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DEPARTMENT OF MECHANICAL ENGINEERING

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BIOMECHANICAL ROBOTS

Instructor: Dr. Carlos Castro

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Assignment #1

Design and Fabrication of Tactile Sensor for Humanoid Robot Applications

By

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ABSTRACT

I designed a tactile sensor for unstructured hominoid robotic application using a combination of 3 transduction methods. The tactile sensor consists of two systems: the tactile sensor unit that measure force and temperature and the haptic feedback unit that displays the force/temperature information gathered into visual feedback. The goal was to integrate the desired sensors into a small module that could be used as a “finger”.

The tactile sensor unit consists of three types of transduction sensors. First, a force sensing resistor (FSR) is used to measure the direct pressure applied on the face of the finger. An inductive sensor, created using a hall effect sensor and magnet, measured the deformation of the finger to add a redundant method of measuring the force. Lastly, a thermistor is embedded under the skin of the tactile sensor to measure the temperature of the object that the finger is interacting with.

The haptic control unit transforms the detected force measurements into visual feedback for the user. A LED matrix is used to provide the visual feedback. The amount of led illuminated is proportional to the magnitude of force detected by each sensor. The color of the led also changes based on the temperature of the interactive object.

Overall, the system works as designed. Using sensor fusion to better the accuracy of the two force sensors the finger can detect forces between 40 grams to 1000 grams. The system does show an average deviation of 12 % of the measured force compared to the know force applied to the sensor. The temperature sensor is relatively accurate, only being +- 2 degrees of true measured temperature. However, the temperature sensor does take a relatively long time to detect the objects temperature due to the thermal resistance of the foam it is placed in. The haptic sensor works as intended and can visually show the percentage of load each sensor is actively experiencing and while changing the color of the lights based on the temperature measured.

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1 Introduction

1.1 Humanoid Robotics

Industrial robots can be found in many industries today, ranging from manufacturing to entertainment. In these applications most robots are programed how to complete specific tasks while operating in premade environments. These workspaces made specifically for robots to operate in are called structured environments. Modern industrial robots are very limited compared to humans who can operate in a vast variety of environments while performing a vast variety of complex tasks. Humanoid robots are attempting to bridge the gap between industrial robots and humans. These machines are inspired by human biology and are designed to interact in unstructured environments. There is a wide range of humanoid robots being developed, each addressing the shortcoming of current industrial robots in different ways. Humanoid robots are designed to have improved the dexterity, locomotion, sensory feedback and intelligence that the commonplace industrial robots currently lack.

1.2 Tactile Sensors

As humans, we utilize our five senses of vision, touch, taste, smell and sound, to experience and interact with our environment. Exploiting one or more of these senses, we successfully interact and adapt to unstructured environments. Humanoid robots use a wide variety of sensor types to give them similar senses as humans. This includes standard cameras, three-dimensional (3-D) cameras, microphones, radar, force and pressure sensors to name a few examples. Vision and touch are the two areas most humanoid robot development is focused in. However, it is the sense of touch that has the greatest level of influence when manipulating and interacting with objects. Sensors specifically designed for touch are called tactile sensors.

Tactile sensors are a category of sensors that acquire tactile information through physical interaction with the environment. (Mohsin I. Tiwana, 2012). Tactile sensors are comparable to nerve endings in the human skin and their task is task to measure similar stimuli, as with humans and the sense of touch. This includes temperature, vibration, hardness, texture, shape, position, shape, weight, slip detection, pressure, and force. As shown in the figure below the information gained from tactile sensors assists robots to manipulate, explore, and respond to their environments.

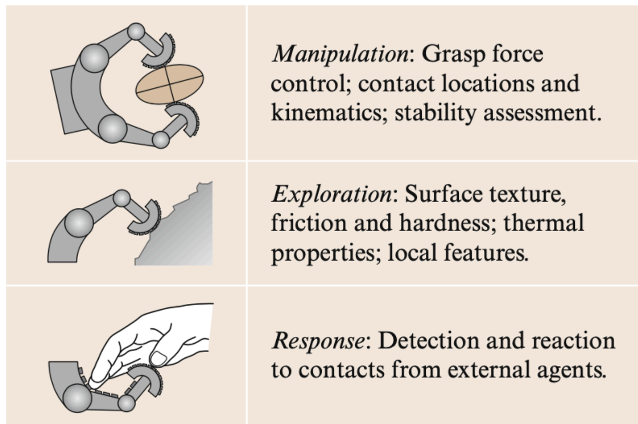

Figure 1 Use of Tactical Sensors

Tactile sensory feedback is the backbone of all human interaction. Without it performing even simple tasks would be difficult. For example, as humans we can easily manipulate delicate items such as eggs. Using our sense of touch, we can gather information such as size, shape, temperature, texture and pressure. We can dynamically adjust the amount of force we grasp the egg with, ensuring enough pressure so that the egg doesn't slip but not so much that the egg breaks. Humans tend to take this level of manipulation for granted. Current research and development are focused on providing this tactile feedback to humanoid robots. Many humanoid robots can already match the human level of raw dexterity, but they lack the dynamic feedback of our senses. Robotic researchers have invented a wide verity of unique tactile sensors capable of giving robots the sense of touch.

1.3 Methods of Tactile Transduction

Transduction is the process of converting physical stimuli to electrical signals. Transduction methods used in tactile sensors can be categorized in two ways: Coupled and Noncoupled electrical mechanical transduction. *Coupled mechanical-electrical transduction* works off the principle that any deformation of the sensor surface/ area due to contact with an external object causes a change in resistance, capacitance or another electrical parameter of the sensor material. (Bruno Siciliano, 2016). *Non-coupled electrical-mechanical transduction* implements measuring the change of other characteristics such as luminance, magnetic flux, or pressure. (Bruno Siciliano, 2016)

Each type of tactile sensor uses a different working principle and is optimal for specific environments depending on the application's requirements. Some of the most common transaction methods used in tactile sensors are:

- Resistive and conductive effect
- Electromagnetic effect
- Capacitive effect
- Piezoelectric effect
- Optical effect

Each method of transduction has advantages and disadvantages. However, no matter the type of transduction method use they all need to meet a few key requirements to be a viable option in use of humanoid robots. These general requirements include:

- Selectivity: ability to detect the desired stimulus.
- Reproducibility: ability to generate identical responses when stimuli are repeated.
- Stability: Ability to have a precise and constant reading with minimal drift or noise
- Sensitivity: minimum amount of stimulus that can be perceived.
- Linearity: the dynamic range of the sensor.
- Cost: the economic viability of the designed sensor
- Size: the space required for each sensing component

2 Tactile System Design

2.1 Tactile Sensor Requirements

The objective of this project is to design and fabricate a custom tactile sensor that could be used on humanoid robot finger. The tactile sensor will be designed to measure the surface temperature and the magnitude of the force exerted on a desired object. To successfully perform the desired task the sensor needs to meet certain requirements. First it needs to meet the standard general requirements for tactile sensors mentioned before: selectivity, reproducibility, stability, sensitivity, linearity, cost and size. Our tactile sensor also needs to meet application specific requirements on top of the general requirements. The application specific requirements include the following:

- The ability to measurement force between 6 grams to 210 grams.
- Use three different transduction methods within the sensor.
- Provide a method of haptic feedback for the sensor.
- Limit the overall size to a 2in Long x 1.5in wide x 2in thick.

After careful considerations to identify the electrical components needed for the sensor, I choose the type of transduction methods I wanted to use in this application. To measure the interaction force I choose to use a Force Sensitive Resistor (FSR) and a Hall Effect array. The FSR will be used to measure medium to large force loads while the hall effect array will be tuned to measure the light to medium force loads. The thermistor will be used to measure the surface temperature of the object. To provide numerical information to the user a lcd screen will be use as a data screen. To provide haptic and sensory feedback to the user a RGB led ring will be used as a visual display.

2.2 Thermistor

To measure the interacting object's surface temperature the custom tactile sensors, use a thermistor. A thermistor is a resistor that changes its resistance with the change of temperature. The resistance goes down as it gets warmer and goes up as it gets cooler, the specific resistor we are using changes about 100 ohms per degree. To convert the change of resistance to change of temperature we use a microcontroller to measure the change of voltage across the thermistor and using the Steinhart-Hart equation we convert the change of volage to a change of temperature. (Ada, Thermistor - 3950 NTC, n.d.)

$$\frac{1}{T} = A + B[ln\,(R)] + C[(ln\,(R)]^2 + D[(ln\,(R)]^3$$

Where:

- T = Kelvin units (°C + 273.15),
- A, B, C, D are curve-fitting coefficients for the specific thermistor (product data sheet)
- R is the measurement of a resistance in ohm, calculated from the measured voltage.
  R = 10K / (1023/ADC - 1)

Figure 2 Thermistor (Ada, Thermistor - 3950 NTC, n.d.)

2.3 Force Sensing Resistor

Force Sensing resistor (FSR) are robust pressure sensors that generates a change of electrical voltage when external pressure is applied to them. FSR's are a category of resistive tactile sensors that are made using two electrodes separated by a compliant conductive medium. When an external force acts on the sensor it deforms the conductive material.

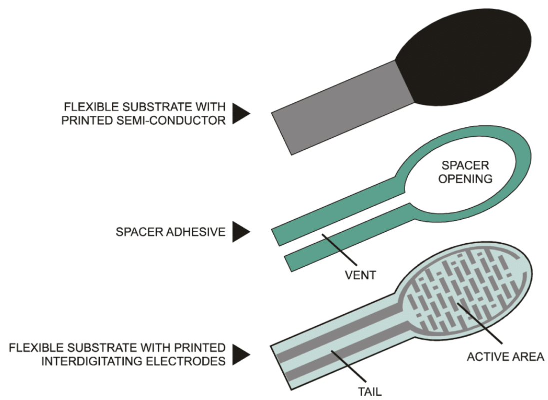

Figure 3 FSR Design

The deformation causes the distance between the two electrodes to change, this intern changes the resistance across the sensor causing a change of measurable voltage. A microcontroller is used to convert this change of voltage to a change of resistance using the following equation: (Ada, Force Sensitive Resistor (FSR), n.d.)

$$Vo = Vcc\ (\ R\ /\ (R + FSR)\ )$$

The measured voltage compared to the FSR'S resistance graph to correlate a force measurement.

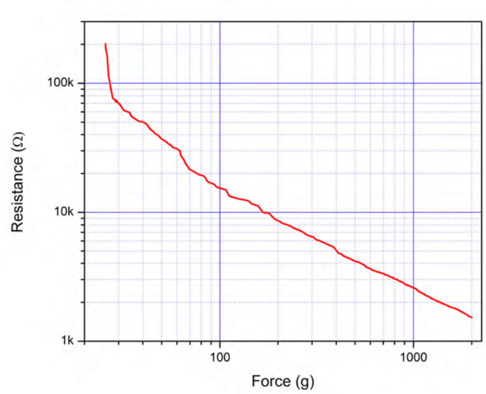

Figure 4 FSR Resistance vs Force Chart

2.4 Inductive Tactile Sensors

The last transduction method used in the custom tactile sensor is an inductive sensor. Inductive tactile sensors measure the change of voltage created when two magnetic fields interact. These sensors use a small permanent magnet held above a Hall effect sensor suspended in a compliant medium. When an external force is applied the distance of the magnet and sensor changes.

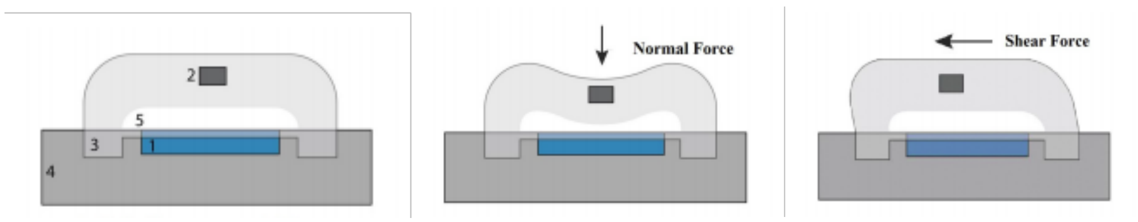

Figure 5 Inductive Tactile Sensors (Mohsin I. Tiwana, 2012)

Like FSR's the deformation and changing magnetic fields causes a change in resistance across the sensor causing a change of measurable voltage. Unlike FSR's the resistance change is linear to the changing magnetic field and can be tuned to the desired range of the application. The sensor. Will then be calibrated using known weights to calculate the measured force reading due to the displacement of the embedded magnet.

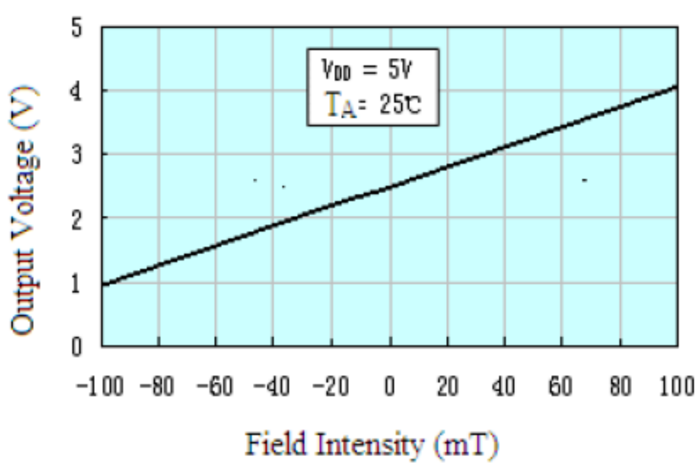

Figure 6 Hall Effect Voltage vs Field Intensity Chart

2.5 Design

Once the type of sensors was identified then the designing of the custom tactile system began. The tactile system is divided into two elements. The sensor unit and the control unit.

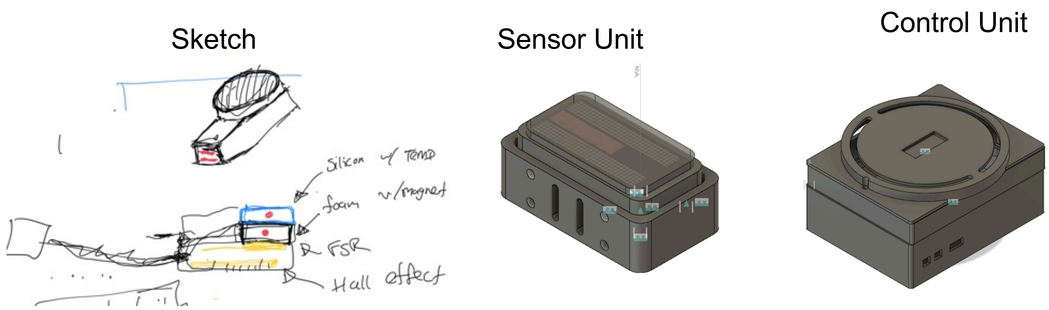

Figure 7 From Sketch to CAD

The sensor Unit consists of two subsystems, the fixed chasse and a free sliding finger plate. The FSR, hall effect's magnet, and thermistor mounted onto the free sliding finger plate while the Hall Effect is mounted onto the fixed chasse. Springs are placed between the two systems allowing for a controlled displacement. Like an adjustable scale, the springs can be adjusted to calibrate the hall effect sensor for a designed mass range by adjusting the overall length and stiffness of the individual springs. Pins are used to fixed all the components together into a final sensing unit.

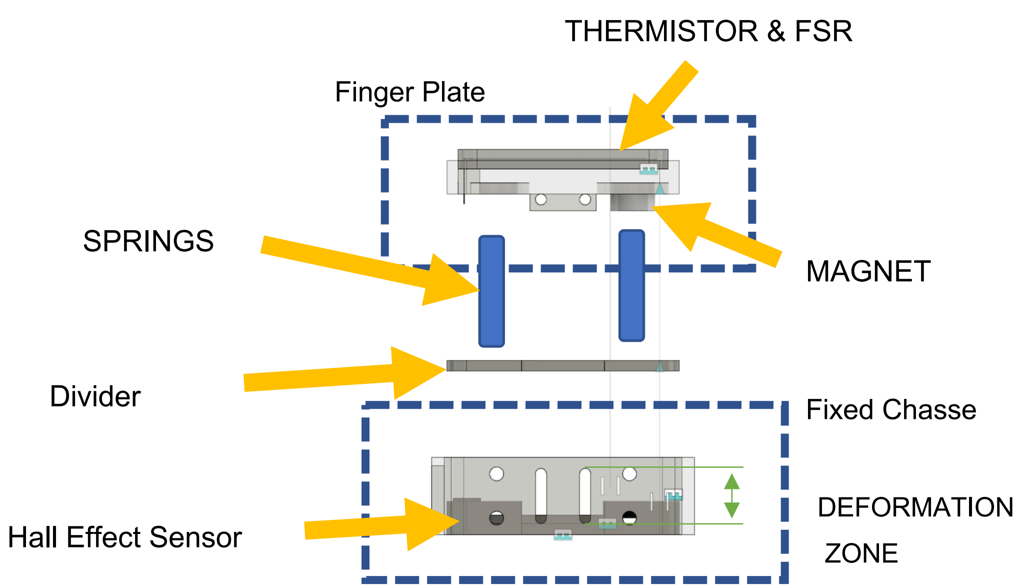

Figure 8 Sensor Unit Components

The tactile sensor control unit houses the necessary controller, wiring, circuit boards and user interface devices. The control unit contains an Arduino nano, which is the microcontroller used to perform the sensor analysis, mathematical calculations and regulate the output devices. The Control unit contains a 35-pixel LED ring. the Led rig is split into two halves, each half is assigned to visually display the force magnitude detected from a corresponding sensor. Lastly the LCD screen located center of the device provided numerical information from the sensors.

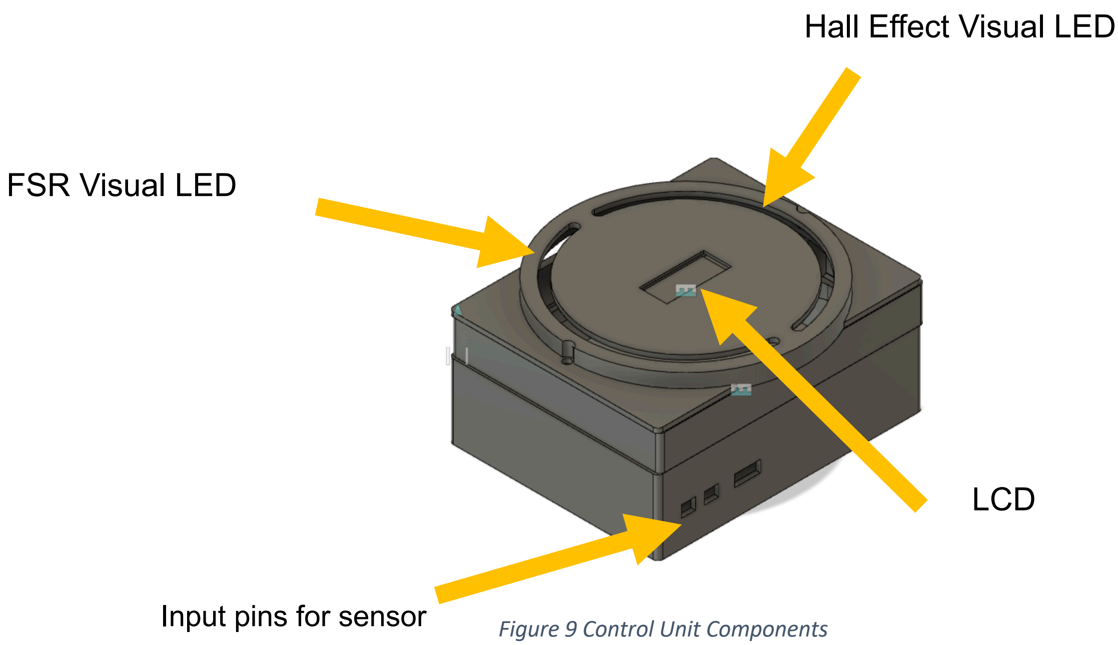

Figure 9 Control Unit Components

3 Materials & Manufacturing

3.1 Materials

Majority of the sensors used in this custom arm are off the shelf units. This made acquisition simple and affordable. Listed below is the list of components used, their specific function in the tactile sensor, and the cost per unit. The final cost of the sensors used in the tactile unit is around $50.

Component ID	Description	Brand	Function	Cost
49E LM393	Hall Sensor	MXRS	Force magnitude	$9.45
2950 NTC	10 K Temperature sensor prob	DROK	Temperature sensor	$2.00
35Xws2812 5050	35 RGB ring	DIYMall	Visual Display	$14
B0936M3WPK	5X3mm magnet	Linlinzz	Magnet	$0.30
ada166	round force sensitive resistor	adafruit	Force Magnitude	$10
Nano	Microcontroller	Ardunio	Microcontroller	$12

3.2 Manufacturing

Once the design of the tactile sensor was completed, I then began the manufacturing of the tactile system. Off the shelf items were ordered using online services, electrical components were wired manually, and custom hardware was fabricated using 3d printing.

All components created in Fusion 360 was fabricated using my personal 3D Printers. I used two typed of 3D printing in this project, SLA and FDM printing. SLA or Stereolithography 3D printing was used for more accurate components, this included the two subsystems chasse for the sensor. The electrical housing that makes up the control unit was fabricated using my FDM printer.

Figure 10 SLA & FDM Printers

3.3 Wiring

Upon receiving the desired sensors, I began by wiring each individually to the Arduino nano. I conducted individual tests to identify the sensitivity, accuracy, calibration method, and the necessary code for each sensor type. After each test I would update the system wire diagram to reflex the proper wiring method that will be used in the final finger prototype. Below are the individual wiring diagrams I used for the FSR and thermistor.

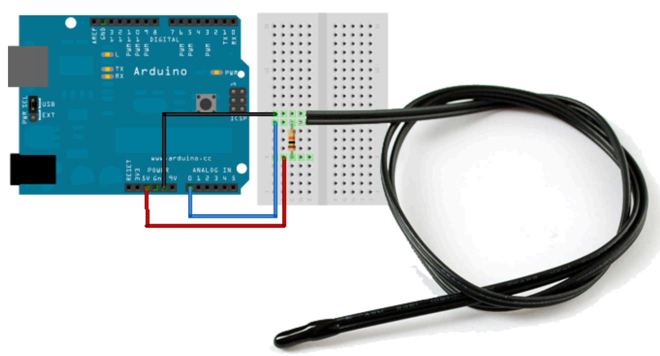

Figure 11 Thermistor Wire Diagram

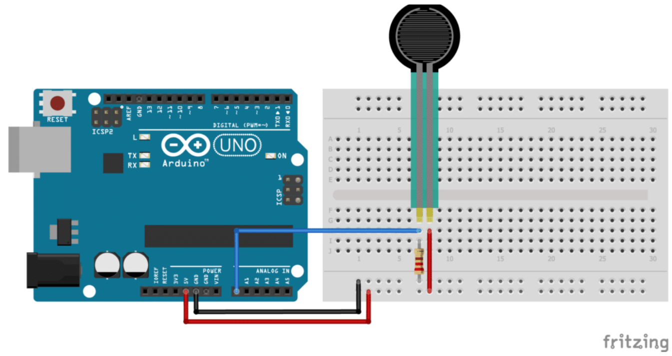

Figure 12 FSR Wire Diagram

After the successful wiring of each system the information was used to design the final protoboard that will contain all the connecting pins and necessary resistors between the microcontroller and the individual sensors. The protoboard was wired as descried by the custom wire diagram listed below.

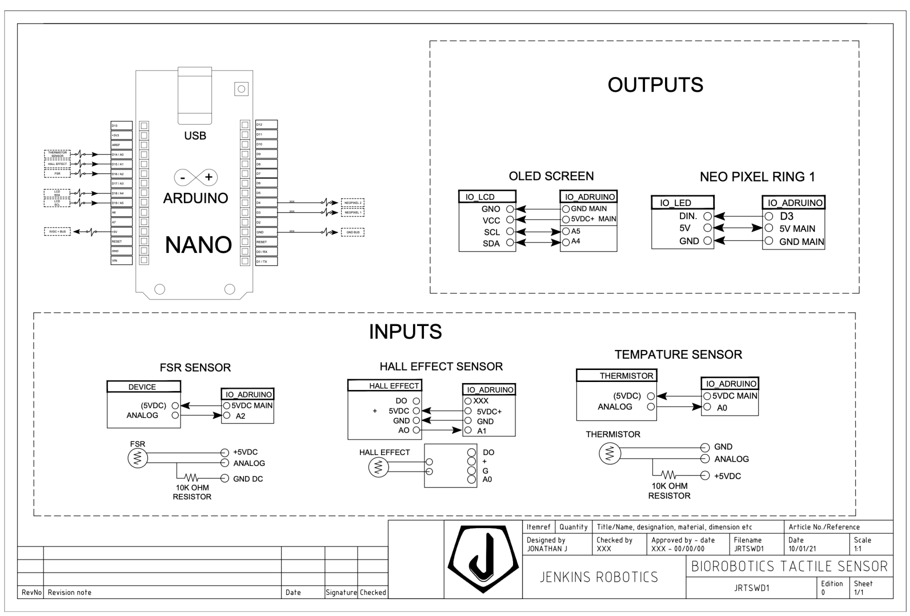

Figure 13 Full Tactile System Wire Diagram

3.4 Programing

After the successful wiring of each sensor to the Arduino nano I then began coding the microcontroller. The microcontroller was programed on the Arduino IDE and uses C as the programing language. The microcontroller and sensors communicate using the analog pins of the Arduino nano. The Arduino then converts the signals using a 10-bit analog to digital converter. The Arduino map input voltages between 0 and 5 volts into integer values between 0 and 1023. From this input value I will perform the necessary mathematical calculating to generate the desired sensor reading. For the thermistor I will use Steinhart-Hart equation to convert the reading into temperature. To calibrate the thermistor, I referenced my inferred thermometer. I apply an offset value to the measured temperature reading so that the sensor correlates to the reading from the master temperature sensor.

As explained before the FSR analog input is first converted into a measurement of resistance. Once a resistance level is determined I can convert that to force based on the resistance-force chart for the specific sensor. To eliminate noise, I incorporated a filtering calculation that averages 30 samples before each force calculation. Like the FSR the hall effect sensor analog input was converted to resistance value measured. From this I created a chart of the measured resistance value vs the amount of weight applied on the sensor. Using a best fit curve from the calibration I then can take raw resistance values and interpolate the theoretical weight applied on the sensor.

Figure 14 Custom Code For Sensor

4 Analysis & Results

4.1 Sensor Evaluation

Upon completion of the tactile sensor, it is now time to evaluate the effectiveness of the system. The tactile sensor was designed to meet general requirements for tactile sensors mentioned before: selectivity, reproducibility, stability, sensitivity, linearity, cost and size. Our tactile sensor also needs to meet application specific requirements on top of the general requirements. The application specific requirements include the following:

- the ability to measurement force between 6 grams to 210 grams.
- Use three different transduction methods within the sensor.
- Provide a method of haptic feedback for the sensor.
- Limit the overall size to a 2in Long x 1.5in wide x 2in thick.

The final size of the tactile sensor was 1.8 long, 1.1 inches wide, and 1.4 thick successfully passing the overall size requirement. The sensor also incorporates three transduction methods, a force resistance sensor, an induction force sensor, and a resistance temperature sensor also meeting the transduction method requirement. The control unit also provides visual and numerical data to the user meeting the haptic feedback reequipment. Another requirement was affordability, and this sensor was design to be affordable to manufacture. The final cost of this sensor was $50 and could be simplified in future versions to be even cheaper.

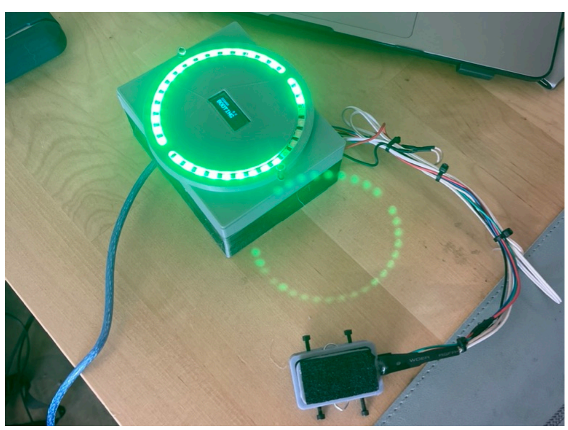

Figure 15 Assembled Sensor and Controller

Next is to test the Force sensitivity, reproducibility, and stability of the sensor. By placing a series of weights, I can compare the measured weight from the sensor to the known weight using a calibrated scale as comparison.

Measurment	Known Weight	Measured Weight	Difference	Accuracy
1	10	0	-10	-100%
2	40	51	11	28%
3	136	102	-34	-25%
4	330	351	21	6%
5	468	480	12	3%
6	650	635	-15	-2%
7	798	711	-87	-11%
8	1100	1000	-100	-9%
			AVG	12%

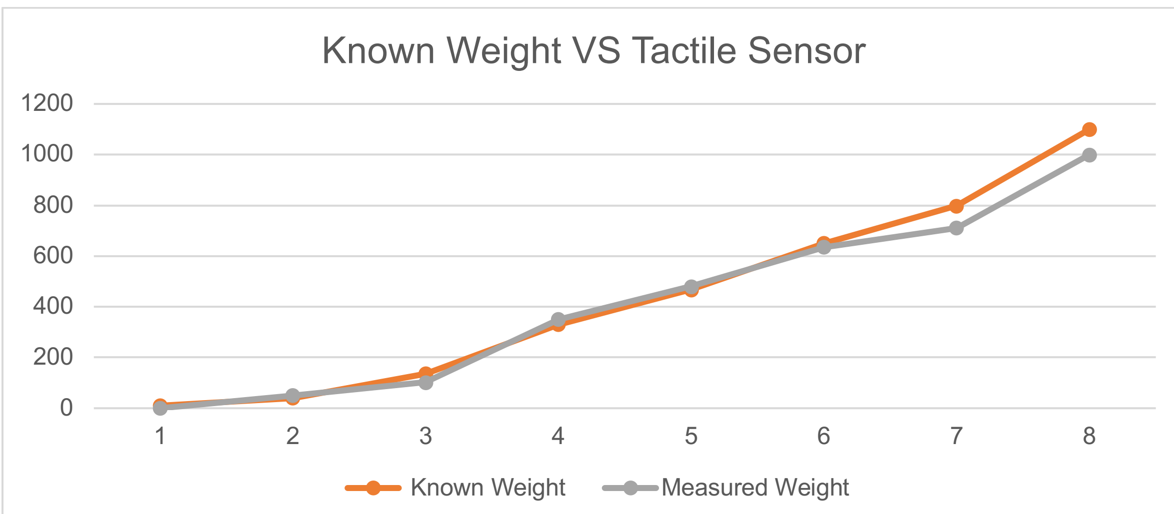

Figure 16 Tactile Sensor Evaluation

After the completion of the test the average deviation measured from the sensor to the reference scall was 12%. The system preformed the most accurate between the range 300 grams to 700 grams with an average deviation of 3.6 %. Under 300 grams the FSR did not read any force and the hall effect sensor was the only method to calculate load on the sensor. Due to the spring design it was unable to detect any load less then 40 grams because the mass was not enough to deform the springs and so the hall effect sensor detected no change. Overall, the system was not able to fully detect the desired 6-250 grams, rather it can detect 40-1000 grams.

The temperature sensor is relatively accurate, only being +- 2 degrees of true measured temperature. However, the temperature sensor does take a relatively long time to detect the objects temperature due to the thermal resistance of the foam it is placed in.

5 Conclusion

Tactile sensors and haptic feedback are critical to the development of humanoid robots that can interact with their environments. There are many tactile sensors being developed for use in humanoid robotics. Our goal was to take inspiration from these other solutions to design and fabricate our own affordable tactile sensor. Our tactile sensor consists of two systems: the tactile sensor that measuring force and temperature and haptic feedback unit that displays the force/temperature information gathered into to visual feedback. The goal was to integrate the desired sensors into a small module that could be used as a “finger”.

The tactile sensor consists of three types of transduction sensors. First, a force sensing resistor (FSR) is used to measure the direct pressure applied on the face of the finger. An inductive sensor, created using a hall effect sensor and magnet, measured the deformation of the finger to add a redundant method of measuring the force. Lastly, a thermistor is embedded under the skin of the tactile sensor to measure the temperature of the object that the finger is interacting with.

The haptic device transforms the detected force measurements into visual feedback for the user. A LED matrix is used to provide the visual feedback. The amount of led illuminated is proportional to the magnitude of force detected by each sensor. The color of the led also changes based on the temperature of the interactive object.

Overall, the system works as designed. Using sensor fusion to better the accuracy of the two force sensors the finger can detect forces between 40 grams to 1000 grams. The system does show an average deviation of 12 % of the measured force compared to the known force applied to the sensor. The temperature sensor has a tested measurement range of 60F to 105F. The temperature sensor is relatively accurate, only being +- 2 degrees of true measured temperature. However, the temperature sensor does take a relatively long time to detect the objects temperature due to the thermal resistance of the foam it is placed in. The haptic sensor works as intended and can visually show the percentage of load each sensor is actively experiencing and while changing the color of the lights based on the temperature measured.

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7 Appendix

7.1 Wire Diagram

Attached is a PDF of the wire diagram created for the tactile sensor

7.1 Arduino Code

Attached is a PDF of the Arduino created for the tactile sensor