Department of Mechanical and Mechatronics Engineering

Rally and Rehab: A Wearable Device to Provide Actionable Data to Racket-Sport Athletes

A Report Prepared For:

Prof. William Owen
Prof. John Thistle

Prepared By Group 13:

Connor Johanson, Christopher Nikolik,
Mina Tawadros, Lucas D’Elia,
Shivraj Singh Vishnoi

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Prof. William Owen & Prof. John Thistle

Instructors, MTE 482

University of Waterloo

200 University Ave W.

Waterloo, Ontario, N2L 3G1

Dear Professor Owen and Professor Thistle,

This report, entitled Rally and Rehab: A Wearable Device to Provide Actionable Data to Racket-Sport Athletes, was written to fulfill the MTE 482 Final Report requirements.

This project involves the design and development of a mechatronic solution that collects, transmits, and presents usable data relevant to amateur racket sport athletes for the purposes of swing analysis and injury detection. This report outlines the detailed design, manufacturing, and testing of such a solution.

This report was written entirely by us and has not received any previous academic credit at this or any other institution. The purpose of the project and the topic of this report were uniquely decided by us.

Best Regards,

Group 13

Connor Johanson – 20905957

Christopher Nikolik - 20879034

Mina Tawadros - 20895975

Lucas D’Elia - 20889592

Shivraj Singh Vishnoi - 20892812

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Executive Summary

This report outlines the mechatronics capstone project titled *Rally and Rehab.* The project presents a novel, wearable sleeve designed to provide racket-sport athletes, particularly amateurs, with actionable, sport-specific data to improve performance, prevent injuries, and support rehabilitation. Built to address a critical gap in the availability of professional-level analytics for non-professional athletes, the device combines embedded sensors with a sleek design and real time processing to track and analyze arm motion during gameplay.

The final prototype integrates three BMI270 inertial measurement unit (IMU) sensors placed on the wrist, elbow, and shoulder. These sensors collect 6-DOF motion data, which is transmitted via Bluetooth Low Energy to an external device powered by a custom software stack. The data is processed through Kalman filtering and stored in an InfluxDB cloud database. A custom-build dashboard using the Plotly Dash Python framework provides athletes with real-time and historical analytics, including swing count, swing velocity, and injurious event detection.

Custom mechanical enclosures were created and manufactured for the sensors, battery, switch and microcontroller to ensure the components were adequately secured and protected during gameplay. The overall sleeve was lightweight, non-intrusive and adaptable to various arm sizes and sport-specific motions. Modifications during development included switching sensor models, redesigning enclosures for better ergonomics, and changing the communication protocol from SPI to I2C to simplify wiring.

Testing confirmed the device's accuracy in detecting swings and identifying high-strain movements that could cause elbow or shoulder strains. The device also exceeded constraints, achieving a 3-hour battery life (compared to the 1-hour requirement) and maintaining a total project R&D cost of $424.62, week below the allocated $1300 budget. The actual cost of the manufactured device, based on the bill of materials, was $252.35.

Rally and Rehab was nominated for the award of "Best Prototype" and won the "Baleshta Special Merit" at the Mechatronics symposium. Some future improvements that are considered include using a flexible PCB for reduced weight, integrating the solution with a mobile app, applying machine learning techniques for motion classification, and expanding the design to additional sports and other areas of capturing motion of the body.

This project provides the foundation of an affordable, data-driven training prototype device that empowers amateur athletes with unique insights previously reserved for professionals.

1.0 Introduction

The goal of this capstone project is to develop a wearable sleeve that delivers precise, sport-specific data for racket sports athletes, coaches and physiotherapists to enhance performance, prevent injuries from repetitive motion, and support athletic rehabilitation. The wearable sleeve aims to track real-time movement metrics, to provide athletes, coaches, and physiotherapists with actionable insights that extend beyond traditional fitness tracking. Given the high risk of injuries from repetitive motions in racket sports, this wearable addresses a crucial gap, offering targeted data to improve training effectiveness and aid in injury prevention and recovery [1].

1.1 Background

Racket sports, such as tennis, badminton, and squash, involve repetitive high-intensity movements, particularly of the shoulder and elbow joints, making athletes vulnerable to overuse injuries. Conditions like tennis elbow (lateral epicondylitis) affect up to 50% of tennis players at some point in their careers [2], while shoulder injuries such as rotator cuff tendinitis are also prevalent in racket sports. Proper rehabilitation of these injuries requires detailed feedback on movement and recovery progress, yet existing fitness trackers do not provide the specific data required for these assessments.

Amateur athletes often lack access to insightful data and metrics that can help them identify areas for improvement, aid in rehabilitation, and prevent injuries. In sports, data plays a crucial role in enhancing performance through personalized coaching and feedback, as well as supporting rehabilitation and injury prevention. The sports analytics market is projected to reach $4 billion USD in 2024 and is expected to grow to $31.4 billion USD by 2034, with an average annual growth rate of 22.9% [3]. This surge in investment is driven by an increasing focus on athlete health monitoring, injury prevention, and data-driven personalized training programs. However, much of this investment is concentrated on professional athletes and teams, leaving amateur athletes with limited access to sport-specific analytics [4]. This capstone project was undertaken to bridge this data gap by providing amateur athletes with the same level of detailed performance metrics and rehabilitation support that professional receive, helping them train smarter, recover more effectively, and reduce the risk of injuries [1].

1.2 Needs Assessment

Amateur racket sports athletes require access to sport-specific data on swing velocity, acceleration, shot power, stroke count and range of motion to enhance their training, prevent injuries, and support recovery. As previously discussed, racket sports involve repetitive motions that significantly increase the risk of injury. For instance, studies show that approximately 50% of tennis players develop symptoms of tennis elbow, often due to improper swing technique and excessive strain on the forearm muscles [2].

Despite the growing demand for data-driven insights in sports, most commercially available fitness trackers, such as Fitbit [5] and Apple Watch [6], primarily focus on general health metrics like heart rate, step count, distance travelled, blood oxygen, etc. These devices do not provide racket specific metrics and data such as shot velocity, stroke count, range of motion etc. Due to this reason these devices are not able to provide athletes with actionable insights that can help them in improving their form and assist in rehabilitation.

This wearable sleeve aims to address this data gap by offering amateur athletes access to detailed motion analytics tailored specifically for racket sports such as tennis, badminton, squash, etc. By tracking key parameters such as swing velocity, power, acceleration, and range of motion, this wearable sleeve empowers athletes with real-time insights to refine their technique, reduce injury risks, and optimize rehabilitation. Providing amateur athletes with professional-level data can help bridge the gap between casual play and elite training, ultimately enhancing performance and longevity in the sport [1].

1.3 Problem Formulation

The problem statement for this project that was formulated in MTE 481 is shown below:

"Design and develop a mechatronic solution that collects, transmits, and presents useable data relevant to amateur racket sport athletes. [1]**"**

This problem statement was modified for MTE 482 to better reflect the purpose and goal of our capstone project. This new modified problem statement is shown below:

"Design and develop a wearable sleeve that collects, processes, transmits, and presents data to help athletes of all skill levels improve their form, enhance performance, and support rehabilitation and injury prevention."

1.4 Constraints

The constraints identified for this project are listed below:

1. Feasibility: The solution should be designed, created, developed, tested, and produced within 6 months, as this is the allotted time period for the capstone.
2. Cost: The solution should be developed within the budget allocated for the project of $1300 (departmental allowance + personal budget)
3. Safety: The solution should adequately meet all mechanical and electrical safety inspections and regulations. The solution should be safe for use by a nonprofessional.
4. Non-intrusive: The solution should not interfere with the athlete or impact their performance.
5. Battery Life: The solution must be usable for at least 1 hour, which is the average length of a training session.
6. Data Requirement: The solution gathers the required data to inform all athletes.

1.5 Criteria

The criteria selected for this project are:

1. Scalability: The solution should be easily manufacturable and scalable to different racket sports such as tennis, badminton, and squash.
2. Adaptability: The solution should be accessible to people of many body sizes and shapes.
3. Data Useability: The data gathered by the solution should be relevant and understandable by athletes of any skill level.
4. Affordability: The solution should be developed on a cost-effective basis to be affordable to athletes of all levels.
5. Sustainability: The components should be long lasting, and sustainability sourced. The design should be durable to prevent waste.

1.6 Design Review

The overall design of our solution is a wearable sleeve device. The sleeve extends across the player's dominant arm. Three inertial measurement unit sensors were placed at three distinct points on the arm: the wrist, elbow and shoulder. While the third IMU is labelled as being placed at the "shoulder", the actual location is closer to the upper bicep. This is because compression sleeves are not typically worn all the way up the arm to the shoulder and are naturally designed to end near the middle of the upper arm. Each of the IMUs within the wearable collects linear acceleration and angular velocity data along the x, y, and z-axes. They are thus characterized as 6 degrees-of-freedom sensors. The sensors are connected to a central ESP-32 microcontroller, placed near the lower bicep, with the sensor data being communicated using the I2C protocol. This data is then wirelessly transmitted by microcontroller to an external receiver using Bluetooth Low Energy. A lithium-ion battery on the sleeve powers the device so it can be used wirelessly. Each component is protected by a mechanical enclosure as shown in Figure 1.

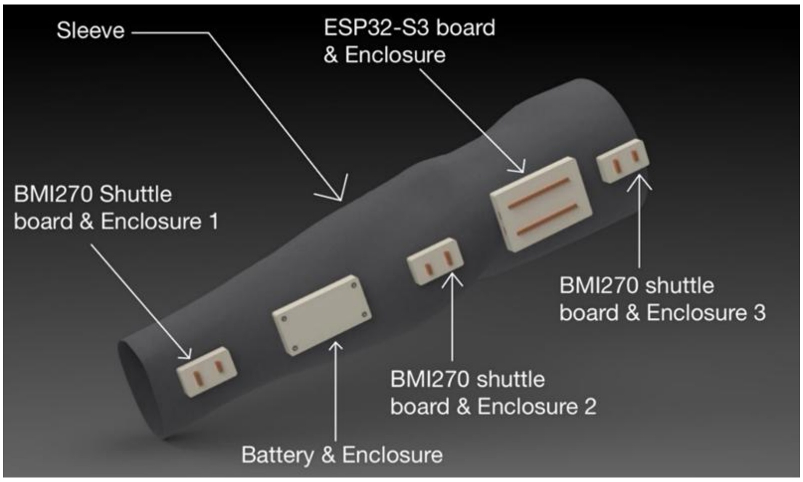


Figure 1: Initial Physical Design [1]

The raw sensor data is processed, stored on a cloud database and displayed on an interactive dashboard. Processed data includes swing speed, the number of swings, and the number of strains caused by improper swing form. An example of sample accelerometer data is shown in Figure 2 below. The design can be used for different racket sports since it does not change depending on the respective equipment. Furthermore, this design meets the criteria of adaptability as it is usable by players of both handedness (right and left).

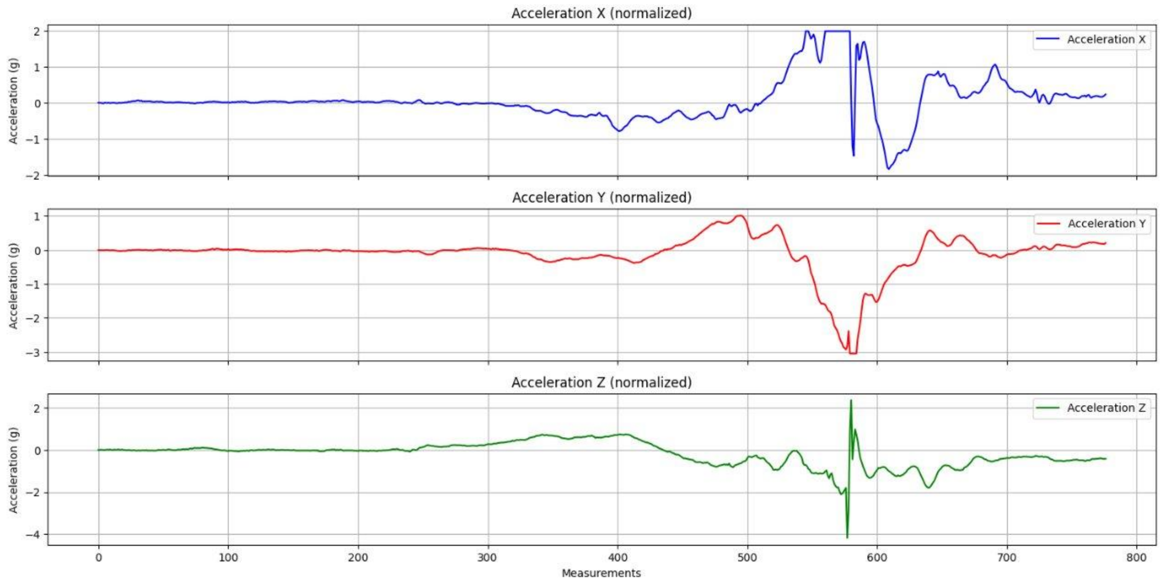


Figure 2: Initial Sampled Data [1]

2.0 Final Design

2.1 Final Design Details

The final design of the project can be categorized into three main components: mechanical; electrical; and software and data analysis. The specifics of each of these components is outlined below.

2.1.1 Mechanical

The final mechanical design includes three sensor enclosures, a battery enclosure, a switch enclosure, a microcontroller enclosure, the wearable sleeve, wire sleeve and elastic knitting band.

The sensor enclosures were specifically designed to securely house the BMI 270 IMUs [7] without adding bulk or making the sleeve feel intrusive [8]. The enclosure consists of two components. The top part of the enclosure covers the sensor and ensures that the sensor is protected from any collisions and high-speed impacts. The bottom part of the enclosures houses the sensors and holds them in place. This part of the enclosure also has a wire port to connect the sensors to the microcontroller. The CAD drawings and measurements of the complete enclosure and its components are provided in Figure 14, Figure 15, and Figure 16, located in Appendix C. The enclosures are placed near the wrist, shoulder and elbow to get data from three different points on the arm. This design and enclosure placement ensured that the sensors remained firmly in place during use, while maintaining the sleeve's non-intrusive and adaptable design.

The battery enclosure was designed to securely hold the DC LiPo battery without adding a lot of weight to the sleeve. The battery enclosure was designed to securely hold the DC LiPo battery [9] without adding a lot of weight to the sleeve. This enclosure consists of two components. The top part of the enclosure includes ventilation slots to address heat buildup during extended use. The heat vents also reduce the weight of the enclosure. The bottom part of the enclosure houses the battery and contains wire ports to connect the battery to the switch and the microcontroller. The final design and measurements of the battery enclosure is shown in Figure 17, Figure 18, and Figure 19, located in located in Appendix C.

A switch enclosure was also designed for the final prototype. This part houses the switch that is used to turn the battery ON and OFF. The switch enclosure has two components as well. The top part of the enclosure has a slit that lets the user turn the switch ON and OFF. The bottom part of the enclosure holds the switch in place and contains wire ports to connect the switch to the battery. The switch is glued to the sleeve near the battery. The CAD drawings and measurements are shown in Figure 20, Figure 21, and Figure 22, located in Appendix C.

The microcontroller enclosure was designed to securely house the ESP-32 [10] and provide connections for the various components connected to the microcontroller. This enclosure consists of three parts. The bottom part of the enclosure contains the prototyping board and has ports for connecting various components to the pins of the microcontroller. The middle part houses the ESP-32 and contains slits through which the pins of the microcontroller can be connected to the prototyping board located in the bottom part of the enclosure. The top part of the enclosure protects the ESP-32 from high-speed collisions and impacts that the sleeve may encounter while it is being used. This design ensures that the microcontroller can seamlessly interface with the various components on the sleeve and also protect the microcontroller from collisions and damage. The CAD drawings and measurements for the microcontroller enclosure are shown in Figure 23, Figure 24, Figure 25, and Figure 26, located in Appendix C.

A wearable sleeve was selected for the final design because it accommodates athletes of various arm sizes and body types, and it can be easily used by both right-handed and left-handed individuals. The wearable sleeve was manufactured by AetherGear [11] and it is made with a nylon and spandex blend. This ensures that the sleeve is lightweight, durable and elastic.

A wire sleeve is also used in the final design to improve wire management and make the overall design less intrusive. The wire sleeve used was manufactured by Aibole [12] and it is made from Polyethylene Terephthalate. This sleeve helps in protecting the wires and makes the design more flexible and adaptable. Heat shrinks were also added to the wire sleeve to assist with wire management.

The final component of the mechanical design is the elastic knitting band [13]. This is made of Polyester, and it is used to sew the wire sleeve on to the wearable sleeve. This makes the overall design more flexible and non-intrusive. It also makes the design more adaptable and improves the overall appearance of the design.

The exploded view of the final prototype for Rally and Rehab is shown in Figure 3.

Figure 3: Exploded view of final prototype

2.1.2 Hardware and Electrical

The hardware components of the device consist of the sensors, the microcontroller and its development board, and the communication protocol. There are three Bosch BMI270 inertial measurement units located at the shoulder, elbow, and wrist. Specifically, the SparkFun Micro 6DoF IMU Breakout boards are used [8]. Importantly, these boards are compact, lightweight, and allow for a simple, yet sturdy Qwiic connection to make wiring simple. The BMI270 provides three degrees of freedom gyroscope and three degrees of freedom accelerometer data. The ESP-32-S3-DevkitC development board is used as a breakout board for the ESP-32-S3-WROOM microcontroller [14]. The board has a LDO 5 V – 3.3 V voltage regulator for powering. It also has 45 GPIOs and is Bluetooth Low Energy 5 and I2C communication compatible.

The development board is used to receive data from the three IMU sensors. This data is then transmitted via Bluetooth Low Energy to an external device for further processing and presentation. The sensors communicate with the board via I2C communication. The elbow and wrist sensor share a single I2C line. This is made possible because the SparkFun breakout boards allow for two different I2C addresses by soldering a connection. The shoulder sensor has its own I2C line. The GPIO pins on the microcontroller are used for this communication. The data is collected at a rate of 50 Hz. The Bluetooth Low Energy communication is done by advertising with the microcontroller. A server is created and a service with a custom UUID is setup. Then, for the purposes of data organization, a characteristic is setup for each of the three sensors. The device then advertises the data it receives from the sensors.

The electrical components of the design consist mainly of the battery, the power routing, and the on-board LDO regulator. The battery used in the final design is a DC Lithium-Ion battery. This battery was chosen because it is small, lightweight, and can theoretically sustain the device for more than an hour. The specs of the battery are summarized in Table 1 below [15].

Table 1: Battery Specifications

Voltage	3.7 V
Capacity	1600 mAh
Size	48.5 x 30 x 10 mm
Weight	27.6 g
Protection	Over charge, over current, and short circuit

At full charge, this battery reaches 4.2 V, which exceeds the allowable voltage for the sensors. Thus, a voltage regulator must be used. It was originally proposed to use a DC/DC regulator, however, in order to save space and money, the on-board LDO was used instead. This LDO is a 5 V – 3.3 V regulator. Upon researching the specific regulator, it was determined that an input voltage 3.7 V or greater, which the battery supplies, will work with the regulator. Thus, the 3.3 V output of the development board are used to supply power to the sensors.

In addition to the battery, a single-pole single-throw switch is used to connect and disconnect the battery [16]. This ensures that, when not in use, the sensors and development board are not draining the battery, which helps to extend the time that the device is usable.

To route the electrical wiring, a small PCB prototyping board is used. This prototyping board helps to minimize the wiring by routing power to the necessary components of the design. The prototyping board also helps with routing the I2C communication from the sensors to the development board. It is soldered directly onto the development board and connects to the necessary pins.

The wiring and communication diagram is shown in Figure 4, below.

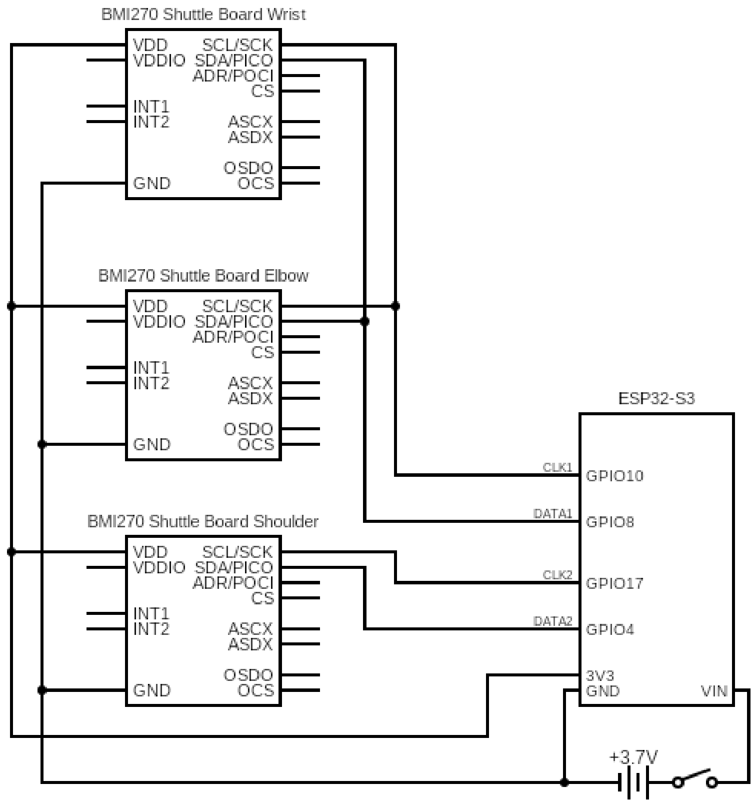


Figure 4: Wiring and Communication Diagram

The prototyping board is not shown in this diagram. Importantly, the wrist and elbow sensors share an I2C line. This helps to minimize the required wiring on the device. Additionally, as discussed previously, all devices share the 3.3 V output of the on-board LDO.

2.1.3 Software and Data Analysis

The device has two major software components: the microcontroller Arduino code and the external device Python code. The microcontroller code consists of the I2C communication with the sensors and the Bluetooth Low Energy advertisement. It collects the data from each sensor and formats it into a JSON-style string. This process loops at a rate of 50 Hz. The device is constantly advertising to allow other devices to connect and receive the data. As discussed previously, each sensor is given its own characteristic that supports reading and notifying. There are checks to ensure that advertising is consistent. If at any point, advertising stops, the device restarts and attempts to advertise once again.

The external device Python code is where the data is received, and all data analysis and presentation are performed. Figure 5, below, depicts the entire data pipeline.

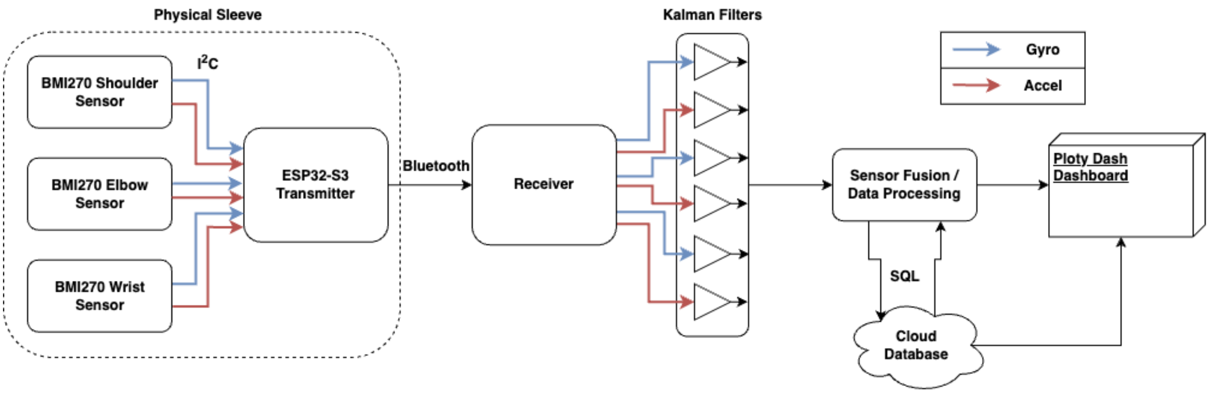


Figure 5: Data Pipeline

The physical sleeve consists of only the sensors and the transmitter. The receiver, data filtering and analysis, communication with the cloud database, and frontend dashboard all occur off the sleeve on the external device. The receiver is able to access the advertised data using Bleak, a Python library which allows for connection to Bluetooth Low Energy devices [17]. A sensor handler is used to read the data every time that new data is received from the sensors. This handler function processes the JSON data and applies a Kalman Filter to each stream. The details of the Kalman Filters are discussed later in the report. The filtered data is then put into a thread-safe queue and written to an InfluxDB cloud database. This handler function runs continuously.

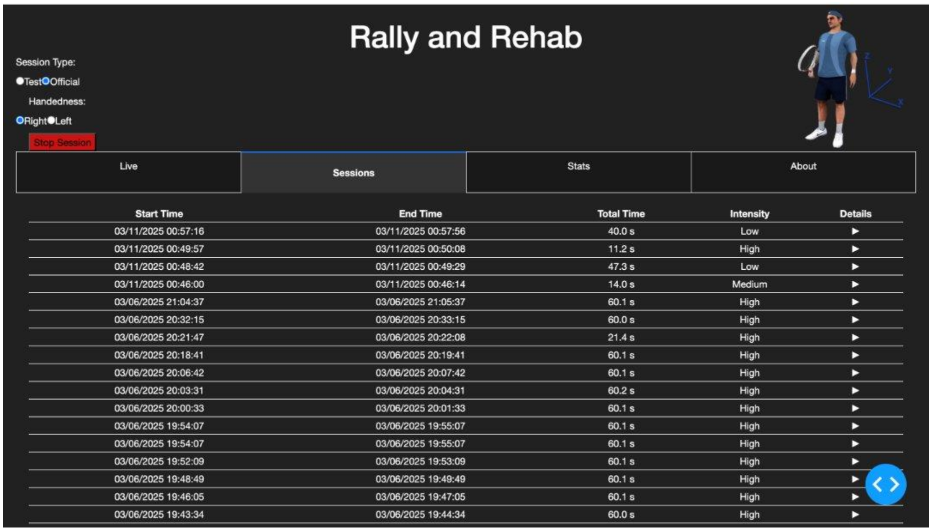
The communication with the InfluxDB database is done using the InfluxDB Client library, which is a Python library specially designed for communicating with that database [18]. All communication is done using an API token, which ensures that the data is private. Flux queries are used when accessing data. Only necessary data is stored in the cloud to minimize required storage. The format of this storage is in outlined in Table 8 in Appendix D. In addition to this, the data from each session is recorded in the database. A session is a collection of data from that specific period of use. It is stored using the format shown in Table 9 in Appendix D.

The front-end dashboard was creating using the Python Dash framework which allows for creation of interactive dashboards [19]. The dashboard has four main tabs: Live, Sessions, Stats and About.

Figure 6 below shows the top portion of the Live tab. The Live tab shows a Live view of the three sensor’s gyroscope and accelerometer data along with the magnitudes of Net Acceleration and Net Angular Velocity. It includes the options for a user to specify the session type between Test and Official. Selecting official will save the session to the profile session history. A further option is available to specify the handedness. The right side of the Live dashboard includes the session statistics including the number of injurious elbow events, and injurious shoulder events, along with the number of swings. The further statistics include the maximum angular velocity at each of the sensors as well as the maximum net angular velocity, and the maximum linear acceleration at each of the sensors, along with the maximum net linear acceleration. There is also a red “Stop Session” button which the user can press to cease the current session and save the statistics to the session history.

Figure 6: Live Tab of Dashboard

The Sessions tab contains the history of all sessions saved under the user profile. A screenshot can be seen in Figure 7 below. It includes the start and end time of the session, the total time of the session, and the session intensity, characterized by Low, Medium or High. Furthermore, the Details column contains a dropdown which the user can select to see the more specific session statistics.



Start Time	End Time	Total Time	Intensity	Details
03/11/2025 00:57:16	03/11/2025 00:57:56	40.0 s	Low	▶
03/11/2025 00:49:57	03/11/2025 00:50:08	11.2 s	High	▶
03/11/2025 00:48:42	03/11/2025 00:49:29	47.3 s	Low	▶
03/11/2025 00:46:00	03/11/2025 00:46:14	14.0 s	Medium	▶
03/06/2025 21:04:37	03/06/2025 21:05:37	60.1 s	High	▶
03/06/2025 20:32:15	03/06/2025 20:33:15	60.0 s	High	▶
03/06/2025 20:21:47	03/06/2025 20:22:08	21.4 s	High	▶
03/06/2025 20:18:41	03/06/2025 20:19:41	60.1 s	High	▶
03/06/2025 20:06:42	03/06/2025 20:07:42	60.1 s	High	▶
03/06/2025 20:03:31	03/06/2025 20:04:31	60.2 s	High	▶
03/06/2025 20:00:33	03/06/2025 20:01:33	60.1 s	High	▶
03/06/2025 19:54:07	03/06/2025 19:55:07	60.1 s	High	▶
03/06/2025 19:54:07	03/06/2025 19:55:07	60.1 s	High	▶
03/06/2025 19:52:09	03/06/2025 19:53:09	60.1 s	High	▶
03/06/2025 19:48:49	03/06/2025 19:49:49	60.1 s	High	▶
03/06/2025 19:46:05	03/06/2025 19:47:05	60.1 s	High	▶
03/06/2025 19:43:34	03/06/2025 19:44:34	60.0 s	High	▶

Figure 7: Screenshot of Sessions tab

The Stats page displays various overall user profile statistics including the average session length, average session intensity and average number of swings. Furthermore, a plot of the number of injurious events per minute of gameplay is available. After this, a set of tables are available which display with the top 3 ranked sessions for each category of top net linear accelerations and angular velocities along with the accelerations and angular velocities for each sensor.

The final page is the About page, which provides a background for the methodology used to compute the metrics.

The data analysis performed consists of 6 different Kalman Filters, basic transformations, and feature extraction. The details of the Kalman Filters are included in the calculations in Appendix A. The sensor noise covariance matrices were found by running base measurements of zero movement and analysing each sensor's noise. The process noise covariance matrix was determined through estimation and trial and error. The basic transformations in the software included axes transformations for switching between left- and right-handedness, as well as rotations for consistent alignment.

Feature extraction is performed using published data on injurious swings. Injurious shoulder events are determined as any swing where the angular velocity exceeds 2000 deg/s. This is a conservative estimate based on studies finding that velocities of 2600 deg/s and 2420 deg/s produce considerable stress on the shoulder muscles [20] [21]. Injurious elbow events are defined as a swing where the combined Z and Y angular velocities of the elbow joint exceeds 1000 deg/s. This is based on a study showing that ulnar collateral ligament stress is induced at these velocities [22].

Throughout the sessions, the maximum of each measurement is stored. This value is only updated if the new data exceeds it. The swing intensity is determined by calculating the swings per minute over a session. If it is below 5, the intensity is low. If it is between 5 and 15, the intensity is medium. If it exceeds 15 then the intensity is high. Swing detection is done using thresholds that were found through testing. The combined gyroscope magnitude must exceed 100 deg/s and the combined accelerometer magnitude must exceed 1.5 g. Additionally, it must be at least 0.5 seconds since the last swing.

2.2 Modifications from Original Design

While developing the prototype for the wearable sleeve a lot of modifications were made to the original design. These modifications have been listed in the sections below.

2.2.1 Sensor Board

The selected sensor boards were changed from the Bosch Shuttle Board 3.0 BMI270 IMU [7] to the SparkFun Micro BMI270 Breakout Board [8]. There were a few reasons for this change. The primary reason was that the Bosch Shuttle Board used an unconventional connection style that required either the use of their bulky prototyping board or excessive modification to the shuttle board design. The SparkFun board used a simple Qwiic connector that could be used directly with the ESP-32. Another reason the sensor was changed was that the micro style offered by SparkFun was much smaller than the Bosch board. This board was also cheaper, as each Bosch board was approximately $47/unit and each SparkFun board was $22/unit. Overall, the capabilities provided by the SparkFun board better fit the requirements and goals of this project.

2.2.2 Enclosure Design

The enclosure design underwent several rounds of modifications to reduce bulk and improve the overall comfort and usability of the wearable sleeve. One of the major challenges with the earlier versions of the enclosures was that they were notably large and bulky. This increased the weight of the sleeve considerably and made the overall design more intrusive.

The ESP-32 microcontroller enclosure was especially large and bulky as it had to house multiple components and wires. This significantly increased the weight of the sleeve particularly near the shoulder, which made it highly intrusive for racket sports. This bulkiness compromised the ergonomic and adaptable design of the sleeve as well and limited its effectiveness for long term use. Another issue with the old enclosures was that it did not have a compartment for the prototyping board which was interfaced with the microcontroller. The old enclosures also had a slot for the UART ports which was redundant as the UART ports on the microcontroller was not used. The old ESP-32 enclosure designs are shown in Figure 26 and Figure 28, located in Appendix C.

This design was changed to a much smaller and compact design that consisted of three components. The bottom component housed the prototyping board and had wire ports that helped with wire management and easy interfacing with the microcontroller pins. The middle component securely held the ESP-32 in place, and it also had slits for connecting the ESP-32 pins with the prototyping board. The top part of the enclosure protected the microcontroller from collisions and impacts that an athlete might experience while using the sleeve in a dynamic sports setting.

In addition to the ESP-32 enclosure, the battery housing was also re-designed. The initial design lacked heat vents which raised concerns about heat build-up during extended use. The old battery enclosure is shown in Figure 29, located in Appendix C. To address this, the battery enclosure was modified to incorporate heat vents, allowing for better airflow and more efficient heat dissipation. These changes collectively contributed to a more streamlined, lightweight, and user-friendly design that enhanced both performance and user comfort.

The sensor enclosures were also made much smaller to make the overall design more adaptable and light weight. The old sensor enclosure is shown in Figure 30, located in Appendix C. The new design for the sensor enclosure was much smaller and compact and housed the sensors more securely.

2.2.3 Battery

The original battery size selected was 1000 mAh [9]. This selection was made based on a simulation of the worst-case current draw from the ESP-32. This sizing was adequate to power the board for over 1 hour of play. However, this battery was on backorder and would not be received before February 11th, which was when the team wished to complete an initial prototype. As an alternative, the 1600 mAh battery discussed in section 2.1.2 was purchased [15]. Since this battery had a larger size, it lasted longer, ensuring that project constraints were met. This battery also had a smaller base, as the length and width of the battery dropped from 50 x 32mm to 48.5×30mm. This was beneficial because the battery took up less surface area on the sleeve's final prototype sleeve than the previously selected battery.

2.2.4 Communication Protocol

The onboard communication protocol was originally selected as SPI but was changed to I2C. This change was made because the Qwiic connectors used after changing sensors support I2C without requiring additional wires. This helped make wiring simpler and reduced the size of the sensor enclosures.
The main concern with this shift was that doing so would reduce the data quality. This concern was especially for the shoulder sensor since it was on the other end of the sleeve. However, this issue was found to be negligible during testing. The frequency of data provided by I2C was adequate because much of the sensor's raw output data was noise. Swing profiles were still possible with a slower frequency because high frequency noise was already being filtered.

2.3 Manufacturing

The first step in assembly of the final prototype was verifying the positioning of components on the sleeve. Positions for the enclosures were marked while the sleeve was worn. Distances between each enclosure was also measured to estimate cable lengths. Measuring with the worn sleeve ensured that placement was necessary because the nylon spandex material stretches when worn. A sample case of this is shown in Figure 8.

Cables were managed with a centralized prototyping board. Wiring on the board reflects the diagram shown in Figure 4. Three Qwiic connector cables were cut to appropriate lengths and soldered on to the prototyping board. A wire sleeve was placed along each cable and cut. The end of each wire sleeve was burnt to melt the ends together and secured on each connector with heat shrink. A similar process was repeated for the battery. The only difference in this case was the 3.7 V battery cable was initially cut and crimped to the switch wiring with a series connection. Heat shrink was used to protect this wiring.

Enclosures for the battery, microcontroller, and sensors were printed with PLA is the Rapid Prototyping Centre. Heat inserts were pressed into each enclosure, and fasteners were used to close enclosures once sensors were placed in their respective enclosure.

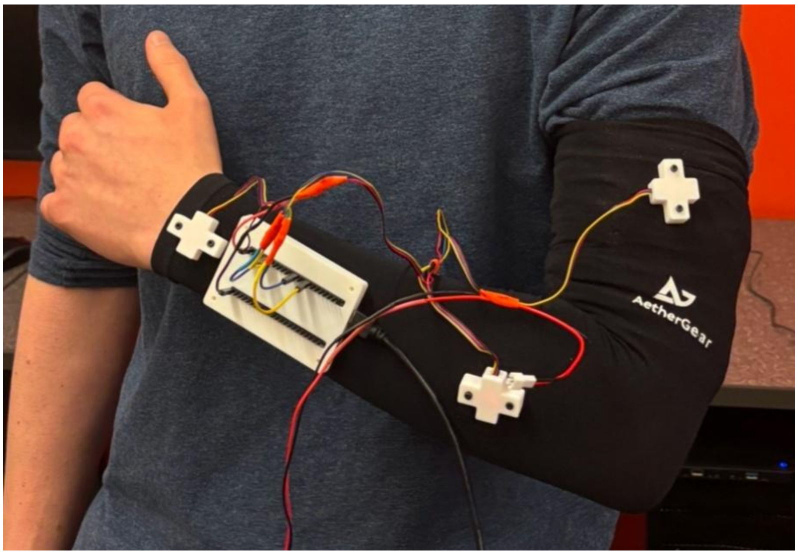


Figure 8: Mid-Construction Prototype

The ESP-32 was soldered to the prototyping board after placing it was placed into its enclosure and flashed with the final code. Next, the three sensors were placed into each of their enclosures. The wiring was organized through the wire sleeves.

Each enclosure was glued to their marked positions on the sleeve. The wire harnesses were placed in pockets of elastic material on the sleeve. These pockets were sewn on to the sleeve. A pocket was also placed across the microcontroller enclosure and sewn into place to ensure the wiring on the prototyping board was undisturbed.

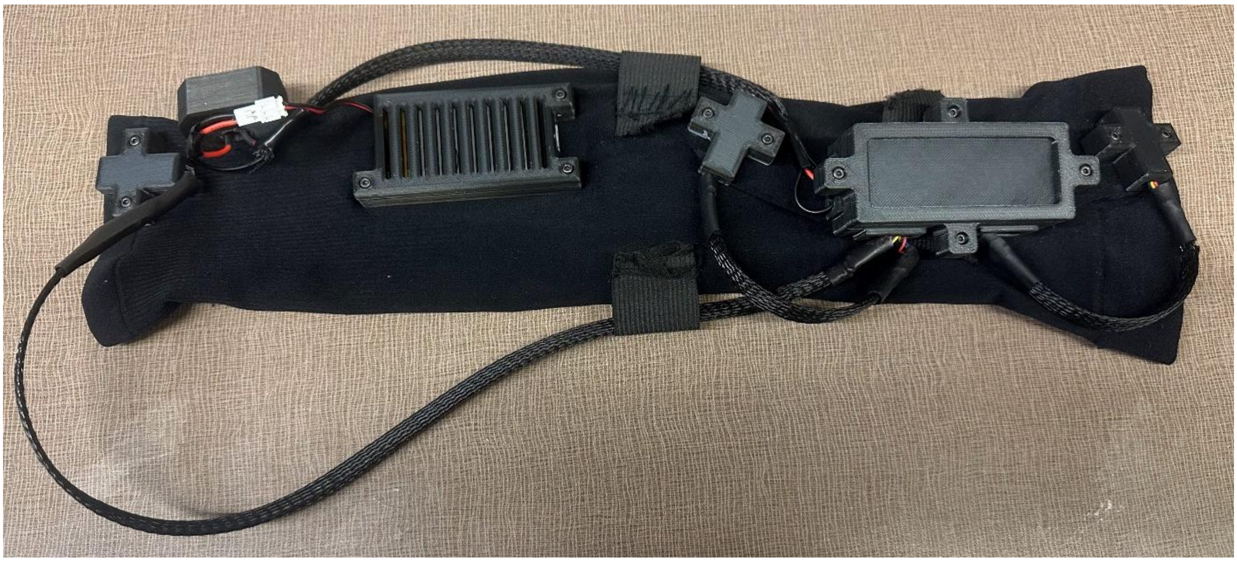


Figure 9: Final manufactured design of wearable sleeve with sensors

Upon full construction of the physical sleeve with the embedded sensors, the data analysis and visualization portion of the project was undertaken. The data from the three sensors was continuously advertised by Bluetooth as long as the switch was turned on.

This data was collected by the external receiver, a Mac laptop, and filtered using Kalman filtering as described in the design review. The data driven live metrics were gathered and displayed on the Live frontend dashboard. The InfluxDB cloud database was configured to hold historical data, and the profile Sessions and Statistics tabs were constructed. Upon completion, rigorous testing was undertaken to ensure reliability of the data and metrics, along with the physical robustness of the device.

2.4 Commissioning

Prior to construction of the multi-sensor system, a singular SparkFun IMU sensor was connected to the MCU. Some very basic Arduino code was written to serially read the sensor data. The data was then plotted for a brief session in Python to ensure data quality and useability. The commissioning integration test can be seen in Figure 10 below.

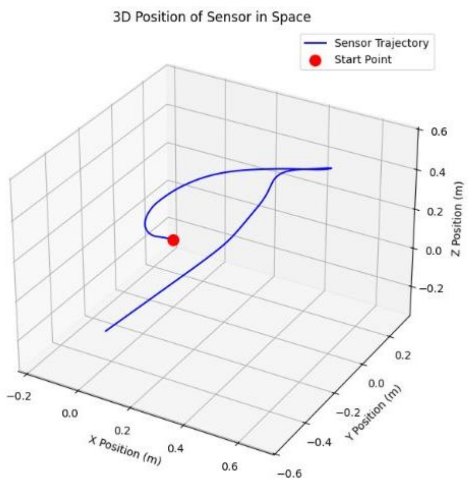


Figure 10: Commissioning integration of singular wrist sensor

Various other straightforward tests were undertaken to ensure that the sensor operated properly and could appropriately be integrated with the other components such as the ESP-32 and Bluetooth advertising.

The ESP-32 code could not be flashed after assembly on the final prototype since access to the microcontroller UART port was blocked to keep the encloser design slim. Thus, it was tested before enclosure placement with a breadboard replicating the wiring shown in Figure 4. Data was collected via Bluetooth for 30 minutes and compared with data gathered through a direct USB connection. Once the data functioned as expected, the ESP-32 could be placed in its enclosure.

Before soldering the power cable to the prototyping board, connections were tested with a multimeter. A continuity test was used at each point of the board to ensure there were no shorts to ground. The battery polarity was also checked to ensure it did not apply power to the ground port of the microcontroller. The wiring was tested by powering the board and checking if the LEDs on each sensor was red, indicating that they were ON. After ensuring this ran for at least 5 minutes, the enclosures were closed, and wire sleeves were sewn in place.

2.5 Testing and Performance

2.5.1 Criteria and Constraint Testing

In general, the final capstone prototype was successful in meeting all the criteria. The prototype was scalable to athletes of all racket sports with different body shapes and sizes. This includes right and left-handed players. The data gathered and transmitted by the sleeve was relevant and understandable by athletes of all skill levels and the device was also developed on a cost effective and sustainable basis [1].

The final capstone prototype was successful in meeting all the criteria. The prototype was scalable to athletes of all racket sports with different body shapes and sizes. This includes right and left-handed players. The data gathered and transmitted by the sleeve was relevant and understandable by athletes of all skill levels and the device was also developed on a cost effective and sustainable basis [1]. In testing, the battery was able to run for much longer than expected. This is likely because the device was not constantly transmitting data. Often, small sessions would be run and then, during rest, the device would be turned off. In this more realistic use case, the battery lasted more than 2 hours, which well exceeds what was desired.

Table 2 is provided below to compare the desired values for each constraint with the actual values achieved by the developed sleeve, demonstrating its effectiveness in meeting the identified constraint goals for the capstone project [1].

Table 2: Constraint Verification

Constraint	Desired Value	Actual Value
Feasibility	Designed, created, developed, tested, and produced within 6 months	The project was completed in the allocated time (6 months)
Cost	\$1300	\$400
Safety	Meet safety standards and regulations	Passed all required safety regulations and standards
Non-Intrusive	Should not interfere with athletes’ performance	Did not interfere with athletes’ performance
Battery Life	1 hour	3 hours
Data Requirements	Gathers data to inform athletes	Collects and displays all data required by athletes

As can be seen in the table, all the identified constraints were successfully met and, in some cases, our final design outperformed the required constraints.

2.5.2 Swing Detection Testing and Performance

To adequately test the swing detection algorithm, a series of test cases were meticulously tested with rigour. The device was evaluated with various numbers and sequences of swings across the sports of badminton and tennis as shown in Table 3.

Table 3: Swing Detection Test Cases

Test Case	True # of Swings	Detected # of Swings
Badminton Forehand Drive	15	15
Badminton Backhand Drive	15	15
Badminton Forehand Serve	10	10
Badminton Backhand Serve	10	10
Badminton Overhand	15	14
Tennis Forehand	10	10
Tennis Backhand	10	10
Tennis Serve	10	10
Tennis Volley	20	22
Random Movements	0	0
Jumping Jacks	0	0

In total, nine unique test cases across badminton and tennis were undertaken for a total of 115 swings. Eight of the nine testing scenarios had the exact correct number of detected swings as the true swings. The only test case that showed a deviation were the volleys in tennis. This shows that the prototype performs best in the case of clear swings with strong axial rotation around the body. Tennis volleys are small quick return swings which can be difficult to accurately interpret. However, even for this specific case, the number of detected swings is relatively accurate with only 2 additional swings detected from the 20 true number.

Two additional failure analysis tests were undertaken with random movements and jumping jacks to verify that no false positives were detected for swings. An example of one of these tests is shown in Figure 11.

Figure 11: Jumping Jack Test Case Example

2.5.3 Injurious Event Testing and Performance

The injurious events were difficult to test as a significant amount of strain on the joints and could cause serious injury to the tester. Thus, the range and path of motion were continuously increased until an injurious event could be detected. Four main testing scenarios that could result in injury were tested within both badminton and tennis. The testing criteria and results can be seen in Table 4 below.

Table 4: Injurious event performance testing

Injurious Motion	Elbow or Shoulder?	Injurious Event Detected
Underhand extension	Both	Yes, both
Forehand cross body spin	Elbow	Yes, elbow
Serve overextension	Shoulder	Yes, shoulder
Backhand rotation extension	Both	Yes, both

The results show that the device was able to accurately detect injurious events for both the elbow and shoulder across the range of strain scenarios. Furthermore, testing was undertaken with non-strenuous gameplay to ensure that no false positives were detected for injurious events when there were not any actual strains. This is shown in Figure 12.

Figure 12: Data Collection for Tennis with the Prototype

3.0 Schedule and Budgeting

This section of the report deals with the schedule and budget for the capstone project.

3.1 Schedule

The schedule followed while implementing and designing the wearable sleeve for the capstone project aligned with the planned schedule from MTE 481. The timeline for this project has been shown in Figure 13.

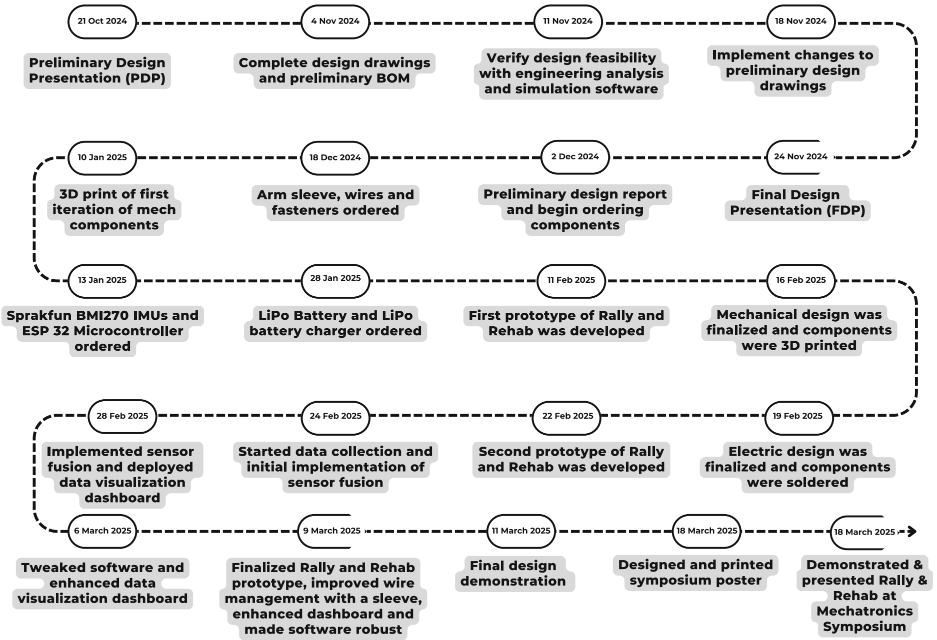


Figure 13: Project Timeline

3.2 Project Budget

The overall budget for this project was $1300. This value was based on the funds provided by the department for 5 group members ($750 total) and a person allowance of $110 per person. Overall costs for the project were split equal between team members using SplitWise [23]. A report for all costs from SplitWise is shown in Table 10 in Appendix F.

The cost for the entire project totals to $424.62. This is well below the planned budget. Most of the expenses went towards components used for the final prototype. The remaining costs were mostly used in iterative design when printing enclosures. A small charge of $12.95 was needed for printing the symposium poster at the Waterloo Public Library [24].

3.3 Expected and Actual Cost of Device

The expected cost for the final prototype was detailed in the final report for MTE 481 [1]. This estimated total after tax was $269.16. A breakdown of these total estimates based on our initial design is shown in Table 6 in Appendix B.

A final bill of materials for the device is given in Table 7 in Appendix B. After totalling the costs of all materials and components used in the final prototype assembly, the actual cost of the device was found to be $252.35. Like the budget, this cost was less than the expected value. However, the breakdown of expected cost was generally accurate and within 10% of the actual cost. This accuracy was due to the final prototype adhering to most of the original design decisions made in MTE 481. Any reductions in price were likely due to pursuing cheaper options, such as the different selected sensors, and a sleeker design reducing material requirements.

4.0 Conclusions and Recommendations

The *Rally and Rehab* wearable sleeve was successful in meeting all the requirements and objectives outlined in MTE 482, resulting in the development of a fully functioning, tested and cost-effective prototype. The final device collects, processes and transmits racket sport specific motion data using three IMU sensors placed along the arm, with an ESP-32 microcontroller that is responsible for transmitting and processing the data. The microcontroller transmits data using Bluetooth Low Energy, this data is sent to an external device where it is processed and visualized using an interactive dashboard.

Throughout the project, several iterations were made to enhance usability, reduce intrusiveness, and improve the robustness of the sleeve. Key changes and improvements included redesigning the mechanical enclosures to make them lighter, more compact and better integrated with the sleeve. In particular, the ESP-32 enclosure was redesigned to house a prototyping board, and the battery enclosure was redesigned to include heat vents for better thermal dissipation. These design choices improved the adaptability and ergonomics of the sleeve and made it more suitable for prolonged use.

The prototype met all the defined constraints and criteria and exceeded expectations in many areas, such as battery life, cost efficiency, and user adaptability. The prototype was also successful in accurately capturing sport-specific motion data, including swing velocity, swing count, and form-related metrics. These data points are useful for enhancing training, monitoring technique, and supporting injury prevention and rehabilitation strategies.

The quality and innovation of this project were recognized at the MTE symposium, where Rally and Rehab was nominated for two awards: Best Prototype and Special Merit. Out of these awards the project won the “Special Merit” award showcasing its technical strengths and impact.

To further improve and evolve the product the following steps are recommended:

- Collaborate with athletes and trainers to gather detailed feedback and identify gaps and issues with the current prototype. This will improve the usefulness and data collected by the device.
- Provide a clear battery indicator that alerts users when the device needs to be recharged.
- Implement a flexible PCB to replace the enclosures, this will reduce the weight and improve comfort and form factor of the product.
- Adding a secondary sleeve to enclose wiring and mechanical components as this will improve user safety and would make the device more durable to water and sweat. This will also improve the look and feel of the final product.

- Incorporating machine learning for swing classification and using a mobile app for real time data visualization would make the device more accessible to users.
- Expand to other sports with repetitive motions like baseball, golf, cricket etc. where limb movements and swing mechanics can lead to injuries.
- The wearable design can also be extended to other body parts such as legs and torsos to capture full-body motion for a more comprehensive data analysis.
- Integrate racket-mounted sensors to capture data such as impact location, racket angle, and shot force, providing deeper insights that complement arm motion analysis.

To conclude this project lays the foundation for a device that can help bridge the data gap between amateur and professional racket sports athletes. With continued development and industry collaboration, Rally and Rehab has the potential to become an essential tool in training, recovery, and long-term athletic performance.

5.0 Teamwork Effort

Teamwork was key to this project's success: each team member was responsible for a particular aspect of the project's design and collaborated for system integration. A regular weekly meeting was also held in which team members worked together to complete all shared tasks. As previously mentioned, costs were split evenly using SplitWise [23]. Each members unique contribution has been listed in Table 5.

Table 5: Team Member Effort Breakdown

Team Member	Contribution
Connor Johanson	• Sensor circuit design and I2C address verification • Circuit and wiring prototyping board assembly • Number of swings and injurious event tracker development • Data collection for badminton and squash
Christopher Nikolik	• Microcontroller code and Bluetooth implementation • Data processing and sensor fusion code • Historical swing statistics dashboard design • Data collection for tennis
Mina Tawadros	• Iterative mechanical enclosure design and printing • Component assembly and testing • Sleeve selection and mounting of enclosures • Updated website log
Lucas D'Elia	• Power circuit with switch design and assembly • Circuit assembly verification • Cable management and sewing on final prototype • Project scheduling and budgeting
Shivraj Singh Vishnoi	• Live dashboard design and implementation • Designed Kalman filter • InfluxDB database design and management • Poster design

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6.0 Appendices

6.1 Appendix A: Calculations

$$\boldsymbol{State\ Vector}:$$

$$x_k = \begin{bmatrix} x_{pos} \\ x_{vel} \\ x_{accel} \\ y_{pos} \\ y_{vel} \\ y_{accel} \\ z_{pos} \\ z_{vel} \\ z_{accel} \end{bmatrix}$$

$$\boldsymbol{State\ Transistion\ Matrix}:$$

$$A = \begin{bmatrix} 1 & dt & \frac{1}{2}dt^2 \\ 0 & 1 & dt \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{Measurement\ Matrices}:$$

$$H_{gyro} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

$$H_{gyro} = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{Process\ Noise\ Covariance\ Matrices}:$$

$$Q_{accel} = Q_{gyro} = \begin{bmatrix} 0.0001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.01 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0001 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.01 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.0001 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{Measurement\ Noise\ Covariance\ Matrices}:$$

$$R_{shoulder-gyro} = \begin{bmatrix} 0.35025 & 0 & 0 \\ 0 & 0.15946 & 0 \\ 0 & 0 & 0.01026 \end{bmatrix}$$

$$R_{elbow-gyro} = \begin{bmatrix} 0.16809 & 0 & 0 \\ 0 & 0.22043 & 0 \\ 0 & 0 & 0.01309 \end{bmatrix}$$

$$R_{wrist-gyro} = \begin{bmatrix} 0.18624 & 0 & 0 \\ 0 & 0.17025 & 0 \\ 0 & 0 & 0.01885 \end{bmatrix}$$

$$R_{shoulder-accel} = \begin{bmatrix} 0.0158 & 0 & 0 \\ 0 & 0.02692 & 0 \\ 0 & 0 & 0.1939 \end{bmatrix}$$

$$R_{elbow-accel} = \begin{bmatrix} 0.0114 & 0 & 0 \\ 0 & 0.00876 & 0 \\ 0 & 0 & 0.0137 \end{bmatrix}$$

$$R_{wrist-accel} = \begin{bmatrix} 0.0090 & 0 & 0 \\ 0 & 0.00951 & 0 \\ 0 & 0 & 0.0164 \end{bmatrix}$$

$$\boldsymbol{Initial\ State\ Covariance\ Matrix}:$$

$$P_0 = \begin{bmatrix} 0.0001 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.01 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.0001 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.01 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.0001 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

6.2 Appendix B: Bill of Materials

Table 6: Initial Bill of Materials (BOM) [1]

EXPECTED COST						
Item	**Manufacturer**	**Purchased from**	**Source**	**Price per Unit / Gram**	**Quantity / Mass**	**Total (before Tax)**
240pcs 10CM and 20CM Jumper Wires	IZOKEE	Amazon.ca	[25]	$11.18	1	$11.18
Nike PRO Unisex DRI-FIT Sleeve 4.0	Nike	Amazon.ca	[26]	$40.31	1	$40.31
LiPo Battery (3.7V 1000mAh)	Canada Robotix	Canada Robotix	[27]	$8.99	1	$8.99
Shuttle Board 3.0 BMI270 IMU	Bosch Sensortec	DigiKey	[28]	$47.41	3	$142.23
ESP-32-S3-DEVKITC-1-N8	Espressif Systems	DigiKey	[29]	$23.77	1	$23.77
M2 x 0.4 mm Heat-Set Inserts	McMaster-Carr	McMaster-Carr	[30]	$0.40	20	$7.96
M2 x 0.4 mm 18-8 Stainless Steel Socket Head Screw	McMaster-Carr	McMaster-Carr	[31]	$0.09	20	$1.86
Printed ABS Components, 54.35 g	-	WATiMake	[32]	$0.04	54.35	$1.90
Total (before Tax)						$238.20
Total (after Tax)						$269.16

Table 7: Final BOM

ACTUAL COST						
Item	**Manufacturer**	**Purchased from**	**Source**	**Price per Unit / Gram**	**Quantity / Mass**	**Total (before Tax)**
240pcs 10CM and 20CM Jumper Wires	IZOKEE	Amazon.ca	[25]	11.18	1	11.18
Sleeve	AetherGear	Amazon.ca	[11]	8.57	2	17.14
Prototyping Board	PTSolns	Amazon.ca	[33]	12.99	1	12.99
Cable Management Wire Protector (25 ft-3/8 inch dia)	Aibole	Amazon.ca	[12]	12.99	1	12.99
Elastic Knitting Band (1.2-inch x 5.5 yard)	yantaisiyu	Amazon.ca	[13]	7.99	1	7.99
Heat Shrink inserts (100 pieces)	HANGLIFE	Amazon.ca	[34]	10.99	1	10.99
DC 3.7V 1600mAh li-ion Polymer Battery	HXJNLDC	Amazon.ca	[15]	22	1	22
MICRO 6DOF IMU BREAKOUT	SparkFun	DigiKey	[8]	24.94	3	74.82
ESP-32-S3-DEVKITC-1-N8	Espressif Systems	DigiKey	[29]	23.77	1	23.77
JST Battery Connector	Adafruit	DigiKey	[35]	1.13	1	1.13
Flexible Qwic Cable - 500mm	SparkFun	DigiKey	[36]	3.6	2	7.2
Switch	C&K	DigiKey	[37]	5.64	1	5.64
Wellson Mini Size Super Glue	Wellson	Farah Foods	[38]	$3.49	1	3.49
M2 x 0.4 mm Heat-Set Inserts	McMaster-Carr	McMaster-Carr	[30]	0.398	20	7.96
M2 x 0.4 mm 18-8 Stainless Steel Socket Head Screw	McMaster-Carr	McMaster-Carr	[31]	0.0928	20	1.856
Printed PLA Components, 49.88 g	-Uwaterloo Enginering Department	Rapid Prototyping Center	[39]	0.04	54.35	2.174
Total (before Tax)						$223.32
Total (after Tax)						$252.35

6.3 Appendix C: Drawings

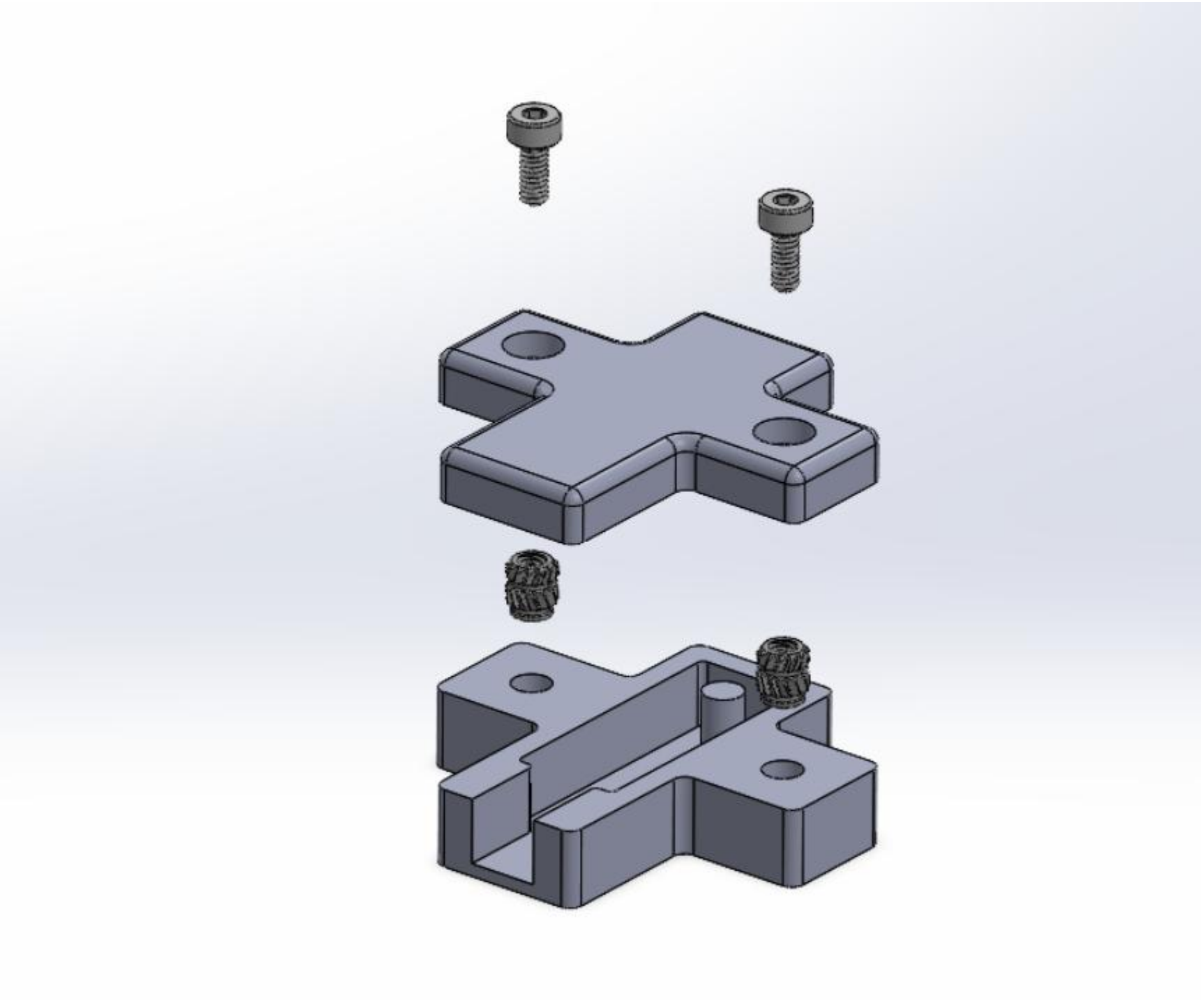

Figure 14: Sensor Enclosure

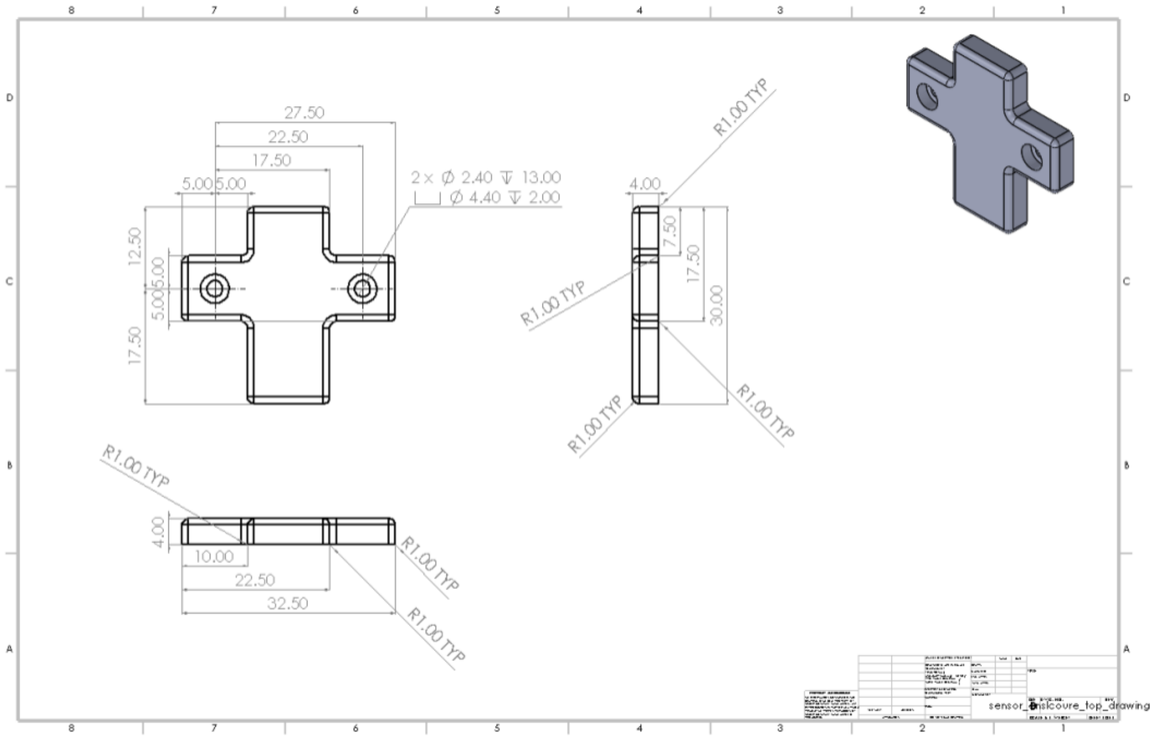

Figure 15: Sensor Enclosure (Top)

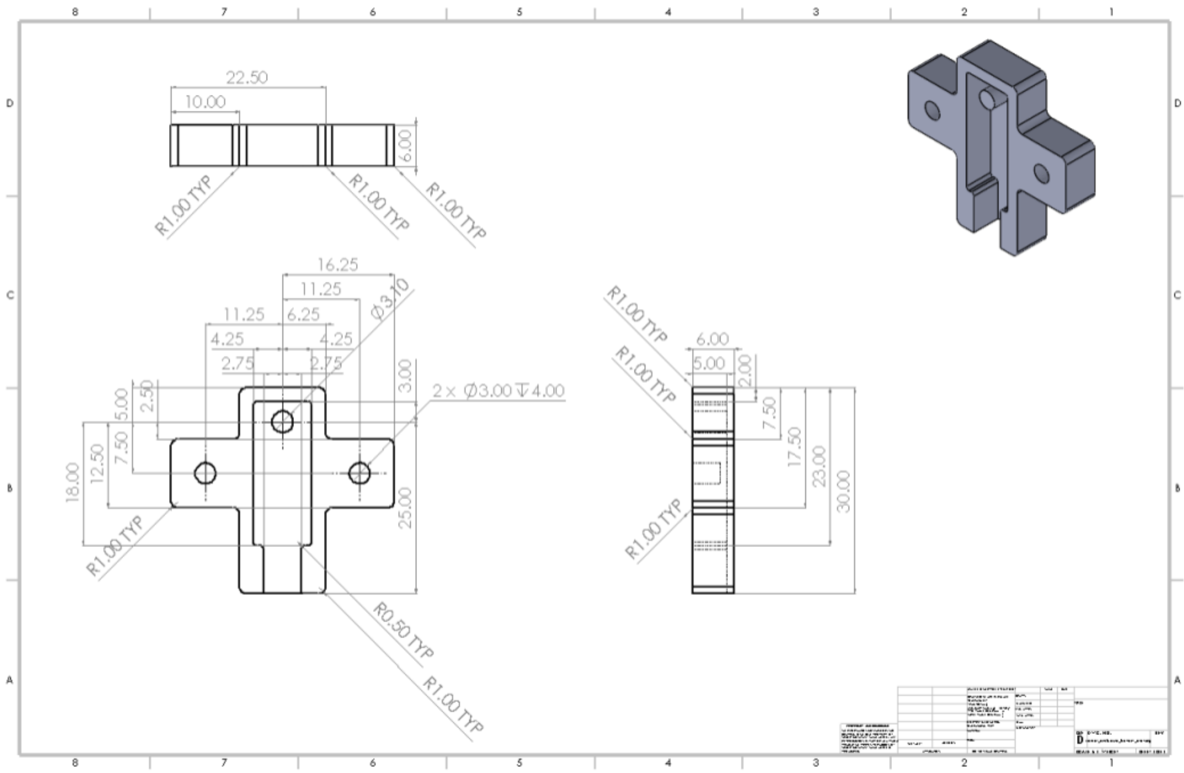

Figure 16: Sensor Enclosure (Bottom)

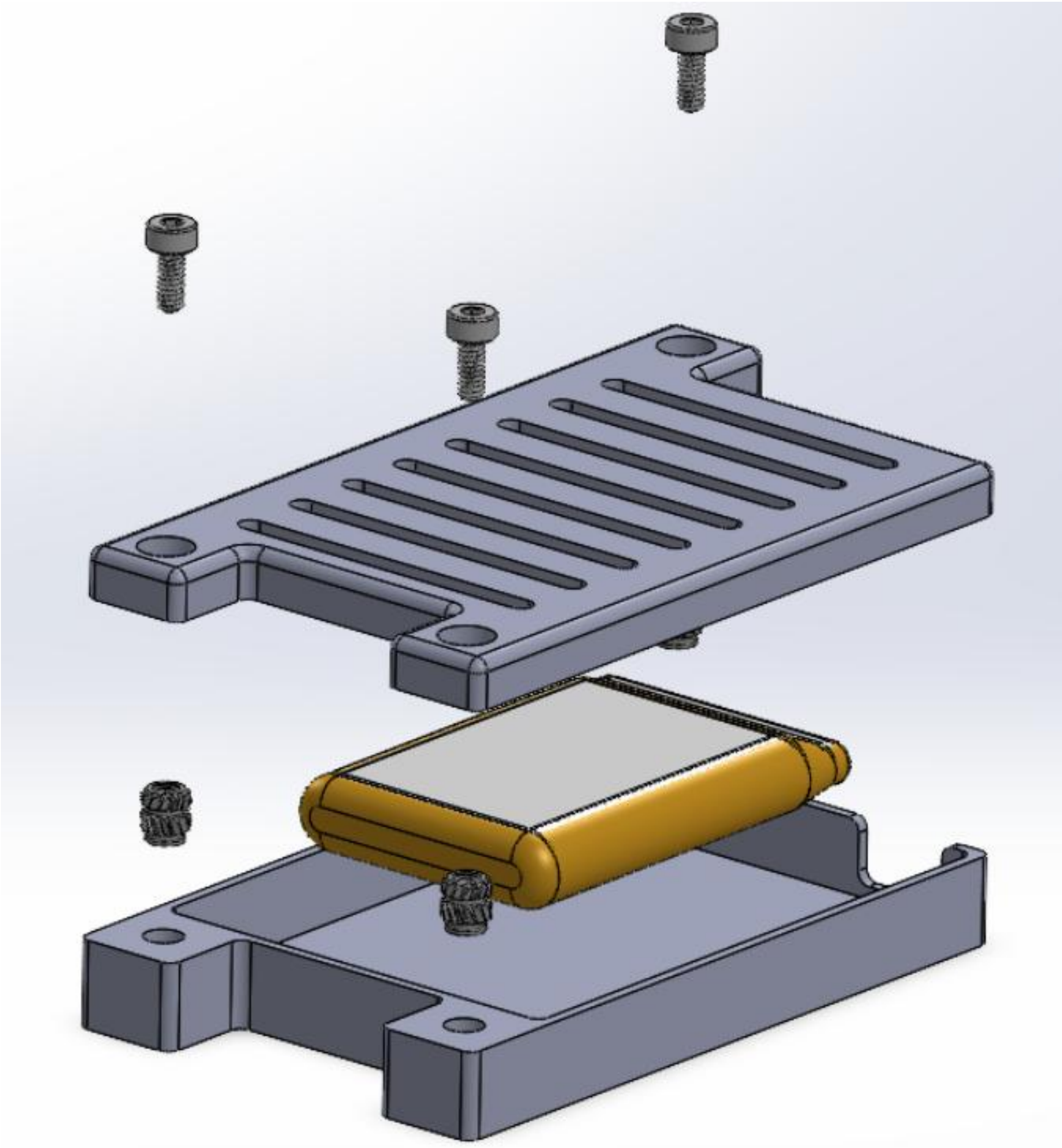

Figure 17: Battery Enclosure

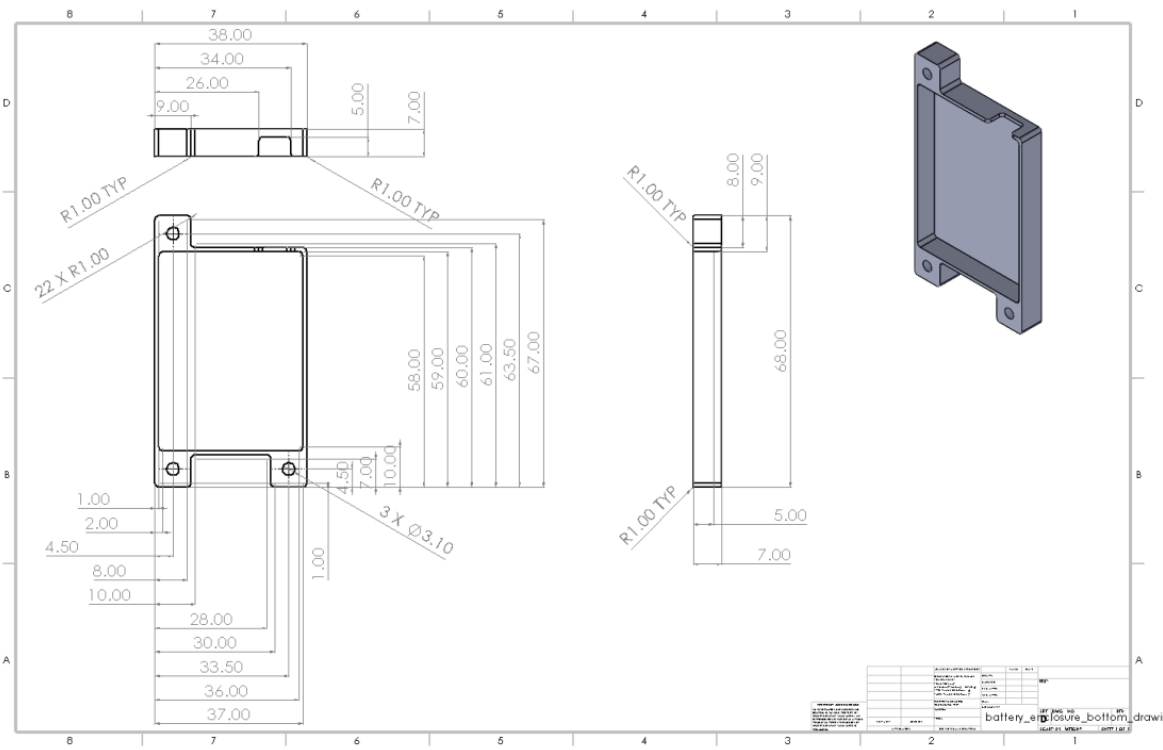

Figure 18: Battery Enclosure (Bottom)

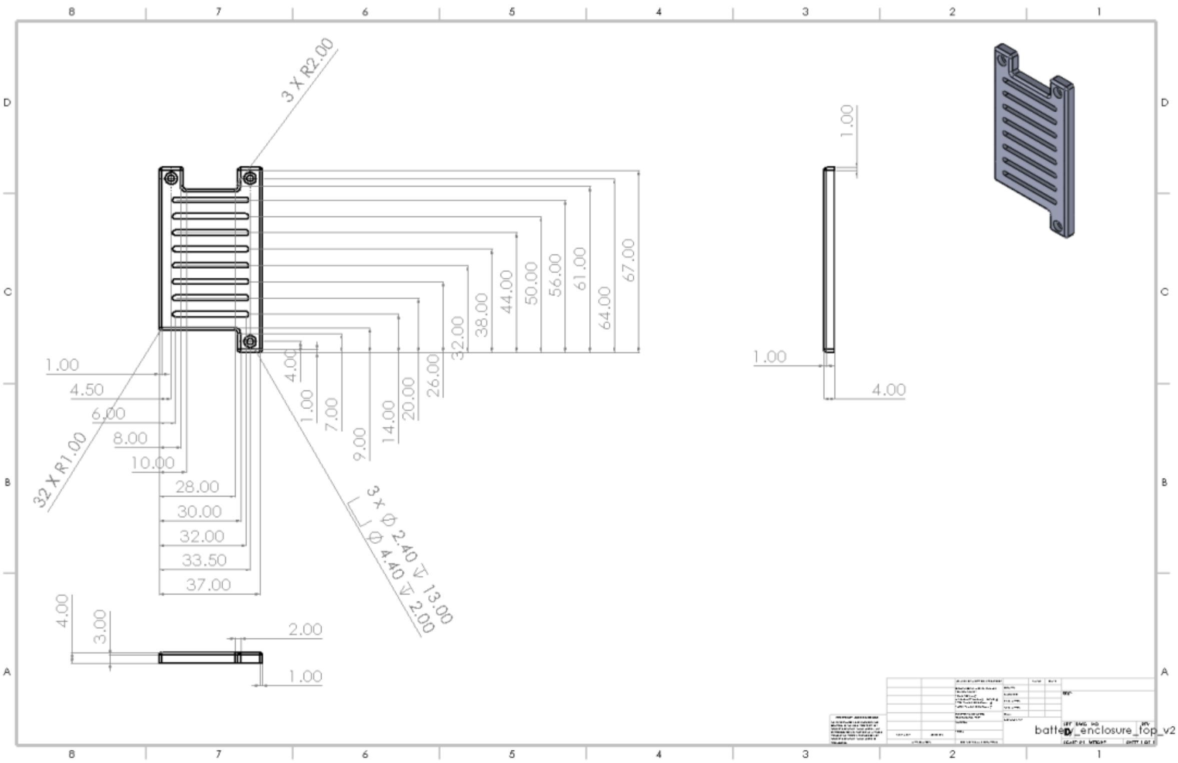

Figure 19: Battery Enclosure (Top)

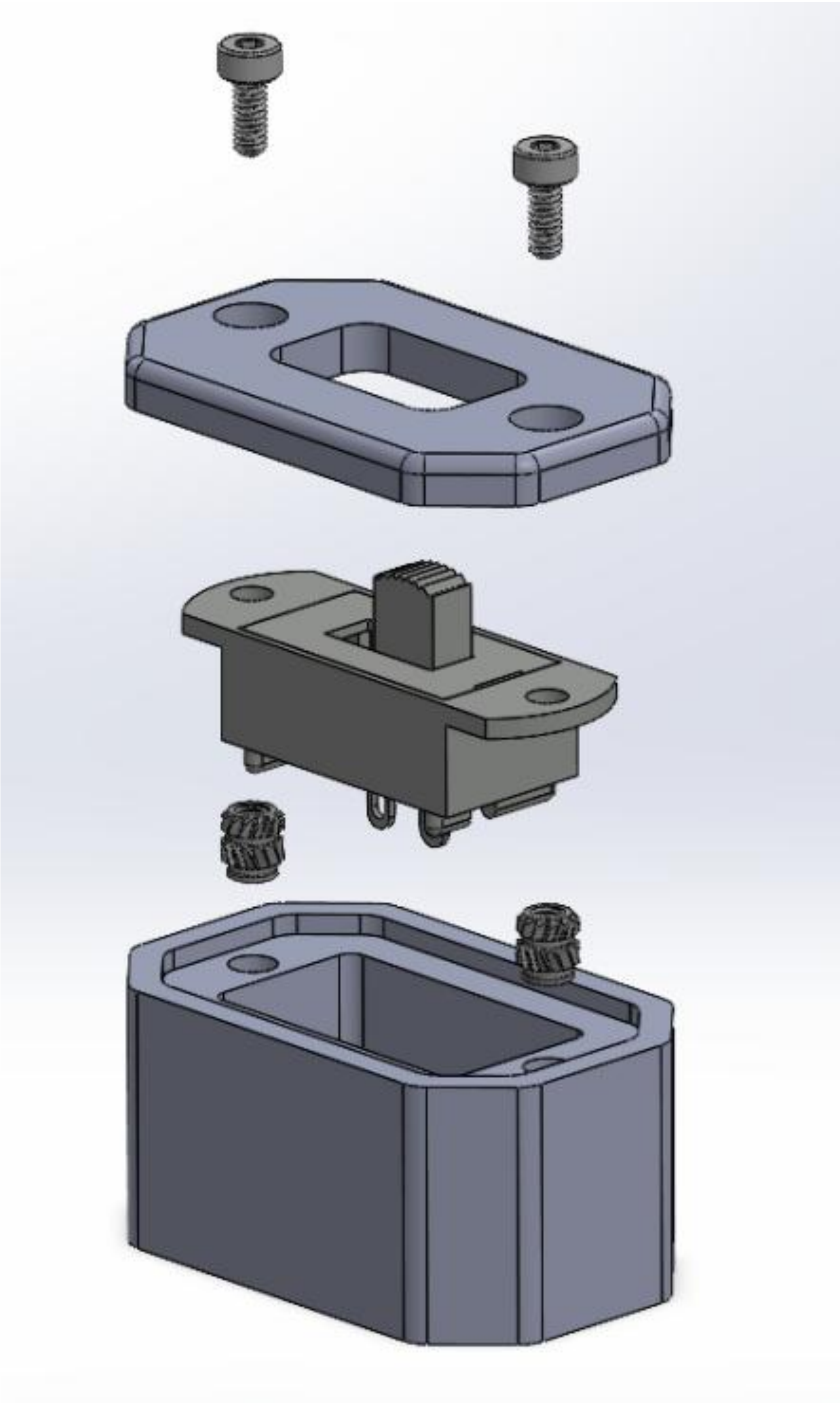

Figure 20: Switch Enclosure

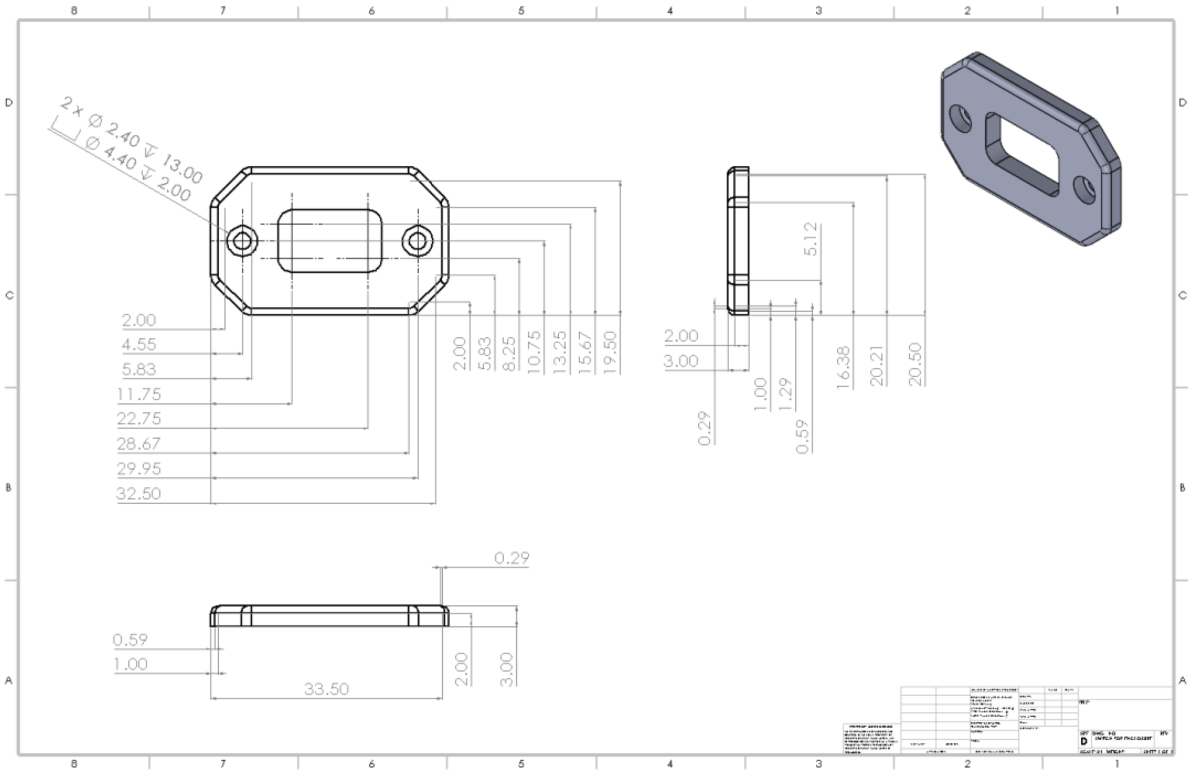

Figure 21: Switch Enclosure (Top)

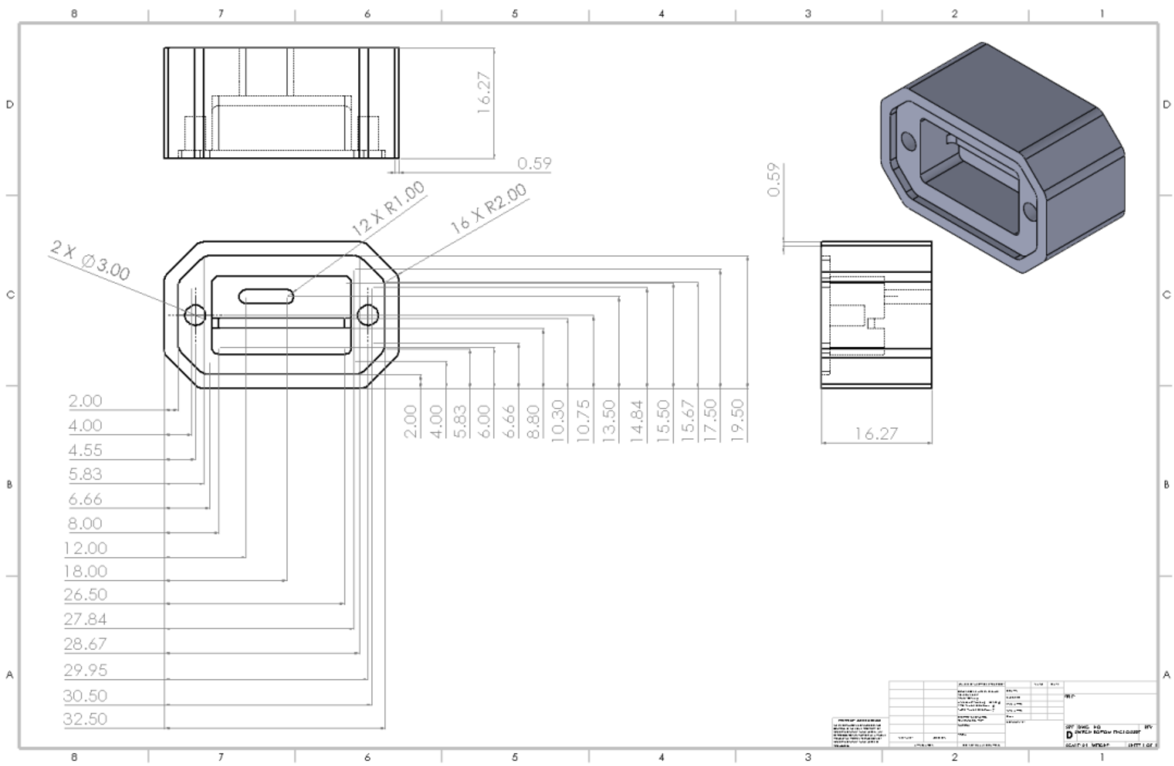

Figure 22: Switch Enclosure (Bottom)

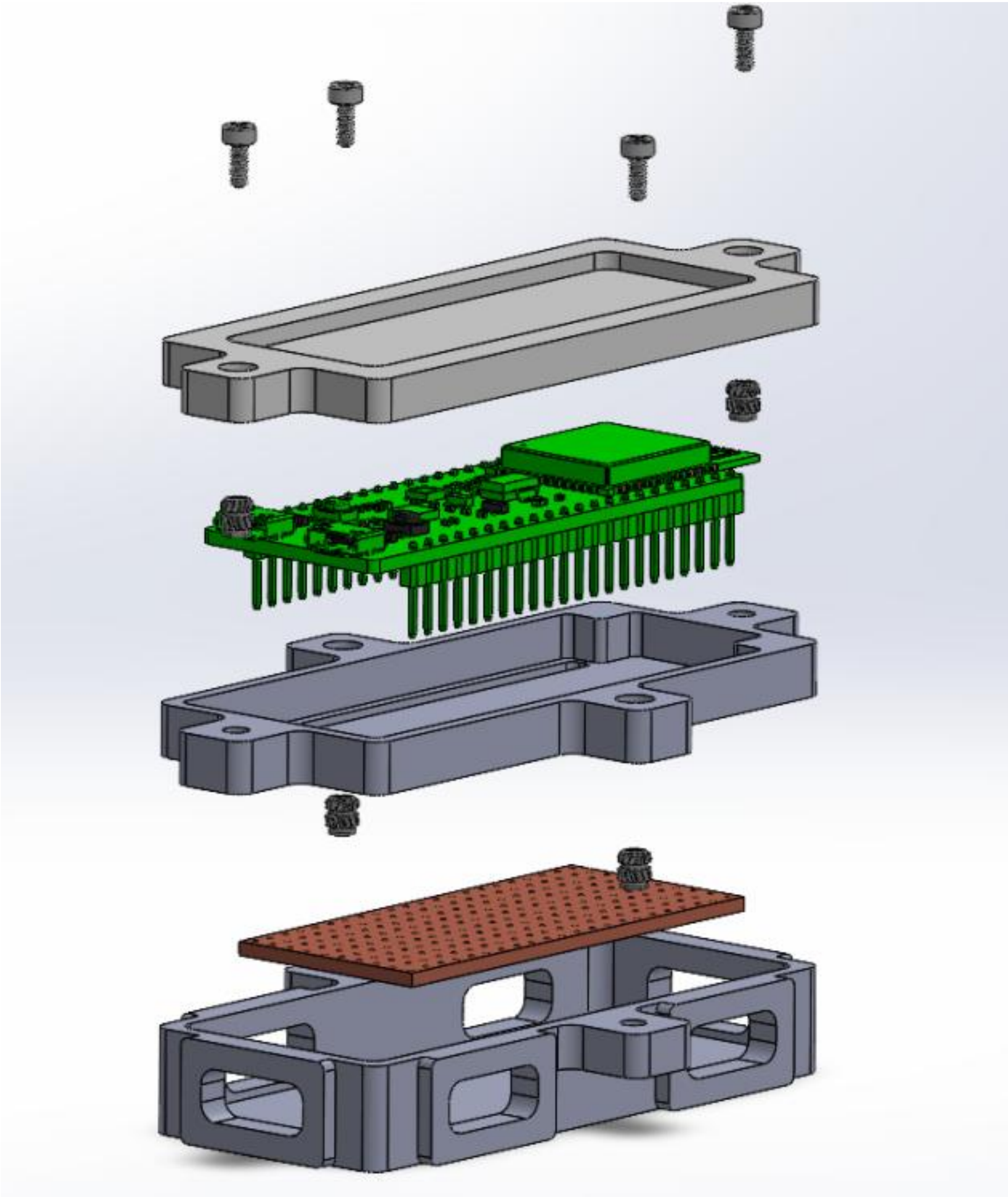

Figure 23: Microcontroller Enclosure

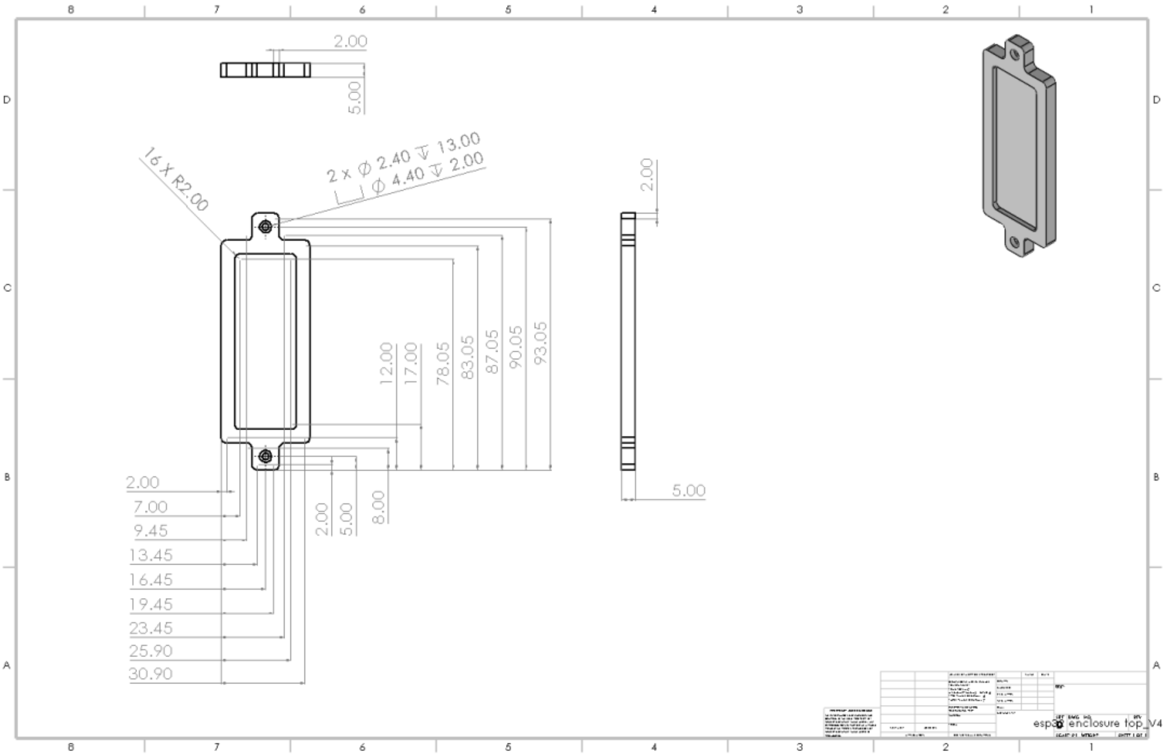

Figure 24: Microcontroller Enclosure (Top)

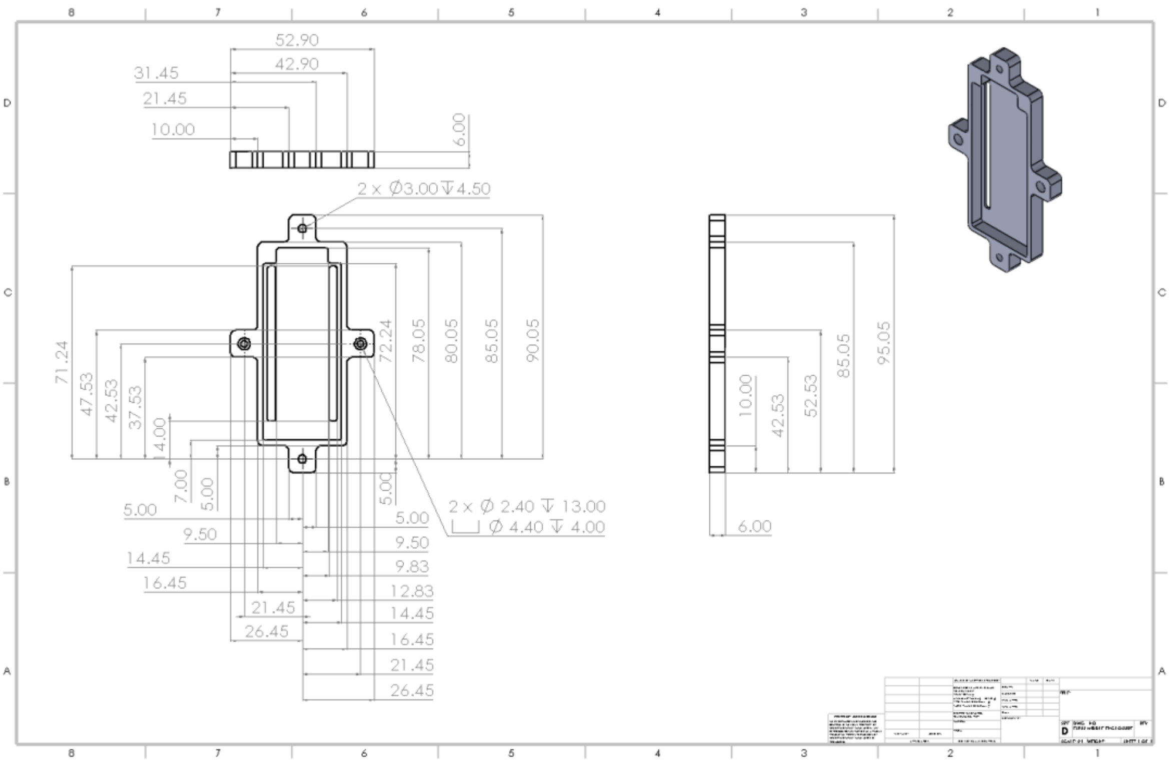

Figure 25: Microcontroller Enclosure (Middle)

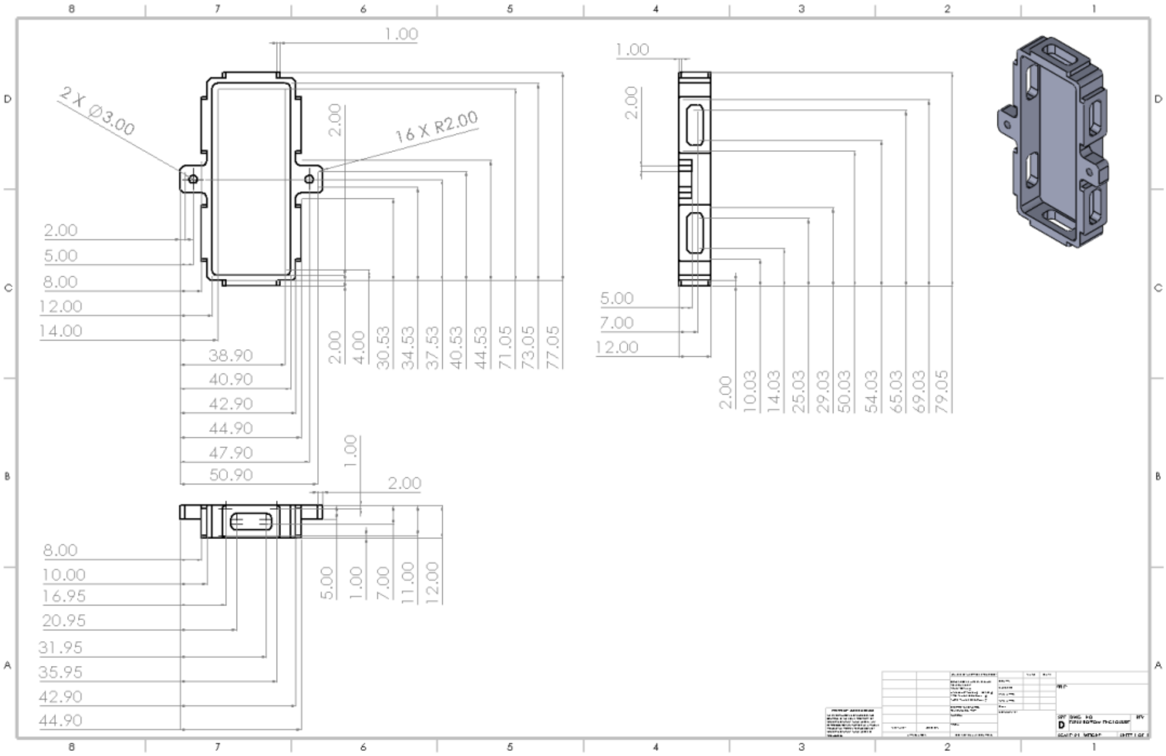

Figure 26: Microcontroller Enclosure (Bottom)

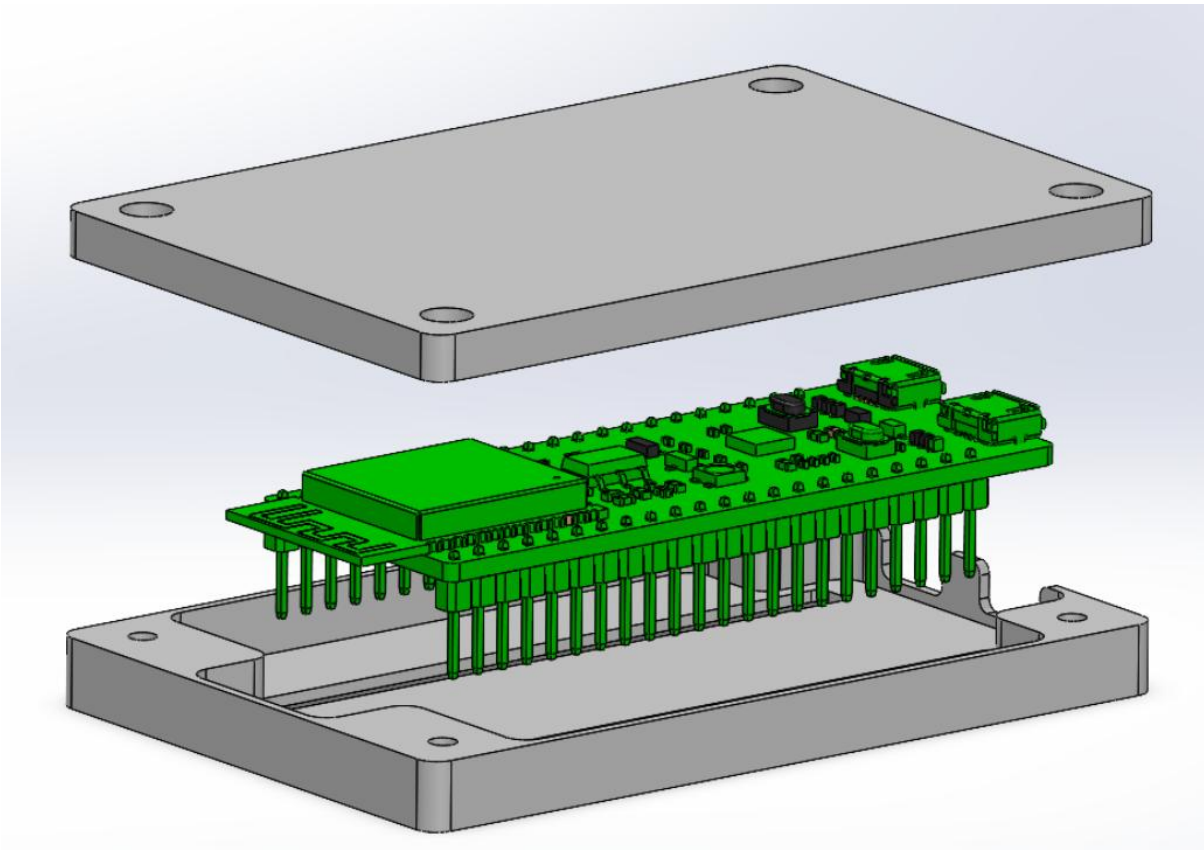

Figure 27: Old ESP-32 Design #1

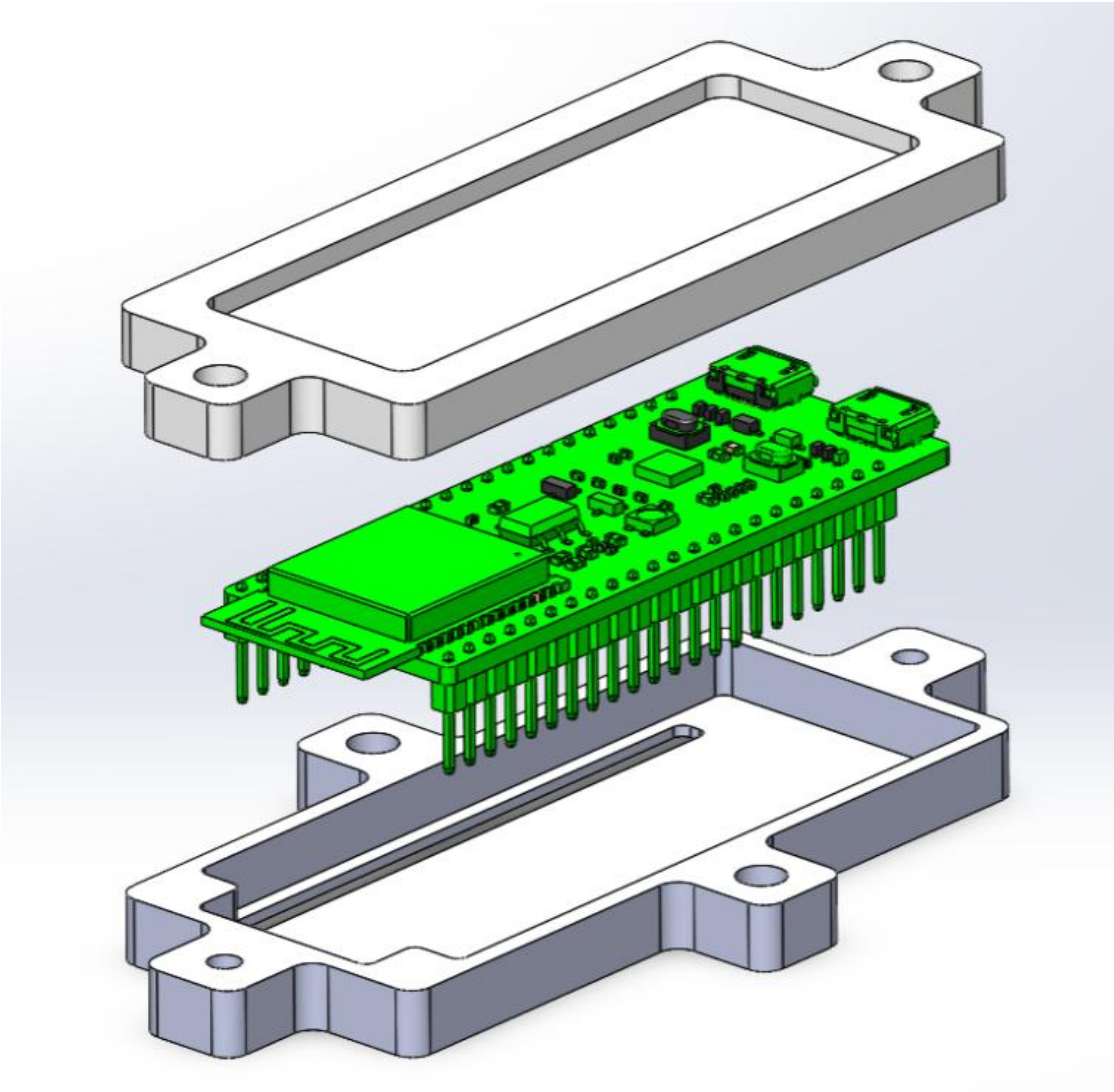

Figure 28: Old ESP-32 Enclosure # 2

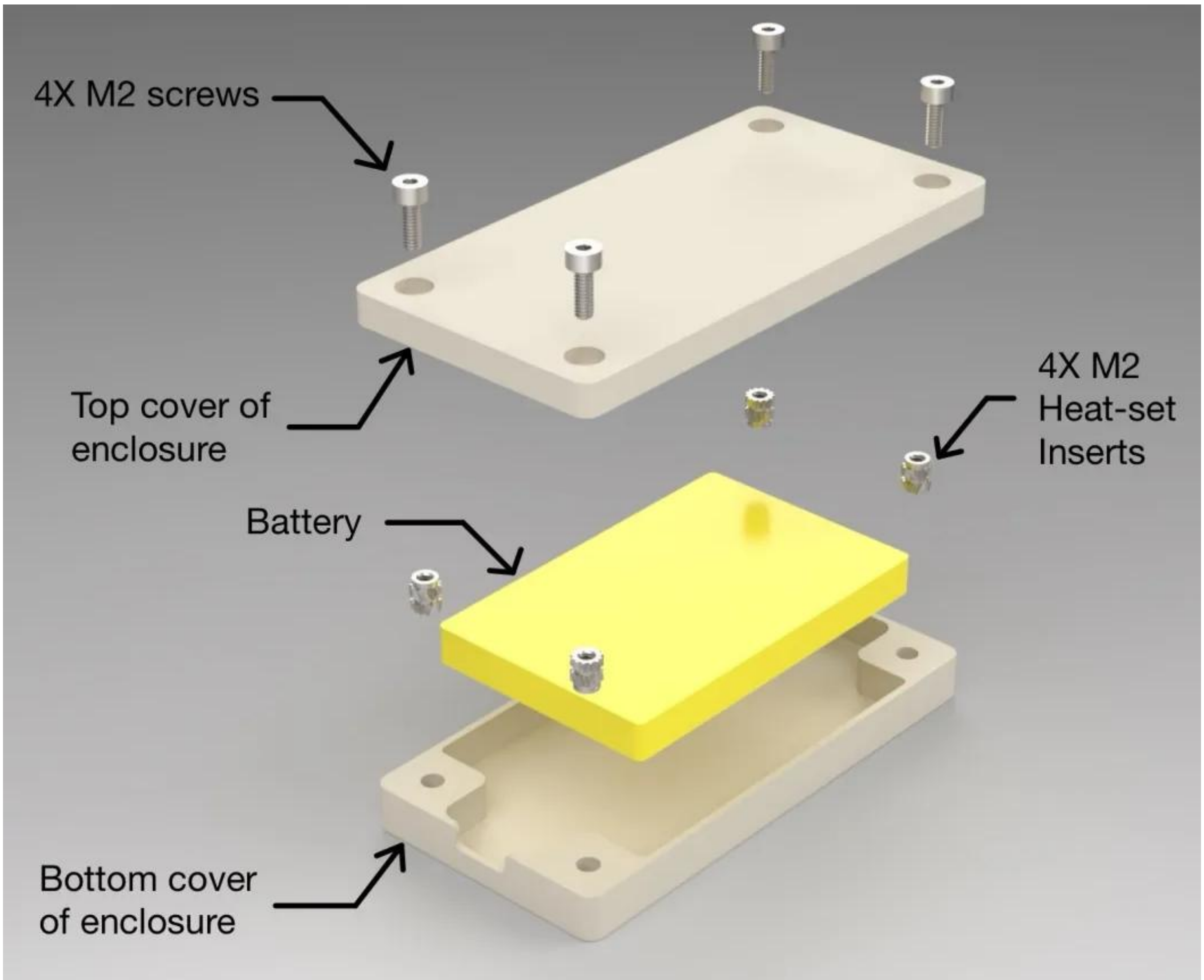

Figure 29: Old Battery Enclosure

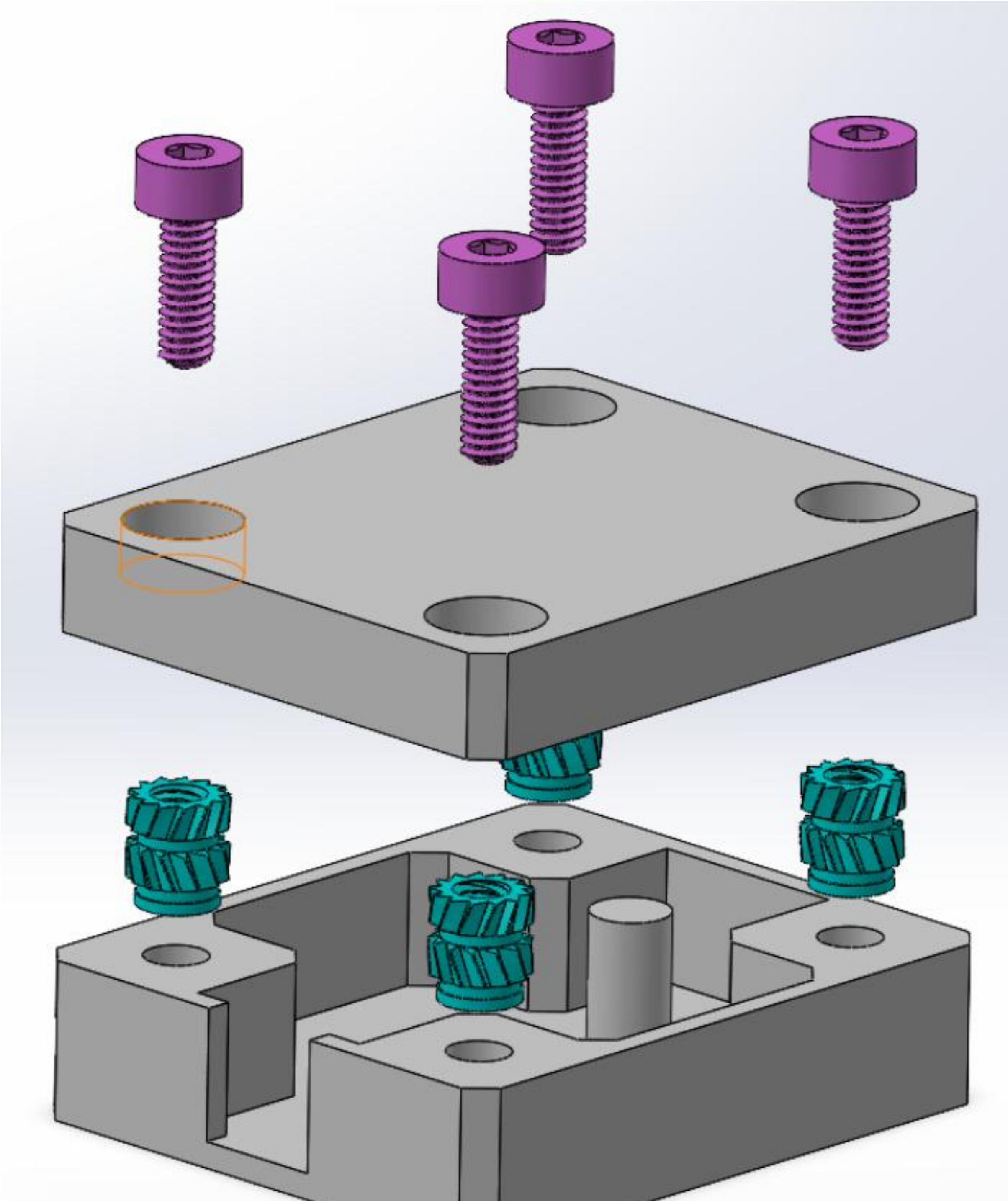

Figure 30: Old Sensor Enclosure

6.4 Appendix D: Data Tables

Table 8: Data Cloud Storage Format

Field	Type	Description
Measurement	String	Specifies which sensor (ie. Elbow_data)
Gyro_x	Float	Angular Velocity in X [deg/s]
Gyro_y	Float	Angular Velocity in Y [deg/s]
Gyro_z	Float	Angular Velocity in Z [deg/s]
Accel_x	Float	Linear Acceleration in X [g]
Accel_y	Float	Linear Acceleration in Y [g]
Accel_z	Float	Linear Acceleration in Z [g]
Time	Timestamp	Exact timestamp of the reading

Table 9: Session Cloud Storage Format

Field	Type	Description
Session_id	Tag	Unique identifier for the session
Start_time	Timestamp	Session start time
End_time	Timestamp	Session end time
Total_time_s	Float	Session Duration [s]
Intensity	String	Session intensity
Num_swings	Integer	Total swings in session
Elbow_strains	Integer	Number of high-risk elbow movements
Shoulder_strains	Integer	Number of high-risk shoulder movements
Max_elbow_v	Float	Max Angular Velocity in X [deg/s]
Max_wrist_v	Float	Max Angular Velocity in Y [deg/s]
Max_shoulder_v	Float	Max Angular Velocity in Z [deg/s]
Max_elbow_a	Float	Max Linear Acceleration in X [g]
Max_wrist_a	Float	Max Linear Acceleration in Y [g]
Max_shoulder_a	Float	Max Linear Acceleration in Z [g]
Max_net_a	Float	Combined max linear acceleration across all sensors
Max_net_v	Float	Combined max angular velocity across all sensors
Time	Timestamp	Exact session end time

6.5 Appendix E: Arduino Code

```
#include <Wire.h>
#include "SparkFun_BMI270_Arduino_Library.h"
#include <BLEDevice.h>
#include <BLEServer.h>
#include <BLEUtils.h>
#include <BLE2902.h>

// Create new sensor objects
BMI270 imu_elbow;
BMI270 imu_shoulder;
BMI270 imu_wrist;

// I2C address selection
uint8_t i2cAddress_1 = BMI2_I2C_PRIM_ADDR; // 0x68
uint8_t i2cAddress_2 = BMI2_I2C_SEC_ADDR;  // 0x69

// BLE service and characteristic UUIDs
#define SERVICE_UUID "12345678-1234-5678-1234-56789abcdef0"

#define SENSOR_ELBOW_UUID "abcdef12-1234-5678-1234-56789abcdef0"
#define SENSOR_SHOULDER_UUID "a66c2d3c-58c6-4de2-a436-1de6ae91d3da"
#define SENSOR_WRIST_UUID "d8b43881-9960-4d1b-a0da-b0daf991119e"

// BLE characteristics (one per sensor)
BLECharacteristic *sensorCharacteristicElbow;
BLECharacteristic *sensorCharacteristicShoulder;
BLECharacteristic *sensorCharacteristicWrist;

// BLE advertising object
BLEAdvertising *pAdvertising;

void setup()
{
    Serial.begin(115200);
    Serial.println("BMI270 Example with BLE");

    // Initialize I2C buses
    Wire.begin(8, 10);  // Elbow and wrist sensor I2C bus
    Wire1.begin(4, 17); // Shoulder sensor on separate I2C bus

    // Initialize IMUs
    if (imu_elbow.beginI2C(i2cAddress_1, Wire) != BMI2_OK)
    {
        Serial.println("Error: Elbow Sensor not connected!");
        while (1)
            ;
    }
```

```
    Serial.println("Elbow sensor connected!");

    if (imu_wrist.beginI2C(i2cAddress_2, Wire) != BMI2_OK)
    {
        Serial.println("Error: Wrist Sensor not connected!");
        while (1)
            ;
    }
    Serial.println("Wrist sensor connected!");

    if (imu_shoulder.beginI2C(i2cAddress_1, Wire1) != BMI2_OK)
    {
        Serial.println("Error: Shoulder Sensor not connected!");
        while (1)
            ;
    }
    Serial.println("Shoulder sensor connected!");

    // Initialize BLE
    BLEDevice::init("ESP-32_IMU");
    BLEServer *pServer = BLEDevice::createServer();
    BLEService *imuService = pServer->createService(SERVICE_UUID);

    // Create BLE characteristic for each sensor
    sensorCharacteristicElbow = imuService-
>createCharacteristic(SENSOR_ELBOW_UUID, BLECharacteristic::PROPERTY_READ |
BLECharacteristic::PROPERTY_NOTIFY);
    sensorCharacteristicElbow->addDescriptor(new BLE2902());

    sensorCharacteristicShoulder = imuService-
>createCharacteristic(SENSOR_SHOULDER_UUID, BLECharacteristic::PROPERTY_READ |
BLECharacteristic::PROPERTY_NOTIFY);
    sensorCharacteristicShoulder->addDescriptor(new BLE2902());

    sensorCharacteristicWrist = imuService-
>createCharacteristic(SENSOR_WRIST_UUID, BLECharacteristic::PROPERTY_READ |
BLECharacteristic::PROPERTY_NOTIFY);
    sensorCharacteristicWrist->addDescriptor(new BLE2902());

    // Start BLE service
    imuService->start();

    // Start advertising
    pAdvertising = BLEDevice::getAdvertising();
    pAdvertising->start();
    Serial.println("BLE started. Waiting for connection...");
    Serial.println("Bluetooth MAC Address: " +
String(BLEDevice::getAddress().toString().c_str()));
}
```

```
// Restart BLE advertising if it stops
void checkBLEAdvertising()
{
    static unsigned long lastBLECheck = 0;
    if (millis() - lastBLECheck > 5000)
    {
        lastBLECheck = millis();
        Serial.println("Restarting BLE advertising...");
        BLEDevice::startAdvertising();
    }
}

void loop()
{
    checkBLEAdvertising(); // Ensure BLE stays active

    // Get measurements from the sensors
    imu_elbow.getSensorData();
    imu_shoulder.getSensorData();
    imu_wrist.getSensorData();

    // Create JSON-like string with gyroscope + accelerometer data
    String elbow_data = "{";
    elbow_data += "\"gyroX\":" + String(imu_elbow.data.gyroX, 3) + ",";
    elbow_data += "\"gyroY\":" + String(imu_elbow.data.gyroY, 3) + ",";
    elbow_data += "\"gyroZ\":" + String(imu_elbow.data.gyroZ, 3) + ",";
    elbow_data += "\"accelX\":" + String(imu_elbow.data.accelX, 3) + ",";
    elbow_data += "\"accelY\":" + String(imu_elbow.data.accelY, 3) + ",";
    elbow_data += "\"accelZ\":" + String(imu_elbow.data.accelZ, 3) + "}";

    String shoulder_data = "{";
    shoulder_data += "\"gyroX\":" + String(imu_shoulder.data.gyroX, 3) + ",";
    shoulder_data += "\"gyroY\":" + String(imu_shoulder.data.gyroY, 3) + ",";
    shoulder_data += "\"gyroZ\":" + String(imu_shoulder.data.gyroZ, 3) + ",";
    shoulder_data += "\"accelX\":" + String(imu_shoulder.data.accelX, 3) +
",";
    shoulder_data += "\"accelY\":" + String(imu_shoulder.data.accelY, 3) +
",";
    shoulder_data += "\"accelZ\":" + String(imu_shoulder.data.accelZ, 3) +
"}";

    String wrist_data = "{";
    wrist_data += "\"gyroX\":" + String(imu_wrist.data.gyroX, 3) + ",";
    wrist_data += "\"gyroY\":" + String(imu_wrist.data.gyroY, 3) + ",";
    wrist_data += "\"gyroZ\":" + String(imu_wrist.data.gyroZ, 3) + ",";
    wrist_data += "\"accelX\":" + String(imu_wrist.data.accelX, 3) + ",";
    wrist_data += "\"accelY\":" + String(imu_wrist.data.accelY, 3) + ",";
    wrist_data += "\"accelZ\":" + String(imu_wrist.data.accelZ, 3) + "}";
```

```
    // Send JSON data via BLE
    sensorCharacteristicElbow->setValue(elbow_data.c_str());
    sensorCharacteristicElbow->notify();

    sensorCharacteristicShoulder->setValue(shoulder_data.c_str());
    sensorCharacteristicShoulder->notify();

    sensorCharacteristicWrist->setValue(wrist_data.c_str());
    sensorCharacteristicWrist->notify();

    // Debug output to Serial
    Serial.println("Elbow: " + elbow_data);
    Serial.println("Shoulder: " + shoulder_data);
    Serial.println("Wrist: " + wrist_data);

    // Send data 50x per second
    delay(20);
}
```

6.6 Appendix F: SplitWise Budget Breakdown

Table 10: SplitWise Report

Date	Description	Cost	Christopher Nikolik	Shivraj Vishnoi	Lucas D'Elia	Connor Johanson	Mina Tawadros
2024-12-18	481 Order	88.87	-17.77	-17.78	71.09	-17.77	-17.77
2025-01-14	Digikey Jan 13	177.16	141.72	-35.43	-35.43	-35.43	-35.43
2025-01-29	Battery	22	-4.4	-4.4	-4.4	17.6	-4.4
2025-02-11	Cable management wire	14.68	-2.93	-2.94	-2.93	-2.94	11.74
2025-02-11	Digikey Feb 11	28.11	22.49	-5.62	-5.62	-5.62	-5.63
2025-02-11	Battery	21.47	-4.3	-4.3	-4.29	17.18	-4.29
2025-02-22	Elastic band spool	9.03	-1.81	-1.81	-1.8	-1.81	7.23
2025-03-01	Arm sleeve x2, glue, heat inserts, 3D prints	50.35	-3.87	-3.88	-3.87	-3.87	15.49
2025-03-19	Poster	12.95	-2.59	-2.59	10.36	-2.59	-2.59
TOTAL							$424.62