Insole Overview

The insole is the component which is inserted in the user's shoe. It is a standalone system requiring no additional assembly or user serviceable parts. The insole is designed to house all hardware, including the micro-controller, energy harvesting system, energy storage devices, force sensors, and wire connections.

The insole is made up of a number of independent components, assembled using no adhesives or machined parts. The components are either 3D printed or come from a third part manufacturer. Once assembled, the insole will be sealed with a liquid rubber to solidify the design to meet the robustness criteria.

The insole will be capable of harvesting the energy from user's steps to provide power to the micro-controller, provide the micro-controller with the tools to measure pressure on different parts of the users foot, and meet all other criteria specified in the system requirements documentation.

In order to harvest the energy of user's steps, the insole will implement two brass discs coated with a piezo ceramic material. This material, when deformed, produces an electrical potential difference between the brass and ceramic material that can be polarized, collected on a capacitor, then transformed to an ideal voltage range to be stored on another capacitor. This is done using a piezo-ceramic bender, housed in a component known as the activator, and connected to a third party energy harvesting device, an LTC3588. The LTC3588 collects the energy from the piezo ceramic on an input capacitor, then uses a low power buck converted to efficiently convert that input voltage to the desired 3.6V stored on a larger output capacitor. This output capacitor is to be the voltage source that powers all other components within the insole.

To measure force, the insole uses two sensors, force sensitive resistors. These sensors decrease in resistance as more force is applied to them. For simplicity of design, the sensors are located in the same place as the piezoelectric buzzers, one on the users heel and the other on the forefoot. The contacts to these resistors will be exposed to the micro-controller, allowing it to determine an estimate for the amount of force the user is applying to that part of their foot.

The other criteria the insole needs to meet deals with robustness and comfort. All components that make up the insole are resistant to heat within the specified range, can withstand all forces that are capable of being applied to it under intended use cases, and is sufficiently waterproof. This is accomplished by using multiple materials to create the components and finalizing the design by sealing it with a liquid rubber.

Electrical Operation

The component that makes it possible to harvest energy from a users step is the piezoelectric buzzers, manufactured by a third party. The buzzers consist of a thin brass disc coated with piezo-ceramic on both sides. The buzzers to be used are known as AB4113B-LW100-R, manufactured by PUI Audio, shown in figure 1.

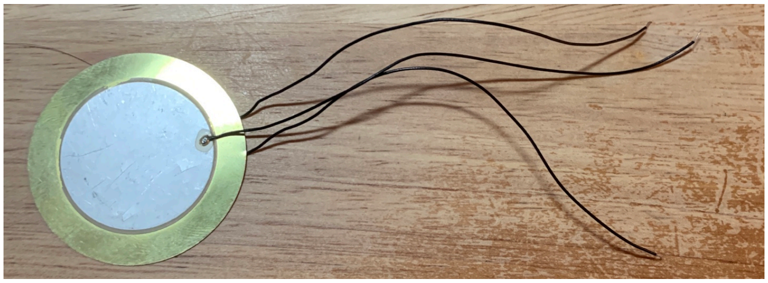


Figure 1. The piezo buzzer.

When the buzzer is deformed, it produces an electrical potential difference between the ceramic and the brass. Under any deformation, each ceramic coating produces a potential difference with the same polarity relative to the brass. The waveform shown in figure 2 shows an example of this.

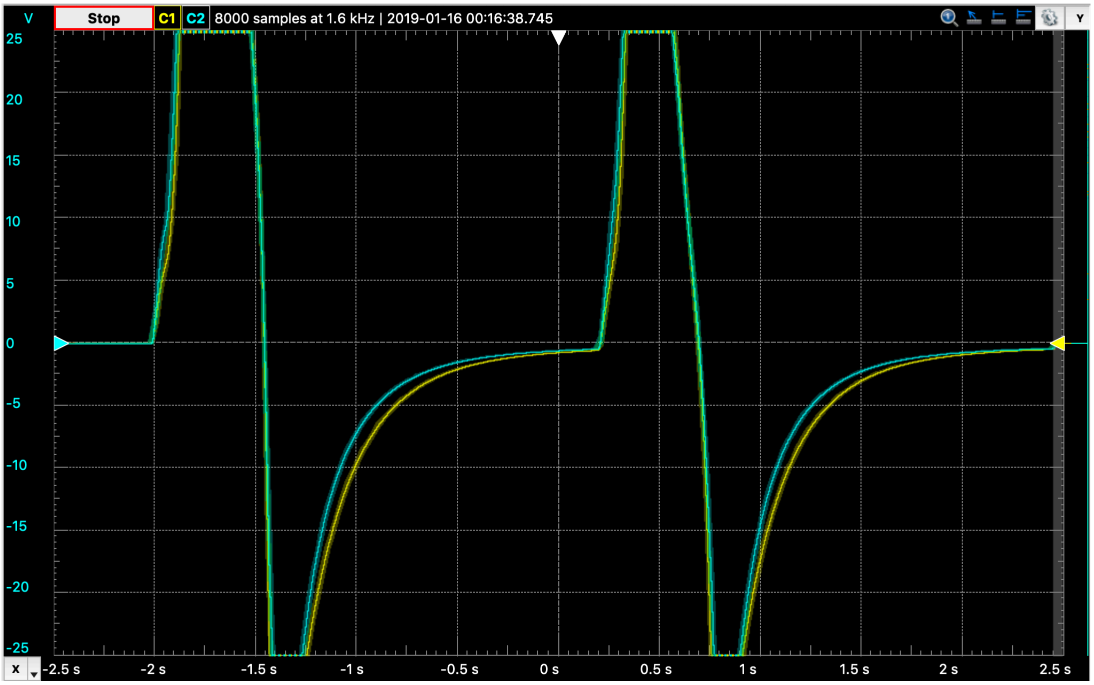


Figure 2. Piezoelectric buzzer waveform when deformed. The voltages shown are produced by the ceramic plates relative to the brass disc, one yellow, one blue.

To use this voltage, it is polarized using a full-bridge rectifier and stored on a capacitor. Because the ceramic plates produce the same polarity voltage relative to the brass, the lead wires of the ceramic can be connected to each other, allowing for a simple two inputs to the rectifier.

When the voltage is stored on the capacitor, it has a potential maximum voltage equivalent to the max voltage that can be produced by the buzzers. This voltage is too great to power the micro-controller however, and needs to be transformed to a proper range first. The voltage the buzzers can produce is >30V while the micro-controller requires voltages in the range of 1.7-3.6V. To transform the voltage, a third party energy harvesting chip is used, the LTC3588, manufactured by linear technology.

The LTC3588 has a full-bridge rectifier on the chip and stores the voltage on a capacitor (C_in), then uses a low power buck converter to transform the voltage and stores it on an output capacitor (C_out). This output capacitor is then used to provide the micro-controller. The circuit diagram including the buzzers are shown in figure 3.

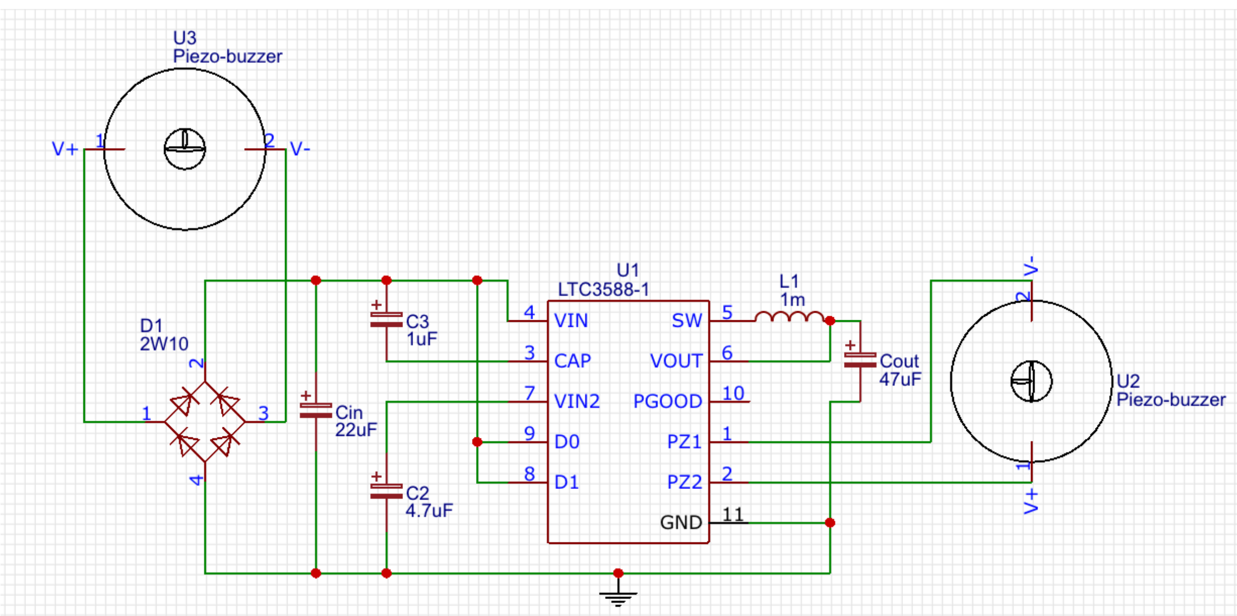


Figure 3. Piezoelectric buzzers connected to the LTC3588 chip.

Because the LTC3588 has only one full-bridge rectifier on it, a second rectifier must be used for the second buzzer. The output of both rectifiers are connected to the same capacitor however, C_in. The capacitors C_in and C_out can be sized to meet electrical requirements and the output voltage can be any of the following values: 1.8V, 2.5V, 3.3V, 3.6V.

The energy stored on capacitors is calculated using the equation:

$$E_{cap} = \frac{1}{2}CV^2$$

To store the most energy on the capacitors, the voltage should be maximized. The micro-controller requires voltages in the range of 1.7-3.6V, so the LTC3588 will be configured to supply the output capacitor with a voltage of 3.6V. The input capacitor can be up to 20V, regulated by a shunt diode to prevent over voltage. The equation to determine the maximum energy capacity of the capacitors is given by:

$$E_{max} = E_{cin,max} + E_{cout,max} = \frac{1}{2}(C_{in} * V_{cin}^2 + C_{out} * V_{cout}^2)$$

The capacitors to be used are aluminum electrolytic capacitors. Sufficient capacitance for C_in have been determined to be 22uF and 47uF for C_out. This gives a maximum energy capacity of:

$$E_{max} = \frac{1}{2}(22uF)(3.6V)^2 + (47uF) * (3.6V)^2) = 4700uJ$$

This maximum energy capacity provides the micro-controller with more than enough power to continue operation uninterrupted between steps. This is necessary because there is no input power between steps and thus the micro-controller will need to exhausted this energy capacity sparingly in such cases. This satisfies the energy requirements determined in the micro-controller section, and if needed, the capacitors can be resized to power up the system faster with less energy capacity, or slower with greater energy capacity.

The test plan described at the end of this insole section will determine how many steps a user needs to take in order to power up the micro-controller, and how much data collection, manipulation, and transferring the micro-controller is capable of per step. This is done by determining the energy the system gains per step and comparing that value to the energy requirements determined in the micro-controller section.

Piezo Buzzer Usage

Energy is produced by the buzzer in the form of a voltage difference between the ceramic plates and the brass disc when the buzzer is deformed, and the more deformation, the greater the energy produced. Harvesting the energy from the piezo buzzer requires that the design be optimized to produce as much of a deformity as possible without damaging the buzzer.

The component that houses the buzzer consists of two parts shown in figure 4 and figure 5. The assembled components with the piezo buzzer included is shown in figure 6.

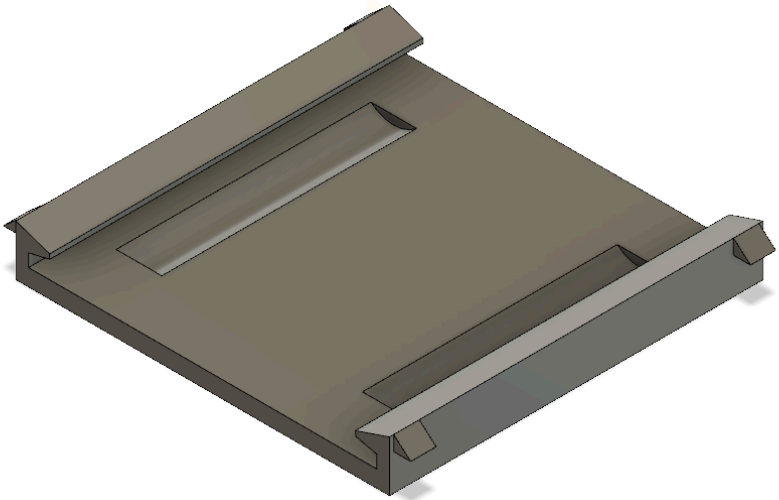


Figure 4. This component is made from PLA using a 3D printer. PLA is a hard plastic. This is to control the maximum amount of bend that can occur on the piezo buzzer, and will be referred to as the buzzer base

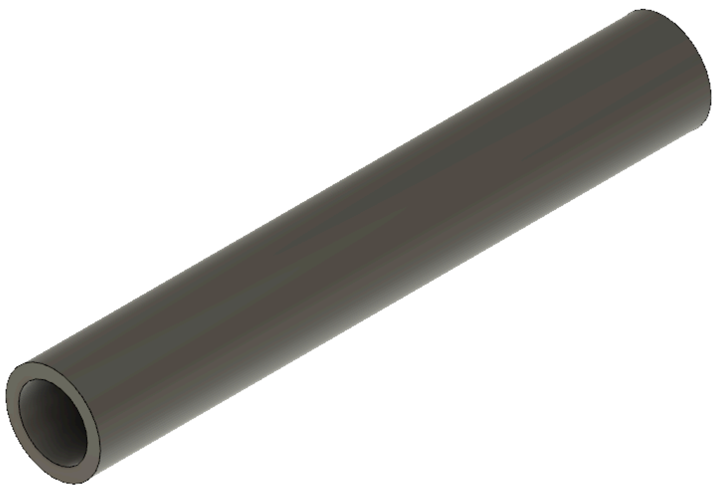
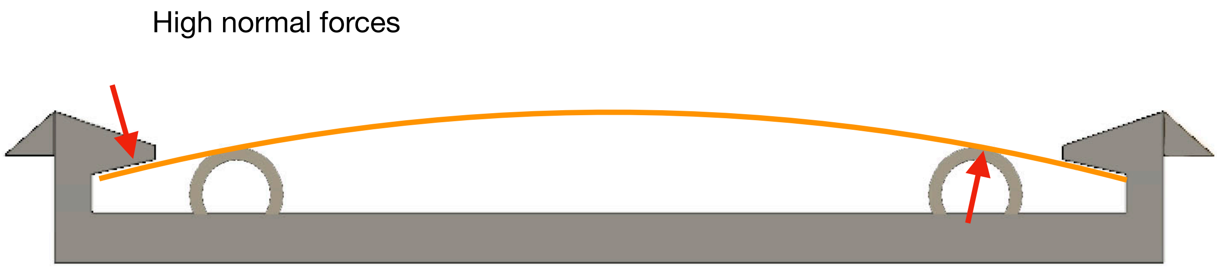


Figure 5. This component is made from TPU using a 3D printer as well. This is a flexible plastic. This is used to deform the buzzer in a direction opposite to the deformity produced by the users foot, returning the buzzer to its original state after being activated. This will be referred to as the buzzer decompressor.

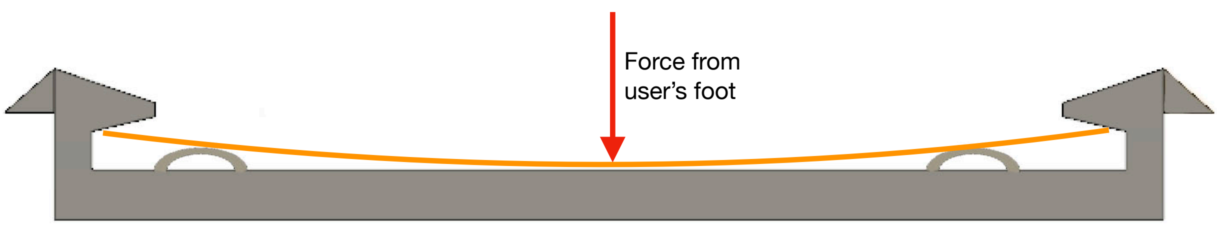
Figure 6. The assembled piezo activating components. Two buzzer decompressors are placed in the semi-circular rivets in the buzzer base. The buzzer is then inserted above the decompressors while being contained in the volume of the base. This will be referred to as the piezo component.

Assembled piezo component - initial state



The decompressor applies an upward force more toward the center of the buzzer than where it is held in place. This causes the center of the buzzer to budge upward.

Assembled piezo component - force applied



The force from the users foot compresses the decompressors and allows the buzzer to deform in the opposite direction.

This method of allowing the piezo buzzer to deform in either direction, up or down, manages to maximize the deformity with minimal space required. The normal forces applied to the edges of the buzzer and the rivets for the decompressor keep every component from moving or rotating, thus no adhesives are required for the piezo component.

The hard plastic the base is made out of prevents the buzzer from being deformed too much, protecting it from damage due to the users foot.

For design flexibility, the radius of the decompressors can be adjusted. Reducing the radius will have the effect of decreasing the initial bend, reducing the energy it is capable of producing when stepped on. Increasing the radius could increase the initial bend and producible energy, but comes at the risk of deforming the bender too much and causing damage under the no downward force condition.

Force Sensor

The sensor used to determine the amount of pressure the user is applying is a force resistor sensor. As the user applies more pressure, the resistance decreases. To use this requires a voltage division technique and an analog to digital voltage conversion to be done by the micro-controller. The circuit technique for this is shown in figure 7

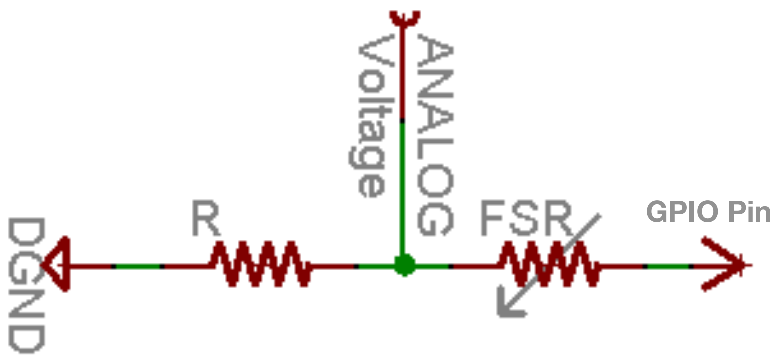


Figure 7. The FSR circuit.

Measuring the voltage between the force resistive sensor (FSR) and the reference resistor allows for the resistance of the FSR to be calculated with the following equation

$$R_{FSR} = (\frac{V_{gpio}}{V_{ADC}} - 1) * R_{ref}$$

Allowing the voltage to be applied with a GPIO pin lets the amount of power dissipated be controlled by the micro-controller. Applying the voltage only during periods of measurement will minimize the energy required by this circuit. Additionally, the reference resistor can be sized to modify the power dissipated during measurement. Increasing the size of the resistance will decrease the power dissipated, but this causes the measured voltage to be less sensitive to the resistance of the FSR, potentially increasing the error of the measurement.

Physical Assembly

The entire assembly will consist of the base insole, two piezo components, two force sensors, the micro-controller, and energy harvesting/storage hardware previously discussed. Once assembled, all cracks and exposed parts are to be sealed with silicone rubber in order to solidify the design and make it water/dust proof. The assembled insole will be capable of providing the micro-controller with enough power to function, and allow it to collect pressure measurements from multiple points. The assembly process will be described here.

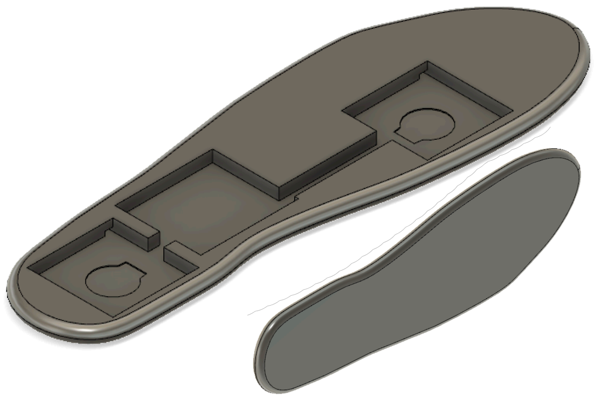


Figure 8. The insole, bottom view left. This component is made of TPU, a flexible plastic. All other components of the insole will be housed within this.

Figure 9. A force resistive sensor. It is thin and flexible. Capable of accurately measuring any pressure above 10g.

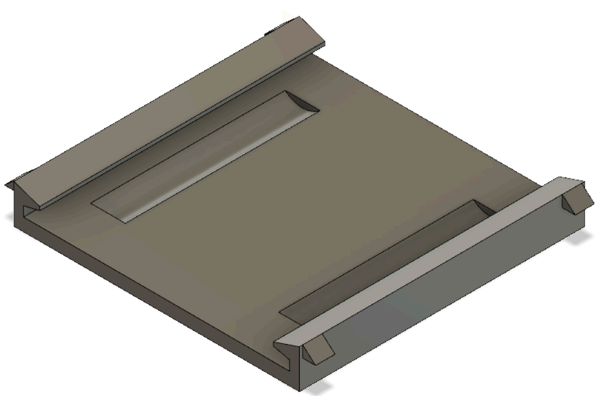
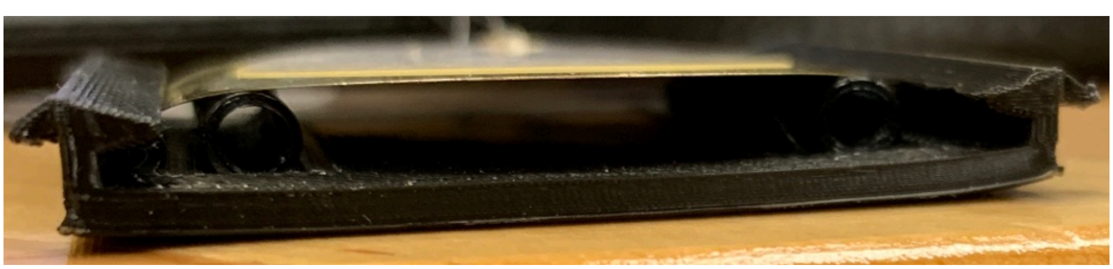
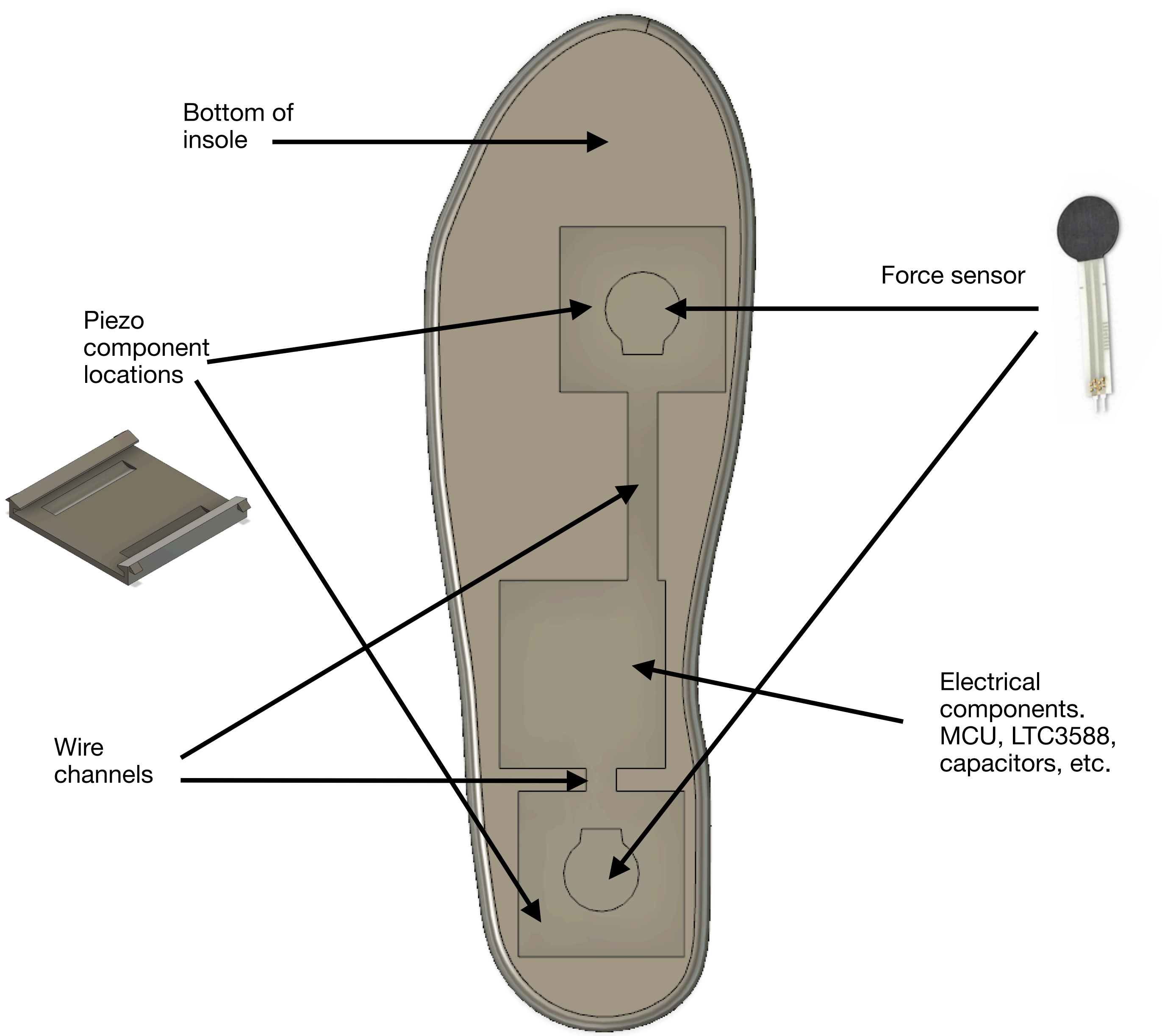


Figure 10. Previously seen piezo base, further discussed. The sharp corners protruding from the sides of this base are used to anchor into the insole, making it difficult to remove.





None of the components needs to be assembled with any adhesives or tools. The wires and electrical components do need to be soldered together however. The force sensors lay underneath the piezo components in this picture. The square section in the middle that houses the electrical components will be filled in with silicone rubber, preventing water for gaining access to these components.

Component Expenses

The component expenses will be analyzed for all parts considered to not be negligible. Negligible parts include capacitors, wires, resistors, and solder. Component tables will be created with a single insole in mind.

3D Printed Parts

	Print Time	Material Type	# Required
Buzzer Base	55 minutes	PLA (hard)	2
Decompressor	17 minutes	TPU (flexible)	4
Insole	9 hours	TPU (flexible)	1

PLA Print Settings:

- 80mm/s
- 210*C Nozzle
- 80*C Bed
- Retraction Enabled
- Support above 80*

TPU Print Settings:

- 40mm/s
- 225*C Nozzle
- 70*C Bed
- No retraction
- No support
- Infill 20% triangles

Third Party Manufactured Purchased Parts

	Manufacturer	Model Name/#	Cost per Item	# Required
Buzzer	PUI Audio	AB4113B-LW100-R	$2.28	2
Energy Harvester	Linear Technology	LTC3588-1	$6.00	1
Force Sensor	adafruit	Interlink 402	$7.00	2
Silicone Rubber	Silicone Depot	Pro Grade RTV	$3.49	1

Overall Tests and Properties

Energy: 180uJ per step

The energy per step is defined as the increase in energy stored on the capacitors within the insole every step. This is measured by counting the number of steps required to charge the input capacitor up to 15V, and the output up to 3.6V, then dividing the energy stored on the capacitors at that voltage by the number of steps.

Water/Dust Resistance: N/A

Water and dust resistance in the future will be tested by submerging the device in a small bucket of water. This iteration though has no waterproofing whatsoever yet.

FSR Sensitivity: ~7kOhms Heel / ~8kOhms Forefoot

FRS sensitivity measures the lowest resistance measured be the force sensor during a brief walk.

Flexibility Result: No damage

The flexibility test was ran by bending the insole 90* and analyzing the damage.

Dimensions: 280mm x 100mm x 8mm

These are the largest dimensions of the insole. It’s 8mm in depths all they way around. The thinness combined with the flexibility makes it very comfortable. The components could however fit into a shoe as small as a 10 male and potentially any larger size.