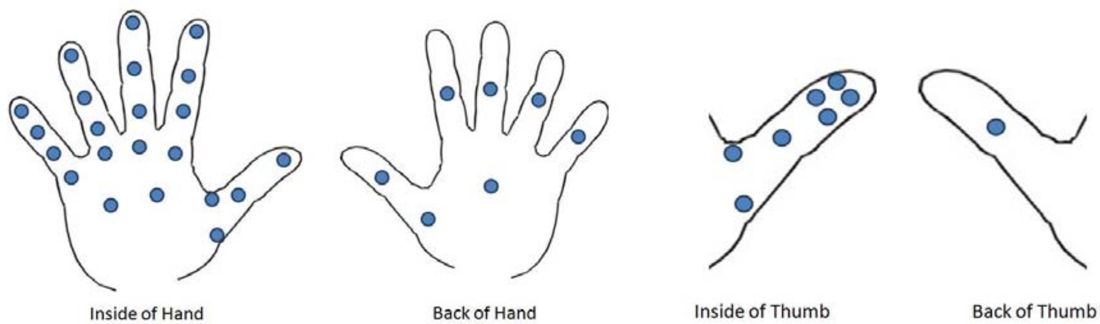
To create a realistic looking glove in which to embed the sensors, a mold of a hand was made using Alja-Safe molding gel. Subsequently, liquid casting plaster was poured into the mold which resulted in a positive plaster hand. By pouring silicone rubber over the cast, a skin-like glove replica of the person's hand was formed. Additional layers of the silicone thickened the glove into a useful shape for ensuing steps (Figure 2).

Figure2. Silicone Rubber Glove

The Force Sensor

Many different types of sensors were considered for this purpose, including capacitive, optical, fluidic MEMS, as well as piezoresistive and piezoelectric sensors. Ultimately, we selected piezoelectric sensors for their versatility, apparent ease of use, lower cost, availability, and the fact that many small sensors could be embedded into the silicone skin with relative ease. However, we decided to manufacture our own piezoelectric sensors from piezo ceramics, 1/8 inch in diameter and 0.0075 inch in thickness. To measure the voltage difference across the sides as a piezoelectric sensor, one only needs to attach a wire to each side of the ceramic.

In this experiment, two prototypes were developed: A hand and a thumb. The hand prototype has 30 sensors, as shown in Figure 3(a). Although many more sensors could theoretically be implemented using the electronics design described later, 30 sensing points on the hand were deemed an acceptable level of resolution without overcomplicating the manufacturing process. The thumb prototype has 8 sensors, as shown in Figure 3(b).



(a) (b)

Figure 3: Location of the sensors within the hand and thumb prototypes.

It should be mentioned here that manufacturing the individual piezoelectric sensors in the lab turned out to be more difficult and time consuming than expected. Extreme care must be taken to keep the ceramic free of dust and oils, and the soldering must be clean and uniform and not damage the ceramic. If many sensors are to be made, a jig to hold the ceramic in place while wires are soldered can be a huge advantage. Still, due to manufacturing variability, many sensors respond non-linearly or collect stray charges and respond inappropriately. In our experience, about 30% of manufactured sensors responded acceptably. Therefore, although significantly more expensive, it is recommended that factory-made sensors be used instead of soldering wires to piezo disks.

To plant the sensors, the silicone rubber glove was placed inside-out over the plaster casting of the hand which served as a working platform. One at a time, sensors were placed onto their correct location and held in place using a small amount of rubber cement or silicone glue. Once a number of sensors were in position, a coat of silicone rubber was poured onto the glove and allowed to dry. In subsequent steps, additional sensors were placed in their correct position, and again covered with a coat of silicone rubber. Lastly, an ample amount of baby powder was applied to the completed hand to coat the silicone and provide a smooth surface for a user’s hand. Figure 4 shows two steps of the process. Please note how the connecting wires were zigzag-shaped to allow stretching and deforming of the skin without tear. The inside-out glove can then be turned right-side out.

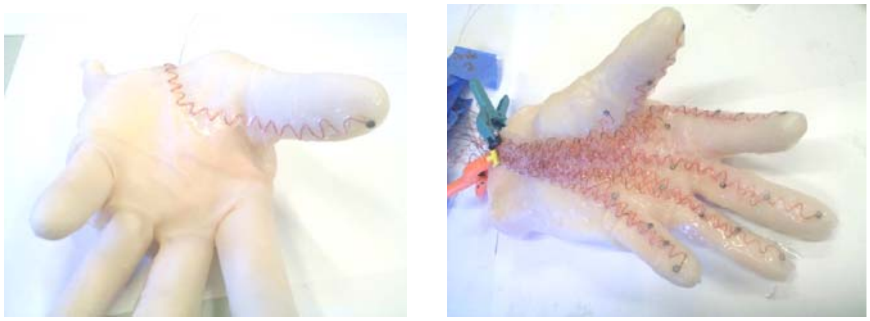


Figure 4: Embedding of sensors onto the prototype skin. Zigzag wire connections were used to allow the stretching and deforming of the skin sensor.

Electronic Interfacing

The output signal of each sensor must be sampled, digitized, and read/recorded by a microprocessor. If each sensor were to be connected directly to the microprocessor for continuous measurement through an analog-to-digital converter (ADC), a tremendous number of input ports would be required. To sample and read the outputs of the piezoelectric sensors in large quantities without requiring too many input ports, it is possible to sequentially sample and record the output of each sensor, one at a time (for the microprocessor we used, as will be discussed later, reading each sensor plugged directly into an analog input port would be sequential. The board features a single analog-to-digital converter that uses a multiplexer to sample one of the 16 analog inputs at a time). However, if this is done at an acceptable rate for acceptable resolution, the data collected can be nearly continuous, and therefore, adequate. In our prototype, the time required to sample and digitize one sensor was about 2.2 ms. Therefore, the hand prototype with its 30 sensors was completely sampled once every 66 milliseconds (nearly 15 times a second) and the thumb with its 8 sensors was completely sampled and read once every 17.6 ms (nearly 57 times a second). With improvements in the program, the rate can be further increased.

To do this, each sensor was connected to an op-amp (or two sensors connected to a TLE032 dual op-amp chip). For the hand prototype with its 30 sensors, 15 op-amps were required. Each op-amp requires a power and a ground line from the microcontroller, the correct feedback line to create the voltage follower circuit, and output connections. The output lines from the op-amps were fed as input to a multiplexer. There are 16 pins on a 16:1 analog multiplexer; however, one pin was grounded and read as well in order to make sure the signal was cleared. Therefore, only 15 pins were available for sensory signals. By sending a signal from the microprocessor to the multiplexer, it sequentially reads one sensor at the time before moving to the next one. Therefore, each 15 sensors require one data line into the microprocessor. At only $5 a piece, with a 10μs delay required between channel switches, multiplexers are a very affordable method of quickly reading a large number of sensors[4].

In fact, fifteen multiplexers can be connected to another multiplexer that sequentially reads them. Therefore, conceivably an enormous number (15^{13}) of sensors can be read using a cascading multiplexer scheme. It is important to note though that this scheme would also require a huge number of multiplexers (15^{12}) and the sampling rate would be extremely compromised.

Figure 5 shows a simplified diagram of the system for two sensors only. Figure 6 shows the complete prototype. For the thumb wiring, the exact same configuration was used, where only 4 op-amps and one multiplexer were required.

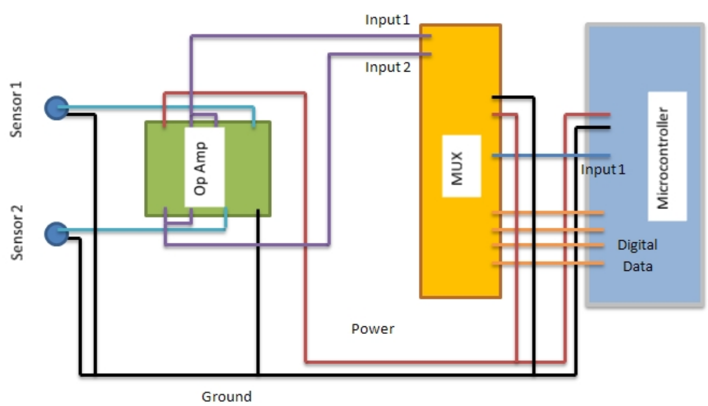


Figure 5: The simplified diagram of the electronics for two sensors only.

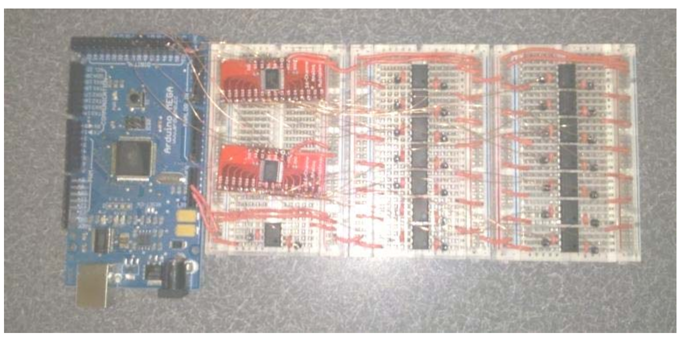


Figure 6: The complete electronic interfacing for the hand prototype.

The Microprocessor

We selected an Arduino Mega microcontroller board for this prototype. Based on the *ATmega1280* microchip, it runs on a 16 MHz crystal oscillator and has 54 digital input/output ports and 16 analog inputs[5].

Interface Design

Figure 7 shows a flowchart of the structure of the basic program. The multiplexer channel is set, the value of a sensor is read, the result is displayed, and the channel is changed for the next reading. The process continues until stopped.

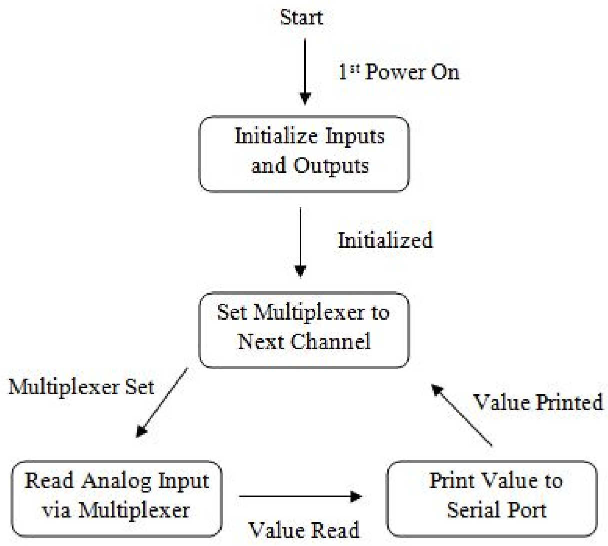


Figure 7: Simplified flowchart of the program used to smaple and display the results.

The open source programming language and environment used is called *Processing*. It was used to create a program that controls the process of reading the data and displaying it in real-time. A graphical user interface (GUI) was developed to display the results, as shown in Figure 8. The GUI displays the location of each sensor and the force value in a color-coded display and barcodes.

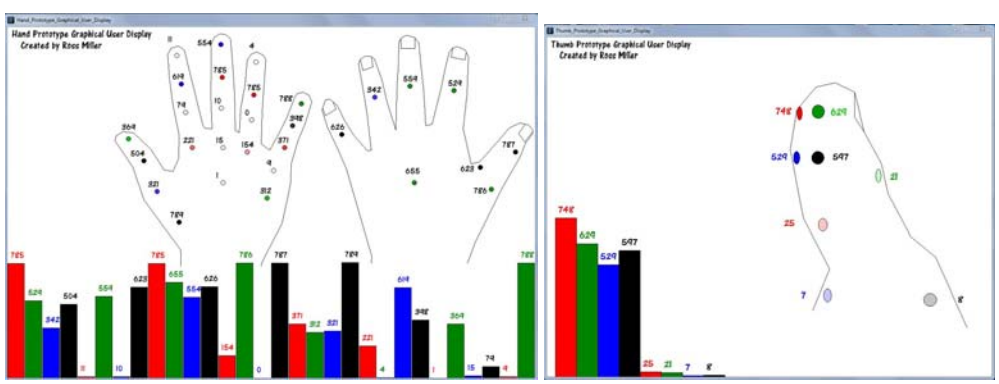


Figure 8: A typical graphical user interface display for the glove and thumb prototypes.

Testing and Results

Much work was performed to learn how to best create sensors from piezo ceramics by soldering wires, and to quantify their response and calibrate them. Unfortunately, only about 30% of the manufactured sensors responded satisfactorily. It should be emphasized here that factory-assembled sensors respond significantly better than lab-fabricated samples; therefore, if funding is available, it is highly recommended that already-assembled sensors be purchased. Figure 9 shows a typical response of a sensor when a force is applied and the voltage between the two sides is measured. In this figure, "Max" represents the maximum voltage from the positive spike when a load is applied, while "Min" represents the minimum voltage from the negative spike, when the load is removed. Figure 10 shows a typical response of a sensor when the signal is read by the microprocessor through the ADC input line while one side is grounded. Notice that if one side of the piezo is grounded, only positive signals are received, as shown in Figure 10, as compared to Figure 9 where a voltage difference is read between sides, resulting in both positive and negative signals

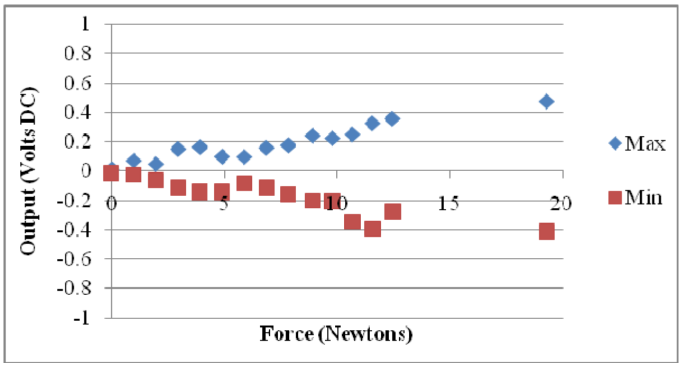


Figure 9: A typical voltage difference between the two faces of a sensor when a force is applied and removed from the sensor.

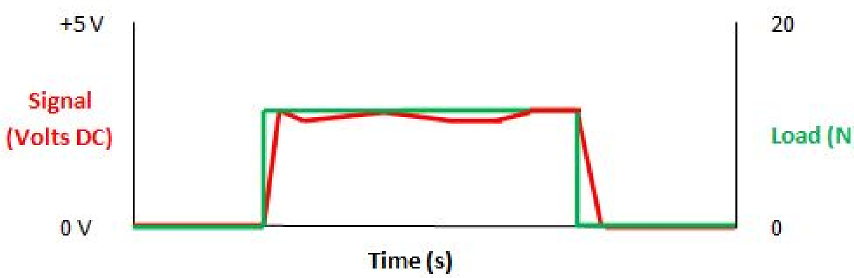


Figure 10: A typical response from the sensors when read through the microprocessor's ADC input line while the sensor is grounded at one end.

Figure 11 shows the thumb prototype worn by a user. Since the addition of the sensors reduced the internal volume of the thumb, the tight fit caused the sensors to register a force even when there was no external force applied to the sensors. Therefore, the initial sample must be made larger to avoid this problem.

With both prototypes completed and connected to their electronics, testing was conducted on both. As mentioned earlier, some of the piezo sensors did not respond as well as expected. However, all sensors responded and the GUI showed the results clearly. Although not a goal of this project, this information could subsequently be used for other purposes such as controlling the prosthesis, control of a hand of a robot, or signals for animatronic reactions.

Figure 11: The thumb prototype worn by a user.

Testing was also done on the prototypes to ensure that they could indeed be stretched and manipulated without causing damage. Figure 12 shows how the thumb prototype was stretched about 75% without any damage. The zigzag-formed wires can easily deform without tearing.

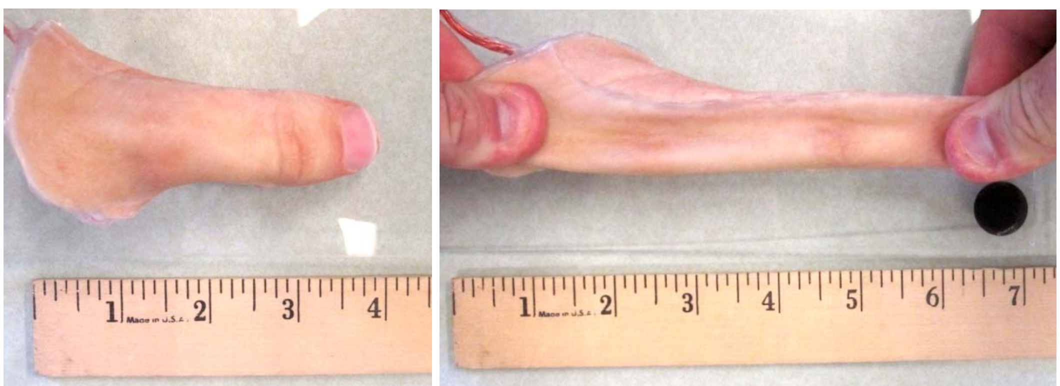
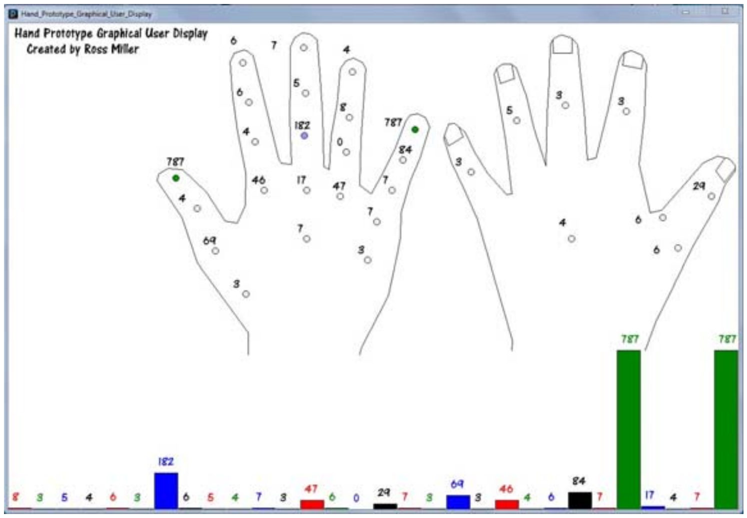


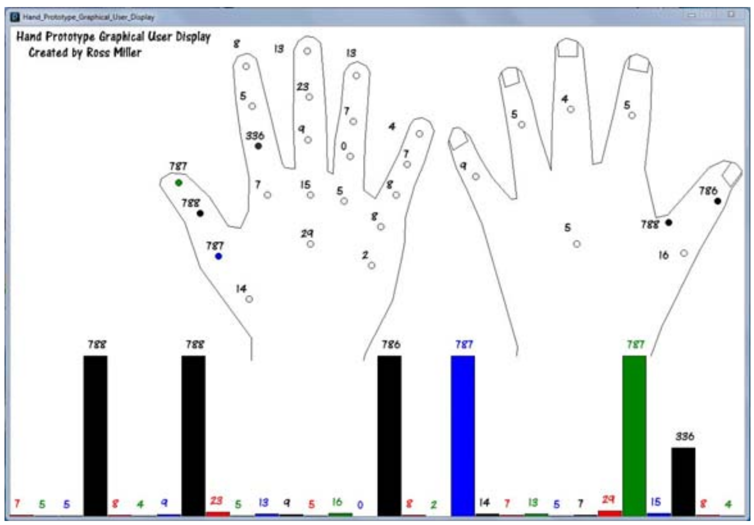
Figure 12: The thumb prototype is stretched 75% without damage.

Figure 13(a) shows the display when the tip of the thumb and the pinky finger are touching. Several other sensors, such as the middle of the pinky and the base of the thumb, experienced small forces, likely due to bending in the silicone rubber glove. When the prototype was gripped around the thumb, as shown in Figure 13(b), nearly all of the sensors embedded around the thumb showed a strong force applied.

Figure 14 shows the result of gripping a cup with the glove prototype. The GUI display shows that an applied force is being read by many of the interior sensors on the fingers. Not only does this allow for detailed information regarding the type of object being held, it could also be used to adjust the grip. For example, both the tip and base of the ring finger are experiencing no force. Therefore, the ring finger could be closed more tightly in order to provide a more even grip on the object.



(a)



(b)

Figure 13: The response of the sensors when (a) the thumb and the pinky touch and (b) when the thumb was gripped.

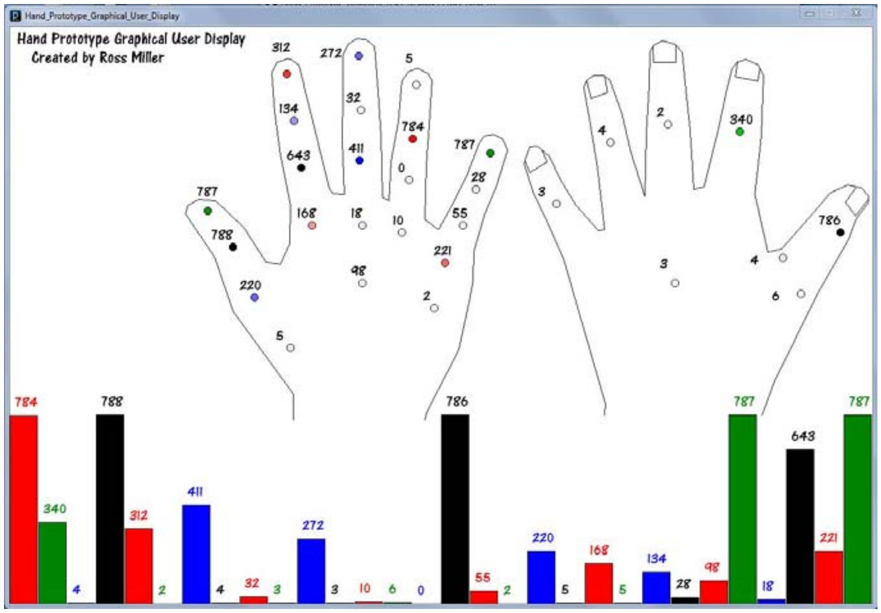


Figure 14: The GUI showing the result of gripping a cup with the prototype.

Further Research and Development

The prototypes were hampered by the piezoelectric sensors’ propensity to pick up stray charge. This remains the most significant area where more research and testing is required, as eliminating stray charge from the sensor readings must be done before the sensors can function in real-world applications. Several solutions were attempted, but none were completely successful. Possible fixes might include coating the piezoelectric sensors in a static-free case prior to embedding them in the silicone rubber, or purchasing commercial piezoelectric sensors that have overcome this problem.

Conclusions

Benefiting from the advances made in electronics, current research is developing the next generation of electromechanical prostheses. These prostheses have the potential to return the use of limbs to people who have lost them. Advanced tactile sensors might also one day return the sense of touch to those who have lost it.

Also with robots becoming ever more common in society, the need for cost-effective tactile sensors is greatly increasing. By combining tactile sensors with other sensors commonly used by robots to navigate their environment, the variety and quality of tasks performed by robots will greatly increase, enabling them to act as capable human-companions or aides. In order for these robots to be accepted into society, perform the types of tasks that humans do, and to use the same tools, they will need to look and perform similarly to humans; sense of touch makes this more plausible. This project was a step in this direction, creating an elastic tactile sensor with a realistic look.

Acknowledgements

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