FR

JAM

Contents

Group 16 0
1 Introduction 2
2 Goals 3
3 Project Plan 4
4 Predictions 5
5 Actual Implementation 6
5.1 Sensor Hardware 6
5.1.1 Prototype Design 6
5.1.2 PCB Implementation 9
5.1.3 Casing Design 11
5.2 Wearable Sleeve 13
5.3 App Implementation 15
6 Critical Problems Solved 17
6.1 Sensor Hardware 17
6.1.1 Size Constraints 17
6.1.2 PCB Defects 17
6.2 App Implementation 17
7 Evaluation and Reflection 18
8 Future Plan 18

1 Introduction

With the advent of the internet, access to fitness programs of all kinds has become universally available to anyone with a phone, tablet, or other screen device. The advantage of this ease of access is that professionally produced content is available for ready consumption across a wide range of exercises: from yoga and stretching for warm-up, to calisthenic and weight training, and programmed cardio such as HIIT. Individuals who would regard themselves as amateur or newcomers to guided exercise have a paralysing number of choices to make with no real framework of what makes a program or demonstration video valid or invalid, worthwhile or pointless, safe or dangerous. With the advent of social media, most sites where newcomers are targeted will over-inflate the efficacy of these programs or provide misinformation about how rapidly someone will experience fitness gains. In reality, many fitness programs and exercises require months or years of 'fundamental' practice, mastering the basic movements and developing a mind-body connection. Muscle building is essentially controlled damage to muscle tissue to encourage new growth, so individuals are encouraged to work at or close to their maximum potential for weightlifting. However, without a strong mind-muscle connection and plenty of time at low weight, one wrong move or a gradual degradation of form during exercise may cause immediate and permanent injury to the body. This is exacerbated by the programs mentioned above, because social media actively discourages discussing the reality that developing prowess in any form of exercise is fundamentally about spending time being conscious and controlled. Why post a video curling a thirty-pound dumbbell with slow, controlled form when you can outshine your social media competitors by swinging eighty pounds around instead? Because newcomers are both the least experienced and most impressionable of those in any form of exercise, this has set a dangerous precedent that this device has targeted. COVID-19 isolation has also further prevented newcomers to all aspects of exercise access to professional guidance. With the increase in individuals working out outside of communal spaces such as gyms and sports fields, athletes, experienced gymgoers, trainers, and coaches often have no way of directly observing and influencing the way their clients or colleagues perform their movements. The burden (and ultimately, the skill) of body-awareness has become the sole responsibility of the individual who has little to no experience and is being actively encouraged to move unsafely for the sake of the social media machine. As such, there is a market (or an ethical need) for some way to enhance the mind-body awareness of newcomers to exercise, as well as anyone at any stage of exercise experience. The group responsible for FRIJAM, the device described in the sections below, aimed to create a device that would provide meaningful feedback about how an individual is moving by targeting the motion of joints as they move across a range of motion. This information, coupled with safety factors (limitations specified by individuals with advanced physiological knowledge like doctors and sports coaches) that strongly notify users of the potential for injury, should help novice and advanced individuals alike. While the resulting technology has further-reaching applications than just protecting novice weightlifters, this was the driving force behind its conception. In time, this convenient, portable, inexpensive device could reach beyond the novice exercise market and into areas such as virtual reality and the gamification of exercise as the software framework created by the FRIJAM group allows for direct access to the data, meaning developers can integrate both the motion and the feedback into their own applications. Additionally, use of standard communication protocols such as BLE (Bluetooth Low-Energy, which all modern smartphones and tablets are compatible with) means that no special hardware other than the device itself is necessary. The FRIJAM group believes that due to its manufacturability and ease of use it has genuine potential to augment the day-to-day experience of novices in the field of exercise and prevent real injuries.

2 Goals

As with any wearable device, the goal is to integrate seamlessly onto the body and pose no interference to the user, both in the context of safe movement and in annoyance, such as a poor fit or uncomfortable material. As such, any portion of the device must be minimized in profile to avoid accidentally catching on nearby items or impacting movement in any way, and any part of the device contacting human skin must do so with safe, comfortable materials and not have any sharp edges or pressure points. At first, this seems like an obvious requirement for any wearable device, but over the evolution of the project from design to test to redevelopment it was a core element that posed many challenges, which will be outlined below. Additionally, the device needed to be hygienic and water-resistant, which also tie in to the convenience factor as it had to be easy to clean. Additionally, to avoid any kind of predatory business model in the future the device was designed to be interchangeable with a variety of sleeves to accommodate both different sizes of user and different placement on the body. As such, it had to be convenient to remove from the physical sleeve for exchanging on the body, washing, and changing the battery. This also meant careful selection of any fastener or permanent fixture to the sleeve as it needed to be durable and machine washable, while also being comfortable. As for device performance, there were few ceilings in regard to hardware limitations. The initial goals for the performance of the device were to be able to accurately calibrate the device's sensor to provide a safe operating limit, process data at a high enough sample rate to accurately gauge user movement and provide both real-time feedbacks, (such as the histogram shown in later sections) but also act as an interrupt when the potential for injury is detected. While initially it may seem counterintuitive to interrupt a workout as the distraction may cause unwanted movement or overreaction, it was deemed more important to jolt a user into focusing on the present situation than it is to alert them after a workout is completed. Additionally, battery capacity and current consumption needed to be sufficient to last through a sports game or extended workout session, with the aim to last numerous before a battery change was required. Lastly, the goal of the software processing was to provide an open-source platform for other applications and tools to access the data either during or after a workout, as well as serve as a single access point for all features of the device; from programming to pairing, calibration and recording.

One goal that was added later into the implementation was the aspect of convenience on the software-side. The FRIJAM software initially ran on a Raspberry Pi microcontroller due to the ease of creating Python-based applications and due to its raw processing power as well as in-built Bluetooth module. However, as will be shown in subsequent sections, the resulting combination of battery, Raspberry Pi microcontroller and touchscreen was, in essence, a cellphone. No one would buy a device that requires a separate brick-like phone just to visualize their movement. Especially if it can't play music.

3 Project Plan

With these goals in mind the general structure of the device was laid out as part of the initial milestones in the first half of Capstone 4OI6. The technology fundamental to the device, that spurred the initial concept, was to be a flexible resistor. Some manner of accurate voltage measurement technique and subsequent transmission was necessary, and the immediate choice was the Bluetooth Low Energy protocol as it boasted extremely low power consumption and high ranges at reasonable data rates (much higher than was necessary to transmit motion data). Lastly, the manner of attachment was decided to be an emulation of the elbow and knee sleeves used to provide compression and support for weightlifting or physiotherapy. Research into the technologies required to complete a theoretical block diagram for the system were found rather quickly, as many commercially available devices were able to either integrate directly or be slightly modified to fit the needs of the device. Because of the relative simplicity of the system architecture the initial proof-of-concept for the device (which ended up being a fraction of the work necessary to create a meaningful invention) came together well ahead of the projected timeline.

4 Predictions

For each of the major deliverables in capstone 4OI6, as well as the face-to-face meetings with the overseeing professor Dr. Xun Li, the FRIJAM group were asked to gauge both the extent of their own personal contributions to the project as well as the predicted level of completion that could be obtained by the date of the Capstone Expo. The FRIJAM group remained optimistic about the outcome of this project due to the relatively linear scope; that is, the group could not completely predict the amount of time required to hit different milestones, but the constrained design space acted to our advantage, as the stringent requirements prevented too many open-ended conversations or design decisions. As the project progressed, it was clear that certain aspects of the project (most notably, the Raspberry Pi auxiliary processing unit) were redundant, but the effect of this was that suddenly the ability to develop Android applications was of high priority in providing a complete system for the deliverable deadlines. With the delivery of Milestone 2 it was accepted that a drastic scope change and the lack of software development experience among the team posed a significant challenge. However, given the combined expertise of the individuals in the field of electrical and computer engineering, the rapid pace at which the hardware had been developed meant that a complete diversion to software design could take place with enough time to create a meaningful user experience. Altogether, with careful decisions regarding the scope of the project as well as the acceptance that user experience can be an extremely subjective and difficult metric to gauge usability of a device, the predicted outcome of the project was a device that:

- Fully complies with the ‘convenience’ goals outlined in Section 2
- Reliably connects over Bluetooth Low Energy to a base device capable of both displaying movement data and notifying the user of unsafe movements
- Detects multiple types of injury that could manifest after a workout was complete
- Can operate for hours and for multiple sessions before requiring a recharge

Section 5 – Actual Implementation will describe the complete chronological development of all aspects of the finished device, and Section 7 — Evaluation and Reflection will reflect both on the goals and outcomes established in Sections 2 and 3, and the issues encountered in Section 6.

5 Actual Implementation

5.1 Sensor Hardware

5.1.1 Prototype Design

The design philosophy of the product is that the device should be cheap to produce, easy to use while being effective at its intended purposes. The sensor circuitry prototype is constructed using breadboards, which each individual components mounted on breakout boards and connected using cables. The circuit should consist of a sensor circuit, an ADC, and a BLE transceiver module. The output of the sensor circuit is to be sent to the analog input of the ADC, and digital output should be sent to the BLE transceiver module to be delivered over the air to the user's computer or mobile device. The resistance change of the flex sensors is measured using a Wheatstone bridge configuration, where the voltage difference between the two legs of the bridge is approximately linearly proportional to the resistance of the sensors within the physically realizable bending

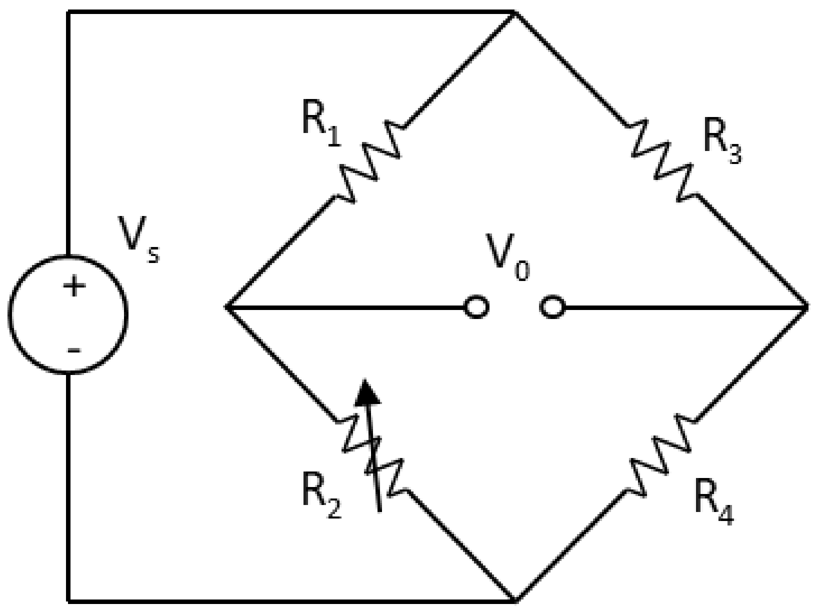


Figure 5.1.1: A Wheatstone Bridge Circuit

range. A two-sensor configuration is used for two reasons: It increases the dynamic range of the voltage difference across the Wheatstone bridge, and the resting voltage (where the sensor is not flexed) is close to 0 volts.

The ADC chosen was the ADS112U04, manufactured by Texas Instruments. It is a 16-bit, 2 differential-input ADC that uses sigma-delta modulation for conversion. This particular ADC is selected because the output digital signal is transmitted over UART, which greatly simplifies the data path and transmitter circuitry as it is asynchronous. Also, the ADC provides a very fine data resolution, with 65536 numbers mapped to the full-scale range of 2*V_{cc}. The 16-bit data is delivered in 2 packets of 10 bits each, which is in the form of the classic 8-N-1 configuration. The voltage difference of the sensor circuitry is sent to a differential analog input pair of the ADC, where the conversion can either be trigger on a command basis, or be triggered to convert continuously, with a maximum rate of 2000sample/s. To program the ADC for command-based, single-shot conversion, the following bytes packets is used to configure the setting registers by sending them to the Rx pin of the ADC. They are:

0x554848

0x554600

0x554206

The hexadecimal number 0x55 (or b01010101) must be used to synchronize the ADC's baudrate with the baudrate of the programmer. The following bytes are used to configure the contents of registers 0x04, 0x03 and 0x01 for single-shot conversion. To trigger a conversion, the bytecodes 0x5508 and 0x5510 are sent in succession, and two packets of converted data will appear at the Tx pin of the ADC. These two bytecodes can be sent continuously at a certain interval defined by a desired sampling rate, and the converted digital data can be received at this sampling rate. The reset code 0x5506 can be used to clear the setting registers and stop any conversions.

The BLE transceiver module chosen is the HM-10. This is a device based on the CC2541 BLE MCU manufactured by Texas Instruments. This module is selected due to its compatibility with the UART digital output of the ADC, whose asynchronous nature renders any additional clock circuitry unnecessary. On top of this, the HM-10 also have a small form factor that is optimal when building wearable solutions. The UART Tx pin of the ADC shall be connected to the UART Rx pin of the HM-10, and the UART Rx pin of the ADC shall be connected to the UART Tx pin of the HM-10. To regulate the supply voltage of the ADC and the HM-10 to 3.3V, the LD1117V33 voltage regulator manufactured by STM Electronics was used. The prototype was first powered by a 9V alkaline battery before being replaced by two 240mAh 3V coin cells in series to further reduce form factor. A switch is added to the reset pin of the ADC, which is nominally HIGH, so manual reset can be done. The power consumption of the prototype was also measured. Under continuous conversion of 20samples/s, the entire prototype circuit draws 19mA of current under 6V supply, which means that the circuit consumes 114mW of power when operating at this capacity. Since the final product will use a custom sampling rate with single-shot conversion, the power consumption will be even less.

The prototype fabrication and testing were completed by January 2022, which is followed by the PCB design and implementation phase.

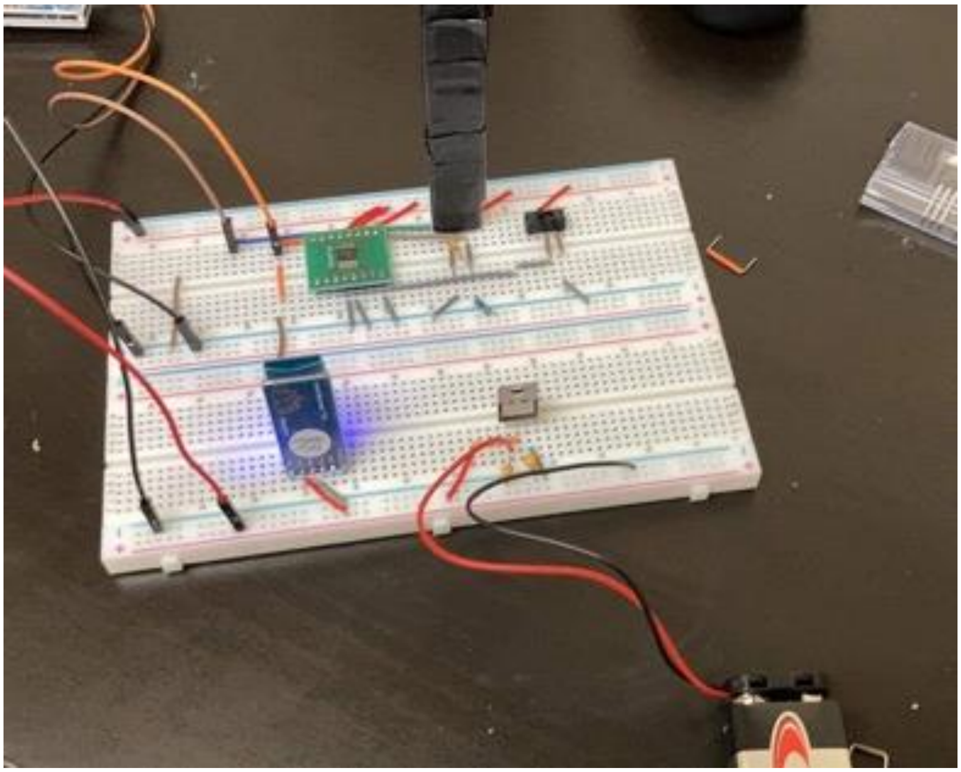


Figure 5.1.2: The Sensor Prototype Upon Completion

5.1.2 PCB Implementation

The PCB design activity was carried out using Altium Designer, and the design process lasted approximately 2 weeks. The decision to integrate a PCB sensor on to a wearable sleeve rather than an adhesive strip comes after some internal discussion regarding the adverse effects of such adhesive on a human body. The goal of the PCB sensor is to reduce the form factor of the entire

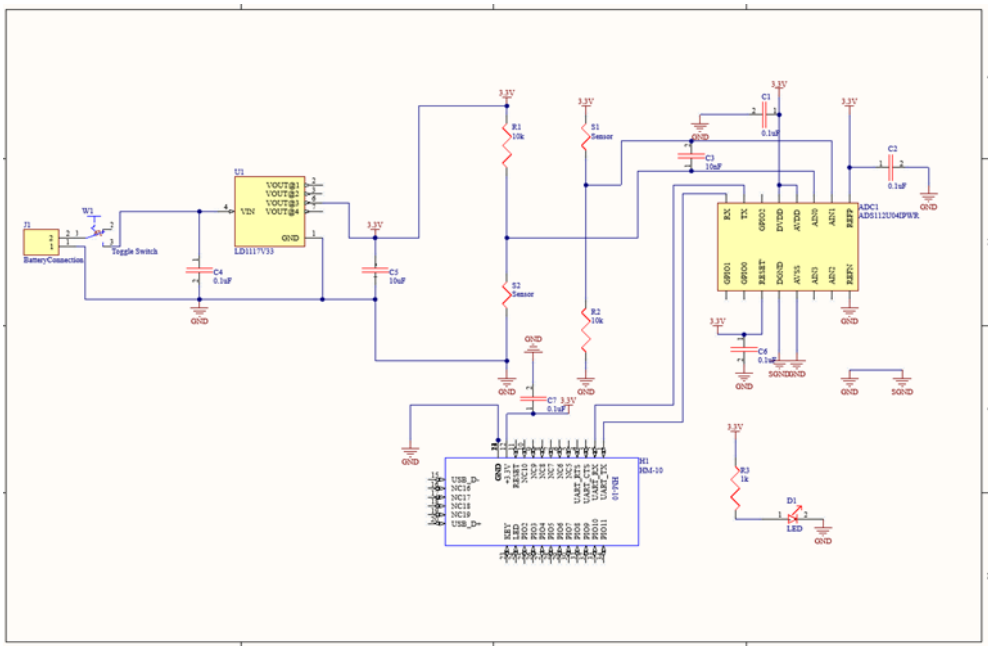


Figure 5.1.3: The Final PCB Schematic.

device while retaining its functionalities. The finalized circuit schematic of the PCB is shown below in Figure 5.1.3.

Two versions of the PCB were designed. The first one used many of the same through-hole components as the prototype, which proved to be cumbersome and uncomfortable to be worn. The final PCB drastically reduced the form factor by re-selecting some components as well as optimizing the position of the components. In the final PCB design, the 32-pin SMD version of the HM-10 was selected instead of the 6-pin through-hole version. This allows the HM-10 module to be placed directly onto the PCB, rather than hovering above it. SMD versions of the decoupling capacitors and sensor resistors were also selected. Furthermore, a toggle switch was added to turn the device on and off, and a power LED was added to indicate the status of the device. The flex sensors will be located away from the PCB and will be connected via cables to S1 and S2, while J1 will be connected to a coin cell battery holder, which is also located off the PCB.

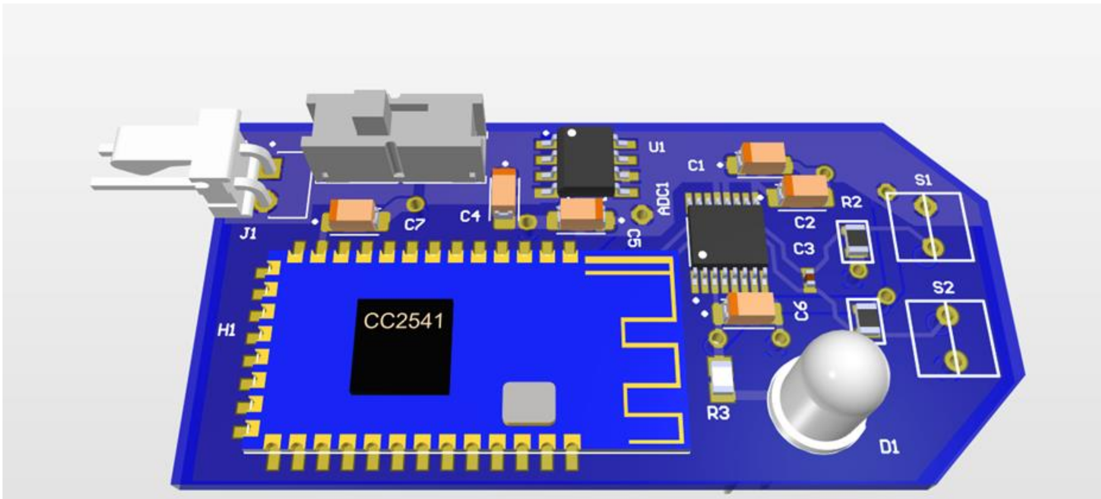


Figure 5.1.3: The Final PCB 3D model.

The Gerber file of the final design was sent to JLCPCB, based in Shenzhen, China for fabrication. The final product was delivered for soldering by March. Testing of the PCB was completed by early March. The final design is approximately 2 inches by 1 inch, and approximately 7mm tall (due to the toggle switch). The weight of the device when populated is negligible.


Figure 5.1.4: The Final PCB Design

5.1.3 Casing Design

The decision to house the PCB within a 3D-printed housing comes after some discussion regarding effective ways to isolate the PCB from outside environment, as well as protection against accidental ESD that may damage the electronics onboard. A casing was designed using Autodesk Inventor, that simultaneously hold the PCB in place without touching the electronic components, as well as provide a protection against the environment. Another advantage of incorporating the printed casing is that it can be easily fixed onto a fabric sleeve by attaching either Velcro or snap buttons on the bottom.

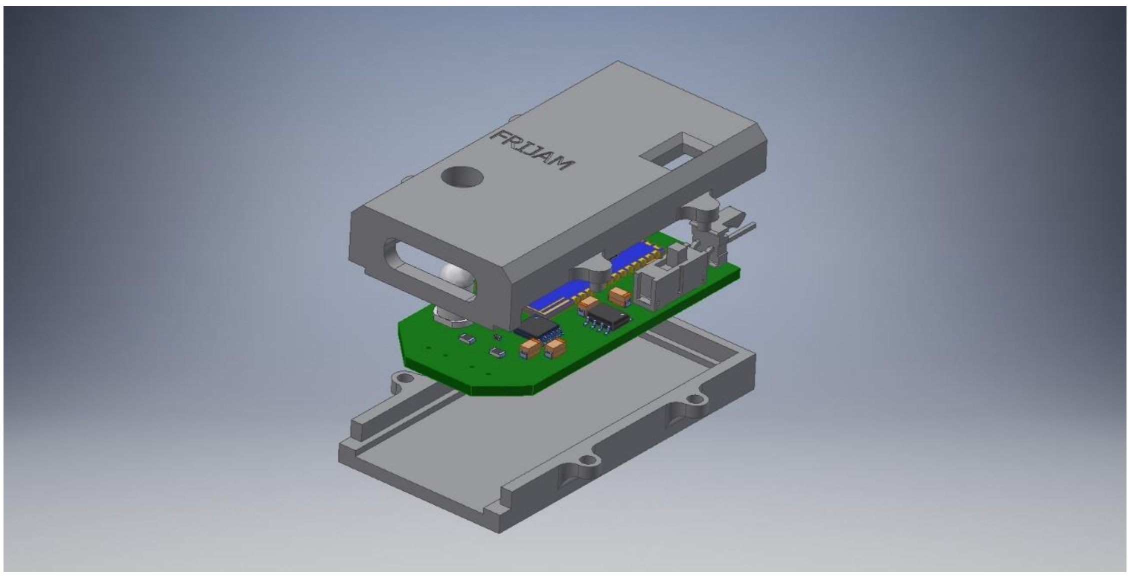


Figure 5.1.5: The 3D model of the casing with PCB

The bottom half of the casing has a ledge such that the bottom of the PCB is elevated above the floor of the casing. This removes any contacts that through-hole components might make with the floor, such as the LED and the switch. The top casing provides another set of ledges that presses onto the PCB at places far from any electrical components, such that the PCB is held in place. To fasten the top and bottom casing together, the four pillars on the top casing is to be inserted into the corresponding holes of the bottom casing. At the top of the top casing, cutouts are made for the LED and the toggle switch, and the at the front and back, cutouts are also made for the sensor cables, as well as the battery holders, respectively. The dimension of the design is measured to be 57mm in length, 29.5mm in width, and 12.8mm in height. The casings are printed using PLA, with an 80% infill. This way, the structural strength of the casings is maintained, while keeping the entire assembly lightweight and the cost low.

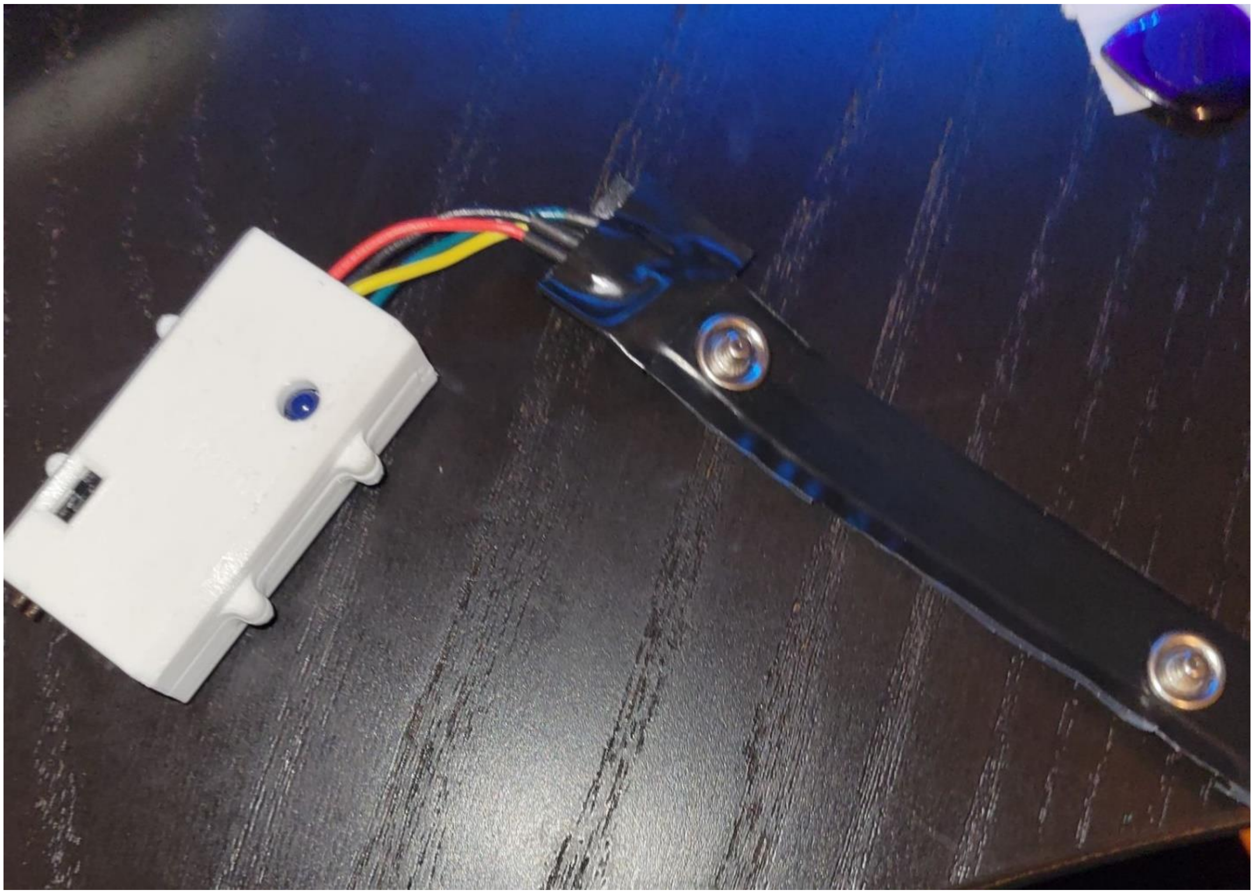
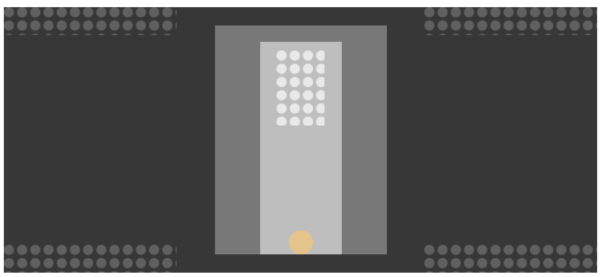


Figure 5.1.6: Physical casing with PCB

5.2 Wearable Sleeve

The sleeve design was a straightforward but important aspect of the project as it determined the comfort and wearability of the device, as well as the regions of the body it could be applied to. For the purposes of achieving specific calibration data in time for the Capstone Expo, the regions of application were limited to the knees and elbow only, to ensure that the prototype sleeve design works well.

The initial design consisted of five components:



The body of the sleeve, in the darkest grey, was to be made from moisture-wicking Spandex material, as spandex has a wide range of flexibility so that a material can be chosen that is tight enough to ensure accurate positioning of the sensor but loose enough as to not impede movement. The lighter grey region is an additional layer of spandex that is not moisture-wicking, to act as a moisture barrier and avoid any contact between sweat and the onboard electronics. The light gray circles represent Velcro patches that were to be sewn onto the Spandex layer and have been positioned in such a way that the sleeve is adjustable in size without the Velcro material impeding movement. To anchor the endpoint of the flex sensor, a snap fastener like those used on winter coats was to be used. Finally, to protect the sensor from wear, the region around where the fastener is placed was to be covered with a final layer of flexible fabric that is loose enough to make inserting/removing the device simple, while protecting it from the outside. An additional advantage to the choice of materials and construction is that the sleeve is machine washable, a requirement for any fitness clothing item. Also, the snap fastener provides a good visual indicator of the alignment of the flex sensor relative to the joint.

The final design was manufactured from the desired spandex material, however the construction was simplified as the multi-layered fabric feature was deemed unnecessary. The base material simply double-layered to produce the cuff, and so the flex sensor fastener could be neatly fastened inside the two layers, and since it was already insulated with electrical tape and properly sealed, moisture was no longer an issue for the sensor. The auxiliary hardware was additionally mounted outside the device so that it could be moved to multiple attachment points depending on the user's desired configuration.

Figure 5.2.1: Sleeve (Exterior)

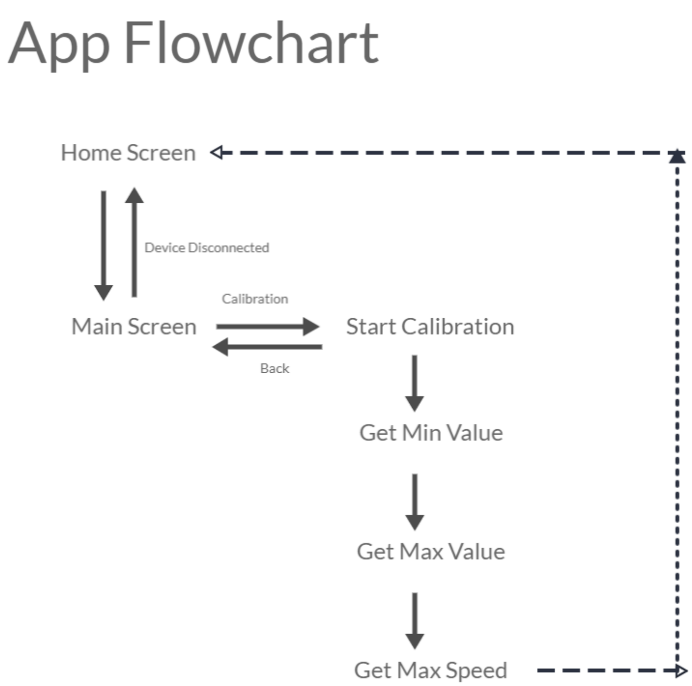
Figure 5.2.2: Sleeve (Interior)

In the final design, the battery casing is housed on the lower portion of the sleeve, with two separate attachment points for the Velcro strips, which are mounted vertically, not horizontally. This is to mitigate the way the fabric moves when horizontally mounted Velcro strips are used. When attached in a horizontal fashion, the difference in radius of the lower and upper arm, or calf and thigh cause uncomfortable and inconsistent stretching of the material. Towards the center of the sleeve, an additional layer of fabric is sewn on the interior to serve as the mounting pocket and features two snap-style fasteners to attach to one of two pairs of snap fasteners on the flex sensor, so that the sensor can be used on either the interior or exterior of the joint as it only produces accurate resistance readings when bent one way. The auxiliary hardware is mounted on the horizontal patch of Velcro in Figure 5.2.1. Altogether, this formed a very comfortable device. It was worn for hours during testing and all afternoon at the Capstone Expo and while it could be felt, it never became exhausting or inconvenient to wear.

5.3 App Implementation

For the app implementation, we used a similar GUI as we had before with a home screen once the app is loaded onto the device. The home screen gives more information regarding how the person should use the device. Below the information is a button that allows for the app to scan for our devices, which has been filtered with the names we gave to the HM10s. Once the device is found and they click on the device, they are brought to the main screen which has the start and stop recording button and the calibration button. When they click the start recording button, the app provides the write functionalities to the ADCs to get the values of the flex sensors to the Android phone. After this process is done, some data processing is done with the values to map the voltage value based off our calibrated values while also calculating the speed. Once this is completed, the phone will graph both the position and speed of the flex sensors onto the phone with the red line indicating position and green line, which is for speed. Afterwards some error checks are performed based off whether the values exceed the calibrated values. If they do, then the writing process is halted, and a vibrating noise is being sent with the accompanying warning message. This process will loop until either the user decides to stop the writing process, or the devices disconnects.

For the calibration, we have a screen that describes the whole process with a button for start calibration. Once the start calibration is clicked, we go through each stage of getting the values while starting the same writing process as for when we did the start recording. At the first stage, we get the value and write it into a file which holds the minimum value for extension. We do that repeatedly until the button is pressed again, and we go to the second stage, which is similar, but now for the maximum value. At the third stage, we tell the person to start moving the elbow at a rapid speed while providing with a gif for reference. Then when they start moving their elbows, we take each value and calculate the velocity based on the same method as with the start writing to provide for consistency and take the maximum value and write it into a file, to which they are done with the calibration, and they are sent back to the home screen so the calibration can be set up.



6 Critical Problems Solved

6.1 Sensor Hardware

6.1.1 Size Constraints

The goal of the PCB is to have the components fit onto as small of an area while retaining its intended functionalities. This is a challenge because on one hand, the components must be chosen and placed in the most spatially efficient arrangement, and on the other hand, the layout must conform to any constraints that the PCB manufacturers may have, such as trace width, pad size and distance, via hole radius, and margin sizes. To achieve the best arrangement, the PCB designer software can be set such that a warning can be generated if one or more of the manufacturer constraints are violated. These constraints can be found on the manufacturer's website, and they are reviewed and applied to the designed software. Within the manufacturer constraints, the most optimal placement can be found using trial and error. Via holes are used to route a signal path to the bottom of the board if the top of the board is too crowded. In the end, 68% of the area of the board is occupied by electrical components, reducing the size of the PCB to 2 inches x 1 inch. This is because the edge of the PCB is purposefully left vacant, such it can be mounted in a 3D-printed housing, as described in section 5.1.3.

6.1.2 PCB Defects

After the shipment of the finished PCBs, a short circuit test is performed to determine whether unexpected connections exist. An unexpected connection was discovered on the board that shorts the ground plane and the 6V plane at a capacitor pad. This defect if undetected can cause the battery to catastrophically discharge, with the potential of starting a fire. Steps were taken to remove the connection using a small X-Acto knife to scrape away the extra copper trace, while retaining the shape of the capacitor pad. Using this method, the short circuit was removed, and the PCB functioned correctly after battery connection.

6.2 App Implementation

One of the biggest problems we faced when designing the app was the Bluetooth Low Energy library to be used for communication between the PCB and the Android phone. At first, we used the library Bleak which had cross-platform support with the Kivy GUI on Python, but because of its use with asynchronous framework, it was hard to integrate it with the GUI. Then using another BLE library called ABLE for Python, we had problems with writing to the PCB, so we decided to switch to Java and use the integrated Android BLE library. But after that also didn’t work, we decided on the solution to use a working framework of another project that was done in Kotlin.

7 Evaluation and Reflection

The FRIJAM device and our team have seen a lot of progress over the past 8 months. During our initial brainstorming sessions, we thought of making a simple posture correcting device which after many long nights turned into the flexible joint monitoring system we have today. Throughout this journey the scope of our device changed numerous times, we went from correcting posture to implementing a device sophisticated enough to prevent deadly sports injuries and aid recovery patients. Even our physical implementations changed from executing our product on a raspberry pi to developing a full-fledged android application.

Our team has endured many difficulties and setbacks on our Capstone journey. From the communication troubles we had while working through our project remotely to the loss of time we had to deal with when our entire team caught covid days before the expo. Through all this and more we persevered. Thanks to our unique skill sets and collective efforts we were able to successfully create our very own circuitry and fine-tune it enough to be printed on a PCB. Nearly 5 months into our project we shifted our entire code base and created a functional android app. In the end, we have achieved all our major product milestones to create a fully functioning wearable device for our users.

As for the execution of the device, the FRIJAM group believes that we achieved the goals outlined in Section 2: A convenient, wearable device that promotes awareness of how the body moves. Our drastic scope change, despite seriously hindering our ability to program towards the end of the schedule, yielded a far better product than one requiring an auxiliary box to deal with.

8 Future Plan

Though we have come a far during these past 8 months we still have many plans and aspirations as to the direction we want to see our FriJam product go. From finishing our Gold Milestones to taking our product to market the team has our work cut out for us if we are to continue this project. Moving forward our first and most sensible plan would be to fulfill each of our silver and gold deliverables that we have been working towards till date. This would be the equivalent of us putting the finishing touches on this stage of our product.

During the next phase of the FriJam device, we want to see our network be able to handle multiple sensor sleeves in parallel. We want to enable the full list of functionalities for our app where the user can calibrate and switch through multiple sleeves at various different joint locations and share the readings with their medical support staff. Additionally, for the hardware, we would like to incorporate a long-lasting rechargeable battery and improve upon our power safety circuitry.