ECE 445
Final Report
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Wearable Pediatric Eczema Tracker

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Abstract

Wearable Pediatric Eczema Tracker aims to provide dermatologists and parents objective metrics for eczema severity of the pediatric population. By measuring bioimpedance from multiple electrodes attached around the forearm, dynamic movement of muscles and therefore the specific gesture involved in scratching can be captured. The impedance data combined with other sensory information is streamed to a host PC via Bluetooth Low Energy in real-time, which through a convolutional neural network, is used to determine if the user is scratching or not. The result is translated into a scratch severity index (SSI) and displayed to a multi-purpose dashboard.

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1. Introduction

Eczema, also known as atopic dermatitis, is one of the most widespread skin conditions affecting nearly 20% of the world population and is more common and severe to young children and infants [1]. Its main symptoms are severe itching and skin cracking which eventually damages the skin. Until this day there is no known universal cure and what dermatologists suggest is to find the "triggers" which may involve consumed food, environmental exposures, or chemicals and to isolate the patient from it. The biggest problem is that it is nearly impossible to track down such triggers as symptoms of itchy skin rash may arise long after 24-48 hours from making contact [2], and since infants and children have limited means to convey their symptoms objectively for dermatologists to diagnose. There should be a viable alternative for such people in need.

Our group finally made a low-cost wearable eczema tracking sensor specialized in the pediatric population that helps dermatologists treat their patients using the scratch monitor. It is equipped with bioimpedance tomography, accelerometer and temperature sensors for high scratch detection accuracy. Users can wear the device on the wrist of either arm with the best comfort in a specific time of interest such as during sleep, where scratching events are detected directly through the inference model in host PC and logged. An indication is given in green, yellow or red LED embedded in the device, depending on the severity of scratching through number and duration of scratches per timeframe, so that guardians can notice right away. Users can also view the daily and hourly trend with an interactive dashboard to see the general trend in eczema severity.

Our prototype is displayed in Appendix B.

2. Design Procedure

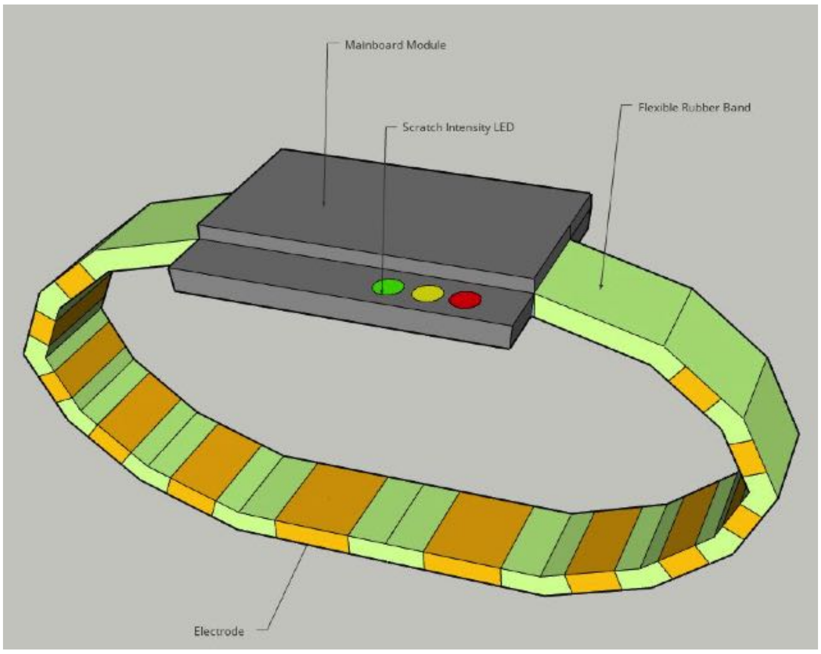


Figure 1: 3D Model design of the device

The Wearable Pediatric Eczema Tracker is a watch-like device that can be worn on the wrist with a flexible band with 8 Electrodes attached evenly on it. On the main module, multiple LEDs are placed to indicate scratch severity.

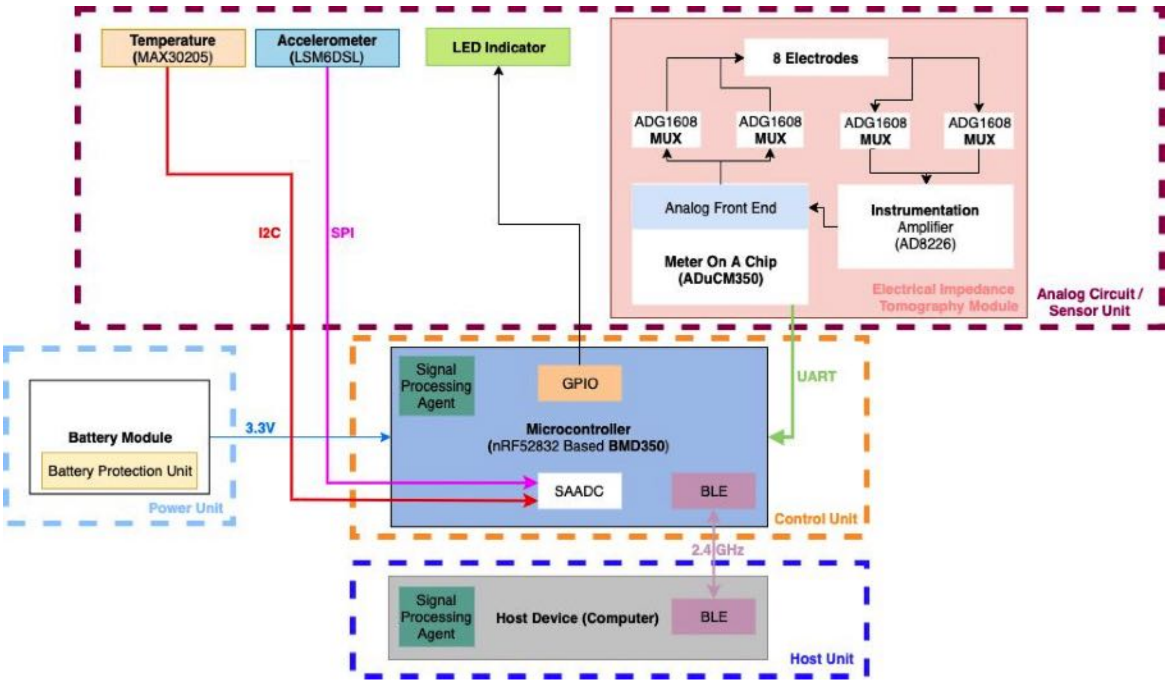


Figure 2: Block diagram of our project

We collect an array of bio-signals from the **Analog Circuit Unit** by utilizing the ADC peripheral on the BMD350 which is based on nRF52832 SoC. The **Control Unit** then orchestrates the conversion of the analog signal of the temperature, accelerometer and EIT data, packages up into one and transfers that package to the host device through Bluetooth Low Energy (BLE 2.4GHz). **Power Unit** provides the necessary power to the **Control Unit** and the **Analog Circuit Unit**. The streamed data from the BMD350 chip are transmitted to the **Host Unit**, processed and displayed through a web-based dashboard.

2.1 EIT Module

2.1.1 Overview

Electrical impedance tomography (EIT) is a tomographic representation of a specific part of the body using multiple electrodes [6]. We can achieve this by selecting 4 electrodes using multiplexers: two for injecting current via current source and two for voltage measurement and switching in specific order. We used EIT to capture the impedance difference in muscle movement involved in scratching activity.

2.1.2 High level description of ADuCM350

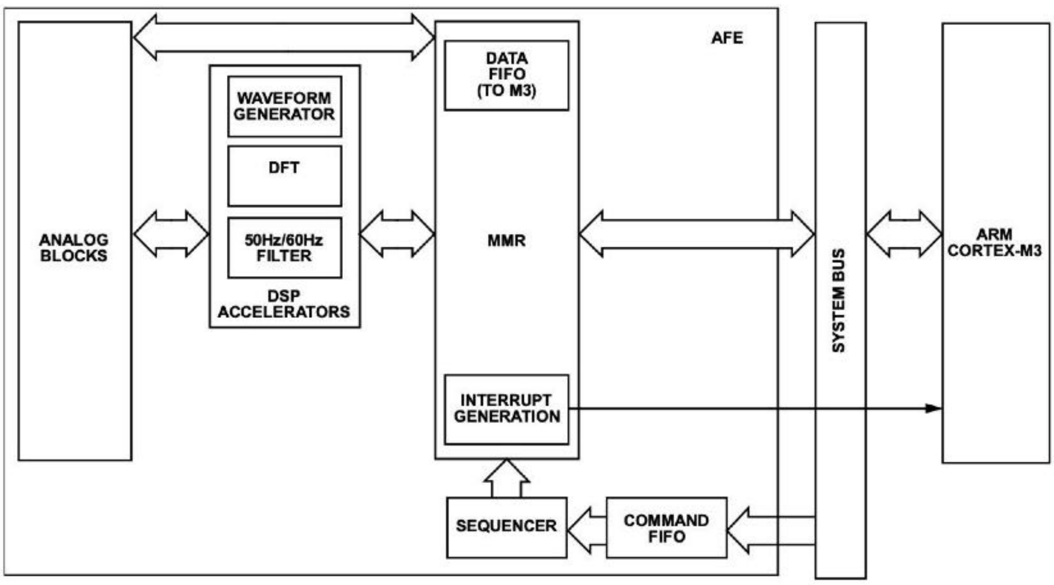


Figure 3: ADuCM350 Analog Front End Control Block Diagram[3]

For bioimpedance measurement, the sensor-controller that we are using is Analog Devices' ADuCM350 meter on-a-chip with integrated 16MHz ARM Cortex-M3 microprocessor. As of today, this chip is the only available on-the-shelf model that supports the 4-pole bioimpedance measurement scheme with low power usage for wearable device applications with an application note [4]. For tasks including various measurements, it has dedicated 16MHz sequencer working independently from processor to lower the operation burden.

Combined with 160kSPS 16bit-ADC and 2048-point DFT, it takes 12.8ms (79Hz) for a single DFT measurement with embedded DFT engine [3]. However, we must have two DFT measurements (R_tia, R_ana) to derive the impedance which meant the actual sampling rate for impedance is 38.5 Hz, which is significantly short compared to our requirement ((188~240 Hz = (28~40) channels * 6 Hz). Therefore it was necessary to come up with a software-based solution using raw ADC values from each sequence runs.

2.1.3 Sequencer Programming

The analog front end sequencer in ADuCM350 is controlled with an array of 32bit FIFO instructions. As specified on lines 230 and 311 in Appendix F, we've set the frequency and amplitude of the excitation signal for the sine wave with 0 phase offset. Since each instruction is progressed on a single clock with the exception of wait calls, with a combination of ADC conversion timing control, is used to get an exact number of raw ADC values. For our implementation, we've set to get 64 ADC values for both R_tia and R_ana.

Based on this instruction and timing diagram for ADC conversion[5], the total time it takes for the sequencer to finish the instructions is 1.44ms with calculation. This gives us an upper bound for a sampling rate of 792Hz, but it is unlikely to hit value this due to significant overhead before and after each sequence runs.

2.1.4 Impedance Calculation

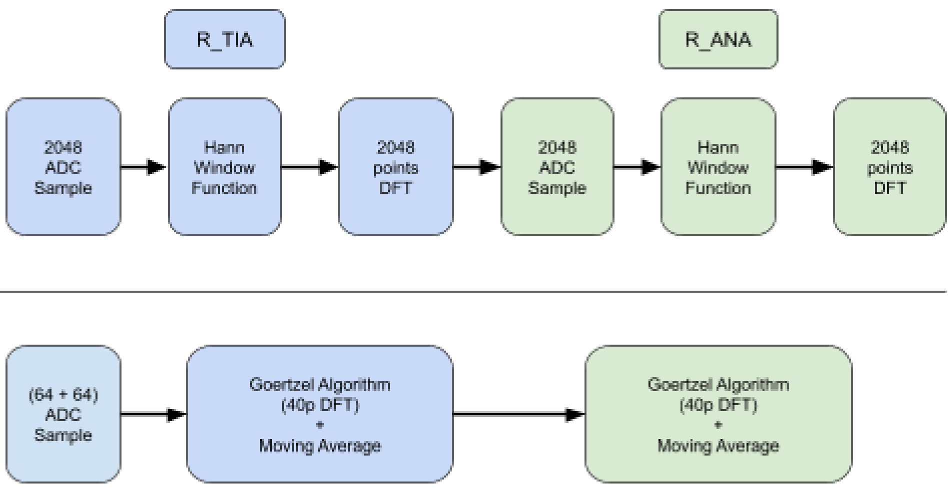


Figure 4: DFT Based measurement Flow (top) Software based measurement Flow (bottom) [3]

$$|X[k]|^2 = X[k]X^*[k] = s^2{}_k[N] + s^2{}_k[N-1] - 2\cos(\tfrac{2\pi k}{N})s_k[N]s_k[N-1] \qquad \text{(eq 2.1.1)}$$

```
c = 0
b = 0
Start n = 1 : N
        a = x[n] + q * b - c          | q = 2cos(2πk/N)
        c = b                         | s[n-2] = s[n-1]
        b = a                         | s[n-1] = s[n]
END
|X[k]| = sqrt(a * a + c * c)
```

Figure 5: Pseudocode for the Goertzel Algorithm[3]

The DFT engine capable of 79Hz data rate is replaced with a software-based method. Since our goal is to measure the magnitude of excitation frequency, the Goertzel algorithm (eq 2.1.1, Figure 5) was implemented for single point DFT calculation.

Furthermore, the excitation frequency of 40kSps was chosen to eliminate the q coefficient and accelerate the calculation speed which would directly reflect on impedance measurement speed. We've also replaced the Hann window function with an 8-point moving average, which can be implemented without multiplication or convolution, for removing FFT boundary effects.

2.2 Software Module

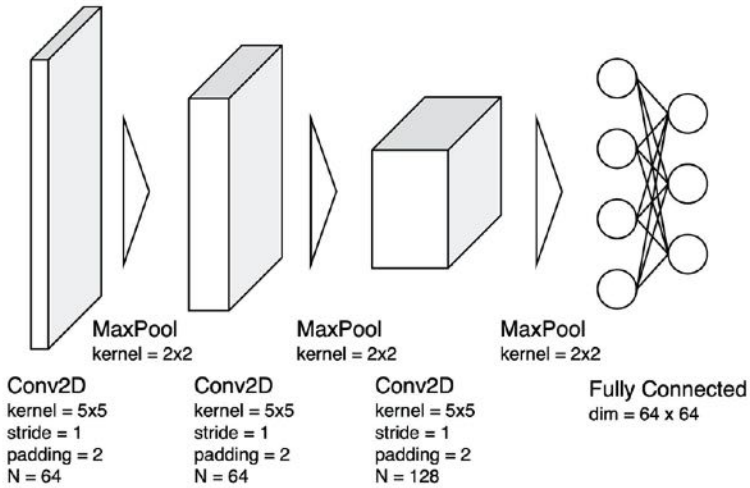


Figure 6: Implemented Convolutional Neural Network Model

For detecting scratching activity we used a 2-dimensional convolutional neural network. For the input, preprocessed 40 channels of impedance data with a 5-second window was used. The preprocessing steps include 2nd order Butterworth filter of 0.5~5Hz and min-max normalization. The output is three channels with each representing different types of activity: noise, waving motion and scratching.

2.3 Host Unit Software

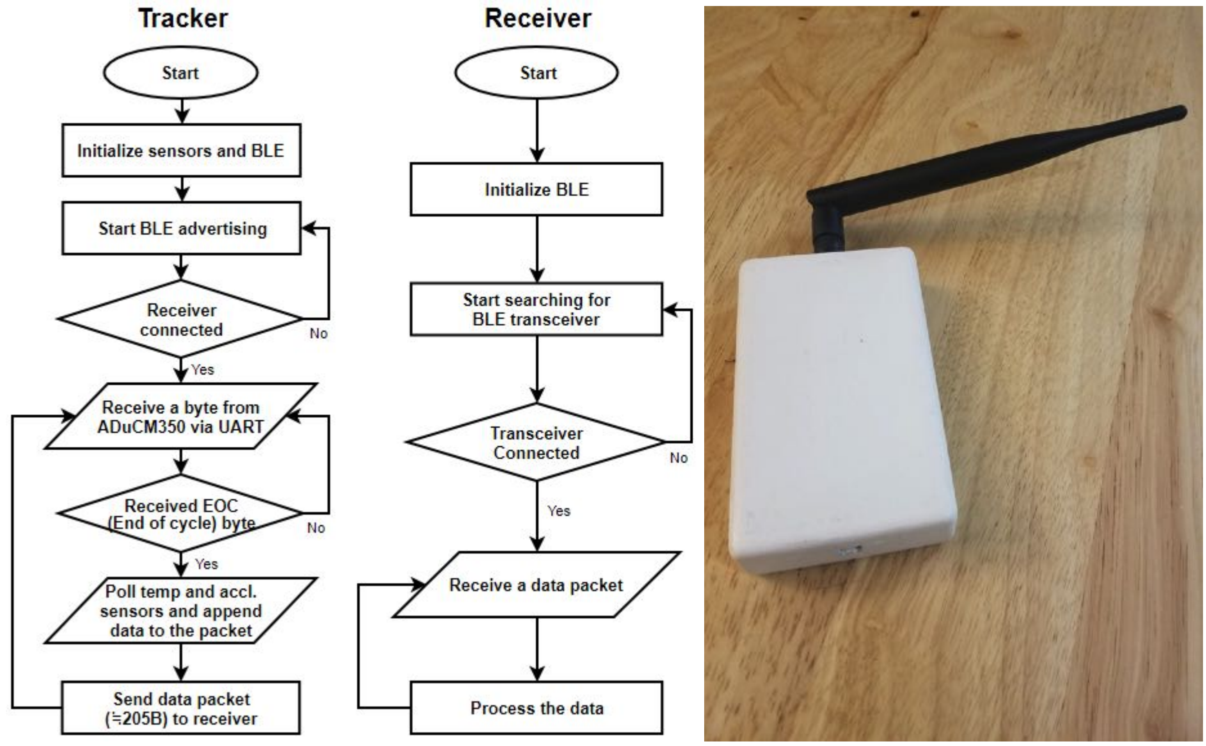


Figure 7: Bluetooth Software Flowchart for the sensor and the host (receiver) device (Right)

The flowchart on the left shows how BLE module is controlled from the sensor device and the host device. On the right is nRF52832-based BLE receiver for the host computer.

3. Design Verification

3.1 EIT Module

3.1.1 Sampling Rate Requirement - Setup

For detecting scratch motion each channel must have sampling rate of minimum 6Hz which is the Nyquist rate of maximum scratching motion frequency [7].

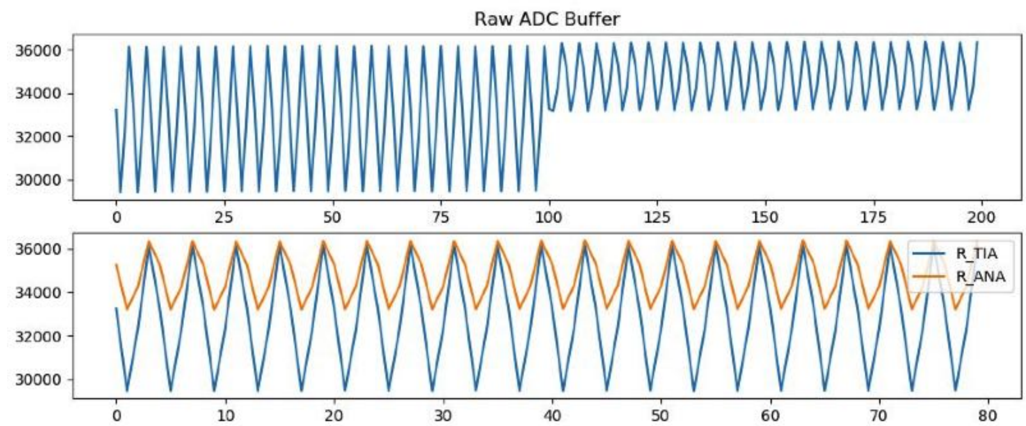


Figure 8: Raw ADC Value

For testing and development, we used the EVAL-ADUCM350 evaluation board for impedance measurement and NRF52832-DK for serial connection to PC.

Before the actual calculation, we directly extracted raw ADC values through J-Link debugger for inspection. The upper plot in Figure 8 shows the result of the buffer with instructions specified in Appendix F with 100 ADC measurements on each R_tia and R_ana. We can observe the difference in measurement amplitude on the 40kHz range, which would be translated to impedance calculation as accordingly.

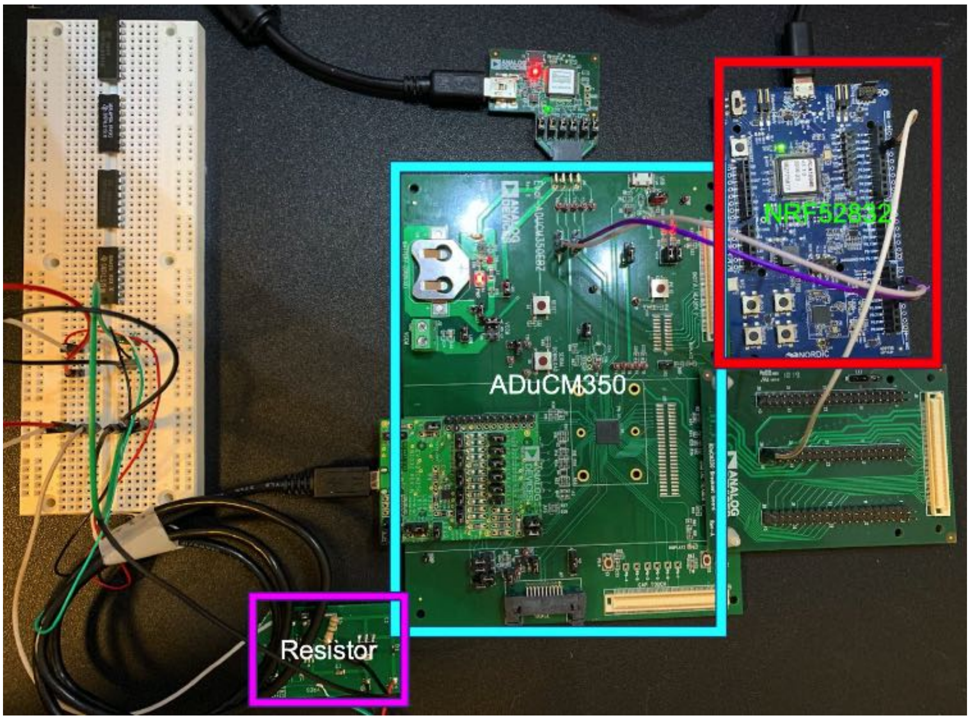


Figure 9: EIT Module Test Setup

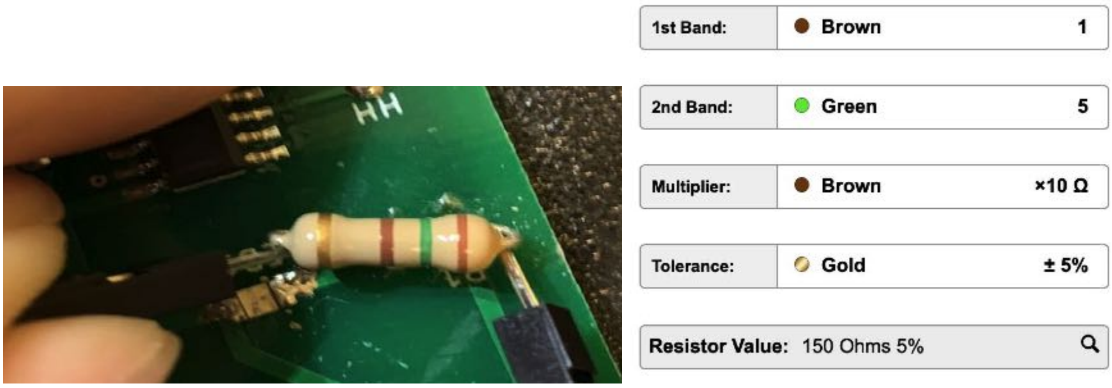


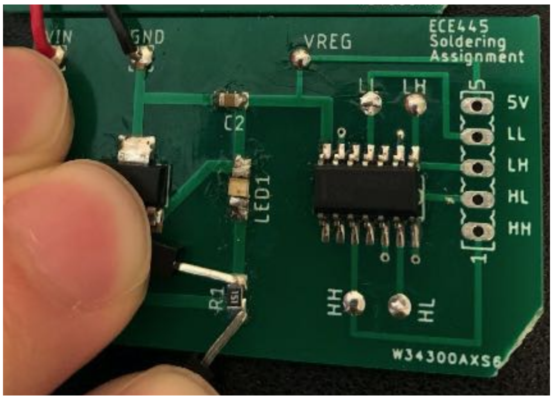
Figure 10: Impedance Measurement Setup

We used two different resistors that were previously used in soldering assignment: RC0805JR-07150RL and other having 4-color band as in Figure 10.

3.1.2 Sampling Rate Requirement - Verification


```
Serial Raw Data:
 b'000194f8fffef5510000437afffffc1300019432fffef93b00004315fffffc7000019021fffef3c0000042feffffb7f00019853fffef97e0000
00018fcefffef9a60000428bfffffc4500019037fffef3c400004304fffffb890001947bfffef7a800004344fffffc4e0001940ffffef77e0000433
Sampling Rate: 302.7547676449783Hz
Measured Impedance: 148.45393428406382
```


Figure 11: Realtime Received Data on 150Ω 4-color Resistor




```
Serial Raw Data:
 b'00018720fffef334000042d7fffffa9300018d87fffef86b00004340fffffbc300018d63ff
000189f2fffef663000042fafffffb3800018bccfffef84300004310fffffba300018973fffe
1896cfffef3480000431afffffad200018d13fffef6a800004356fffffb8400018c7dfffef6e
f1fffef6fa000042b1fffffb2500018d22fffefcf1000042f2fffffc3c000186e7fffef34a00
ffef36c00004368fffffb1a00018c6dfffef7a30000432dfffffb9a00018991fffef3810000
f6e90000434cfffffb8d00018cd4fffef94b00004319fffffbd600018be2fffef9060000431
a00004283fffffaeb000189befffef2bb00004334fffffac700018d76fffef85b00004345fff
Sampling Rate: 287.50805001893616Hz
Measured Impedance:

150.48652392239535 150.45570157274028 150.4695127821032 150.4737013794798
150.45570157274028 150.4695127821032 150.4737013794798 150.499043176508
150.4695127821032 150.4737013794798 150.499043176508 150.47751331390316
150.4737013794798 150.499043176508 150.47751331390316 150.51119215374942
150.499043176508 150.47751331390316 150.51119215374942 150.483126492077
150.47751331390316 150.51119215374942 150.483126492077 150.6327832093065
150.51119215374942 150.483126492077 150.6327832093065 150.47804504291494
150.483126492077 150.6327832093065 150.47804504291494 150.55466533456126
150.6327832093065 150.47804504291494 150.55466533456126 150.45938068617826
150.47804504291494 150.55466533456126 150.45938068617826 150.4417616493416
```


Figure 12: Realtime Received Data on 150Ω RC0805JR-07150RL

As shown in Figure 11, the derived impedance value was 148.45Ω, which is well under the 5% tolerance range. The test was further conducted on assignment boards with actual RC0805JR-07150RL, where value was I obtained was average of 150.49Ω. The sampling rate was in steady rate of 302.75Hz on single channel and 287.5Hz with mux switching enabled. As this data rate is evenly distributed into 40 channels, **sampling rate on each channel is 7.18Hz**, therefore meeting the requirement.

Finally, it should be noted that our final sampling rate for each channel was 15Hz, after further optimization and double buffer implementation.

3.1.3 IEC60101-1 Requirement - Setup

As the device is intended for direct contact with human skin, the hardware must be equipped to comply with IEC 60101 standards, which in our case is that current should not exceed 300µA [4]. For validation, we used the IDEAL 61-486 multimeter to measure both AC and DC.

3.1.4 IEC60101-1 Requirement - Validation

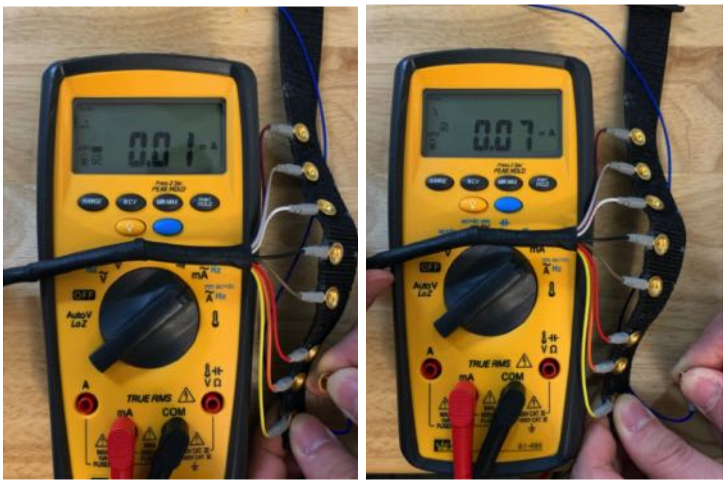


Figure 13: Current Measurement (Left:DC, Right:AC)

As shown in Figure 13, the maximum current we observed was 70µA, therefore meeting the requirement.

3.1.5 Tomography Image Requirement - Setup

For tomography image reconstruction we used an acrylic cylinder with 15cm in diameter. 8 Electrodes are placed evenly and tap water with 3cm depth. We used two plastic objects and captured the impedance in various locations.

3.1.6 Tomography Image Requirement - Validation

We used pyEIT for tomographic reconstruction[12]. The results are attached in Appendix E. As the figures suggest, the reconstructed images does match well with actual placements.

3.2 Software Module

3.2.1 Setup

To train and test the machine learning model, we collected 40 channel impedance on three classes of activity: noise, waving and scratching. In total, we gathered 400 data points that are comparable to the UCR time series dataset in terms of numbers. The data were randomly split 50/50 with one used for training and others for testing. The model was trained over 5000 iterations using PyTorch with NVIDIA RTX2080.

3.2.2 Verification

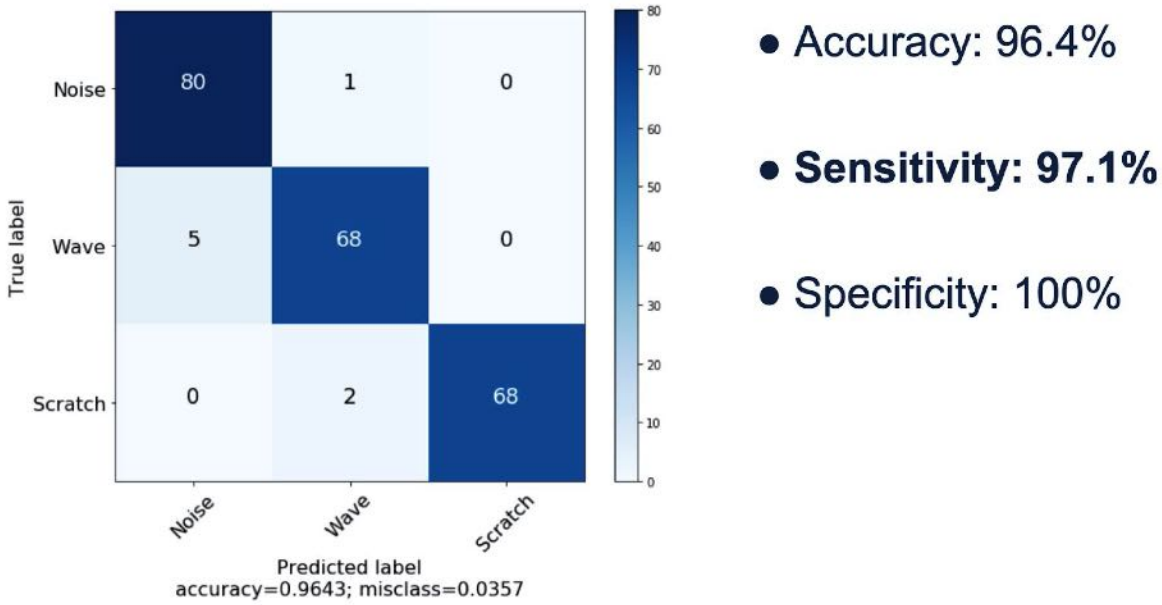


Figure 14: Confusion matrix of machine learning model

We compared the results on the test dataset and created the confusion matrix as in Figure 14. As the results suggest, our machine learning model had 97.1% sensitivity in scratch detection, therefore, meeting the requirement of a minimum of 90% [7].

3.3 Analog Circuit Module

3.3.1 Temperature Module Verification

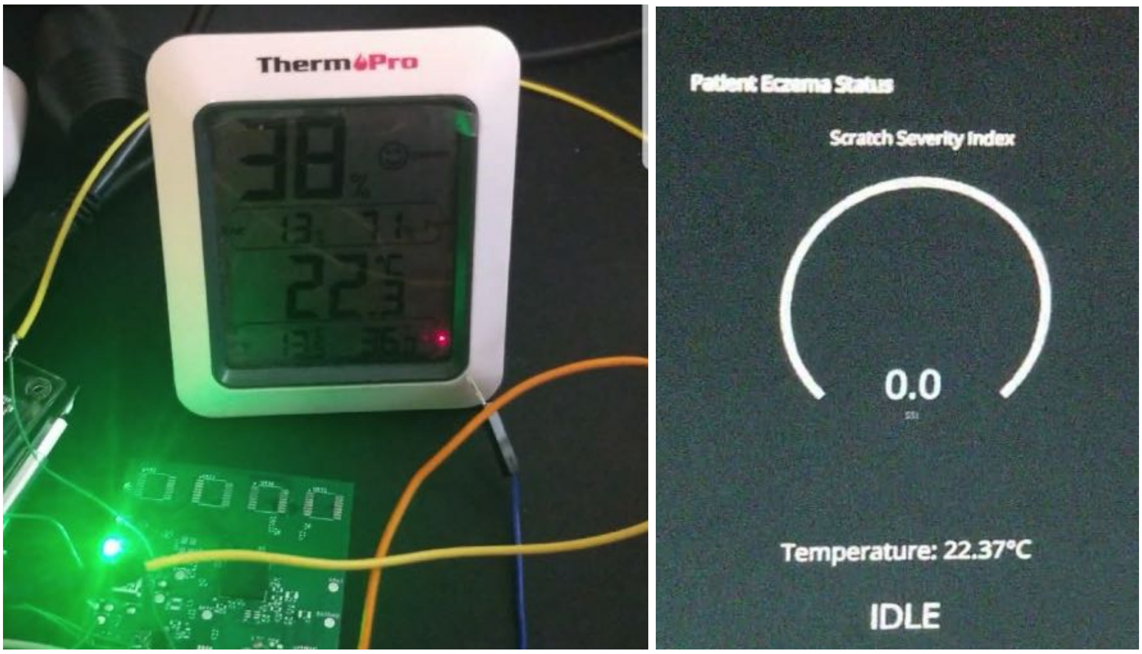


Figure 15: Digital Thermometer (Left), MAX30205 Value (Right)

As shown in Figure 15, we validated the temperature module by buying a digital thermometer named ThermPro TP50 product and comparing the ambient temperature between those two. The room temperature was 22.3 degrees Celsius and the MAX30205 temperature sensor we used measured the temperature to be 22.37 degrees Celsius. Error range is 0.31%.

3.3.2 LED Indicator Module Verification

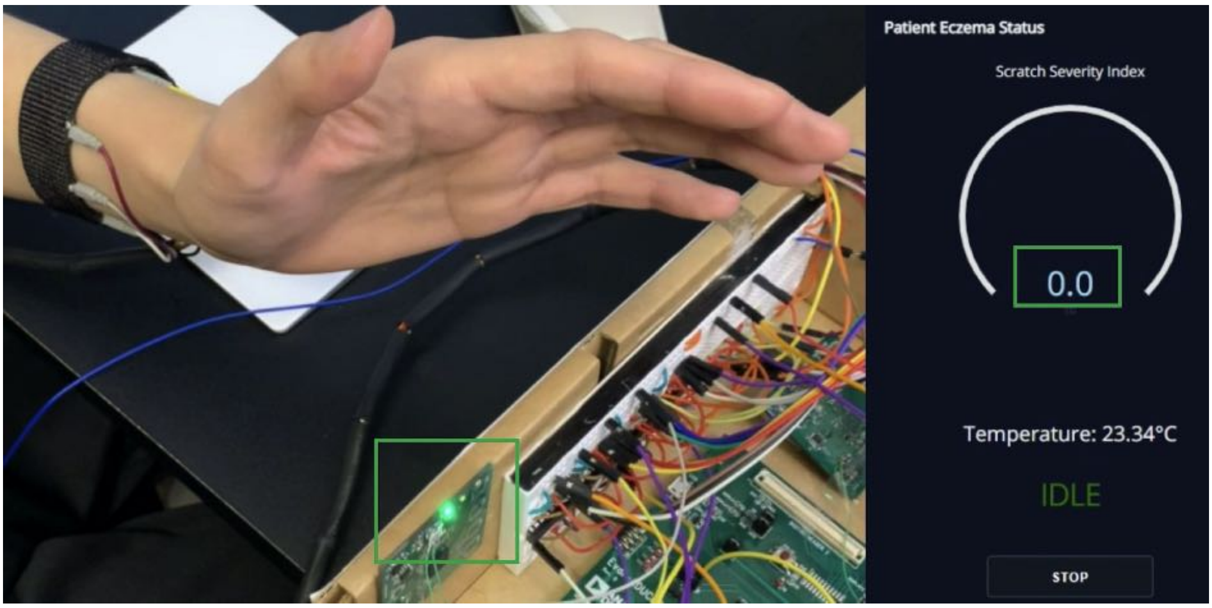


Figure 16: LED in Idle State

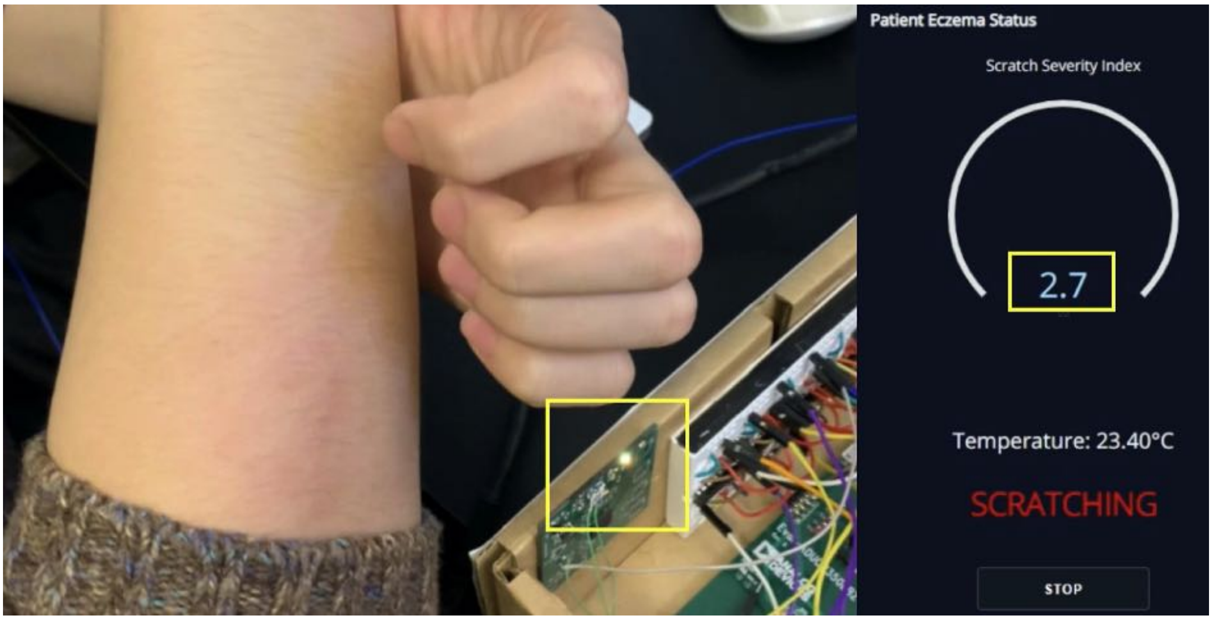


Figure 17: LED in Mildly Scratching State

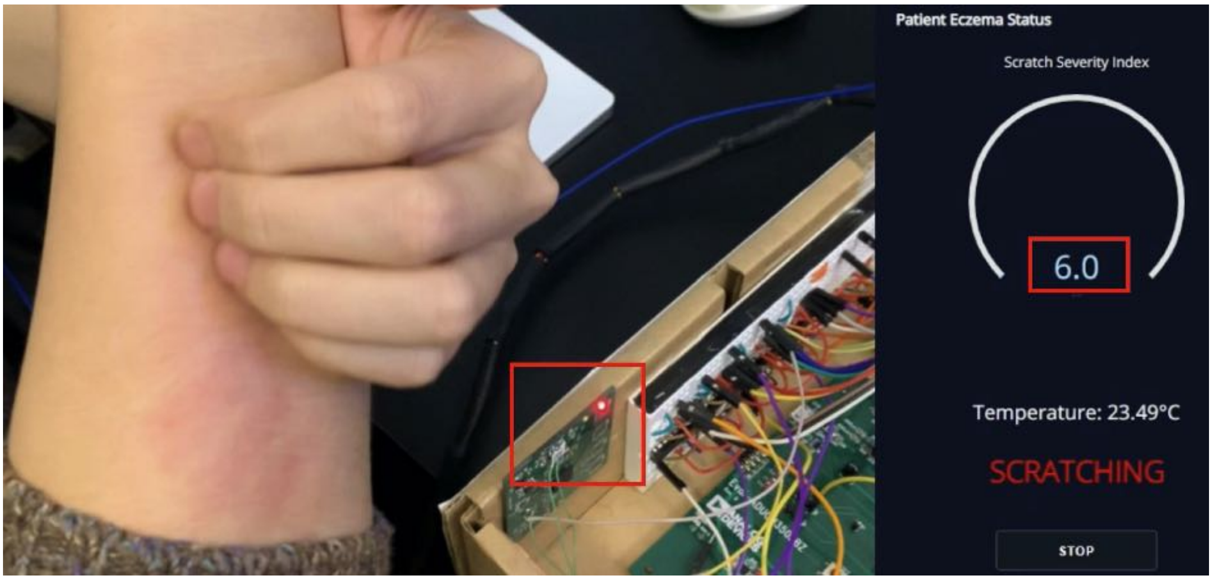


Figure 18: LED in Severely Scratching State

As shown in Figures 16, 17, and 18, LEDs show a difference in scratching activity. As the scratch severity index (SSI) is below 1.5, the green LED shows up indicating the patient is not scratching (or in idle state). If SSI is between 1.5 to 5.0, the yellow LED turns on indicating that the patient is mildly scratching and if SSI is above 5.0, the red LED turns on indicating that the patient is severely scratching. From the figures, the inflammation on the spot user scratched also worsens as the user scratches more severely.

Thus, from Appendix A, the LED module requirement has been validated.

3.4 Power Module

3.4.1 Battery Module Verification

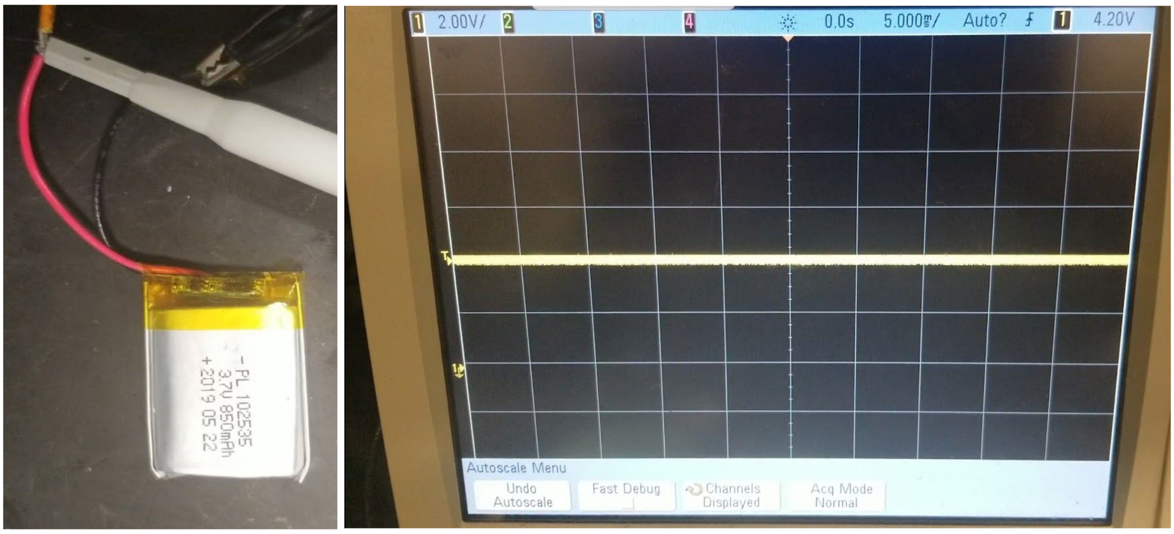


Figure 19: 3.7, 850mAh Lipo Battery (Left), Fully Charged Voltage (Right)

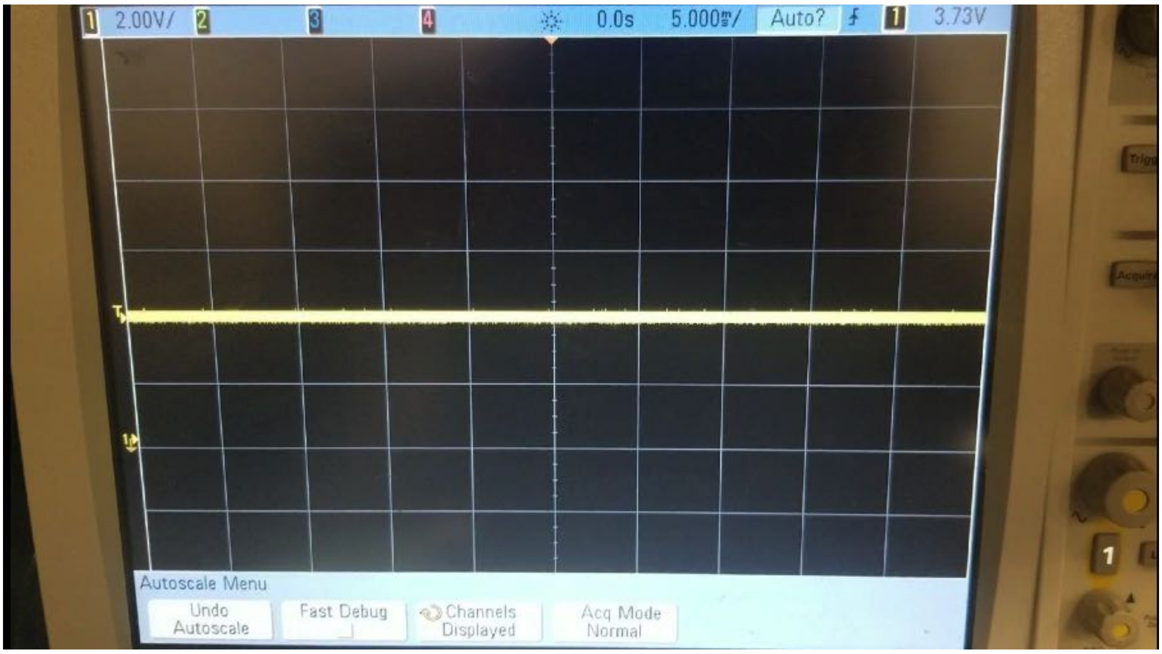


Figure 20: Battery in normal 3.7V

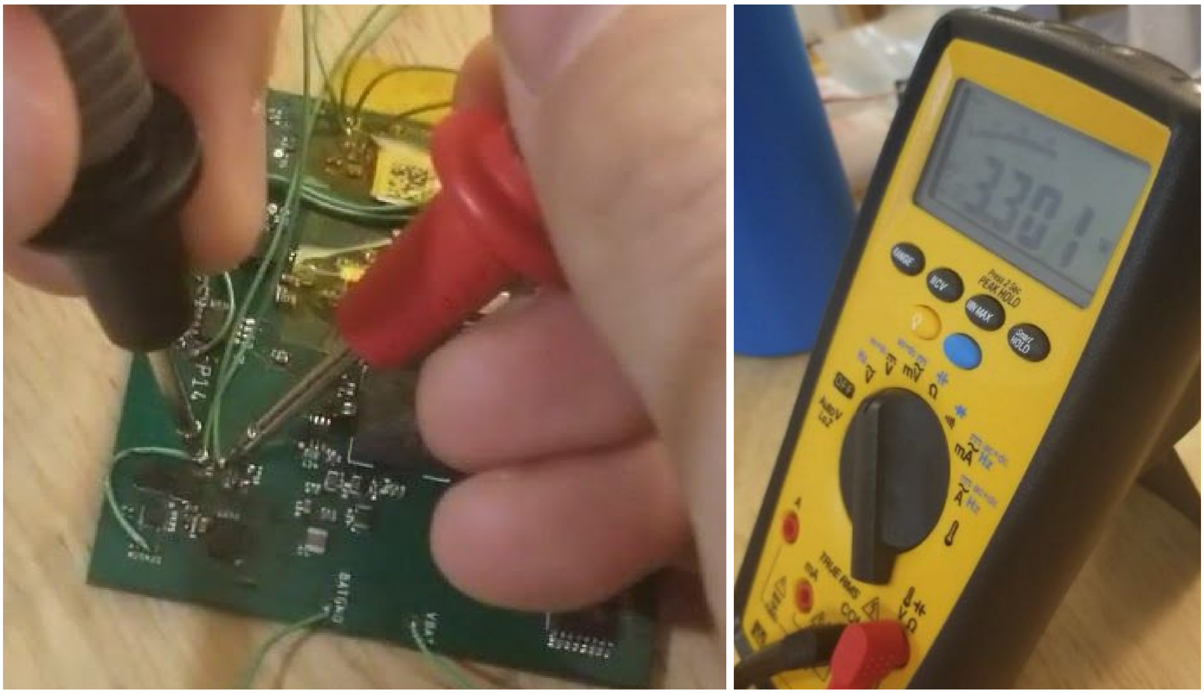


Figure 21: Battery Through TPS62740 Buck Converter Supplying Constant 3.3V

There were originally 2 requirements for power module according to Appendix A. The 3.7V battery with 850mAh [10] has to provide fixed 3.7V in the tolerance of ±3% requirement is validated by Figure 20 above. 3.73V is the reading for the oscilloscope and therefore the tolerance range is 0.81% which exceeds the requirement. The second requirement that the charged voltage after protection circuit should not exceed 4.2V is validated by Figure 19 above. All have been used by the oscilloscope in ECE445 and the voltage value is on the top right corner of the oscilloscope screen.

The third requirement we added, later on, is that when 3.7V 850mAh Lipo battery is connected with the TPS62740 step-down buck converter, it should supply constant 3.3V to the whole circuit. We have tested out by soldering every component for the power circuit with the protection unit to test out the pads for VDD and GND test pads on the circuit and came out as a constant 3.3V using the IDEAL 61-486 multimeter according to Figure 21 above.

3.5 Control Unit

3.5.1 Bluetooth Low Energy (BLE) Module Verification

Our team's required minimum data bandwidth calculation was:

EIT Data - 400 Samples/s × 2 Bytes/Sample = 800B/s
Accl. Data - 10 Samples/s × 2 Bytes/Sample = 20B/s
Temp. Data - 1 Sample/s × 1 Byte/Sample = 1B/s
Total: 821 Bytes/s

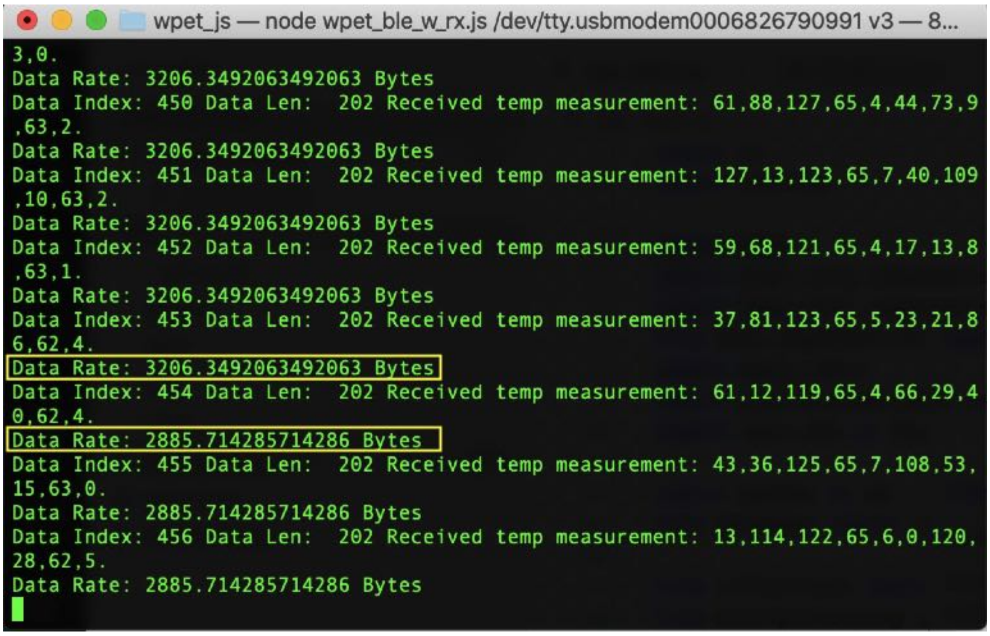


Figure 22: Bluetooth Low Energy Data Transfer Rate Validation

According to Figure 22, our team was able to achieve maximum BLE transfer rate of **3000B/s or 3KB/s** which exceeds the overall BLE Module requirement.

Moreover, we managed to pre-compress the sensor data so that one cycle of 40-channel measurement was only 200 bytes, allowing the sensor to continuously send complete EIT data packet at 15Hz. This also exceeded our minimum requirement of 6Hz, the Nyquist rate of scratching motion.

4. Costs

4.1 Labor

Team Member	Hourly Wage [$ / hr]	Weekly Hours	Number of Weeks	Multiplier	Cost per Member
Sung Hoon Lee	34.21	15	16	2.5	$20,526
Dong Hyun Kim	34.21	15	16	2.5	$20,526
Hyoungjo Hahm	46.40	15	16	2.5	$27,840
				Total Cost	**$68,892**

4.2 Parts

Part Name	Description	Manufacturer	Quantity	Unit Cost	Total Cost
LSM6DSLTR	Accelerometer	ST Microelectronics	1	$4.09	$4.09
MAX30205MTA+T	Temperature Sensor	Maxim Integrated	1	$3.64	$3.64
BMD350	SoC Microcontroller	Nordic Semiconductor ASA	1	$11.27	$11.27
BQ29700DSER	Battery Protection Unit	Texas Instruments	1	$0.69	$0.69
CSD16301Q2	MOSFET	Texas Instruments	2	$0.54	$1.08
TPS62740DSSR	Bluetooth Voltage Regulator	Texas Instruments	1	$1.74	$1.74
ADUCM350BBCZ	16 bit Low Power Microcontroller	Analog Devices Inc.	1	$16.52	$16.52
ADG1608BRUZ	8 Channel MUX	Analog Devices Inc.	4	$8.80	$35.20
AD8226BRMZ	Output Instrumentation Amplifier	Analog Devices Inc.	1	$5.06	$5.06
B0749KNFL3	3.7v 850mAh Battery	Three Stone	1	$4.75	$4.75
				Total Cost	**$84.04**

5. Conclusion

5.1 Accomplishments

The Wearable Pediatric Eczema Tracker was able to accurately track eczema condition through measuring the severity of scratching. Using 8 electrodes, the bioimpedance of the forearm was captured in high-speed corresponding to the muscle movement involved in scratching motion, which was sent to the host PC combined with other sensory data. With high accuracy impedance measurement of 40 channels and convolutional neural network classifiers, our eczema tracker was able to determine if the user is scratching or not in real-time. This result was translated into scratch severity index and displayed to an interactive dashboard that dermatologists and parents can use to monitor the user's severity of eczema.

5.2 Ethical Considerations and Safety Hazards

According to the IEEE Code of Ethics, technologies, by all means, must avoid causing human injury [8]. Since the product is a wearable technology that directly touches and wraps around a human body with electric circuitry, there are many possible safety concerns that must be handled in order to comply with the code. For example, the circuitry contains a battery, which might cause a skin burn when the electric flow is poorly designed or handled and result in heat up in the circuit. The electric current must be strictly controlled and cut off in necessary situations where any malfunctioning is detected.

As the device is intended for direct contact with human skin, the hardware must be equipped to comply with IEC 60101 standards. Therefore we must add additional bio-isolation circuitry to ensure the upper limit for current injection and prevent any DC voltage through an additional instrumental amplifier (AD8226), capacitors for DC removal and current limit resistors with values according to the voltage output of AFE in ADuCM350. In addition, the wristband material must be strictly controlled so that the product does not cause any form of irritation to the user's skin.

From the Battery module, we will be using a 3.7V LiPol battery as our power source, which has on average a capacity of 800mAh and electrical concerns such as discharge will be at a minimum. Other than electric hazards, the wrist band might also affect blood flow if worn too tightly. A way to properly adjust band should be provided to prevent adverse effects on the wearer's body while ensuring signal quality to be high enough for smooth processing.

The device is stretchable to some extent in order to fit patients' wrist and the electrodes should stick right on to the skin in order to minimize the noise. Depending on the subject type, 8~32 electrodes are placed evenly around the device for even spatial resolution. Since we will be measuring and storing biological metrics which is sensitive and personal, it is necessary to come up with a reliable way to protect privacy. For example, all stored data can be encrypted and the local raw data can be deleted right after the analysis. Also, we may obtain the user's consent to process his or her health data before conducting any measurements.

Lastly, in order to detect scratching, we use colored LED indicators: Green for normal activities, yellow for mild scratching and red for severe scratching. According to IEC 60601-1-8 standards [9], in the collateral standards, tests and guidance for alarm systems in medical equipment are necessary using colors of indicator lights. Red indicates that immediate user intervention is required or used in dangerous situations. Yellow indicates that "prompt" user action or attention required or caution. Green indicates a normal situation and equipment is ready to be used. We will be following IEC 60601-1-8 collateral alarm standard and implement an alarm system into the wearable device.

5.3 Future Work

With some additional modification with the electrodes, the device can also be strapped around the chest to monitor the Respiratory Distress Syndrome as well as any lung-related diseases.

Reaching out further, this device can be utilized as an nRF Connect Platform for mobile connection/application that will eventually be enhanced with a machine learning model to detect scratched location and places went using GPS data from the sensor. That way, dermatologists can more accurately predict the cause of eczema. Additionally, users can use their smartphone cameras to detect inflammation or infection for the scratched area.

References

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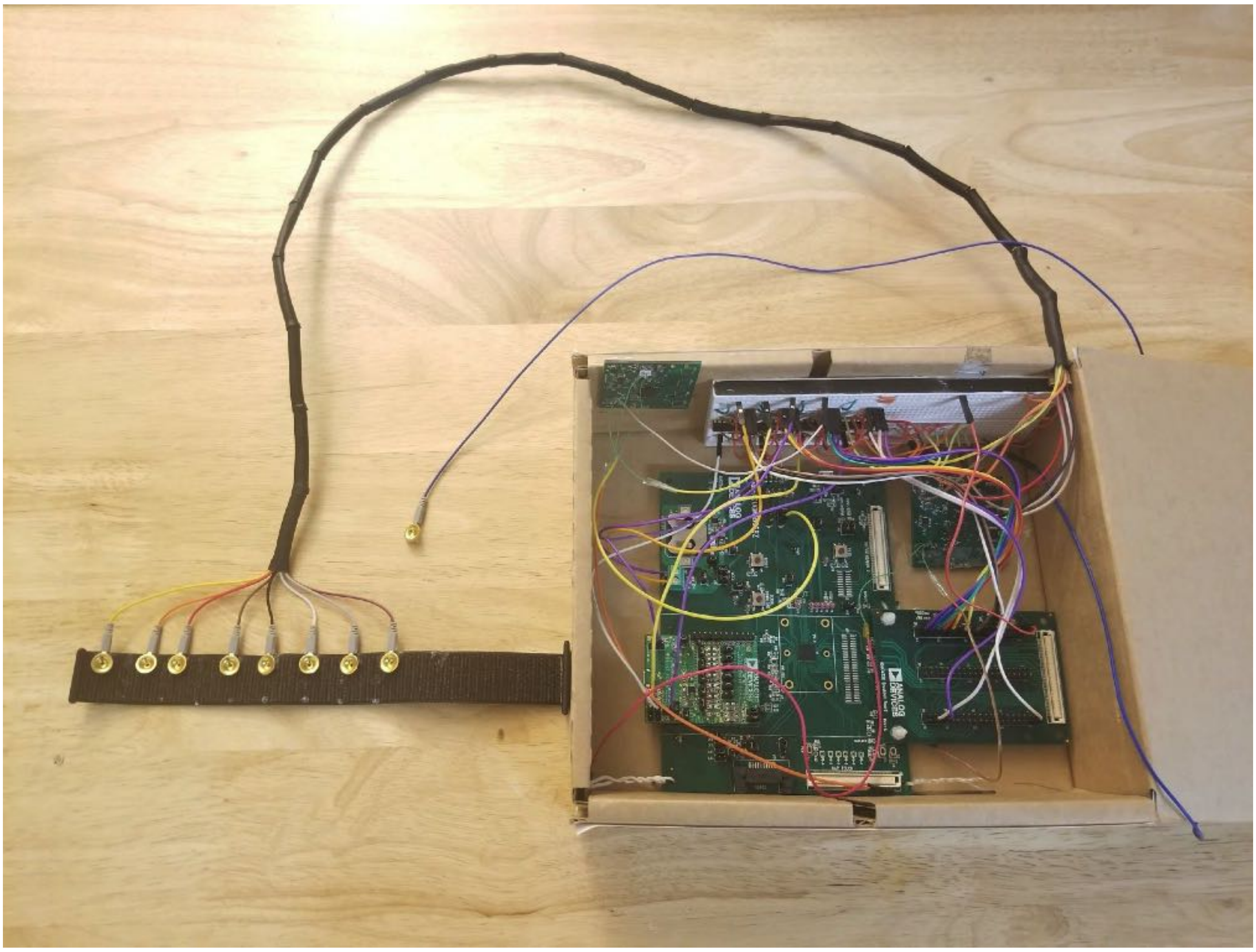
Appendices

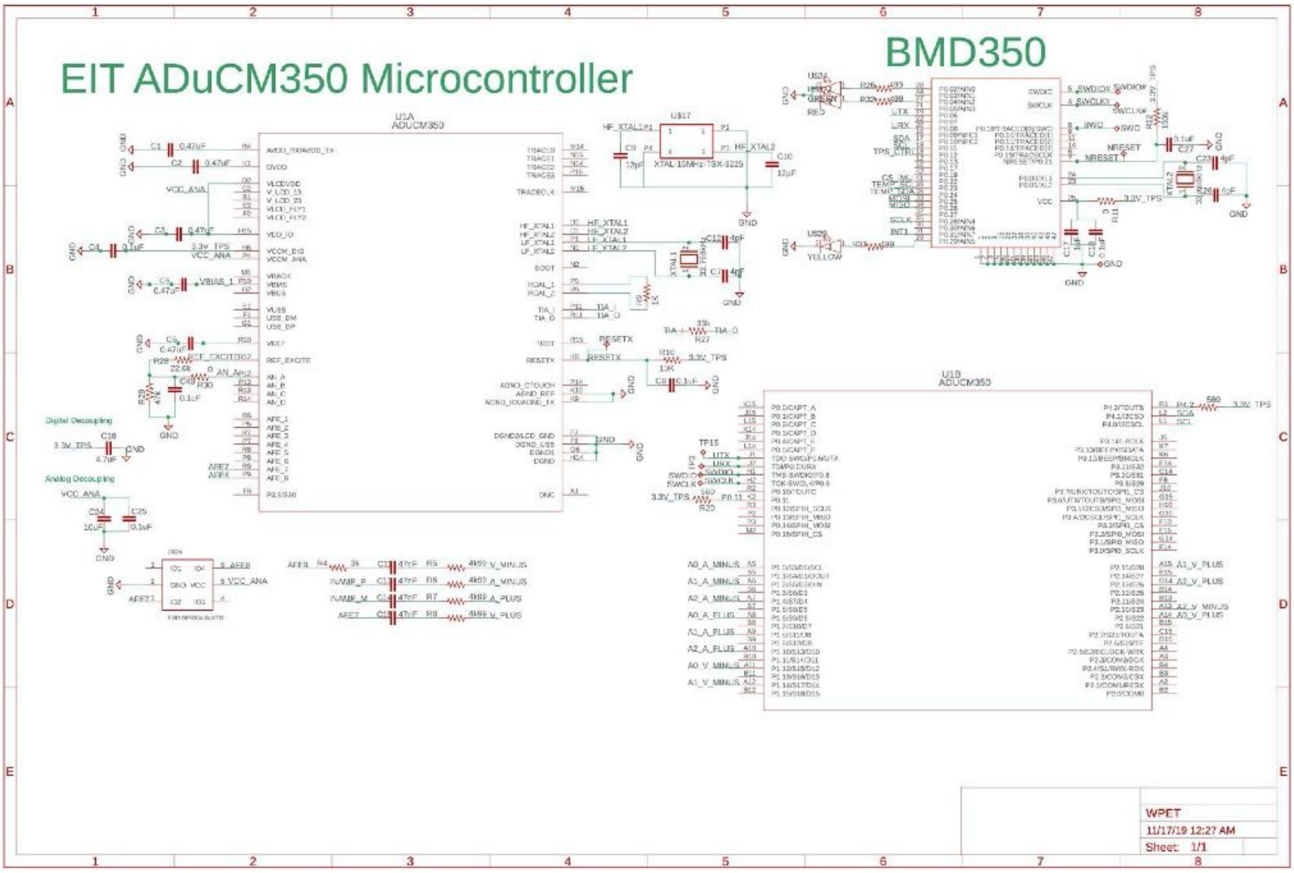
A. Requirements and Validation Table for Each Module

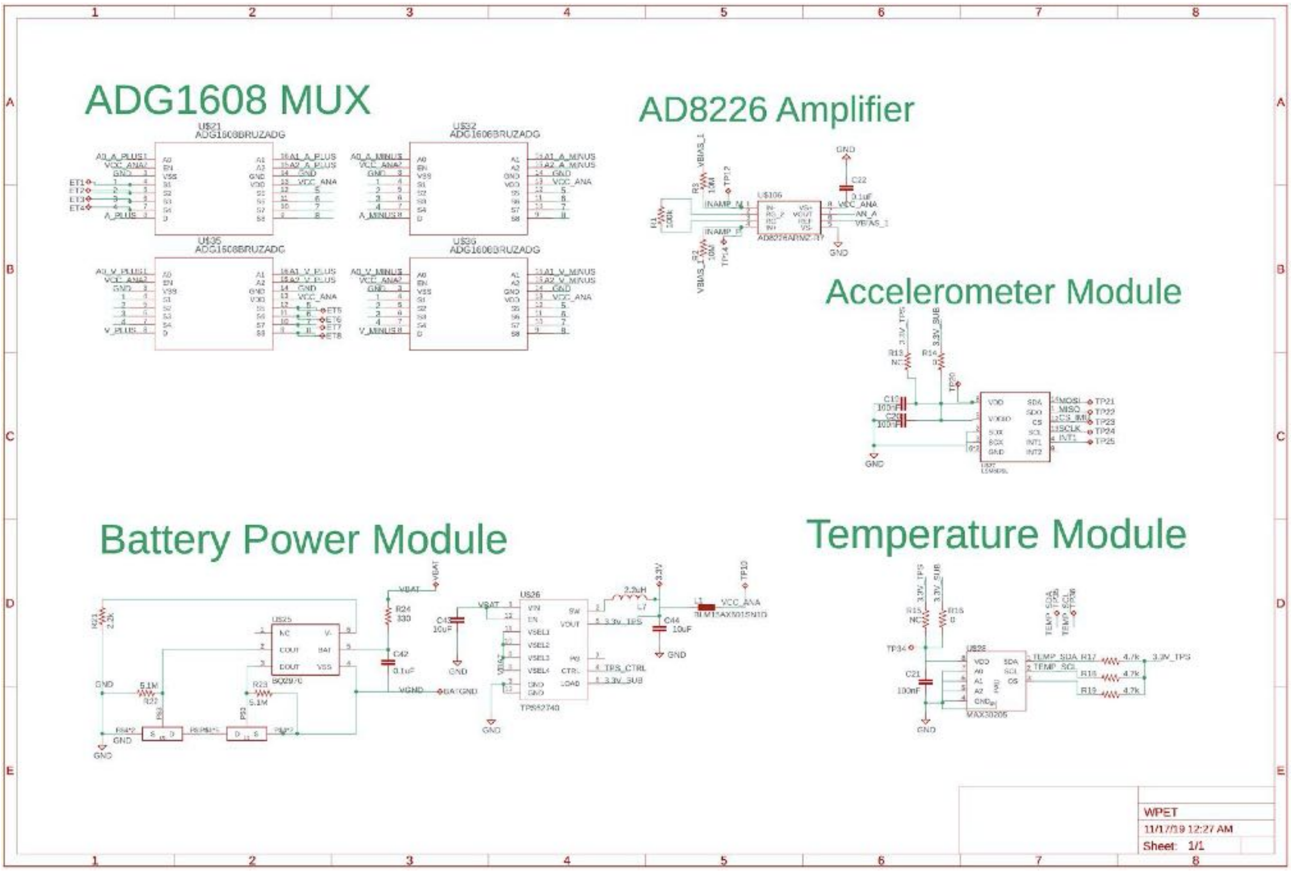
Requirements	Validation	Verification Status(Y/N)
1. Bioimpedance must be measured with minimum sampling rate of 6Hz for each channel	1. ADC in ADuCM350 is capable of pulling data at 160 kSPS. With <30kHz excitation AC current, therefore all the delays for measuring one sample of each channel must be summed and compared with the timing requirement (ex: 2.5ms for 40 channels with 10Hz sampling rate) A. Use an oscilloscope to measure the time delay for excited current to converge in steady state in <30kHz B. sum with minimum sampling number of ADC required for impedance calculation	**Y**
2. Meets the IEC 60101-1 standards and current should not exceed 300µA rms [4]	A. Use additional instrumental amplifier (AD8226) for bio-isolated 4 pole scheme and prevent DC current bias B. Use R_limit in order to guarantee upper limit in current C. Using multimeter, test if electrodes meets the current limit standards	**Y**
3. Robust tomographic image reconstruction, one figure with approximate with bone placement and second with muscle movement visualization	A. Prepare acrylic cylinder with embedded electrodes connected to EIT module B. Fill up 3-5cm of saline water with similar conductivity to that of human tissue C. Place EIT "phantoms (ex: wood, plastic object or vegetables)" with multiple placement D. Compare actual placement with reconstructed image	**Y**
4. Scratch detection classifier has 90% detection sensitivity against other activities	A. Generate dataset with scratch, wave, walk activity on multiple subjects similar to gold standard B. Perform 5-fold cross validation on the dataset, performance on testing set is reported.	**Y**
5. Supports minimum data transfer rate of 821B/s to host device.	A. Program two test boards with throughput test application provided on Nordic online documents. B. Setup one board as master and connect to an external terminal through UART/USB. Open a serial connection to COM port of the master board. C. Setup the other as slave. D. Start the application using onboard button and check the throughput displayed on the console.	**Y**
6. Temperature sensor module has to collect accurate skin ambient temperature with precision of ±0.2°C with actual temperature within skin ambient temperature (20°C ~ 34°C) range [5].	A. Get a thermometer and measure the ambient temperature B. Acquire temperature data using temperature sensor C. Compare thermometer data with temperature sensor data to figure out the error range D. Repeat several times to ensure precision	**Y**
7. Three LED indicators have to show user not scratching (Green LED blinking), mildly scratching (Yellow LED blinking), or severely scratching (Red LED blinking)	A. Acquire machine learning data and load each data of a person not scratching, mildly scratching, and severely scratching onto the microcontroller B. Check for the LED change when loading different data	**Y**
8. The 3.7V battery with 850mAh has to provide fixed 3.7V in the tolerance of ±3%	A. Use a multimeter to check constant 3.7V data without severe discharge B. Using a multimeter, check to see if the battery provides fixed 3.7V in the tolerance range	**Y**
9. Charged voltage after protection circuit should not exceed 4.2V(± 0.1V) for inputs from 2.8V-4.2V the range .	A. Sweep voltage at the input connector from 2.8-4.2V using an oscilloscope when charging B. Voltmeter at the output of the protection circuitry should not read more than 4.2V(± 0.1V).	**Y**

B. Finalized Prototype and Interactive Dashboard

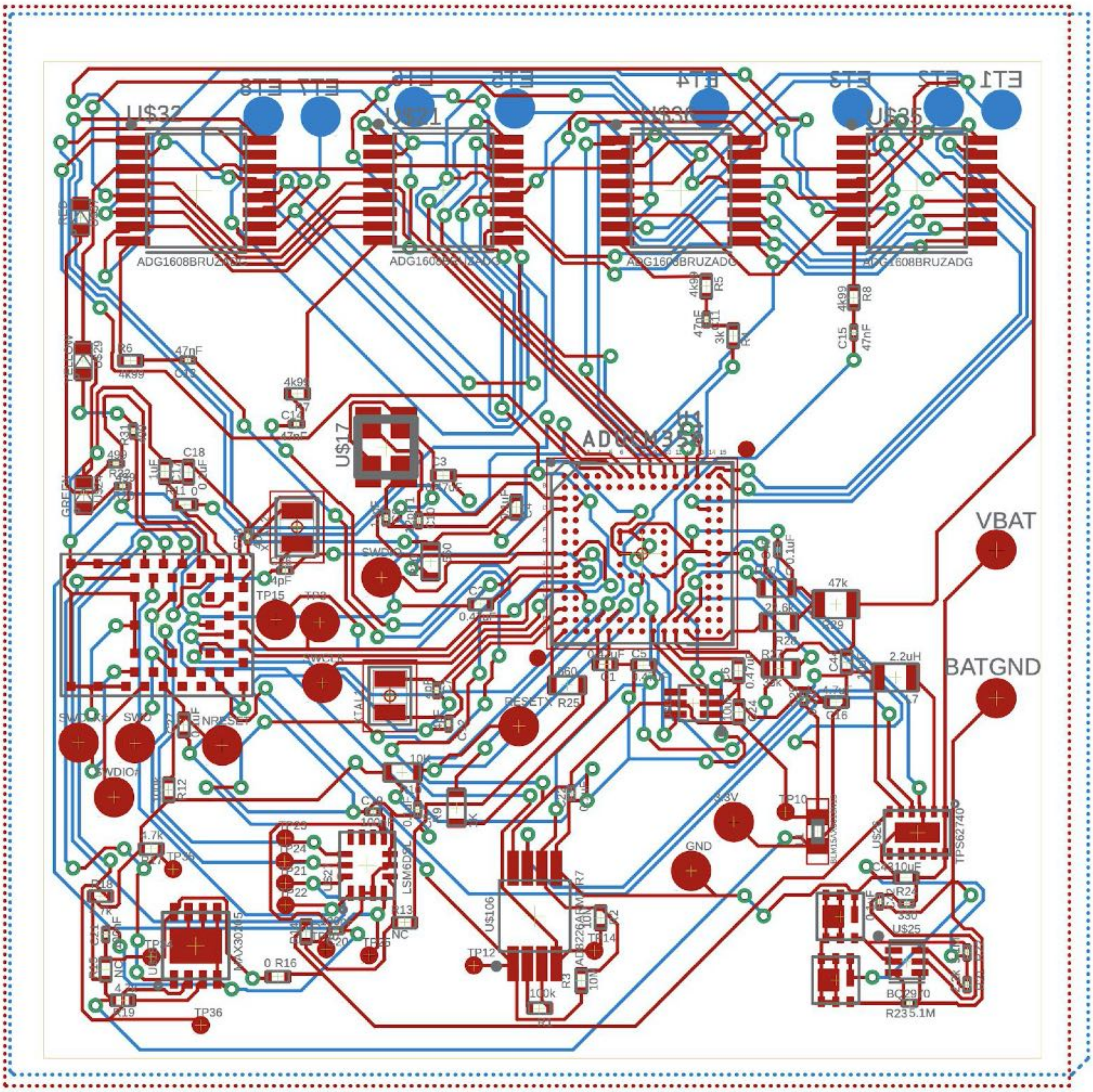


C. Schematics

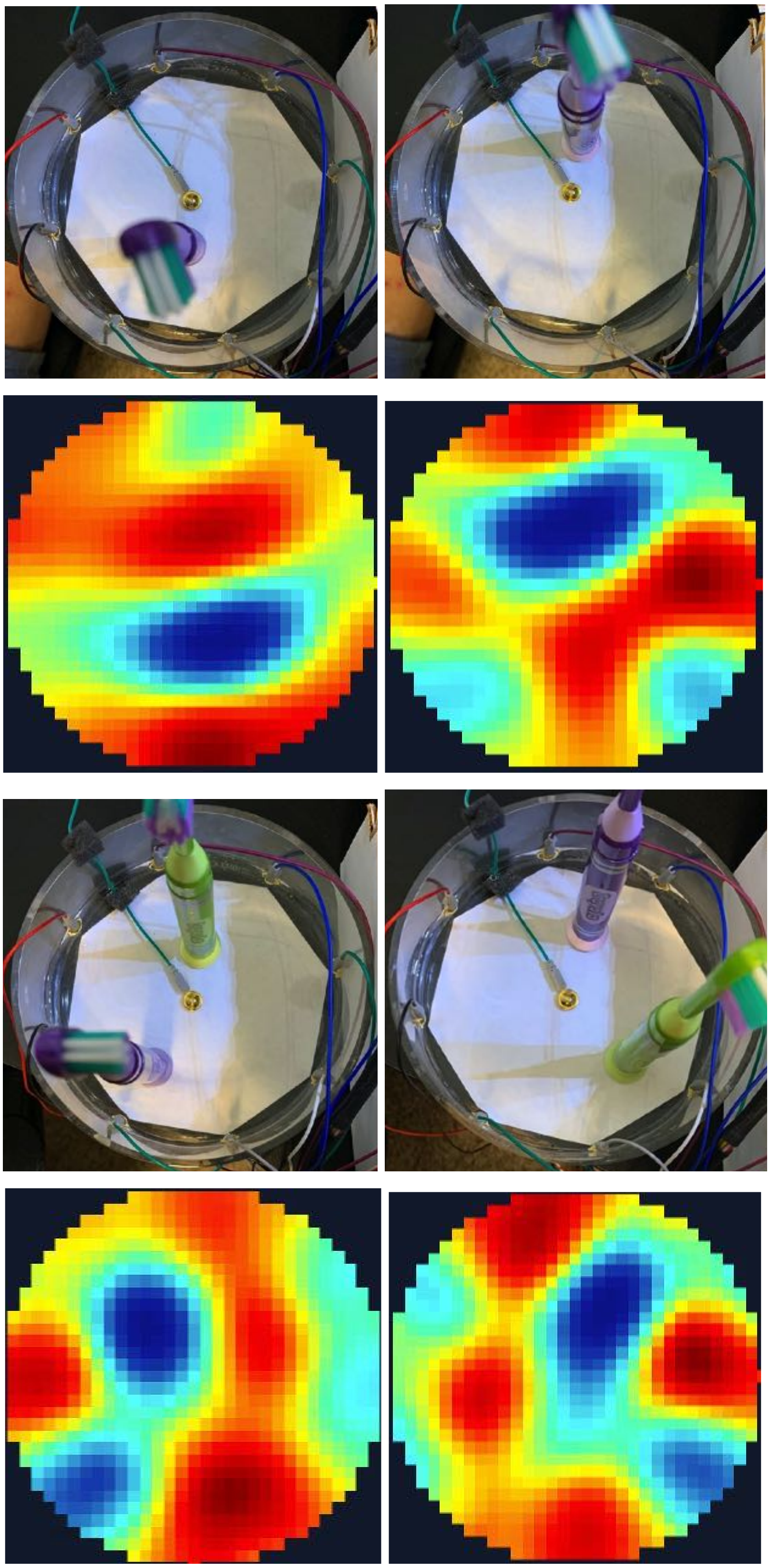




D. Board Design



E. Electrical Impedance Tomography Reconstruction



F. 32Bit FIFO Sequencer

```c
uint32_t seq_afe_adc_raw[] = {

    23 << 16 | 0x43,

    0x84001818,   /* AFE_FIFO_CFG: DATA_FIFO_SOURCE_SEL = 00    */
    0x8A000034,   /*  2 - AFE_WG_CFG: TYPE_SEL = 10 */
    0x98000000,   /* AFE_WG_CFG: SINE_FCW = 0 (placeholder, user programmable)                */
    0x9E000000,   /* AFE_WG_AMPLITUDE: SINE_AMPLITUDE = 0 (placeholder, user programmable)  */
    0x88000000,   /*  5 - AFE_DAC_CFG: DAC_ATTEN_EN = 1 */

    /* TIA  */
    0xA0000002,   /*  6 - AFE_ADC_CFG: MUX_SEL = 00010, GAIN_OFFS_SEL = 00 */
    0x00000640,   /* Wait 200us                                                             */
    0x80020E70,

    0x86007788,   /* DMUX_STATE = 8, PMUX_STATE = 8, NMUX_STATE = 7, TMUX_STATE = 7         */
    0x00000640, /* Wait 100us */
    // enable wavegen
    0x80024E70, // enable wavegen, ADC still off
    0x00000040, // wait 40 clk

    // power up ADC
    0x80024EF0,
    0x0000063E, // Wait 1598 clock cycles (ADC settling)

    0x80024FF0,   /* AFE_CFG: ADC_CONV_EN = 1, DFT_EN = 1                                   */
    0x00000000,   /* Wait (100 * ADC Sample #) + 341 Clk */
    0x80024EF0,   /* AFE_CFG: ADC_CONV_EN = 0, DFT_EN = 0                                   */
    /* AN_A */
    //0x86007788,   /* DMUX_STATE = 8, PMUX_STATE = 8, NMUX_STATE = 7, TMUX_STATE = 7         */
    //0x00000010,   /* Wait 100us */
    0xA0000208,   /* AFE_ADC_CFG: AN_A, Use GAIN and OFFSET AUX                             */
    0x00000640,   /* Wait 200us                                                             */
    0x80024FF0,   /* AFE_CFG: ADC_CONV_EN = 1, DFT_EN = 1                                   */
    0x00000000,   /* Wait (100 * ADC Sample #) + 341 Clk */
    0x80024EF0,   /* AFE_CFG: WAVEGEN_EN, ADC_CONV_EN = 0, DFT_EN = 0                       */
    0x82000002,   /* AFE_SEQ_CFG: SEQ_EN = 0                                                */
};
```