ME 423 Report

Shoe-stopper: Step Counting using Piezoelectricity

GROUP 8

Guide: Prof. Ramesh SIngh

23/11/2022

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INTRODUCTION AND SOCIETAL NEED

This project aims to introduce a novel approach to sustainability by integrating the concepts of piezoelectricity and footstep counting technology. An often overlooked sustainability concept is repurposing energy that would anyway have been wasted by converting it into some usable form. Millions of footsteps land on the ground every second, generating significant pressure that is entirely lost as heat. The application we are utilizing the piezo-sensor technology for is for counting footsteps, which requires us to sense fluctuations in pressure per footstep to count each footstep. The energy from the footsteps is taken as an input signal to sense a footstep. As the energy generated by the piezo sensor is not enough, we supply an external DC power source to amplify the voltage produced. With a more sensitive circuit, one would not need this amplification, and the energy from the footsteps can be harnessed completely by the smart footwear.

Certain crystalline materials, when subjected to pressure, develop positive & negative charges on opposite ends of crystals, essentially creating localized dipoles. When the applied pressure is relieved, they lose their charge, and consequently, an electric current flows across the material. Such materials are characterized as being piezoelectric and can be coupled with wireless power transfer modules to use the generated electricity for various applications. This makes for an appealing product and brings us closer to achieving some global sustainability goals.

Though global energy generation is shifting toward renewable and alternative power sources, about 82% of total energy still comes from fossil fuels (Source: Gapminder foundation). Part of the reason behind the slow adoption of these resources is the infeasibility of implementing these solutions individually. Piezoelectric elements are small enough to easily be engineered into shoe soles and light enough not to add too much weight. These properties, combined with their affordability, make it a very commercially viable solution.

Harvesting mechanical energy from human motion is an attractive approach to obtaining clean and sustainable electric energy. However, in our application of piezoelectricity in footstep counting, the energy generated through pressure variation is very small, as concluded from initial testing of circuit configurations and the literature review available, and is not sufficient to power a counter independently. Hence, we use piezo sensors for their sensing capabilities instead.

Although we limit ourselves to shoes in this project, potential large-scale applications include the use of pressure mats for powering street lamps on walkways, self-powering travelators in malls & airports, etc. Let's not even think too far from home - we could use it to power the lights in the institute's infinity corridor. Although these may sound like convoluted approaches to fairly straightforward problems, small-scale solutions like this help us inch closer to bringing about a paradigm shift in energy generation worldwide.

LITERATURE REVIEW

Before getting into the ideation & manufacturing stages, we started by analyzing existing literature that discusses the electrical & design aspects of existing prototypes. A major portion of this theoretical research was based on *Project Power Shoe: Piezoelectric Wireless Power Transfer – A Mobile Charging Technique by*

Joses Paul P. et al. This paper discusses several key details regarding piezoelectricity, circuit design using various electrical elements, and wireless power transfer using WiFi/Bluetooth.

We also needed to get an idea of the amount of power that could potentially be extracted using piezoelectricity, and account for losses incurred due to wireless power transmission methods. We consulted the paper Design of Piezoelectricity Harvester using Footwear by Nabeel Ahmed et al. This paper discusses a general block diagram of the final circuit and a study of voltage variation versus the number of piezoelectric disks used.

This was where we faced a major challenge regarding the project's feasibility. According to the results discussed in the above-mentioned paper, the maximum power generation was on the order of a few milliwatts. This is too low to be able to consistently power a mobile charging circuit, especially combined with wireless power transmission losses. Due to this, we decided to fall back on the mobile charging application and instead go ahead with something less demanding such as step tracking.

Finally, we also referenced some online literature and blogs regarding the pressure points generated on a shoe sole while walking to get a sense of how many piezoelectric elements we would need to use and where to place them in the sole. The following figure represents the major areas of pressure fluctuation generated on a shoe sole while walking.

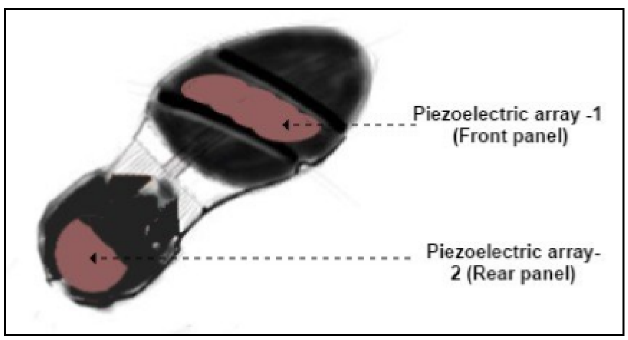


Fig 1: Main pressure points generated while walking

DESIGN SPECIFICATIONS

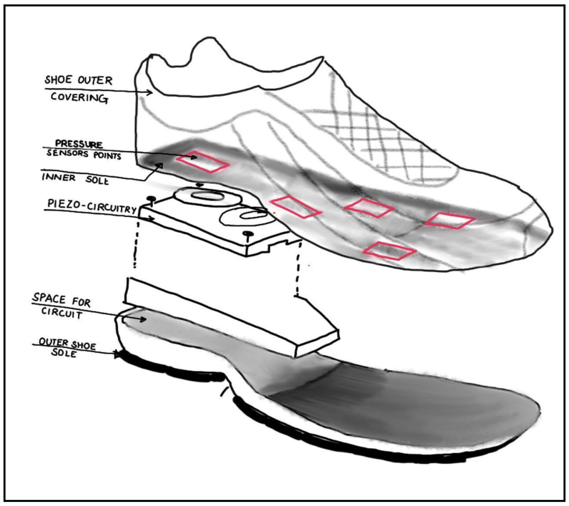


Fig 2. Rough Sketch of the Shoe

- Length of footwear: 27 cm
- Average width of footwear: 8.3 cm
- Diameter of piezo sensor: 3.5 cm
- Number of piezo sensors: 8 units

ANALYSIS AND SELECTION CRITERIA OF MATERIALS

Sole Material Selection

To choose the material for the sole the main criteria we wish to prioritize are the comfort of the user and the pressure transmission to the piezo sensors. Additional criteria that we also consider include weight, thermal insulation, wear resistance, flexibility, durability, water resistance, and cost. The table below lists the criteria we consider, along with the indices used to measure these criteria.

Criteria	Objective	Material Index	Desired Value
User Comfort	Material must be soft enough so as not to cause shoe-bites Material must be hard enough to protect the circuit from damage	Hardness	Maximal Tradeoff

Pressure Transmission	High-pressure transmission to piezo sensor required	Damping Coefficient (ζ)	Low
Weight	Material must be lightweight	Density (ρ)	Low
Thermal Insulation	Material must be temperature independent	Thermal Conductivity (λ)	Low
Wear Resistance	Material must be resistant to wear	Wear Rate Constant (K_a)	High
Flexibility	Material must be flexible	Elastic Modulus (E)	Low
Durability	Material must be strong and resistant to cracks	Yield Strength (σy) Fracture Toughness (K_{Ic})	High
Water Resistance	Material must be waterproof	Water Absorption Rate	Low
Cost	Material must be low cost	-	Low

Analytical Selection of Material using Property Charts

Objectives:

1. Minimize energy per unit weight stored in the sole
2. Minimize electrical conductivity
3. Minimize wear of the sole (wear coefficient)

Primary references: Material selection by Ashby, Materials Engineering Materials Selector, Chapman and Hall Materials Selector, and the Handbook of Polymers and Elastomers.

Secondary references: After consulting the following textbooks, we came to the conclusion that polymers like rubber, polyurethane, and EVA were the best primary options to choose from. For a deeper analysis, we made use of the open-source software, “MatMatch.”

Constraints:

We modeled the sole as a spring, for which we need to minimize the internal energy stored per unit mass. After we obtained the material indices for this, we worked on being within the constraints and, finally, optimizing for cost. The main material properties we deal with in this analysis are

1. Yield Strength
2. Insulation
3. Electrical insulation - conductivity

The Model:

The elastic energy stored per unit volume in a block of a material stressed uniformly to a stress σ is

$$W_v = \frac{\sigma^2}{2E}$$

where E is Young's modulus. It is this W_v that we wish to maximize. The spring will be damaged if the stress σ exceeds the yield stress or failure stress σ_f; the constraint is $\sigma \leq \sigma_f$. So the maximum energy density is

$$W_v = \frac{\sigma f^2}{2E}$$

In our case, weight, rather than volume, matters more as users prefer a light shoe, we must divide this by the density p (giving energy stored per unit weight) and seek materials with LOW values of

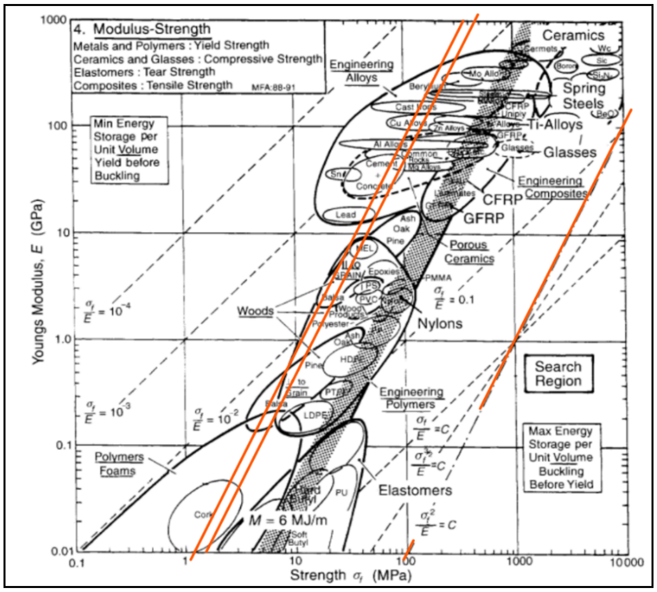
$$M_2 = \frac{\sigma f^2}{\rho E}$$

Material Chart Plots:

As we see from the derivation, we seek a low value of the square of tensile stress value divided by density and the young's modulus to minimize the energy storage by the sole so that it transmits all the energy (force) that it receives from the user.

Following the $\frac{\sigma f^2}{E} = C$ line on the plot and accounting for the density of the material as well, we obtain polymers (PU, EVA, NBR), Al alloys, woods, and nylon to be part of the optimal solution.

Keeping in mind the fact that the sole must be soft enough for the user to wear yet durable and strong enough that the circuit does not get crushed, after further research, we circled into polymers.



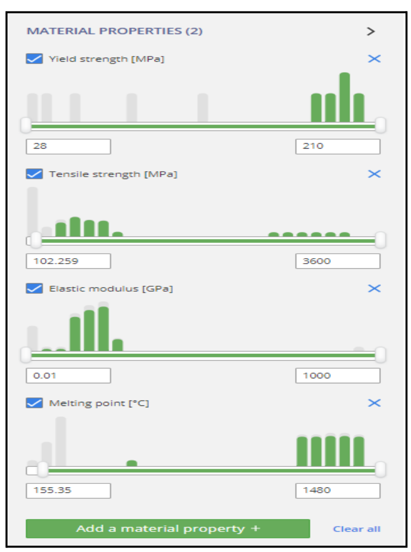
Source: Ashby textbook for material selection.

Detailed Analysis of Materials:

For a more nuanced view, we referred to the popular material selection software, MatMatch.

Gauging the distribution of the material properties: (yield and tensile strength, elastic modulus, and melting point), we saw that rubber and polymers like Polyurethane (flexible and non-flexible), Pebax, Twaron, and Rilsan are within our pre-defines constraints.

Performing a detailed analysis with visualization of the same in an Ashby chart yields the following result on the left, and a comparison of materials used for shoe soles in the industry gives us the following chart (on the right):



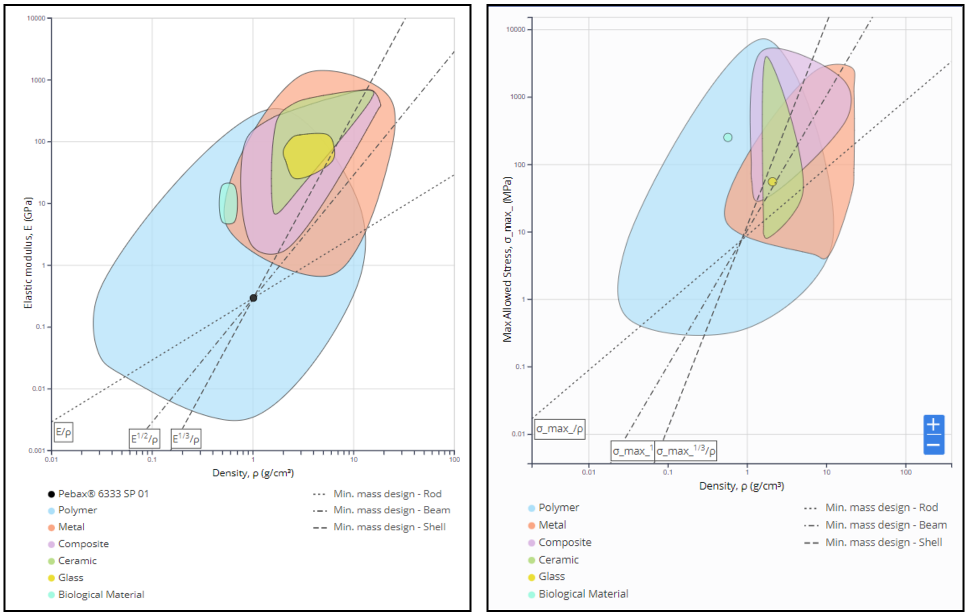
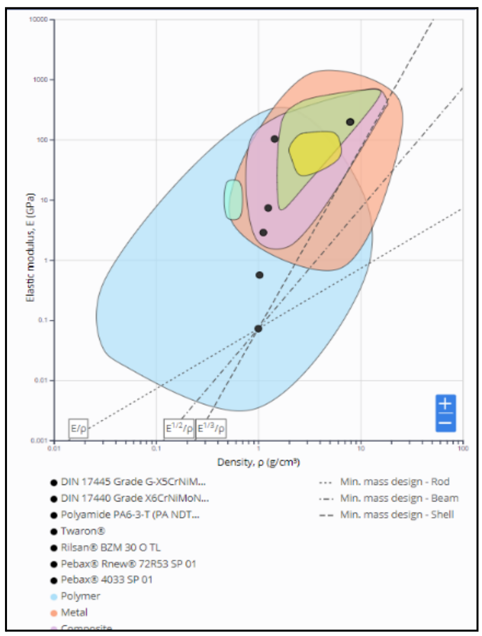


Fig 3: Process of material selection using Ashby charts

A comparison of materials used for shoe soles in the industry gives us the following chart:

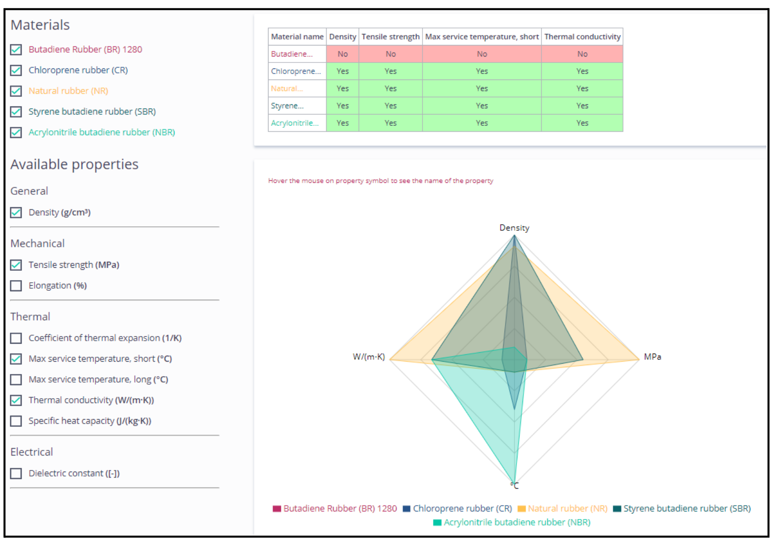


Detailed Analysis of Rubber Types:

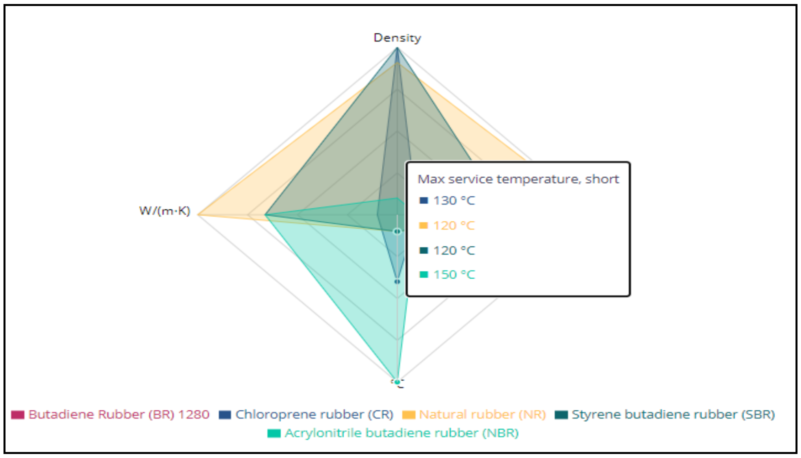
The rubbers that we saw on this had different types, so, our first step of the analysis was to find which rubber type will be best suited for us, then compare with the rest of the materials. We did a deep-dive analysis into the different kinds of rubber available in the market. The comparison between the tensile strength and density is given below.

For the same density, we see natural rubber has the highest strength NBR, though has a lower density, has a much lower tensile strength, the difference of which is much more significant than the density difference.

Our system uses a power source - batteries + voltage generation by the piezo sensors, and further, due to environmental conditions and heat generation in the foot (sweat, etc.), the system will be susceptible to heat. Hence, doing a further analysis with the thermal conductivity and the maximum service temperature:



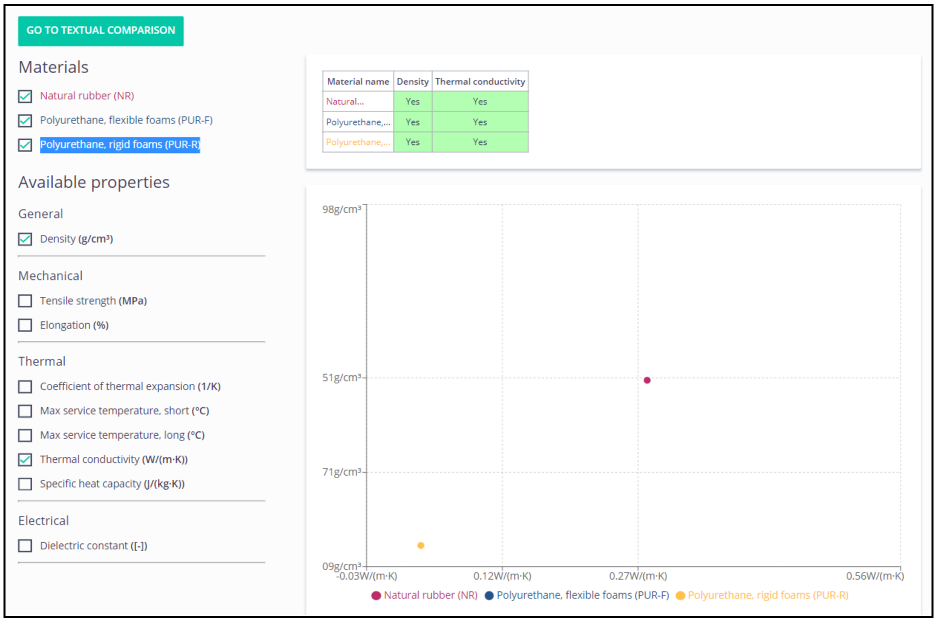
In the comparison diamond, we can see that the optimal performance is of natural rubber in all cases, except for maximum service temperature. On further analyzing the values:



We can see the difference in the max. The service temperature of natural rubber and NBR is only 30 degrees. Hence, we can neglect this small difference, and finally, conclude that the best rubber out of the above is natural rubber. Now, on comparing natural rubber with polymers, we get :

As we can see from above, the density of polyurethane is much lesser as compared to natural rubber, which is better for us in order to optimise the weight of the shoe sole. Further, we see that the rigid foam of PU is a better choice than the flexible foam, so we go ahead with the rigid foam amongst the PU options.

Doing a further analysis with thermal conductivity:



We see that polyurethane(rigid foam) does better on this aspect too as its thermal conductivity is low so it will not transfer the heat from our circuit to the wearer.

Hence, the conclusions from our analysis:

1. Polyurethane (rigid foam) is one of the better materials to be considered for our shoe sole based on constraints and optimisations, including softness etc.
2. Natural rubber comes second to the rigid foam, and has a better tensile strength as well.
3. A third option for testing is another polymer, EVA, which also came within our constraints.

PU>Rubber> EVA

Hence, we went ahead to order these materials and proceeded to test our set-up with the two.

Procurement of Material

We analyzed the current natural rubber soles available in India and did a non-official cost analysis and ease of procurement analysis to find our ideal brand for natural rubber soles : Pazzo. We obtained a sheet of PU online and ordered that as well, as we did not find much difference in the brands for the same.

We also tested on another polymer to validate the results obtained by our theoretical material selection analysis, and we got satisfactory results to validate our hypothesis. EVA (the other polymer under consideration) was ordered and tested - and it did not give as good a result as PU and rubber as it was not transmitting the required force from the user's foot.

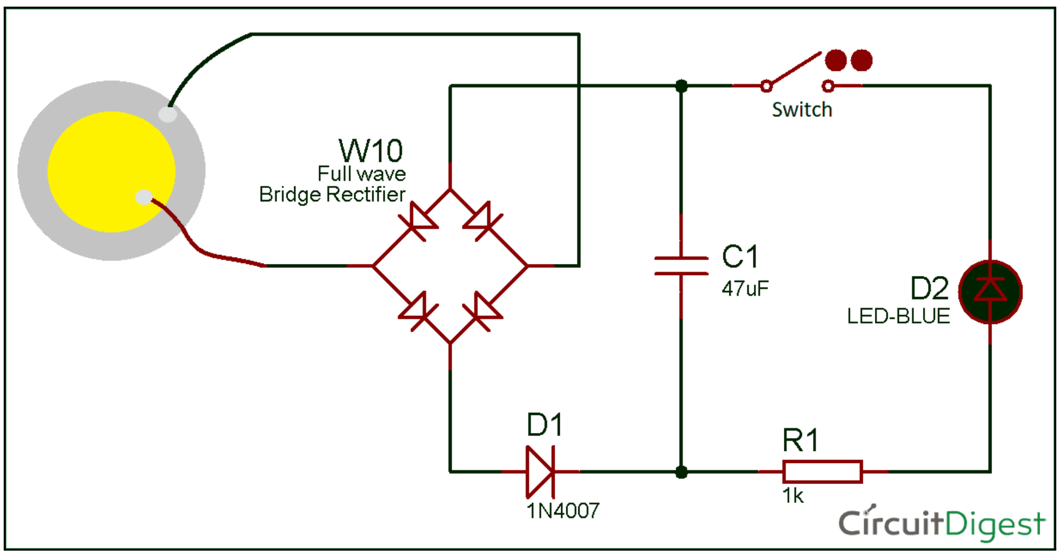
The result obtained with polyurethane material was also significantly better than natural rubber.

Hence, this corroborated our theoretical result and we proceeded to make our prototype with polyurethane.

SYNTHESIS AND INTEGRATION OF COMPONENTS

Preliminary Circuit for a Piezo Sensor

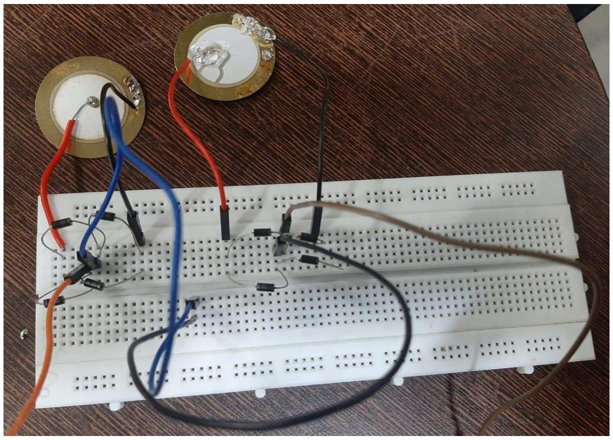
We first implemented and tested a preliminary circuit design for a single piezo sensor. As shown in the figure given below, the piezo terminals are connected across a Full Wave Bridge Rectifier. This helps to convert the AC voltage produced by the piezo to DC voltage and also gives full wave rectification. This is then connected to a 1N4007 diode which regulates the flow of current in one direction. The capacitor connected in parallel with this setup acts as a reservoir and gives a smoother DC output which can then be detected by a glowing LED bulb.

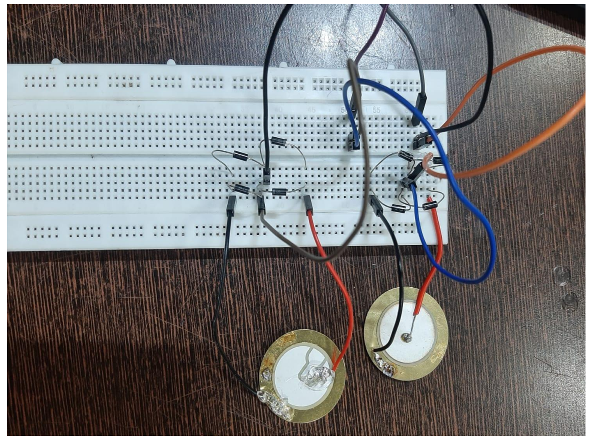


Connecting Multiple Piezoelectric Sensors

In this circuit since the primary source of voltage is the piezoelectric sensors, we mapped the positive and negative terminals and made a test circuit on a breadboard for series and parallel connection with resistors as shown in the figures below. We chose a series circuit as it was the one yielding larger voltage values. The results of tests with 10 readings each are as follows:

Series: Parallel:





Data obtained for the test circuit:

TYPE OF CIRCUIT	Max voltage	Average Voltage
Series - 2 piezos	0.080 V	0.077 V
Parallel - 2 piezos	0.045 V	0.036 V

Arduino Nano Circuitry and Integration with Android app

a. Read the DC signal from Piezo circuit to the analog pin on Arduino Nano. Using Analog pin, we could measure voltage as low as 0.005V

b. When no signal passes, the pin is attached to a pull down resistor which helps neglect any environment noise.

c. Everytime, the signal generated by piezo surpasses the threshold, a step count is registered in the system, henceforth leading to incremental counting.

d. A bluetooth module enabled by UART communication protocol is connected to arduino nano, which sends the step count to android through which a user could accurately know the number of steps he walked.

Pseudo Code for Step Counting

```
variable initialization (critical variables are int step_count = 0 and bool is_counting = 1, float threshold = 3.5)

initialization of EMA_alpha and EMA_s (variable denoting the registered part count, out of 1024)

setup code (define input pin from which to read EMA_s value)
```

```
main step-counting loop
 read analog value from input pin every second (stored in val)
 calculate input voltage using EMA_s, EMA_a, val value
 if ((voltage > threshold) AND is_counting)
    {
      is_counting = !is_counting; (stop to prevent false counts)
      step_count++;
    }
 else if ((voltage < threshold) AND !is_counting)
    {
      is_counting = !is_counting; (start counting again)
    }
 debug output prints voltage, EMA_s (parts out of 1024) and step_count
```

System Prototype Integration

To integrate the piezo-sensors to the shoe sole, we first identify the prime points of pressure application when a step occurs, which results in three piezo sensors placed at the top portion of the sole below the toes, and the four other sensors at the heel. These sensors are placed onto the sole material that resulted from an extensive material selection procedure. We then place another sole on top of this, to obtain an insole that can be placed in any footwear. The piezo-sensors have their positive and negative terminals connected and soldered to the PCB, onto which other electrical components like the Arduino Nano, resistor, soldered connections, etc. are placed. These wires are wrapped neatly around the sole, and the PCB is fitted into a pouch that can be tied around the ankle for ease while walking. The code that counts steps based on the threshold value of voltage (here, 3.5V) is integrated with this circuit by powering the Arduino Nano with the help of a charged laptop, with a cable connecting the two. To display the number of steps, the Arduino IDE software is installed in the laptop, that displays the voltage applied due to the step, and the incremental step variable as well. This is how the entire system prototype is integrated, with both the mechanical and electrical components combining to achieve our application.

BILL OF MATERIALS

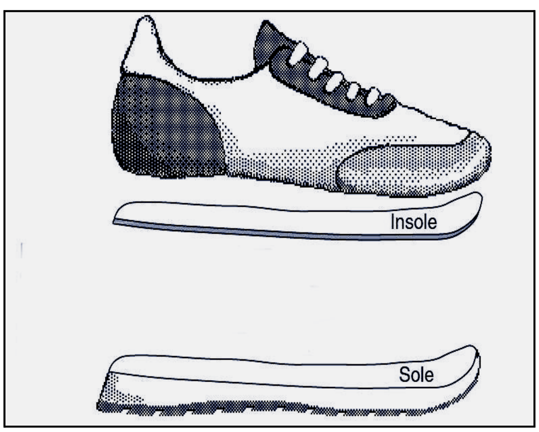
The following bill consists of a comprehensive list of materials purchased and their corresponding quantities. Such a centralized source of information provides us with an overview of the cost that is incurred in manufacturing the product, here, the piezo sensor-powered step counter shoe. The total cost is equal to Rs. 7054, which is a testament to this product's cost-effectiveness and economic feasibility in the market.

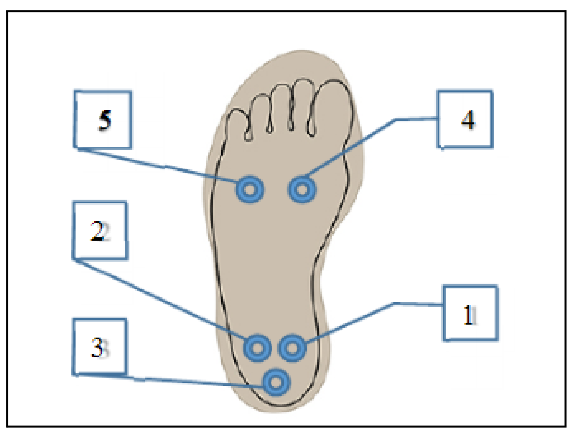
Sr. No.	Component	Cost/piece (Rs.)	Quantity	Total cost (Rs.)
1	PCB	70	2	140

Sr. No.	Component	Cost/piece (Rs.)	Quantity	Total cost (Rs.)
2	Jumper	2.5	40	100
3	Spring (2 small + 1 big)	-	3	110
4	Wire	10/meter	12 meter	120
5	LED	3	10	30
6	Resistor	2	12	24
7	Piezo (Big)	20	32	640
8	Piezo (Small)	15	30	450
9	Diode	3	82	246
10	Capacitor (47microF)	4	12	48
11	Nano	450	2	900
12	Li-Ion cell	200	2	400
13	HC05	280	1	280
14	Li-Ion battery holder	25	2	50
15	7805	15	1	15
16	Slipper pair	119	1	119
17	11.1 Battery	700	1	700
18	3.7 V battery	200	6	1200

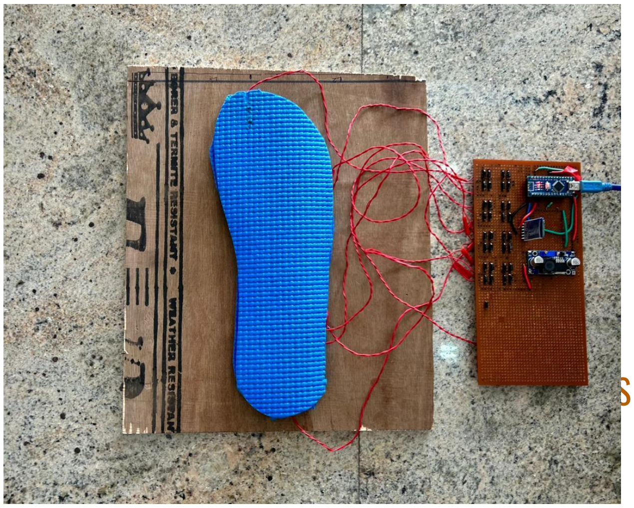
Sr. No.	Component	Cost/piece (Rs.)	Quantity	Total cost (Rs.)
19	2eu holder	60	1	60
20	Boost converter	140	2	280
21	DST	30	1	30
22	Cutter	50	1	50
23	Wire stripper	50	1	50
24	Shoe sole foam	713	1	713
25	Fanny pack	299	1	299
			TOTAL (Rs.)	7054

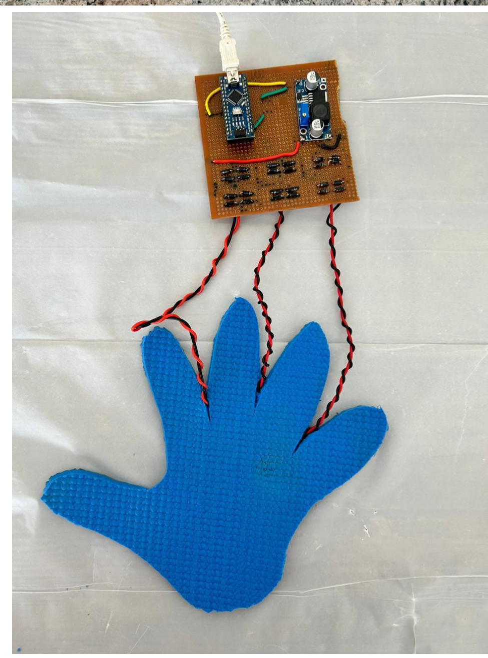
MANUFACTURING DRAWINGS





FINAL PRODUCT





- Length of footwear: 27cm
- Average width of footwear: 8.3cm
- Diameter of piezo sensor: 3.5cm
- Number of piezo sensors: 8

SUMMARY AND HIGHLIGHTS

Nowadays, the need for energy resources has increased, and efficient energy use has become important. Our project aims at effectively harvesting the energy an individual expends daily by harnessing the pressure applied on his/her shoe sole to power a pedometer counting his/her steps. We started with a detailed shoe sole material analysis, optimizing for multiple criteria. Post this analysis, we narrowed our material choices to natural rubber, EVA and polyurethane. After testing these three materials, we obtained the best results with polyurethane, finalizing this as our sole material. We also parallelly developed and tested a preliminary piezo circuit for a single piezo sensor. We then developed a complex circuit integrating multiple piezos to get enough voltage to power our pedometer. This was then integrated with the Arduino Nano Circuitry to register the step count whenever the signal from the piezo surpasses the threshold. The system was further integrated with the Android app to display the step count to the user.

REFERENCES

1. Project power shoe: Piezoelectric wireless power transfer — A mobile charging technique (IEEE Xplore)
2. Design of Piezoelectricity Harvester using Footwear (researchgate.net)
3. Piezoelectric generator creates power from shoes (newatlas.com)
4. Smart Shoe using Piezoelectric Transducer.pdf (cit.ac.in)
5. Can Piezos Power My Cell Phone by Walking
6. Piezoelectric Energy Harvesting Shoe - Appropedia

KEY LEARNINGS AND TAKEAWAYS

- Iterative procedure is a must during any product development.
- We learnt the basics of circuitry such as design, soldering. We also faced some issues with the initial circuits, which we had to test with a multimeter and correct accordingly.
- Wire thickness is also a factor in the flexibility of the system, with a thinner wire being less stiff and easier to integrate with the bulky circuit.
- A stiffer material would be preferable between the ground and the piezo sensors, to allow pressure to be transmitted effectively from the foot to the piezo sensor.
- Tuning the threshold value in the step counting code is essential to deal with the counting latency and improve the frequency of measurements

Future Work:

- To be integrated as an add-on shoe sole with bluetooth
- Can be integrated with a wooden slipper as well easily
- Another application can be to signal to the user that his shoe is being worn by someone else (an alert that the shoe is being used- and if it is not the user, he will know it is being stolen) can be used in temples, etc, where chappals/shoes get stolen a lot