ECE 445: Senior Design Laboratory

Running Cadence Monitor Belt

Team 5

Alex Jin, Dante Vasudevan, Nick Bergerhouse

Professor: Viktor Gruev

TA: Koushik Udayachandran

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1 Introduction

1.1 Problem and Solution

Running cadence is the number of steps a runner takes per minute while running, commonly measured in strides per minute (SPM). It is a useful measurement for runners as it can provide insight into efficiency, form, and stride length. An ideal cadence for most runners typically falls into the range of 170 to 180 SPM although this is dependent on height and pace.

Currently there are already products on the market that can measure running cadence. For example, most “running watches” have cadence as an included measurement. However, it can be cumbersome for runners to constantly switch through display screens to monitor multiple data points at the same time such as pace, heart rate, distance, and cadence. Furthermore, unless a runner is running with their arm locked in front of them, continuous monitoring of cadence is impossible with a running watch. Other products take a different approach such as the foot-mounted ARION Footpod non-GPS 1.0 and Stryd. These products can track the cadence throughout the run in much the same way that a running watch would, but they can not provide that information to the runner without the use of a watch or smartphone. In both the watch and foot-mounted solution, there is a lack of a product that provides easy, hands-free haptic feedback to the runner informing them when their cadence falls outside of the ideal cadence range.

The product will consist of a lightweight, belt-mounted device consisting of several PCBs that utilize an IMU for step detection. A running mean time between a certain number of previous steps will be used to calculate the runner’s current cadence. Based on the measured cadence, the microcontroller will control vibration motors to create haptic feedback, which will inform the user based on vibration patterns in real time how to adjust their cadence to achieve perfect running efficiency. The device itself will be mounted on the user’s back, as this is already a popular spot for runners to store items, such as phone mounts or fanny packs. This also increases user comfort by keeping the device clear of the front and sides, where there may be hand movement. The system will be powered by a mobile battery, such as a LiPo battery, that is also connected to the belt. Our solution also offers user customization. Users can adjust their target cadence from the default

180 to any lower target cadence they want. Users will also be able to adjust the strength of the feedback from the haptic motors.

The system will consist of three separate boards, and a battery pack. The first board, the Microcontroller Board, will have an ESP32 microcontroller as its main feature, which handles step detection and haptic feedback activation decisions. The board will calculate the Strides Per Minute (SPM) metric to do this

The second board, the IMU board, will contain a BNO086 Inertial Measurement Unit. This sends step data to the microcontroller via an exclusive SPI bus interface.

The third board, the Haptic Feedback board, contains a Battery Management System (BMS) that interfaces with the battery pack and provides power supply to the rest of the system. Vibration motors will also be present on this board to signal the need for SPM adjustment to the user.

All three boards will be mounted onto a flexible waist belt in close proximity to each other. The battery pack will be mounted next to the Haptic Feedback Board as our BMS will be located on that board. The vibration motors on the Haptic Feedback Board will be as close to the user as possible to allow them to feel the vibration. The entire system, while mounted on the belt, will be enclosed in plastic such as a 3D printed shell.

1.2 Visual Aid

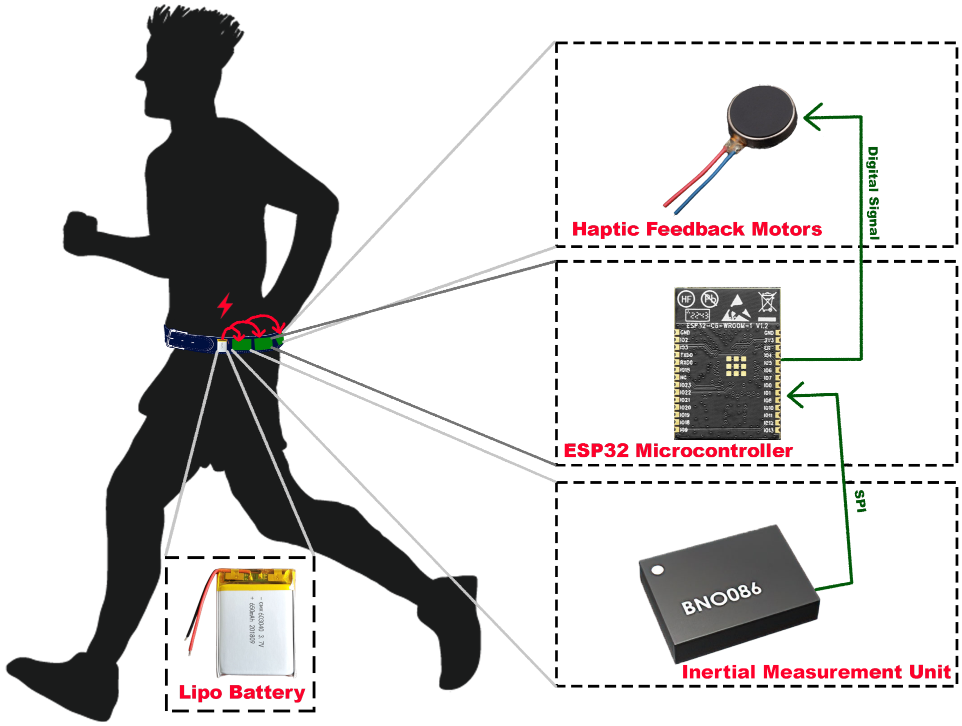

Figure 1: Visual Aid Showing the Major Components on the Belt

1.3 High Level Requirements List

1. The product shall detect the strides of the user through an Inertial Measurement Unit (IMU) and derive from them a strides per minute (SPM) metric. The default SPM goal is 180.

2. The product shall notify the user of a measured SPM outside of the set limit (+/- 5) of a user-adjustable goal SPM via vibration motors located on the device.

3. The product shall have the goal SPM be user adjustable in increments of 5 through a tactile switch located on the Haptic Feedback board.

4. The product shall be solely powered by a portable 3.7V Lithium Polymer (LiPo) battery capable of 1.5A current output.

2 Design

2.1 Block Diagram

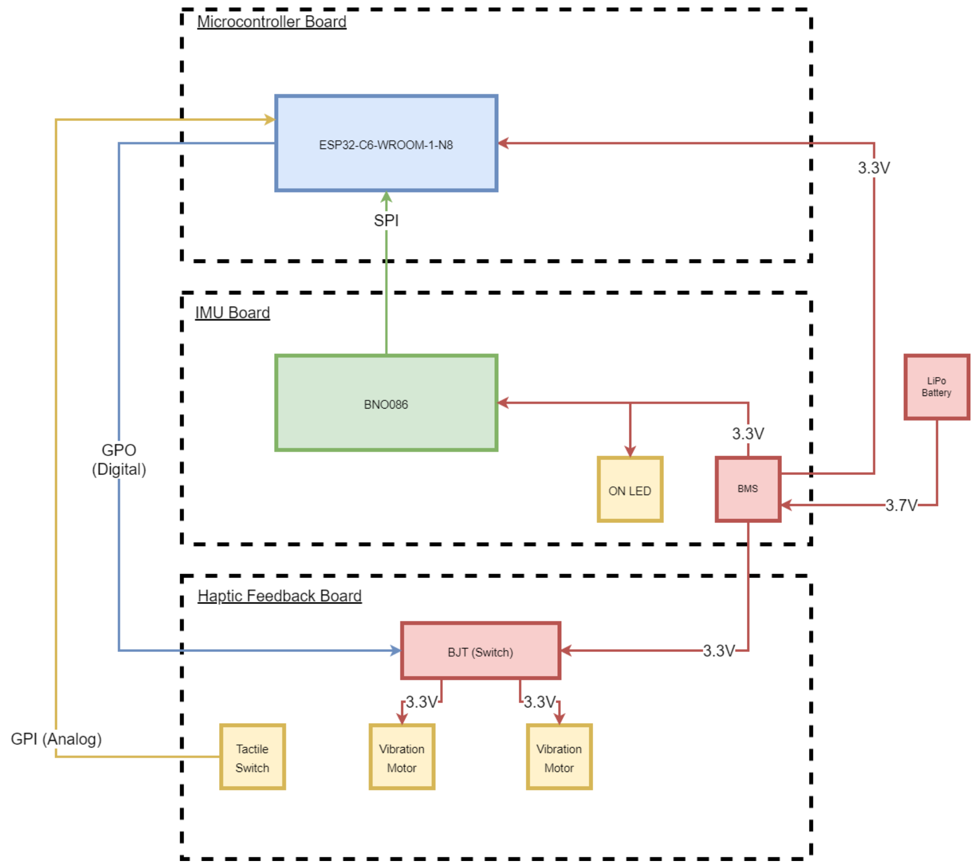

Figure 2: Block Diagram

2.2 Physical Design

The illustration below shows a rough layout of the high-level boards and components of our design on a theoretical belt. Of particular note is the location of the BNO086 IMU sensing unit on the side of either leg, in order to locate it near the legs and increase step detection accuracy. Note that the spacing between the left/right boards and the front of the belt (represented by buckle halves) has been shortened in the interest of ease of display.

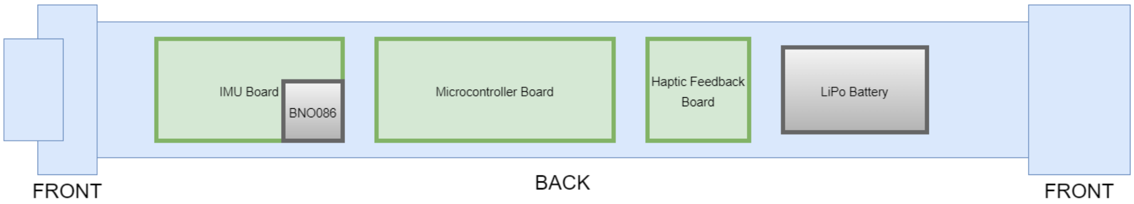

Figure 3: Physical Diagram

2.3 Microcontroller Board

This board contains the ESP32 microcontroller that we will be using. It is connected to the IMU board through an SPI data connection, as well as to the haptic feedback board through several GPIO pins to receive button inputs and activate the vibration motors. The SPI interface it uses to connect to the BNO086 IMU will be on the HSPI SPI-enabled pins. The GPIO pins it uses to communicate with the Haptic Feedback Board's systems will be on unused GPIO pins.

The microcontroller will receive step data from the IMU and calculate the SPM of the user. It will then compare this value to the customized goal SPM of the user, and if it is outside of the tolerance range, alert the user to fix their SPM by activating different vibration lengths/patterns on the vibration motors. It will also receive tactile switch inputs from the Haptic Feedback Board to alter the goal SPM and the vibration strength.

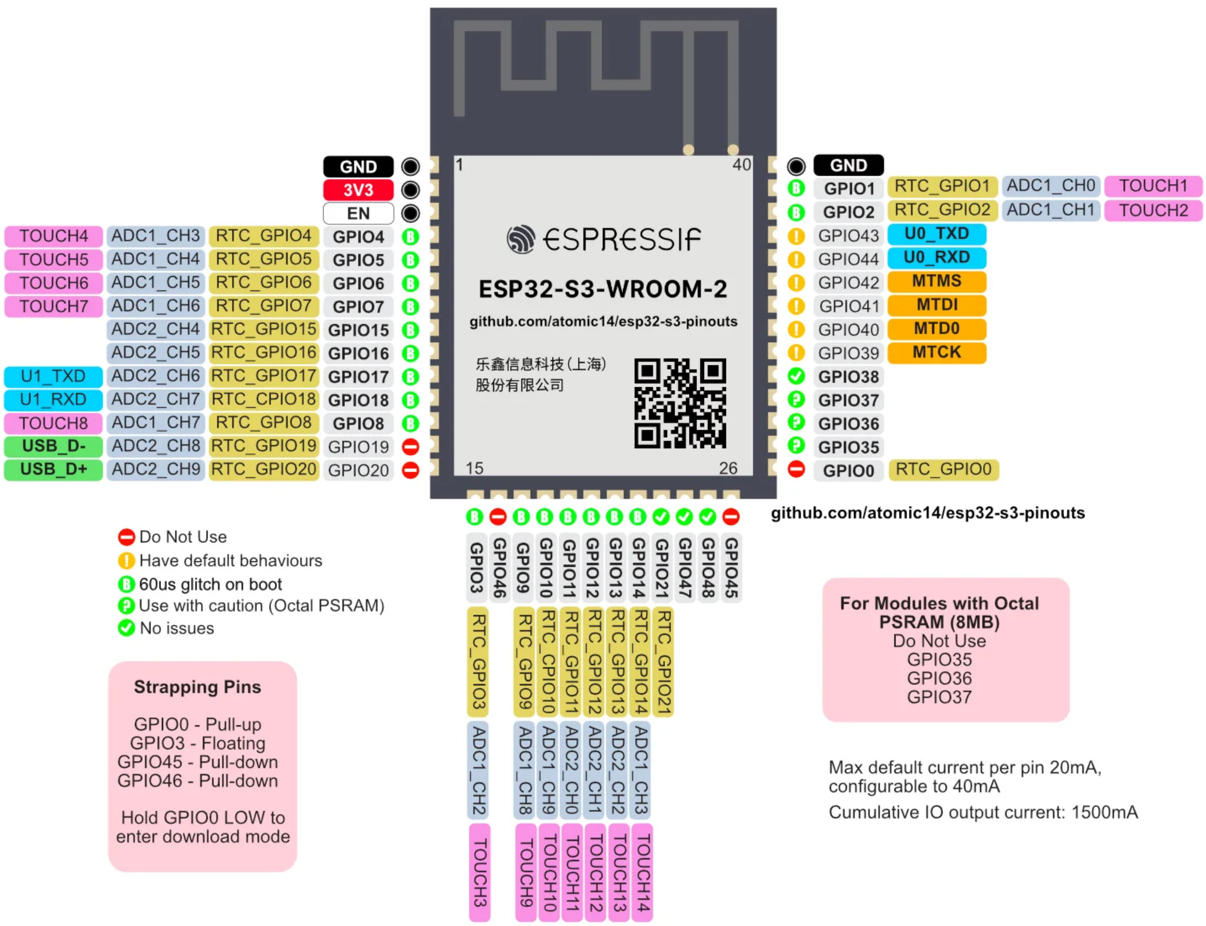

Figure 4: ESP32 Illustrated Pinout [9]

Requirement	Verification
The Microcontroller Board shall connect the supplied 3.3V power line from the BMS to the ESP32 MCU.	Equipment: DMM Procedure: 1. Set DMM to 1x DC Voltage. 2. Power system. 3. Attach positive probe to ESP32 3.3V Line. 4. Attach negative probe to ESP32 GND Line. 5. Record Voltage on DMM screen. Reporting: DMM measured voltage should be consistent with 3.3V +/- 0.1V tolerance.
The Microcontroller Board shall allow the ESP32 MCUto communicate on the HSPI_SCK (P14), HSPI_MISO (P12), and HSPI_MOSI (P13) pins, which shall be routed to the IMU Board.	Equipment: Debugging MicroUSB Cable Laptop w/ Arduino Procedure: 1. Power system. 2. Load SPI Testing program onto ESP32. 3. Jostle IMU Board, observe reported SPI metrics. Reporting: Testing program should receive SPI communication data consistent with desired output metrics per IMU datasheet.
The Microcontroller Board shall allow the ESP32 MCU to communicate on the GPIO25 (P25), GPIO26 (P26), GPIO32 (P32), and GPIO33 (P33) pins, which shall be routed to the Haptic Feedback Board.	Equipment: Debugging MicroUSB Cable Laptop w/ Arduino Procedure: 1. Power system. 2. Load GPIO Testing program onto ESP32 3. Actuate tactile switch on Haptic Feedback Board, observe reported metrics. 4. Observe vibration motors on Haptic Feedback Board, vibration pattern should be present. Reporting: Testing program should detect tactile switch actuation. Vibration motors should exhibit vibration pattern defined in testing program.

Table 1: Requirements and Verification for Microcontroller Board Subsystem

2.4 IMU Board

This board contains a BNO086 IMU. The data from this IMU will be routed to the ESP32 by a SPI connection. Specific desired metrics will be Linear Acceleration Vector, Absolute Orientation, and Absolute Rotation.

A BMS will also be present on this board, specifically a ZIO LIPO BATTERY MANAGER[3] BMS. The BMS will handle turning the device on and off, as well as allowing for the recharging of the LiPo battery. 3.3V power from the BMS will be routed to the other two boards. An ON LED will be present to indicate whether the system is powered from the BMS.

Requirement	Verification
The BMS shall supply up to 1.5 A at 3.3 +- 0.1V to the IMU Board, Microcontroller Board, and Haptic Feedback Board.	Equipment: DMM Procedure: 1. Set DMM to 1x DC Voltage. 2. Power system. 3. Attach positive probe to BMS 3.3V Line. 4. Attach negative probe to BMS GND Line. 5. Record Voltage on DMM screen. 6. Set DMM to 1x DC Current. 7. Jostle IMU Board to simulate steps. 7. Record Current on DMM Screen Reporting: DMM measured voltage should be consistent with 3.3V +/- 0.1V tolerance. DMM measured current should be below 1.5A tolerance.
The BNO086 IMU shall supply Linear Acceleration Vectors, Absolute Orientation Vectors, and other metrics to the Microcontroller Board through a SPI interface.	Equipment: Debugging MicroUSB Cable Laptop w/ Arduino Procedure: 1. Power system. 2. Load SPI Testing program onto ESP32. 3. Jostle IMU Board, observe reported SPI metrics. Reporting: Testing program should receive SPI communication data consistent with desired output metrics per IMU datasheet.

Table 2: Requirements and Verification for IMU Board Subsystem

2.5 Haptic Feedback Board

This board will consist of a 2N7002ET7G[4] MOSFET, with its gate connected to a GPO signal from the Microcontroller Board, and its drain connected to the power for two SEEED STUDIO 2.0MM MINI[5] vibration motors. These motors will not be able to activate independent of one another, rather different vibration patterns will indicate to the user whether they should decrease or increase their SPM. For example a repeated sequence of short vibrations will be used to inform the user to increase their cadence. A repeated sequence of long vibrations will be used to inform a user to decrease their cadence. A PTS526 SM15 SMTR2 LFS[6] tactile switch will be present, connected to the Microcontroller Board through a GPI signal. The tactile switch will allow the user to adjust the goal SPM; a single press will lower the goal SPM by 5 from a maximum of 180, and a long press will reset the SPM to 180.

Requirement	Verification
The Haptic Feedback Board shall connect the supplied 3.3V power line from the BMS to the 2N7002ET7G MOSFET and the PTS526 SM15 SMTR2 LFS tactile switch.	Equipment: DMM Procedure: 1. Set DMM to 1x DC Voltage. 2. Power system. 3. Attach positive probe to ESP32 3.3V Line. 4. Attach negative probe to ESP32 GND Line. 5. Record Voltage on DMM screen. Reporting: DMM measured voltage should be consistent with 3.3V +/- 0.1V tolerance.
The PTS526 SM15 SMTR2 LFS tactile switch shall connect to the Microcontroller Board via signals connected to the GPI pins of the ESP32 MCU.	Equipment: Debugging MicroUSB Cable Laptop w/ Arduino Procedure: 1. Power system. 2. Load GPIO Testing program onto ESP32. 3. Actuate tactile switch on Haptic Feedback Board, observe reported metrics. 4. Observe vibration motors on Haptic Feedback Board, vibration pattern should be present. Reporting: Testing program should detect tactile switch actuation. Vibration motors should exhibit vibration patter defined in testing program.
The 2N7002ET7G MOSFET shall provide the supplied 3.3V power line to both SEEED STUDIO 2.0MM MINI vibration motors when sufficient voltage is applied to its gate via the GPO signal from the Microcontroller Board.	Equipment: DMM Procedure: 1. Set DMM to 1x DC Voltage. 2. Power system. 3. Attach positive probe to motor positive Line. 4. Attach negative probe to motor negative Line. 5. Record Voltage on DMM screen. Reporting: DMM measured voltage should be consistent with 3.3V +/- 0.1V tolerance.

Table 3: Requirements and Verification for Haptic Feedback Board Subsystem

2.6 Tolerance Analysis

One aspect of our design that poses a risk to the completion of this project is the maximum power output of the BMS. The BMS has a maximum current output of 1.5A. Below is the estimated peak current consumption for the entire product. The entire system will run off of the 3.3V power supplied by the BMS.

Component	**Estimated Current (mA)**	**Comment**
ESP32	1000	To be safe, peak power consumption is doubled from minimum. Minimum power consumption is defined as standby mode in datasheet.
BNO086	<100	13.7mA abstracted from the datasheet of model component is derived from. (BNO055)
Vibration Motor x2	160	80mA each from datasheet.
Misc. Components	<100	100mA margin for miscellaneous components on boards, such as resistors, capacitors, diodes, CMOS, etc.
Total Current	**1360**	

Table 4: Estimated Peak Current Consumption of Design

The estimated current is less than the 1.5A max current output of the BMS. There is also enough margin for unexpected power consumption. We conclude that the BMS we chose can fulfill the power supply needs of our product. To power the entire system, a HXJNLDC 103048 Li-ion battery [7] will be connected to the BMS. This battery is rechargeable and has a voltage range of 4.2V to 3.7V depending on the charge level. The BMS has a maximum input voltage of 6V meaning this battery is well within the range of the BMS. The battery has a maximum current of 1.6 Amps. The maximum power this battery is capable of outputting is thus.

$$P_{Li-Po\,Max} = I_{Max}V_{Max} = 1.6 * 4.2 = 6.72 \;\; Watts \tag{1}$$

The maximum output current at a voltage of 3.3V for the BMS is 1.5A. The maximum power output of the BMS is thus.

$$P_{BMS\,Max} = I_{Max}V_{Max} = 1.5 * 3.3 = 4.95 \;\; Watts \tag{2}$$

The limiting factor in terms of maximum power output is the BMS. Both devices have overcurrent protections built-in limiting the risk of overcurrent-induced failures.

Another tolerance factor to consider when designing our product is the predicted G-forces on the BNO086. The center of mass of a human is located in front of the spine, below the navel. An assumption made is that the BNO086 located class the the back of the spine on the waste area will experience the same G-forces as the center of mass. As such, our device will act similarly to other belt-mounted pedometers and even phone step counters. From the datasheet, the acceleration vector has a frequency of 100 Hz and a precision of 0.001G which is sufficiently accurate for our use case.

3 Cost and Schedule

3.1 Cost Analysis

Include a cost analysis of the project by following the outline below. Include a list of any non-standard parts, lab equipment, shop services, etc., which will be needed with an estimated cost for each.

- Labor: The average starting hourly rate of a UIUC electrical engineer is roughly \$42 per hour equivalent. Assuming each member works 10 hours per week for 10 weeks, the cost of labor would be

$$Labor = \frac{\$42}{hour} * 10\ hours * 10\ weeks * 3\ people = \$12,600 \tag{3}$$

- Parts:

Part	**Function**	**Vendor**	**Unit Cost**	**Qty**	**Cost**
Zio LiPo Battery Manager	BMS	Smart Prototyping	$19.90	1	$19.90
HXJNLDC	LiPo Battery	Amazon	$14.99	1	$14.99
Mini vibration motor 2.0mm	Vibration Motor	Seeed Studio	$1.20	2	$2.40
BNO086	IMU	DigiKey	$15.97	1	$15.97
ESP32-S3-WROOM-1-N16	MCU	Digikey	$3.48	1	$3.48
2N7002ET7G	MOSFET	DigiKey	$0.21	1	$0.21
PTS526 SM15 SMTR2 LFS	Tactile Switch	DigiKey	$0.14	1	$0.14
LTST-C190TBKT.PDF	SMD LED	ECE Serv. Shop	$0.00	1	$0.00
Misc. Resistors/Diodes/Caps	Misc.	ECE Serv./DigiKey	$7.00	1	$7.00
Total Cost = $64.09					

Table 5: Estimated Cost of Components

- Sum of costs into a grand total

$$Total = \$12,600 + \$64.09 = \$12,664.09 \tag{4}$$

3.2 Schedule

Week	Task	Member(s)
February 26 - March 1	Complete Bill of Materials Initial Part Order Begin PCB Design Research IMU Signal Processing Algorithm	Nick Nick Alex Dante
March 4 - March 8	Submit PCB For Order Begin Board Assembly Continue IMU Signal Processing Algorithm	Nick Alex Dante
March 18 - March 22	Explore Mounting/Casing Solutions Finalize Board Assembly Finalize IMU Signal Processing Algorithm	Nick Alex Dante
March 25 - March 29	Finalize Mounting/Casing Solutions Hardware/Software Integration	Nick Alex & Dante
April 1 - April 5	Order & Fabricate Mounting/Casing Solutions Unmounted Debugging/Testing Explore Reach Goal	Nick Alex & Dante Unassigned
April 8 - April 12	Hardware/Mounting Integration Algorithm Debugging/Improvement (Optional) Reach Goal Development	Alex & Nick Dante Unassigned
April 15 - April 19	Mock Demo Fixes/Improvements from Mock Demo Create Mock Presentation	Everyone Everyone Everyone
April 22 - April 26	Final Demo Mock Presentation Complete Final Presentation	Everyone Everyone Everyone
April 29 - May 3	Final Presentation Complete Final Paper	Everyone Everyone

Table 6: Schedule Per Week

4 Discussion of Ethics and Safety

With regards to the IEEE Code of Ethics I-1, There is a meager chance of injury caused by physical interaction such as snagging, and the product itself will be quite flush with the belt. There is a potential safety issue with a wearable electronic device powered by a LiPo rechargeable battery. To mitigate this risk, OSHA [8] recommends inspecting rechargeable batteries for damage or other signs of degradation. OSHA also recommends only using batteries that have been certified such as a UL2054 certified battery. We will greatly increase the safety of our product by following these OSHA-recommended practices when dealing with the battery. There is a risk of injury for exposed batteries in the event of a battery puncture. To combat this risk, we will also ensure the battery will be hard to puncture (e.g. in a small casing). To prevent overheating, vents will also be added to the small battery casing. We will use self-contained coin-type vibration motors, meaning no rotating parts or pinch points will be exposed to the user.

While there is a low risk of the product overheating or otherwise burning the user, we will take precautions to minimize this risk. Selection of wires between boards will use at least 22-gauge insulation-coated wire to isolate any electrical current. A 22-gauge wire at 60 degrees Celsius has an ampacity of 3 amps. The maximum current our BMS can supply is 1.5 Amps meaning that 22-gauge wire provides plenty of margin.

Sweat is a concern when creating a wearable exercise device. Excessive moisture may lead to damage to the system through short circuits or corrosion, and may even cause contacts to conduct to the user if touched with bare skin. To protect the device from sweat, all wires will be insulation-coated, and potentially sensitive components such as PCBs will be enclosed in plastic. Our device is not intended to be used in the rain or other extreme weather conditions.

We do not anticipate our project to be accidentally or intentionally misused, and it does not collect any high-level or complex information about the user. The user would be informed of what the belt does, and what kind of information it collects. If we were to implement our stretch goal of Bluetooth functionality, we would not have to worry about the cybersecurity challenge of securely transferring a user's personal information. We would only be transferring the SPM metric over Bluetooth.

Sections II and III of the IEEE Code of Ethics are not product-specific and do not apply to this section.

References

[1] ”ESP32-S3-WROOM-1-N16 Engineering Module - 8 MB Quad SPI Flash,” Digikey. https://www.digikey.com/en/products/detail/espressif-systems/ESP32-S3-WROOM-1-N16/16162647

[2] ”BNO086,” Digikey. https://www.digikey.com/en/products/detail/ceva-technologies-inc/BNO086/14114190

[3] ”ZiO LIPO Battery Manager (QWIIC, 3.7ViN, 0.5A/Charger, 3.3VoUt, 1.35Amax),” Smart Prototyping. https://www.smart-prototyping.com/Zio-LiPo-Battery-Manager.html

[4] ”2N7002ET7G,” Digikey. https://www.digikey.com/en/products/detail/onsemi/2N7002ET7G/13886993

[5] ”Mini vibration motor 2.0mm,” Seeed Studio, Sep. 26, 2023. https://www.seeedstudio.com /Mini-vibration-motor-2-0mm-p-2300.html/

[6] ”PTS526 SM15 SMTR2 LFS,” Digikey. https://www.digikey.com/en/products/detail/c&k/PTS526%2520SM15%2520SMTR2%2520LFS/10056633

[7] ”HXJNLDC 103048 Li-ion battery” Amazon. https://www.amazon.com/dp/B091XYZ2V3?ref=emc_s_m_5_i_n

[8] ”Preventing fire and/or explosion injury from small and ...”. OSHA. https://www.osha.gov/sites/default/files/publications/

[9] ”Quick Guide on ESP32-S3 Pinouts”. GitHub. https://github.com/atomic14/esp32-s3-pinouts