ECE 445: Senior Design Laboratory

Design Document: Neuroband

Arrhan Bhatia(arrhanb2), Vansh Rana (vhrana2), Vishal Moorjani (vishal6)

Professor: Arne Fliflet, TA: Wenjing Song

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1 Introduction
1.a Problem and Solution

As augmented reality (AR) glasses become more capable and integrated into daily life, a new challenge has emerged in how users naturally and efficiently interact with them. Voice-based input, though convenient, quickly becomes impractical in public or noisy environments and raises privacy concerns. Camera-based hand tracking—another common approach—depends on external hardware, clear lighting, and an unobstructed line of sight, which makes it unsuitable for mobile or discrete use. Other fallback methods, such as gaze or head-pose tracking, are either too coarse for precision control or cause user fatigue over time.

To address this unmet need, our project, NeuroBand, introduces a two-band wearable controller that enables private, low-latency, and high-fidelity interaction with AR systems. The design consists of a wrist band and a forearm band working together to emulate a standard Bluetooth HID mouse. The wrist band, which houses an IMU, maps wrist orientation to cursor movement on a 2D plane, providing continuous pointing control. The forearm band uses surface Electromyography (EMG) sensing to detect muscle activations corresponding to gestures such as pinching or squeezing, translating them into click and drag commands. Together, these two components create a discreet and intuitive “virtual trackpad” that allows users to control digital interfaces without voice or external cameras.

1.b Visual Aid

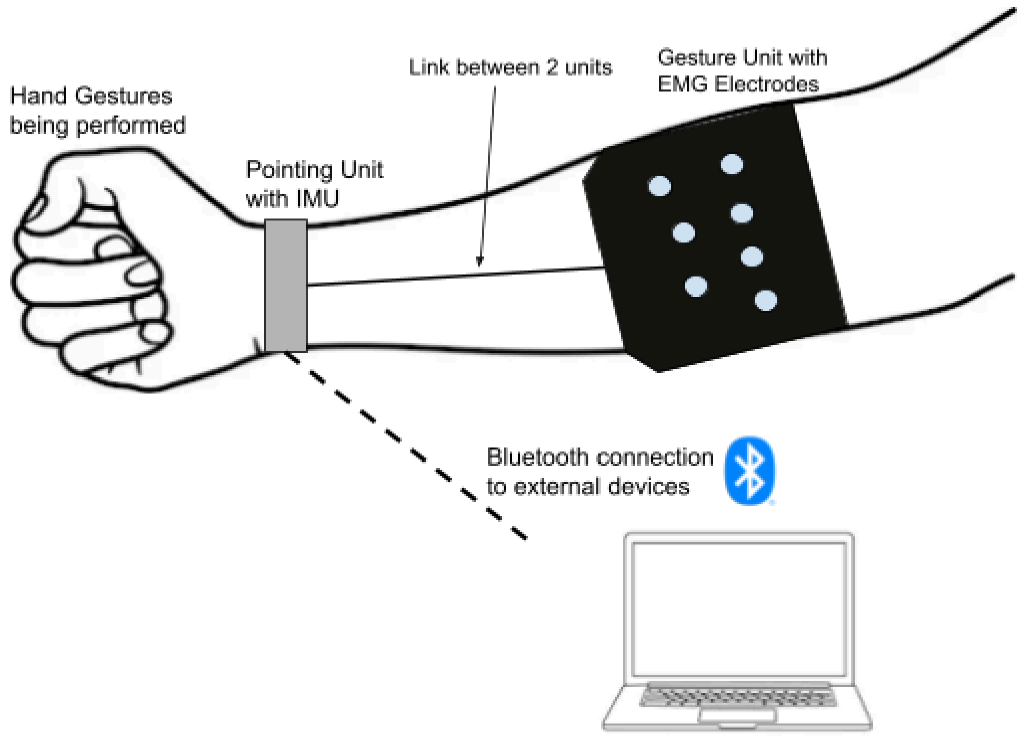

Figure 1: Visual Representation of NeuroBand

1.c High-Level Requirements

To successfully solve the interaction problem and achieve our design goals, the NeuroBand system must meet the following high-level requirements:

- Responsiveness: The total latency from physical motion to cursor response on the host device must be less than 60 ms, ensuring real-time control without perceivable lag.
- Gesture Accuracy: The EMG-based gesture recognition system must achieve at least 90% true-positive accuracy for core gestures (click, drag, scroll) with a low false-positive rate during normal use.
- Operational Time: The combined system must operate continuously for a minimum of 4 hours on a single charge to support typical daily use.

2 Design

2. a Block Diagram

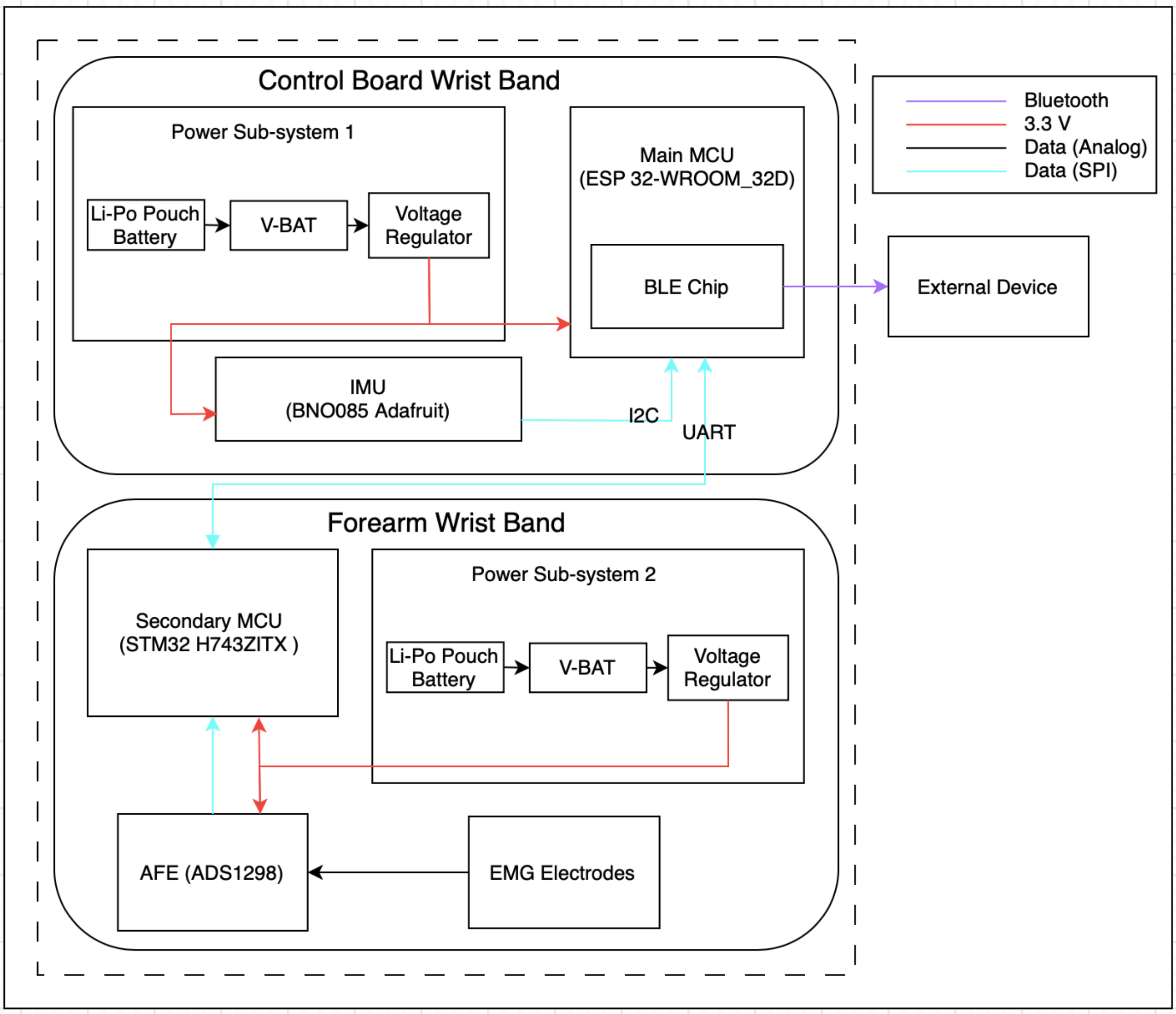

Figure 2: High-level Block Diagram

2.b Subsystem Overview

Our device is composed of two primary systems: the Control Board Wrist Band and the Forearm Wrist Band, each containing dedicated subsystems that work together to provide seamless AR interaction. The wrist band hosts the main MCU (ESP32-WROOM-32D), BLE HID link to an external device and the IMU chip (Adafruit BNO08). This wrist band is responsible for capturing wrist orientation, to get the absolute 2-D cursor motion and transmitting it wirelessly to external devices. The forearm band holds a secondary MCU (STM32H743) and the EMG subsystem (ADS1298 + electrodes). This part amplifies/digitizes muscle activity, extracts features, decides on gestures (pinch/squeeze), and forwards events to the wrist band over a short wired UART. Furthermore, each of these bands have their own power system. Together, these systems share sensor, processing, and communication responsibilities, creating a robust wearable that functions as a Bluetooth HID mouse.

2.b.i Wrist Band

We plan that the wrist band will be made of a Nylon-spandex blend in order to give the user comfort while ensuring a tight fit for the electronics attached to ensure the sleeve doesn't keep moving from place to place and interfere with readings.

2.b.i.1 Main MCU Subsystem + Bluetooth System + IMU

This subsystem fuses IMU pointing data from the wrist band along with EMG gesture data received from the forearm band to decide mouse action (e.g., clutch to freeze, pinch to click/drag) and then outputs the result as standard Bluetooth HID mouse reports to the host device at 100-125 Hz. We've chosen the MCU ESP-32-WROOM-32D which is BLE 4.2/5 compatible and can communicate the results from the MCU to the host device. The IMU (inertial measurement unit) sensors will be integrated into the wrist band to capture wrist orientation and motion data. The chip that we've chosen to work with, the Adafruit BNO085, allows for 9-DOF using both a gyroscope/accelerometer and a magnetometer. These signals will be communicated to the ESP 32 MCU through I2C. This chip is the primary pointing mechanism of the device.

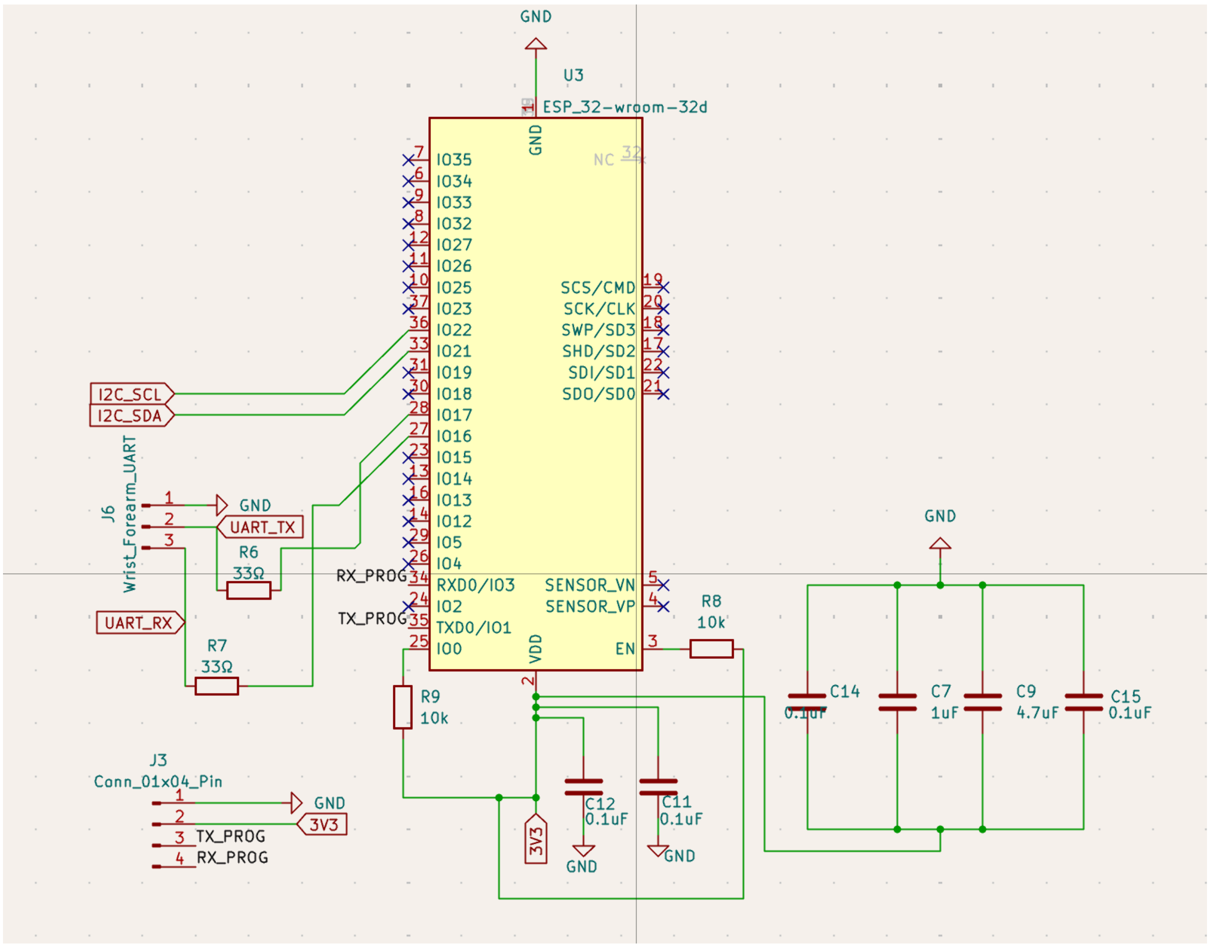

Figure 3: Wristband MCU Schematic

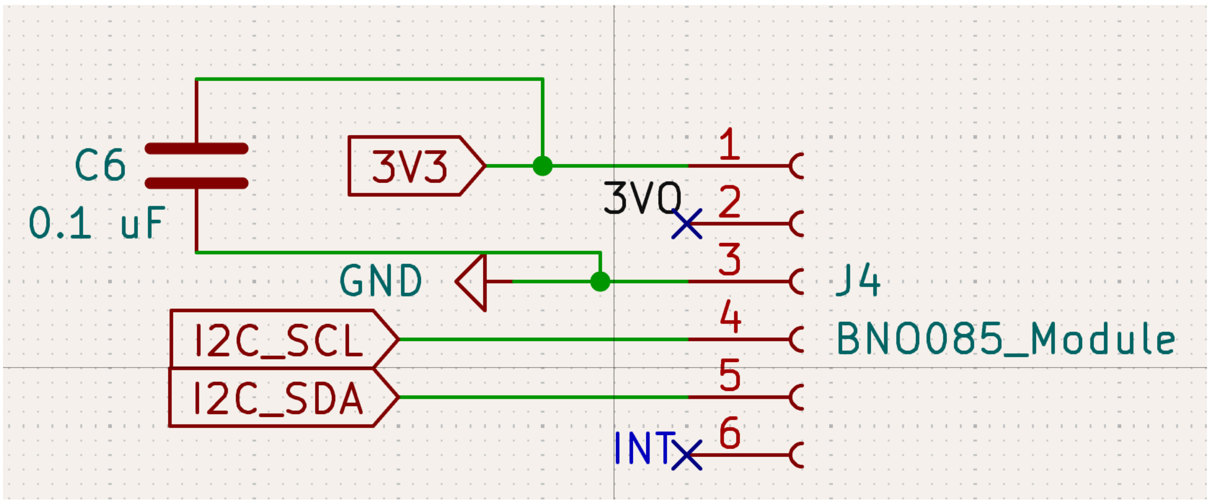

Figure 4: Wristband IMU Schematic

2.b.ii Forearm Band

The forearm band will also be made of a nylon-spandex blend to provide both comfort and a snug, stretchable fit that ensures consistent contact between the EMG electrodes and the user's skin, while also making sure that all electronics remain snuggly in place to prevent any error in readings.The Secondary MCU and EMG subsystem will be mounted to this band in fixed positions to simplify development and ensure robust data collection.

2.b.ii.1 Secondary MCU

The Secondary MCU Subsystem manages the acquisition and transmission of EMG signals from the forearm band. A microcontroller, the STM32H743ZIT6, will receive digitized signals from the EMG subsystem, run a small TinyML classifier (clutch, pinch, pinch-hold, none), and send gesture data via a short wired link (UART). Given the 2MB flash memory limit for the selected MCU, we are currently aiming for a 1 layer CNN. Although we haven't actively started working on the model, we are considering INT4/INT8 quantization techniques to ensure we can fit as large of a model on the MCU. Doing ML at the source cuts bandwidth and adding this secondary MCU prevents noise and error in the data by ensuring that it doesn't get distorted over longer distances.

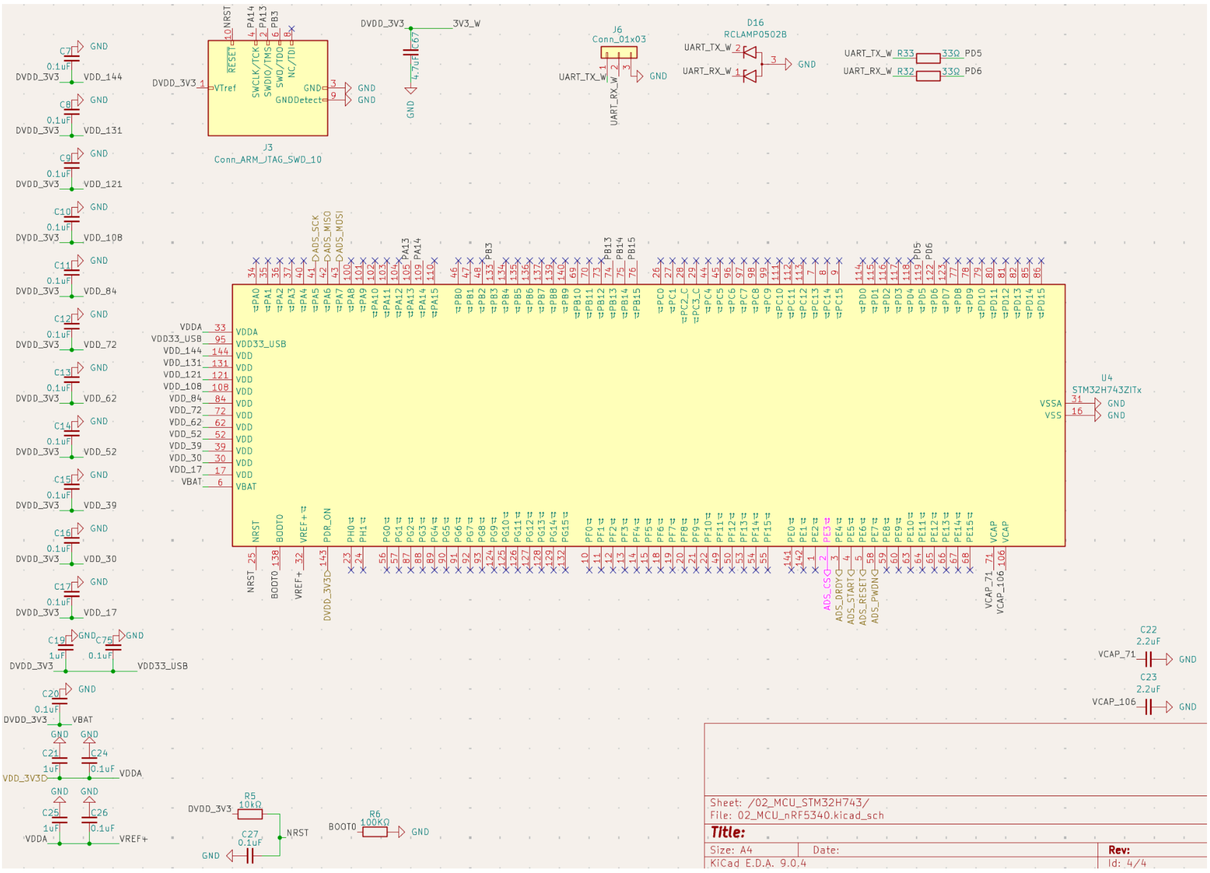

Figure 5: Schematic for Forearm MCU

2.b.ii.2 EMG Subsystem

The EMG Subsystem is responsible for detecting muscle activation signals in the user's forearm to enable gesture recognition. Surface electrodes will capture electrical activity from muscle contractions, such as pinching or squeezing. These signals will be conditioned through an analog front-end (AFE) for amplification and filtering before being digitized and sent to the STM32. We have selected the ADS1298 AFE as it has support for up to 8 channels. On our V1 PCB, we have added connectors for all 8 channels to study how many we will finally need, and what kind of processing/ feature extraction we should do. The processed EMG data will then be transmitted using a wired connection to the Main MCU in the wrist band for integration with IMU-based pointing control. We have settled on the UART interface for communication between the 2 PCBs, as it supports a bandwidth that is high enough for the model output at the selected rate, and the low number of wires makes the system easier to use.

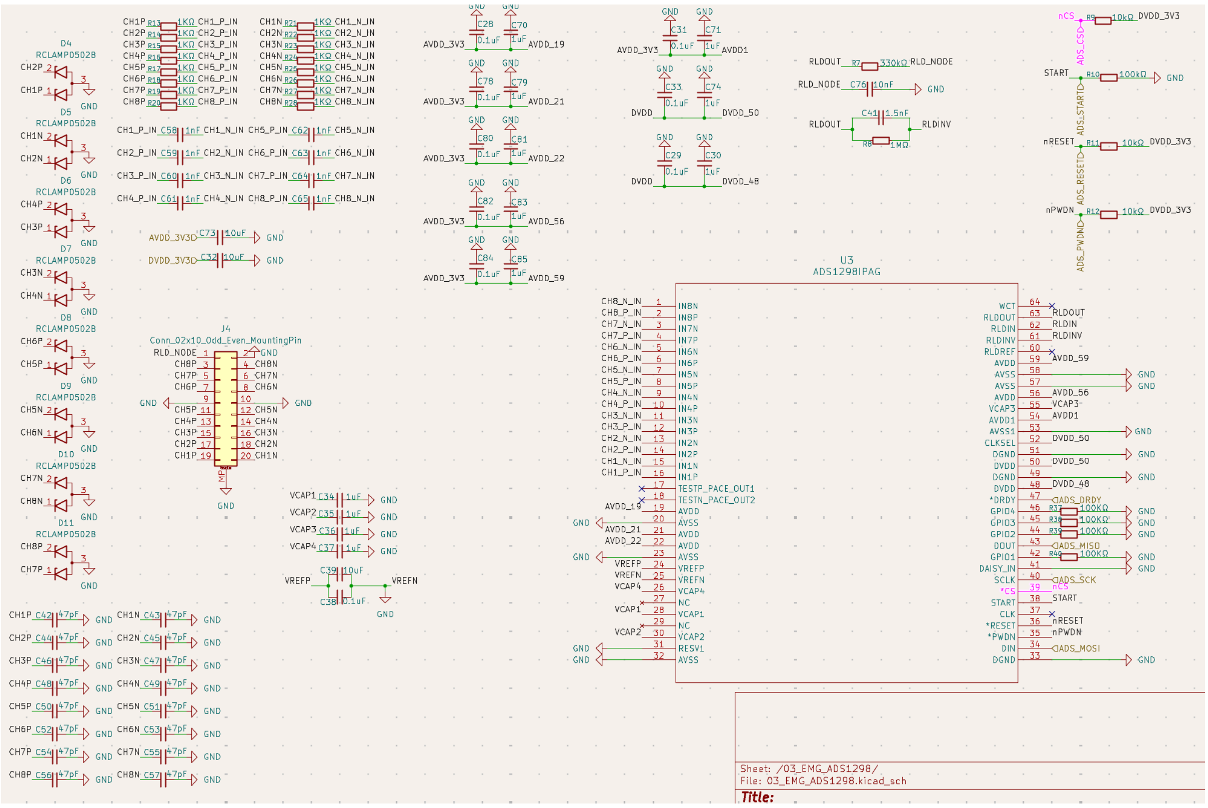

Figure 6: Schematic for EMG Subsystem

2.b.iii Power Subsystem

Power is split by band: the wrist and forearm each have their own single-cell Li-Po pouch (which comes with its own BMS), local charger, and regulation. The regulators ensure a consistent 3.3 V supply for the MCUs, IMU, and EMG front-end, while the battery management system (BMS) protects against overcharging and undervoltage. We are using 2 separate LDOs, the AP2112K and the TPS7A2033. The TPS7A2033 is a low noise LDO, which we are using for the analog power rail. Both LDOs regulate the input voltage to 3.3 Volts, which will be used to power the MCU and

AFE. The LiPO batteries usually have a standard charging current of up to 425 mA, we are regulating the charging current to 425mA, with the help of the MCP73831. This is despite the maximum charging current being up to 850 mA, to ensure safety for the V1 PCB.

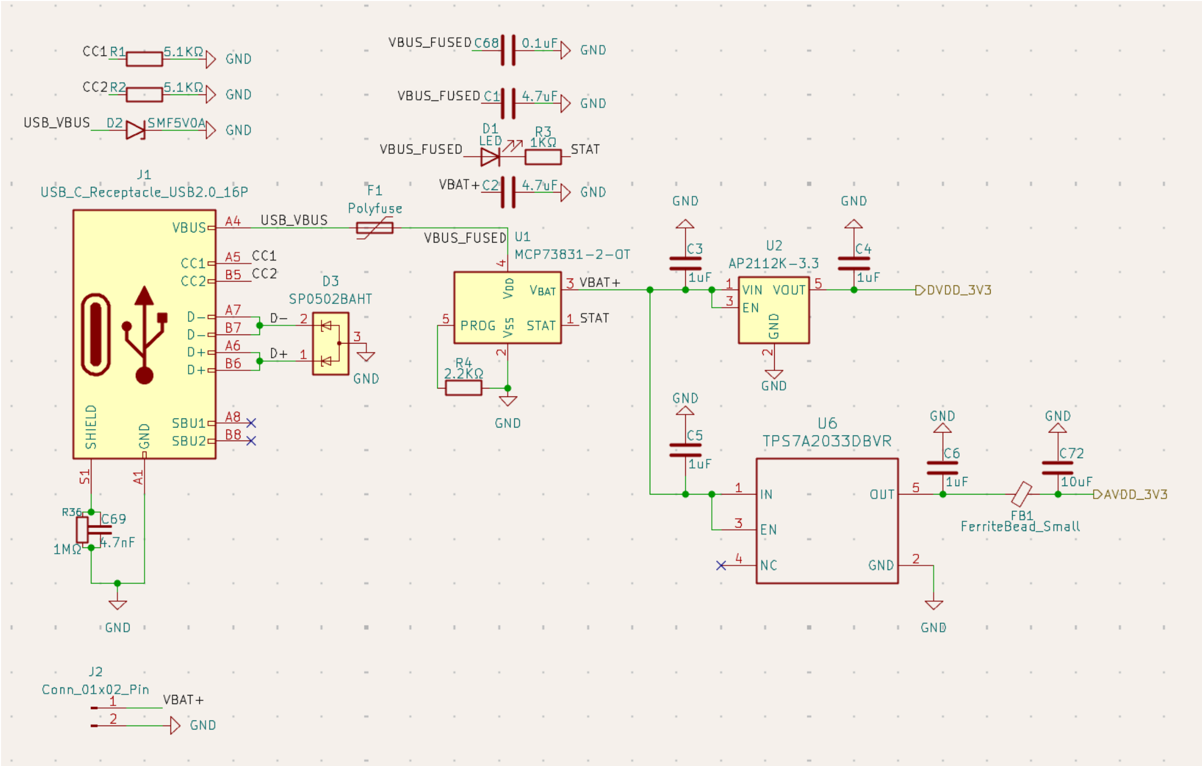

Figure 7: Schematic for Forearm Power Subsystem

Requirements and Verification Table

Subsystem	Requirement	Verification Methodology
ESP32 MCU + IMU	BLE data path ≥1 Mb/s	Analyze notifications and measure rate using something like nRFConnect
	HID report rate ≥100 Hz without missed intervals.	Analyze timestamps for BLE packets on MCU, as well as on the user device.
	>4H Battery Life	Measure current draw during Normal Operation, and run the system for several cycles (100% -> 0%)
STM32 + ML Model	>90% true positive rate for gestures	Measure model performance on a validation set to ensure accuracy requirements are met
	>4H Battery Life	Measure current draw during Normal Operation, and run the system for several cycles (100% -> 0%)
Power Subsystems	Charging current = 425mA.	Ensure battery charging current is regulated to 425mA at the output of MCP73831

	Output voltages regulated to 3.3 V	Use an oscilloscope to verify that output voltages from all 3 LDOs are at a stable 3.3V during operation.
	ESD Diodes protect against voltage spikes	Verify functioning of ESD Diodes + resettable fuse using a bench power supply / function generator, to ensure correct functioning even outside of normal voltage ranges (>5V)
General Requirements	All exposed conductors insulated except electrodes; operating at 3.3 V rails.	Measure voltage at LDO output, visually inspect all conductors
	End-to-End latency < 60ms	Analyze timestamps for EMG Data Read + BLE packet on the users device using something like nRFConnect to analyze incoming packets.

2.c Tolerance Analysis

We want to make sure that our users can use their band for a sustained period of time. We want to ensure they can interact and use our product without interrupting the work they are doing, such as dying while in the middle of a task. Now to make sure of this we have made one of our high level requirements that the system remains operational for 4 hours on a single charge. This gives the user ample time to complete multiple tasks and use our system with their device multiple times before a recharge is required.

In order to ensure that the battery lasts for 4 hours, we will perform a tolerance analysis based on estimated current draw from each major component:

Wrist Component	**Typical Current Draw**
ESP32-WROOM-32 (with BLE)	160 mA
BNO085	11 mA
Pull ups + miscellaneous overhead	10 mA

This results in an expected maximum current draw of 171 mA in the wrist band during continuous operation and thus we require a battery that can supply at least 708 mAh.

$$Runtime = 171\, mA * 4\, hours = 684\, mAh$$

Forearm System:

Forearm Component	**Typical Current Draw**
STM32H743ZIT6	165 mA

ADS1298	2 mA
Pull ups + miscellaneous overhead	10 mA

This results in an expected maximum current draw of 177 mA in the forearm band during continuous operation and thus we require a battery that can supply at least 708 mAh.

$$Runtime \ = \ 177\,mA \, * \, 4\,hours \, = \, 708\,mAh$$

We plan to use an 850 mAh battery for the forearm and wrist sub system.This satisfies the target of ≥ 4 hours helping ensure we reach high level requirement 3 helping make sure the user has a continuously smooth experience with our device.

3. Cost and Schedule

3.a Cost Analysis

Labor: The average Computer Engineering major from the University of Illinois makes ~118,000 dollars per year. Assuming a 40 hour work week, this works out to approximately 57 dollars an hour. We estimate that this project will take us approximately 25 hours per week, for the 16 weeks in the semester. So, our cost of labor works out to:
3 (# group members) x 57 ($/hour) x 25 (hours/week) x 16 (weeks) x 2.5 = $171,000.

3.b Parts List

Part Name	Description	Quantity	Price per Unit	Total
1uF Capacitor	1uF SMD Capacitor	22	0.08	1.76
0.1uF Capacitor	0.1uF SMD Capacitor	32	0.08	2.56
47pF Capacitor	47pF SMD Capacitor	16	0.1	1.6
1.5nF Capacitor	1.5nF SMD Capacitor	1	0.39	0.39
10nF Capacitor	10nF SMD Capacitor	1	0.08	0.08
10uF Capacitor	10uF SMD Capacitor	4	0.08	0.32
4.7nF Capacitor	4.7nF SMD Capacitor	2	0.27	0.54

4.7uF Capacitor	4.7uF SMD Capacitor	6	0.08	0.48
2.2uF Capacitor	2.2uF SMD Capacitor	2	0.08	0.16
1nF Capacitor	1nF SMD Capacitor	8	0.08	0.64
100KΩ Resistor	100KΩ SMD Resistor	6	0.1	0.6
330KΩ Resistor	330KΩ SMD Resistor	1	0.1	0.1
5.1KΩ Resistor	5.1KΩ SMD Resistor	4	0.1	0.4
10KΩ Resistor	10KΩ SMD Resistor	6	0.1	0.6
1MΩ Resistor	1MΩ SMD Resistor	3	0.1	0.3
2.2KΩ Resistor	2.2KΩ SMD Resistor	2	0.1	0.2
1KΩ Resistor	1KΩ SMD Resistor	18	0.1	1.8
33Ω Resistor	33Ω SMD Resistor	4	0.1	0.4
RCLAMP0502B	ESD Protection Diodes	9	1.25	11.25
02x10 IDC Header	02x10 Headers for Electrodes	1	1.5	1.5
ADS1298	Analog Front End	1	45.86	45.86
01x02 JST Header	01x02 Header for Battery	2	0.1	0.2
AP2112K	LDO For Digital Power Rail	2	0.22	0.44
Ferrite Bead	Ferrite Bead for Analog Power Rail	1	0.1	0.1
USB C Receptacle	USB C Port for Charging	2	1.19	2.38
SMF5V0A	ESD Protection Diode	2	0.19	0.38
01x03 JST Header	01x03 Header for UART Between boards	2	1.91	3.82
MCP73831	Charging Regulator	2	0.76	1.52
TPS7A2033	Low Noise LDO for Analog Power Rail	1	0.32	0.32
SP0502	ESD Protection Diode	2	0.62	1.24

LED	Charging Indicator LED	2	0.24	0.48
Fuse	Polyfuse for current protection	2	0.55	1.1
STM32H743ZI Tx	MCU for Forearm Band	1	16.37	16.37
02x05 IDC Header	02x05 Header to program MCU	1	1.5	1.5
850 mAH Battery	850 mAH LiPo Pouch Battery	2	9	18
ESP32	ESP32-WROOM-32D MCU for Wrist PCB	1	3.8	3.8
01x04 Header	ESP32 Programming Header	1	0.13	0.13
01x06 Headers	Headers for the IMU	2	0.14	0.28
IMU	Adafruit BN0085 IMU	1	24.95	24.95
Total				148.55

3.c Schedule

Week	**Goals**	**Task Owners**
Oct 13 - 19	Finalize architecture + design schematic/PCB layout + Place PCB order + Figure out where to buy parts	Vishal (work forearm layout) Vansh (Work on wrist layout) Arrhan (Verify, help and buy required parts)
Oct 20 - 26	Collecting parts and soldering on PCB	Vansh, Vishal and Arrhan all work together on this
Oct 27 - Nov 2	Start experimenting and working with MCUs, exploring bluetooth connection and reading IMU data	Arrhan (IMU data + bluetooth) Vishal (EMG data and categorization of signals) Vansh (UART for sending data between 2 MCUs)
Nov 3 - 9	Collecting EMG data and training ML model using breadboard setup	Vansh, Vishal and Arrhan all work together on this
Nov 10 - 16	Finalize workflow and code for EMG data collection, processing and sending to wrist MCU; figure out translation of IMU data to mouse movements and coordinates	Vishal (EMG data collection and processing) Vansh (sending EMG data to secondary MCU via UART) Arrhan (IMU data processing)

Nov 17 - 23	Finalize transmission of EMG output and IMU output to device via BLE, work on finalizing any other parts that still need work + Do mock demo	Arrhan (EMG output and IMU output to device via BLE) Vansh and Vishal verify and make changes to any other remaining parts
Nov 24 - 30 (Thanksgiving)	Test system + make sure gestures such as click, scroll and right-click work correctly	Vansh, Vishal and Arrhan all work together on this
Dec 1 - 7	Prepare for final demo and presentation	Vansh, Vishal and Arrhan all work together on this

Safety And Ethical Consideration

We ground our work in the IEEE and ACM Codes of Ethics: putting user safety and the public interest first; being truthful and realistic about capabilities; respecting privacy and autonomy; and fixing mistakes quickly when they arise. In practice, we will present the wrist/forearm bands strictly as a human–computer interface—not a medical or diagnostic product—communicate limitations and risks in clear language, and make only those claims we can back with measured data (e.g., latency, accuracy, battery life).

Because the device sits directly on skin, user wellbeing is a primary design constraint. All electronics are powered by low-voltage 3.7 V Li-Po cells with integrated protection and regulated to 3.3 V. All exposed conductive parts will be insulated except the EMG electrodes themselves, which are intended for surface bio-potential sensing. To reduce battery-related risks, each pack is paired with a charger and BMS.

We also treat motion and EMG signals as sensitive data. We do not store any raw data, feature extraction and inference occur entirely on edge. For model training, we will collect motion/EMG data only with informed consent that clearly states the purpose, scope, and duration.

By keeping these ethical commitments and safety practices in mind and by making user safety and privacy explicit requirements we aim to comply with the IEEE and ACM codes for safety.

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