ECE 445

Senior Design Laboratory

Carpal Tunnel Wrist Glove Final Report

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1. Introduction:

1.1 Problem

Digital artists often experience fatigue and discomfort in the wrist, knuckles, and fingers after prolonged drawing sessions. This strain typically goes unnoticed until pain develops. Continued stress on the hand muscles can lead to more serious conditions, such as carpal tunnel syndrome (CTS), which can cause hand/wrist pain, burning/numbness in fingers, and overall weakness in the wrist and hand [1]. The repetitive motions of digital art that come with brush strokes, sketching, and rendering, can cause significant swelling around the tendons in the carpal tunnel, resulting in pressure on the median nerve [1].

Although there are existing compression gloves used to alleviate symptoms related to carpal tunnel syndrome, they primarily function by providing mild pressure to reduce swelling and improve circulation. However, they do not necessarily do much to address poor wrist and hand habits that contribute to repetitive strain injuries (RSIs). Many digital artists and professionals unknowingly adopt prolonged repetitive motions without incorporating sufficient rest periods; taking short, frequent breaks to gently stretch and bend hands and wrists can make a difference in preventing pressure and preventing RSIs [2].

1.2 Solution

While compression gloves can be a supportive tool, they should be complemented with ergonomic practices and habitual breaks to ensure long-term hand and wrist health [2]. To address this gap, the propose solution would use strain gauge sensors and inertial measurement units (IMUs) to monitor the user's grip and joints/muscles that undergo prolonged repetitive motion. These sensors will collect real-time biomechanical data, allowing a software/communication component to analyze patterns of repetitive strain and movement. The communication component aims to provide notifications, reminding users to take breaks at optimal intervals. Based on target muscles identified by strain gauges, it would suggest targeted stretches and exercises tailored to specific regions experiencing strain. By combining real-time monitoring and proactive intervention, this solution can not only help prevent RSIs, but also encourage long-term behavioral changes.

1.3 High-level requirements/functionalities

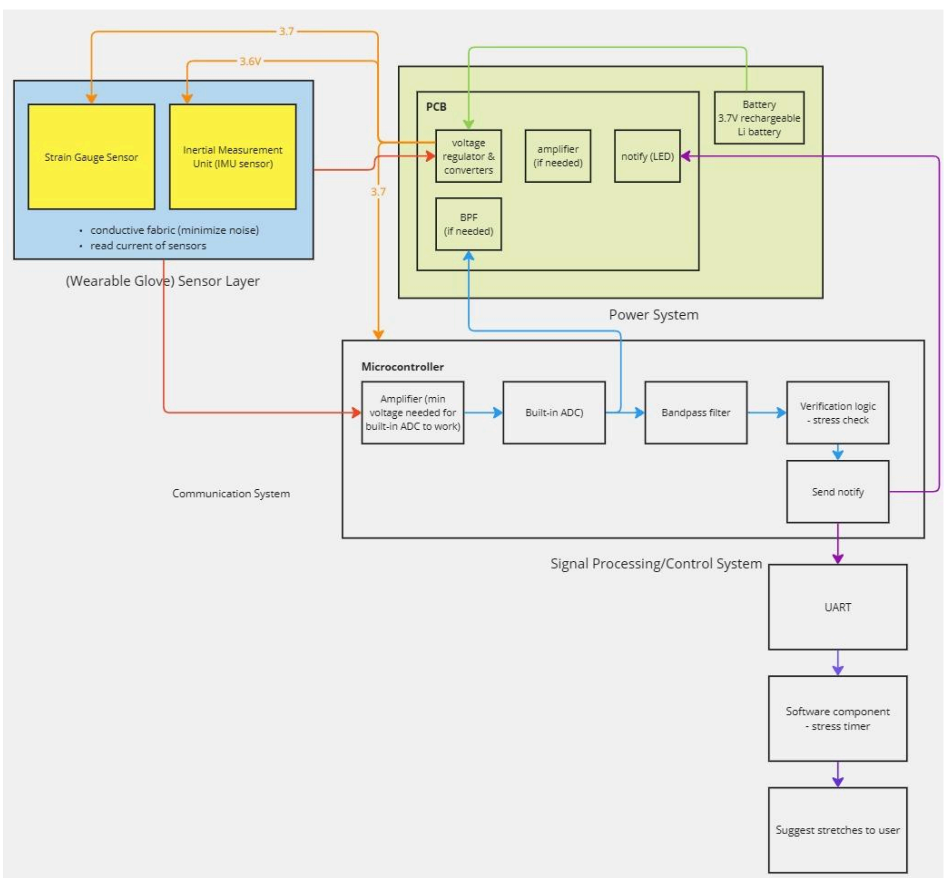
The following is a list of 3 quantitative characteristics this project should exhibit to solve the problem.

Accuracy: The device must accurately measure repetitive motion, location of motion, and angle of wrist flexion and extension – then use live data filtered through scientific metrics to notify the user of prolonged muscle strain compared to threshold value with 80% accuracy. To determine this, the application will show 100% of the filtered and compared data, and user testing of the LED functionality should send a notice of unsafe muscle grip patterns at least 80% of the time it was identified on the application.

Unique User Compatibility: Since the hand/wrist anatomy of the user is unique, the system must be able to detect signals from both strain gauges and inertial measurement units and send notifications to user & data updates to application for 2 different individuals with different grips and patterns of hand/wrist motion to ensure adjustment to unique users.

Output to user: To notify user of prolonged muscle strain and repetitive motion, an LED light is used to notify the user to take a break. A wireless connected application additionally will propose hand stretches that target the specific muscles under the most stress based on medically proven techniques. Suggested stretches engage and relieve target specific muscle identified from signals from the strain gauges.

Figure 1: Block diagram



1.4 Subsystem Overview

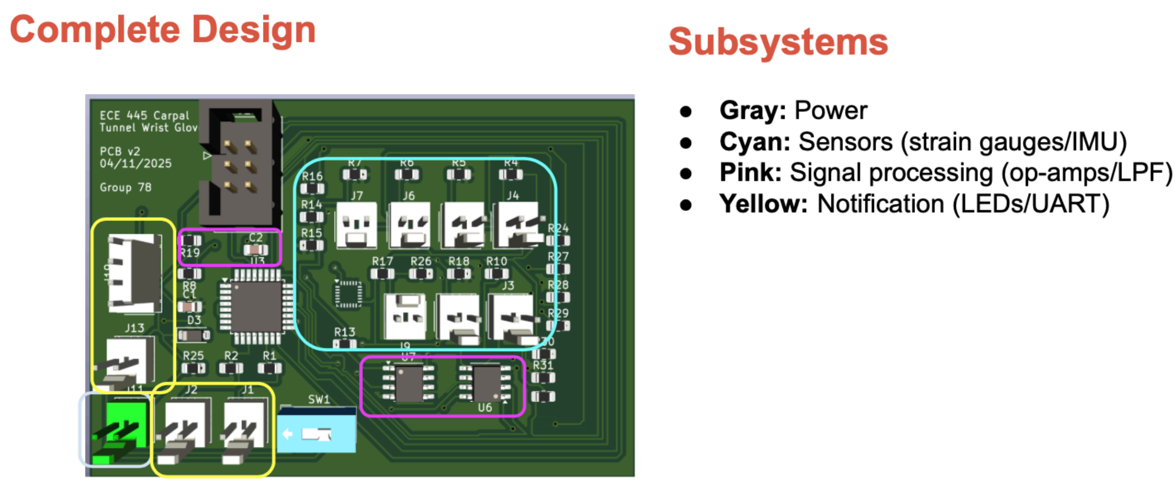


Figure 2: PCB Schematic

1.4.1 Power Subsystem

As shown in the block diagram, the main power systems are transferring the required amount of voltage from the PCB to the battery, communication module, and MCU. The biggest component to discuss is the rechargeable battery which will connect to the glove. We will most likely use a lithium ion battery.

The PCB will be designed on KiCad and will be the 'brain' of the system. The design will route the microcontroller signals to the notification system, ensuring that power will be supplied to both portions of the design (live input & user-facing). Both subsystems will likely have varying current limits and required voltage inputs, which will be taken care of on the PCB using voltage regulation and power conversion techniques - possibly a buck converter or linear regulator.

1.4.2 Sensor Layer Subsystem

The sensor layer subsystem is powered by the power subsystem and outputs data signals to be processed by the signal processing subsystem (2.2.3). The sensor layer comprises 2 different sensors: strain gauges and inertial measurement units (IMUs).

Strain Gauges

Strain gauges can measure deformation or mechanical strain within a material by changing its electrical resistance when stretched or compressed, which works well for applications related to structural load analysis. Strain gauges used in tandem with IMUs allow for a fuller picture of mechanical movement within the hand, i.e. wrist angle and flexion detection (which correlates to potential nerve compression risks). A strain gauge rosette can measure wrist angles and analyze strains that occur during wrist flexion/extension/radial and ulnar deviation, and will be placed near key ligaments such as the wrist, digital branches of the median nerve, and thenar muscle. This approach adds a biomechanical analysis layer to the glove, which may detect harmful wrist postures even when muscles are not active.

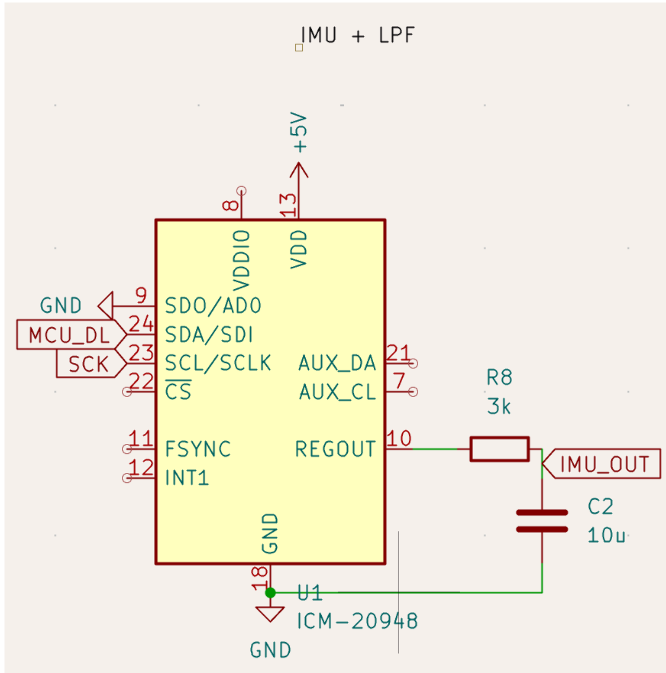


Figure 4: PCB Schematic of IMU

Inertial Measurement Unit (IMU)

IMUs can track repetitive motion by measuring linear acceleration and angular velocity, which makes them useful to detect wrist and hand movements associated with repetitive strain which can then contribute to nerve compression. An option for an IMU would be a ICM-20948, which is a low-power sensor making it suitable for wearable applications such as our glove. These IMUs would be placed in specific positions of the wrist (such as the dorsal side to capture radial/ulnar deviation), just above the wrist to track forearm rotation, and the back of the hand (near the metacarpals) to monitor fine motor motion such as finger extension/flexion dynamics.

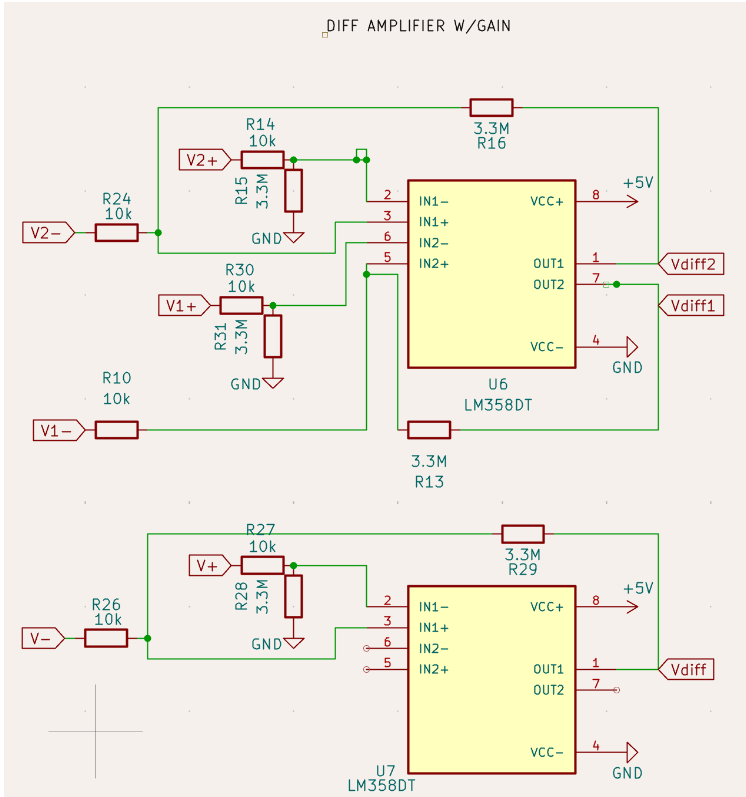


Figure 4: PCB Schematic of Signal Processing Subsystem

1.4.3 Signal Processing Subsystem

The signal processing subsystem takes signals from the sensor layer subsystem (2.2.2) as input, processes the signals with necessary amplification/filtering, and outputs the processed signals to some verification logic to decide whether to notify the user to take a break and, if so, to an additional software component that displays the user which muscle to stretch and suggests a specific stretch for that target muscle.

Strain Gauge Signal Processing

Strain gauges measure strain by changing its electrical resistance; to convert these tiny resistance changes into measurable voltages, a Wheatstone bridge is used to amplify changes in resistance caused by strain (we aim to use a full-bridge with four gauges to maximize sensitivity and thermal stability). The output of resistance changes into voltage is usually too small; the signal will first be amplified and filtered (will likely use low-pass filtering to remove high-frequency noise since strain gauge signals are typically maximum 5 Hz for human motion [3]) prior to analog-to-digital conversion. Then, the microcontroller will calculate wrist angle and stress based on the digital signal and trigger any feedback (i.e. user notification or display system).

Inertial Measurement Unit Signal Processing

The raw data from the IMUs will likely involve filtering to remove noise unrelated to actual motion. Useful data related to motion frequency, range of motion, and angular velocity can be derived with

FFT for orientation tracking (the IMU collects time-series data and would include periodic signals if repetitive tasks are being performed). Processed IMU data can then be correlated with strain gauge outputs to identify patterns of repetitive motion and grip.

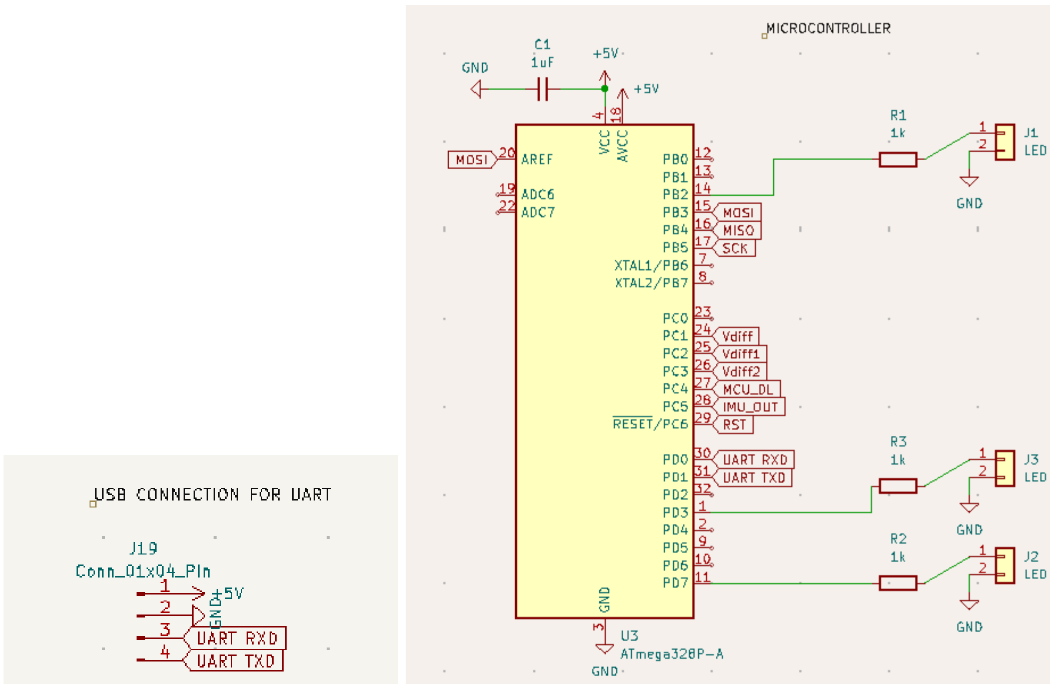


Figure 5: PCB Schematic of Communication Protocol Subsystem

1.4.4 Communication Protocol/Display Subsystem

This subsystem will receive signals from 2.2.3 and compare them with threshold values we set to assess whether the user is applying prolonged stress that may lead to harmful muscle activity. The output voltage readings (Vout) across the strain gauge is proportional to the change in electrical resistance. We can calculate the strain by dividing the ratio of vout/vin by the gauge factor (the ratio of the relative change in electrical resistance and relative change in length). Force is then calculated by multiplying the strain, young's modulus of the material, and the cross-sectional area of the stressed material. We can then use this force value for our Maximum Voluntary Contraction (MVC) comparison with a threshold value of 20%. The stress readings from the strain gauge, along with their duration, will be compared to the 4% threshold. The wrist flexion/extension will be compared to the value 30º and radial deviation will be compared to the value of 15°.

We will have an application that communicates the result of this comparison. If any of the readings exceed the threshold, the system will suggest the user take breaks every 30 minutes [4] (through an LED light on the glove). Additionally, strain gauge readings will provide insights into which joints undergo repetitive motion and, subsequently, relevant muscles. The external app will also display various stretches to help reduce stress and tension in those muscles and joints. We will explore the possibility of exporting real-time signal data from the MCU to a PC via UART through implementing a very simple program that interprets the data and intelligently suggests a stretch out of a database.

2. Design

Component	Operating voltage	Current Limit
MCU (ATmega328P)	1.8V - 5.5V	40 mA
Op-amp (LM358)	3V - 32V	30 mA
UART cable	3.3V - 5V	*N/A*
IMU (ICM-20948)	1.71V - 3.6V	3.11 mA

Figure 6: Voltage limit and current limit for chip resources

2.1 Power Subsystem Design Description & Justification

Figure 6 is a table of the required turn-on voltages obtained from the datasheet of each component on the PCB. Based on these values, we decided on a 3.7 Li-Po battery to power the board. This board was attached to a power switch and voltage regulator, which generated the 3.4V turn-on voltage for the IMU, seeing as that was the only component with a lower requirement. The relevant schematics for these designs are shown below:

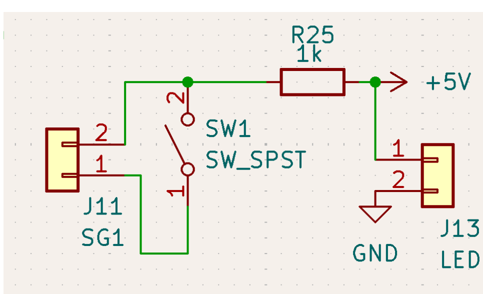


Figure 7: Original power switch design

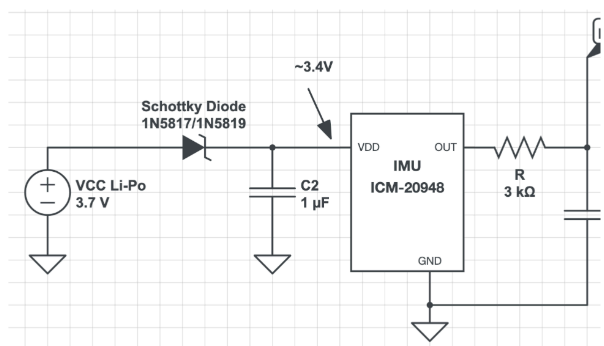


Figure 8: Voltage regulator for IMU

2.1.1 Power Subsystem Design Alternatives

The biggest issues with the power subsystem were the following:

1. In the initial design, the ≤3.6V turn-on voltage for the IMU was not considered, so the voltage regulator was a last minute design addition. Figure 8 shows illustrates the design of a Schottky Diode to clamp voltages due to its voltage drop at forward biases in the range of 0.15V-0.46V [5].

2. The initial iteration of the power switch was incorrect, as the closing of SW1 prompted a short circuit of the positive terminal and ground - since it creates a closed loop with no resistance. The second iteration of the switch design had been modified to the following - this creates a series connection rather than a parallel closed loop.

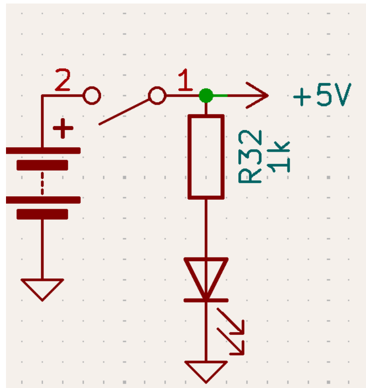


Figure 9: Refined power switch design

2.2 Sensor Layer Subsystem Design Description & Justification

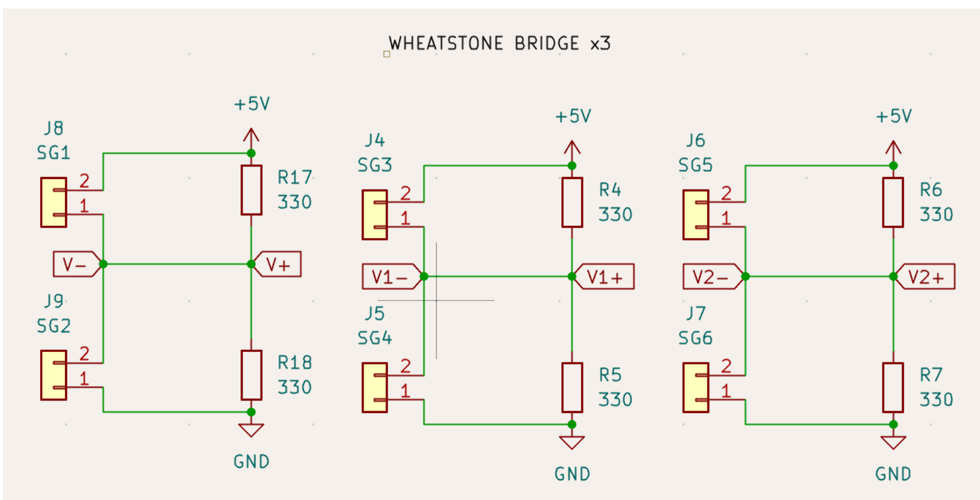


Figure 10: Wheatstone bridge schematic

2.2.1 Strain Gauges

The strain gauge portion of the subsystem was the bulk of the design, as the sensor sublayer system was the "connection" between the physical system and the technological addition to the glove.

The purpose of the strain gauges is to detect and measure strain at key areas of flexion/extension in the wrist and hand at key points on the glove. Strain gauges measure strain by changing their electrical resistance in response to change of length of the gauge itself. The gauge factor (GF) determines change through magnitude of resistance change. Our strain gauge had specs of GF = 2 and nominal resistance = 350 Ω. Based on the following relationship - $\frac{\Delta R}{R} = GF \bullet \epsilon$ [6], we expected to see a change in electrical resistance of $2(500 \cdot 10^{-6})$= 0.1% of 350 Ω = 35 Ω.This resistance change is then used as an input to the strain gauge component of the signal processing subsystem. The figures below show a visual representation of how physical movements correlate to electrical changes.

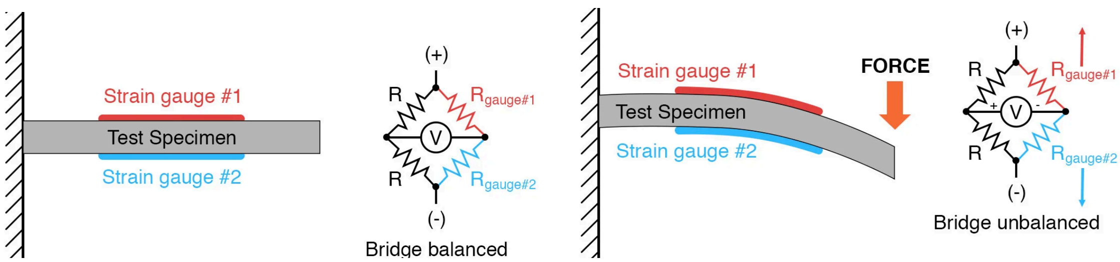


Figure 11: Example of pair strain gauges bonded to test specimen [6]

After experimenting with the wheatstone bridge configuration Figure 11 below illustrates the placements we decided on for the gloves.

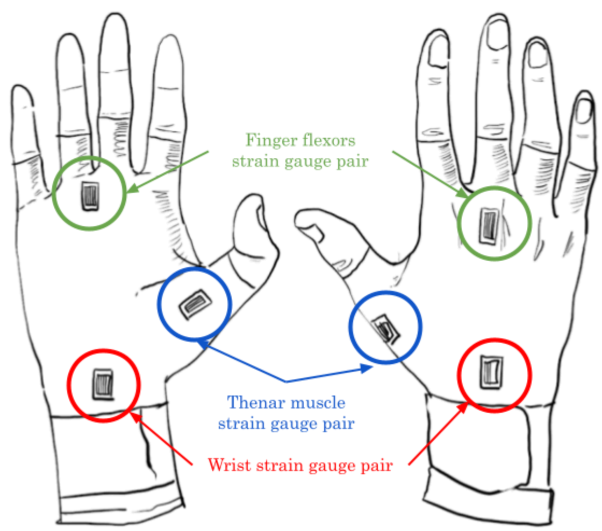


Figure 12: Example of pair strain gauges bonded to test specimen

Once the change in resistance has been gathered, the values are then routed into a Wheatstone Bridge, converting ΔR into ΔV. ΔV is then transmitted to the signal processing layer for amplification. The Wheatsone bridge schematic is as shown in Figure 12 below.

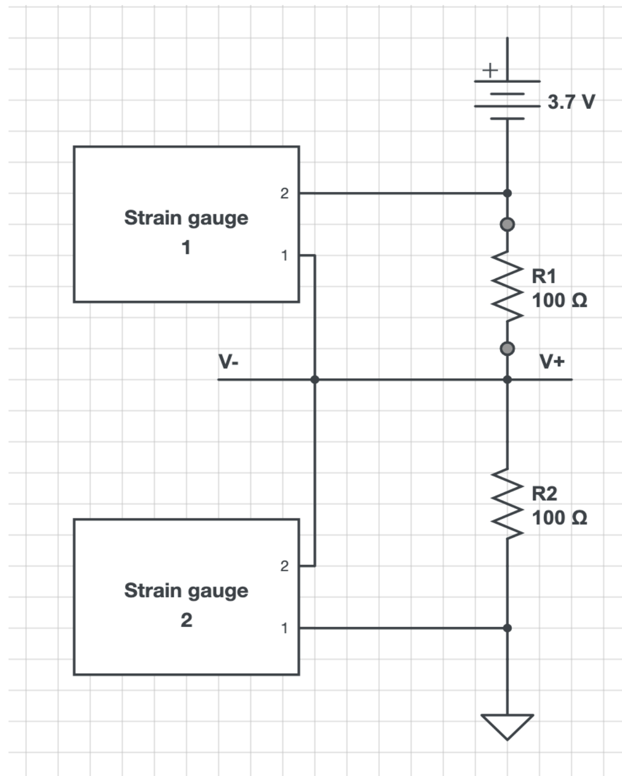


Figure 13: Example wheatstone bridge configuration

2.2.2 Sensor Layer Design Alternatives – Strain Gauges

Design alternatives for the Strain Gauges revolved around 2 main factors:

1. Selecting a strain gauge with a spec of higher nominal resistance would make the change in electrical resistance much higher - currently it was only 35 Ω. This would have made the amplification of the voltage signal much higher (currently between 3-5mV), which would have permitted less noisy amplification, making movement patterns much more intuitive to detect.

2. Strain gauges are traditionally used on hard materials, such as steels and other metals. More extensive testing on various materials (plastic, cardboard, etc.) would have given us more realistic readings rather than having such a large gap between experimental readings and real-time glove readings. Experimental readings were conducted on cardboard, which had much clearer voltage changes than when the strain gauges were mounted directly to the glove fabric. This can seemingly be attributed to the flexibility of the glove fabric stretching to account for the change in length upon hand movements, which made **ΔL** too negligible for the strain gauges to make meaningful readings of post-mounting.

2.2.3 Inertial Measurement Unit (IMU)

The purpose of the IMU sensor in our subsystem is to detect and measure *repetitive* human motion. We discovered that 5 Hz is a suitable maximum for human motion [3], therefore we designed a low-pass filter connected to the IMU to remove high-frequency noise and signify relevant movement.

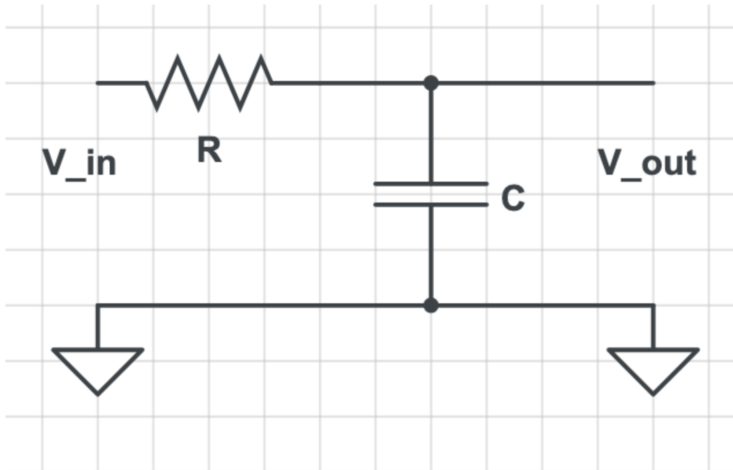


Figure 14: Low-pass filter circuit

Recall the equation for the cutoff frequency of an RC circuit is: $f = \frac{1}{2\pi RC}$. We must solve for the values of resistance and capacitance to get the outcome cutoff frequency $f = 5\ Hz$.

$$5 = \frac{1}{2\pi RC} \quad (1.1)$$
$$R = 3\ k\Omega \quad (1.2)$$
$$C = 10\ \mu F \quad (1.3)$$

Since we cannot exactly get 5 Hz because we are limited by the resistances and capacitances available to us, we landed on the resistance and capacitance values as outlined in equations 1.2 and 1.3. Therefore, our cutoff frequency is: $f_{actual} = \frac{1}{2\pi(3k)(10\mu)} = 5.3\ Hz$.

2.2.3 Sensor Layer Design Alternatives – IMU

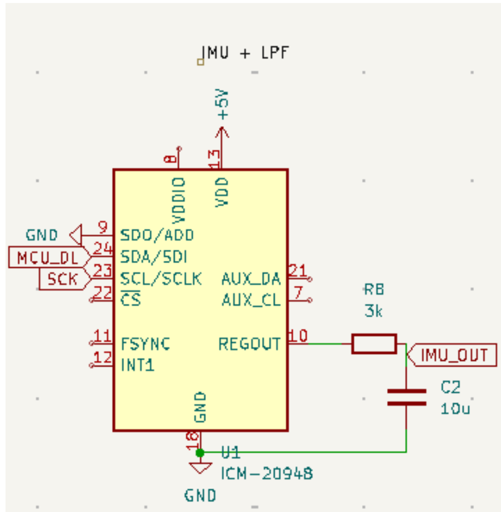


Figure 15: Current pin-out of the ICM-20948 IMU

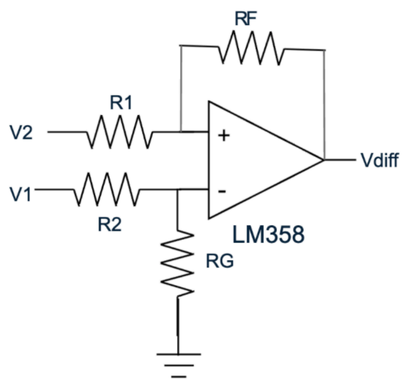
Our pinout design of the IMU on our last iteration of the PCB was unfortunately incorrect due to our misunderstanding of the data output protocols for the IMU. We initially wanted to use I2C protocol to transmit data from the IMU into the pin of our microcontroller. In order to read from ICM-20948 via I2C, then we have to link the IMU's SDA pin to the MCU's PC4 pin and the IMU's SCL pin to the MCU's PC5. We connected SDA to PC4 correctly, but incorrectly wired SCL to to the MCU's SCK. It is crucial the the IMU's SCL pin is connected to PC5, as PC4 and PC5 are both hardwired to the MCU's dedicated I2C peripheral, and are the only pins that are capable of I2C communication [7].

Additionally, I2C protocol depends on open-drain points, which means that the ATmega328P has to return lines to a high (3.3V), and must therefore use pull-up resistors. We can use 4.7kΩ resistors to passively pull SDAC/SCL to VCC.

2.3 Signal Processing Subsystem Design Description & Justification

2.3.1 Strain Gauge Signal Processing

The first step of the Signal Processing Layer is the amplification of the **Δ**V from the output of the Wheatstone bridge. Using a basic operational amplifier with gain, the following setup was built:



$$V_{diff} = \frac{(R_F+R_1)}{(R_g+R_2)}V_2 - \frac{R_F}{R_1}V_1$$

$$V_{diff} = \frac{R_F}{R_1}(V_2 - V_1) \quad if \quad R_F = R_G \; and \; R_1 = R_2$$

Figure 16: Schematic of the operational amplifier

Using values of $R_F = R_G = 100k\Omega$ and $R_1 = R_2 = 2.2kk\Omega$, we achieved a calculated & measured gain of 45.45. This safely magnified a 5-7mV reading into a 0.4-0.6V signal. This signal was then read into the ADC port of the microcontroller.

ADC:
This 0.4-0.6V signal was then magnified into 2.4V with further amplification, then put through the ADC which had a minimum turn on voltage of 1.1V. The ADC converted AnalogRead values from the microcontroller into digital values that could be read by serial.print() to be printed on the user's monitor via UART.

2.3.1 Strain Gauge Signal Processing Design Alternatives

The required voltage for clean ADC readings with minimal noise was 1.1V. Due to the bias currents and offset voltages of the LM358, this voltage had been achieved through a bit of tweaking, however since the bias currents could not be mathematically accounted for, the final readings of V_{diff} were extremely noisy. This may have been due to several reasons:

- ➔ The terminal wires connecting the strain gauge terminals on the glove to the PCB were significantly long, to prioritize user comfort. However, this added too much nominal resistance, considering that the system alone only generated a ~35Ω change.
- ➔ A cascaded op-amp configuration could have been attempted to achieve a higher gain with less noise.
- ➔ Increasing the voltage difference from across the Wheatstone bridge (the op-amp input) would have significantly improved results, since a 5-7mV V_{in} is extremely difficult for any op-amp to magnify. The best option would have been a precision op-amp to handle such low input values, but the precision op-amps had a turn on voltage much higher than 3.7-5V, which didn't align very well with a primarily low voltage and current system. This could have been achieved by purchasing strain-gauges with a higher nominal resistance.

2.3.1 IMU Signal Processing

We aimed to sample the IMU at 100 Hz (collect data every 10ms). We chose N=128 samples as our FFT size, which yields a frequency resolution of $\Delta f = \frac{100Hz}{128} \approx 0.78\,Hz$. Thus, the FFT can detect frequencies in steps of 0.78Hz, which is feasible to detect frequencies up to 5 Hz, as this resolution may reliably detect motion frequencies between 1-5Hz which is typical for human wrist/hand motion [8]. The frequency bins correspond to 0 Hz, 0.78 Hz, 2.34 Hz, 3.12 Hz, 3.90 Hz, 4.68 Hz, and 5.46 Hz.

2.3.2 IMU Signal Processing Design Alternatives

Unfortunately, we were not able to test the success of the low-pass filter in a real-world setting, despite confirming the cutoff frequency of the RC circuit through simulation. However, considering that the application of the LPF was relatively straightforward (< 5Hz to signify relevant human action), this portion of the design was relatively straightforward.

2.4 Communication Subsystem Design

2.4.1 Communication Subsystem

The communication subsystem incorporates the microcontroller and the notification system, which includes LEDs on the PCB and a software component—both of which provide feedback to the user. The microcontroller is programmed using the USBasp cable to sample and perform verification checks by using live user readings and comparing them to predetermined threshold values. If any of the live readings exceed these values, the LED on the PCB is turned on.

A wired communication protocol is also established using USB for UART communication. In this setup, the microcontroller's TX and RX pins are connected to the RX and TX pins of the USB-to-UART cable, respectively, with the cable grounded to enable data transmission and reception via the COM2 serial port on the PC. A Python script continuously reads live user data from the serial port and performs analyses. A pop-up notification is prompted to the user in two scenarios:

1. To take a break if repetitive motion persists for more than 30 minutes.
2. If the strain gauge sensor readings exceed the predetermined threshold values. In this case, the notification includes an image of a recommended stretch, based on which strain gauges are detecting high levels of strain.

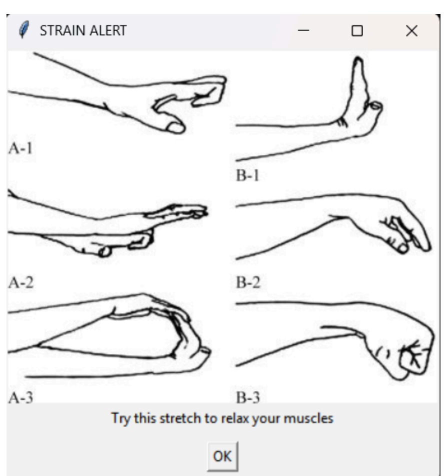


Figure 17: Software popup when voltage threshold is exceeded

2.4.2 Communication Subsystem Design Alternatives

During the initial stages of the project, the TI-MSP430FR5994 microcontroller was considered due to its low power consumption, high-resolution conversions, and noise filtering capabilities. However, after evaluating our options, we opted to use the ATMega328p microcontroller due to it being more accessible as it was available in the eshop and it could be programmed using the USBasp cable used in prior coursework. Additionally, it offers a greater number of I/O pins, which support the output requirements of our sensor sublayer.

We also considered two different communication protocols for interfacing with the PC: wired and wireless. Initially, we explored a wireless setup where the microcontroller would be used in conjunction with a Bluetooth module to receive and transmit data. This approach enhanced the portability of the project and allowed the user to move their hand more freely while wearing the glove. However, due to time constraints and the added complexity of establishing a reliable wireless link, we chose a wired USB connection using UART. This provided a faster and more stable data transfer and simplified debugging during the development and testing phase.

3. Requirements & Verification

For the following design verifications, please refer to Appendix A for our full Requirements & Verification tables for each of our subsystems.

3.1 Power Subsystem Verification

Note that we have made a few modifications to the power subsystem are as follows (and, as such, the requirements have slightly changed):

- ➔ Strain Gauges: Used BF350-3AA rather than Vishay CEA-06-062UR-350
    - ◆ Strain Gauges didn't necessarily have a turn-on voltage, but we tested various voltage inputs to increase the differential output over the wheatstone bridge.
- ➔ Microcontroller: Used ATMega328P rather than TI-MSP430FR5994
    - ◆ The ATMega328P has a turn on voltage of 1.8-5.5V for 0-4 MHz (0-10 MHz → 2.7-5.5V)

The PCB's power ended up being a 3.7V Li-Po battery which satisfied all of these requirements. Our power subsystem works correctly with the components mounted on the board, and Figure 17 shows our quantitative measurements.

Component	Operating voltage	Current Limit	Actual V	Actual input current
MCU (ATmega328P)	1.8V - 5.5V	40 mA	3.687 V	32 mA
Op-amp (LM358)	3V - 32V	30 mA	3.687 V	11mA (static res.) 16 uA (strain gauge)
UART cable	3.3V - 5V	*N/A*	3.687 V	34 mA
IMU (ICM-20948)	1.71V - 3.6V	3.11 mA	*N/A*	*N/A*

Figure 18: Full table of voltmeter and ammeter measurements

3.2 Sensor Layer Subsystem Verification

During the initial testing phase, the strain gauges were mounted on a paper card, which was then secured to a flat surface using adhesive tape. This setup allowed controlled bending of the gauges to specific angles, which were verified using a protractor. A set of readings obtained through this method is presented below.

- **Requirement:** Strain gauges must detect wrist flexion and extension angles within ±5° of actual movement.
  - **Verification:** The angles were measured using a protractor and are likely to be observed within ±2° accounting for human error.
  - **Quantitative Results:** Measurements were first taken with the card lying flat with no strain applied. Subsequently, the card was bent to +30°, and readings were recorded, followed by measurements taken at -30° to examine the effect of strain applied in the opposite direction.

Angle [°]	**Voltage Difference Across Bridge at rest (0°) [mV]**	**Change [mV]**
0	3.100	0.000
-30	2.947	-0.060
+30	3.010	+0.030

- **Requirement:** IMU must sample motion data at a frequency of ≥ 100Hz to capture fine motor motion and repetitive movements
  - **Verification:** Because our final PCB did not correctly implement the I2C protocol for the IMU, we were not able to get accurate values for the accelerometer, but we were still able to test polling the IMU at 100Hz with the following procedure:
    - Program MCU to poll REGOUT of the ICM-20948 every 10 ms

        - Output REGOUT value to MCU's TX pin/input to UART RX pin
        - Test how many messages have been received by the serial monitor in 5 seconds & calculate the average polls sent by the MCU

    We repeated this test numerous times, and the software correctly received data at a frequency of 100 Hz (or 100 messages per second).

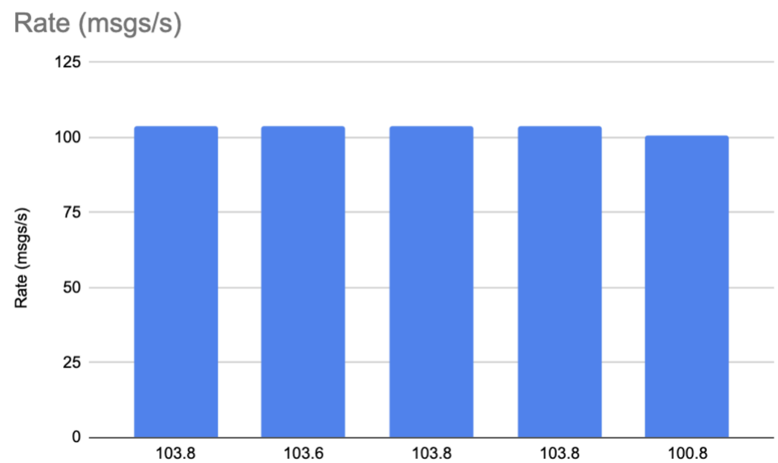


Figure 19: Bar graph of IMU poll rate trials

- **Requirement:** Sensors must have a combined response time of ≤ 50ms for real-time motion tracking & strain/motion analysis (not verified)
    - **Outcome:** Changes in strain gauge readings were visible to the serial monitor (output signal), but were not consistent

3.3 Signal Processing Subsystem Verification

- **Requirement:** Utilize wheatstone bridge to bring resistance changes of strain gauges to at least a 1 V signal
    - **Verification:** The output of the differential op-amp with gain was measured using a voltmeter to ensure it was greater than 1V as required by the microcontroller.
    - **Quantitative Results:** The measured voltage difference of the wheatstone bridge configuration was around 4-7mV. This was amplified to 0.4-0.6V and further amplified to 2.4V.

- **Requirement:** Use MCU to filter human motion from noise & determine notification status (not verified)
    - **Outcome:** This requirement could not be met in practice due to our PCB implementation failing to connect the I2C pins correctly (as detailed in 2.2.3)
- **Requirement:** Process IMU data to identify patterns of repetitive motion and grip (not verified)
    - **Outcome:** Due to time constraints and IMU PCB wiring, we were not able to meet this requirement

3.4 Communication Protocol Subsystem Verification

- **Requirement:** Communicate readings with user through application and LEDs on PCB.
    - **Verification:**
        - Established connection with PC using USB cable for UART communication was verified using device manager on PC.
        - LED was turned on when strain gauge sensor readings exceeded a hard-coded threshold value. The microcontroller was programmed to conduct the verification checks.
        - A pop-up notification is displayed on the PC when strain gauge sensor readings exceed a hard-coded threshold value.
        - The pop-up notification contains an image of a recommended stretch based on which strain gauge sensor readings were experiencing high levels of strain.

- **Requirement:** Compare stress level with medically approved threshold values to assess user patterns that may lead to harmful muscle activity
    - **Verification:** This requirement was not met as the output of our amplified strain gauge sensor output was not working as expected (section 2.3.1 details design issues that may potentially address and/or cause this issue)
- **Requirement:** The subsystem must calculate force on user's grip
    - **Verification:** This requirement was not met as the output of our amplified strain gauge sensor output was not working as expected (section 2.3.1 details design issues that may potentially address and/or cause this issue)

4. Cost & Schedule

4.1 Cost

Part	Cost Per ($)	# Ordered	Total Cost ($)
ICM-20948 IMU	$7.11	2	$14.22
BF350-3AA Strain Gauges	$0.86	20	$17.2
ATMega328P MCU	$2.80	9	$25.2
3.7V Li-po battery	$7.99	1	$7.99
Superglue (12pk)	$5.03	1	$5.03
LED (Red, 1.95V)	$0.32	3	$0.96
Switches (4V, 300mA, SPDT, slide switch)	$0.42	5	$2.10

LM358DFN Op-Amp	$0.24700	20	$4.94
3 MΩ Resistor 0805	$0.04200	20	$0.84
10 kΩ Resistor 0805	$0.01600	20	$0.32
3 kΩ Resistor 0805	$0.03500	20	$0.70
1 kΩ Resistor 0805	$0.01800	20	$0.36
330 Ω Resistor 0805	$0.01800	20	$0.36
1 μF Capacitor 0805	$0.08300	20	$1.66
10 μF Capacitor 0805	$0.08100	20	$1.62
Walgreens Hand Support Glove	$13.99	1	$13.99
		Total Cost of Parts	$97.49

Labor cost: $25/hr * 2.5 * (~180) hrs = $11,250
Sum of Costs = ~$11,347.49

4.2 Schedule

	Team Goals	Deadline
Week of 3/3	➔ Complete Design Document (everyone) ➔ Test strain gauges mounted on cardboard to determine expected voltage signal (Deepika/Rawnie) ➔ Use actual readings to finalize mathematical design of amplifier (Rawnie)	Thursday 3/6: Design Document Due
Week of 3/10	➔ Breadboard Demo Milestone: read signal from strain gauge & signify physical meaning (everyone) ➔ Begin notification system programming (Li) ➔ Begin building IMU lowpass filter (Deepika) ➔ Experiment with board to ensure current limits are satisfied (Rawnie)	Monday 3/10: Breadboard Demo Thursday 3/14: Second Round PCB Order
Week of 3/24	➔ Continue experimental analysis and modify design (everyone)	

Week of 3/31	➔ Complete functional prototype with breadboard (everyone) ➔ Test various use cases and document results (Li)	Monday 3/31: Third Round PCB Order Wednesday 4/2: Individual Progress Report
Week of 4/7	➔ Test signal processing subsystem requirements (Li) ➔ Test communication protocol (Deepika) ➔ Complete PCB Design (Rawnie)	Monday 4/7: Fourth Round PCB Order
Week of 4/14	➔ Modify design to ensure power subsystem requirements (Rawnie, Deepika) ➔ Solder all components onto board (everyone)	Friday 4/18: Team Contract Assessment
Week of 4/21	➔ Program microcontroller (everyone) ➔ Test sensor sublayer system compatibility with microcontroller (everyone) ➔ Modify and order PCB, solder once arrived (Rawnie)	Tuesday 4/22: Mock Demo
Week of 4/28	➔ Finalize communication and notification subsystem programs (Li) ➔ Mount strain gauges to fabric for prototype glove (Li, Deepika) ➔ Attempt to debug amplification issues in strain gauge readings (Rawnie) ➔ Prepare for final presentation (everyone) ➔ Record video (everyone)	Tuesday 4/29: Final Demo Friday 5/2: Extra Credit Video
Week of 5/5	➔ Complete final paper (everyone) ➔ Submit lab notebook (everyone)	Tuesday 5/6: Final Presentation Wednesday 5/7: Final Paper Thursday 5/8: Lab Notebook

5. Conclusion

5.1 Accomplishments

Our final project design resulted in a fully functional, self-powered PCB that eliminated the need for external modules. Through extensive experimentation, adjustments were made to the initial circuit designs to accommodate current limitations while maintaining performance. Despite some design constraints, workarounds were implemented to ensure all critical high-level requirements were successfully met, demonstrating the project's adaptability and problem-solving approach.

Although we struggled with the readings from our sensor layer, we were ultimately able to implement the operational amplifier with gain and the Fast-Fourier Transform program. Additionally, we were able to fully implement the communication between the microcontroller on the PCB and the user-side software program to actually show a warning when the signals exceed a certain threshold and, based on what specific pair of gauges on the glove exceed the voltage threshold, the user was suggested stretches that target that area on the hand or wrist.

5.2 Uncertainties

The most significant uncertainties occurred in the sensor subsystem layer. As explained in section 2.3.1, the inability to read clear signals of a changing voltage from the strain gauge outputs made it difficult to prove functionality of the signal processing & notification subsystems, although they had been completed and accurate.

Additionally, if the PCB had been designed & thought out earlier in the schedule as expected, we may have been able to avoid errors such as the lack of voltage regulator to supply 3.4V to the IMU. Along with that, of course, would have come the possibility of having sufficient time to order strain gauges with a higher nominal resistance to ensure the amplification would be successful, as also explained in section 2.3.1.

5.3 Future Work / Alternatives

Power Subsystem Changes

Since we struggled so much with working with small voltage outputs with the strain gauges, I think it would be beneficial if we increased the excitation voltage across the wheatstone bridge, so the changes in voltage are more readable and consistent. Additionally, since the voltage across the wheatstone bridge is in the magnitude of milliVolts, it would be beneficial if we increased the turn-on voltage of the operational amplifier to allow for higher gain, thus further improving signal strength.

Additionally, for better safety, it would be beneficial to implement an emergency shutoff mechanism if any of the input currents to the microcontroller or certain parts of the subsystem uncommonly exceed the current and voltage limits of the system.

Sensor Layer Subsystem Changes

Future improvements and potential design alternatives for the project include conducting more diverse experiments with sensors under variable environments, fabrics, and placements to enhance reliability and adaptability. This way, we can ensure that we have exhausted all possible ways the strain gauge is mounted on the glove and we are certain that the method of mounting will result in more consistent readings of change in resistance. Additionally, refining the strain gauge mounting method—such as attaching it to an intermediate substrate before securing it to the glove—may enhance durability and accuracy.

Signal Processing Subsystem Changes

Implementing a filter at the output of the op-amp could help isolate clean voltage changes, reducing noise. The output voltages we saw from the operational amplifier had a lot of noise, therefore it would be beneficial to single out important, notable voltages.

Communication Protocol Changes

Our current system uses UART, and the usage of wires makes the overall system not as ergonomic and too fragile. I think it would be beneficial to integrate a Bluetooth module for wireless communication between the microcontroller and the software side of the communication protocol.

Overall Changes

Future improvements for the overall project would be to design a wireless device that is more easily mountable onto the glove itself, as our current design is inhibited by many wires. A more portable and compact design could be achieved by enclosing the device in a smaller, mountable form.

5.4 Ethical Considerations

Our project recognizes the risks associated with prolonged stress on the wrist and hand. We aim to enhance wrist and hand health by developing a glove with sensors that actively monitor the stress level in these areas. This glove will then provide feedback on how to alleviate this tension if detected. However, for this project to be successful, users will need to wear a glove containing sensors that will be taking these readings, and this may introduce some safety concerns.

In reference to the IEEE's Code of Ethics Section I.1 "to hold paramount the safety, health, and welfare of the public" [7], the user may be subjected to safety concerns when using the glove. These concerns include:

1. Electrical Safety - Users may be at risk due to inadequate insulation or faulty wiring. Our solution is to mitigate this is to ensure wires are properly insulated as well as proper grounding. In addition to this, we will ensure that the current flowing through the only sensors mounted directly onto the glove is safe for humans (1 mA [8]), especially since in practice, the glove will be worn for long periods of time.
2. Physical Safety - Certain materials may feature sharp edges, posing a risk of injury. Our solution to avoid this is to create smooth-edged casings for all mechanical components of the glove.
3. Skin Safety - Some materials may cause irritation to the skin. Our solution would be utilizing hypoallergenic materials to minimize the risk of skin irritation.

In addition to IEEE's Code of Ethics Section I.1, we also reference Section I.2: "2. to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems" [7]. Specifically, we do not claim to scientifically *prevent* carpal tunnel syndrome (CTS) or repetitive strain injuries (RSIs), but we aim to promote better hand/wrist habits.

The user may also be at risk to receive inaccurate data due to errors with sensor readings or data analysis which is in reference to the IEEE's Code of Ethics Section I.5 "to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data", and Section I.6 "to maintain and improve our technical competence" [7]. To try and mitigate this concern, we will be conducting thorough testing and incorporating error handling.
By implementing these measures, we aim to ensure the safety and well-being of all users while adhering to IEEE's Code of Ethics.

6. References

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Appendix A – Requirements & Verification Tables

A.1 Power Subsystem R&V

Requirements	Verification
Must be able to supply 2.4 V / 600 µA to strain gauge (Vishay CEA-06-062UR-350) ● Ended up using BF350-3AA instead ● No turn-on voltage for the strain gauges necessarily, but testing voltage for what powers the turn-on voltage	● Use a multimeter or oscilloscope to measure the output voltage at the strain gauge terminals. Verification must pass criteria of 2.4 V ± 0.05 V. ● Use a precision ammeter in series with the strain gauge to measure the current. Verification must pass criteria of 600 µA ± 10% (540 µA to 660 µA).
Must be able to supply 1.7 V / 220 µA to IMU (ICM-20948) ● VDD operating range of 1.71V to 3.6V	● Use a multimeter or oscilloscope to measure the output voltage supplied to the IMU. Verification must pass criteria of 1.7 V ± 0.05 V. ● Use a precision ammeter in series with the IMU to measure the current.Verification must pass criteria of 220 µA ± 10% (198 µA to 242 µA).
Must be able to supply 1.8 V / 45 nA to MCU (TI-MSP430FR5994) ● Ended up using ATmega328P ○ 1.8 to 5.5 volts ○ 0-4MHz@1.8-5.5V, ○ 0-10MHz@2.7-5.5	● Use a multimeter or oscilloscope to measure the output voltage supplied to the MCU. Verification must pass criteria of 1.8 V ± 0.05 V. ● Use a precision ammeter in series with the MCU to measure the current.Verification must pass criteria of 45 nA ± 10% (40.5 nA to 49.5 nA).
● Must be able to supply 1.8 V / 7 µA to Bluetooth Module (TI-CC2564C)	● Use a multimeter or oscilloscope to measure the output voltage supplied to the Bluetooth Module. Verification must pass criteria of 1.8 V ± 0.05 V. ● Use a precision ammeter in series with the Bluetooth Module to measure the current.Verification must pass criteria of 7 µA ± 10% (6.3 µA to 7.7 µA).

A.2 Sensor Layer Subsystem R&V

Requirements	**Verification**
IMU must sample motion data at a frequency of ≥ 100Hz to capture fine motor motion and repetitive movements	• Have test subject enable continuous repetitive motion with the IMU • Use logic analyzer to verify the IMU outputs data at ≥100Hz (A sampling rate around 100 Hz is sufficient for capturing daily life human activities [4])
Strain gauges must detect wrist flexion and extension angles within ±5° of actual movement when compared to a reference protractor. • If this requirement was removed, the IMU may still detect repetitive motion and prompt the user for breaks, but the communication subsystem would fail to present to the user an accurate stretch to relieve target muscles of strain	• Have test subject wear glove and perform wrist flexion and extension at set angles (e.g., 15°, 30°, 45°); use a protractor to measure angle • Record strain gauge output data and convert it to angular measurements; verify computed angles are within ±5° of measured angle
Sensors must have a combined response time of ≤ 50ms for real-time motion tracking & strain/motion analysis	• Apply a sudden, quick strain such as a tap and record the time from input to output signal • Ensure that the system registers the signal within 50ms

A.3 Signal Processing Subsystem R&V

Requirements	Verification
Utilize wheatstone bridge to bring resistance changes of strain gauges to at least a 1 V signal	• Design & fabricate wheatstone bridge on PCB to receive signal through bluetooth from the glove & complete initial amplification • TI MCU requires 1 V signal to reliably filter data.
Use MCU to filter human motion from noise & determine notification status	• Route amplified signal to TI MCU • Further amplify and filter with an LPF designed for a maximum of 5 Hz [3] • Route filtered signal to built-in analog-to-digital converter & use digital signals to categorize wrist angles to determine stress levels as referenced in 2.2.4 • Trigger user notification through display system/application based on stress levels
Process IMU data to identify patterns of repetitive motion and grip	• Utilize angular velocity, motion frequency, and force calculations as referenced in 2.2.4 through FFT to track grip • Use pattern recognition to identify repetitive harmful motion

A.4 Communication Protocol Subsystem R&V

Requirements	Verification
Communicate readings with user through application; this requirement is absolutely necessary for the communication subsystem to notify the user to take a break	● Design a user friendly application that allows the user to view grip and stress patterns ● Suggest user to take breaks every 20-30 minutes through an LED light on the glove if readings exceed threshold ● Provide insight into which joints and muscles undergo repetitive motion ● Explore the possibility of intelligently suggesting wrist stretch out of a database utilizing real-time data via UART
Compare stress level with medically approved threshold values to assess user patterns that may lead to harmful muscle activity	● Use force value for Maximum Voluntary Contraction (MVC) comparison with a threshold value of 20% to set a 'normal force' (unique per user) [9] ● Compare stress readings & durations from the strain gauge to the 4% threshold [6] ● Compare wrist flexion/extension to the 30º wrist angle & radial deviation to the 15° value [7].
The subsystem must calculate force on user's grip	● Calculate strain by dividing the ratio vout / vin by the gauge factor ● vout = proportional to the change in electrical resistance ● gauge factor = ratio of relative change in electrical resistance & length ● Calculate force by multiplying strain, young's modulus of material, and cross-sectional area of stressed material