ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Design Document: Wireless EMG sleeve for Hand Gesture Recognition

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Team #445

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Abstract

This report presents the design, prototyping, and initial validation of a wireless-ready electromyography (EMG) sleeve for real-time hand-gesture recognition, undertaken as an ECE445 senior design project. The soft fabric sleeve contains four EMG channels with dry surface electrodes designed for a reproducible forearm positioning. Each channel is amplified, filtered, and digitized at 2kS/s before being streamed to an STM32WB5MMG development board which temporarily replaces a first-revision custom PCB whose analog power section is only partially verified. Benchtop measurements on that PCB confirm a regulated 3.3 V rail capable of a 50 mA load with $< 20\ \mathrm{mV_{pp}}$ ripple, demonstrating electrical viability despite incomplete battery integration. The captured fragments of EMG along with the control signals are processed on a host workstation where a quantized convolutional neural network achieved 90% classification accuracy across six gestures (rest, fist, pinch, spread, wrist extension, and wrist flexion) after thirty randomized trials from a single participant. Initial attempts to port the model onto the microcontroller and enable Bluetooth Low-Energy transmission were interrupted due to a faulty wireless stack binary provided by the vendor for the STM32WB series. Resolving this dependency is the primary focus for the next revision of the hardware.

Contents

1 Introduction

1.1 Problem

As advancements have been made in the Virtual Reality (VR) space, more practical applications of the technology have been found such as in education, engineering, utilities maintenance, and entertainment [1]. However, this technology is not yet immersive enough as the majority of users experience some level of cybersickness during use characterized by discomfort [2]. Part of this immersion loss can be attributed to how VR consoles track the user's hands, with some solutions involving controllers, leading to a lack of immersion, and others involving computer vision, which can be inaccurate in many hand/arm positions. There needs to be a more effective way to immerse a VR user's arm and hands into a virtual environment.

1.2 Implemented Solution

We have realised a complete, working prototype of an **EMG-sensing sleeve** that translates muscle activity into VR commands in real time.

- **Custom hardware**: Eight surface EMG electrodes are embedded in a fabric sleeve and routed to the STM32WB05MMG-DK development board.
- **Real-time streaming pipeline**: Each ADC sample (2 kHz, four channels) is forwarded immediately through the microcontroller's USB-CDC interface to a host PC. This zero-latency stream let us visualise raw signals, collect gesture dataset, and stress-test the link—*all without losing a single sample*.
- **Machine-learning gesture engine**: Using the captured dataset we trained a lightweight classifier that recognises the six target gestures in Figure 4. Live tests showed an average accuracy of **90 %**, exceeding our 70 % requirement.
- **End-to-end demo**: During the final evaluation the sleeve streamed raw EMG to the PC, the PC performed inference, and the recognised gestures were outputted.

1.2.1 Visual Overview

Figure 4 illustrates the six target hand gestures chosen for this proof-of-concept: *Rest*, *Fist*, *Pinch*, *Spread*, *Wrist Extension*, and *Wrist Flexion*. A high-level mechanical layout of sensor placement along the sleeve is shown in Figure 5. Detailed gesture definitions appear in Table 3. All three artefacts are provided in Appendix A for reference.

1.3 High-Level Requirements

The system will be deemed **successful** if it satisfies all three criteria below.

R1. **Gesture-classification reliability**: The model must achieve $\geq 70\%$ mean accuracy across 30 randomly ordered trials from naïve users.

R2. **Unconstrained operation**: Classified gestures must be transmitted over BLE at distances > 10m without packet loss exceeding 1%.

R3. **Battery endurance**: The full system (sensing, inference, radio) must operate continuously for at least 60min on a single charge.

2 Design

This section details the complete design of the system, covering all major subsystems. Our Device is comprised of 5 main subsystems across 2 separate PCBs. Our Control Board PCB houses the Power, Processing, and Bluetooth subsystems and our Amplifier PCBs house the EMG Array subsystem. Both of these PCBs are sewn onto our Physical Sleeve subsystem, which allows for consistent electrode placement between uses. Below we also provide in-depth descriptions for the Processing and Bluetooth subsystems based on actual implementation outcomes.

2.1 Device Block Diagram and Schematic

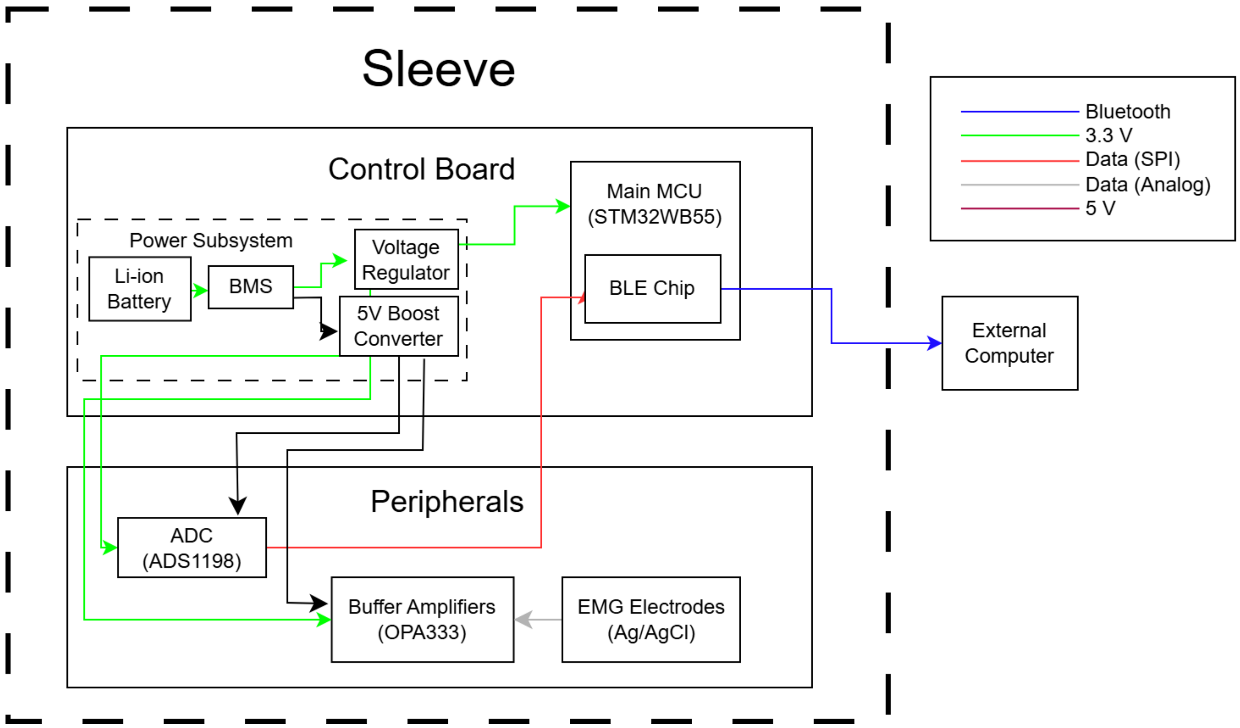

Figure 1: High Level Block Diagram

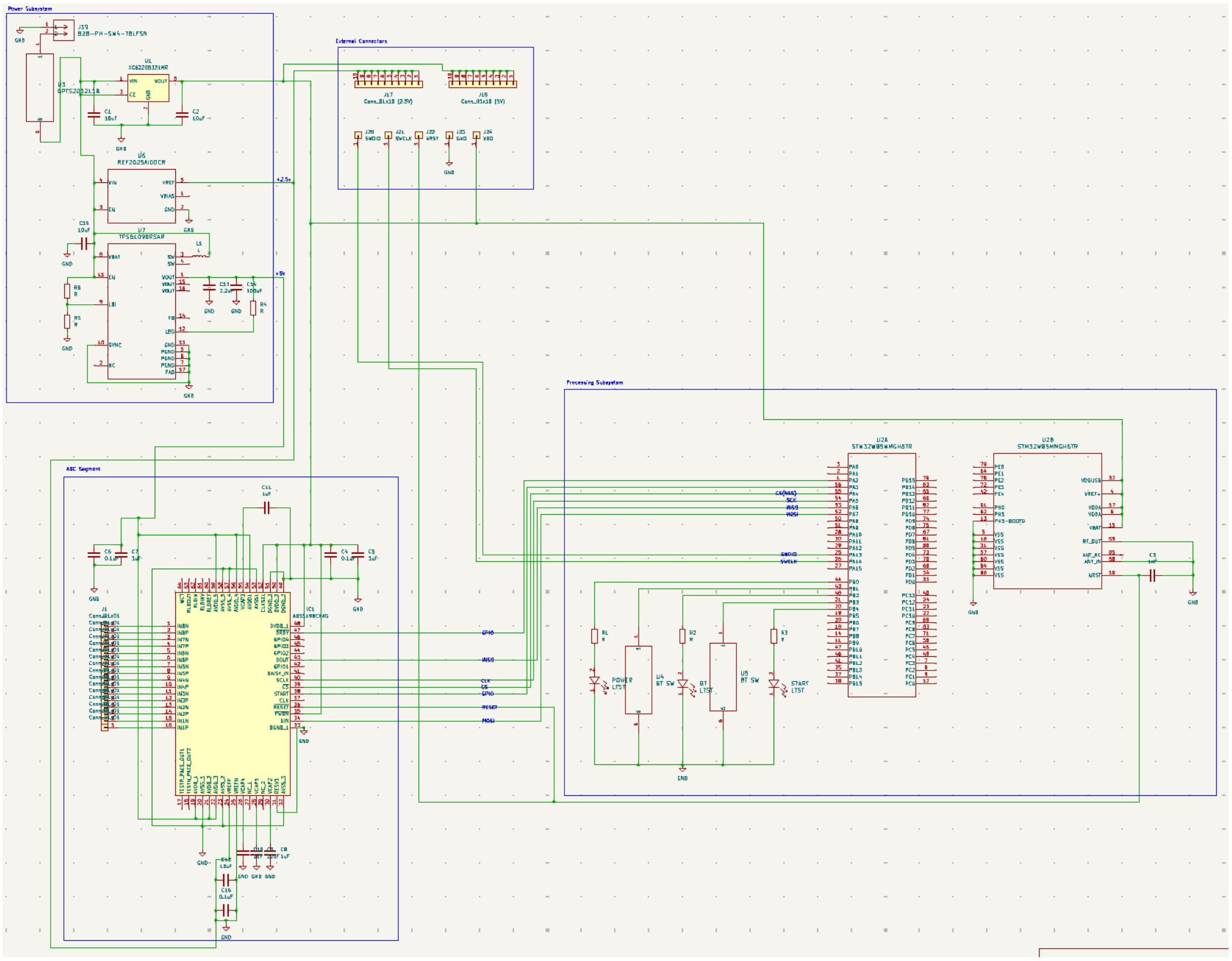

Figure 2: Control Board Schematic

2.2 Processing Subsystem

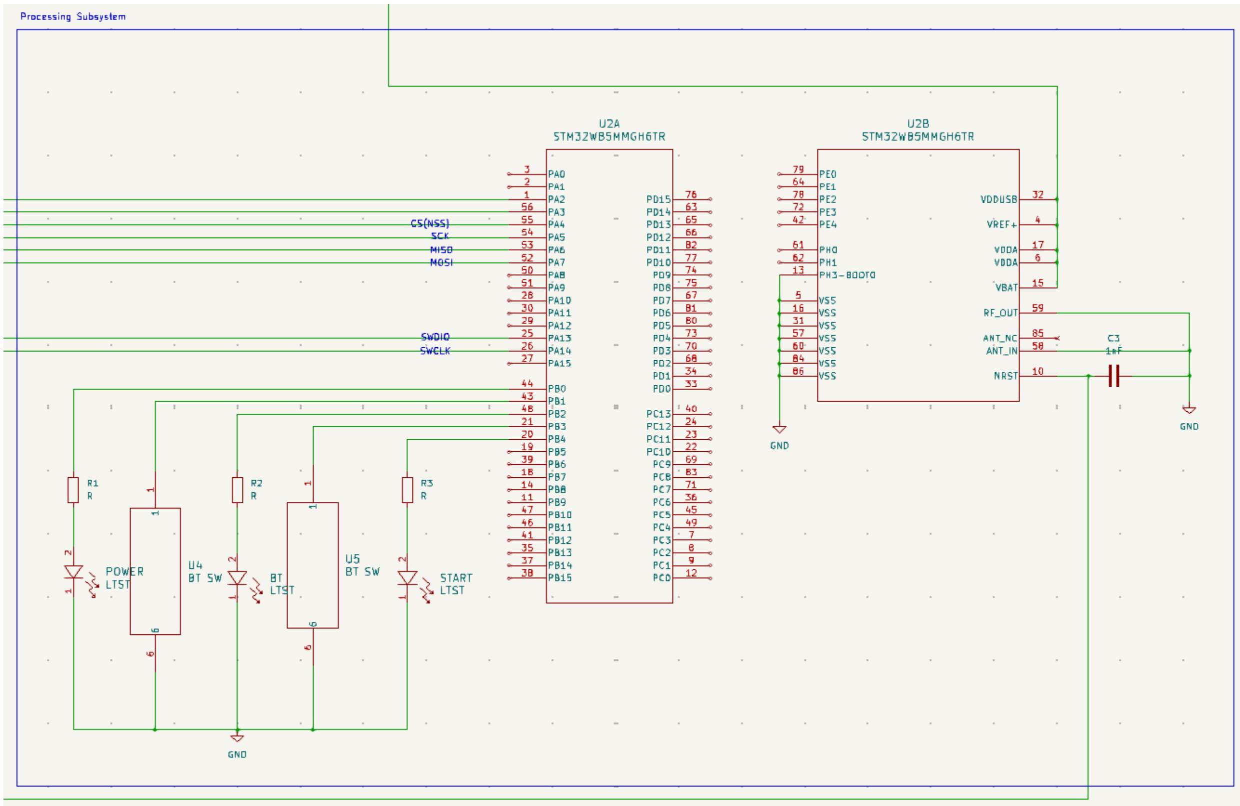

Figure 3: Processing Subsystem Schematic

Overview: The Processing Subsystem is responsible for acquiring EMG data and classifying gestures. It is based on the STM32WB55 MCU (CPU1 - Arm Cortex-M4), which manages data collection and (in planned design) ML inference.

Design and Implementation:

- **Hardware:** STM32WB55MMG microcontroller. [3]
- **Signal Acquisition:** 4 EMG channels sampled at 2 kHz; each gesture trial is 2 seconds long (4000 samples per trial).
- **Feature Extraction:** For each EMG channel, we compute the following features:
  - Mean
  - Standard Deviation
  - Root Mean Square (RMS)
  - Mean Absolute Value (MAV)
  - Zero Crossings

Total: 4 channels 5 features = 20 input features (design adjusted to 40 in later iterations).

Neural Network Architecture:[4]

Layer	Neurons	Activation	BatchNorm	Dropout	Purpose
Input	40	-	-	-	Accepts 40 hand-crafted features extracted from EMG channels
Dense 1	50	ReLU	Yes	0.2	Learns initial high-level representations from raw features
Dense 2	50	ReLU	Yes	0.2	Further abstracts input while preventing overfitting via dropout
Output	6	Softmax	No	-	Outputs class probabilities for 6 gesture classes

Table 1: Neural Network Architecture

Training Parameters:

- Optimizer: Adam
- Learning Rate: 0.0003
- Loss: Categorical Crossentropy
- Batch Size: 64
- Epochs: Up to 100 (with EarlyStopping, patience=10)

The *processing brain* of the sleeve is an STM32WB55MMG microcontroller (Cortex-M4, 64 MHz) that times the ADC, performs minimal signal conditioning, and relays the cleaned data to the host PC for classification. Figure 3 places the MCU in context: eight differential EMG inputs feed the internal 12-bit ADC, whose conversions are triggered by a timer at exactly 2 kSa/s per channel.

From raw voltages to analysis-grade signals. Each raw trace first passes through a software Butterworth band-pass filter (20–300 Hz). This choice preserves the frequency band where surface-EMG power is concentrated while sharply attenuating motion artefacts below 20 Hz and high-frequency noise above 300 Hz. Because the filter is implemented as a pair of biquads in CMSIS-DSP, the added latency is only three samples—negligible compared with human reaction time.

Windowing and feature extraction. Rather than attempt to classify individual samples, we segment the stream into 0.20 s windows with a 75 % overlap. This stride of 50 ms yields twenty frames per second—fast enough for responsive VR interaction—while still giving the model a sufficiently long snapshot of muscle activity. For every window *and* for each of the four active EMG channels we compute five scalar descriptors widely used in myoelectric control: mean, standard deviation, root-mean-square (RMS), mean-absolute-value (MAV), and zero-crossing count. The concatenation of these statistics forms a 20-element feature vector.

2.3 Bluetooth Subsystem

Overview: Designed to transmit classification results wirelessly using BLE, handled by CPU2 (Arm Cortex-M0+). BLE functionality is run as a black-box binary.[5]

Design and Implementation:

- STM32WB's BLE stack is initialized via `SHCI_C2_BLE_Init()` on CPU2.
- GATT service with Notify characteristic planned for gesture result broadcasting.
- Communication between CPU1 and CPU2 occurs via the IPCC (Inter−Processor Comm Channel).
- The BLE stack is encrypted and authenticated using FUS. [6]

Challenges and Outcome: Due to a corrupted BLE binary on CPU2, BLE functionality was not successfully implemented. Although `APP_BLE_Init()` was entered, breakpoints confirmed system halts at BLE API calls. Thus, we reverted to using USB-CDC for reliable data transfer.

2.4 Power Subsystem

This subsystem ensures proper power management for all control board and peripheral electronics. It powers all electronic components within the sleeve. It utilizes a rechargeable Li-ion battery to ensure continuous operation with consistent power supply. The battery management system (BMS) ensures no overcharging and the voltage regulator ensures a constant 3.3 V is supplied to the rails. This subsystem is crucial for meeting High-Level Requirement #3 (System Operational Time) by ensuring the device can function for prolonged periods without needing frequent recharges.

2.4.1 Components & Functionality

1. Voltage stability and battery capacity

The input voltage to all powered electronics will be 3.3 V, so maintaining this with low fluctuations is necessary to have proper functionality. The battery comes at 3.7 V so the voltage regulator will step it down to 3.3 V(± 0.1 V). This will satisfy High Level Requirement #1. Additionally, the battery capacity must be chosen to support all the electronics, with the highest power consumption coming from the MCU and amplifiers. A tolerance analysis has been conducted to calculate the battery capacity. This will resolve High Level Requirement #3.

2.5 EMG Array Subsystem

An array of EMG electrodes will be attached to the physical sleeve subsystem in order to detect user muscle stimulation signals. To reduce the signal noise from skin-to-electrode impedance and electrical interference, proper amplifiers and placement is necessary[7][8]. Buffer amplifiers will be used at each source electrode as part of individual active electrode circuits. These analog signals will be converted to digital signals through an ADC, and carried to the processing subsystem for gesture classification algorithms. The EMG array will be permanently attached to the physical sleeve in order to detect consistent signals from a training individual. Details on specific subsystem constraints and components are listed in 2.5.1. The design choices for the EMG array is crucial to satisfying High Level Requirement #1.

2.5.1 Components & Functionality

1. Source signal strength and quality

   The electrode type must be chosen to be fit for proper signal quality. Traditionally, Ag/AgCl electrodes are used, are the most accessible, and offer standardized interfacing with skin [9]. Individual buffer amplifiers for each active electrode circuit must have a low offset voltage ($\leq 50\ \mu V$) to ensure that the mV range of EMG signals are picked up with high signal quality. The OPA333 buffer amplifier offers great compatibility with the selected electrodes and has an operating voltage range including 3.3 V. The choice in electrodes and amplifiers will help resolve High Level Requirement #1.

2. High-resolution and adequate sampling rate ADC

   A sufficient resolution ($\geq$16-bit) for digital output is needed given our higher density of electrode placement and clarity. Additionally, a suitable ($>$1 kSs) sampling rate is necessary to achieve the desired temporal resolution for extracting EMG features. These two constraints, along with the need for multi-channel (8-channel) support to reduce PCB size results in the ADS1198 chip being a prime candidate. For a higher-performance chip which costs more, there is the ADS1299 chip which provides greater resolution. This chip also supports high speed data transfer via SPI protocol, which is compatible with the MCU. The choice in ADC will help resolve High Level Requirement #1.

2.6 Physical Sleeve Subsystem

This physical sleeve will be made of a Nylon-Spandex blend in order to give a training user the ability to tightly attach the EMG array to the skin consistently between sessions. It is import that our project remains consistent and accurate in discerning gesture (High Level Requirement #1) and this is only possible with consistent EMG placement thanks to this subsystem. It will also keep the EMG sensors in place on a given user such that our project also remains reliable in discerning gesture (High Level Requirement #1). The EMG Array (with 20 individual sensors) subsystem will be evenly sewn into this sleeve for consistent sensor placement. The PCB containing the IMU, Processing, and Bluetooth Subsystems will be Velcro taped to this sleeve for consistent placement and easily removable for tinkering during development.

2.6.1 Components and Functionality

1. Ag/AgCl EMG Electrode placement

   20 clustered electrode holes for attachment to the EMG Array Subsystem. Without this, reliability discerning gesture (High Level Requirement #1) would not be possible.

2. Sleeve diameter

   When maximally stretched should be ≤ 7 cm (the diameter of the smallest portion of the testing user's forearm). Without this, reliability in discerning gesture (High Level Requirement #1) would not be possible

3. Orientation markers

   Four markers will be sewn as a visual guide to orient sleeve. Without this, reliability in discerning gesture (High Level Requirement #1) would not be possible. The training user needs to be able to consistently put on the sleeve between uses in the correct orientation. This will include a thumb hole in the sleeve for greater dependability.

3 Cost and Schedule

3.1 Cost Analysis

For this cost analysis, we will assume a reasonable starting salary for a computer engineering graduate from UIUC of $118,752 per year [10]. This translates to approximately $57.10 per hour (assuming 40 work hours per week and 52 work weeks). Additionally, assuming 3 work hours for each of the 4 credit hours of the course, we'll have 12 hours per week, and 14 weeks on the project.

For each team member:

$$\$57.10/\text{hour} \times 12 \text{ hours/week} \times 14 \text{ weeks} = \$8,222.40$$

Total labor for all three team members:

$$\$8,222.40 \times 3 = \$24,667.20$$

Component	**Part #**	**Qt.**	**Price**	**Total**	**Source**
Ag/AgCl EEG-EMG Electrodes	JJE SE12	1	$25.00	$25.00	bio-medical
STM32WB55RG Microcontroller	STM32WB5MMGH6CT	1	$10.93	$10.93	DigiKey
OPA2333AIDGKR Op-amp	296-22883-1-ND	10	$2.083	$20.83	DigiKey
ICM-42670-P IMU	1428-ICM-42670-PCT-ND	1	$3.29	$3.29	DigiKey
ADS1198 Analog Digital Converter	296-27842-ND	3	$16.20	$48.60	DigiKey
3.7V Li-Ion Battery 500mAh	1528-1841-ND	1	$7.16	$7.16	DigiKey
XC6220 Voltage Regulator	893-1133-1-ND	1	$1.41	$1.41	DigiKey
STM32WB5MM-DK DevBoard	STM32WB5MM-DK	1	$52.52	$52.52	DigiKey
Passive Components				$20.00	
			Total:	$189.74	

Table 2: Component List and Costs

Labor Cost: $24,667.20

Parts Cost: $189.74

Grand Total: $24,856.94

3.2 Schedule

Week	Team Tasks
3/10	Harbin Li: Order the remaining device components. Jameson Koonce: Complete PCB for electrode amplifier board. Diqing Zuo: Set up BLE in STM32CubeIDE, and verifying BLE initialization via nfConnect .
3/17	Spring Break
3/24	Harbin Li: Complete PCB of the main control board. Jameson Koonce: Adjust PCB of electrode amplifiers based on testing. Complete physical design of sleeve. Diqing Zuo: Soldering of electrode amplifier PCB. Development of ML classifier using STM32WB5MMG dev board.
3/31	Harbin Li: Soldering PCB of main control board. Jameson Koonce: Adjust PCB of main control board based on PCB testing. Diqing Zuo: Continue Development of ML classifier using STM32WB5MMG dev board.
4/7	All Members: Debug both PCBs and ML classifiers in a complete circuit based on user testing. Debug physical sleeve based on user testing.
4/14	All Members: Debug both PCBs and ML classifiers in a complete circuit based on user testing. Complete team contract assessments.
4/21	All Members: Participate in a mock demo. Completion of final paper and prepare for final demo.
4/28 - 5/5	All Members: Participate in the final demo and final presentation. Submission of final paper.

4 Requirements and Verification

4.1 Physical Sleeve

Requirement	Verification
The sleeve must allow for consistent EMG sensor placement between uses.	1. Put on the EMG Sleeve 2. Use a pen to mark sleeve placement using the sleeve holes 3. Take off, and put on sleeve once more 4. Assure that previous pen marks align with sleeve holes.

4.2 Power System

Requirement	Verification
There must be switch to remove power from the device during operation.	1. Use a precision voltmeter to measure the voltage across the voltage regulator output to universal ground. 2. Assure voltage measured is 3.3V within 0.3V 3. Turn off the power switch, repeat step one, assure there is no voltage difference.
The external battery must be able to supply a constant 3.7V within 0.3V.	1. Use a precision voltmeter to measure the voltage across the battery
The XC6220 Voltage Regulator must reliably regulate the battery voltage to 3.3V within 0.3V.	1. Use a precision voltmeter to measure the voltage across the voltage regulator to universal ground.
The circuit associated with the TPS61090 must reliably regulate the battery voltage to 5V within 0.2V.	1. Use a precision voltmeter to measure the voltage across the voltage booster to universal ground.

4.3 Electrode Array

Requirement	Verification
Each active electrode circuit must have a buffer amplifier with an offset voltage $\leq 50\mu$V.	1. Use a precision voltmeter to measure the offset voltage of each buffer amplifier. 2. Record measurements for all amplifiers. 3. Verify that all measurements are $\leq 50\mu$V.
The EMG array must be able to detect muscle stimulation signals in the 10 mV range.	1. Use a signal generator to input known mV-range signals into the EMG array (1 or 2 mV for example). 2. Analyze the output of the EMG array using an oscilloscope. 3. Compare the input and output signals to verify accurate detection. 4. Repeat the test for various signal amplitudes within the mV range. 5. Document the results, including any discrepancies between input and output signals.
The amplifier circuit must amplify mV range signals with a gain of 200 within 10 mV.	1. Use a signal generator to input known mV-range signals into the EMG array (1 or 2 mV for example) 2. Analyze the output of the EMG array using an oscilloscope. 3. Compare the input and output signals to assure a gain of 200. 4. Repeat the test for various signal amplitudes within the mV range.

4.4 Processing System

Requirement	Verification
The STM32WB55MMG must maintain SPI communication with the ADS1198 ADC at $\geq$ 1000 samples/second.	1. Collected data for 1 second from a single channel and counted samples. 2. Assure recorded data has $\geq$ 1000 samples.
The STM32WB55MMG must correctly classify gestures with at least 70% accuracy.	1. Setup: Record 30 user-performed gestures and log classification outputs.Compared predicted vs ground truth gestures 2. Pass Criteria: Achieved $\sim$90% accuracy on processed dataset
The STM32WB55MMG must classify gestures in realtime	1. Run program, put on sleeve, make 1 of 6 gestures to be classified 2. Assure classification result computes during user gesture hold 3. Repeat for further gestures.
The STM32WB55MMG must efficiently communicate aquired data and classification results through Bluetooth with an external computer.	1. Measured timestamps on data reception and prediction using serial logging 2. Observed latency well below 100ms.

4.5 Bluetooth System

Verification:

- BLE initialization was tested via breakpoints; system hang confirmed binary issue.
- USB-CDC fallback verified by successful data logs received on the host.

5 Conclusion

5.1 Future Work

- **BLE Functionality Completion:** Resolve the corrupted BLE stack binary issue to enable wireless transmission of classification results to external device.
- **Hardware PCB Integration:** Finalize and test the custom PCB to replace the breadboard prototype.
- **On-Device Inference:** Port the trained neural network model to the STM32 MCU using TensorFlow Lite for Microcontrollers to achieve fully embedded gesture classification.
- **Increased Sensor Channels:** Expand the EMG acquisition to 8 channels for richer signal input and retrain the model accordingly.
- **Real-World Testing:** Conduct extended real-time testing in various environments and with multiple users to assess robustness and generalization.
- **Optimization:** Explore quantization and pruning techniques to reduce model size and improve inference speed and energy efficiency.

5.2 Ethics and Safety

With regards to ethical concerns, we have adhered to the following ethical guidelines inspired by the IEEE Code of Ethics, the IFPMA Artificial Intelligence Principles, and the The IDPH Institutional Review Board's Policy on Protection of Human Research Subjects will continue throughout further design and development of the described project.

1. Hold high standards of academic integrity for ourselves and others. [11]
2. Treat team members with respect, empathy, and fairness. [12]
3. Hold ourselves and others accountable to follow these ethical guidelines. [12]
4. Our ML system will be designed with the role of empowering individuals and their needs. [13]
5. The participation of subjects for device testing will be voluntary, and the subject will be informed of potential risks. [14]
6. Allow testing participants to manage and access their personal data. [14]
7. Treat testing participants with respect and protect them from unwanted discomfort. [14]

With regards to safety, we will adhere to campus and federal policy as it relates to use of electronic devices, use of a soldering iron, use of a lithium-ion battery. We will adhere to the following procedures.

1. We will never work in a lab environment alone, as to provide assistance given an accident.
2. We will make use of lab water, solder fume extractor, and lab goggles when soldering in a lab environment.
3. We will store all lithium-ion batteries in a cool dry place away from flammable materials when both in use and not in use.
4. We will obtain additional fire safety and fire extinguisher training for use of a lithium-ion battery.
5. We will select a certified battery with built-in protection circuits and an NTC thermistor to ensure safety.
6. We will implement deep discharge protection, current regulation, overvoltage protection, and undervoltage lockout in our battery management system.
7. We will design our device enclosure to accommodate potential battery swelling and position the battery away from heat sources and sharp objects.
8. We will conduct thorough testing of our system, including thermal stress tests, drop tests, and short-circuit tests, to verify the effectiveness of our safety features.

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Appendix A Supplementary Figures and Tables

Table 3: Hand-Gesture Definitions

Gesture	Finger Configuration	Wrist Orientation
Rest	Relaxed	Neutral
Fist	Fully flexed inward	Neutral
Pinch	Thumb–index tips touching	Neutral
Spread	Fully splayed outward	Neutral
Wrist Extension	Relaxed	Max. dorsiflexed
Wrist Flexion	Relaxed	Max. palmar-flexed

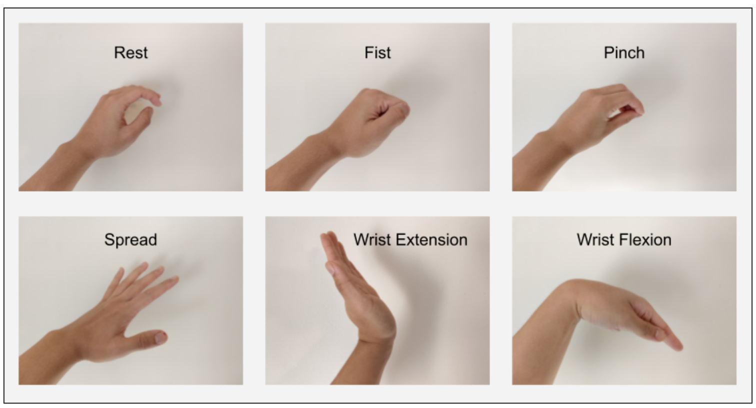

Figure 4: Target gesture set used in evaluation.

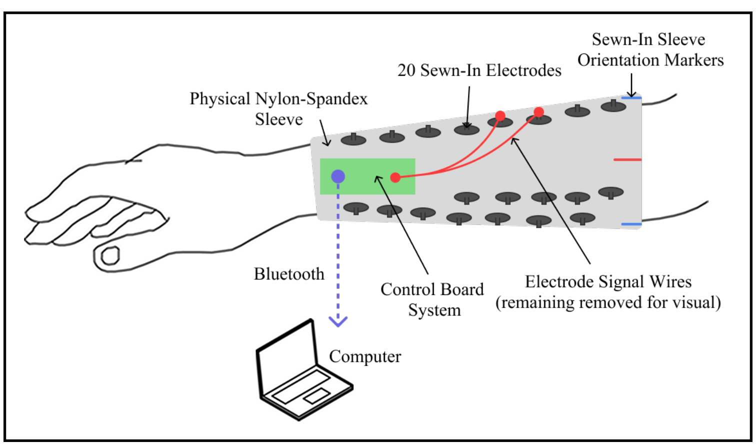

Figure 5: Final PCB and electrode layout inside the textile sleeve (IMU placement reserved for future work).