Healthcare at Play

Final Report

University of Colorado Denver

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I. Project Description

The main purpose of our project is to create a device that allows patients to stretch their hand without the direct supervision of a therapist, while also producing an engaging environment through the use of a game. From the countless types of hand injuries or conditions, our project’s scope has been narrowed down to osteoarthritis. By using video games, we will motivate arthritis patients to exercise their hands, primarily fingers, without resorting to the use of menial exercises. Hand exercises are essential in combating the strain resulting from poor ergonomics, repetitive tasks, and aging.

The goal of this project is to measure the flexibility of a user’s fingers by utilizing sensors to quantify the angle of the finger with respect to the palm of the hand. The fingers can perform a variety of motions; the thumb, however, is much more complex in terms of its ability to maneuver, as can be seen in the following image.

![Figure 1: Movements of the thumb](image)

In addition, according to statistics from the Center for Disease Control (CDC) in 2013-2015, in the United States, 54.4 million adults aged 18 year and older have been diagnosed with arthritis by doctors. The CDC also predicts that by 2040, this number will increase to 78.4 million (25% of projected total adult population). As engineers, we want to develop a product that can help arthritic patients exercise their hands while also providing doctors and physical therapists with usable data that may help them in their field.

![Figure 2: CDC statistics showing projections for arthritis](image)
II. Design Methodology, Constraints, Specifications, and System Requirements (CLO 1)

Our project “Healthcare at Play” is centered around creating a device that will motivate arthritic patients to flex their fingers, without repeating boring exercises. This project, controlled by an Arduino placed within a wearable 3D-printed housing, records the motion of each finger when playing a game. The goal of the game is to have the patient match a desired pose at the right time to test flexibility. After the game is complete, the captured data from these sensors will be saved to a file which can be sent to Spotfire software for analysis. Spotfire provides graphs for visualization purposes. With enough data, it can also point out any trends based on historical data.

Our prototype from the previous semester included flex sensors and force sensors. Based on recommendations and valuable feedback, we decided to remove force sensors because arthritis mostly limits the movement of the joints and does not necessarily reduce the force. For this semester, we focused on getting more reliable positional data and tracking the movement of the thumb in multiple directions.

We are working on two parallel prototypes. One primarily uses short flex sensors and the other uses linear Hall-effect sensors. Each prototype has two primary areas of focus for testing: targeting the thumb’s intricate movements in two dimensions and the general movement of all 5 fingers. The goal of this is to determine the feasibility, practicality of each sensor, and their ideal placement. If sufficient testing is performed, the combination of prototypes may allow the creation of a product containing the best aspects of each.

Our first prototype is focused on improving the flex sensor design by emphasising the movement of the thumb. This is accomplished by attaching an additional flex sensor in the crook of the thumb to sense the degree of bend with respect to the index finger.

![Figure 3: 2D Short Flex Sensor Prototype (looking into the palm)](image-url)
Figure 4: 2D Short Flex Sensor Prototype (looking into the back)

Figure 5: Short flex sensors connected to thumb (left) and all 5 fingers (right)

With our second prototype, we aim to measure the motion of fingers by using a linear hall-effect sensor, which will be able to measure the distance from a magnetic source based on the strength of the magnetic field at that point in space. By locating the magnet at a stationary point in the palm, we can use the information provided by the hall sensors to determine the position of the fingers. These sensors can be used with either permanent magnets or electromagnets; however, our project utilizes permanent magnets due to time constraints resulting from shipping.
There are also limitations introduced with the type of glove used, so various materials have been tested. The fabric gloves allow for more flexibility than the rubber-dipped glove. The images below show the different setup options with linear Hall sensors. In order to view the actual sensors, the insulation from the white glove was removed.
We bought five different types of Hall-effect sensors: DRV5053, DRV5055A1, DRV5055A4, DRV5056A1, DRV5056A4. Sensor DRV5053 cannot work for this project since it is a *latch* Hall sensor, which only outputs a binary on/off depending on the magnetic field near it and is primarily used for rotational counting such as revolutions per minute. The other four are *linear* Hall sensors, which will output a voltage based off of the strength and polarity of the magnetic field it is at. To determine the best sensor for the prototype, preliminary tests were performed to quantify their output characteristics.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Type of Sensor</th>
<th>Sensitivity (“Gain”)</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRV5053</td>
<td>Latch Sensor</td>
<td>Very short range; magnet must be near-touching</td>
<td>Cannot be used for our purposes.</td>
</tr>
<tr>
<td><strong>DRV5055A1</strong></td>
<td>Bipolar Linear (North and South poles)</td>
<td>Medium range; ~1-5 inches (depending on magnetic source)</td>
<td><strong>Best choice.</strong> Very forgiving if the magnet isn’t facing the correct direction. Good range of sensitivity (tested with Neodymium magnets)</td>
</tr>
<tr>
<td>DRV5055A4</td>
<td>Bipolar Linear (N&amp;S poles)</td>
<td>Short range; 0-2 inches</td>
<td>Can be used for accurate measurements at short ranges. Potential for accurate fingertip positioning.</td>
</tr>
<tr>
<td>DRV5056A1</td>
<td>Unipolar Linear (South pole only)</td>
<td>Medium range; ~1-5 inches</td>
<td>Because finger motion inherently requires rotation, we try to use more flexible sensors (55A*) that give results at different orientations.</td>
</tr>
<tr>
<td>DRV5056A4</td>
<td>Unipolar Linear (South pole only)</td>
<td>Short range; 0-2 inches</td>
<td>Similar to 55A4, but with less flexibility as it only detects a single pole. With the right setup, this could be a positive (i.e. less false readings when facing away from desired orientation)</td>
</tr>
</tbody>
</table>

**Table 1: Sensor Characteristics Conclusion**

The available magnets were also tested with each sensor to parameterize the range of viable outputs.

<table>
<thead>
<tr>
<th></th>
<th>Small Magnet Range</th>
<th>Large Magnet Range</th>
<th>Baseline Output</th>
<th>Min Output</th>
<th>Max Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>55A1</td>
<td>5.5 cm</td>
<td>11.5 cm</td>
<td>497</td>
<td>66</td>
<td>947</td>
</tr>
<tr>
<td>55A4</td>
<td>3.5 cm</td>
<td>7 cm</td>
<td>495</td>
<td>72</td>
<td>942</td>
</tr>
<tr>
<td>56A1</td>
<td>5.5 cm</td>
<td>12 cm</td>
<td>170</td>
<td>66</td>
<td>947</td>
</tr>
</tbody>
</table>

**Table 2: Sensor Characteristics Specific Data**

The hall effect sensors were found to have a degree of noise in their output. This noise manifested as a high frequency signal superimposed on the data. To isolate the signal, a low pass filter was implemented for each sensor.

The results from the sensors, either hall effect or flex, are then read through the analog ports of an arduino microprocessor, which then sends the data through the serial port to our software. This software will initiate a game controlled by the serial data, allowing the user to interact with a game. Once this game is completed, the results describing the range of user’s motions are exported to the Spotfire application for additional data analysis.

**Figure 9: Data Flow of Prototype from sensor to spotfire**
III. Engineering Documents (CLO 3)

A. Flex Sensors

For the first prototype, we chose a short flex sensor attached in the crook of the thumb as well as the 5 sensors attached to the front face of each finger. To create a voltage divider, we connect one leg of the sensor to 5V and the other to a 22kΩ resistor. When the analog port of the arduino is connected to the output of this, it will read a voltage that changes as the flex sensor bends.

![Figure 10: Short Flex Sensor connection](image)

The short flex sensors behave like a variable resistor. When they’re configured as a voltage divider, where one resistance is known, we can calculate the resistance of the flex sensor. And once we know the resistance, we can use its datasheet, like the one in Figure 11, to easily convert it into a bend angle.

![Figure 11: Datasheet of Flex Sensor Resistivity vs Bend Angle](image)
Designing a smooth and straightforward flow of data is imperative for a positive user experience. The image below is a flowchart that shows the flow of data from the flex sensor prototype to Tibco software.

![Flowchart](image_url)

*Figure 12: 2D Short Flex Sensor Prototype Block Diagram*

**B. Hall Sensors**

Our second hall effect prototype utilizes 6 sensors whose outputs are fed through a passive RC low-pass filter before being read through the analog ports. To power these sensors, one of the pins is connected to 5V, the other is grounded, and the third outputs the current measurements. The signal chain for this prototype is similar to the previous one, as it uses the analog ports to send serial data to the software.

![Prototype Image](image_url)

*Figure 13: Linear Hall Effect Sensor Connection with Low-Pass Filter*

The DRV5055A models can sense both the north and south magnetic field. When there is no field present, its default output is half of the supplied voltage.

*Figure 14: Magnetic field response of the linear hall effect sensor DRV5055A*
The DRV5056 models are unipolar - they only respond to the south pole of a magnetic field. When there’s no field present, its output is near zero.

Figure 15: Magnetic field response of the linear hall effect sensor DRV5056A

Figure 16: Hall Sensor Prototype Block Diagram
IV. Computer Design Tools (CLO 4)

A. Arduino

This project utilizes Arduino as a sensor interface for both the hall effect and flex sensors by reading the available measurements and sending serial data to the computer for processing. Here is the Arduino code for a short flex sensor. The Arduino will read data and return an angle in the range of 0 to 90 degrees corresponding to the flex of the finger.

```cpp
const float VCC = 5;  // voltage at Arduino 5V line
const float R_DIV = 47000.0;  // resistor used to create a voltage divider
const float flatResistance = 250000.0;  // resistance when flat
const float bendResistance = 100000.0;  // resistance at 90 deg

float flexAngle(int sensorReading){
  float Vflex = sensorReading * VCC / 1023.0;  // convert to voltage
  float Rflex = R_DIV * (VCC / Vflex - 1.0);
  float sensorAngle = map(Rflex, flatResistance, bendResistance, 0, 90.0);
  return sensorAngle;
}
```

*Figure 17: Arduino Code for Short Flex Sensor*

A visual representation of the Arduino’s output is shown below; it depicts the response when a user bends and stretches their fingers.

*Figure 18: Serial plotter of flex sensors on five fingers*

The blue line in the graph represents the thumb, red is the index, green is the middle, yellow is the ring, and pink is the pinky. Using this we can see the results of bending each finger.
For the prototypes utilizing Hall sensors, we used the following code to send the sensor readings over the serial connection. This data can be visualized using the Arduino IDE’s Serial Plotter.

```c
// the data sends over in the order of these pins
const int sensorPins[] = {A0, A1};
size_t totalPinCount;

void setup()
{
  Serial.begin(9600);
  Serial.flush();
  totalPinCount = sizeof(sensorPins)/sizeof(sensorPins[0]);
}

void loop()
{
  read_and_send(sensorPins);
  // optional to separate this to include math operations
}

void read_and_send(const int pins[])
{
  for(int i = 0; i < totalPinCount - 1; i++)
  {
    int rawReading = analogRead(sensorPins[i]);
    Serial.print(rawReading);
    Serial.print(',');
  }
  int lastRawReading = analogRead(sensorPins[totalPinCount-1]);
  Serial.println(lastRawReading);
}
```

**Figure 19:** Linear Hall Effect Sensor Arduino Code (raw data)

![Figure 19: Linear Hall Effect Sensor Arduino Code (raw data)](image)

**Figure 20:** Serial plotter of raw data of five linear Hall sensors

The orange line represents the thumb in the abduction direction, green is the thumb in the flexion direction, red is pointer, pink is middle, blue is ring and grey is pinky. If there is no magnetic field present near the Hall sensors, they will output their designed base values, which depends on the sensor model.

Via this plot, we can see that the bending angle for the pinky (grey) and thumb on 2D (orange and green) has not changed since wearing the leather glove. This is due to the stiff material limiting the motion of these fingers.
Figure 21: Serial plotter of raw data of 6 linear hall effect sensors

The orange represents the thumb in abduction direction, pink is the thumb in flexion direction, red is index, green is middle, blue is ring, and gray is pinky.

This glove was made with fabric, and contains a combination of multiple types of Hall sensors. The magnet was placed in the center of the palm. We can barely see the gray line move at all, and that is because the pinky had a low-gain 55-model Hall sensor. It has to get much closer to the magnet to produce an output.

B. Solidworks - 3D Modeling

The design of the housing unit for the arduino is shown below. The final product is printed using PLA filament.

Figure 22: 3D Housing with Dimensions
The housing for the arduino is small but it has enough room to place the arduino board, an expansion board (PCB or Bread broad) as well as a 9V battery. We did intend to create a smaller housing to make it more comfortable for the user to wear, however we also want the user to have better mobility of the hand and arm while playing/exercising. The housing for the hardware has been redesigned for better performance, as shown below.
Figure 25: New Arduino Housing

Figure 26: Design Schematic of Arduino Housing
C. Unity

In the previous semester, we sent the data to a program called Processing to give the users a visual display. This semester, we chose to use a much more robust engine called Unity. Figure 27 is an example of the Main Menu for our game, where we can set up the connection to the Arduino along with adjusting settings to calibrate the sensors to each finger. Once connected and calibrated, the Play button will become available to capture and record data as needed.

Figure 27: Main Menu Page

Figure 28: Configuration Page
In this game, we first have to connect to the correct serial port, which will transfer data from the Arduino to Unity over a USB connection. After it’s connected, we need to configure the individual sensors by designating a ‘min’ and ‘max’ value respective to ‘extending’ and ‘flexing’ for each finger.

The game is simply pose-matching, where different poses will appear in the background and approach the hand which the user controls. The user must get their fingers to match the target pose as closely as possible before the target reaches the user’s hand.

![Figure 29: Gameplay Screenshot of Pose Matching. Target Hand Displaying a Number “1” in Sign Language](image)

**D. Spotfire**

Finally, once a game has been played, and data has been captured, it will have been formatted into a comma-separated values (.csv) file that can be easily imported into Spotfire. Spotfire is an online software for data analysis created by Tibco Inc., this project’s sponsor. Its data analysis is based on machine learning, data mining, and predictive modeling. It also provides rich graphs and 3D charts to graphically represent the data in a format that is easy to understand. More on this will be shown in the ‘Proof of Concept’ section.
V. Patent and Standards Research Related to Design (CLO 6)

By no means is our project considered unique. According to a paper posted in Microelectronics Journal, accurate data acquisition methods have been “divided into six categories: 1) Flex sensor based; 2) Accelerometer based; 3) Vision based; 4) Hall-effect based; 5) Stretch sensor based; and 6) Magnetic sensor based.” Many of the advanced systems available on the market may cost up to a couple thousand dollars, which makes it less available for the general public. Hall sensors are rather inexpensive; with the right design setup and accompanying software, this could become much more accessible.

The design to include Hall-effect sensors for a glove has been patented already. The patent doesn’t include any information regarding their results and effectiveness, nor what type of magnet or hall-effect sensors were used. The patentees also have a similar design where they use radio-frequency (RF) transmitters and small IMUs to capture positional data. See the Works Cited section for related links.
VI. Proof of Concept (CLO 8)

For this project, we’ve created two prototypes that utilized different sensors and glove materials. The first prototype used six short flex sensors, one for each finger and an extra between the thumb and forefinger to capture the multi-directional motion of the thumb. The second prototype has a similar setup but with six linear Hall sensors.

![Figure 30: Final prototype of short flex sensor glove](image)

![Figure 31: Final prototype of linear hall effect sensor glove](image)
It was found that the fabric glove provided easier sensor placement as well as increased comfortability. There is a fabric insulator to cover over the sensors and wires to protect the user and the electronics, along with a fabric pocket to cover over the magnet on the palm. While reading the measurement, a large amount of noise was present in the output signal. To counteract this, we included an RC low-pass filter to smooth the output. The noisy and filtered signals are shown below.

**Figure 32: Noisy Signal (Red) vs. Filtered Signal (Blue)**

When the image is enlarged, the effect of the noise becomes more apparent. The implementation of a low pass filter results in the blue line, which has significantly less noise.

**Figure 33: Zoomed-In Serial Plotter of Noisy Signal (Red) and Filtered Signal (Blue)**
Testing the four different types of linear Hall sensors yielded the following results:

The plot above was made using four different linear Hall-effect sensors: 55A1 in yellow, 55A4 in blue, 56A1 in green, and 56A4 in orange. The permanent magnet was placed below the hand. The “55” model sensors hover in the middle (~500) when there is no magnetic source near it, whereas the “56” models hover close to the bottom (0) for its analog output. The green and yellow lines have a higher sensitivity (or gain), which can be seen by their ability to create much larger swings in output. Because the “56” sensors only react to a southern magnetic field, the level of accuracy is much more precise than the “55” models which have to shrink its output in half in order to fit both poles of data over the same output span. With this information and after further testing, we determined that we can obtain more accurate readings by using the “56A1” linear Hall sensors.
By using two Hall sensors connected to the thumb (where they are 90° apart), we can detect thumb movement in two orthogonal directions: left-right & up-down. This experiment also used two magnets oriented to have opposite poles facing where the thumb may move. By visual inspection of the Serial Plotter outputs, this is a feasible configuration to capture multi-directional thumb movement or obtain more accurate positional data. The more Hall sensors that can be included on any finger, the more precise we can determine its orientation.

The game we developed only was configured for a maximum of five sensors, and only with the motion pair of flexion and extension. We’ve recorded some gameplay data, which consists of columns of target position paired with actual position for each individual finger. This was saved to a local file, which can be uploaded to Spotfire for analysis. The following images show the breakdown of the data along with a graphical representation.

**Figure 36:** Gameplay Data of Each Finger’s Actual vs Target Position

**Figure 37:** Spotfire Boxplot of Data for Visual Analysis
The boxplot shown illustrates the pose-matching accuracy of each finger. The y-axis value of zero means the user is right on target. If the value is closer to 1, they are over-flexing. Conversely, if it's closer to -1, they aren't flexing enough. We can see that the user did a much better job with their pinky, ring, middle, and index fingers since the margin between the first and third quartile is much smaller and it is centralized around zero. However the data for the thumb has quite a larger spread of data and is below zero, which could indicate either there is an error with the sensor or the user is having trouble with their thumb mobility.

This data visualization is also very useful to show us any areas of potential error in our design. For example, there are many outliers near -1 for all of the fingers, which could be random noise in the system, but is more likely caused by latency between the systems when the user is moving their fingers.
## VII. List of Project Design and Implementations Task and Responsibilities

<table>
<thead>
<tr>
<th>Date</th>
<th>Task</th>
<th>Assigned Member(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2021</td>
<td>Meeting with Dr Gaffney for information about the project idea.</td>
<td>Mauricio, Burak, Nick, Trevor, Linh</td>
</tr>
<tr>
<td>1/2021-2/2021</td>
<td>Research on which sensor is best fit for this project.</td>
<td>Mauricio, Burak, Nick, Trevor, Linh</td>
</tr>
<tr>
<td>2/11/2021-2/13/2021</td>
<td>Gantt chart</td>
<td>Nick, Burak, Trevor</td>
</tr>
<tr>
<td>2/8/2021-2/18/2021</td>
<td>Status report 1</td>
<td>Linh, Nick</td>
</tr>
<tr>
<td>2/2021 &amp; 3/2021</td>
<td>Make orders</td>
<td>Linh</td>
</tr>
<tr>
<td>3/12/2021</td>
<td>Create 3D housing</td>
<td>Mauricio</td>
</tr>
<tr>
<td>3/28/2021</td>
<td>Create 3D magnet/sensor holder</td>
<td>Mauricio</td>
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<tr>
<td>4/6/2021-4/7/2021</td>
<td>Export the data in Spotfire</td>
<td>Linh</td>
</tr>
<tr>
<td>4/1/2021-5/1/2021</td>
<td>Create game</td>
<td>Trevor</td>
</tr>
<tr>
<td>4/10/2021-4/18/2021</td>
<td>Design final poster</td>
<td>Linh</td>
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<td>4/12/2021-4/16/2021</td>
<td>Arduino code</td>
<td>Trevor, Nick</td>
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<tr>
<td>4/6/2021-4/12/2021</td>
<td>Testing sensor again</td>
<td>Trevor, Nick, Burak</td>
</tr>
<tr>
<td>4/13/2021-5/1/2021</td>
<td>Testing glove</td>
<td>Nick, Burak, Trevor, Linh</td>
</tr>
<tr>
<td></td>
<td>Export data in Spotfire</td>
<td>Mauricio, Linh</td>
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<tr>
<td>4/9/21-4/15/21</td>
<td>Proof of Concept</td>
<td>Trevor, Nick, Linh</td>
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<tr>
<td></td>
<td>Record 8 minutes video</td>
<td>Mauricio, Burak, Nick, Trevor, Linh, Faisal</td>
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<tr>
<td>4/17/2021-2/22/2021</td>
<td>Final report</td>
<td>Linh</td>
</tr>
<tr>
<td>5/6/2021</td>
<td>Final presentation</td>
<td>Mauricio, Burak, Nick, Trevor, Linh, Faisal</td>
</tr>
</tbody>
</table>

*Table 3: List of Member Responsibilities This Semester*
VIII. Project Budget

With the remaining funds from the previous semester, and an extra EE member this semester, our budget for this semester started with $1300. There were many directions we could have gone for this project, such as expensive visual tracking or using pre-configured systems that serve a similar purpose. However, we wanted to make an affordable product so that it was much more accessible. Overall, we only used $512 of our total budget to create and test our prototypes, with a cost breakdown displayed below.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Subtotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block magnet</td>
<td>Magnetic source for sensor</td>
<td>$2.85</td>
</tr>
<tr>
<td>Electromagnet</td>
<td>Magnetic source for sensor</td>
<td>$15.00</td>
</tr>
<tr>
<td>Short flex sensor</td>
<td>Finger flex measurement</td>
<td>$111.55</td>
</tr>
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<td>DRV5053</td>
<td>Latch Hall-effect sensor</td>
<td>$11.25</td>
</tr>
<tr>
<td>DRV5055A1, DRV5055A4, DRV5056A1, DRV5056A4</td>
<td>Linear Hall-effect sensors. Measure strength of magnetic fields</td>
<td>$71.46</td>
</tr>
<tr>
<td>Capacitor set</td>
<td>Used for low-pass filters</td>
<td>$9.99</td>
</tr>
<tr>
<td>M2F wires</td>
<td>Wires for connecting sensors to arduino</td>
<td>$11.99</td>
</tr>
<tr>
<td>24 AWG electrical wire</td>
<td>Wires for connecting sensors to arduino</td>
<td>$10.98</td>
</tr>
<tr>
<td>Large circle magnet</td>
<td>Allows for a stronger magnetic field</td>
<td>$30</td>
</tr>
<tr>
<td>Force sensor</td>
<td>Measure force applied on surface area.</td>
<td>$98.28</td>
</tr>
<tr>
<td>Waterproof finger covers</td>
<td>Initial idea to use in place of gloves</td>
<td>$13.20</td>
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<tr>
<td>Arduino board</td>
<td>Control the data flow</td>
<td>$25.84</td>
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<tr>
<td>Bluetooth box</td>
<td>Game with wireless control</td>
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<td>Proto shield</td>
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<tr>
<td>Shipping fee</td>
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<td><strong>Total</strong></td>
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</tbody>
</table>

*Table 4: Budget for Both Semesters*
Figure 38: Budget Separated by Category
IX. Acknowledgement

University of Colorado Denver:
- Dr. Daniel Jensen, Electrical Engineering Professor
- Prof. Jeffrey Selman, Electrical Engineering Professor
- TA. Alexander Mroz, Electrical Engineering Teaching Assistant

University of Colorado Anschutz:
- Dr. Brecca Gaffney, Biomedical and Mechanical Engineering Professor

Westmont College:
- Dr. Adam Goodworth

Previous “Healthcare at Play” Members:
- Matthew Bertschman
- Tiffany Chang

TIBCO Software, Inc:
- Ms. Meena Krishnan, Tibco Senior Manager
X. Works Cited


- Last Minute Engineers. “In-Depth: Interfacing Flex Sensor with Arduino.” Last Minute Engineers, Last Minute Engineers, 6 Apr. 2020, lastminuteengineers.com/flex-sensor-arduino-tutorial/


