ECE 445
Spring 2025
Project Proposal

SMART COGNITIVE-MOTOR REHABILITATION MAT FOR REMOTE EXERCISE MONITORING

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1. Introduction

Problem:

Multiple Sclerosis is an autoimmune disease that affects the nervous system. Older adults are an expanding demographic in this area and many people with this disease have a hard time walking. Older adults also have a more limited range of rehabilitation due to their age and the SmartMat was designed last year to help this demographic; however, the initial prototype has had some issues with the microcontroller doing too much, and having trouble with communication between the mat and tablet. Additionally, there were separate PCBs and lots of messy wiring.

Solution:

The microcontroller is doing a lot of computation since it is both measuring the data from the steps and computing this data to send to the tablet. We will be upgrading to a newer dual core ESP32 for more processing power. Additionally, we can look into moving the computation heavy tasks to the tablet. If the tasks are handled by the tablet then the communication time needs to be lowered to allow for the tablet to get the data, compute it then send it before the next step.

Next, the idea of communicating through bluetooth or a local network. The project originally had the ESP in station mode and it lost connection to the internet; however, in order to get the routines from the web page, the internet was needed. So a solution is to either use bluetooth low energy to connect the tablet with the at all times during the workout or a network between the tablet and mat. Successfully implementing wireless communication between the mat and the tablet will be very useful.

Additionally, a new PCB design which can implement the new microcontroller and all subsystems onto one PCB, allowing for a cleaner setup that is more ready for an end user.

Visual Aid:

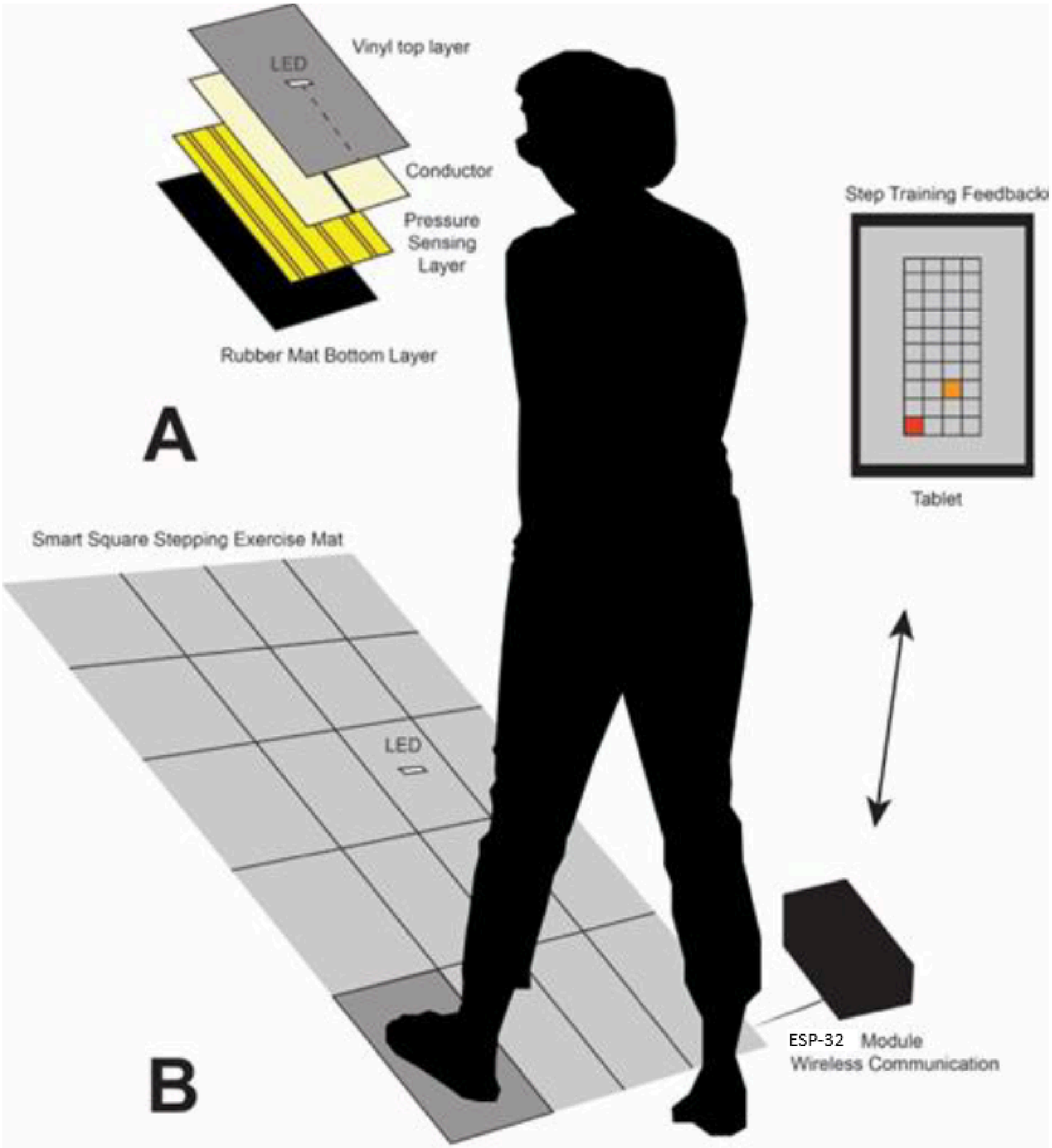


Figure 1. A) Cross-section of sensing mat, and B) Smart Square Stepping Exercise Mat (s-SSE) system.

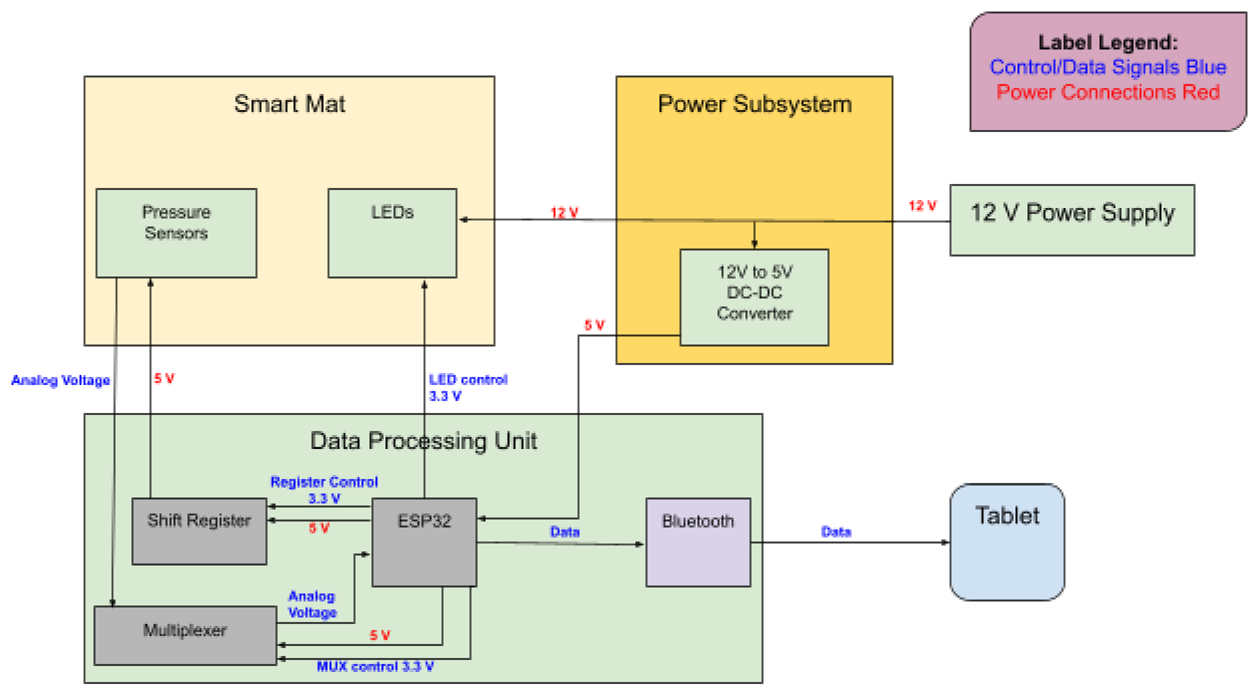
Figure 1: Visual Aid for smart mat (image credits: Professor Hernandez)

High-level requirements list:

- Data Transmission Latency: The system must provide real-time feedback with a data transmission delay of no more than 1 second between the smart mat and the mobile device.
- A single more concise PCB which implements all of the subsystems for ease of use with mat.
- Improve reliability of mat while maintaining high step detection accuracy.

2. Design

2.1 Block Diagram:



Label Legend: Control Signals Blue, Power Connections Red

2.2 Smart Mat

This mat was made in the previous year and has little to iterate on. It consists of 40 stepping blocks in a 10 by 4 array. Each of these blocks are 30 cm by 25 cm and have lines of LEDs that are used to indicate where to step and if the block that was stepped on was correct. There are also pressure sensors to determine where a person has stepped and the mat is made of anti-slip material to ensure safety.

2.2.1 Mat

The mat is made of an anti-slip material similar to a yoga mate to prevent any injuries that could occur during the exercise. The mat is also 3m by 1m to allow for adequate sized blocks.

2.2.2 Pressure Sensors

The sensors need to be foldable to allow the mat to be moved with relative ease. In order to do this the previous group used Velostat since when pressure is applied to it its resistance drops. This resistance can be used to measure the voltage drop to measure if a block has been stepped on. Another resistor is added in series to allow a voltage divider rule with the Velostat to allow for an easier calculation

Table 1: Table R&V for Sensors

Requirement	Verification
1. The sensor should detect pressure applied 2. The sensor should maintain its accuracy after multiple uses	1. The voltage difference will be measured for applied and unapplied pressure and should be 1V -5% or larger 2. Roll and unroll the mat a minimum of 30 take measurements from 1 to determine if accuracy has degraded.

2.2.3 LEDs

The LEDs that were used last semester were WS2812b LED strips. These were used for their cheap price and ability to easily convey what block was stepped on and needs to be stepped on.

Table 2: Table R&V for Sensors

Requirement	Verification
1. LED needs to be programmable 2. The LED should convey what needs to be stepped on and what is correct	1. This specific strip is programmable[1] 2. When given data front he microcontroller and it lights the

	correct block it succeeds

2.3 Data Processing Unit

The data-processing unit consists of a microprocessor, multiplexers and shift-registers to scan through each of the blocks a person might step on. It then determines where the voltage difference is and records that data with a 10Hz clock cycle.

2.3.1 Microcontroller

The DPU uses an ESP-32 with a wifi module. However, if we are thinking of moving to dual core we will need the ESP32 S series and the S3 will be the best fit since it has bluetooth capabilities.

Table 3: Table R&V for Microcontroller

Requirement	Verification
1. Should collect data at 10Hz 2. Should have bluetooth capabilities 3. Should be dual core 4. Should perform tasks of previous microcontroller	1. From datasheet [2] 2. From datasheet [2] 3. From datasheet [2] 4. This will be done by comparing the data from the previous controller to compare with the new one

2.3.2 Multiplexers and Shift-registers

These were determined last year and will not be changed. A CD74HC4067M multiplexor is used as well as a 74HC595 8-bit shift register.

Table 4: Table R&V for Multiplexers and Shift-registers

Requirement	Verification

1. Correctly get voltage readings from the correct block in the clock cycle and relay that to the microcontroller	1. Read the information the microcontroller gets and if it outputs the correct block then it works

2.3.3 Bluetooth

In the previous prototype the transmission was done over wifi which meant a wifi connection was needed. We will be updating this with bluetooth to allow the mat to be used without wifi and instead bemused with a device and an app.

Table 5: Table R&V for Bluetooth

Requirement	Verification
1. Send and receive data to tablet using bluetooth with a max latency of 1 second 2. Data that is sent and received should be accurate	1. Measure the time it takes for the microcontroller to call for information and when it receives it. 2. Compare data from the sender and receiver and make sure no errors are made when transfering

2.4 Power Subsystem

The power subsystem will take power from a 12V DC power supply and supply power to the LEDs in the Mat subsystem. It will also convert 12V to 5V DC and supply power to the microcontroller in the Data Processing Subsystem.

Table 6: Table R&V for Bluetooth

Requirement	Verification
1. Supply power to LEDs on Mat from 12V DC power supply	1. Measure voltage and make sure voltage is within 5% of 12V 2. Measure voltage and make sure voltage is within 5% of 5V

2. Convert 12V to 5V and supply that power to the microcontroller	

2.5 Risk Analysis:

The most critical risk in this project is ensuring stable and low-latency Bluetooth communication between the smart mat and the tablet. If the connection is unstable or too slow, real-time feedback could be delayed, making the rehabilitation exercises less effective.

- Bluetooth Latency & Packet Loss

BLE operates in the 2.4 GHz band which is prone to interference from Wi-Fi and other devices.

Constraint**:** The total end-to-end latency ($T_{latency}$) must be ≤ 1s for real-time response. If the latency exceeds 1 second, the system may fail to provide real-time step tracking. The latency consists of:

$$T_{latency} = T_{transmission} + T_{processing} + T_{retransmission}$$

where

- $T_{latency} = \frac{Packet\ size\ (bits)}{BLE\ data\ rate\ (bps)}$
- $T_{transmission}$ = *the internal delay of ESP32 processing the data (~5-10ms per step)*
- $T_{retransmission}$ = *depends on the BLE error rate*

However, a possible mitigation is to optimize BLE settings, reducing packet size to optimize transmission time, use error-checking mechanisms, and implement adaptive frequency hopping to reduce interference, depending on testing results.

- Signal Dropouts Over Distance

The range of BLE is typically 10–30 meters indoors, but obstacles can reduce it, potentially even a user's own body parts. If the connection drops mid-exercise, data may be lost, affecting rehabilitation accuracy.

BLE signal strength tends to deteriorate over distance following the Friis transmission equation:

$$P_r = P_t + G_t + G_r - 20\log_{10}(d) - L$$

Where:

- P_r = received power (dBm)
- P_t = Transmit power (dBm)
- G_t, G_r = Antenna gains
- d = distance (m)
- L = path loss (typically, 30-40 dB at 10m for indoor environment)

Constraint: The BLE receiver requires at least -90 dBm signal strength to maintain a stable connection, else the connection drops.

A possible mitigation is to test in various environments and optimize antenna placement, as well as finding the optimum higher power for BLE if needed.

3. Ethics and Safety

Data Privacy and Security (IEEE Code of Ethics, Principle #1 & #5)

- The smart mat collects user activity data, which could include sensitive health-related information. Unauthorized access or misuse of this data has the potential to lead to privacy violations.
    - To mitigate risks, we will be aiming to encrypt data transmission for the Bluetooth implementation and have the mat ready to comply with relevant privacy laws such as GDPR and/or HIPAA if used in a medical setting

Reliability and Accuracy (IEEE Code of Ethics, Principle #3 & #6)

- When making modifications to the existing prototype, we would need to ensure the mat continues to accurately detect user steps and respond with minimal latency to avoid incorrect feedback, which could lead to ineffective training or injury
- Proper testing and verification against ground truth data would need to be conducted before the mat is ready to be used in a consumer setting

Accessibility and Inclusivity (ACM Code of Ethics, Principle 1.4)

- The mat would ideally be designed for a diverse range of users, including those with disabilities, to ensure inclusivity and as many recovering patients as possible to use the smartmat

Responsible Development and Testing (IEEE Code of Ethics, Principle #9)

- We would seek to **ensure safety during actual mat testing if any**, making sure there is no possibility of loose electrical components or improper sensor readings that could mislead users.

4. References

"IEEE Code of Ethics." IEEE.org. Accessed: Feb. 12, 2025. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html

"ACM Code of Ethics and Professional Conduct." ACM.org. Accessed: Feb. 12, 2025. [Online]. Available: https://www.acm.org/code-of-ethics

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[1]"WS2812B Intelligent control LED integrated light source Features and Benefits." Available: https://cdn-shop.adafruit.com/datasheets/WS2812B.pdf

[2]Le, S. Supporting, I. 11, G. Wi-Fi, and Le), "ESP32-S3 Series Datasheet 2.4 GHz Wi-Fi + Bluetooth Including." Available: https://www.espressif.com/sites/default/files/documentation/esp32-s3_datasheet_en.pdf