ECE 445 Design Document

Insole for Gait Monitoring and Fall Risk Research in Older Adults

Jessica Sun (jzsun2)
Nasym Kushner (nasymjk2)
Lily Hyatt (lhhyatt2)

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1. Introduction

1.1. Problem

Falls are a leading cause of injury among the elderly, with eight million adults over 65 suffering fall-related injuries each year. Of these, approximately three million require emergency medical care. In the U.S. alone, falls account for an average of 32,000 deaths annually, and globally, they are the second most common cause of unintentional fatalities [1]. Currently, the market offers only solutions that detect falls after they occur. Despite the evident need for preventative technology, existing smart home fall detection systems for high-risk individuals are insufficient, as they fail to incorporate real-time monitoring of fall risk factors and frailty progression.

1.2. Solution

To address this gap in the market, Dr. Manuel Hernandez's lab developed a triboelectric nanogenerator (TENG) sensor designed to be embedded in a shoe insole. This sensor generates a voltage proportional to the pressure applied when a person walks [2]. Our goal is to integrate this sensor into a wearable device that tracks gait patterns for data collection. Gait, which is the manner in which a person walks, provides key indicators of fall risk, such as poor balance and slow walking speed. The device will be worn on both feet, allowing us to measure step timing and synchronize data from both sensors. The collected information will be transmitted via Bluetooth to a mobile app, where users can view their gait analysis.

1.3. Visual Aid

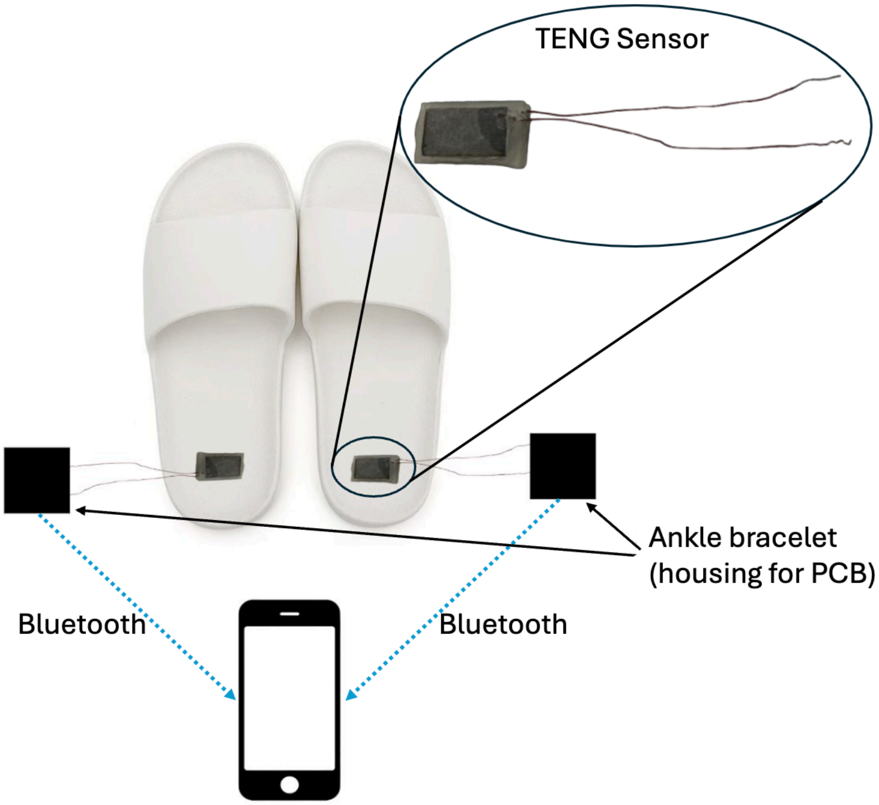


Figure 1: Visual Aid

1.4. High Level Requirements

1. The system must accurately measure the timing between steps with no more than one malfunction or error occurring per 1,000 steps.
2. The system must be able to synchronize two sensors in order to collect data from both feet while walking. The two sensors should be synchronized to an error margin of no more than 12ms.
3. The output of the voltage divider must be stepped down by a factor of $\frac{10}{43}$ ±5% to ensure that the signal can be clearly sent through the ADC without voltage clipping to be interpreted by the microcontroller.

2. Design

2.1. Block Diagram

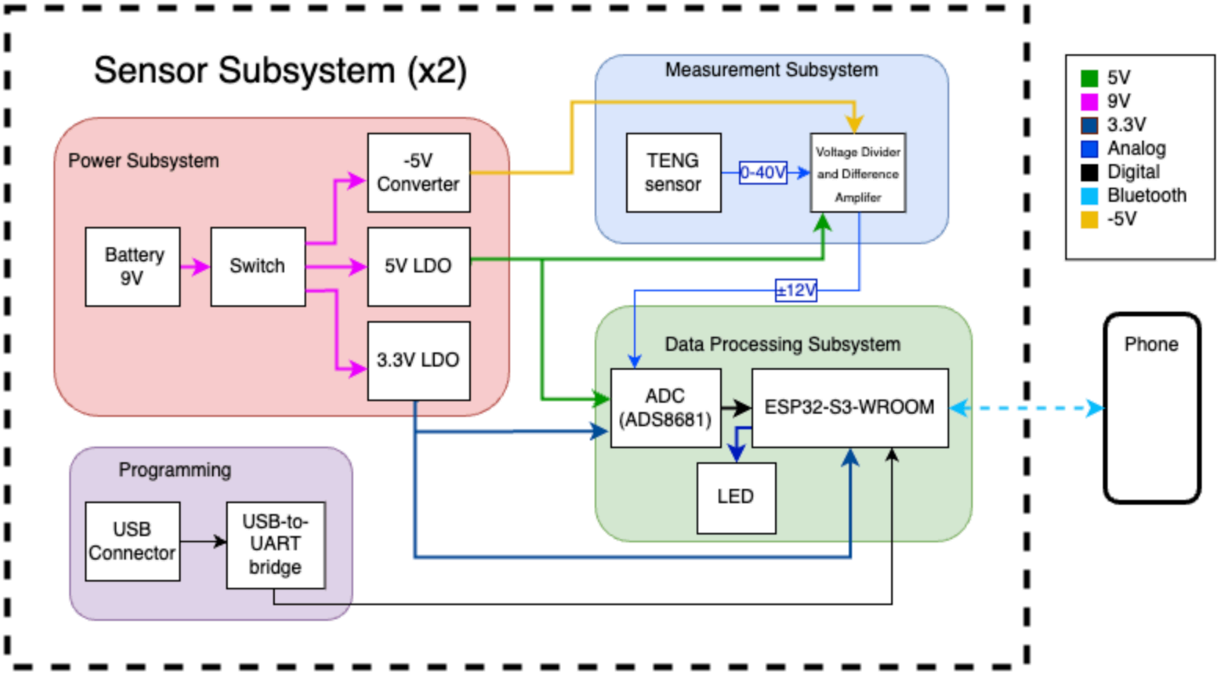


Figure 2: Overall Block Diagram of PCB Design

The overall design includes measurement, processing, power, and programming subsystems. The power system distributes the correct power values to the different components. It operates off a +9V battery which is connected to a power switch, enabling the user to turn the entire system on and off. The battery power is subsequently fed in parallel through a 5V regulator, 3.3V regulator, and -5V converter to be directed to components throughout the rest of the board. The programming system consists of a microUSB protected by a transient voltage suppressor diode, which are connected to a UART module to exchange data through the microUSB and program the microcontroller. The processing system consists of an ESP32-S3-WROOM-1 which communicates with the ADC through SPI protocol, allowing data to be collected. The measurement subsystem consists of a connector to safely link the TENG sensor to the board, a voltage divider to bring the high voltage input down, a difference amplifier to convert the TENG differential signal into a single-ended signal, and a programmable input range ADC to convert the signal to digital.

2.2. Power Subsystem

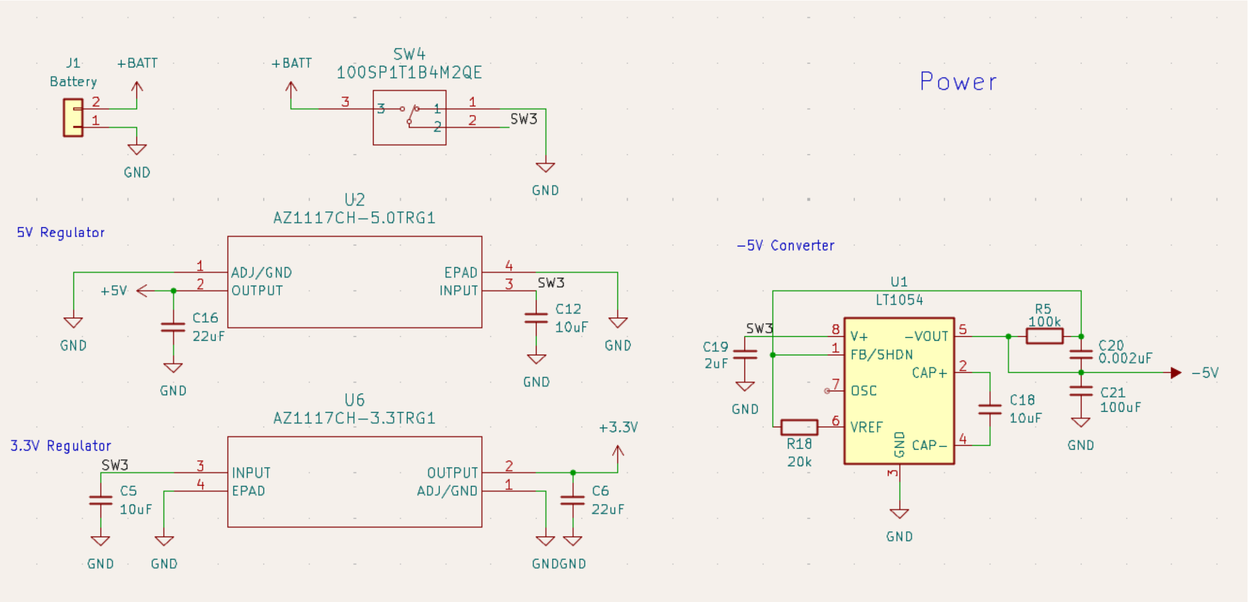


Figure 3: Power Subsystem KiCAD Block Diagram

<u>Description and Purpose:</u>

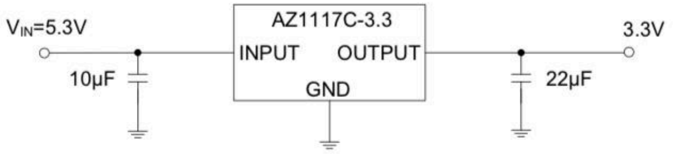
The entire PCB derives power from the power subsystem, which includes a 9V battery, board connector, switch, 5V regulator, 3.3V regulator, and -5V converter to provide the correct power to components in the measurement, processing, and programming units. The power subsystem runs off a 9V battery. The 9V battery will be housed separately from and fed into the PCB by a connector. The battery is connected to a toggle switch that allows the user to turn the device on and off. An LDO will output 5V, which is used for biasing the differential amplifier, supplying analog input voltage to the ADC. Another LDO outputs 3.3V that provides power to the USB-to-UART bridge, microcontroller, and digital supply voltage of the ADC. We are also using a voltage converter to convert 9V to -5V for biasing the differential amplifier.

<u>9V battery input</u>

The 5V and 3.3V regulators have a max drop out voltage of 1.2V. If 9V is applied to these LDO's, the difference between the input and output voltage is 4V and 5.7V for the 5V and 3V regulators respectively, which is above the drop out voltage in both cases. The 9V battery was chosen because it can be reasonably stepped down and converted accordingly to the operating conditions of the AZ1117CH-5.0/3.3 regulators and LT1054 converter. The 9V battery is also a readily available battery, making it easy for the user to swap out when necessary.

<u>5V and 3.3V Regulator:</u>

The AZ1117CH was chosen for the purpose of its fixed output voltage options of 3.3V and 5V, allowing for minimal configuration, as shown in Figure 4. According to the data sheet electrical characteristics, the output voltage is typically 5.0V, while the offset min is 4.950 and max is 5.05. This small voltage range is important for the input voltages to the other components. For the 3.3V LDO, the output voltage ranges from 3.267V to 3.333V with a typical value of 3V [3].

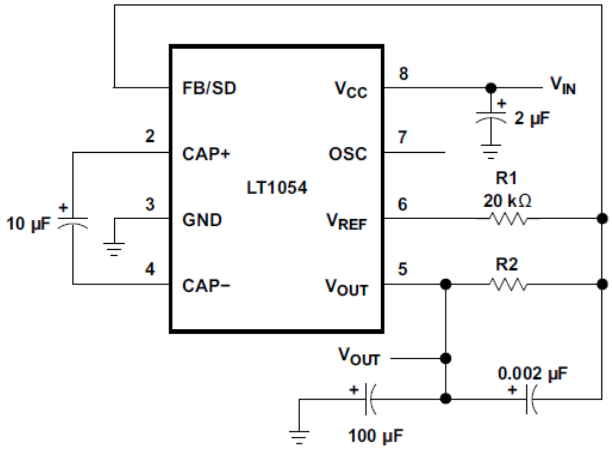


4. The AZ1117C is compatible with low ESR ceramic capacitor. The ESR of the output capacitors must be less than 20Ω. A minimum of 10µF output capacitor is required.

Figure 4: Configuration of AZ1117C-3.3 Example [3]

-5 V Converter:

The difference amplifier in the measurement subsystem requires -5V for biasing, which can be easily derived by this converter. It is configured according to the datasheet for typical application of a basic voltage inverter/regulator. As documented based off of Figure 5 from the LT1054 datasheet, the calculated value for R2 is: $R2 = 20k\Omega(\frac{|-5V|}{1.21V} + 1) = 102.645k\Omega$ so we chose the readily availabe 100kΩ resistor with a percent error of $|\frac{100k-102.645k}{102.645k}| \times 100 = 2.577\%$.



$$R2 = R1\left(\frac{|V_{OUT}|}{\frac{V_{REF}}{2} - 40\text{ mV}} + 1\right) = 20\text{ k}\Omega\left(\frac{|V_{OUT}|}{1.21\text{ V}} + 1\right)$$

are for the P package.

Figure 15. Basic Voltage Inverter/Regulator

Table 2. Design Parameters

Design Parameter	Example Value
Input Voltage Range	3.5V to 15V
V_{OUT}	-5V
I_{OUT}	100mA

Figure 5: LT1054 Circuit Design and Design Parameters for Voltage Inverter/Regulator Application [5]

Requirements	Verification
The voltage converter should output a voltage in the range -4.7V to -5.2V to bias the differential amplifier. The differential	Use a multimeter to probe the output of the converter and ground to ensure the voltage is within the specified range.

amplifier can take a maximum ±18 supply voltage, so the output from the converter should not approach the maximum. In addition, the minimum and maximum input voltages of the difference amplifier are $-V_S+40$ and V_S-40, respectively, and assuming $V_s=5V$, the range is -35V to 35V, which is large enough to handle the output from the voltage divider.	
The +5V regulator must output a voltage that is within the range of input voltage of the ADC analog supply voltage, which is 4.75 to 5.25.	Use a multimeter to probe the output of the LDO and ground to ensure the voltage is within the specified range.
The +3.3V regulator must output a voltage that is within the range of input voltage of the microcontroller and ADC digital supply voltage. The ESP32-S3-WROOM-1 microcontroller has input voltage from 3V to 3.6V, and the ADC digital supply pin has a wider tolerance and can handle an input from 1.65V to the voltage on the analog supply pin, which is around 5V.	Use a multimeter to probe the output of the LDO and ground to ensure the voltage is within the specified range.

2.3. Measurement Subsystem

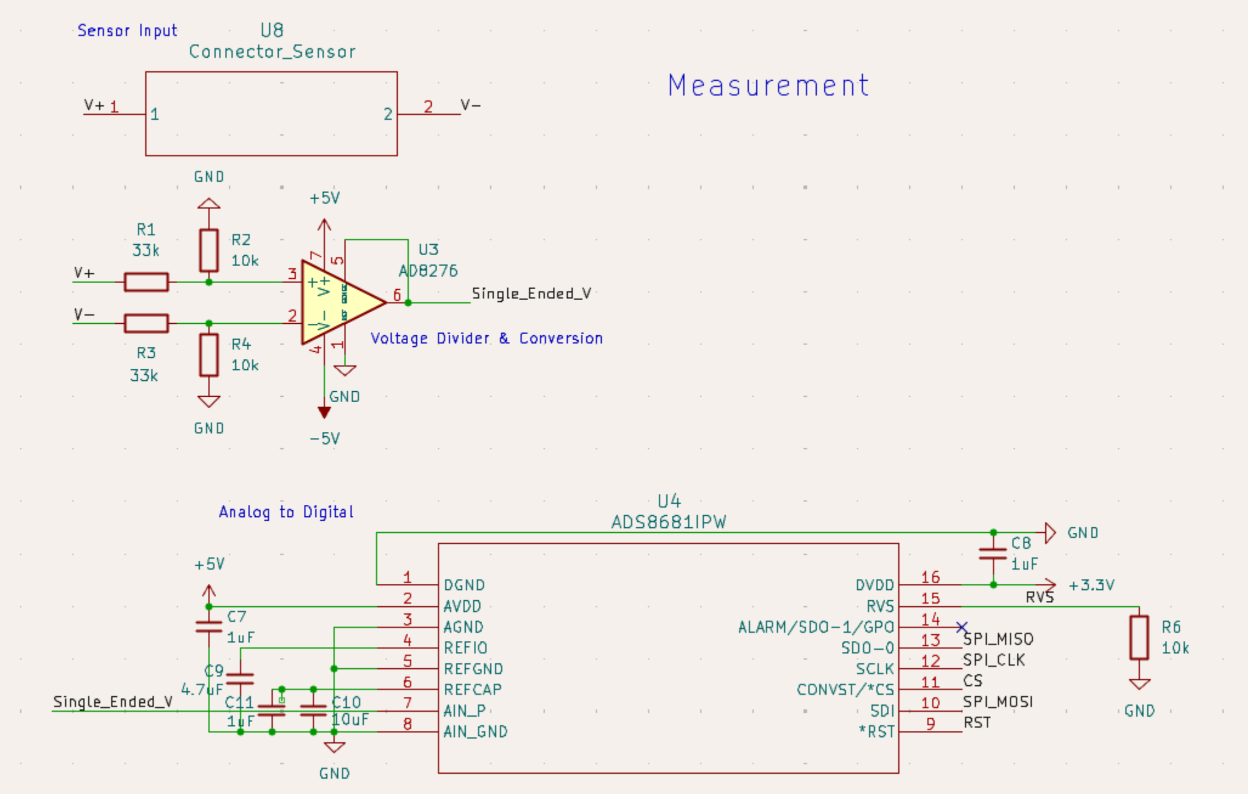


Figure 6: Measurement Subsystem KiCAD Block Diagram

<u>Description and Purpose</u>:

The measurement subsystem is responsible for safely connecting the sensor, stepping down the input voltage from the sensor, converting the sensor signal from differential to single-ended, and converting the signal to an appropriate 3.3V digital signal to be collected and interpreted by the microprocessor in the processing subsystem.

As observed in Figure 7, the custom made TENG sensor outputs a differential signal up to about 40 V from two wire outputs. These two wires will be fed to a wire-to-board header connector. The signal will then be voltage divided, estimating a maximum magnitude of 20V on each end, to about 5V so the rest of the circuit can safely handle it.

$$Vout \ = |\,20V|\frac{10k}{10k+33k} = |4.65V|$$

Since the output voltage of the sensor is proportional to the pressure applied, we do not want to step down the voltage so magnitude information is retained. The differential signal is then sent through a difference amplifier to obtain a single-ended signal of up to ~9.30 V. The ADC used, ADS8681, only takes a single ended signal, so this step is necessary. The ADS8681 was chosen for its input programmability, which in this case we will be using the ∓10 V input setting. The ADS8681 communicates with a processor via SPI protocol. The ADC will interface with the ESP32-S3-WROOM microprocessor and the difference amplifier, AD8276, takes 5V and -5V from the power system while the ADC is powered by the 5V signal on the analog end and 3.3V on the digital end. ADC internal reference is used to output a digital signal of 3.3 V to be safely delivered to the microprocessor.

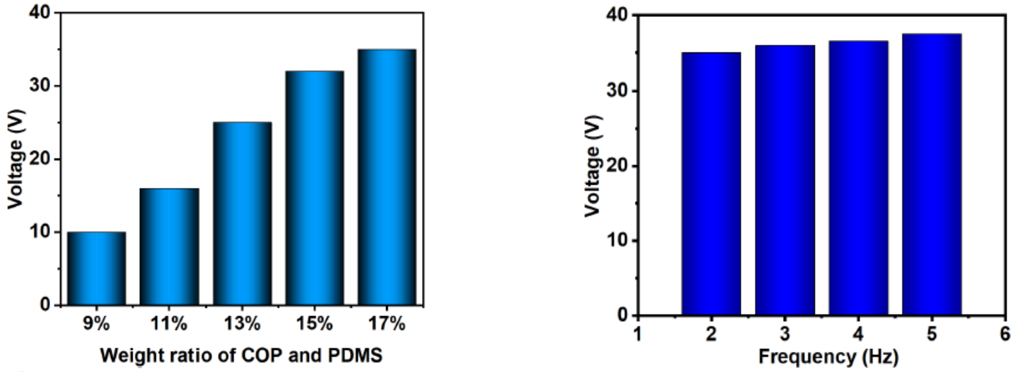


FIGURE 5: VARIATIONS IN THE TRIBOELECTRIC NANOGENERATOR (TENG) VOLTAGE FOR PDMS WITH DIFFERENT CARBONIZED ORANGE PEEL (COP) WEIGHT RATIOS AT A FREQUENCY OF 2 HZ AND A FORCE OF 10 N

FIGURE 6: OUTPUT PERFORMANCES OF TENG VOLTAGE WITH 17% CARBONIZED ORANGE PEEL (COP) AND PDMS MADE ELECTRODE AS A DIFFERENT FREQUENCY

Figure 7: Custom Triboelectric Nanogenerator Voltage Testing [2]

Difference Amplifier (AD8276):

The AD8276 was chosen for its ability to function in a single-ended configuration with a gain of +1. As seen in Figure 8, it can be easily configured to output a single-ended signal of a magnitude sum of the two differential inputs.

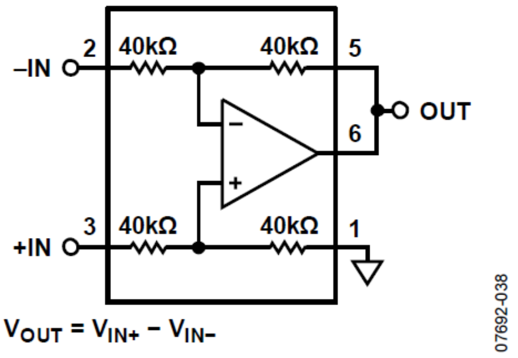


Figure 42. Difference Amplifier, Gain = 1

Figure 8: AD8276 Difference Amplifier G=1 Configuration [6]

ADS8681:

The ESP32-S3-WROOM-1 microprocessor contains a built-in ADC of 12-bit resolution, but input voltages must be attenuated to at least 3.1V before they can be converted by this internal ADC [7]. This is not ideal for the signals from the TENG sensor, as the integrity of the sensitive analog signals must be preserved. As discussed above, after the voltage division and difference amplifier, the signal will maximize at 9.3V. The ADS8681 has a unipolar input range programmability feature that ranges up to 0V to 12.288V [8]. For the expected signal behavior, the 0-10.24V input voltage range will be utilized. However, if needed, any of the ranges included can be used, and a planned feature is using the microprocessor to program the ADS8681to increase resolution at lower voltage reflecting dynamic changes in the sensor output varying person to person and over time. The ADS8681 is also 16-bits, as opposed to the microprocessor’s 12 bits, which will provide much higher precision and capture slight but important variations in data which are key for categorizing the custom TENG sensor used. Thus, the ADS8681 is chosen for its higher resolution and programmable input voltage, which helps preserve the integrity of the input signal from the custom made triboelectric nanogenerator signal. The ADS8681 also has a built-in low-pass filter. This will remove noise ensuring a cleaner signal, meaning more accurate data. Additionally, it has overvoltage protection, so if the sensor does produce unexpectedly high voltages, the remaining electronics are protected. The ADS8681 is capable of sampling at a max of 1000 kSPS, which is more than adequate given the Nyquist frequency calculated in the tolerance analysis.

Requirements	Verification
Handle up to 40 V differential input and step down to ~10V differential	Using a waveform generator, generate 40V as input to the overall circuitry and probe the output of the voltage divider circuit to ensure that the peak to peak is around 9.3V as expected.
Successfully convert to single-ended signal for ESP32-S3-WROOM-1 compatibility	Using the multimeter, probe the output of the difference amplifier and the ground reference and ensure the entire signal of ~9.3 is available.
Collect data at every signal input.	Use an oscilloscope to track every spike from the sensor and compare with the data outputted by the ADS8681.

2.4. Processing Subsystem

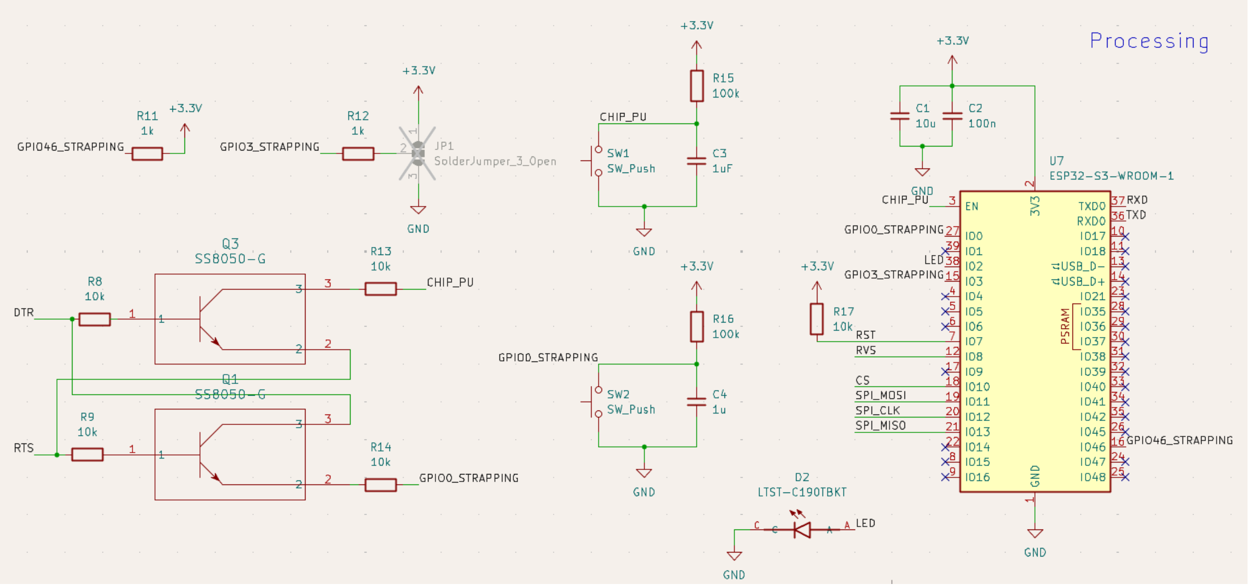


Figure 9: Processing Subsystem KiCAD Block Diagram [9]

The processing subsystem consists of an ESP32-S3-WROOM1 microprocessor which interfaces with the ADC to program it to collect data at the correct frequency sampling, store the data, and communicate through Bluetooth with a 3rd party mobile device to display the data. It also outputs different blinking patterns through an LED to display the status of the system.

FSPI:

The ESP-32 will be utilizing the FSPI data lines to communicate serially with the ADC. The 4 FSPI lines used are CS, MOSI, MISO, AND CLK, while the RST and RVS are arbitrary GPIO signals that interface with the ADC. The LED is connected as an output of GPIO2 to display the status of the whole design [10].

Bluetooth:

The ESP-32 will be utilizing its Bluetooth Low Energy functionality to transmit the sensor data to a mobile device. The Bluetooth system is capable of transmitting data up to 1 Mbps which is more than adequate for the simple data we will be transmitting. The device will also transmit status information so users can easily see errors written out on the mobile application.

Requirements	Verification
The ADS8681 functions based on SPI protocol, the correct FSPI GPIO pins must be utilized for correct data collection	Use an oscilloscope to ensure correct outputs from each of the pins.

The system must transmit 99.9% of data packets over Bluetooth successfully.	Measure data through analog pins and compare with data received via Bluetooth.

2.5. Programming Subsystem

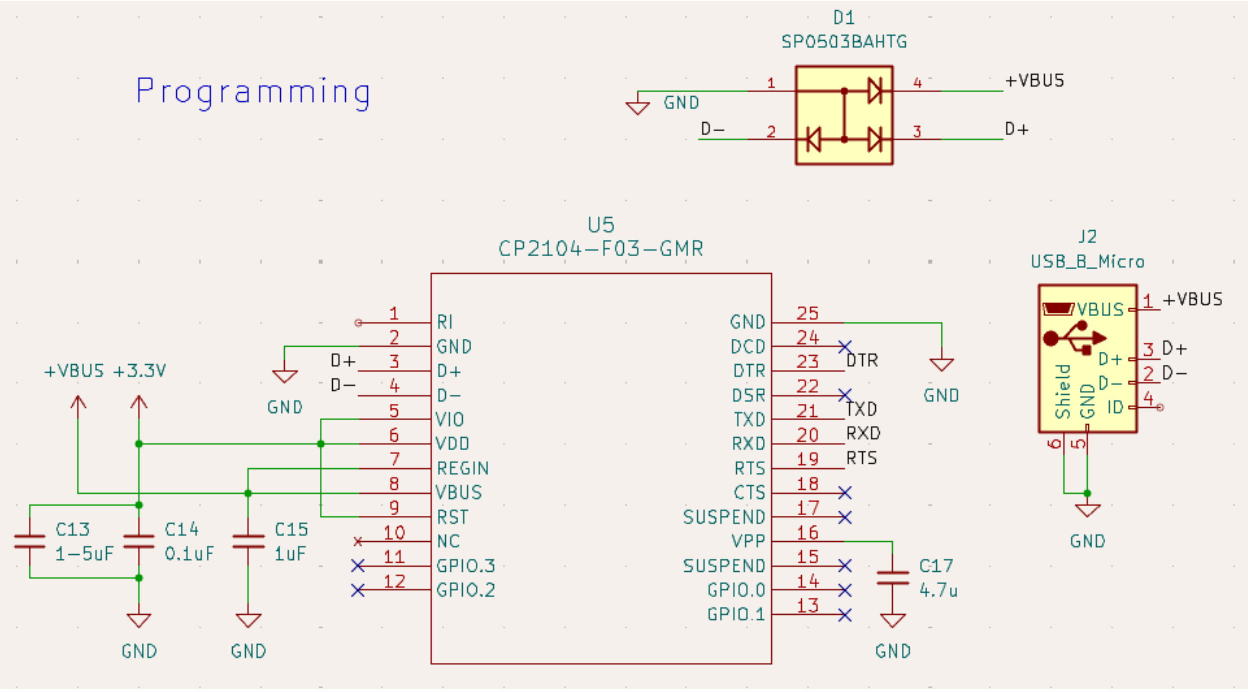


Figure 10: Programming Subsystem KiCAD Block Diagram

Our ESP32 must be programmed to collect data from the ADC, so the USB and UART serve as a bridge between the computer and microcontroller during programming phases. The USB Micro was chosen for its simplistic wiring design, optimizing PCB room and track routing. It is powered by the device it will connect to and features two data lines: D+ and D-. The UART receives data from the USB connector through the D+ and D- data lines. The UART transmits and receives data to and from the microcontroller along the TXD and RXD lines, respectively. The UART also outputs two signals DTR and RTS. The DTR (data terminal ready) signal, when pulled low, signals to the microcontroller that the UART is ready to communicate. The RTS (request to send) signal when pulled low tells the microcontroller that it can send data. Transient voltage suppression diodes are included and connected to the USB connector for ESD protection [12].

Requirements	Verification
The input voltage range into the UART is 3.0V to 5.25V.	Use a multimeter to probe the V_{DD} pin on the UART to ensure the voltage is within the specified range.
Data is transferred from the connector to the UART through the D+ and D- lines, so these lines must be directly connected.	Use a multimeter to probe the D+ pins as well as the D- pin on the connector and UART to ensure continuity.

Ensure that VBUS on the micro B connector is operating at 5V±5% (4.75V to 5.25V).	Use a multimeter to probe the VBUS pin of the connector and ground to ensure the voltage is within the specified range.
The VBUS, D+, and D- signals coming from the connector must be directly connected to the transient voltage suppression diodes for ESD protection.	Use a multimeter to probe the VBUS pins, D+ pins, and D- pins on the connector and shock protector to ensure continuity.
The UART transmits and receives data to and from the microcontroller through the TXD and RXD lines, so these pins must be directly connected.	Use a multimeter to check the continuity between the TX pin on the UART and RX pin on the microcontroller and vice versa.

2.6. Tolerance Analysis

TENG Sensor Voltage Regulation: The TENG sensor generates a high voltage signal of up to 40V, however, the measurement subsystem must regulate this to ensure compatibility with the ADC. The voltage regulator circuit must maintain an output range of ±12V to ensure the ADC collects all the relevant data to prevent data clipping and signal distortion.

ADC Sampling and Signal Conversion: The ADC converts the TENG signal from analog to digital. The shortest measured signal in testing was 10 ms (100 Hz). Given, the ADC must accurately capture each voltage fluctuation. Based on the Nyquist criterion $fs \geq 2 \times fm$, the ADC must sample at least 200 Hz. However, since the TENG sensor is a custom made device, it might fluctuate, which must also be accounted for, so we will oversample by 10 times to a frequency of 2 kHz.

Synchronization Between Sensors: Since two TENG sensors will be used, one for each foot, synchronization between the two sensors must be achieved to ensure accurate timing and gait analysis. The sensors should be synchronized within 12 ms.

Bluetooth Data Transmission: Data is transmitted from the ESP32 microcontroller to a mobile device via Bluetooth. The system must transmit 99.9% of data packets successfully.

3. Cost and Schedule

3.1. Cost Analysis

Description	Manufacturer	Part Number	Quantity	Unit Price
9V Battery	Energizer	EN22	1	$2.37
9V Battery clip	Keystone	233	1	$0.84
Toggle switch	E-Switch	100SP1T1B4M2QE	1	$2.97
+5V LDO	Diodes Incorporated	AZ1117CH-5.0TRG1	1	$0.46
+3.3V LDO	Diodes Incorporated	AZ1117CH-3.3TRG1	1	$0.43
-5V Voltage Converter	Texas Instruments	LT1054	1	$3.22
ADC	Texas Instruments	ADS8681	1	$9.09
Difference Amplifier	Analog Devices Inc.	AD8276	1	$4.50
Sensor Connector	Phoenix Contact	1715721	1	$0.97
USB Micro Connector	Amphenol ICC	10118194-0001LF	1	$0.41
Transient Voltage Suppression Diode	Littelfuse Inc.	SP0503BAHTG	1	$0.70
USB-to-UART Bridge	Silicon Labs	CP2104-F03-GMR	1	$6.47
Microcontroller	Espressif Systems	ESP32-S3-WROOM-1	1	$5.49
BJT	Comchip Technology	SS8050-G	2	$0.24

LED	Lite-On Inc.	LTST-C190TBKT	1	$0.34
10µF Capacitor	Murata Electronics	GRM21BR61H106ME43L	5	$0.26
0.1µF Capacitor	Samsung Electro-Mechanics	CL21F104ZAANNNC	2	$0.10
22µF Capacitor	Samsung Electro-Mechanics	CL21A226MQQNNNE	2	$0.10
4.7µF Capacitor	Samsung Electro-Mechanics	CL21A475KAQNNNE	2	$0.10
2.2µF Capacitor	Yageo	CC0805KKX5R9BB225	1	$0.25
2000nF Capacitor	Samsung Electro-Mechanics	CL21B202KBANNNC	1	$0.10
100µF Capacitor	Samsung Electro-Mechanics	CL21A107MQYNNWE	1	$0.97
1µF Capacitor	Samsung Electro-Mechanics	CL21B105KBFNNNG	7	$0.10
100kΩ Resistor	Stackpole Electronics Inc.	RMCF0805JT100K	5	$0.10
1kΩ Resistor	Stackpole Electronics Inc.	RMCF0805JT1K00	2	$0.10
10kΩ Resistor	Stackpole Electronics Inc.	RMCF0805JG10K0	6	$0.10
33kΩ Resistor	Panasonic Electronic Components	RT0805BRD0733KL	2	$0.10
20kΩ Resistor	Panasonic Electronic	ERA-6AEB203V	1	$0.10

	Components			
Total Cost				**$44.26**

The average starting salary of an electrical engineering graduate from UIUC is $87,769, which is an hourly salary of $42.20. Each teammate will work about the same amount of hours. We plan on working 15 hours per week on the project. The total amount of labor cost is calculated as follows:

$42.20/hours * 2.5 * 15hours/week * 13 weeks * 3 = $61,717.5

The total cost of this project including parts and labor is $61761.76..

3.2. Schedule

Week	Tasks	Assignment
2/24	1. Initial testing with the TENG sensor 2. Initial schematic and PCB design	1. Everyone 2. Lily and Jess
3/3	1. Teamwork evaluation 1 2. Design document 3. Begin microcontroller programming setup 4. Work on power subsystem for breadboard demo 5. Work on voltage divider and difference amplifier circuit for breadboard demo	1. Individual 2. Everyone 3. Nasym 4. Lily 5. Jess
3/10	1. Breadboard demo 2. Solder and test 1st PCB design 3. Continue programming microcontroller and integrating Bluetooth	1. Everyone 2. Lily and Jess 3. Nasym
3/17	SPRING BREAK	
3/24	1. Review PCB design improvements 2. Testing hardware subsystems 3. Design enclosure for PCB	1. Everyone 2. Lily and Jess 3. Nasym
3/31	1. Individual progress report 2. Begin integrating testing with all subsystems 3. 3rd round PCB order 4. Begin creating an app that the data will be sent to	1. Individual 2. Lily and Jess 3. Everyone 4. Nasym
4/7	1. 4th round PCB order if needed 2. Continue integration testing of all subsystems 3. Continue app creation	1. Everyone 2. Lily and Jess 3. Nasym
4/14	1. Set up device how it will be used by the user and test 2. Team contract assessment	1. Everyone 2. Individual 3. Everyone

	3. Prepare for mock demo	
4/21	1. Mock demo 2. Use feedback to prepare for final demo 3. Create presentation	1. Everyone 2. Everyone 3. Everyone
4/28	1. Final demo 2. Mock presentation 3. Prepare for final presentation with feedback from mock presentation 4. Begin working on final paper	1. Everyone 2. Everyone 3. Everyone 4. Everyone
5/5	1. Final presentation 2. Final paper due	1. Everyone 2. Everyone

4. Ethics and Safety

In developing our gait monitoring system, we will prioritize the safety, health, and privacy of the users based on ethical engineering principles. A primary safety concern is the TENG sensor's capability to produce up to 40V under high loads. To ensure user safety, we must design a secure enclosure that prevents exposure to this voltage, mitigating any potential risk. In alignment with the IEEE Code of Ethics Section 1 [13], we have a responsibility to protect the well-being of users and transparently disclose any safety considerations associated with the sensor.

From an ethical standpoint, since our project is being developed in collaboration with Professor Hernandez's research group, we must properly acknowledge and credit all prior and ongoing contributions, in accordance with ACM Code of Ethics Section 1.5 [14]. The sensors used in this project are custom-made and thoroughly documented, so we must recognize the efforts of those who designed and developed them. As we continue working alongside Professor Hernandez and his team, we must ensure that all contributions are fairly attributed. By adhering to these ethical standards, we uphold integrity in our professional activities while ensuring our technology benefits society responsibly.

5. Citations

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