ECE 445
SENIOR DESIGN LABORATORY

Project Proposal:
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[2]. 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

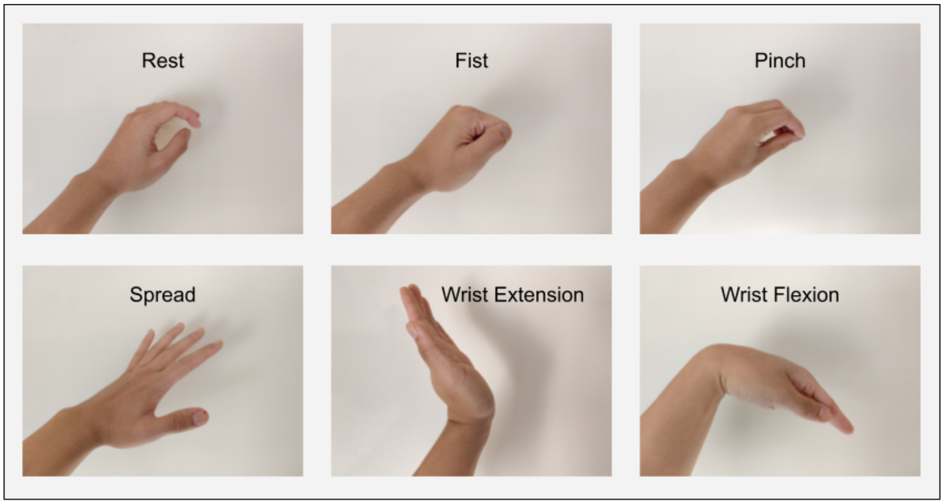

Figure 1: Hand Gesture Classifications Visual

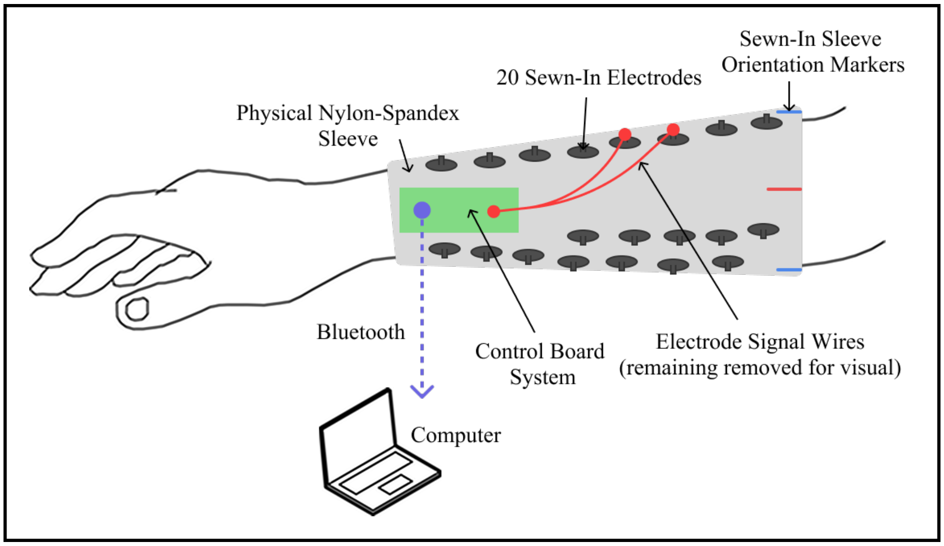

Figure 2: High-Level Overview of Sleeve

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. Consistency in Discerning Gesture

   Verification: Maintain a 70% accuracy in correct classification between the 6 gestures over 30 random user tests with a replacement of the device (taking off and putting back on) between 2 testing sessions.

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

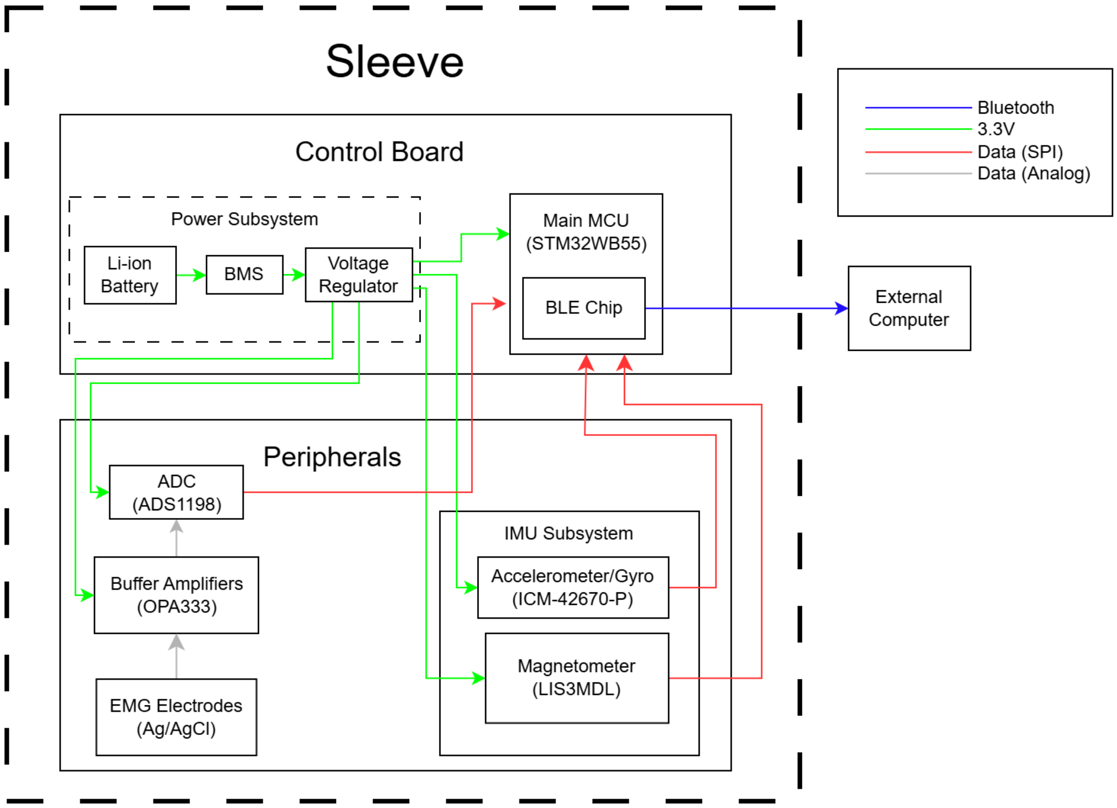

Figure 3: High Level Block Diagram

2.2 Subsystem 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.

2.2.1 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 in discerning gesture (High Level Requirement #2) 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.

2.2.2 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] [6]. 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 2.3.2. The design choices for the EMG array is crucial to satisfying both High Level Requirements #1 and #2.

2.2.3 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 both High Level Requirements #1 and #2.

2.2.4 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 both High Level Requirements #1 and #2.

2.2.5 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 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.

2.2.6 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.

2.3 Subsystem Requirements

2.3.1 Physical Sleeve Subsystem

1. Electrode placement

   20 clustered electrode holes for attachment to the EMG Array Subsystem. Without this, consistency discerning gesture (High Level Requirement #2) 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, consistency in discerning gesture (High Level Requirement #2) 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.

2.3.2 EMG Array Subsystem

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[4]. 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 Requirements #1 and #2.

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 Requirements #1 and #2.

2.3.3 IMU Sensor Subsystem

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 along with the compatible 3-DOF magnetometer on the LIS3MDL 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 Requirements #1 and #2.

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.

2.3.4 Bluetooth Subsystem

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, violating High Level Requirement #2.

2.3.5 Processing Subsystem

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 #2.

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 #2. 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.

2.3.6 Power Subsystem

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.

2.4 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.

2.4.1 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 2: Comparison of Wet and Dry Electrodes

Given the electrode characteristic comparison in Table 4, it is recognized that use of wet electrodes may prohibit the achievement of High-Level Requirement #2, 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, which we recognize could inhibit achievement of High Level Requirement #1.

2.4.2 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 3: Comparison of Close and Far Signal Amplification Proximity

Given the amplifier placement characteristic comparison in Table 3, 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 #2. 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 4: Comparison of High and Low Density Placements

2.5 Tolerance Analysis

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. 1x LIS3MDL (270 μA)
4. 3x ADS1198 (0.55 mA/channel)
5. 20x OPA333 (0.017 mA/channel)

$$\begin{aligned}\text{[Current consumption]} &= 53\ \mu A + 0.55\ mA + 270\ \mu A + 20 \times 0.55\ mA + 20 \times 0.017\ mA \\ &= 12.2\ mA\end{aligned}$$

To run this system with all components in high-performance mode, the current draw will be 12.2 mA so running for 1 hour will require a battery of greater than 12.2 mAh capacity. We've chosen a 3.7 V, 50 mAh Li-ion battery which will suffice for power consumption and it is a small size.

3 Ethics and Safety

With regards to ethical concerns, we have adhered to the following ethical guidelines inspired by the IEEE Code of Ethics and will continue throughout further design and development of the described project.

1. Hold high standards of academic integrity for ourselves and others.[3]
2. Treat team members with respect, empathy, and fairness.[3]
3. Hold ourselves and others accountable to follow these ethical guidelines.[3]

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.[5]
4. We will obtain additional fire safety and fire extinguisher training for use of a lithium-ion battery.[5]

References

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