ECE 445
SENIOR DESIGN LABORATORY

Design Document: Wireless EMG and IMU sleeve for Hand Gesture Recognition

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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[3]. However, this technology is not yet immersive enough as the majority of users experience some level of cybersickness during use characterized by discomfort[1]. 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 Solution

We are looking to create a system which tracks arm movements and recognizes hand gestures for more immersive Virtual Reality (VR) Environments. Specifically, we are going to develop a wireless sleeve lined with Electromyography (EMG) and Inertial Measurement Unit (IMU) sensors in order to detect electrical signals, orientation, and acceleration information from a user's arm and use on-device processing of machine learning algorithms to classify individual finger gestures and track arm movement.

This system will be more immersive than existing solutions because the user's hands will be free in a VR environment, and the arm motion will be tracked even when the arm is out of view. The system will make use of EMG and IMU sensors on a physical sleeve, connected to a wireless module to assure that the information can be used as a controller for external devices and the user is physically unconstrained. The data will be pre-processed in our on-sleeve control board system and then sent to the ML inference for classification and tracking (also in the control board system).

Throughout the semester, we will develop the sleeve to classify the 6 gestures depicted in Figure 1 to demonstrate how this technology can be used for more dynamic VR gesture recognition than previous attempts.

1.3 Visual Aid

Figure 1 depicts the 6 goal hand gestures to be classified by our device. The level of finger and hand flexion or extension is defined in Table 1.

Figure 2 depicts a high-level overview of our sleeve device with EMG electrode and IMU sensors placed as shown.

Gesture Name	All Five Fingers State	Wrist State
Rest	Relaxed	Relaxed
Fist	Maximally inwardly flexed	Relaxed
Pinch	Partially flexed, with their ends meeting	Relaxed
Spread	Maximally outwardly flexed	Relaxed
Wrist Extension	Relaxed	Maximally extended upwards
Wrist Flexion	Relaxed	Maximally flexed downwards

Table 1: Hand Gesture Classifications

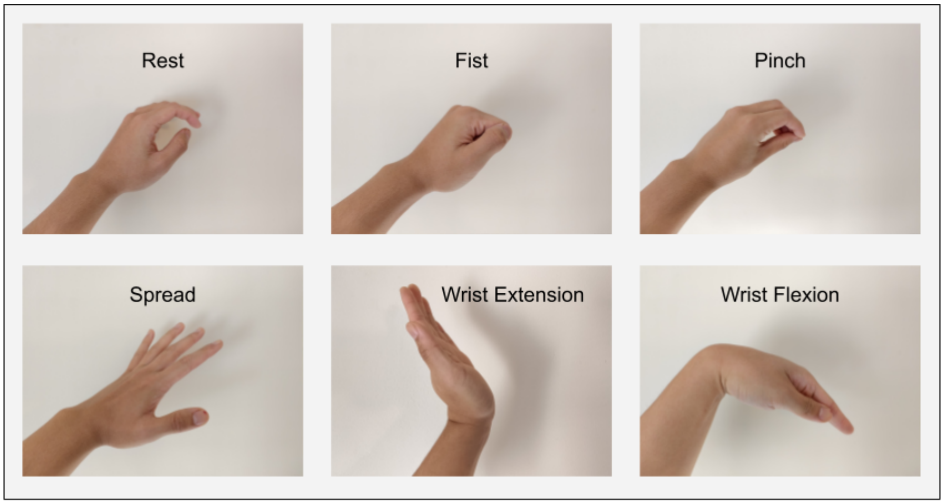

Figure 1: Hand Gesture Classifications Visual

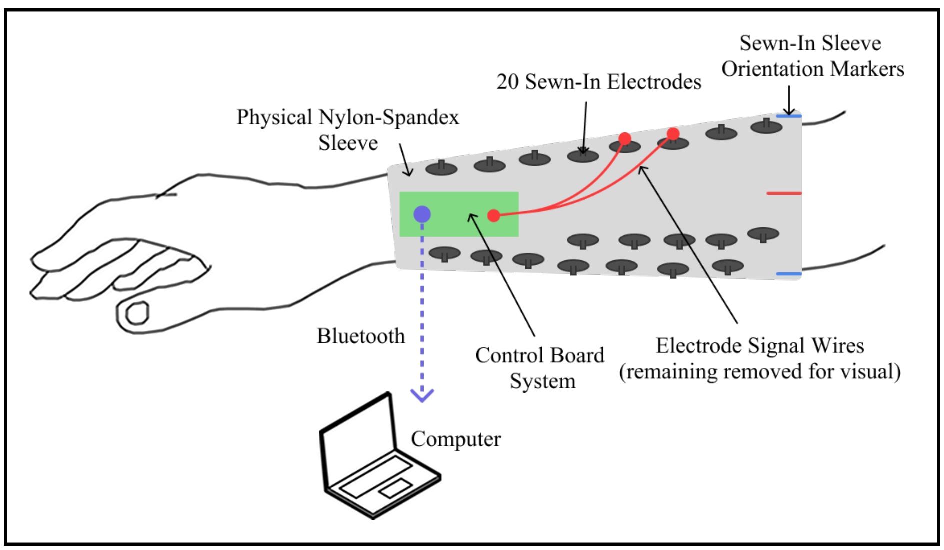

Figure 2: High-Level Overview of Sleeve

1.4 High-Level Requirements

To be considered successful, we aim to achieve the following high-level requirements. These requirements will be tested throughout development using the associated verifications.

1. Reliability in Discerning Gesture

   Verification: Achieve an 80% accuracy in correct classification between the 6 gestures over 30 random user tests.

2. Unrestrained Device Use

   Verification: Classification result from each user test sent wirelessly between our device and an external computer from a distance greater than 10 meters.

3. System Operational Time

   Verification: Ensure the device can be used for 1 hour without need of a battery recharge.

2 Design

2.1 Block Diagram

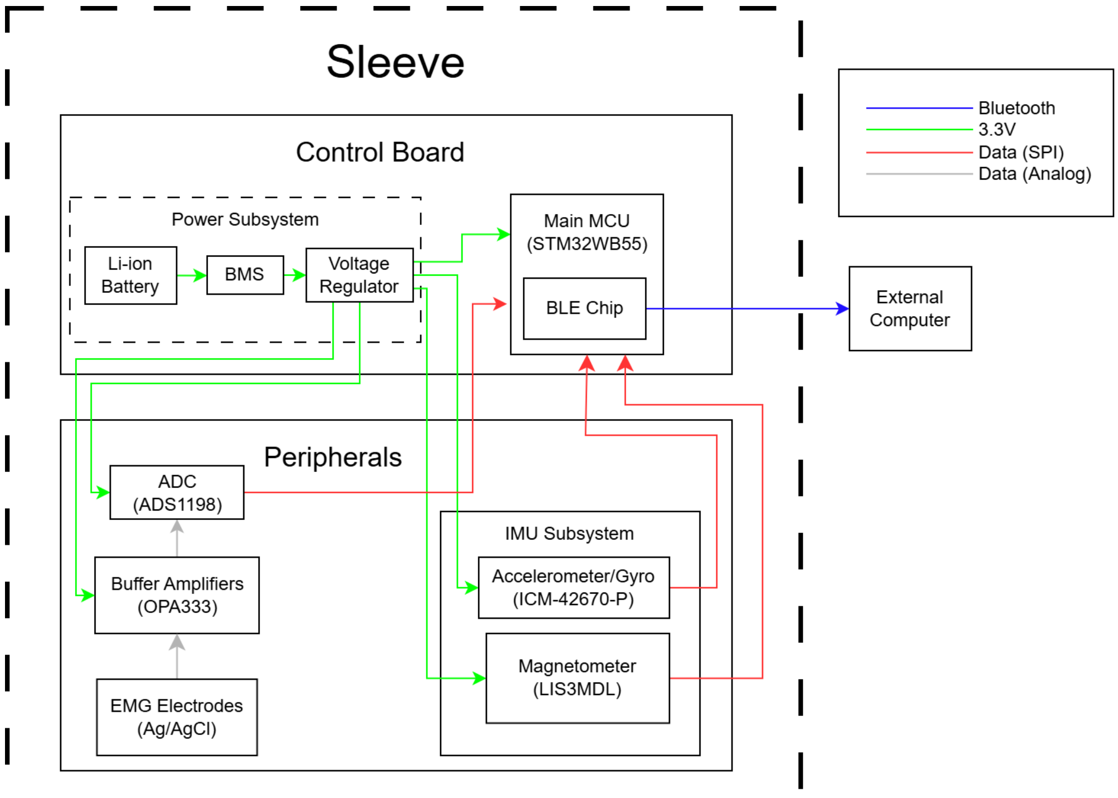

Figure 3: High Level Block Diagram

2.2 Subsystems Overview

Our Device is comprised of 2 main systems each with 3 subsystems. The first system is the Sensing System made up of the Physical Sleeve Subsystem, EMG Array Subsystem, and the IMU Sensor Subsystem. This system contains the physical sleeve component and sensors for our device. The second system is the Control Board System made up of the Bluetooth Subsystem, Processing Subsystem, and Power Subsystem. This systems takes the sensor data from the Sensing System and computes the gesture classification to be sent to a computer.

2.3 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.

2.3.1 Requirements and Verifications

Requirement	**Verification**
The sleeve diameter when maximally stretched must be ≤ 7 cm.	1. Use a flexible measuring tape to measure the sleeve's diameter when fully stretched. 2. Take measurements at multiple points along the sleeve's length. 3. Record all measurements and ensure they are ≤ 7 cm. 4. Document the results in a table, including the maximum measured diameter.
The sleeve must allow for consistent EMG sensor placement between uses.	1. Mark the positions of the EMG sensors on the sleeve. 2. Have multiple users put on and remove the sleeve several times. 3. After each application, measure the distance between marked sensor positions and actual sensor positions. 4. Calculate the average deviation in sensor placement across all trials. 5. Ensure the average deviation is within an acceptable range (e.g., ± 5 mm). 6. Document the results in a table, including individual and average deviations.
The sleeve must securely hold the PCB containing the IMU, Processing, and Bluetooth Subsystems.	1. Attach the PCB to the sleeve using the Velcro tape. 2. Perform a series of arm movements (e.g., flexion, extension, rotation) while wearing the sleeve. 3. Check that the PCB remains securely attached after each movement. 4. Attempt to remove and reattach the PCB multiple times to ensure the Velcro maintains its grip. 5. Document the results of the movement tests and Velcro durability in the verification report.

2.3.2 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.

2.4 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[10] [9]. 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 2.4.2. The design choices for the EMG array is crucial to satisfying High Level Requirement #1.

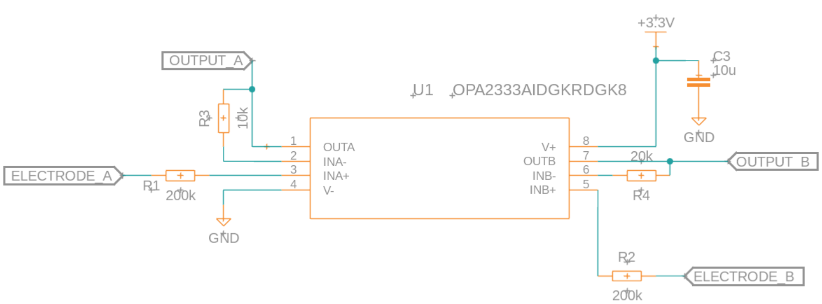

Figure 4: Active Electrode Circuit Schematic

2.4.1 Requirements and Verifications

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 20 amplifiers. 3. Verify that all measurements are $\leq 50\mu$V. 4. Document results in a table, highlighting any values exceeding the threshold.
The EMG array must be able to detect muscle stimulation signals in the mV range.	1. Use a signal generator to input known mV-range signals into the EMG array. 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 EMG array must maintain signal quality with skin-to-electrode impedance < 10 kΩ.	1. Use an impedance meter to measure the skin-to-electrode impedance for each electrode. 2. Record measurements for all 20 electrodes. 3. Verify that all measurements are < 10 kΩ. 4. If any measurements exceed 10 kΩ, adjust electrode placement or skin preparation. 5. Document final impedance values for all electrodes in a table.

2.4.2 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[7]. 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 (≥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.

2.5 IMU Sensor Subsystem

The Inertial Measurement Unit (IMU) Sensors will be physically attached to the physical sleeve subsystem in order to record position and inertial data from a training individual. These signals will be passed to the Processing Subsystem for gesture classification. The structure for the IMU sensor subsystem is needed to demonstrate viability for VR use, and helps to satisfy High Level Requirement #1.

2.5.1 Requirements and Verifications

Requirement	Verification
The IMU must be able to measure accelerations up to 4G.	1. Check the specifications of the ICM-42670-P chip to confirm its acceleration measurement range. 2. Use a calibrated motion simulator to subject the IMU to accelerations up to 4G. 3. Record and analyze the IMU output to verify accurate measurements up to 4G. 4. Document the results, including any deviations from expected values.
The IMU must have on-chip motion processing capabilities.	1. Examine the ICM-42670-P datasheet to confirm the presence of on-chip motion processing features. 2. Implement a test program that utilizes the on-chip processing capabilities. 3. Compare the results of on-chip processing with raw data processing on the MCU. 4. Document the processing capabilities and any performance improvements observed.
The IMU must communicate with the MCU using SPI protocol with a minimum data transfer rate of 1 Mbps.	1. Configure the SPI communication between the IMU and MCU. 2. Use an oscilloscope to measure the SPI clock frequency and data transfer rate. 3. Verify that the measured data transfer rate exceeds 1 Mbps. 4. Record the actual data transfer rate achieved in the verification report.

2.5.2 Components & Functionality

1. High-DOF

   For proper tracking of forearm movement, an IMU will be used. The IMU must be able to withstand most arm movements. We've chosen a desired 4Gs as most arm movements lay below this acceleration. Additionally, Therefore, the 6-DOF accelerometer and gyroscope combination on the ICM-42670-P chip provides the best solution for low power consumption, on-chip processing, and high precision. Altogether, this is a

9-DOF IMU system that will be located on the main control board. The choice in IMU and amplifiers will help resolve High Level Requirement #1.

2. On-chip processing

   To offload processing power off the MCU, the chip needs to have edge processing of sensor data. The ICM-42670-P has on-chip motion processing and gesture recognition, with low power consumption, which relieves load off the MCU. Lastly, for high speed data transfer between the IMU chips and the MCU, we've chosen to use SPI protocol for fastest data transmission.

2.6 Bluetooth Subsystem

The Bluetooth Subsystem leverages the STM32WB55 built-in BLE radio capabilities to manage wireless communication between the wearable device and external systems. The classification data from the Processing Subsystem will be sent to this Bluetooth Subsystem to be wirelessly sent to a computer for data visualization during testing. The design choices of the Bluetooth susbsystem would be critical to satisfy High Level Requirement #2.

2.6.1 Requirements and Verifications

Requirement	Verification Procedure
The Bluetooth module must maintain a stable connection with a minimum data transfer speed of 2 Mbps.	1. Setup: Connect the sleeve to a paired computer or mobile device via Bluetooth. 2. Data Transmission Test: Continuously send packets of classification results at regular intervals (e.g., every 50ms). 3. Speed Verification: Use a software-based Bluetooth debugging tool to monitor data rates. 4. Pass Criteria: The logged transmission speed must remain $\geq$ 2 Mbps over a continuous 5-minute period.
The Bluetooth connection must remain stable for at least 1 hour of continuous operation.	1. Setup: Connect the sleeve to a host device and initiate continuous data transmission. 2. Logging Stability: Every 5 minutes, log whether the device remains connected. 3. Reconnection Test: If the connection drops, record the time and whether the system automatically reconnects. 4. Pass Criteria: The device must stay connected for at least 1 hour without requiring manual reconnection.
The Bluetooth subsystem must successfully transmit gesture classification results within 100ms.	1. Setup: Implement a simple test where the sleeve sends a test gesture classification result upon a button press. 2. Timestamp Logging: Log the system time at (a) the moment the button is pressed and (b) when the receiving device logs the result. 3. Pass Criteria: The difference between these timestamps must be $\leq$ 100ms in at least 95 % of test cases.
The system must be able to handle multiple reconnections within 5 seconds if disconnection occurs.	1. Setup: Pair the sleeve with a receiving device, then manually disconnect Bluetooth via the software settings. 2. Reconnection Test: Time how long the system takes to automatically reconnect. 3. Pass Criteria: The device should reconnect within 5 seconds in at least 90% of test attempts.
The Bluetooth transmission should have an error rate of $\leq$ 1% over 1000 messages.	1. Setup: Configure the system to send 1000 consecutive classification messages to a paired device. 2. Logging Errors: Compare the number of messages sent vs. received using a serial log on the receiving end. 3. Pass Criteria: The error rate (missed or corrupted messages) should be $\leq$ 1% over the full test run.

2.6.2 Components & Functionality

1. Data transfer rate

   Must deliver a stable connection with a minimum data transfer speed of 2 Mbps to ensure real-time data transmission. If this requirement is not met, the real-time performance of gesture recognition could be significantly delayed, impacting user experience and system functionality.

2.7 Processing Subsystem

This subsystem serves as the computational center of the device, using the STM32WB55 MCU to implement our ML-based gesture recognition after taking signals from the EMG Array Subsystem and the IMU Sensor Subsystem in order to accurately classify a user's gestures from our 6 training gestures in realtime. We plan to train a CNN model on our gestures dataset and convert it into TensorFlow Lite[8] format for MCU deployment. The result of this classification will be sent to the Bluetooth subsystem for application. Choosing the correct algorithms and data processing techniques will help resolve High Level Requirements #1 and #2.would result in delays that degrade the user experience, contravening High Level Requirement #2.

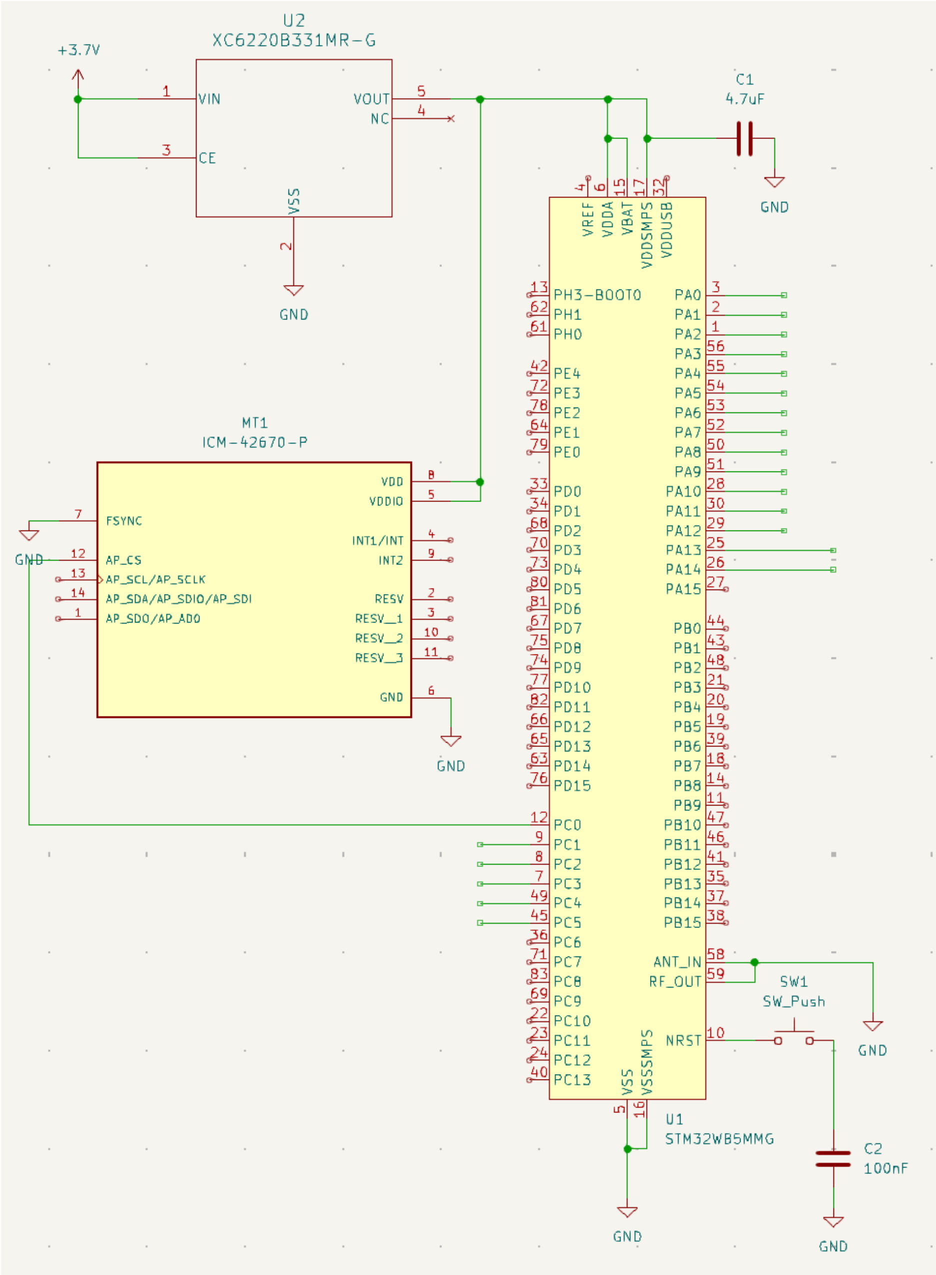

Figure 5: Control Board Schematic

2.7.1 Requirements and Verifications

Requirement	Verification Procedure
The STM32WB55MMG must process EMG and IMU sensor data with a latency of 100ms.	1. Setup: Simulate continuous EMG and IMU sensor data being fed into the STM32WB55MMG MCU. 2. Logging Execution Time: Use built-in timers to record timestamps (a) when data is received, (b) when classification is completed. 3. Pass Criteria: Ensure the total latency (time from receiving sensor data to classification result output) is $\leq$100ms in 95% of cases.
The STM32WB55MMG must execute TensorFlow Lite models efficiently for real-time gesture inference.	1. Setup: Convert a pre-trained gesture recognition model into TensorFlow Lite format optimized for the MCU. 2. Test Execution Time: Run inference on test data and log the duration using the MCU's internal clock. 3. Pass Criteria: Confirm that inference time is $\leq$ 50ms per sample while maintaining classification accuracy $\geq$80%.
The system must maintain high-speed SPI communication with the EMG/IMU sensors at $\geq$1 Mbps.	1. Setup: Send a fixed-size data packet (e.g., 100 bytes) from the sensors to the STM32WB55MMG over SPI. 2. Measure Throughput: Use a logic analyzer or timestamp comparison to measure SPI transfer speed. 3. Pass Criteria: Ensure the transfer rate is $\geq$1 Mbps with an error rate of $\leq$1% over 1000 transfers.
The STM32WB55MMG must correctly classify gestures with at least 80% accuracy.	1. Setup: Record 30 user-performed gestures and log classification outputs. 2. Compare with Ground Truth: Match each classification result against manually labeled gestures. 3. Pass Criteria: Ensure $\geq$80% of gestures are correctly classified.
The processing system must remain operational without crashes or memory leaks over a 1-hour continuous test.	1. Setup: Run the gesture recognition system continuously for 1 hour with simulated or live sensor data. 2. Monitor Stability: Check for MCU resets, memory allocation failures, or performance degradation. 3. Pass Criteria: No unintended reboots, crashes, or increasing memory usage over the full test period.

Table 2: System Requirements and Verification Procedures

2.7.2 Components & Functionality

1. Process rate (data preprocessing and ML inferencing)

   The STM32WB55 MCU must efficiently execute TensorFlow Lite models, specifically optimized for real-time machine learning inference. This execution supports critical machine learning operations necessary for processing EMG and IMU sensor data into actionable gesture commands. Must process incoming sensor data and run machine learning algorithms within a latency of less than 100 milliseconds to ensure real-time responsiveness. Insufficient processing power would result in delays that degrade the user experience, contravening High Level Requirement #1.

2. Interface requirements

   SPI for high data transmission rate to handle real-time, high-frequency sensor data. Although more complex in terms of wiring, since each slave device would need to require four pins (MISO, MOSI, SCK, and SS), faster data rates and individual control over each sensor is key to achieve High Level Requirement #1. Must maintain a high-speed SPI interface with a minimum throughput of 1 Mbps to ensure timely data exchange between the MCU and sensors. A failure in this interface would lead to bottlenecks in data processing, affecting the overall system performance and violating High Level Requirement.

2.8 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.

2.8.1 Requirements and Verifications

Requirements	Verification
The system must provide a stable 3.3V power supply (±0.1V tolerance) to all components.	1. Setup: Power on the device with a fully charged battery. 2. Voltage Measurement: Use a multimeter to measure voltage at the STM32WB55MMG MCU and other critical components (e.g., Bluetooth module, sensors). 3. Pass Criteria: Confirm that the voltage remains between 3.2V and 3.4V under both idle and active conditions.
The Li-ion battery must support continuous operation for at least 1 hour on a full charge.	1. Setup: Fully charge the battery, then run the device under normal operating conditions (Bluetooth enabled, gesture classification active). 2. Monitoring: Log system runtime until the device shuts down due to low power. 3. Pass Criteria: The system must operate for at least 1 hour before requiring a recharge.
The power management system must prevent overcharging and over-discharging of the battery.	1. Overcharge Test: Charge the battery from 0% to 100% while monitoring voltage levels with a multimeter. 2. Over-discharge Test: Discharge the battery until the system shuts down, ensuring it does not drop below the safe minimum voltage (e.g., 3.0V for Li-ion). 3. Pass Criteria: The system must stop charging when voltage reaches 4.2V and shut down before voltage drops below 3.0V.
The power system must support peak current demands without voltage drops exceeding 10%.	1. Setup: Introduce a high-power event (e.g., simultaneous Bluetooth transmission and gesture classification). 2. Voltage Monitoring: Use an oscilloscope to track voltage fluctuations during peak activity. 3. Pass Criteria: The voltage must not drop more than 10% (0.33V drop at 3.3V) under peak load conditions.
The system must safely handle a sudden power loss without data corruption.	1. Setup: Power cycle the system unexpectedly during operation. 2. Functional Check: After restart, verify that the system boots correctly and processes gestures without errors. 3. Pass Criteria: System must resume normal operation without requiring manual resets or data loss.

2.8.2 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($\pm$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.

2.9 Risk Analysis

Given the decisions made in our design approach, there are existing risks that may prevent us from reaching our provided High Level Requirements. Below we will break down the design decisions that are necessary to reach our High Level Requirements, their respective risks, and alternative approaches which may be more suitable after initial testing.

2.9.1 Physical Electrode Design

When determining how to attach the sewn-in electrodes to a given user's skin, there are two general approaches: the use of a wet electrode, in which a paste is applied between the skin and the electrode in order to establish an electrical connection, or the use of a dry electrode, in which the electrode is simply set upon the skin. A wet electrode typically creates a better electrical connection between the skin and the electrode, resulting in a lower noise signal, with the trade off of being more difficult to apply (especially with multiple electrodes) and the intermediary paste drying out after a short duration.

Characteristic	Wet Electrodes	Dry Electrodes
Signal Noise Level	Low	High
Setup Time	Long	Short
Duration	Short-Term	Long-Term

Table 3: Comparison of Wet and Dry Electrodes

Given the electrode characteristic comparison in Table 5, it is recognized that use of wet electrodes may prohibit the achievement of High-Level Requirement #1 over time, as the EMG signals will change based on the moisture level of the intermediary paste, making ML gesture classification challenging. Further, the wet electrodes require a longer setup time, leading to a less practical device where a user needs to apply a paste globule to each individual electrode before use. Therefore, we made the initial decision to build with dry electrodes, despite the higher signal noise level.

2.9.2 Signal Detection to Amplification Proximity

The electrical signal of each individual EMG electrode needs to be amplified before it can be processed and used to classify a given gesture. However, the proximity level of where the amplification occurs can impact the resulting signal and the difficulty of sleeve manufacturing. If each signal is amplified immediately after signal detection, it would result in a less noisy signal, but would require manufacturing challenges as an amplifier would need to be placed near each individual electrode. If each signal is amplified at our Control Board System, each resulting signal may have more noise, but the sleeve design would be more simple.

Characteristic	Close Amplification	Far Amplification
Signal Noise Level	Low	High
Design Complexity	High	Low

Table 4: Comparison of Close and Far Signal Amplification Proximity

Given the amplifier placement characteristic comparison in Table 4, is is recognized that the close proximity placement may result in a cleaner signal, but will require a much more complex sleeve design, potentially inhibiting long term use, and preventing the achievement of High Level Requirement #1. Therefore, we made the initial decision to build with further proximity amplification.

Characteristic	High Density	Low Density
Signal Noise Level	Higher	Lower
Cross-talk	Higher	Lower
Precision	Higher	Lower
Mobility	Lower Flexibility	Larger Design
Complexity	Higher	Lower

Table 5: Comparison of High and Low Density Placements

2.9.3 Processing System Risks in Computational Limits

The STM32WB55 MCU is chosen for its efficiency and capability to run TensorFlow Lite models, as well as the fact that it contains an embedded bluetooth radio, which significantly simplifies the hardware architecture by eliminating the need for a separate Bluetooth module. This integration not only reduces the physical footprint and complexity of the design but also enhances the overall energy efficiency and cost-effectiveness of the device. However, there is a risk that future enhancements or more complex gesture recognition algorithms might exceed the processing power available, thus hindering High-Level Requirement #1 focused on accuracy and reliability.

To mitigate this risk, we consider the following strategies:

1. **Modular Design Approach**: Design the system with modularity in mind, allowing for the addition of supplementary processing units or co-processors in the future. This could provide the necessary boost in computational power to handle more demanding algorithms without a complete system overhaul.
2. **Algorithmic Optimization:** Implement model quantization for algorithm optimization if needed, reducing the precision of the numbers used in the model from floating-point to integers, which decreases model size and speeds up inference without significant loss of accuracy. Additionally, considering to apply techniques to remove redundant or non-informative parts of the model, thus boosting execution speed.

2.10 Tolerance Analysis

2.10.1 Power Consumption

To ensure the efficacy of our design, we'll need to find a proper battery capacity to satisfy High Level Requirement #3. This will be done by looking at the power consumption of all components in our design. The components with nonnegligible power consumption and their maximum operating current draw will be

1. 1x STM32WB55 (53 μA)
2. 1x ICM-42670-P (0.55 mA)
3. 3x ADS1198 (0.55 mA/channel)
4. 10x OPA2333 (0.034 mA/channel)

$$\begin{aligned}[\text{Current consumption}] &= 53\ \mu A + 0.55\ mA + 20 \times 0.55\ mA + 10 \times 0.034\ mA \\ &= 11.9\ mA\end{aligned}$$

To run this system with all components in high-performance mode, the current draw will be 11.9 mA so running for 1 hour will require a battery of greater than 11.9 mAh capacity. We've chosen a 3.7 V, 500 mAh Li-ion battery which will suffice for power consumption and it is a small size.

2.10.2 EMG Signal Amplification

The EMG signal amplification stage is critical to meeting High-Level Requirement #1: "Reliability in Discerning Gesture." This tolerance analysis evaluates the feasibility of amplifying EMG signals for accurate gesture recognition.

Critical Parameters

1. EMG signal amplitude: 0.1 mV to 50 mV
2. OPA2333 buffer amplifier offset voltage: $\leq 50\,\mu$V

3. Amplifier gain tolerance: $\pm 1\%$
4. ADC resolution: 16-bit

Calculations

1. Required gain to amplify 50 mV to 2 V for the ADC:

$$\text{Gain} = \frac{2\,\text{V}}{50\,\text{mV}} = 40$$

2. Worst-case scenario for minimum detectable signal is to use minimum EMG signal of 0.1 mV

   Maximum offset voltage: $50\,\mu\text{V}$

   Effective minimum signal: $0.1\,\text{mV} - 0.05\,\text{mV} = 0.05\,\text{mV}$

   Amplified signal range:

$$\text{min: } 0.05\,\text{mV} \times 40 = 2\,\text{mV}$$

$$\text{max: } 50\,\text{mV} \times 40 = 2\,\text{V}$$

   Gain tolerance:

$$\text{min: } 40 \times 0.99 = 39.6$$

$$\text{max: } 40 \times 1.01 = 40.4$$

   ADC resolution with voltage per level:

$$V_{\text{level}} = \frac{2\,\text{V}}{2^{16}} = 30.5\,\mu\text{V/level}$$

Analysis

1. The minimum amplified signal (2 mV) is well above the ADC's voltage per level ($30.5\,\mu$V), ensuring that even the smallest EMG signals can be detected.
2. The ADC's resolution is sufficient to capture the amplified EMG signals with good precision, providing 655 levels for the smallest expected signal (2 mV) and 65,536 levels for the full range.

The proposed EMG signal amplification stage can feasibly meet the requirements for accurate gesture recognition. The worst-case tolerances still allow for reliable signal detection and digitization.

This tolerance analysis demonstrates that the EMG amplification stage can meet High-Level Requirement 1 and provide reliable gesture recognition within specified tolerances.

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[2]. 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 6: 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: Prepare for breadboard demo to demonstrate use of single amplified EMG electrode signal.
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 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. [4]
2. Treat team members with respect, empathy, and fairness. [4]
3. Hold ourselves and others accountable to follow these ethical guidelines. [4]
4. Our ML system will be designed with the role of empowering individuals and their needs. [6]
5. The participation of subjects for device testing will be voluntary, and the subject will be informed of potential risks. [5]
6. Allow testing participants to manage and access their personal data. [5]
7. Treat testing participants with respect and protect them from unwanted discomfort. [5]

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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