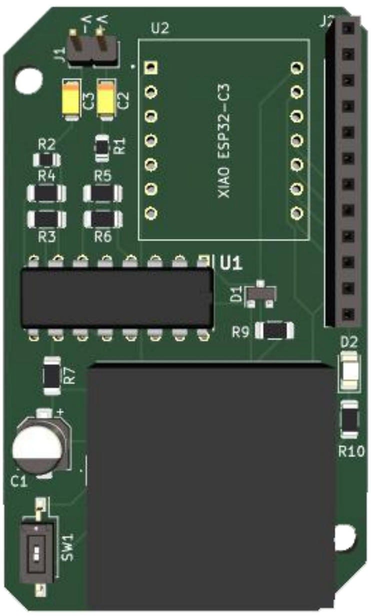
Portable Sampling Device for textile-embedded Triboelectric Nanogenerators Sensors



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Triboelectric Nanogenerators for self-sustainable Wearable Electronics

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Introduction

Textile triboelectric nano-generators (TENGs) are emerging as a promising solution for wearable self-powered sensing technology. The flexible TENG presents a stable output performance under strong deformation and its sensitivity to movement can be explored as wearable sensor to monitor biomechanical movements. In this Internship, we engaged in the conceptualization of small portable electronic device that could harness the signals produced by the TENGs acting as sensors to further process the data.

While the self-sustainability of the circuit proved unfruitful to power said device, for now, we opted in designing a low-power and low-profile system powered by two single coin batteries who could be able to sample the sensors data and transmit it to another device with higher processing capabilities to more efficiently manage said data in real-time, allowing the users to better track biomechanical movements in a every-day or medical environment.

Methodology

Throughout the conceptualization and testing of the devices, the following instruments were used:

- **Tektronix TBS 1000C Series Digital Oscilloscope**
- **Agilent 33210A Function Generator**
- **TriboTester** – Perpendicular Oscillatory Movement Stimulator
- **Arduino Uno** – ADC used to sample the output signal. 10-bit 0 to 5 V ADC with an input impedance of 10 MΩ.

The circuits were tested in TENGs with single electrode configuration, where the sensors were labelled has the positive electrode and another textile surface as it's negative/reference counterpart.

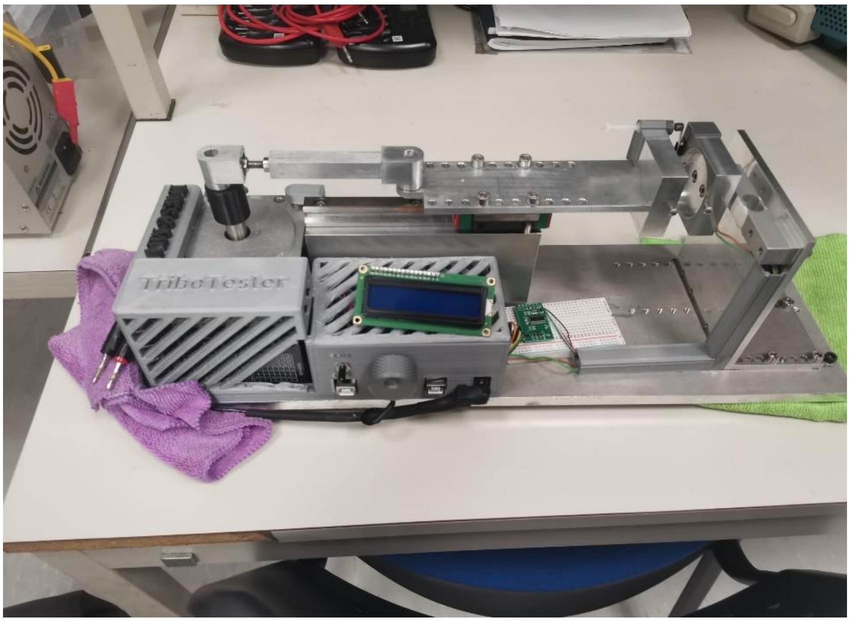
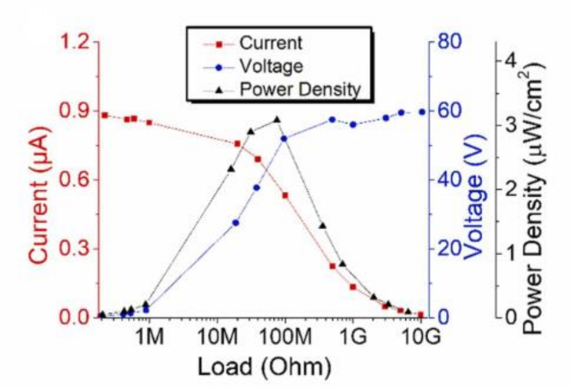


Image 1 – TriboTester, developed by Ismael Domingos. Using a DC motor, simulates the back-and-forth movement to stimulate the sensor and generate a differential voltage between the two electrodes.

The force exerted in the electrodes and the frequency of said movement can be defined. For the entire testing the force defined was around 0.23 N.

Conceptualization

Has shown in the research made by Ismael Domingos and his team, on *"Printed graphene electrodes for textile-embedded triboelectric nanogenerators for biomechanical sensing"*, we can observe that the higher the resistive load on the TENG, the higher were the voltage spikes observer when the sensor was cautiously stimulated.

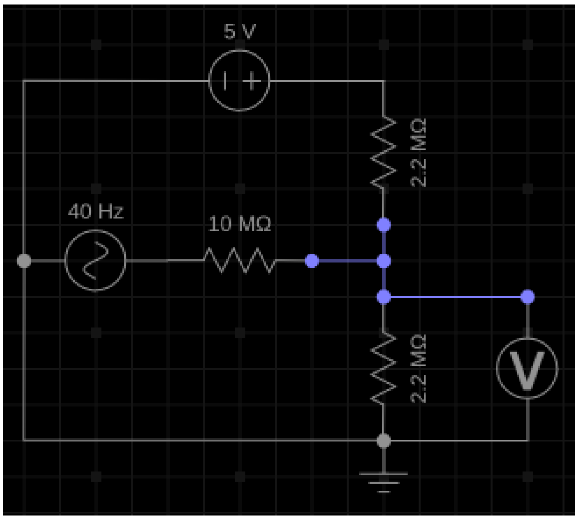


Thus, the first premiss of the solution was set out: the circuit's input impedance had to be around 10 MΩ. This way we could achieve signals strong enough (expected peak value of around 20 V) to be greatly defined when sampled, even after conditioning to fit in the ADC range, whilst maintaining a high power density.

Image 2 – Current, Voltage and Power Density in relation to the load seen by the TENG.

The average ADC has a range of 0 to 5V, meaning if the input signal is not within this range the ADC will saturate, so the process would be to make a signal fit this range. For this we would have to attenuate the output to ±2,5 V and add a offset of 2,5 V.

The first circuit consisted of a simple voltage divider with a pull-up resistor. The idea beyond it was that the AC signal (sensor signal) would see a voltage divider and a constant voltage would be applied to establish a DC resting point for the circuit.



In theory, if we define the voltage source in this schematic as the sensor, the problem would be solved, however, we were interpreting the ADC as device with infinite input impedance. On normal circuits that would be the case, but since we are working with such high impedance resistors the ADC can´t be ignored as just a "voltmeter" and as to be considered as a resistor to ground.

Image 3 – First circuit conceptualized. Embodies a theoretical resolution of the conditioning problem.

To fix this issue, a buffer was introduced between the output signal and the ADC, using a OPA340PA operational amplifier. The idea behind a buffer is that, when externally powered, it has a near infinite input impedance and can output the voltage in it´s input without affecting the circuit it's reading from.

In these conditions, given that the circuit is being powered by the 5 V output of the Arduino Uno and we have no negative voltage in this simpler solution, the Amplifier is limited to and input and output of around 0 to 5 V, but since the signal received would be already conditioned to the ADC, this won't be a problem.

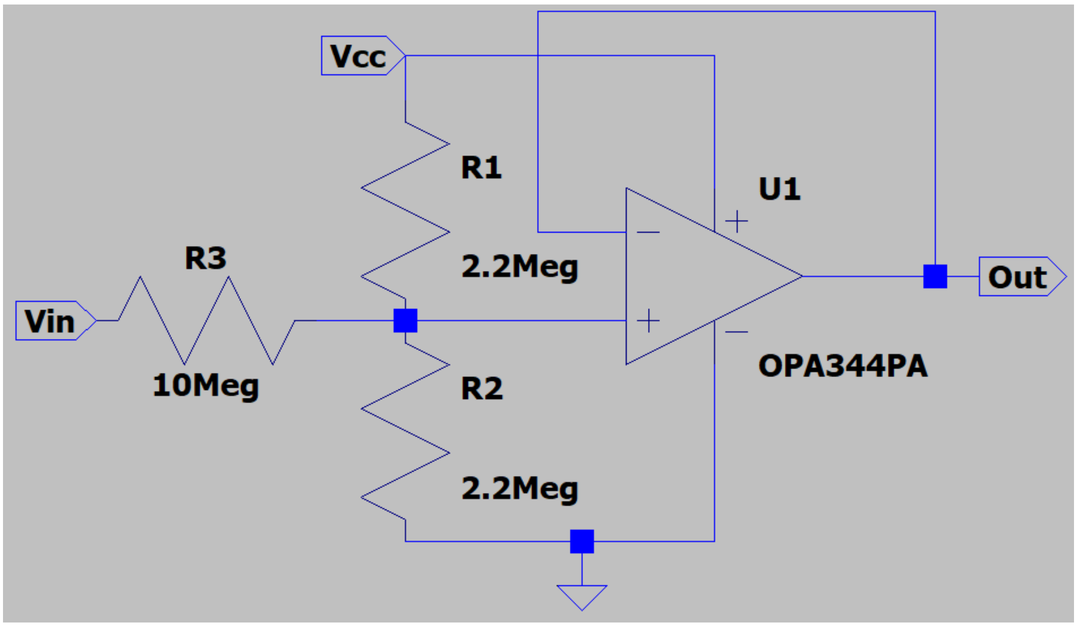


Image 4 – Second design used and tested; the addition of the buffer fixed the interference that the ADC caused in the resistors balance.

The following results were obtained stimulating the circuit using the Wave Function Generator, the signal had a frequency of 10 Hz (near the expected maximum frequency of biomechanical motion) and variable amplitude:

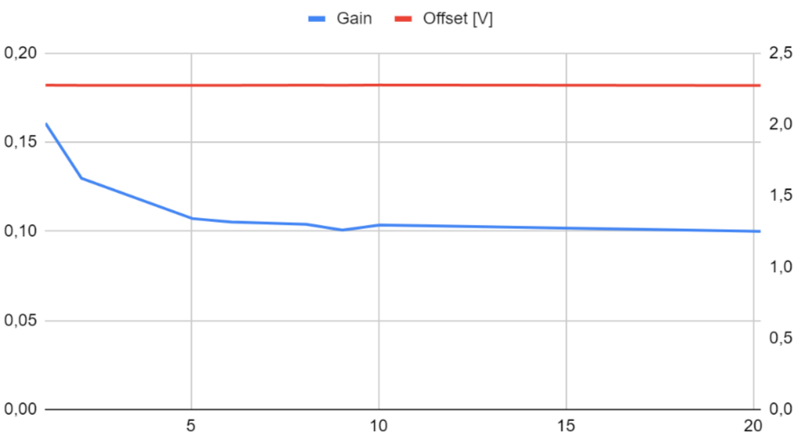


Image 5 - Gain & Offset in relation with input voltage (peak-to-peak) [V]

As shown in the graph the circuit proved to have an unstable gain, thus an unstable output, with weak signal. Meaning less precision when measuring small voltages in the sensors. A steady Offset value is a good indicator because in this way the signal can be more efficiently corrected digitally back to its original form.

However, when the circuit was tested with a sensor sample in the TriboTester for the first time the results proved unfruitful. The output signal was very weak and was mixed with noise to a point were actual weak signal generated by the sensors were unrecognisable. Discussing the problem, we came to the conclusion that there was a strong presence of noise deriving from the electrical network.

A band-stop filter was introduced between the buffer and the ADC to cutoff spectral components of 50 Hz (Anti-Hum filter for the European Electrical Network). A decoupling capacitor was also placed in the input, to filter any DC component of the sensor's signal.

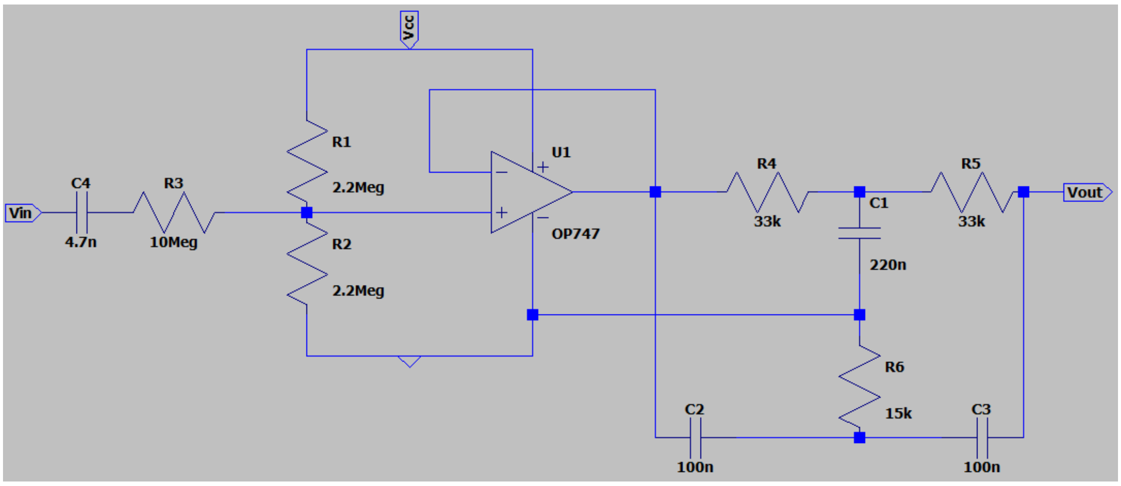


Image 6 – Third circuit used and tested; a decoupling capacitor and a band-stop (50 Hz) filter were added to better condition the signal and the output, respectively.

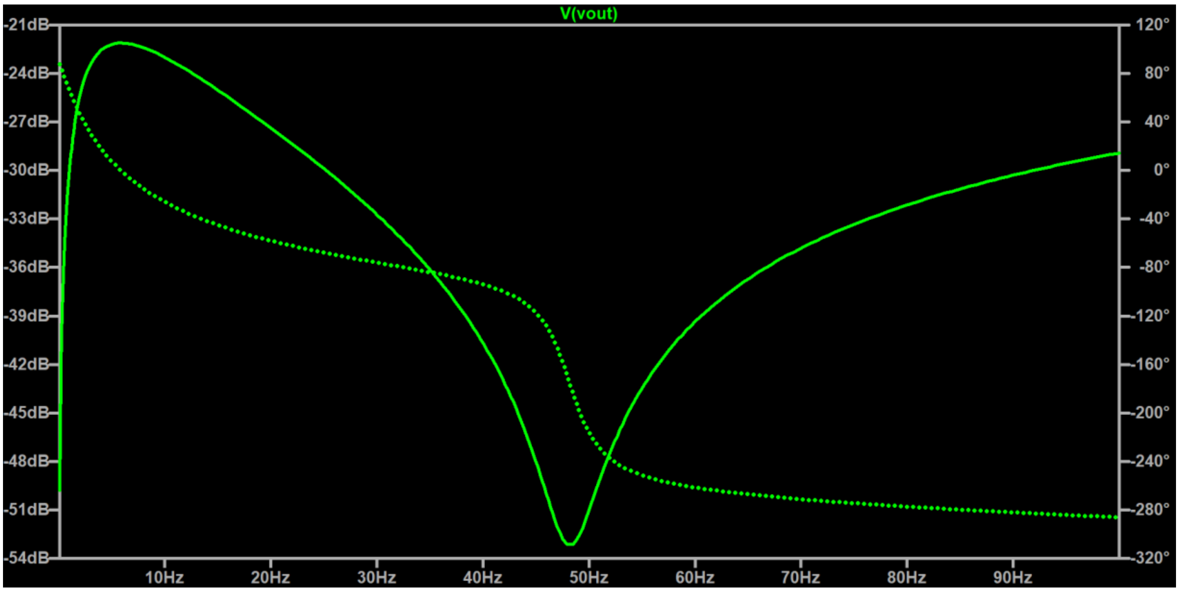


Image 7 – Spectral Analysis (using LTSpice software) of the output voltage, solid green line represents the Voltage gain in logarithmical scale and dotted line the output's phase shift; as expected, there is a significand drop in the gain in the frequencies surrounding the 50 Hz and in the very low frequencies (DC components).

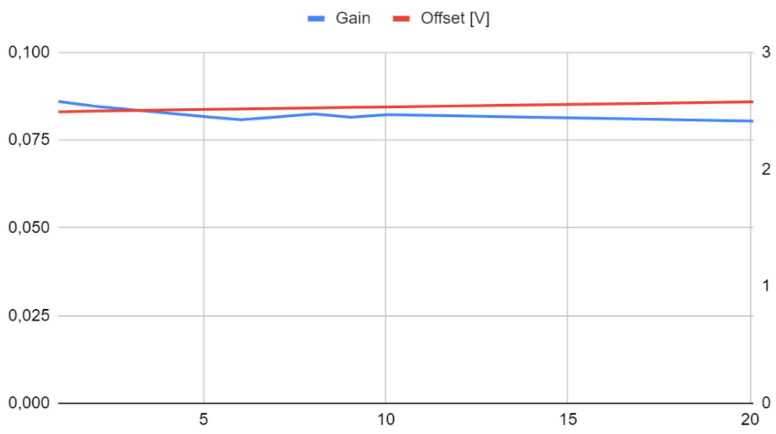


Image 8 - Gain & Offset in relation with input voltage (peak-to-peak) [V]

When tested with the Wave function Generator, it's important to note a significant improvement when it comes to the precision of weaker signals.

However, once again when the tested with samples in the TriboTester, the outputted signal was still very noisy and weak, even with the 50 Hz filter applied, meaning that the noise source lied elsewhere.

Given that the band-stop filter was proved useless, it as swapped with a simple low-pass filter with a cutoff frequency of around 2.8 Hz. This makes it that frequencies above this one have a drop of -20dB per decade, meaning signals around 28 Hz are 10 times smaller, around 280 Hz, 100 times, etc. This also ensures that the Nyquist-Shannon Sampling Theorem is respected: signal components that have a frequency higher than half of the sampling frequency, will be mirrored in lower frequencies when they are sampled by the ADC; but if filtered, this effect is greatly decreased and can even be ignored.

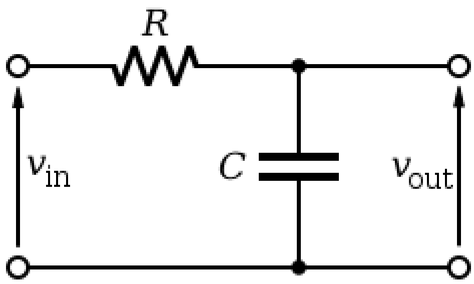


Image 9 – Example of a simple low-pass filter; for this solution we will use a 47 µF capacitor and a 1.2 kΩ resistor, resulting in a cutoff frequency of around 2.8 Hz.

Until now we haven't been considering the ambient noise that is absorbed by the sensors (and connecting wires), this noise is common to both electrodes of the sensor, meaning if we subtract the voltage in the negative electrode to the voltage in the positive electrode we should, in theory, remove the common voltage, cancelling most of the ambient noise. For this we will use the INA125P Instrumentation Amplifier (as "subtractor"), again with single supply of 0 to 5 V.

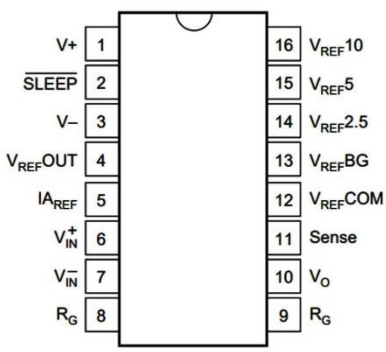


Image 10 – INA125P Pin layout

In this configuration the amplifier will only read inputs above 200 mV, so now both of the inputs require a DC offset, for this we will use the reference voltage pins in the IC package. The amplifier already as a gain of around 8 times (when it´s two resistor pins are connected to a 1 MΩ resistor), this means the signal has to be at least 8 times small when in enters the amplifier to compensate its gain. Using the V_{REF}BG connected to the V_{REF}OUT we can have a stable supply of 1.25 V that will be used to give a DC offset to both inputs, but since the output signal has to be above zero because of the supply conditions, let's make the negative terminal have a smaller offset, make it half the offset given to the other terminal.

To fix the weak signal issue the input resistance was increased to about 505 MΩ, now the signal was strong enough to be defined when sampled, the resulting circuit is as follows:

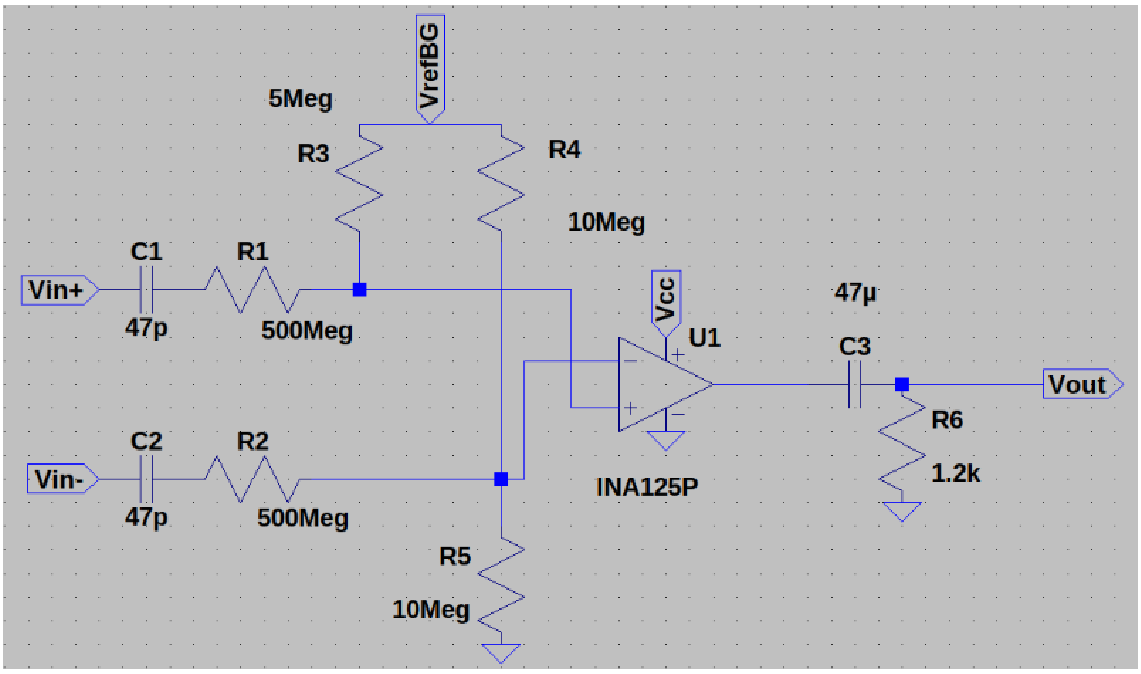


Image 11 – Fourth and final circuit tested and used; the addition of the subtractor and the filter allowed for a cleaner signal, whereas the increase in the input impedance allowed for stronger ones.

When we make an AC analysis (the V_{REF}BG is ground), both signals see the same simple voltage divider that makes a signal around 100 times smaller (actual gain of 0.0099). But the other way around, in a DC analysis, the negative terminal as an injection of half the DC value in the positive one, because of the 10 MΩ voltage divider. A bypass capacitor is also present to decouple any DC components of the signal, but with a lower capacity to accommodate for the higher impedance.

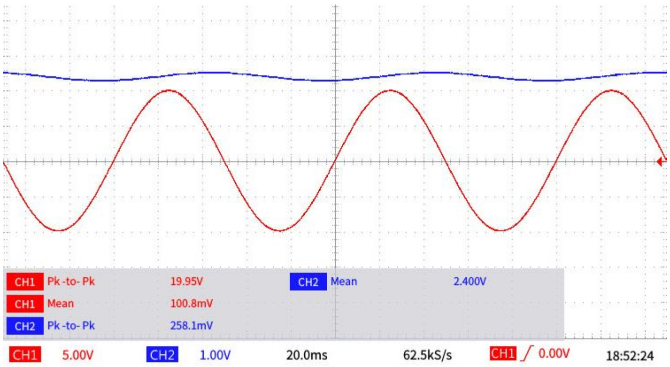


Image 12 – Output of the system (Blue) when the input (Red) is a 10 V amplitude Sine wave.

Using the data as shown in **image 12** we can estimate an approximate gain by dividing the output signal's amplitude by the input signal's amplitude, giving us a value of around 0.013.

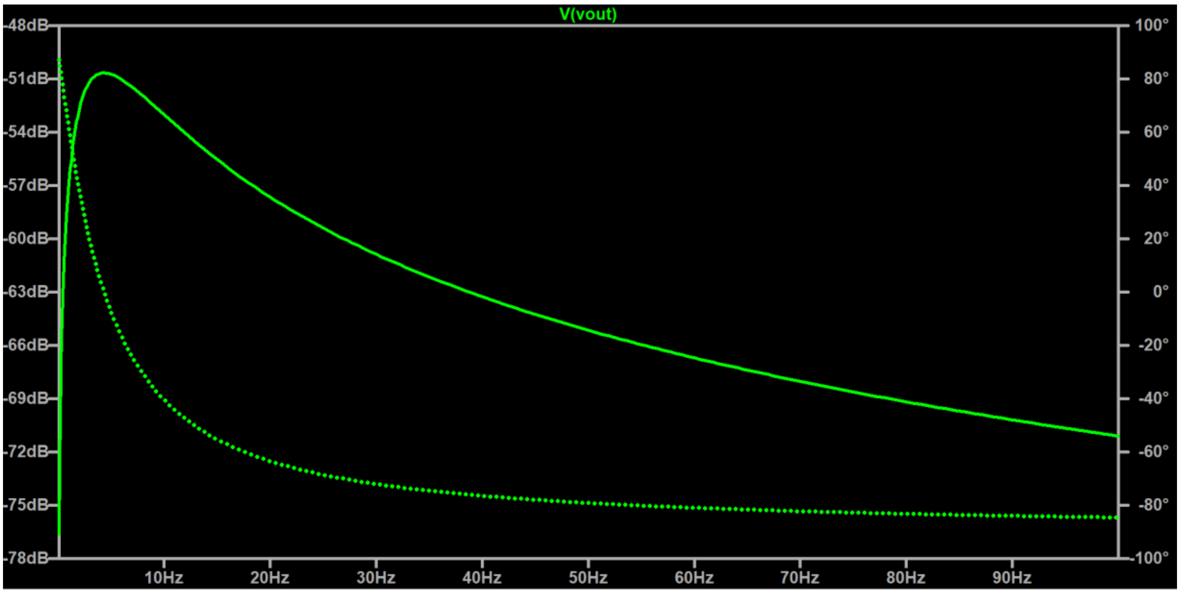


Image 13 – Spectral Analysis (using LTSpice software) of the output voltage, solid green line represents the Voltage gain in logarithmical scale and dotted line the output's phase shift; as expected, the DC and higher frequency components are reduced leaving only a small band where the signal remains intact, this low frequency band is around the those of natural biomechanical movements.

Transcribing the circuit to a breadboard, the result is as follows:

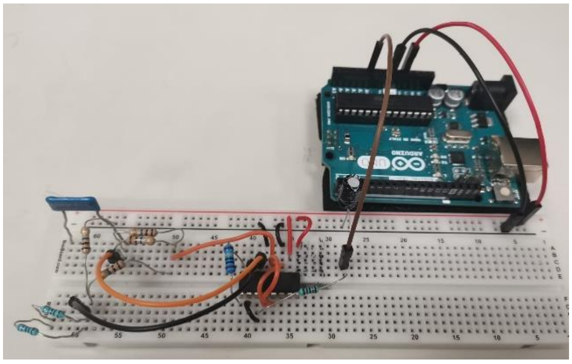


Image 14 – Breadboard with the circuit mentioned above, from left to right we have conditioning part of the system, the instrumentation amplifier and the filter. The output is then sampled by the UNO's ADC, the entire circuit also has a voltage supply of 5 V deriving from the Arduino.

Sensor-Shirt Testing

As mentioned before these sensors can be used the detect and measure biomechanical movement, whence a shirt with two TENGs near the bicep's region (in the upper arm) were used to test the circuit in a more "real-life" scenario.

Image 15 – Sleeve of the shirt with the two TENGs; the one to the left has a cable soldered that runs to the zone near the collar-bone, the other has it's terminal exposed (as seen by the copper wire).

As seen in the image above, there are two sensors in the shirt, the only difference being that they use a different batch of adhesive (see *"Printed graphene electrodes for textile-embedded triboelectric nanogenerators for biomechanical sensing"* for fabrication process), this later proves to be a differentiating factor between the results of the two.

For simplification purposes let's identify each sensor:

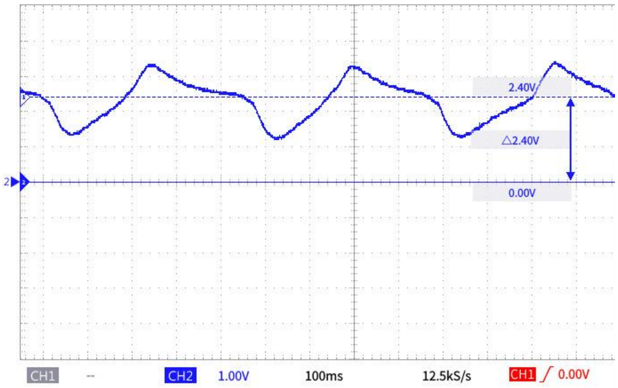
- A – Sensor with the old adhesive.
- B – Sensor with the new adhesive.

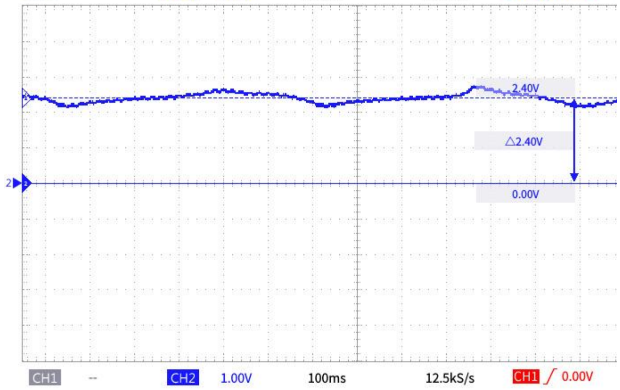
Image 16

For testing, the positive electrode would be the copper wire connected to the sensor and the negative would be its counter surface, the textile fabric in the lower arm, they would be connected to their respective pins in the circuit (**image 11**). The executed movement would be as shown in the image to the right. In this configuration extending the muscle will result in a positive varition and the other way around when flexing.

Two tests were made for each sensor, using our device still in the breadboard to condition the signal and the oscilloscope to measure it, one would test the sensor's behavior to strong motion, and another to a weak one. For better understanting let us imagine the devices being used in a phisical therapy enciorment, we have to undertsand how the sensor would react to a person who barely has any strenght to flex their arm.

It's important to note that now the importance here isn't much on the signal's strengh and fidelity but on how defined it is and how well it can be distinguished from noise, to later be efficiently processed.





Images 16 & 17 – Output of the circuit when applying a normal force while extending the muscle to sensor A and B respectively.

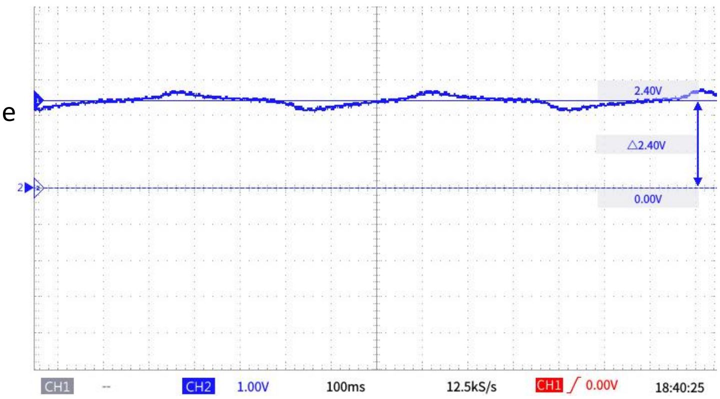
It is easy to conclude that sensor A showed by far the greatest results. The signal is well defined and distinguished from the noise, so when it's digitally converted back to it's original form it can be easly processed.

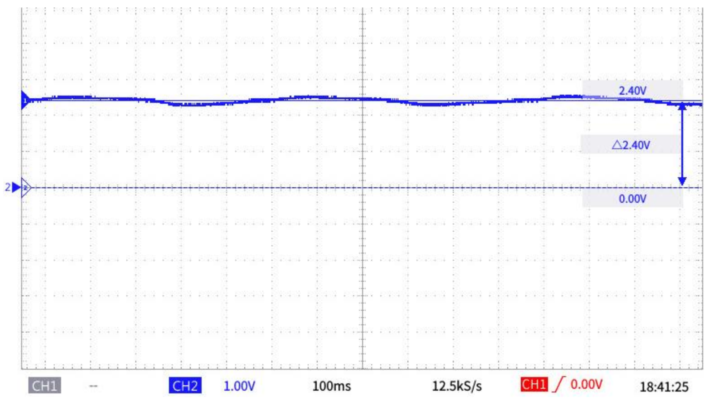
As for B, we can spot the movement happening but weaker signals might get lost in the noise.

Images 18 & 19 – Output of the circuit when applying a weaker force while extending the muscle to sensor A and B respectively.

In this test there is no doubt that sensor A proved to be the most effective in converting biomechanical motion in a voltage between the electrodes. It is evident that weak signals in sensor B get almost lost in the noise.

In conclusion these tests gave us an idea of what a signal would look like in an actual "real-world" scenario and how we can use that information to process the data in real-time.





TriboSampler

Circuit Design

There is no doubt about the practicality of this circuit on a breadboard. The initial idea was to have a small sampling device to read the sensors output, on this note, we have to make this system portable, smaller, and wireless. Being so we will make the power supply two small coin cell batteries, and the microcontroller (and ADC) will be a SEEEDuino XIAO ESP-C3, capable of establishing a Bluetooth and Internet connection to communicate the data.

Using KiCad, a circuit was design based on the previously design one, to be later fabricated as a PCB, this small new design is about 4x6 cm^2, powered by two 2032-coin-cell batteries (2* 3 V) and capable of transmitting data either through Bluetooth or Wi-Fi connection, while still being able to power and communicate with other I^2C devices, like a Liquid Crystal Display. The result was the following board:

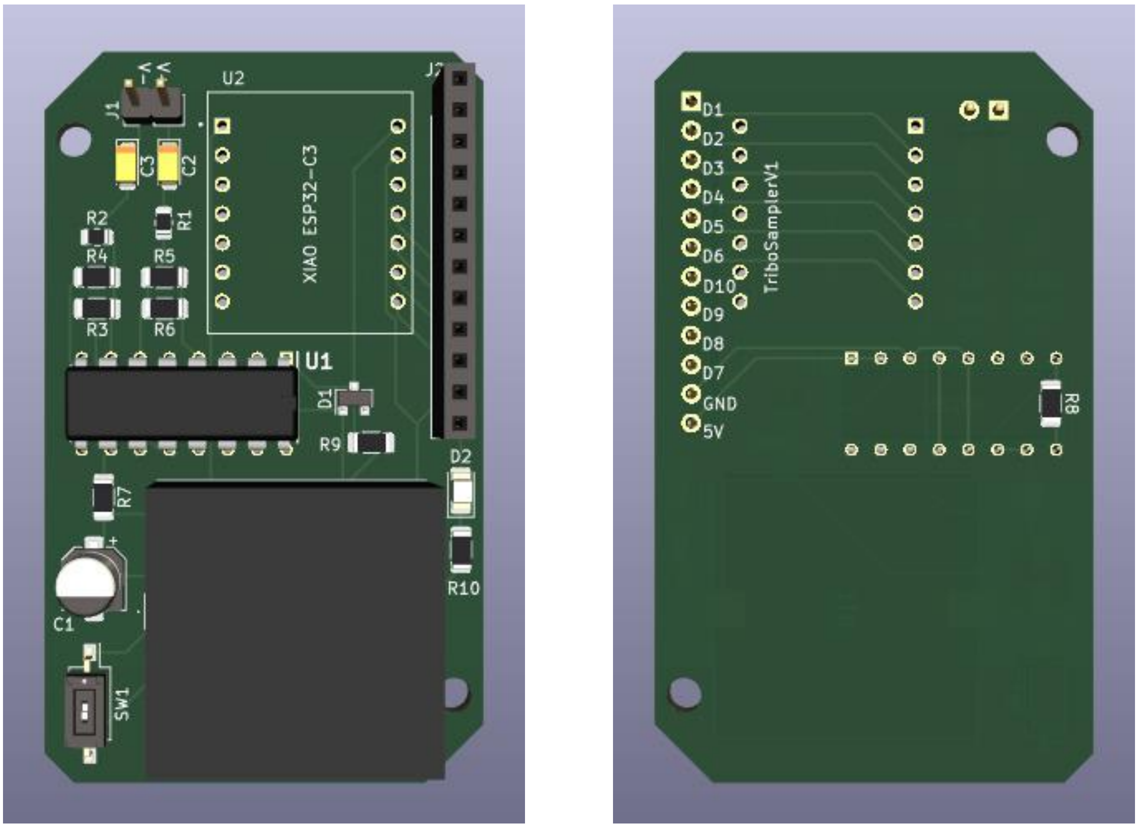


Image 20 – Front and Back view of the PCB

The material list is as follows:

- R1 & R2 – 500 MΩ SMD Resistor (2012 Metric)
- R3, R4, R5 & R6 – 10MΩ SMD Resistor (3216 Metric)
- R7 – 1.2 kΩ SMD Resistor (3216 Metric)
- R8 – 1 MΩ SMD Resistor (3216 Metric)
- R9 – 100 Ω SMD Resistor (3216 Metric)
- R10 – 1.2 kΩ SMD Resistor (3216 Metric)
- C1 – 47µF SMD Electrolytic Capacitor (5x5.4)
- C2 & C3 – 47 pF SMD Tamtalum Capacitor (Kemet-I 3216 Metric)

- D1 – 5.1 V Zener Diode (SOT-23 ANK)
- D2 – LED SMD (3216 Metric)
- BT1 – Battery Holder Keystone 1062
- J1 – 01x02 Vertical Connector PinHeader (2.54 mm)
- J2 – 01x12 Vertical Connector PinSocket (2.54 mm)
- SW1 – Button Switch SMD Omron A6S-1101-H (1 circuit)
- U1 – INA125P
- U2 – XIAO ESP32-C3

Case

To accommodate the circuit a case was 3D printed using grey PLA filament, the dimensions are as follows: 4x6x3 cm^3. It is divided in two halves, the lower half has pins made for sliding in the circuit trough the screw holes, said pins are used to later stick on the top half. A hole was inserted in the lower half to pass the input signal cables.

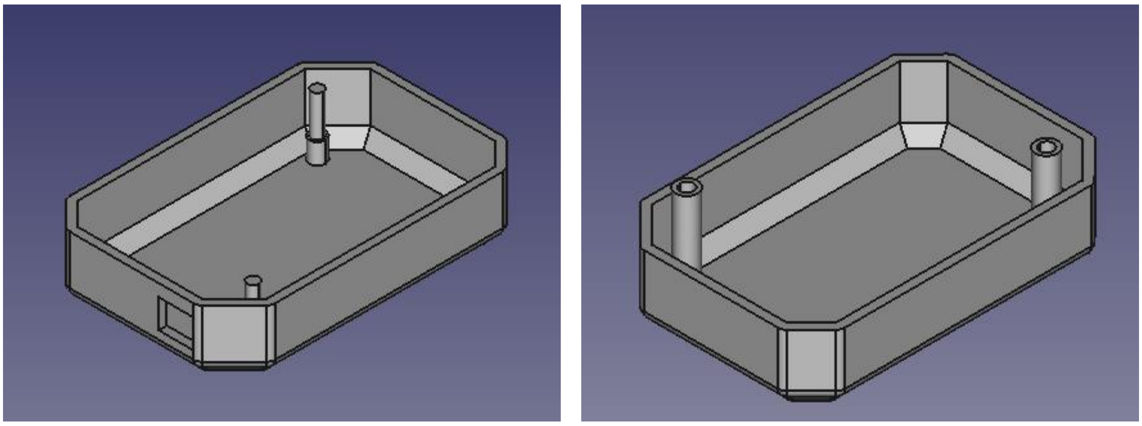


Image 21 – 3D models of the lower and bottom halves of the case, made in FreeCad.

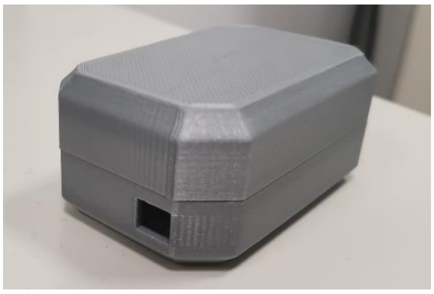


Image 22 – Finished and Polished 3D printed case.

Circuit Specifications

Conditioning

- **Input Impedance -** $R_{IN} \approx 505\ M\Omega$
- **Input Amplitude Range** – $V_{IN} \in [0.019, 130]\ V$
    - Lower Voltage Limit set by the ADC's precision.
    - Upper Voltage Limit set by Amplifier limit.
- **Bandwidth -** $f_{IN} \in\ ]0,\ 10]\ Hz$
    - Lower frequency limit set by Decoupling Capacitor.
    - Upper frequency limit set by Output Low-pass Filter.
- **Gain** – G = 0.0128894
- **Offset** – Off = 2.4615
- **Amplifier Noise** – $n_{RMS} = 40\ nV/\sqrt{Hz}$
    - Given the Bandwidth, the expected noise RMS in the amplifier output is ≈ 126.4 nV.

$$\boldsymbol{Real\ Value: V_{OUT} = \frac{V_{ADC} - Off}{G}}$$

Sampling

- **ADC Range** – LSB = 224 µV
- **ADC Noise -** $n_{RMS} = 64.7\ \mu V$

Microcontroller

- **CPU** – 32-bit RISC-V
    - **Clock –** Up to 160 MHz
    - **SRAM –** 400 KB
    - **Flash Mem –** 4 MB
- **Communication**
    - **Wi-Fi subsystem –** Complies with IEEE 802.11b/g/n protocol and supports Station mode, SoftAP mode, SoftAP + Station mode, and promiscuous mode.
    - **Bluetooth –** Supports features of Bluetooth 5 (BLE) and Bluetooth mesh.
    - **USB-C Connection**
- **Ultra-Low Power** – Deep sleep power consumption is about 43 µA

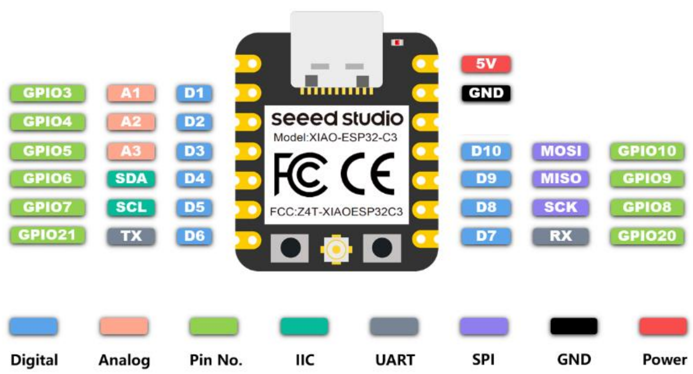
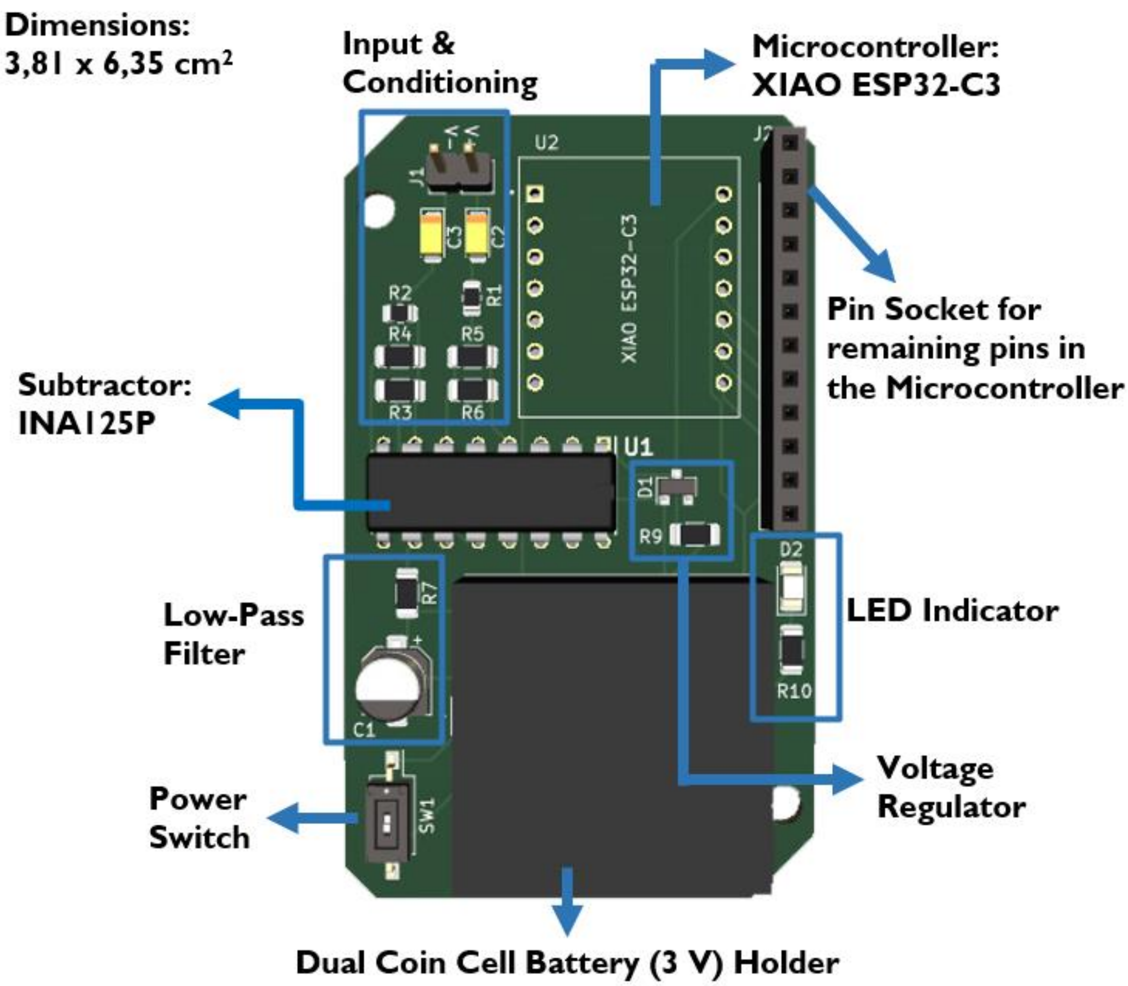


Image 23 – XIAO ESP32-C3's Pinout diagram; Pin GPIO2/A0/D0 is being used as the ADC for the Sampling Circuit, the remaining pins are available in the 12-pin header socket next to the Controller.


Dimensions:
3,81 x 6,35 cm²
Input &
Conditioning
Microcontroller:
XIAO ESP32-C3
Pin Socket for
remaining pins in
the Microcontroller
Subtractor:
INA125P
Low-Pass
Filter
LED Indicator
Voltage
Regulator
Power
Switch
Dual Coin Cell Battery (3 V) Holder