IntelliSOLE

Design Document

ECE 445 (Spring 2022)

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1. Introduction

1.1. Description of Problem

Walking and running are activities many of us take for granted. Yet, any disruption to these activities could pose enormous challenges to our daily lives. As such, studying human motion is important in monitoring health and preventing injury. Mapping foot plantar pressure can provide insights into the wearer's foot posture, and identify potential health issues that stem from having abnormal gait, which range from flat feet to feet ulceration problems caused by diabetes [1]. While there are solutions for foot pressure mapping, such as pressure mats and treadmills, these are often high-cost products that are not easily accessible to the average person. Current pressure-mapping shoe insoles on the market also suffer from the issue of high-cost, and face many complaints of being uncomfortable and bulky to wear.

1.2. Solution

The aim is to develop a low-cost, comfortable solution to map foot plantar pressure and provide the average user with information regarding their foot posture without having to see a doctor or spend lots of money on. The plan is to develop a shoe insole sensor that is compatible with any shoe and pair it with a mobile device application that allows the user to see their foot pressure in real time. As seen in Figure 1.2.1, the pressure information will be gathered by a network of force-resistive sensors (FSRs) attached to the shoe insole. The data is then transferred via ribbon cable to an assembly hanging on the shoe ankle, which houses the components necessary to process the pressure data. The data is then transferred to a mobile device via Bluetooth, where the software uses the data to generate a heatmap available to the user.

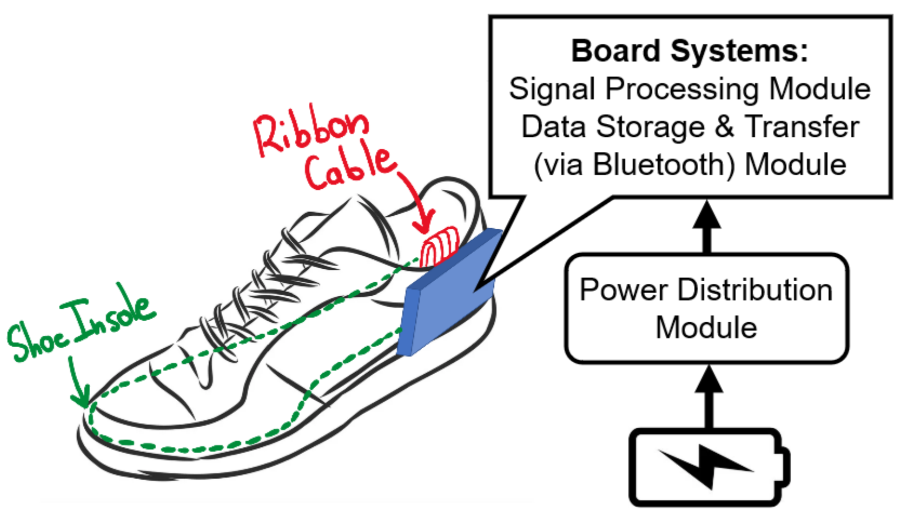

Figure 1.2.1. High-level Overview of Product Components (Visual Aid)

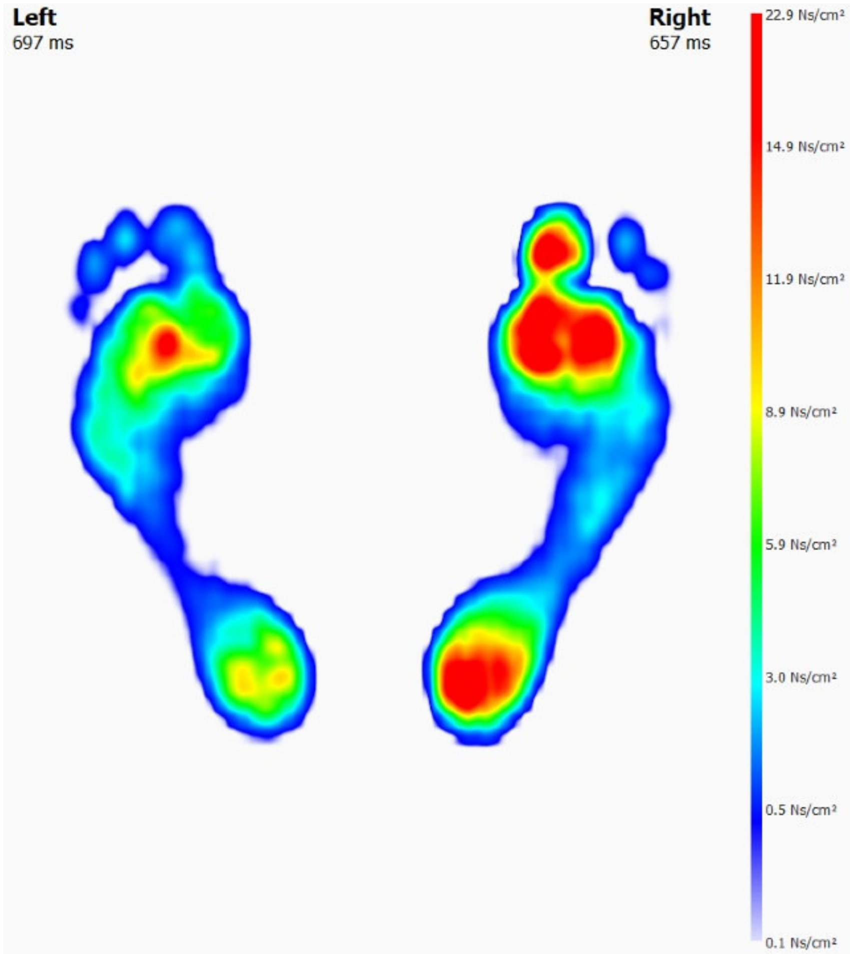

Figure 1.2.2. A visual representation of a pressure heatmap for both feet [2]. The scale bar (left) indicates foot pressure, from lowest (blue) to highest (red).

1.3. High-level Requirements List

Our success is defined by our ability to meet the criteria below:

1) Ability to sense up to 100 kPa ± 20% of pressure per sensor for accurate plantar pressure mapping. The shoe pressure insole can sense 1000N ± 20% of force applied normal to the sensing plane.
2) Develop a heatmap corresponding to this range, with blue indicating 0 kPa ± 20% to red showing 100 kPa ± 20% of pressure.
3) The power source must be composed of small batteries with a voltage output between 3V ± 5% to 6V ± 5% and still efficiently use the power to function for more than 30 minutes.

2. Design

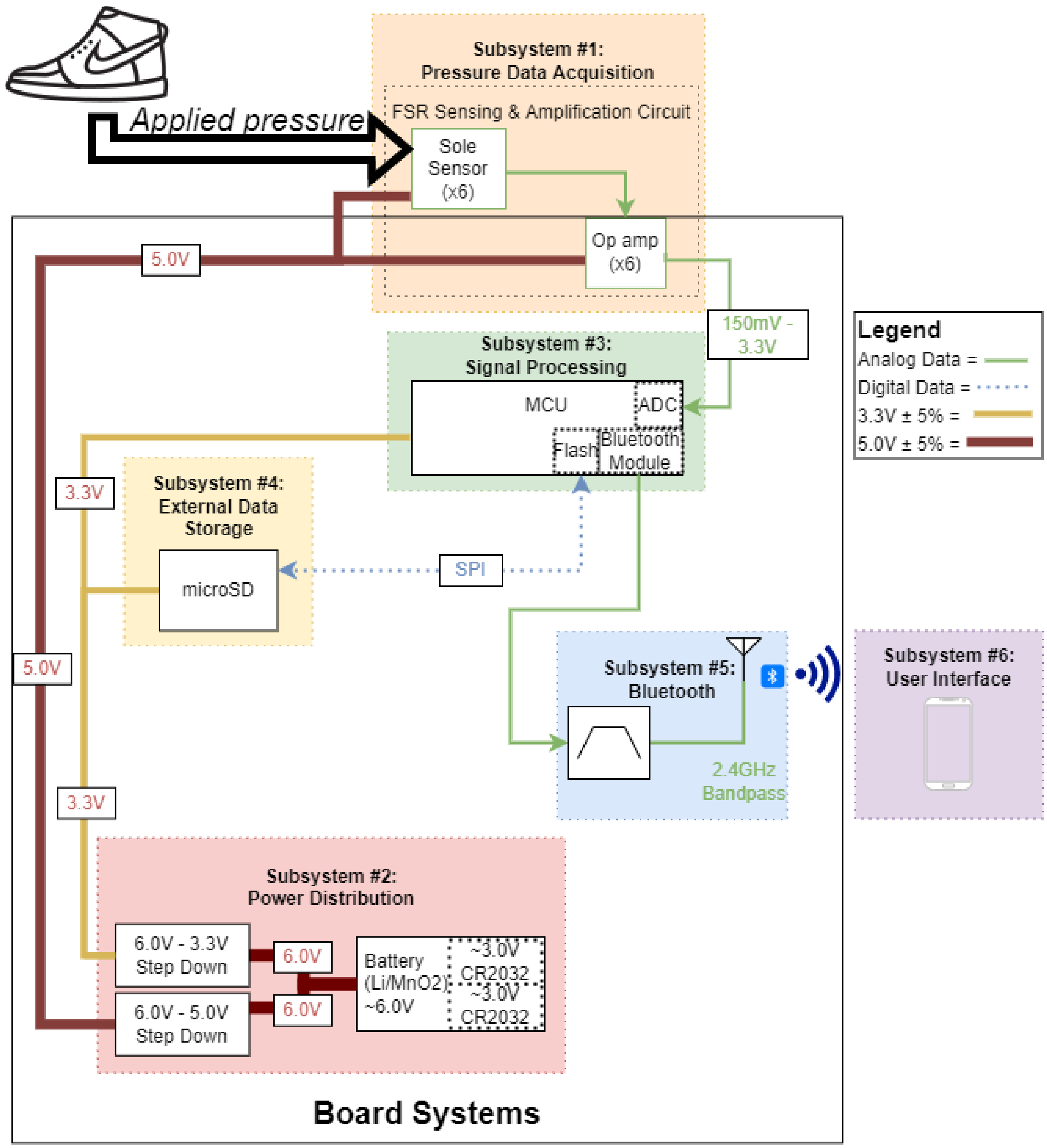

Figure 2.0.1. Subsystem Block Diagram

2.1. Subsystem Overview: Pressure Data Acquisition

The Pressure Data Acquisition subsystem is composed of an array of six Interlink Electronics 400-Series Force Sensing Resistors (FSRs) placed throughout the shoe insole, as seen in Figure 2.1.1. These FSRs will be laminated to the insole to protect from excessive shearing force present between the foot and the insole. As seen in figures 2.1.1 and 2.1.2, a single FSR is modeled as a variable resistor within an adjustable buffer circuit, with R_{FSR} linearly decreasing based on pressure applied normal to the sensing plane. When no pressure is applied, R_{FSR} is expected to measure greater than 10 MΩ. The minimum activation force for sensor response is expected to be 0.2 N ± 20%.

An adjustable buffer circuit was an ideal choice for analyzing FSR pressure data, as the gain can be easily adjusted based on the ratio of R2 and R1. In addition, a greater degree of linearity was observed between resistance and output voltage compared to a standard voltage divider circuit. The ideal value of R3 was chosen to be one-twentieth the value of either R1 or R2 (no difference in circuit behavior was observed between these two changes). By running LTspice simulations, it was determined that a lower R2/R1 ratio resulted in higher output gain (VOUT). As such, the ratio was tweaked until the maximum output voltage of ~3.3 V was achieved. Figure 2.1.2 denotes the resistance values of R1 and R2.

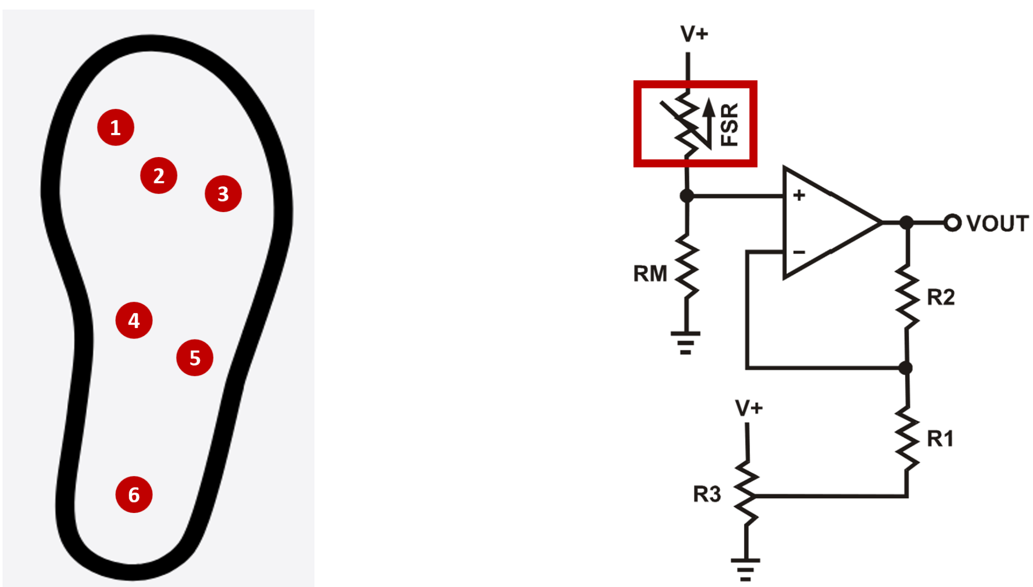

Figure 2.1.1. Placement of FSRs within shoe insole numbered 1-6 (left) and adjustable buffer circuit diagram with FSR component highlighted (right).

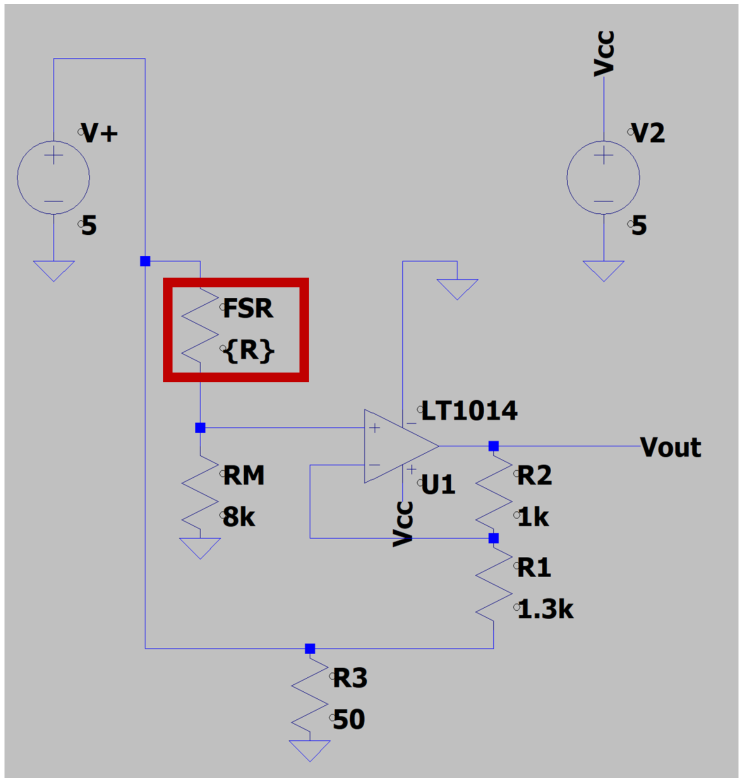

Figure 2.1.2. FSR Circuit Diagram. The FSR component is highlighted in red.

Subsystem Requirements:

Requirement	**Verification**
1. The maximum output voltage of the FSR circuit must be within a range of 3.3V ± 5% when the FSR is under maximum load.	**1A.** The FSR circuit must be prototyped on a breadboard using a power supply to generate 5V± 5% . **1B.** The output must be measured using an oscilloscope/voltmeter while the sensor is fully pressed.
2. The maximum current flowing through each sensor cannot exceed 1 mA with an input voltage range of 5.0V ± 5%	**2A.** The FSR circuit must be fully assembled on a breadboard using a power supply to generate 5V ± 5%. **2B.** Use an ammeter to determine if current across FSR is less than 1 mA.
3. FSR linearity must be observed between force and resistance while the sensor load is less than 10 kg.	**3A.** FSR circuit must be fully assembled on breadboard. **3B.** Use a multimeter to verify that each sensor exhibits a resistance greater than 10 MΩ when no force is applied.

Requirement	Verification
	3C. Place 2 kg weight on the FSR sensor and record output voltage using a voltmeter. **3D.** Process is repeated with each corresponding 2 kg increase in weight. **3E.** Record at least two data points where linearity relationship is lost (ie. no changes in output voltage with increasing weight) and see if the weight limit is above 10 kg.

2.2. Subsystem Overview: Power Distribution

The power distribution subsystem is incharge of powering all the board system components. All components of the system require an operational voltage between 2.8V and 3.3V. The power is supplied by two CR2032 battery cells in series. The cells are chemically powered by a reaction between lithium and manganese dioxide. Two CR2032 cells in series are capable of a max voltage of 6V±5% and rated for 220mAH.

The voltage from the two cells is stepped down by the TPS62203 step down converter from ~6V to 2.8V - 3.3V with 95% efficiency. The TPS62203 has a maximum current limit of 300mA which will be limited by passive elements. The design will limit the output current further to 75mA ±3mA using passive elements such as diodes.

<u>Subsystem Requirements:</u>

Requirement	Verification
1. DC-DC step down from ~6V to 5V ±5% with a current limit of 125mA ± 5mA	**1A.** Use an oscilloscope to measure the output voltage is within 5V ±5%. **1B.** Use a multimeter to verify the current values are within 125mA ± 5mA.
2. DC-DC step down from ~6V to 2.8V - 3.3V with a current limit of 75mA ± 3mA	**2A.** Use an oscilloscope to measure the output voltage is within 2.8V - 3.3V. **2B.** Use a multimeter to verify the current values are within 75mA ± 3mA.
3. Prevent electronic failure due to erroneous battery installation	**3A.** Use a power supply to simulate flipped battery insertion with a negative voltage matching the battery voltage and

Requirement	Verification
	validate the current is properly handled by the probed zener diode on the oscilloscope.

2.3. Subsystem Overview: Signal Processing

The microcontroller samples the analog resistance coming in from the pressure data acquisition subsystem and applies an embedded FIR filter to remove noise. After the filter is applied, the filtered values are stored onboard flash. If bluetooth is not connected, the data is written to the external memory in the form of microSD. ADC convergence timing of 1000ns so the convergence frequency is 1MHz convergence frequency.

Subsystem Requirements:

Requirement	Verification
1. Trigger the supply voltage supervisor on the MCU to safeguard the electronics and prevent failure when the MCU voltage drops below 2.8V	**1A.** Simulate a low voltage condition using a power supply with an output of 2.7V and verify the voltage supervisor is triggered on the MCU via a JTAG debugger. **1B.** Verify if the voltage supervisor is triggered by an illuminated LED warning a low voltage condition.

2.4. Subsystem Overview: Data Storage

The filtered data from the signal processing subsystem needs to be stored on the 256MB Micro SD memory card. The DM3AT-SF-PEJM5 Micro SD connector will be used to connect the microcontroller to the memory card via Serial Peripheral Interface[3]. Once the data is written to the microSD, the data on the microSD can be used by the device with the user interface subsystem implemented on it. The Bluetooth data transfer module is intended as a convenient alternative to transfer data between the microcontroller and the phone.

The writing cycle of Micro SD requires a large amount of power supplies, so in order to reduce power usage and increase battery efficiency a writing buffer the size of one page of pressure data will be used and SD card will only be written to when the buffer is ready.

Subsystem Requirements:

Requirement	Verification
1. The supply voltage needs to be within the range of 3.3V ±5% and power 1.5mA of current during write cycles	**1A.** Using an oscilloscope, ensure the power supplied is above 3.3V ±5%. **1B.** Using a multimeter, verify the power draw during write cycles is below 1.5mA
2. The system would be able to detect and eliminate noises in data.	**2A.** Simulate a noise signal and add it to one of the lines. Then check on an oscilloscope to see if the signal is filtered out.

2.5. Subsystem Overview: Bluetooth Data Transfer (OPTIONAL)

The bluetooth module serves as a more convenient medium to communicate data from the microcontroller to the device with the user interface module. The module uses the CC2564 bluetooth module. The bluetooth module receives the data from the MCU via the I2S protocol. The bluetooth module encodes the data and runs through a bandpass filter before it is transmitted by a 2.4GHz antenna printed on the PCB.

Subsystem Requirements:

Requirement	Verification
1. 256KB of data sent from MCU via Bluetooth is received by software.	**1A.** Check to see if Bluetooth data is being transmitted at a rate of 2.4 GHz. **1B.** Analyze data received by software via Bluetooth for any missing/corrupt sensor readings within the packetized 6x10 array.
2. Successfully pair with an Android device.	**2A.** See if IntelliSole is recognized as a Bluetooth device on the software host.

2.6. Subsystem Overview: User Interface

The user interface interprets the sensor data and displays a heatmap for the user to visualize the foot pressure over time. This is accomplished by reading collected sensor data from hardware in an array form defined by sensor location and instance of time in which all six sensor values were collected, as visualized in Figure 1.2.2. The array will be composed of ten timestamps, and will be packetized in the same format if the Bluetooth feature is implemented.. The software reads the FSR values of a specific time instance (column), and assigns the ADC values of each specific sensor onto a virtual map of the shoe insole denoting the location of each FSR (see Figure 2.6.1). The graphical portion of the software involves generating a foot pressure heatmap from these given values, and will aim to look similar to that of Figure 1.2.2.

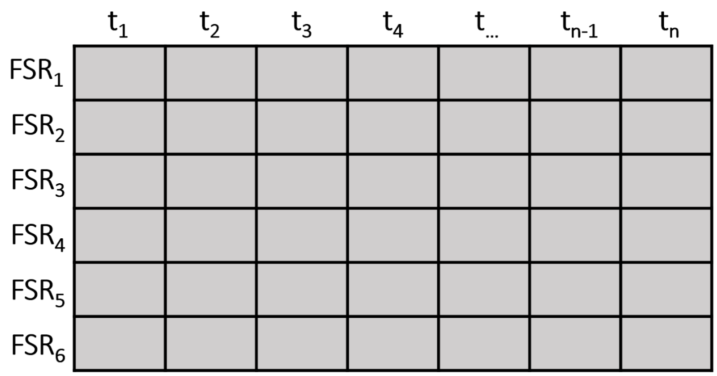

Figure 2.6.1. Visualization of buffer setup with rows denoting a sensor and columns denoting specific time instances.

<u>Subsystem Requirements:</u>

Requirement	**Verification**
1. Software must retrieve correct sensor values and not lose any timestamp of data in the process.	**1A.** Read through ADC sensor data stored in SD card (or Bluetooth) by . **1B.** Check to see any corruption of values within the 6x10 array.
2. Given sensor data, the front end must display the recorded data in the form of a heatmap.	**2A.** Use the android studio debugger to step through the visualization of the pressure heatmap. **2B.** Verify the playback on the user interface by replaying the same data again.

2.7. Tolerance Analysis

One aspect of the design that poses the greatest challenge to the success of the project stems from acquiring accurate data from the sensors. To ensure the design meets our high level tolerance goals of 100 kPa ± 20%.

Each sensor will be powered by 5.0V± 5% input voltage.

$$V_{in} = 5.0V \pm 5\% \simeq [4.7V,\ 5.3V]$$

Given the input voltage range, the FSR circuit, as illustrated in figure 2.1.2, can be simulated to attain the simulated amplified sensor voltage range. The simulation results are shown below in figure 2.7.1.

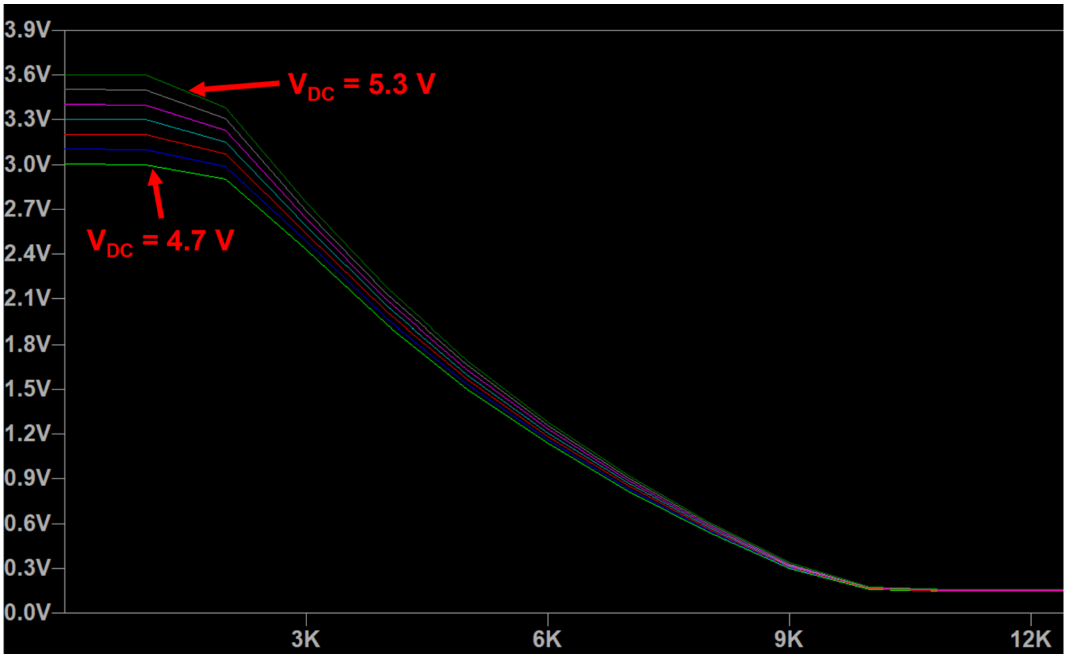

Figure 2.7.1 - LTspice FSR circuit tolerance simulations.

The max voltage attained is within the calculated range below under maximum load conditions.

$$V_{DATA,max} \simeq [3.0V,\ 3.6V] \ \simeq 3.3V \pm 9.1\%$$

Additionally, the ADC conversion precision tolerances due to manufacturing limitations need to be considered. According to the MCU datasheet [2], the precision tolerance is within a range of 6%. Combining the manufacturing tolerance provides us with the following range for sampled data.

$$v_{DATA,max}[n] \simeq 3.3V \pm 15.1\% \ \simeq [2.8V,\ 3.8V]$$

In order to convert the sampled voltage readings to a measurement of pressure, the manufacturer's measurements need to be considered. The datasheet for the FSR sensor [5] states the maximum force value of 1000 g directly corresponds to our sampled data value of 3.3V ± 15.1%. Thus the sensor has a force and pressure tolerance of ± 15.1%. According to our analysis, our design should meet our tolerance goal of ± 20%.

3. Cost and Schedule

3.1. Cost Analysis

Parts Cost:

Component	Subsystem	Total Item Cost (Quantity)
LM324PWRG3 Operational Amplifier	Pressure Data Acquisition	$4.04 (x10)
FSR 402 Force Sensing Resistor	Pressure Data Acquisition	$51.84 (x6)
BAT-HLD-003-SMT Battery Retainer	Power Distribution	$1.84 (x4)
36-1058-ND Battery Holder	Power Distribution	$4.92 (x4)
CR2032 Battery	Power Distribution	$4.66 (x12)
TPS62203 Voltage Step-Down	Power Distribution	$5.22 (x3)
ESP32-DEVKITC-32D	Signal Processing	$19.94 (x2)
ESP32-U4WDH	Signal Processing	$6.21 (x3)
HR1964TR-ND Micro-SD Connector	Data Storage	$2.50 (x1)
AP-MSD256ISI-1T Micro-SD	Data Storage	$12.92 (x2)
		TOTAL: $116.65

Table 3.1.1. Cost breakdown of parts

Labor Cost:

$$Cost = \$43.75/hr * 3\,people * 2.5 * 10\,weeks * 10\,hrs/week = \$32,812.50$$

$$\frac{Cost}{person} = \$43.75/hr * 2.5 * 10\,weeks * 10\,hrs/week = \$10,937.50$$

Total Cost: $\$32,812.50 + \$116.65 = \$32,929.15$

3.2. Schedule

Week	Alkesh	Ritvik	William
2/21	Verify the FSR design with signal amplification through a simulation.	Verify step down to 3.3V and 5.0V designs through simulations.	Finalize the bill of materials and order remaining parts.
2/28	Design the first iteration of the data acquisition circuit schematic.	Design the first iteration of the power distribution schematic.	Design the first iteration of the data storage subsystem schematic.
3/07	Validate the data acquisition circuit.	Validate the power distribution circuit.	Validate the storage circuit.
3/21	Limit-test the data acquisition circuit.	Assemble PCB components.	Enable Bluetooth functionality.
3/28	Start limit-testing FSR circuit and establish linearity range.	Assemble PCB components Begin validation of power on PCB.	Design Front End.
4/04	Integrate FSRs into shoe insole, conduct product testing.	Validate power on PCB.	Testing Bluetooth Data transmission.
4/11	~BUFFER WEEK~	~BUFFER WEEK~	Validate data storage and bluetooth on PCB.
4/18	~BUFFER WEEK~	~BUFFER WEEK~	~BUFFER WEEK~

4. Ethics and Safety

4.1. Ethics

The primary aim of this project is to map the user's foot plantar pressure in order to provide information on the wearer's foot posture. This correlates with IEEE's Code of Ethics Section I.2, which is to "improve the understanding by individuals of the capabilities of conventional and emerging technologies, including intelligent systems [4]," as information is being provided regarding the wearer's health.

The mapping of the user's feet plantar pressure will be done by obtaining a finite set of sensor values from the shoe insole and using software to generate a continuous heatmap visualizing high and low areas of pressure (see Figure 1.2.2). As such, it must be ensured that the visuals seen by the user are as accurate as possible to the data collected. However, in accordance with IEEE's Code of Ethics Section I.5 [4], it must be acknowledged that there will be limitations of this accuracy based on the sensor resolution and sensitivity, the placement of sensors on the shoe insole, and the algorithms used in software to generate the pressure heatmaps.

4.2. Safety

As this is a wearable product meant for regular use, extra steps were taken to ensure the safety of the user and developers in order to prevent injury, in accordance with IEEE's Code of Ethics Section I.1 [4]. The device power is supplied by CR2032 batteries, which were an ideal choice due to their low-profile and robust construction. These batteries utilize a Li/MnO_2 chemistry, which have the potential to explode or cause serious burns caused by the lithium component. As such, ensuring good handling of power distribution is essential for safe operations, and fail-safe mechanisms designed to cut-off battery power are implemented to ensure user safety. For example, Schottky diodes are connected in parallel with the battery to prevent current flow in the opposite direction if battery polarity is reversed. In addition, design considerations such as choosing slim FSRs and keeping the microcontroller/battery assembly as light as possible are considered to improve user comfort. This is particularly important as this product is aimed to be worn for extended periods of time.

In addition to ensuring user safety, considerations to minimize risk are taken within the design process. As this device requires PCBs, the use of soldering is required to attach the components to the board. Soldering produces dust and fumes which are considered hazardous, and so much of this work will be conducted under a fume hood to minimize exposure.

References

[1] A. H. Abdul Razak, A. Zayegh, R. K. Begg, and Y. Wahab, "Foot Plantar Pressure Measurement System: A Review," Sensors, vol. 12, no. 7, pp. 9884–9912, Jul. 2012, doi: 10.3390/s120709884.

[2] Espressif Systems, "ESP32 Series," ESP32-U4WDH datasheet, Aug. 2016 [Revised Oct. 2021].

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[4] IEEE, "IEEE Code of Ethics," *ieee.org*, 2018. https://www.ieee.org/about/corporate/governance/p7-8.html.

[5] Interlink Electronics, "FSR 400 Series Data Sheet," 30-81794 datasheet