Delivering Effective Physical Therapy Remotely via a Wearable Sleeve and Mobile App

A Technical Report submitted to the Department of Electrical and Computer Engineering

Presented to the Faculty of the School of Engineering and Applied Science

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In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Evan Magnusson

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Technical Project Team Members

Christopher Hassert

William Kodama

Hart Lukens

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Harry C. Powell, Department of Electrical and Computer Engineering

Statement of work:

William Kodama

My main contribution to the team is serving as project manager where I spend most of my time assigning tasks to be completed and making sure that the team remains on schedule. This works usually involves planning, discussion with individual or multiple members at a time, and evaluating our objective key results at the end of the week. Additionally, I manage the flow of communication between members conducting parallel tasks in tandem as stated in our Gantt chart.

I also mainly contributed to the KiCAD schematics having imported, routed, and designed our circuits. I have also contributed to the development of the parts lists, gathering of datasheets, and background research into the key components within the schematic. Finally, my last contribution thus far is the development of the software flowcharts for the embedded system and will be taking on that role completely once our boards are designed and assembled.

Evan Magnusson

My contributions to the team include designing and integrating the overall software architecture, managing the software development process between the iOS app and web portal, and selecting components for the power subsystems within our schematic. For the overall system, I chose the front-end frameworks (SwiftUI and React.js) and the backend system (Firebase). Also, I have designed the database structure and implemented the necessary backend functions into the iOS app, specifically those that create, read, update, and delete records for patients and exercise results. Each week, I have selected and overseen the tasks completed on both the iOS app and web portal, and have ensured that the two work seamlessly together. In addition, I was responsible for creating the Bluetooth service within the iOS app that connects to our embedded system.

My contributions to the embedded system have primarily concerned selecting the correct components for our power systems. I reviewed schematics of similar systems, datasheets for the subsystems selected and calculated various resistor and capacitor values that satisfy our design requirements.

Hart Lukens

My contributions to our capstone group have been mainly in the form of developing an iOS app as our physical therapy patient portal. I have changed the user interface of the profile page, login and signup pages, and home page. I have also added functionality such as an image picker so the user can select their profile image, a settings page so the user can edit their information, and an XP system that is based on the number of exercises a patient completes. Finally, I have added a messaging system where patients and therapists can communicate with each other through their respective portals.

For my secondary role as a hardware designer/tester, I've worked with Chris to develop the test plan for our PCB. I've also been providing insight on board design and component selection for our schematic. This has involved reading datasheets and referencing previous material from the

FUN series. After our board was manufactured and assembled, I on worked with Chris to test the functionality of the board and ensure that everything is working as it should.

Christopher Hassert

My contributions to our capstone group have mainly been in the form of developing our PT web portal. I have changed the user interface of our dashboard and provided redirect functionality to individual patient pages. I have also learned multiple libraries such as three.js, Firebase, react-three-fiber, and many more to implement the necessary features of this web application. Most recently I've been using three.js and react-three-fiber to provide 3D visualization of human motion tracking data on our web portal. This has involved reading 4D coordinate data from our Firebase database and calculating quaternion rotations to move a 3D character on the screen to show patient movements.

For my secondary role as a hardware designer/tester, I've worked with Hart to develop the test plan for our PCB. I've also been providing insight on board design and component selection for our schematic. This has involved reading datasheets and referencing previous material from the FUN series. After our board was manufactured and assembled, I worked with Hart to test the functionality of the board and ensure that everything is working as it should.

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Abstract
Monitoring patient health via remote technologies has become increasingly prevalent in today's pandemic driven world. With new wearables and computer vision algorithms, medical devices are beginning to revolutionize the world of telehealth. Similarly, there is an increasing need for physical therapists to provide a novel way of prescribing at home exercise programs (HEPs) with proper patient compliance and the ability to be remotely accessible [1]–[3]. After receiving feedback and hearing about the problems plaguing the physical therapy space, the research group identified a need for a solution to patient compliance, data sharing, and automation. Thus, the deliverables of this project is a wireless motion capture sleeve that tracks, analyzes, and shares human motion data over Bluetooth Low Energy. The sleeve will consist of 9-axis inertial motion units and Bluetooth Low Energy chip that will send quaternion coordinate data to a phone or central server utilizing the Bluetooth beaconing method, where the peripheral sensors are the beacon and the phone or central server is the scanner.

Background
Wearable technology is a category of electronic devices that can be worn as accessories providing hand-free capabilities and sending/receiving data via the Internet. From the invention of eyeglasses to smartwatches, wearable technologies have continued to dominate the consumer marketspace. Over the past few years there has been a shift to more specialized and practical applications for such technologies. These include virtual- and augmented-reality, physical therapy, fitness, and general user wellness.

One specialized area of wearable technology adoption can be found in physical therapy. If someone were to simplify the entire physical therapy space into a process of getting a patient from point A to point B, it would be a mess. The physical therapy world is riddled with inefficiencies and unknown variables which often leads patients down paths developing into chronic pain, long-term drug use, or reinjury. Three key problems in the physical therapy space include:

1. Most patients are unable to perform effective and compliant exercises at the cost of their job, time, and money.
2. There is no quantitative data demonstrating the ultimate effectiveness of each physical therapy session.
3. Insurance companies are paying an excess on surgeries and long-term drug use that could be prevented with the completion of physical therapy.

These are only three key issues amongst hundreds of problems the group has identified after half a year of talking to physical therapists, patients, surgeons, and the researches in the field.

With patients already suffering from a life changing event, the need to recover quickly and efficiently is placed at a greater importance. Yet, patients are overwhelmed by the number of visits per week to PT clinics, travel constraints, and the opportunity cost of time away from jobs and families. This causes patients to end their course of physical therapy well before successfully recovering. Research indicates that 70% of patients do not complete their prescribed course of treatment and never reach their full potential wellbeing [4]. This is because as patients begin to see even slight improvements in mobility and relief from crippling pain, their incentives to sacrifice time, work, and family obligations for PT sessions drop significantly. Thus, our suit provides the convenience of enabling complaint at-home therapy routines with quantitative data collection to ensure recovery. This eliminates the need to sacrifice time by receiving professional care anywhere, anytime.

Health insurance companies spend unnecessary costs per year for patients with a physical injury who undergo long term drug use, chronic pain, or reinjury. These can all have a high likelihood of being avoided if patients undergo physical therapy as stated anecdotally and in literature by PTs and surgeons. For example, in a APTQI report from 2017, beneficiaries who receive therapy within the first 15 days, compared to 45-90 days after being diagnosed, are observed to have downstream costs that are ~ 27% lower on average [5]. However, insurance companies, Medicare, and physical therapists are missing the quantitative measurements and reports needed to justify such claims and treatments are effective. Additionally, Medicare has become the most susceptible government mandated program in the United States to lose money due to fraudulent claims, with over $60 billion lost to waste in 2017 [6]. This can be mitigated through the accurate data reporting using the group's suit.

Overall, the currently available approaches are not practical because physical therapy practices are often inefficient and ineffective, or emerging technologies fail to offer solutions that benefit patients, insurance, and physical therapists/clinics together since they are all interconnected stakeholders in physical therapy. Thus, the current innovation is, in embodiments, a full-body physical feedback system with motion tracking capabilities that can be modulated into upper-body, lower-body, or arm only sections. For the deliverable for this project, the research group aims to develop a separate motion tracking sleeve combined with a mobile app and web portal to visualize and analyze the data from a patient. Additionally, the research group has a stretch goal for a resistive elbow system prototype, but the group will evaluate this goal depending on the milestone reached.

The team will draw from their Fundamental series coursework for designing and testing the board schematics and layouts in Multisim. Additionally, knowledge pertaining to designing an embedded system both in terms of hardware and software will draw from a variety courses including Introduction to Embedded Systems (ECE 3430), Advanced Embedded Systems (ECE 4550), Computer Architecture (ECE 4435), and FPGA Lab (ECE 4550). Regarding the Bluetooth implementation, Radio Frequency Circuits (ECE 4209) is one of the only courses available at UVA which teaches anything similar so foundational knowledge about the Bluetooth system will be drawn from there.

Constraints

Design Constraints

The group will be in housing the manufacturing parts of the sleeve using their own 3D printers [7]. The manufacturing of the PCBs and their assembly will be handled with the guidance of the two professors. For in housing the electronics, the team plans to use Digikey [8] for all of the electronics. One design constraint is that the unit needed to be portable and rechargeable. This led to the development of the LiPo power circuit on board to charge the LiPo battery and control how the circuit is powered when a USB power source is connected.

Economic and Cost Constraints
With a three-pronged approach to improving the physical therapy experience, there exists a method to develop a hardware system meant to replace at home exercise equipment while focusing on selling the software platform with the 9-axis motion capture system. With an approximate $63 million home therapy equipment market [9]–[11] there definitely is a niche for a device such as the one described in this proposal. In terms of cost, initial research has led to competitors including MIO Therapy who sell a motion capture system with a mobile application. The goal would be to match the costs to produce the same number of units and technology for below or under the same amount.

External Standards

For the BLE protocol, from the team's understanding, the product will need to meet either Apple or Android protocols which have started to be implemented within the code. If the group decides to use Android, the use of Eddystone guidelines would need to be followed, whereas if Apple products are used, the team would need to follow iBeacon guidelines using major and minor implementation [12].

Additionally, the group will most likely need to abide by FCC regulations and eventually pursue FCC approval for the system. Since our BLE module is anticipated to operate at around 100 MHz, it is required to be type accepted for part 15 Federal Communications Commission (FCC) regulations. Our modules are designed for wireless communication, so they are classified under Part 15 Subpart C as intentional radiators. Within this part both sections §15.247 [13] and §15.249 [14] apply to our project.

§15.247 states the following for digitally modulated intentional radiators [13]:

1. The minimum 6 dB bandwidth of the signal shall be at least 500 kHz.

2. For digitally modulated systems, the power spectral density conducted from the intentional radiator to the antenna shall not be greater than 8 dBm in any 3 kHz band during any time interval of continuous transmission.

3. In any 100 kHz bandwidth outside the frequency band of operation the power shall be at least 20 dB below that in the 100 kHz bandwidth within the band that contains the highest level of the desired power.

§15.249 States the following for operation within the 908 - 928 MHz band [14]:

1. The maximum permitted field strength at a distance of 3m from the radiating source is 50mV/m.

2. The maximum permitted field strength of harmonic components is 500µV/m at a distance of 3m from the radiating source.

3. Emissions (other than harmonics) radiated outside of the 908 - 928 MHz band shall be attenuated by at least 50 dB below the level of the fundamental frequency. Since our

microcontroller operates at a frequency above 9 kHz, it is regulated under the FCC's Part 15, Subpart B as an unintentional radiator.

Tools Employed
The CAD tools that the research group will be required to use include Autodesk Fusion 360 [15] and KiCAD [16]. The Programming Tools required include Xcode, Swift 5, SwiftUI framework, Visual Studios, C, and C++. The CAD tools were used in the design 3D modeling of the sleeve for the project. The Swift 5 programming language and the SwiftUI framework were used to develop the mobile application, which includes the Bluetooth connectivity and the motion tracking software. Further software tools used for mobile application development includes the Xcode IDE. C and C++ were used for the embedded code, which includes a Bluetooth module and I2C code.

Ethical, Social, and Economic Concerns

This product will allow physical therapists and their patients to have better communication and better treatment. Ideally, this system would be covered by health insurance if it were available in the market, allowing access to both high-income and low-income patients. It is critical to protect patient's healthcare information and data, our system uses Firebase with Google Cloud Identity which are HIPAA compliant and encrypted. We expect with our physical therapy system implemented, that the number of patients who do not complete their assigned treatments will decrease and it will also lead to higher satisfaction rates among therapists and their patients.

Environmental Impact
Plastics used for manufacturing, packaging, and transportation are the major concern when looking at the environmental impact of the hardware. However, the group also aim to reduce the need for extensive transport from and to PT clinics along with the decrease in use of paper documentation which is still a prevalent medium of taking notes among private clinics.

Thermoplastic Polyurethane (TPU) is the main flexible material that we will use for our sleeve. This can either be disposed either through recycling or specific 3D printing filament recycling plants. The electronics can be disposed at a local electronic recycling center.

Sustainability
The product aims to be sustainable via the software application which is meant to draw in physical therapy patients to a secure and engaging environment. Using this platform and through the development the hardware, the products can then be sold and used to users and stakeholders within the physical therapy space for a more efficient and remote therapy experience. The products can be reused and can be circulated among larger group, with the appropriate steps of sanitation and privacy, making it a suitable product for sustainability. COVID has opened the world further into the field of telehealth that provides a ramp to gaining users as people become more accustomed to a socially distanced world.

Health and Safety
With the current COVID pandemic, the team is taking into consideration the capability of the device being used amongst multiple users. This would involve cleaning and sanitizing the device after every use to ensure that it remains virus free.

Manufacturability
Currently, the product utilizes both additive and subtractive manufacturing methods. The group has four 3D printers that can print pieces utilizing various filaments to achieve different material properties. Additionally, the team is implementing traditional subtractive manufacturing such as water jetting, water cutting, and lathing.

Ethical Issues
One major consideration for the ethics behind the device is the data privacy and security of the patient data. With user privacy being a large topic today, it is critical that the group creates follow ethical codes such as HIPAA [17] when it comes to analyzing and sharing human motion tracking data.

Intellectual Property Issues
Patents *US8589114B2*, *US20160125348A1*, and *US10433033B2* have claims that encompass material similar to the group's project in the realm of wearable human motion capture. These claims do not however prevent the group from patenting the technology [18].

For *US8589114B2*, while the system architecture is similar to the group's project, each independent claim (claims 1, 22, 23, 24) mention that the physical embodiment of the invention is a "non-wearable" motion sensor unit, whereas the group's project specifically is a "wearable" motion sensor unit [19].

For *US20160125348A1,* the independent claim 1 describes a similar system to the group's project, with the difference being that the invention includes "a base unit including docking component configured to recharge the rechargeable battery and configured to communicate with the transceiver to receive the movement data." The group's project does not include any base unit and has a transceiver configured to communicate with a mobile device rather than a docking station. As the independent claim in which the dependent claims build off of, this patent would not hinder the group's project's patentability [20].

For *US10433033B2*, the independent claims (claims 1, 10, 15) all include a system similar to the group's project, with the key difference being that the wearable peripheral communicates with a separate wearable "communication hub." The group's project does not include such a thing, and has all communication capabilities built into each singular peripheral.

Detailed Technical Description of Project
The scope of this project includes the research and development of a Bluetooth Low Energy (BLE) mesh network that communicates and shares information between peripheral devices and a mobile application. This includes the design of a 9-axis motion capture mesh, a mobile application and online dashboard to visualize and analyze the incoming motion capture date, and a power system. A system of minimally viable products has been completed for:

1. A BLE mesh network of 9-axis motion processing unit (MPU) sensors communicating with a central processing unit using BLE beacons
2. A mobile app to collect and display sensor data

3. A rudimentary power bank system to provide power to the electronics and sensors (the motors are still being powered separately).

The group is looking to combine, minimize, and optimize these systems for the need in moving from the hobby leagues to an alpha stage commercial product. The focus of the project will be first placed on the peripheral motion capture sensors with the central and motor systems being a stretch goal for the group, only to be developed after completing the motion capture peripherals. The high-level block diagram of the system is shown below in Figure 1. However, after reviewing the feasibility of designing both systems, the group will only focus on the sensor peripheral system outlined below.

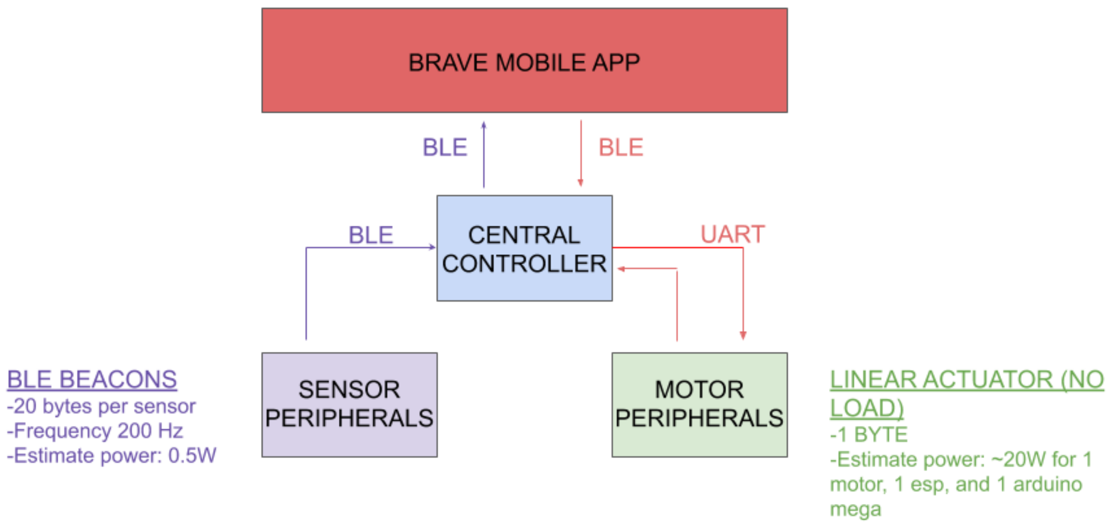

Figure 1. Overview of the System

9-axis Motion Capture System

The overall design of this system would be to strip down, combine, and repurpose off the shelf based systems that are currently use into a single system. The project currently uses the MPU-9250 which is a System in Package (SiP) that combines two chips: the MPU-6500, which contains a 3-axis gyroscope, a 3-axis accelerometer, and an onboard Digital Motion Processor capable of processing complex MotionFusion algorithms; and the AK8963, a 3-axis digital compass. This then communicates over I2C with an ESP32 DevKit board that uses an attitude and heading reference system algorithm to fuse the sensor data to get output quaternions of the orientation of the sensors in 3D space in real time over BLE through the use of beaconing.

Beaconing is a BLE term that involves the use of beacons, a server that advertises data either constantly or in intervals. Beacons can then be scanned for and data there scan response data can be read up to 31 bytes. The reason for implementing beacons into this design is the unique aspect that the client scanning for the beacon does not need to connect beacon to receive the data. The client can just receive the scan response associated with the beacon and move onto the next device. This is extremely useful in that this method saves both time and power when needing to read from multiple peripheral sensors. In this application, the beacons will the peripheral sensor systems that will be advertising 22 bytes of motion sensor data. Additionally, we will be utilizing an operating system to maximize throughput by implementing multithreading and to utilize the dual cores of the ESP-Wroom-32D which contains a dual core Xtensa processor.

The final major aspect of the design is the power system associated with each peripheral device. The group aims to implement a power supply that automatically switches between USB and LiPo supplies depending on whether the micro-USB is plugged into the board or not. Additionally, the group wants to research into power charging to implement a multi-charging approach of charging multiple peripheral systems at once.

The expanded view of one of many identical sensor peripheral systems for the motion tracking BLE mesh network is shown in Figure 2 below.

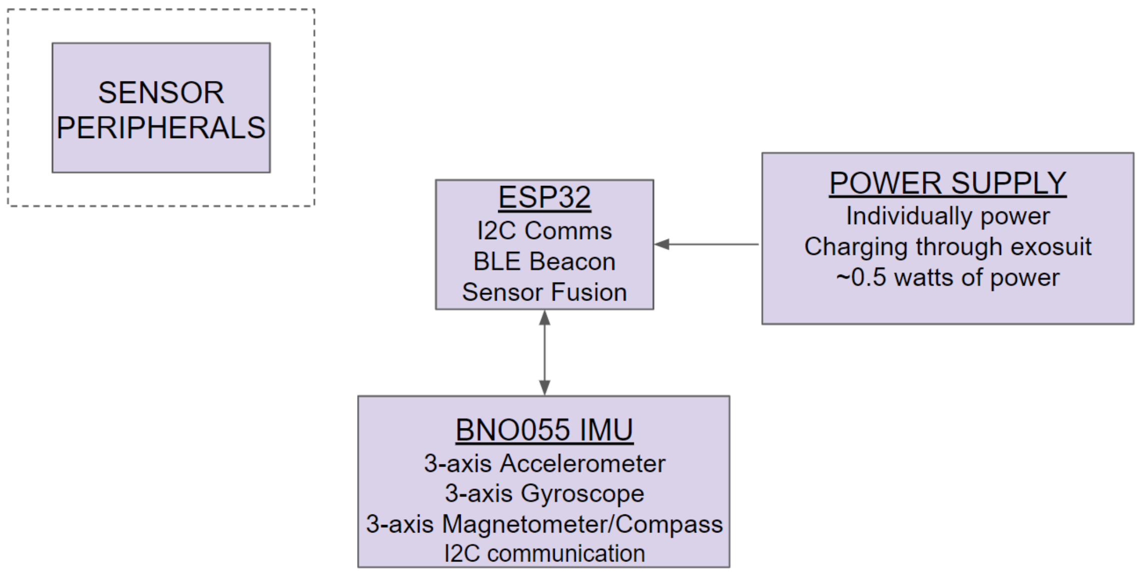

Figure 2. Expanded View of Sensor Peripherals

The schematics for this system are shown below in Figure 3 and Figure 4.

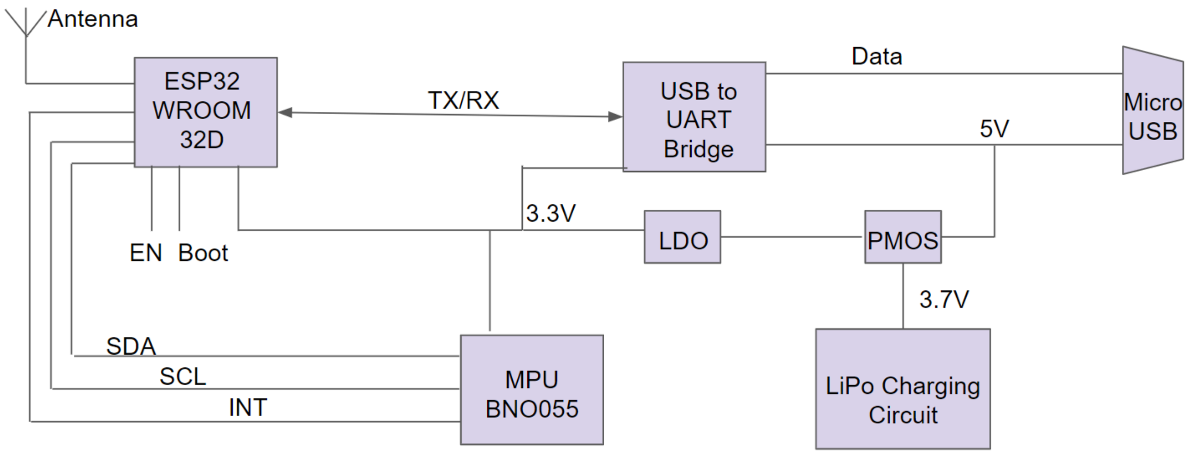

Figure 3. Schematic View of the Sensor Peripherals

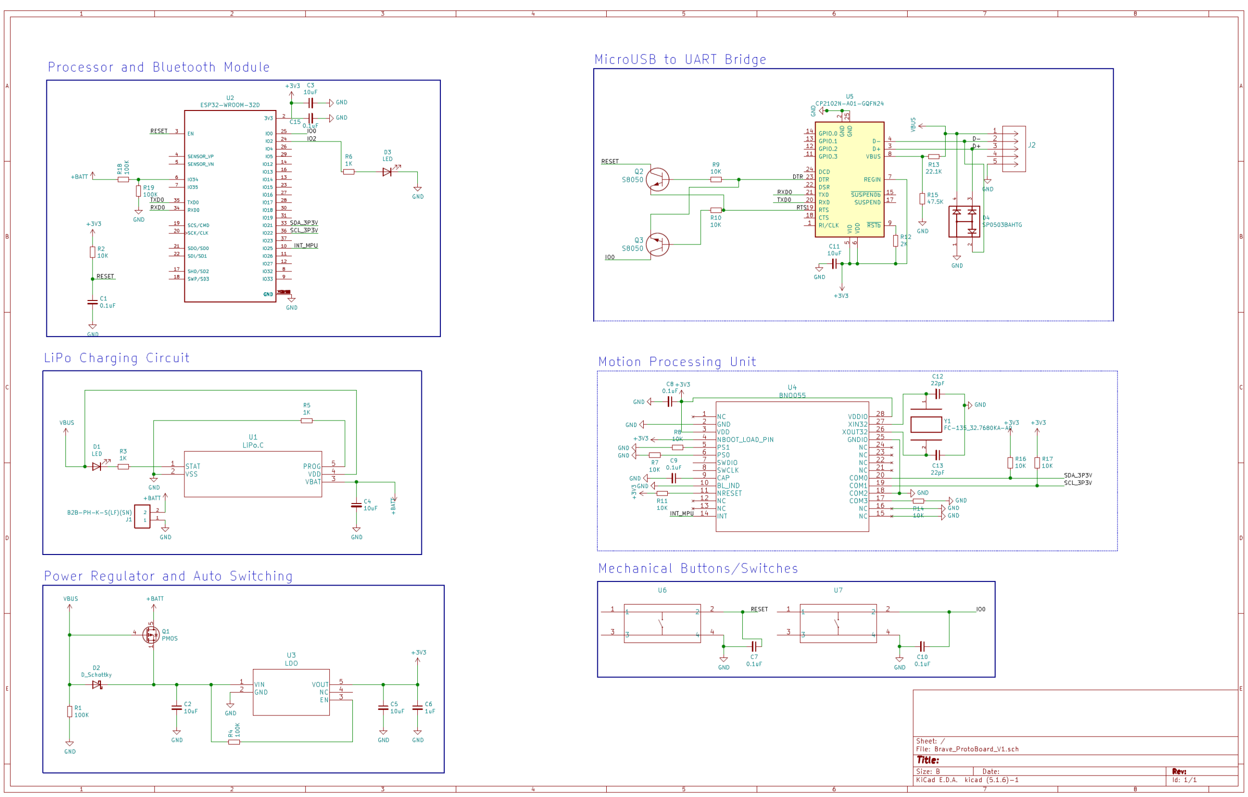

Figure 4. KiCAD Schematic

The ESP32-WROOM-32D module in Figure 5 was chosen due to its integration of a dual core Xtensa processor and Bluetooth module. Since the part is already cleared and verified by the FCC, the team decided to choose this module over designing our own RF circuit that will cost more time and money in the short and long term.

Processor and Bluetooth Module

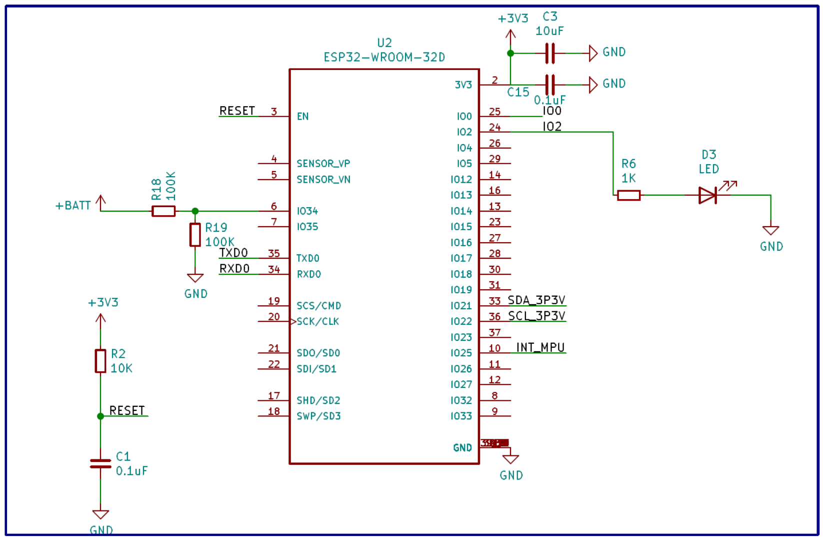

Figure 5. ESP32-WROOM-32D Processor and Bluetooth Module

The next hierarchal block is the LiPo charging circuit that is being implemented in Figure 6. Since the circuit will run mainly off of battery power, a charging circuit is necessary to recharge the LiPo. The initial LiPo battery that we have chosen will be a 4.2V with 1000 mAhs, thus the progress resistor we have chosen is 1K ohms to charge the LiPo as quickly possible without damaging the battery.

LiPo Charging Circuit

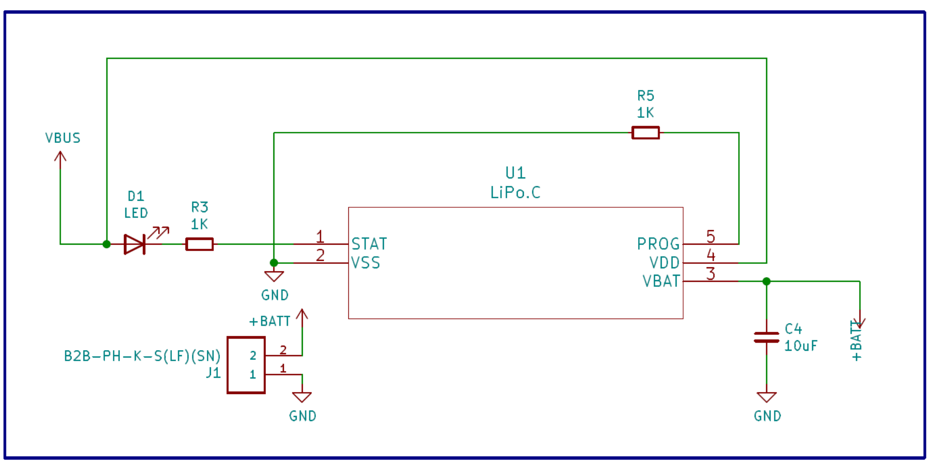

Figure 6. LiPo Charging Circuit

In addition to the LiPo charging circuit, the circuit Figure 7 regulates the voltage from USB power and battery power. The PMOS at the top of the diagram acts as a switch where as when USB power is applied at the base, current from the battery is switched off. When there is no voltage at the base, current from drain to source is allowed to flow into the low dropout votlage regulator but it prevented from going back up the VBUS line because of the Schottky diode.

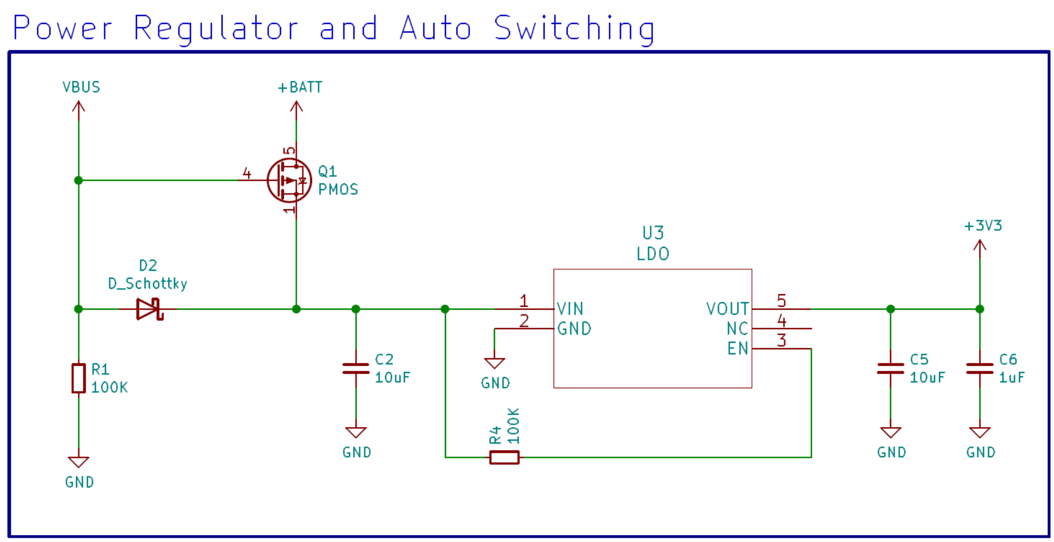

Figure 7. Power Regulation and Autonomous Power Supply Switching

The motion processing unit we will be using is the BNO055 integrated circuit seen in Figure 8. The design around this chip mainly stems from its datasheet. A few key components and features would be the pull up resistors on the I2C lines to provide stable data transfer and the external crystal to increase the accuracy and timing of the chip. We will also be using the interrupt pin from the motion processor to let the main processor know when there is new motion data available.

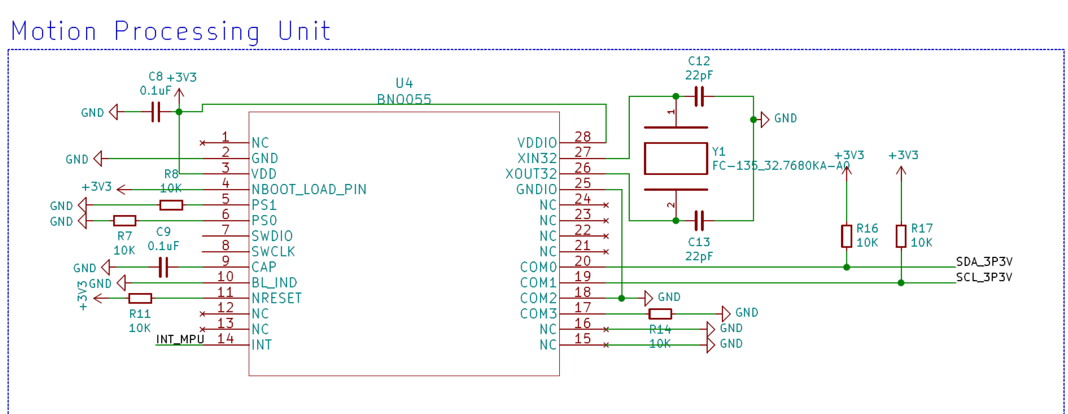

Figure 8. Motion Processing Unit and Peripheral Circuits

The micro-USB to UART Bridge circuit design is seen in Figure 9 that utilizes documentation from the CP2102N-A01-GqFN24 datasheet. The circuit includes the connector for micro-USB and the converter of USB 2.0 data into UART. This overall design, including the BJTs, draws from Espressif's open-source developer kits utilizing the ESP32-WROOM-32D and CP2102. After talking to Espressif support and a recent manufacture working with Espressif modules we have determined that the BJTs to implement an exclusive type of XOR logic that involves the DTR and RTS pins of the UART bridge. There is very little documentation explaining as to why they utilize this method, however, multiple, working designs utilize this circuit in their schematic.

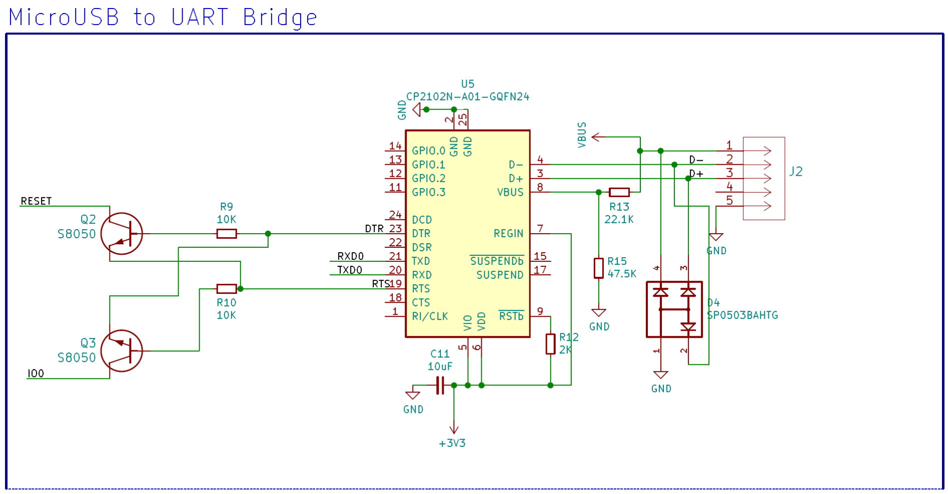

Figure 9. MicroUSB to UART Bridge Circuit

Description of board layout

For the overall design of the board layout, the overall design decisions revolved around three major parts: the ESP32-WROOM-32D module, the BNO055 IMU sensor, and the micro-USB connector. The ESP32 and micro-USB connector needed to be at either edge of the board due to functional reasons such as the antenna and port placement. Additionally, the BNO055 is ideally placed as close to the center of the board as to not complicate the orientation data coming in by being offset from the center of the board/band placement.

Other design rules were followed and were relatively straightforward which included as little ground plane connection as possible, no acute angles formed between routes, wider routes for power lines and connections, bypass capacitor were placed as close as possible to the component that they were associated with, little tot no route beneath the BNO055 as to not interfere with the sensor.

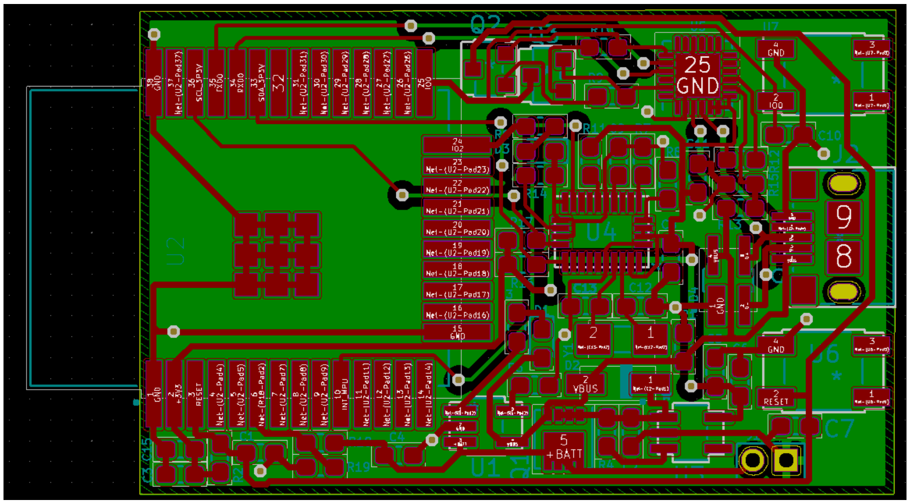

Figure 10. KiCAD Final Board Layout

Software

In order to process the 9-axis motion capture as well as provide an effective user interface, the embedded microcontroller connects to the user's mobile device via Bluetooth Low Energy. On the mobile device, the motion data will be processed live to track the user's exercise form, how many repetitions they are completing, and how much force they are outputting throughout a physical therapist prescribed routine.

As this process occurs live, the app cues the user during a workout with visual and audio cues when their exercise form deteriorates beyond a reasonable threshold. This prevents reinjury from occurring and ensures proper training while forming good habits. In addition, users will be able to see the time elapsed for each set, how many repetitions they have done, and their force output all in one robust graphical user interface.

After the completion of a full workout, the necessary recorded data is sent to a Google Cloud Firestore database for each user to then be reviewed by their physical therapist. The database entries are organized in a scalable fashion to ensure that the platform can handle *every* physical therapy clinic in the United States. Data is only stored and accessed after a user goes through two-factor authentication by Google Cloud Identity, ensuring that the solution is (Health Insurance Portability and Accountability Act) HIPPA compliant from end-to-end [17].

The application is designed to be a physical therapy platform for patients, connecting them directly to workout programming scheduled by their physical therapist. Patients can directly message their physical therapist, receive push notifications reminding them to complete their workout, and visually track their recovery progress over time all in one platform. Complementing the mobile application is a web portal that allows physical therapists to select, edit, and push workouts directly to their patient's phones, message them directly, and track their progress over the course of their recovery.

All of the software for the microcontrollers currently uses Arduino. However, the group plans to port all of the code base into C or C++. The code includes the motion capture and Bluetooth low energy implementations.

3D CAD Designing

The design of the 3D model will be completed primarily using Autodesk Fusion 360 [15]. This is a CAD development tool with the capability to also assess structural criteria such as safety factors, deformation of material under static/dynamic load cases, and also thermal stress analysis for 3D printed components and electronic hardware. The initial designs will include housing for the 9-axis motion capture system that will be attachable and detachable to an external prosthetic/exoskeleton suit system. This will serve the purpose of changing out the system for charging or replacement. The first iteration of this housing is shown below in Figure 11 that was used for the first and second iterations of the printed and assembled circuit boards.

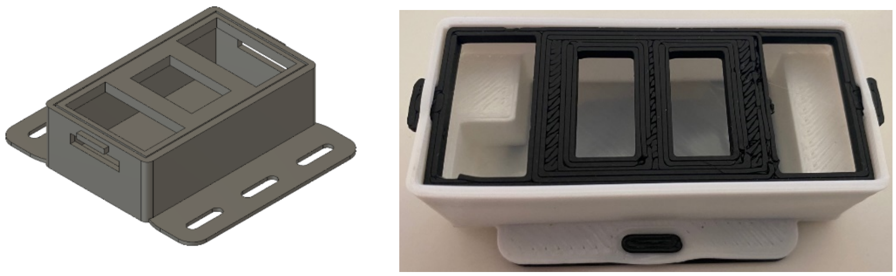

Figure 11. First Version of the Electrical Housing

The final iteration of the electrical housing for the final printed and assembled circuit board is shown below in Figure 12. The modifications include dimensioning of the overall housing to better fit the smaller printed circuit boards. Other changes include the additional covering layers to make the device water resistant for rowers who we will be testing with in February 2021.

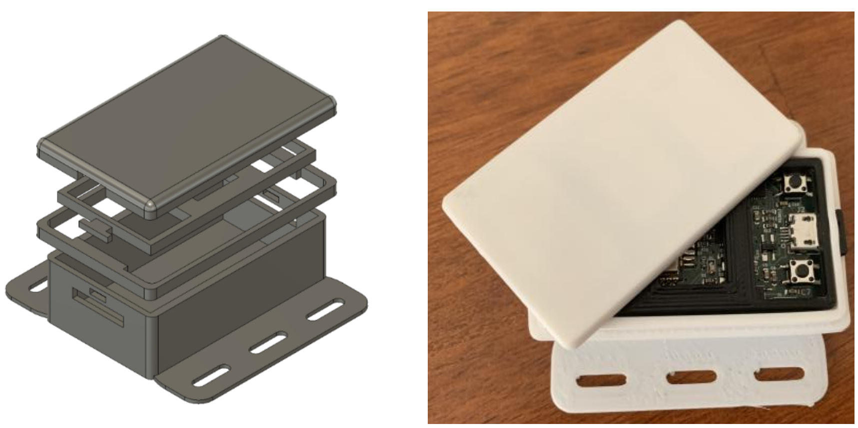

Figure 12. Final Version of the Electrical Housing

Design Problems and Modifications

The first board iteration encountered many problems from simple to complex. Through the use of the team's outlined test plan, issues were able to be resolved one by one. One of the first issues involved a lower-than-expected output voltage coming from the micro-USB which involved the extra Schottky diode place on the VBUS line in order to serve as extra protection to the device connected. Additionally, issues such as incorrectly place resistors on the TX/RX lines, on the voltage divider going into the UART bridge, and flipped RX/TX lines made it impossible to upload embedded code to the ESP32 and these changes were made by hand to resolve the issues as seen in Figure 13 below.

After resolving the issues with the USB to UART bridge, embedded code is now able to be uploaded and ran on the ESP32. The next issue faced involved the BNO055 sensor not sending data over I2C. Through multiple modifications seen in Figure 13 around the IMU, the team determined that the only resolution was to modify some of the connections of the IMU in accordance to the datasheet that we had missed on this iteration. Attempts to resolve these issues remained unconfirmed since the pins to the sensors were incredibly close together and it was difficult to determine whether the connected lines with in fact electrically connected with the IMU.

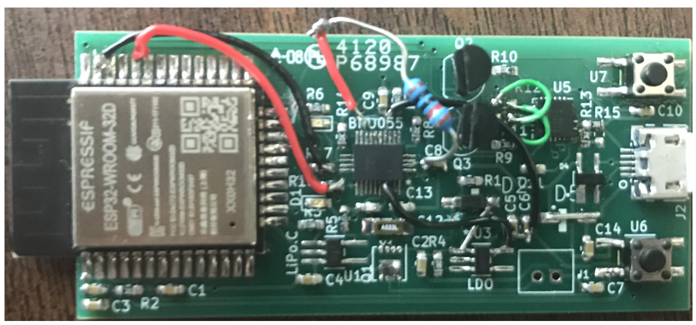

Figure 13. Version 1 Printed and Assembled Circuit Board

After an extensive two-week testing period on the first iteration of the printed circuit board, fixes and modifications were made to resolve known and lingering issues from the first iteration. The fixes include resistor additions and subtractions around the USB-UART bridge mentioned previously, removing of the extra or redundant components, and redesigning the connections involving the BNO055 IMU sensor.

Modifications to the design included different parts for the BJTs in order to save board space and reduce the height of the board. The overall size of the board was kept constant due in order to reduce the need of redesigning and reprinting the electronic housings made for the first iteration. Additionally, after gaining a better understanding of the circuit's power requirements and constraints, final resistor values were chosen for the LiPo charging circuit to enable fast charging capabilities to the LiPo battery.

After implementing these fixes and modifications, the board worked as expected. The team tested and validated the ESP32 to USB communication, the BNO055 sending motion data over BLE through the ESP32, and the LiPo charging circuit charged and protected the LiPo battery as expected. The resulting printed and assembled circuit board is displayed in Figure 14 below.

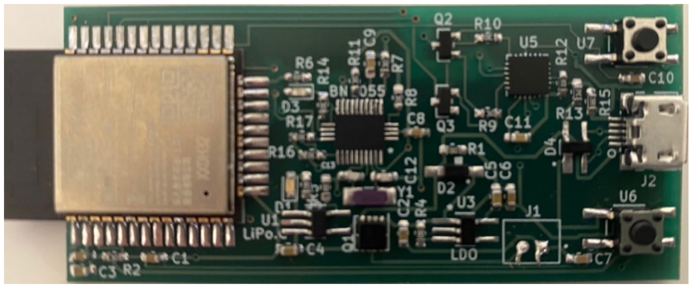

Figure 14. Version 2 Printed and Assembled Circuit Board

The final modifications made for the final printed and assembled circuit board seen in Figure 15, include the reduction of unused space and making the design more compact. Additionally, a voltage divider from the LiPo battery to an ESP32's ADC pin enables the monitoring of the voltage levels of the LiPo battery to determine mathematically the power level remaining in the battery for future implementation.

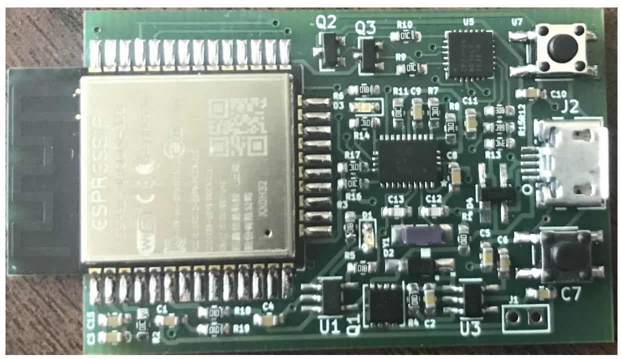

Figure 15. Final printed and assembled circuit board.

Project Timeline

Figure 16 shows our original Gantt chart from our proposal, and Figure 17 shows our final Gantt chart. In our original schedule we had a two-week buffer near the end of the semester. We realized that we would end up needing to use those two weeks due to adjustments to online classes and realizing information that our group did not know prior to starting the project. Therefore, we had to push some of the dates back regarding our circuit designs, layouts, and testing. Additionally, the team wanted to focus on hammering out the schematic designs for our circuit as soon as possible so that we can begin writing and testing our embedded code with the ESP32-WROOM-32D. The slight push back in due dates did not majorly affect our final deliverables, and we were still able to finish the project on our proposed timeline.

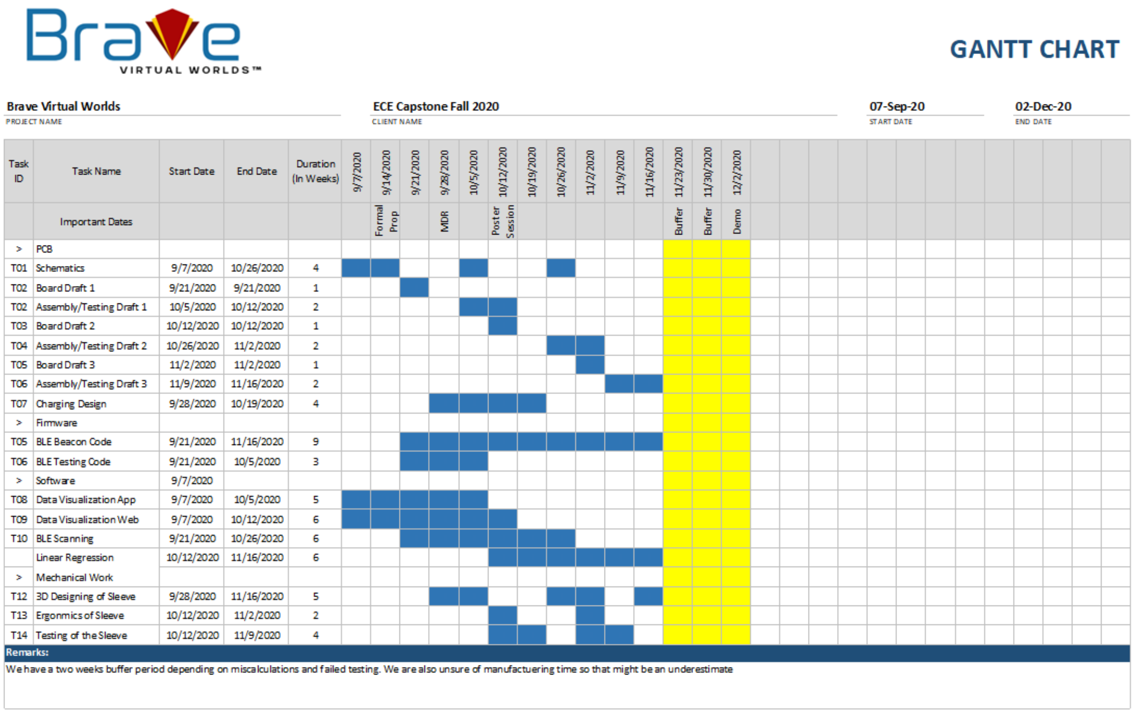

Figure 16. Original Gantt Chart from Proposal

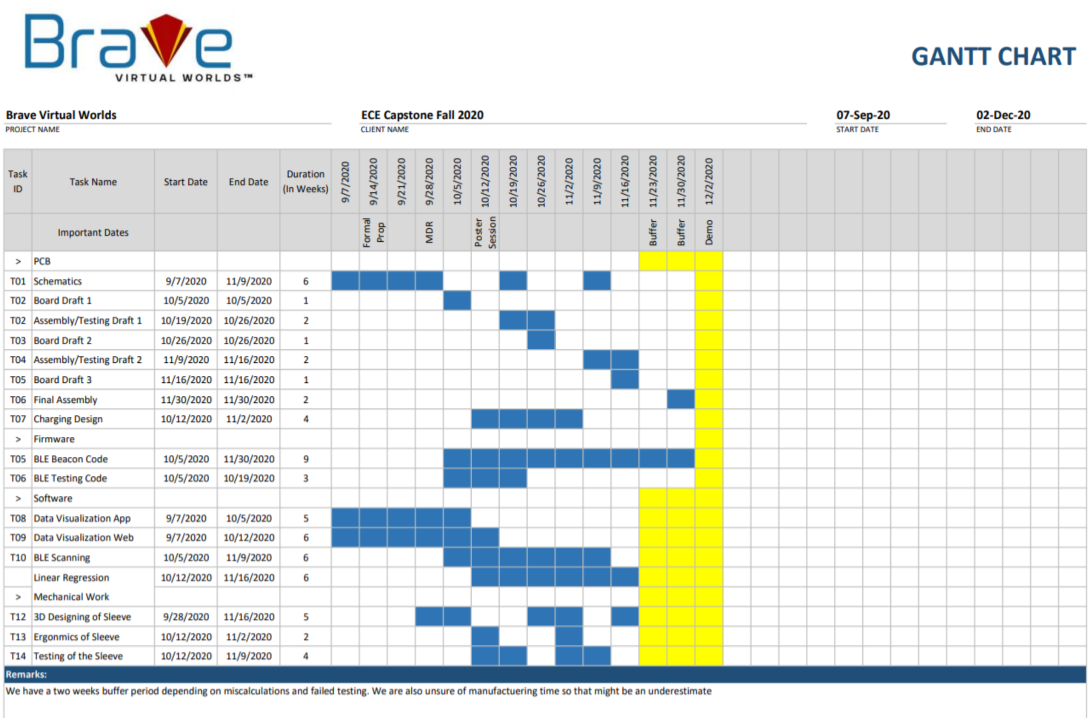

Figure 17. Final Gantt Chart

In terms of breaking up the tasks, the software, hardware, and 3D modeling were done in parallel in order to maximize time. William mainly worked on the hardware design and testing while having a secondary responsibility of working on the embedded programming. Evan mainly worked on developing the embedded code, while also working on the motion data visualization and Bluetooth for the mobile application. Hart primarily worked on developing the mobile application's UI and Bluetooth while also helping out with hardware design and testing. Finally, Chris took the lead on the web portal development and motion tracking, while also working on hardware design and testing.

Test Plan

Our test plan will mainly focus on measuring voltages between sub circuits and making sure everything is connected correctly. The first part of the test plan will be making sure that when the USB module is plugged in all the subsequent voltages are correct. This is modeled by Figure 18. The second part of the test plan will be making sure that all the voltages are correct when the battery is the main voltage source. This is shown by Figure 19. Once all the voltages have been verified, we will then start to test our module with visualization, and other embedded testing procedures, such as first making sure we can upload code to the MPU, and then making sure the IMU is sending correct data.

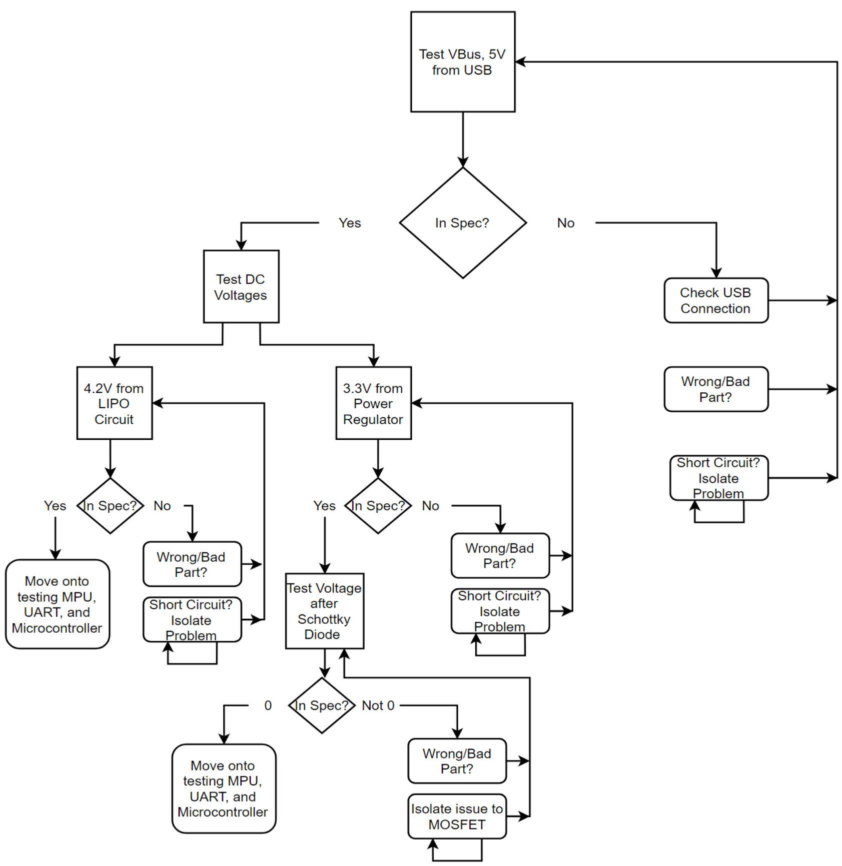

Figure 18. Test Plan for USB Connection

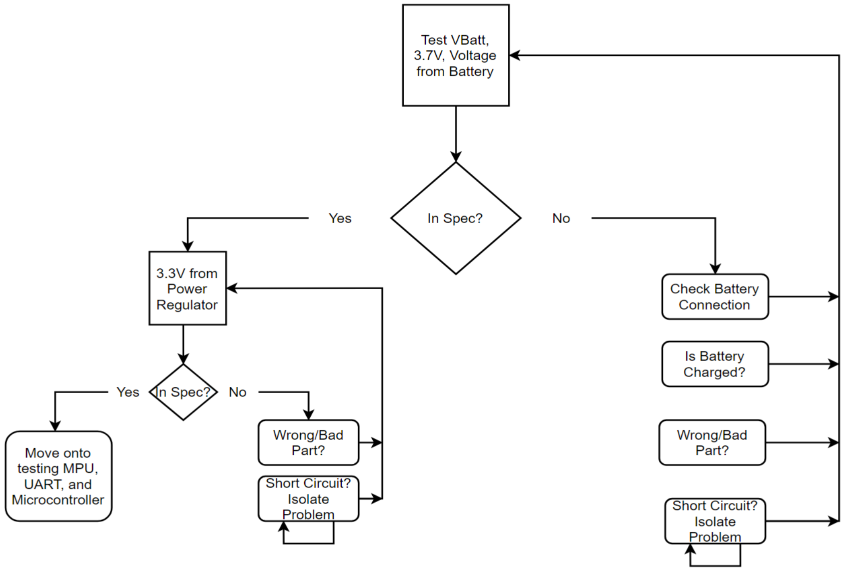

Figure 19. Test Plan for Battery Connection

Final Results

The final results include a functioning motion capture wearable, an iOS mobile application to collect and visualize the motion data in real-time, and an online dashboard with patient resource management system. The Brave motion capture suit can be seen below in Figure. 20 with six onboard sensors sending motion capture data for a rower's rowing form on an indoor rowing machine. Each peripheral device has an assembled circuit board and LiPo battery within 3D printed housing in order to capture motion data. This motion data is then sent over BLE to the mobile application using a BLE technique known as beaconing to continuously advertise new and updated motion data. This data can then be read by the iOS mobile device using BLE scanner code that scans for a unique identification number and reads the scan response of the advertisement that holds the motion data and the sensor identifier as well.

Figure 20. Brave Motion Capture Suit

The iOS mobile application includes an explore page, workout page, messaging system, and profile page. The main functionality within the app is shown in the workout page and profile page as shown in Figure 21. The workout page displays the workout of the day for the patient. Once the patient clicks on the image, they will be redirected to a workout video and a model visualizing their results live. Next, there is a profile page where the experience has been gamifyied. This page features an xp system, badges for number of workouts completed, and weekly statstics based on the number of workouts. The user can also change their profile picture, update their password, and log out of their account.

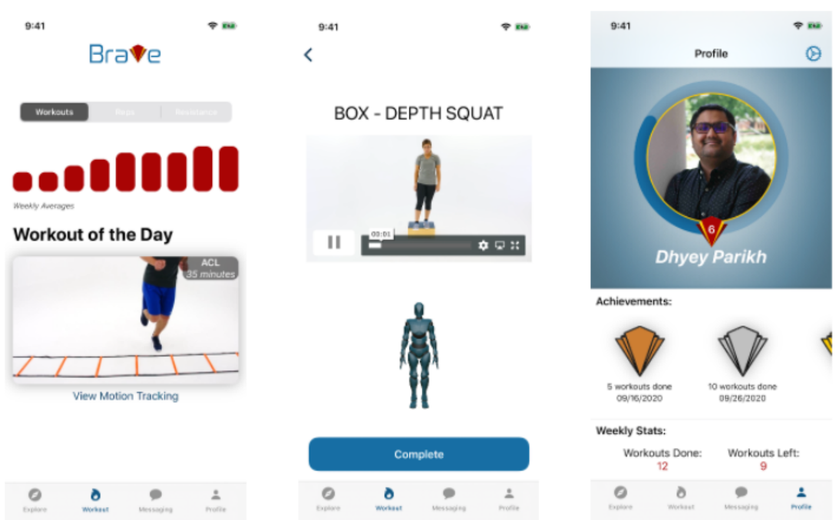

Figure 21. iOS App Screenshot for Patient, PT, and Hardware Interfacing

The web portal allows physical therapists to create an account to allow them to use the features on the website. After registering, an e-mail verification is sent to their e-mail address for them to confirm. We are using Google Cloud Identity, which is HIPAA compliant, to create/store the authentication details of the therapists and their patients. We have implemented a library of different videos that demonstrate exercises. Therapists can select from these videos and assign them to different routines for patients to complete them.

Therapists can also go to their patient dashboard, which shows them all of their current patients. When selecting a patient, they are presented with all important information about the patient such as: personal information, messages between patient/therapist, schedule, and visualization of their workouts. Therapists can also assign routines to their patients through the calendar, add new patients, search through patients, and track patient progress.

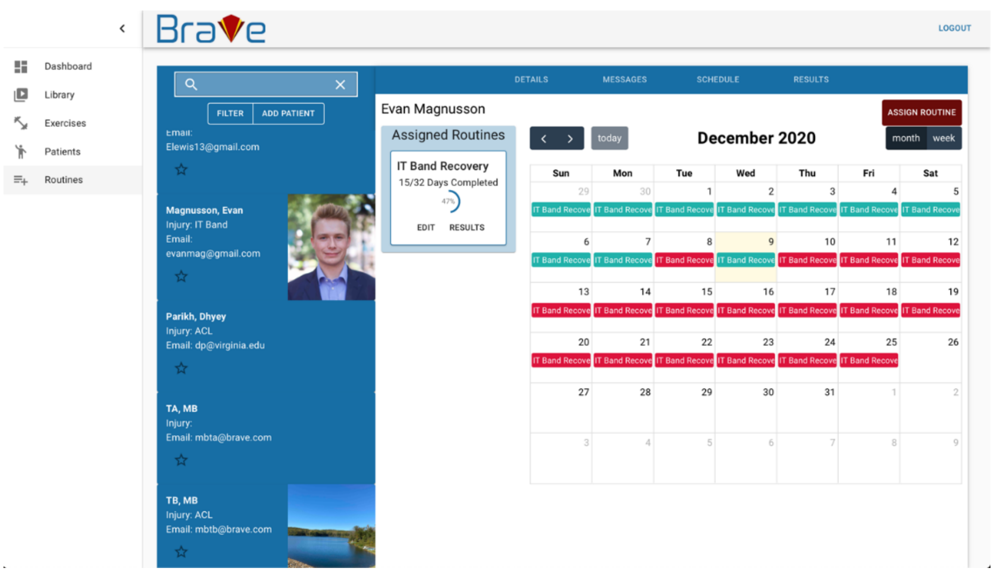

Figure 22. Online Dashboard for Review Patient/Athlete Data

In summary, the team has delivered what had been stated in the original project proposal which was a BLE peripheral system that collects motion data around a human's knee joint, sends that data over Bluetooth to a mobile application, and stores the data in a cloud storage system that an online dashboard can retrieve and send specific information to and from the mobile application. The peripheral units are able to be charged and hold enough power at the moment for three hours of high activity. Additionally, 3D visualizations have been constructed to display the motion capture data as real-time feedback for users using the Brave suit. Finally, plots of the orientations around a human's knee can be seen below in Figure 23 over 190 sample of a step-down exercise labeling a motion defect, superficially known as knee valgus collapse. Valgus and non-valgus data sets can be seen in this figure, in which machine learning algorithms can now be implemented to autonomously classify knee valgus collapse whenever new data is acquired from the Brave mobile application and the motion capture hardware.

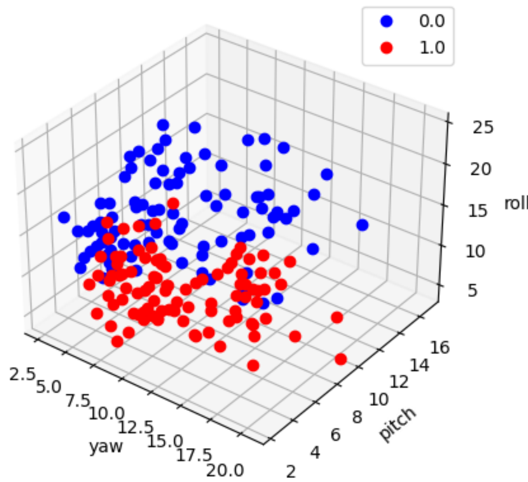

Figure 23. All valgus (blue) and normal (red) samples plotted for yaw, pitch, and roll

Costs

The cost per board ended up being around $20 per board and through 3W Electronics' quotes for quantities for 20, 25, 30, and 100 boards, the costs for the parts and labor were evaluated to provide an accurate understanding of how much the entire production of a certain quantities of board would cost as well as the cost for assembly and labor. These numbers are very important as the cost of labor for 3W Electronics is actually more expensive than the parts which include their markups. Therefore, it is reasonable to deduce that in order to reduce the final costs of the Brave suits, the orders need to be larger or find cheaper labor through offshore suppliers and manufactures.

Pricing for turnkey production (All you need to give us is the Gerbers & assembly documentation for the board, we supply PCB's and parts).

Order # "BRAVE_IMU"*		
Quantity	Price per Assembly	TOTAL:
20	$63.65	$1,273.00
25	$58.35	$1,458.75
30	$56.85	$1,705.50

Pricing if you want to supply the boards and parts (labor Only):

Order # "BRAVE_IMU" (Labor Only)		
Quantity	Price per Assembly	TOTAL:
20	$43.45	$869.00
25	$40.35	$1,008.75
30	$39.15	$1,174.50

Order # "BRAVE_IMU"*		
Quantity	Price per Assembly	TOTAL:
100	$44.60	$4,460.00

Alternately, the pricing can be broken out as labor and parts as follows:

Order #	Quantity	Price per Assembly	TOTAL:
BRAVE_IMU_LABOR	100	$25.70	$ 2,570.00
BRAVE_IMU_PARTS*	100	$18.90	$ 1,890.00
			$ 4,460.00

Figure 24. 3W Electronics' Quote for 100 Units for Parts and Assembly

Future Work

One improvement of the project would be to continue make the board smaller, to compete with current products on the market, and for comfort when doing exercises. This might not be as easy as it sounds, as smaller components might be more expensive, and limited amounts of space make design decisions harder. Some other improvements could be coming up with 3D designs that are waterproof or sweat proof to protect the device when exercising. In terms of building off of the current product, new mobile application platforms aimed for specific athletics could bring motion tracking to a whole new level. Instead of just focusing on physical therapy, focus on different sports and give feedback based on technique and help athletes recover more quickly from injuries.

References[21]

[1] J. A. Grant, N. G. H. Mohtadi, M. E. Maitland, and R. F. Zernicke, "Comparison of Home versus Physical Therapy-Supervised Rehabilitation Programs after Anterior Cruciate Ligament Reconstruction: A Randomized Clinical Trial," *Am. J. Sports Med.*, vol. 33, no. 9, pp. 1288–1297, Sep. 2005, doi: 10.1177/0363546504273051.

[2] A. B. Tuncer, N. Ergun, A. H. Tuncer, and S. Karahan, "Effectiveness of manual therapy and home physical therapy in patients with temporomandibular disorders: A randomized controlled trial," *J. Bodyw. Mov. Ther.*, vol. 17, no. 3, pp. 302–308, Jul. 2013, doi: 10.1016/j.jbmt.2012.10.006.

[3] S. M. Coppola and S. M. Collins, "Is physical therapy more beneficial than unsupervised home exercise in treatment of post surgical knee disorders? A systematic review," *The Knee*, vol. 16, no. 3, pp. 171–175, Jun. 2009, doi: 10.1016/j.knee.2008.09.001.

[4] "7 Facts About Physical Therapy You Can't Ignore," *WebPT*, Feb. 19, 2018. https://www.webpt.com/blog/7-thought-provoking-facts-about-physical-therapy-you-cant-ignore/ (accessed Dec. 10, 2020).

[5] admin, "Physical Therapy for Back Pain - Spine Therapy - Low Back Pain Rehabilitation," *Athletico*. https://www.athletico.com/services/specialized-services/spine-specialty-program/ (accessed Dec. 10, 2020).

[6] "Medicare Fraud, Medical Identity Theft And Scams." https://www.aarp.org/money/scams-fraud/info-2018/medicare-scams-fraud-identity-theft.html (accessed Dec. 10, 2020).

[7] "Official Creality Ender 3 3D Printer,Official ender 3 3d printer store – Creality3D Store® Official Store for Creality 3D Printers and Accessories." https://www.creality3dofficial.com/products/official-creality-ender-3-3d-printer (accessed Sep. 14, 2020).

[8] "DigiKey Electronics - Electronic Components Distributor." https://www.digikey.com/ (accessed Sep. 14, 2020).

[9] "Medical Technology Industry Spotlight | SelectUSA.gov." https://www.selectusa.gov/medical-technology-industry-united-states (accessed Aug. 03, 2020).

[10] "Physiotherapy Equipment Market Size, Industry Report, 2027." https://www.grandviewresearch.com/industry-analysis/physiotherapy-equipment-market (accessed Aug. 03, 2020).

[11] J. LaRosa, "U.S. Physical Therapy Clinics Constitute a Growing $34 Billion Industry." https://blog.marketresearch.com/u.s.-physical-therapy-clinics-constitute-a-growing-34-billion-industry (accessed Aug. 03, 2020).

[12] "Getting Started with iBeacon," p. 11, 2014.

[13] "47 CFR § 15.247 - Operation within the bands 902-928 MHz, 2400-2483.5 MHz, and 5725-5850 MHz.," *LII / Legal Information Institute*. https://www.law.cornell.edu/cfr/text/47/15.247 (accessed Dec. 10, 2020).

[14] "47 CFR § 15.249 - Operation within the bands 902-928 MHz, 2400-2483.5 MHz, 5725-5875 MHZ, and 24.0-24.25 GHz.," *LII / Legal Information Institute*. https://www.law.cornell.edu/cfr/text/47/15.249 (accessed Dec. 10, 2020).

[15] "Fusion 360 | 3D CAD, CAM, CAE & PCB Cloud-Based Software | Autodesk." https://www.autodesk.com/products/fusion-360/overview (accessed Sep. 14, 2020).

[16] "KiCad EDA." / (accessed Sep. 14, 2020).

[17] O. for C. Rights (OCR), “HIPAA for Professionals,” *HHS.gov*, Sep. 10, 2015. https://www.hhs.gov/hipaa/for-professionals/index.html (accessed Sep. 14, 2020).
[18] A. G. Papadourakis, “Motion capture and analysis,” US8589114B2, Nov. 19, 2013.
[19] D. Dyer, T. Dyer, and R. Gore, “Motion Tracking Wearable Element and System,” US20160125348A1, May 05, 2016.
[20] P. A. Touma, H. Murr, E. Bachaalany, and I. Maalouf, “Wireless motion sensor system and method,” US10433033B2, Oct. 01, 2019.
[21] “Zotero | Your personal research assistant.” https://www.zotero.org/ (accessed Dec. 10, 2020).

Appendix

Code branches for each section has been uploaded to Collab. These include the iOS app code, embedded code, online dashboard code, and python code for the machine learning.

Note: To build the embedded code and flash it to the ESP32, the esp-idf needs to be installed here - https://docs.espressif.com/projects/esp-idf/en/latest/esp32/get-started/index.html

Additionally, the CAD files for the electrical housing and circuits have also been uploaded to Collab.