Interdisciplinary Capstone Design Course Final Project Report

Piezoelectric Crosswalk

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Executive Summary

Pedestrian Fatalities have increased by 35% since 2008 and accounted for 16% of the 36,560 U.S. traffic related deaths in 2018. In July of 2019 a young woman with close ties to Georgia Tech Research Institute was hit and killed while on vacation with her fiancé in Charleston, SC. The design problem is to create a piezoelectric crosswalk system that alerts oncoming traffic of a pedestrian in a crosswalk. This system would make it safer for pedestrians to cross roads without the need to activate the alert manually.

The design problem is to create a system to be deployed on crosswalks that alerts oncoming traffic of pedestrians in the crosswalk that utilizes piezoelectric elements. The technical challenges of this problem include selection of a housing of the piezoelectric elements that can be feasibly deployed by two people, the feasibility of power generation from piezoelectric elements, designing a warning system, and designing a controller that knows when a vehicle or pedestrian is crossing.

A proof of concept is that there are already crosswalks with warning lights, however those crosswalks require the pedestrian to press a button to trigger it. With the piezoelectric tile system, the need to press a button to trigger the warning signal will be removed. Also, those systems must be connected to the power grid, the goal is for the system to be independent of the grid and 100% sustainable.

The minimum viable product is a tile or mat system that deploys over one lane of traffic that can send a signal to trigger a warning system when a pedestrian steps on the crosswalk. The selected design is a piezoelectric tile sensor system and isolated warning system. When a pedestrian steps on the tile, the tile will send a signal wirelessly to the warning system, which could consist of LEDs within the ramp of the tile system. The warning system is isolated as the piezoelectrics do not generate enough electricity to power the entire set of LEDs for a sustained amount of time. The tile will be able to tell if a car is on it, so it does not trigger the warning signal if a car is crossing, only if there is a pedestrian in the crossing.

In order to validate the design, tests were conducted on an instron machine to determine the energy generated per deflection of piezoelectric element, and extrapolated that figure throughout a tile's worth of piezoelectric elements. To make sure that the design could withstand the load of traffic, finite element analysis software was used on a digital model of the tile. To test the electronics, electrical and computer engineering students researched different piezoelectric circuits, built them on a prototyping breadboard, and tested them with an oscilloscope to make sure the circuitry was working properly.

Drawings and a manufacturing process were created for a dual layer piezoelectric system that can detect if a person or a car is on top of the tile and drawings of the accompanying ramp from the road to the tile that could contain the warning system. Although, the system is flexible that the warning system does not have to be contained in the ramp, it just has to be near the tile. The design was validated by creating the molds necessary for the creation of the basin, and a 3d printed mini-tile prototype that can send a signal wirelessly from the "detecting" microcontroller to a microcontroller that represents a "warning system".

The future of this project would be to quantify the power generation in a real world setting, not just extrapolated numbers from one deflection by testing a battery charger circuit using piezoelectric elements. Also, coding the "detecting" microcontroller to go into a deep sleep low-power mode while not sending a signal and fine tuning the detection circuitry. When the circuit and microcontroller work, a printed circuit board should be designed to fit under the piezoelectric layers of the tile. Using the drawings and manufacturing, a full size prototype can be created for further testing in real world situations, with real loads. After one of the tiles works, because the system is modular, multiple tiles are manufactured until there are enough to cover an entire crosswalk.

Nomenclature

GTRI - Georgia Tech Research Institute

Piezoelectricity - electric charge that accumulates in certain solid materials in response to mechanical stress

PZ - Piezoelectric (in nature)

MUTCD - Manual on Uniform Traffic Control Devices

HOQ - House of Quality

FOS - Factor of Safety

FEA - Finite Element Analysis

FMEA - Failure Mode Effect and Analysis

Shore - measure of the resistance a material has to indentation

RPN - Risk Priority Number

1. Introduction and Background

The piezoelectric crosswalk system is to be a tile system deployed on top existing crosswalks. The piezoelectric elements will harvest energy from passing traffic, and when a pedestrian is sensed by the microcontroller and piezoelectric elements, a wireless signal will be sent to a separate alert system. Because LEDs will require much more energy than the microcontroller, they will be integrated into the ramp and powered by solar panels. The goal is for the system to be independent from the power grid and harvest as much energy as possible from piezoelectric elements.

The system benefits pedestrians the most as it will make crossing the street safer by being able to alert drivers automatically when they are in the crosswalk. This benefits drivers because it provides additional feedback to know when a pedestrian is in the crosswalk, especially in times of low visibility like night time. GTRI benefits from the development of the crosswalk because they'll be able to market a self-sustaining safety system to local governments to increase the safety of their community. Bike and scooter riders will benefit both as drivers and pedestrians as bikers and scooter riders can cross traffic both on foot and as a driver.

The minimum viable product is a mat or tile system deployed over one lane of traffic that can at least sense if a pedestrian is walking on it, and trigger the alert system, energy should be harvested from the piezoelectrics to send a bluetooth signal to the warning system.

A large technical issue is that piezoelectrics do not generate a lot of energy, one deflection of the PZ element in a lab setting generated 50uJ of energy. They generate a large impulse like voltage spikes when force is applied and then a negative voltage impulse as the force is reversed. After conducting tests and research, it was found to not be feasible to power the LED warning system via the harvested piezoelectric energy. The harvested energy is stored in a battery that powers the microcontroller, that remains in a deep sleep mode, that only wakes to send the signal when a pedestrian is detected.

Another technical challenge is that the PZ elements themselves are very fragile, and they have to be protected from being stepped on and ran over by automobiles on a daily basis. That is where the data from the finite element analysis was most valuable in determining if the design will hold up to those forces.

The prototype validated the pedestrian detection aspect of the system, as it was able to send a signal when the PZ elements were depressed. A mold prototype was designed and created for the basin of the tile, to be made of concrete. The ramp was also designed to contain the warning system, however, the system is flexible enough so that the warning system just has to be near the crosswalk, not within the ramp, if it is desired to not be within the ramp.

The rest of this document will discuss existing products, how codes and standards apply to the system, the customer's specific requirements, the market research conducted, design concept ideation, concept selection, industrial design factors, technical analysis, experiments, and design performance predictions, the final selected design, mockups and prototypes, manufacturing methods and the future of this project.

2. Existing Products

An existing product that utilizes piezoelectric elements to generate electricity is the Sustainable Dance Floor, which is shown below in Figure 1. The Sustainable Dance Floor, or the Dancer, produces electricity from the movement of club-goers and can reduce 30% of the total energy used at the dance club at maximum capacity[1]. These tiles can be permanent fixtures or can be rented for 75 euros per tile per day, and have been used at various events such as Coachella and the World Science Festival to showcase the power that can be generated by piezoelectric elements[2]. The Dancer tiles are 750x750x200mm in size and weigh 50kg each, which would require multiple people to install a system of tiles.

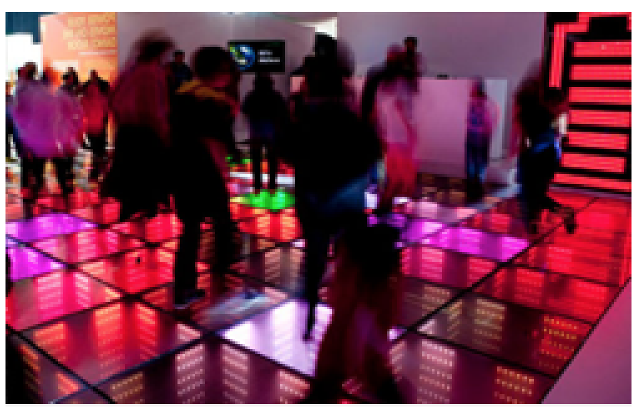


Figure 1: Sustainable Dance Floor [1]

The Power-Generating Floor developed by the Sound Power Corporation has also successfully used piezoelectric elements to generate electricity. The tiles the Sound Power Corporation developed were installed at Shibuya Station in Tokyo at the turnstiles, as shown in Figure 2, to maximize the number of people who would come in contact with them. The train station tiles produced enough energy to power the turnstiles and displays [3].

POWERleap, a company formed from Elizabeth Redmond's 4th year thesis at the University of Michigan, also explored the possibility of using piezoelectric elements to harvest energy from pedestrians[4]. Redmond submitted a patent application, but this application has been abandoned and POWERleap no longer exists as a company. The Innowattech Piezo Electric Generator (IPEG) also explores using piezoelectric elements to generate electricity from both pedestrians and vehicles. IPEGs are able to be installed into a variety of road surfaces, however, they are permanent fixtures since they are embedded into the roads. They also have to be installed over several hundreds of meters and require high volume traffic to produce useful electricity[5]. Another existing product that converts kinetic energy into electricity are the Pavegen tiles shown in Figure 3. These tiles do not use piezoelectric elements to convert the kinetic energy into electricity and instead utilize a flywheel to capture and convert the energy[6]. However, in the patent for Pavegen, it is mentioned that piezoelectric elements could be a possible option in the future that could be incorporated into their design. Majority of the charge created by pedestrians walking on Pavegen tiles can be stored in batteries for later use while a small portion is used immediately to power LED lights. The tiles can also generate a Bluetooth signal to smartphones and act as a data miner[7].

Figure 3: Pavegen [6]

NASA's Kennedy Space Center also uses piezoelectric elements in an outdoor system that was developed by GTRI. The tiles at the Kennedy Space Center (Figure 4) can draw on power through piezoelectricity, solar panels, or a lithium battery and transmits a wireless signal to pedestrian with information about NASA space missions [8]. The tiles successfully protect the electronics from being damaged by the elements and are a permanent fixture at the Kennedy Space Center. GTRI has additionally developed piezoelectric and piezoresistive mats that are used in assessing soldiers. The mats can be rolled up for transportation, but are not meant to withstand outdoor conditions. As GTRI is the sponsor for the piezoelectric crosswalk, access to the research behind both the tiles and the mats will be accessible for review through the development of the crosswalk.

Figure 4: Kennedy Space Center [8]

There are many differences between existing products and the intended design of the piezoelectric crosswalk. Some of the existing products, such as the Dancer, have individual tile weights of 50kg which could increase the time of installation and require multiple workers to install. A similar weight for a tile or a mat for the piezoelectric crosswalk could cause the goal of thirty minute installation by two workers not to be achieved. The piezoelectric crosswalk will also have less pedestrian traffic than the Dancer and the Power-Generating Floor, so ways to power the system outside of solely using piezoelectricity should be considered. The tiles developed by GTRI utilize multiple power sources, but they are permanent fixtures when the crosswalk needs to be temporary. Cost of the crosswalk will be another important factor to consider because current systems can range from about 75 euros per tile per day to up to 160 dollars per square foot to install.

3. Related Patents

US Patent 8,283,794 claims a floor suitable for generating, converting, and/or storing energy from the placement or displacement of mass on the floor. The floor can be comprised of modules, each with its own energy generating system [9]. The system described in this patent uses the energy generated as a supplement to energy drawn from the power grid. The piezoelectric crosswalk should generate enough energy to power a Bluetooth signal without additional power sources.

US Patent 5,801,475 claims a piezo-electricity generation device without an external power supply unit [10]. Multiple circuit diagrams are shown in the patent which could be useful in building the circuits for the crosswalk. The generation device described is not meant to withstand the humans walking over it and was suggested for use in alarm systems for earthquakes.

US Patent 10,381,957 claims a power generation device that uses power generation plates composed of vibration plates and piezoelectric elements [11]. The piezoelectric elements in this device are stacked on top of each other so that all pieces deflect and generate power when the device is activated. The piezoelectric crosswalk being developed will have two layers of piezoelectric elements, but the piezoelectric elements will not be in direct contact with each other.

US Patent 8,400,046 claims a power generation unit that utilizes stacked piezoelectric elements to increase the power generated by piezoelectric elements [12]. This patent provides useful information about how piezoelectric elements can behave when multiple pieces are stacked because it was found that the inner elements could have issues with deflection and decrease the power generation efficiency. This was useful in deciding whether to pursue stacking the elements and deciding to separate the layers with separate housings.

US Patent 8,278,800 claims a multilayer piezoelectric generator made up of a box with electricity generating layers comprised of piezoelectric rods [13]. Pressure applied to the top of the box deforms the piezoelectric rods generating electricity. This generator can be installed in roadways, however, it is only for harvesting energy and can't send a signal using the energy.

Japanese Patent 2011153469 claims flooring capable of accommodating power generation equipment. The flooring developed had to efficiently generate power through piezoelectric elements in the power generation equipment [14]. The piezoelectric crosswalk will also need to accommodate power generation equipment, but will have to consider weather proofing and weight of vehicles.

4. Codes and Standards

The Manual on Uniform Traffic Control Devices (MUTCD) [15] chapter 3B section 3B.18 lists the construction and labeling criterion for crosswalks. This is important to the design as the final design of the crosswalk must maintain its identity as a crosswalk, and may do so by imitating a standard crosswalk pattern.

Section 4L.03 of the MUTCD covers warning beacons. This section covers how beacons may look and operate. This is important as the tile system will use a strip of LEDs that will flash to alert drivers to the presence of pedestrians crossing the street.

Section 4N covers in roadway lights, and specifically section 4N.02 of the MUTCD covers in-roadway warning lights at crosswalks. The section details how warning lights should be used, how they should look, how they should operate, and how they must be laid out along the crosswalk. This is important to the design as the system on the crosswalk includes lights in the roadway.

5. Market Research

Initial market research began with gathering existing data on distracted driving, distracted pedestrians, and the impact of high visibility crosswalks on driving behaviors to help define the problem that the piezoelectric crosswalk aims to address.

Since 2008, pedestrian fatalities have increased by 35% and now account for 16% of all traffic fatalities [16]. Of the accidents that resulted in pedestrian fatalities, 75% of the accidents occurred in dark conditions and 80% occurred in urban settings [17]. Cities and universities have taken action to help protect pedestrians by investing in upgrades and installing rapid flashing beacons at crosswalks that used to rely on the standard signs. A study by the Federal Highway Administration found the percentage of drivers who yielded to pedestrians increased from 18% to 81% when flashing beacons were present [18]. However, this relies on the pedestrian pushing the button to activate the beacons and the beacons are only activated for a specific time frame. The reported cost of two rapid flash beacons including installation fees could range from $10,000 to $15,000 [19]. A contributing factor to unsafe pedestrian crossings could be due to distracted pedestrians. One study looked at two urban college campuses and found that over one third of pedestrians were distracted while crossing the road [20]. However, this should be investigated more due to the study only collecting data from about 8am to 6pm and the previous source stating that majority of pedestrian accidents occurred in the dark. Unsafe driving behaviors such as speeding, distracted driving, and alcohol impairment are also large contributors to unsafe pedestrian crossings with about half of traffic accidents with a pedestrian fatality reporting an unsafe driving behavior in 2017 [16].

Based on initial research, the target market the piezoelectric crosswalk will aim to focus on are urban colleges and cities due to the large percentage of accidents occurring in those settings. As a piezoelectric crosswalk is a new concept, picking a smaller target market of Georgia Tech and Atlanta would be beneficial in establishing this product prior to moving into the rest of the market.

6. Customer Requirements

Having established a basis for this project's deployment, it is now beneficial to identify the entities who may be concerned with its outcome. These stakeholders, which are called out firstly in the stakeholder matrix, are sorted by their relative importance to the project's success in the 2x2 Stakeholder Chart, shown below in Figure 5.

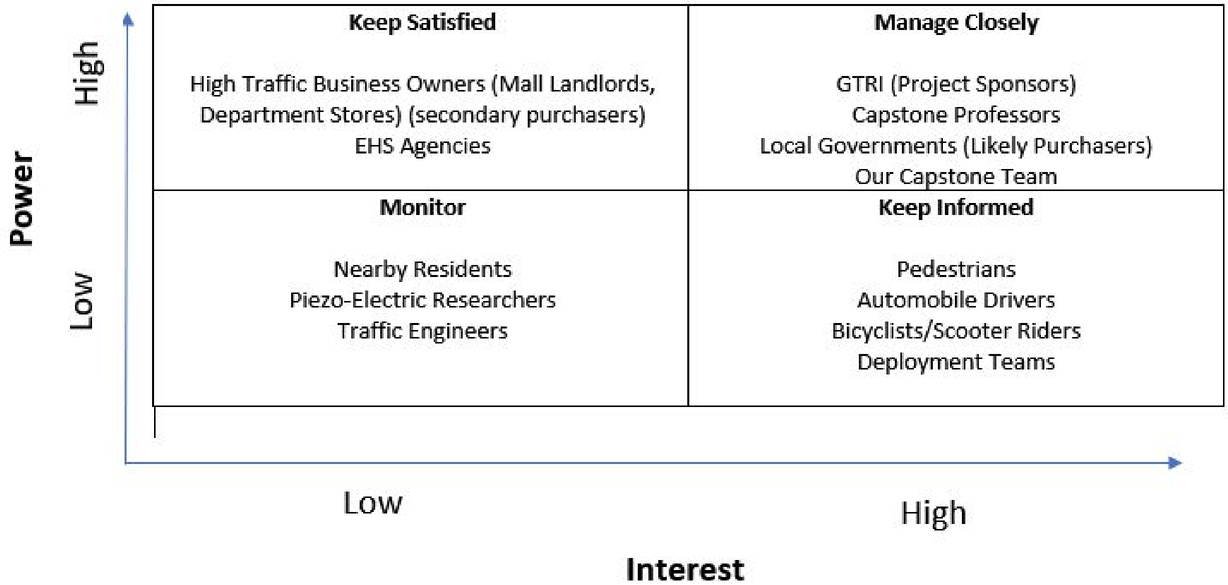


Figure 5: 2x2 Stakeholder Chart

Without discussing every stakeholder entity, it is important to note those in the 'Manage Closely' category, as these stakeholders have significant influence on the success of the project, as well as a very high interest in it. For instance, the Georgia Tech Research Institute might be quite upset if pressure transducers were used rather than piezoelectric elements, since their research is centered on the latter. As they fund the project, retaining their satisfaction is essential. Similar situations apply to other stakeholders in this category.

With the stakeholders identified, it is now possible to identify their requirements for this project. Just as GTRI will expect piezoelectric elements to be used in the project, every other stakeholder will have requirements of it as well. The list of identified requirements includes, but is not limited to:

- Cost
- Ease of Deployment
    - Ease of Manufacturing
    - Ease of Assembly

- Ease of Installation
- Durability
    - Reliability
- Energy Generation
    - Inclusion of piezoelectric elements
- Safety
    - Pedestrian Protection Ability
    - Trip Hazard
    - ADA Accessibility
    - Hygiene
- Aesthetics
- Secondary Functionalities
    - Electrical Power Source (phone,laptop charger, etc)
    - Data Collection
    - Autonomous Vehicle Interfacing

7. Engineering Design Specifications

These customer requirements will be essential to a critical analysis of proposed design concepts, which will be discussed later. Prior to creating these design concepts, however, there is an additional analysis that can be performed. Namely, engineering design specification analysis can be used to construct a detailed specification sheet. Again, this is a tool which can be used to evaluate how well certain designs meet project requirements. The specification sheet for this project is shown below in Figure 6.

No.	Changes (date)	D/W	Requirements	Responsible	Source
				Issued:	**9/4/2019**
			Specification		
			For: Piezoelectric Crosswalk		**Page:**
1		D	Complete electro-mechanical packaging system	Team	Customer Requirement
			Geometry		
2		D	Overall Width: >3'	ME's	Customer Requirement
3		D	Overall Length: >9'	ME's	Customer Requirement
4		W	Height: <0.5"	ME's	ABA Standard; if <0.25" no treatment required
5		W	Slope Between Asphalt & Maximum Height: <1:2	ME's	ABA Standard
			Force		
6		W	Weight of Overall System: <50 lbs	Team	OSHA Recommendation for Single Person to Lift Alone
7		D	Max weight capacity: 80,000 lbs	Team	Federal Limit on Gross Vehicle Weight
			Energy		
8		W	Store at least 700 mAh	ECE's	Energy Requirements Calcualtion
		D	Generate at least 50 uJ/deflection with PZs	MEs	Energy Requirements Calcualtion
		W	Generate at least 20000 J/day with Solar	ECE's	Energy Requirements Calcualtion
		W	Keep Microcontroller in sleep >23.5 hours per day	ECE's	Energy Requirements Calcualtion
			Signals		
9		W	Transmit Wireless Signal: TBD	ECE's	Customer Requirement
		W	Detect Person 100% of time	ECE's	
		D	Distinguish between car and person 100% of time	Team	Customer Requirement
			Assembly		
10		D	Manpower: <=2 people to set up	Team	Customer Requirement
11		D	Set up/Removal Time: <30 minutes	Team	Customer Requirement
		W	Assembly Time: <2hours per tile	Team	
			Material		
12		D	Service Temperature Range: TBD	Team	Check with Customer
13		D	Compressive Strength: >TBD	ME's	
14		W	Material must be UV Resistant	ME's	Customer Requirement
15		D	Slip Resistance: TBD	ME's	No Standard Defined; Federal Requirements only state slip resistant
			Quality Control		
16		W	Require no maintenance for 1 year Time Period	Team	

Figure 6: Engineering Specifications Sheet

Note that the specification sheet differs from customer requirements in that the spec sheet deals with design constraints and projectected uses of the product. It gives quantitative measurements for success where possible.

With these tools developed it is now possible to analyze the relationship between each of the customer requirements, constraints, and engineering design specifications using a House of Quality (HOQ). The HOQ denotes the correlation between the requirements as set forth by the design team and those set forth by the customers. It is used to manage trade-offs in design conceptualization and compare proposed solutions. The HOQ is shown below.

		Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
		Direction of Improvement	▲	▼	▼	▼	▼	▲	▲	▲	▲	▼	▲	▼	▲	▲	◇	◇
Category	Weight	Customer Requirements (Explicit and Implicit) / Engineering Requirements	Energy Storage Capacity (kWh)	Operating Voltage (V)	Ramp Angle (deg)	Tile Height (in)	Tile Weight (lbs)	Compressive Strength (psi)	PZ Generation Rate (Joules/Deflection)	Lifetime Actuations (#)	Light Intensity (lumens)	Chip Power Reqs (Watts)	Chip Frequency (Hz)	Tile Assembly Time (mins)	System Install Time (mins)	Bluetooth Signal Strength	Tile Width (in)	Tile Length (in)
Economy	8	Cost	●			▽	▽	●			○	○	○			●		
	2	Deployment Ease					●							○	●			
	6	Energy Independence	▽						●		○	○						
Operational Function and Design	8	Stability			●		●											
	4	Aesthetics						○			○							
	9	Roadway Coverage															○	○
	4	Multi-functionality	●						●		○	●						
	7	Durability			○													
	8	Accident Reduction									●		○					
	4	Interaction Speed											●					
Safety	5	Trip Hazard Reduction			●				▽									

Figure 7: HOQ Main Body

8. Design Concept Ideation

A. Design Functions

a. Resist environmental damage and physical pressure from traffic.

b. Conduct enough electricity to send a low- frequency bluetooth signal.

c. Be wheelchair and scooter accessible.

d. Deployable by 2 minimally trained workers in 30 minutes or less.

e. Control an LED lighting system using a signal sent from each tile.

B. Design Concepts

a. Blinking LED lights to alert drivers.

b. Rolling mat design for easy deployment.

c. Multiple layer designed to conduct maximum electricity.

d. Control hub at the end of mat for all digital logic.

e. Independent control system integrated with the traffic lighting system.

C.

Light Pattern	Blinking	Static
Tile arrangement	Hexagonal tiles with half hexagons marking the edge of the sidewalk.	Square tiles arranged in a grid pattern.
Light Arrangement	Hexagonal tiles with lights on each edge of the hexagon	Square tiles with lights on the outer edge of the square.
Tile Design	Rolling mat (similar to a carpet or projector screen)	

D. Integrated Concepts

a. A lightweight tile system that can be installed by unrolling it.
b. A strip of LED lights that are controlled by the pressure readings coming from the tiles.
c. A micro- controller that reads in the tile data through bluetooth and uses this information to alert drivers.
d. An integrated power system that draws current from the tiles and supplements any additional energy using solar cells.
e. Using multiple piezoelectrics within each tile in order to increase the resolution as well as the maximum power generation.

9. Concept Selection and Justification

To more easily refine the choice of design, several design decision matrices, shown in Figures 8-10, were created. Design Criterion are sorted by whether they should be maximized or minimized, and categorized by High (H), Medium (M), or Low (L)

Deployment Arrangement	Minimize	Size	Weight	Obtrusiveness	Maximize	Feasable given design time	Communicative	Reliability of Power	Durability	Recognizability	Deployability	Surface Grip (Roughness)	Stability
Hexagonal Tiles		L	L	M		H	L	M	H	L	M	M	L
Square Tiles		L	L	M		H	M	M	H	M	M	M	L
Wide Tiles		M	H	M		H	H	M	H	H	M	M	M
Solid Mat		M	M	L		M	H	L	L	H	H	L	M
Mat with Tiles		H	M	H		L	M	L	M	M	L	M	H

Figure 8: Deployment Design Decision Matrix

Signal Alert	Minimize	Power Consumption	Obtrusiveness	Maximize	Understandable	Noticeability
Blinking Light		L	M		H	M
Static Light		H	M		M	L
Music		H	H		L	H
Sound Effect		M	L		L	M

Figure 9: Alert Style Design Decision Matrix

Alert Location	Minimize	Power Consumption (Individual)	Power Consumption (System)	Cost	Maximize	Visibility to Driver
Hex/Square tile edges		L	H	H		L
Along side of crosswalk		H	M	M		H
Light facing traffic on roadside		M	L	L		M

Figure 10: Alert Location Design Decision Matrix

Based on the required specifications of the project, a smaller, lighter system would be largely beneficial to the ease of deployment. The generation of power will not fluctuate much between the different types, but some may function better with specific tiles dedicated to the collection of energy from either cars or pedestrians. A pure mat system may also be harder to design, as a flexible, less rigid material for deployment might not withstand the durability requirements.

The largest potential risks in each design include the risk of a pedestrian tripping on the system, the alert system being too distracting and causing a driver to notice it over the pedestrian, and the system running out of its stored power.

Tripping is most likely to increase in chance if tiles are not fully interconnected or become so, or if a mat system that deploys by unfolding may not have as rough of a surface to maintain a deployable flexibility. The tile issue can be offset with increased weight or a shell system to lay the tiles in, such as a mat underneath.

To counter issues with notifications being too distracting, the light level or dB level of the notification can be kept beneath a certain point. The frequency of notifications that turn on and off will be kept low, to approximately 60-70 rotations per minute.

Another potential flaw in several of the designs is the potential to run out of stored power. If solar panels are used as a main or auxiliary power source, the system will have reduced access to power generation at night, but the main source of power should be coming from the piezoelectric system. To conserve power, the notification system may benefit from reduced output. For instance, lowering the ratio of a blinking light being on to being off per second while active.

The initial design of the system used tiles with solar panels, and a piezoelectric sensor in the center to detect footsteps. At the request of the project sponsor, the design was altered to include a bluetooth signal powered by piezoelectrics sent from the tile.

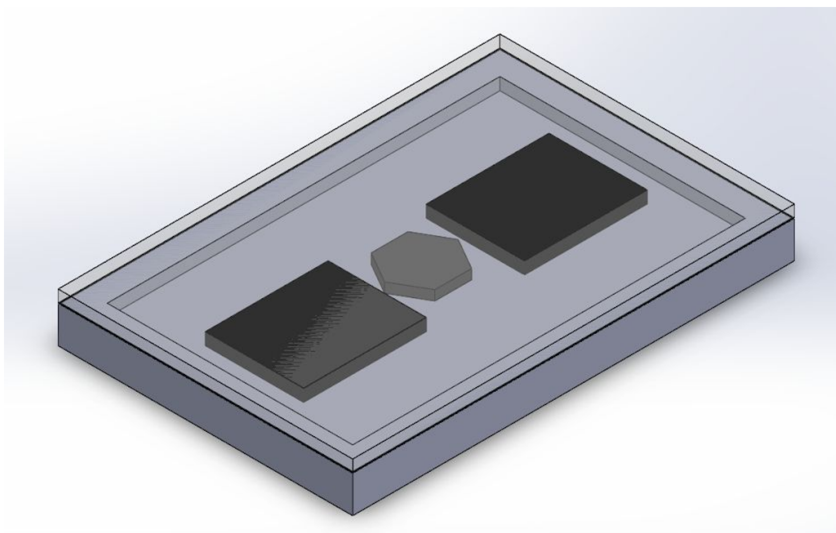


Figure 11: Initial Design

For the final design, the tile shape was chosen over a mat system because it’s rigidity allows it to better house and protect piezoelectric elements, and a square shape was chosen to allow the tiles to easily fit in the crosswalk area. It also allows smaller parts to be designed and deployed individually instead of needing to deploy the entire system at once. In addition to the tiles, a ramp will be added to each side of the system with it’s own solar panels and batteries. This is because the piezoelectric elements do not generate much power, and in this design will only be powering a microcontroller and a bluetooth signal. The warning system was chosen to be an LED strip, as it was found to be the most effective warning signal, in addition to having a low power requirement. The LED strip will be on the side of the ramp to face oncoming traffic for maximum noticeability.

Figure 12: Second Iteration of Tile Design

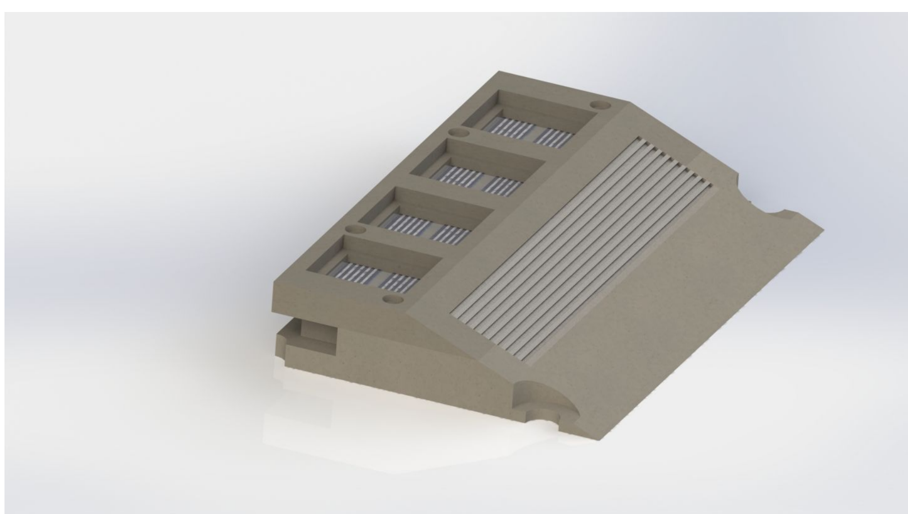


Figure 13: Selected Design of the System Ramp

10. Industrial Design

The workers who install the crosswalk system have a high impact on the industrial design of the system. Since the system should be deployable by two workers, minimizing the weight of the overall system will be important to ensure workers can easily install the system. OSHA recommends that a single person does not lift more than 50 pounds on their own [21], so the weight of a single tile should not exceed 50 pounds to ensure the safety of workers and to aid in ease of installation. Additionally, designing the crosswalk to where extensive electrical work is not required at the site will aid in ease of installation. The crosswalk cannot impede the walking of pedestrians, so considerations to ensure that the surface is slip resistant and flat are important. To ensure that it is easily identified as a crosswalk, tiles can be colored so that when the system is assembled it has the white stripes that typically identify a crosswalk.

The crosswalk system must display a flashing yellow signal to meet the requirements outlined by MUCTD for in-roadway warning lights. The flash rate must be no less than 50 and no greater than 60 flashes per minute. Additionally, the flash rate cannot be between 5 and 30 flashes per second due to frequencies in that range triggering seizures.

11. Engineering Analysis and Experiments

Following conversations with the project sponsor, the necessity of power generation requirement verification testing became apparent. A testing procedure was developed utilizing an INSTRON 3330 Universal Testing machine and custom developed molds to evaluate the power generation capabilities of the PZ elements. This testing procedure, which is detailed more specifically in Appendix A, used compressive motion, similar to what the PZ elements will experience in the crosswalk deployment to deflect the PZ elements to varying magnitudes at approximately the frequency of a footstep. The resulting energy was stored in a capacitor, and the capacitor’s voltage was measured to determine an energy generation rate per deflection of the piezo. The amount of force required to deflect the PZ elements was also monitored. The results of the test are displayed in Appendix B. Following the results, it was possible to determine how many PZ elements were required to obtain the maximum amount of energy from the average human adult*[1].

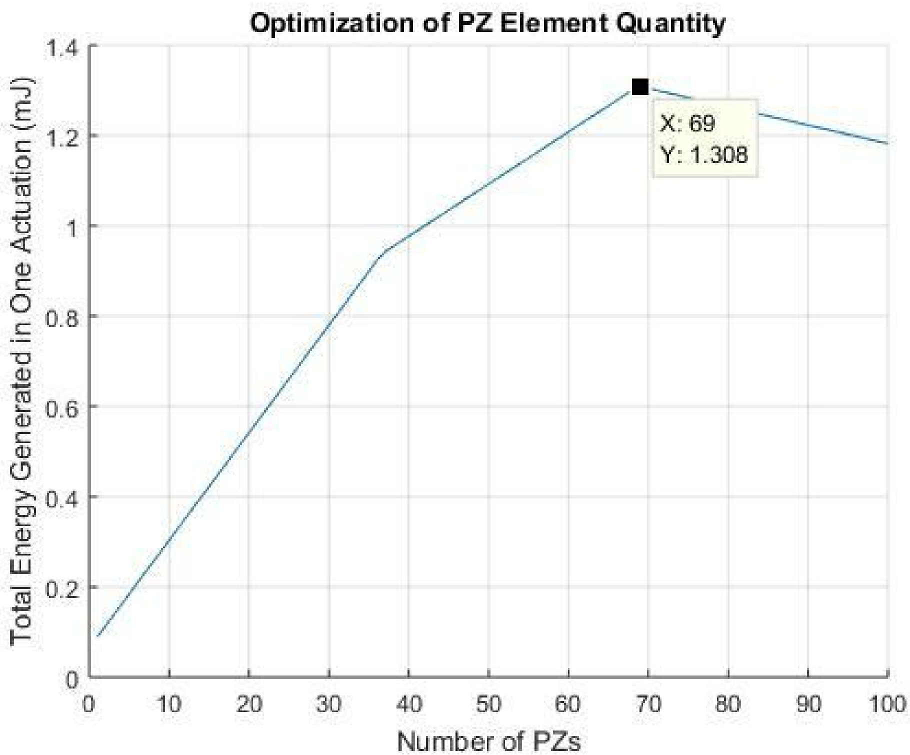


Figure 14: Optimal Number of PZ Elements for Energy Harvesting of an Adult Human

It was further possible, based on the low energy generation rate (1.3 mJ per person), to eliminate the idea of powering the LED warning system with PZ generated electricity. This system was thus separated to a solar powered system, leaving only a microcontroller to be powered by the PZs, and allowing for the final quantification of 2 layers of 68 PZ elements, each generating at least 50uJ of energy per deflection.

Solidworks Simulation was used to perform FEA to determine the FOS and deflection of each layer when an average sized human (180 pounds) steps on the center of the tile and for maximum loading conditions. Maximum loading conditions would occur if an 80,000lb semi truck stopped on the crosswalk. The distributed load per wheel of an 80,000lb semi truck was determined to be about 29,000N using the Bridge Formula shown in Figure 15.

[1] The experimental setup used zener diodes, which were discovered to be a source of non-negligible loss. Similar experiments were consulted, suggesting power generation in the Instron experiment was roughly half of what could be expected using different diode types.

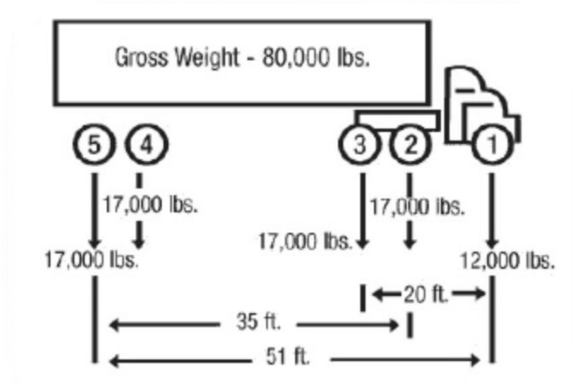


Figure 15: Bridge Formula [22]

To run FEA, the Young's Modulus, yield strength, density, and Poisson ratio of each material were required. These properties were obtained from data sheets of potential suppliers when possible and supplemented with data from CES EduPack and Matweb. Table 2 in Appendix C shows materials with their properties that were used throughout the various simulations. Simulations were run with various thicknesses and shores of rubber to determine the optimal material to control the deflection of the PZ layers. For the final design, the material properties used in the simulation are shown below in Table 1.

Component	Material	Young's Modulus (N/m^2)	Poisson Ratio	Density (kg/m^3)	Yield Strength (N/m^2)
Top Cap	ABS Sheet	2.90E+10	0.41	1200	35163262
Holster Plates	PA66 30% Carbon Fiber	2.40E+10	0.328	1301	330258875
Press Insert	PEEK 30% Carbon Fiber	4.00E+10	0.47	1470	268895535
Layer 1 Rubber	40A Neoprene	1.35E+06	0.48	1230	10342136
Layer 2 Rubber	70A Neoprene	2.73E+06	0.48	1230	10342136
Basin	Concrete	3.00E+10	0.235	2600	55000000

Table 1: Final Materials

Figure 16 shows the displacement results in mm of the internal layers of the tile when maximum loading conditions occur. Probing into the model found that a PZ in the pedestrian layer deflected 1.106mm (0.04in) , a PZ in the vehicle layer deflected 1.42mm (0.056in), and the deflection of the overall system was 2.99mm . The FOS was checked for the basin, top cap, holster, and press insert as shown in Figures 3-6 of Appendix C with minimum FOS called out.

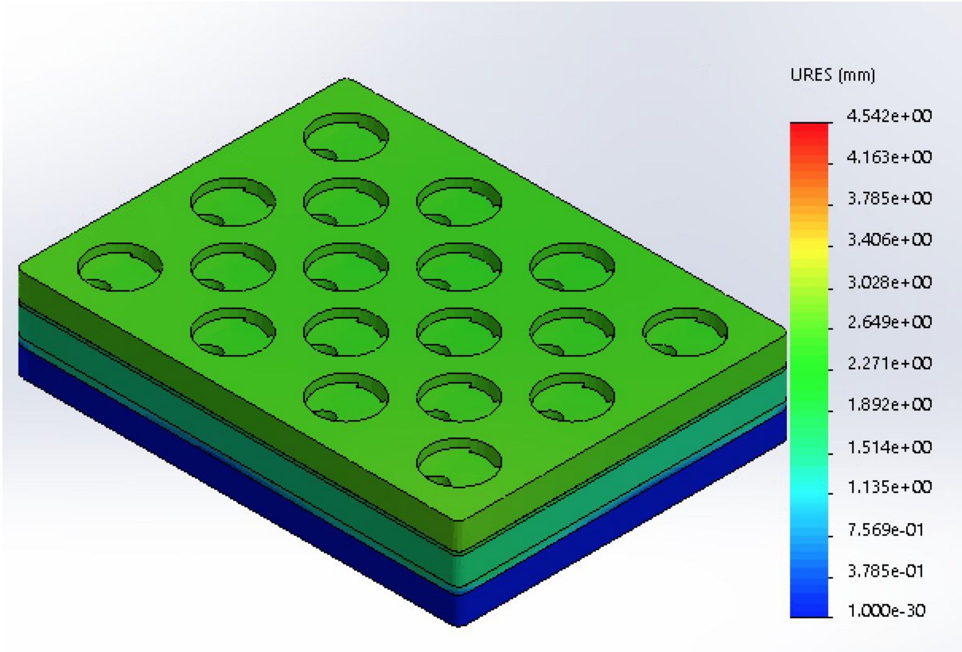


Figure 16: Displacement of Internal Components with Maximum Loading

The maximum deflection when a 180 lb person is standing on the middle of the tile was determined to be 0.1281 mm as shown in Figure 17. While energy generation at this deflection will be very low, it satisfies the requirement of detecting pedestrians in the road way.

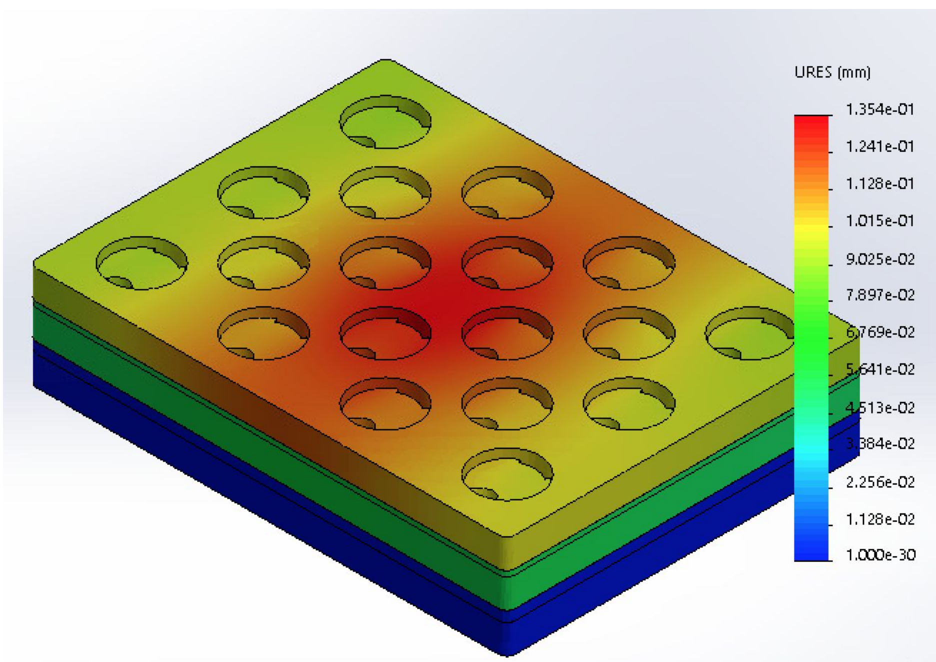


Figure 17: Displacement of Internal Components with Human Weight

To verify the FEA model, the tile was modeled as a simply supported beam with a spring in the middle to represent the internal components. The equations and the MATLAB code used to verify can be found in Appendix C. The maximum deflection for the 180lb person was calculated to be 0.11 mm and the maximum deflection of the system for the maximum loading condition was calculated to be 3.81 mm. Both these calculations are in the same magnitude as the FEA calculations, however differences were expected due to the software's ability to model a distributed load and using a point load for the MATLAB code.

The first step in validating the electronics was to check to see if a viable signal would be generated from pressing the PZs, wired in parallel. To accomplish this, four PZ elements were inserted into the 3d printed tile prototype, and the wires were spliced together so that all four would be in parallel. The positive and negative leads of this circuit were then connected to an oscilloscope and viewed to make sure that there is a voltage spike generated when the PZs are pressed all at the same time. One fear of the piezoelectrics in parallel was that there could be destructive interference between the PZs instead of outputting a voltage, however this was not observed.

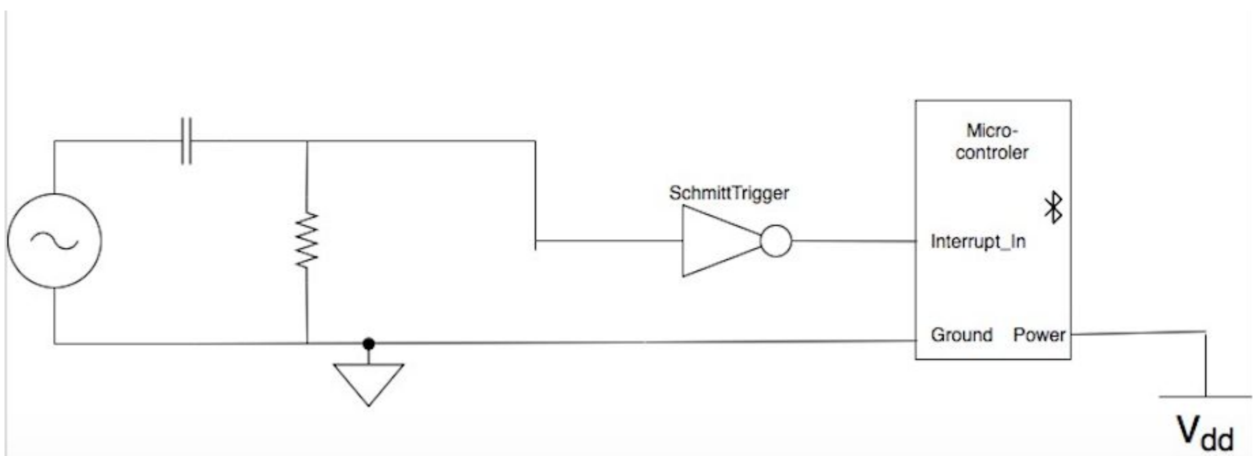


Figure 18: Schmitt Trigger circuit with microcontroller

Using a schmitt trigger, a device that can pass a high signal when a voltage threshold is reached, circuit (figure 18) with a microcontroller in the configuration shown above, the PZs were able to be pressed and have it activate code that sends a wireless signal to another microcontroller, that would flash an LED. However there were issues with what seemed to be a capacitor issue. The smallest available capacitors from the lab was 10 pF, and the circuit called for 1pF. So the signal would continue to be sent as the capacitor discharged after being charged up from the PZs. The smaller capacitor may solve this issue. Artificially decreasing the capacitance by connecting more series capacitors decreased the ability to detect the PZ press, and was not viable.

12. Final Design, Mockup, and Prototype

The final design was chosen to be a tile system that utilizes two layers of piezo elements to optimally generate electricity from both pedestrians and cars while also being able to distinguish between them. Inside of a concrete base, three layers of PA66 with neoprene sheets between them will house PEEK inserts that hold the piezo discs.

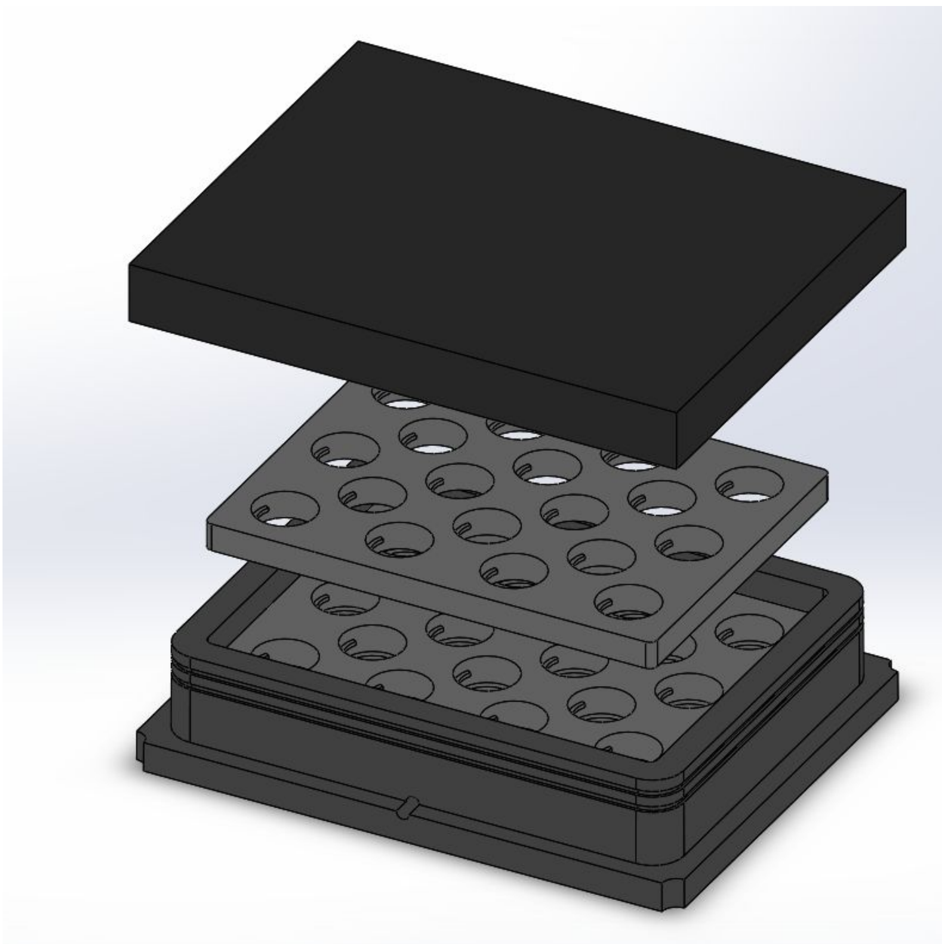


Figure 19: Layering of Final Design

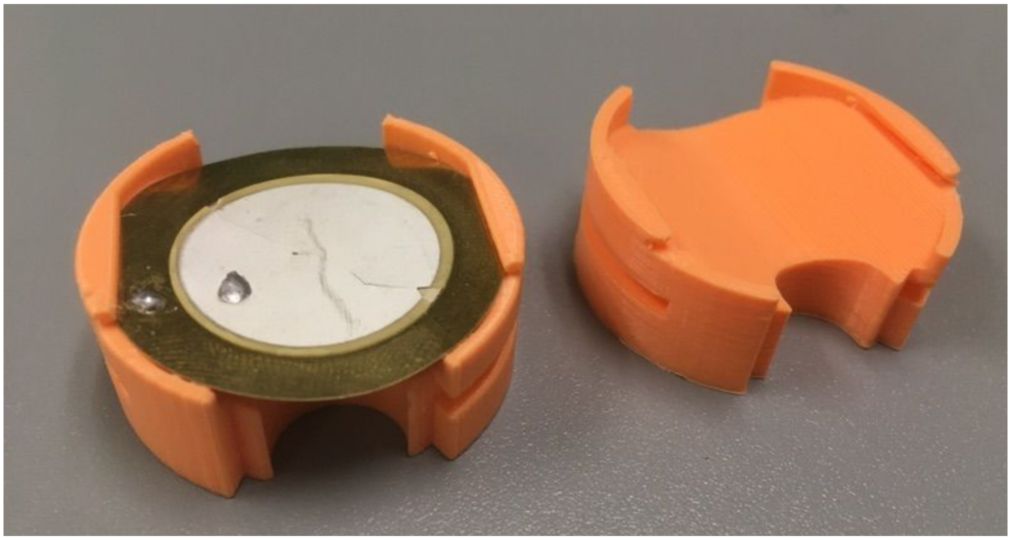


Figure 20: Piezo Holding Inserts for Bottom Layer

The inserts from the upper layers also have presses under them that press down upon the piezo discs below them. A small amount of adhesive applied between the insert and the concrete will prevent it from rotating unnecessarily. Only the top two inserts have presses, and only the bottom two inserts hold piezo discs.

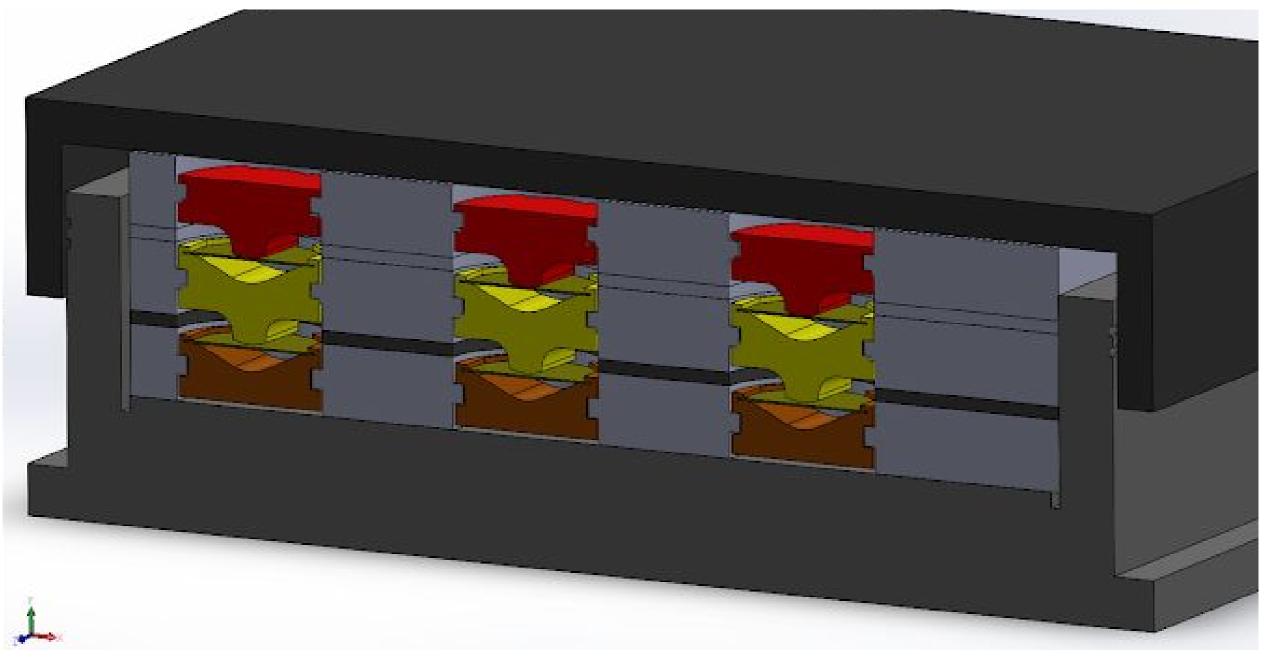


Figure 21: Section View of Final Design

The base of the material beneath the piezo layers is thicker so that channels can be cast for electrical wiring. The tile will be topped with an ABS plate that wraps around the sides of the tile and grips two O-rings to water-seal the tile. Additionally, when deployed on the road, the tile will be bolted down in the corners to secure the tile in place and prevent improper movement.

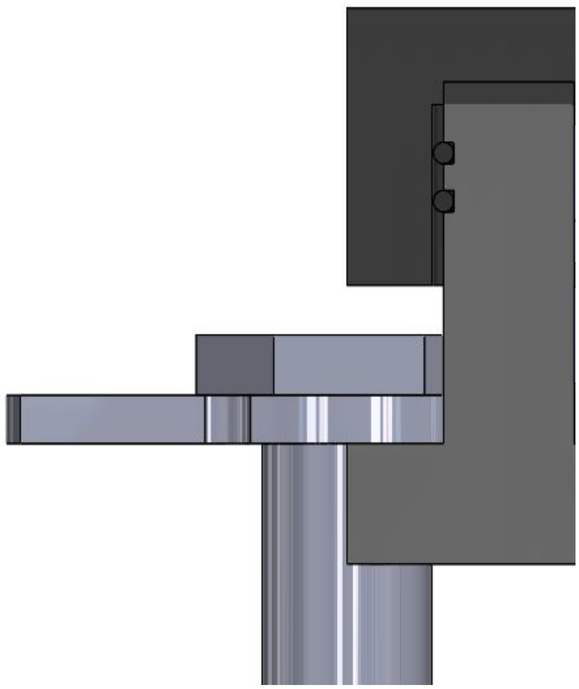


Figure 22: Bolt System

To test the design, a small scale prototype was 3D printed from PLA. The prototype featured 8 piezo inserts per layer, and did not feature buffering layers, as it was not designed to withstand the pressure of a vehicle.

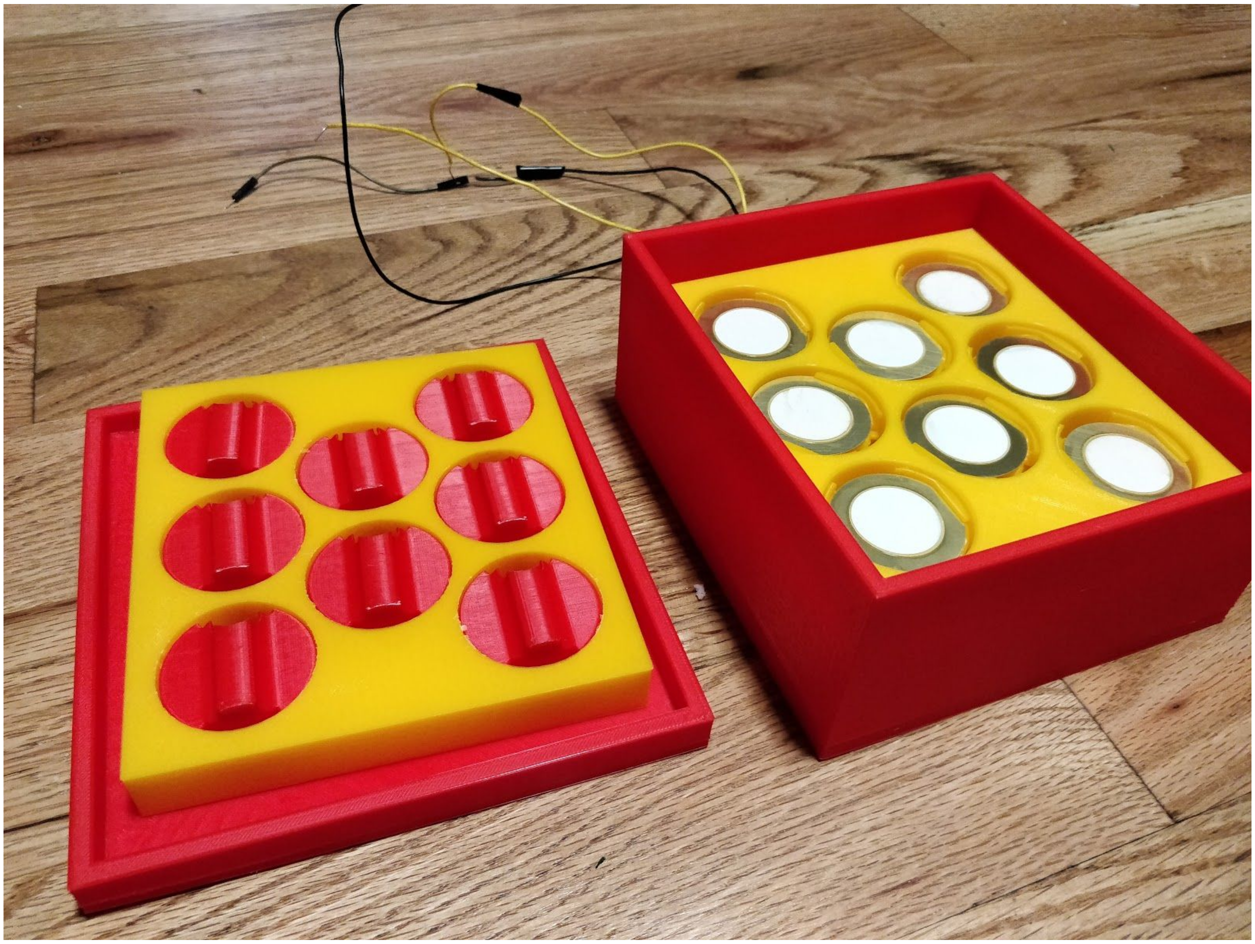


Figure 23: Prototype Layers and Outer Shell

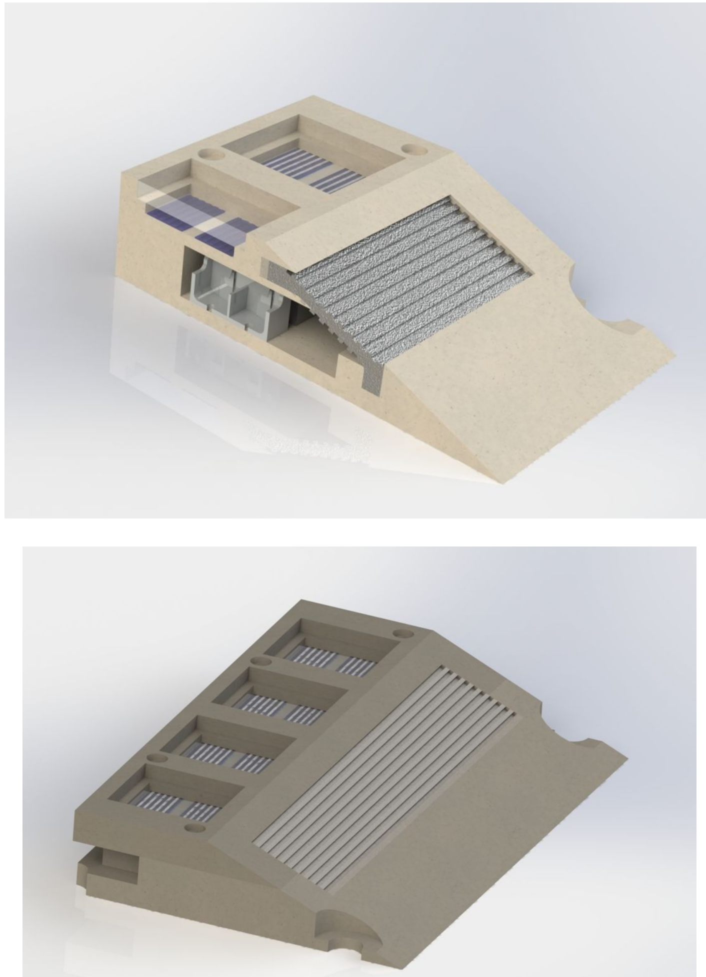


Figure 24: Design of the Ramp Assembly

13. Manufacturing

When manufacturing a tile, the base and holster layers will be cast out of C35 concrete. The piezo holding inserts will be injection molded using PEEK. The lid will be manufactured by machining an ABS plate.

In the final design, a printed circuit board that houses all of the electronic components should be designed after a valid and stable electronic circuit is created. Our prototype implementation requires more testing to be valid for a printed circuit board. The printed circuit board will house the microcontroller, wireless modules, and connections for the piezoelectric elements. Four piezo elements will be wired in parallel on each layer for detection and connected to the circuit board, and the rest will be used to charge a battery that powers the microcontroller.

When assembling the tile, two O-rings will be placed around the lip of the base of the tile into the grooves before the assembled electrical components will be placed into it. For each layer of piezoelectric elements, after soldering wires onto the piezo element, the piezo disc will be inserted into the piezo insert, slid into the holster plate. And rotated 90 degrees to lock into place. A small amount of adhesive will then be applied along the edge of the insert connecting it to the holster plate. This process shall be repeated for both layers that hold piezo discs, and then for the top layer without inserting piezo discs.

When assembling the layers, after the damper layer of Shore 70A neoprene between the bottom and middle layer has been applied, the wires from each piezo will be run down in front of the disc, and the ones from the middle layer will be run down past the discs from the layer below it so the wires can reach the base of the tile. The wires will then be connected to the electrical system in the base of the tile. The bottom and middle layers will then gently be placed in the base to ensure no wires are being crushed or disconnected. The top dampening layer of Shore 40A neoprene will then be applied before the top holster layer is set on top. Finally, the lid will be set on top of the tile.

The ramp body will be cast out of C35 concrete. When assembling the ramp, the battery will first be inserted into the base. The solar panels will be placed into the slots on the top, connected to the electrical system, and then covered with clear high strength glass panes and sealed in. The LED strip will be run across the front of the ramp and connected to the electrical system.

When deploying a group of tiles onto a crosswalk, the tiles will cover the crosswalk in one lane in an 11 x 3 pattern. Between each corner of 4 tiles or two exterior tiles and the ramp, bolts will be applied to secure the assembly to the roadway.

14. Societal, Environmental, and Sustainability Considerations

To assess the social impact of the product, Tables 1 and 2 in Appendix D were created to identify lifecycle stages, stakeholders in each stage, and impact indicators. The piezoelectric crosswalk has multiple potential positive social impacts throughout its lifecycle stages. It has the potential to increase the safe living conditions for the local community in which it is installed by eliminating the need for a pedestrian to press a button to activate warning lights which could help reduce pedestrian fatalities. Additionally, the manufacturing and use stages could provide jobs locally and support local suppliers by sourcing through them.

Potential negative impacts are anticipated for the worker stakeholder group due to the potential injuries while working. The assembly process of the piezoelectric crosswalk has the potential of being a highly manual process which could introduce the potential for ergonomic injuries. Also, the workers will have to be in the roadway while installing the system which puts them at risk of being hit by a distracted driver. Due to the concern with the possible number of injuries, it is suggested to block off one lane of traffic at a time while installing the system so workers. It is also suggested to automate repetitive parts of the assembly process when possible.

15. Risk Assessment, Safety, and Liability

A Design FMEA was used to identify potential failures and the impact on the function of the crosswalk. A RPN was assigned to each failure method based on the severity of the failure, the potential for failure, and the potential for detection of the failure. In Appendix E, the FMEA shows that the PZ cracking had the highest RPN of 224. The PZ cracking would render the system inoperable because it wouldn’t be able to harvest energy or detect pedestrians. The design originally had hard stops on the holsters to aid in preventing the press from deflecting the PZ to the point of breaking, however, the hard stops showed as points of failure in FEA. After redesigning the holster and press into a holster with a press insert, the probability of the piezoelectric element cracking was reduced from 7 to 3 due to maximum loading conditions showing a maximum deflection of X mm. The next highest RPN was 105 and was assigned to the PZ not deflecting. This would occur if the system is too stiff to allow for deflection when a human walks across. The RPN for this failure mode was reduced to 45 after changing the shore of rubber to Shore 40A which reliably allowed for the PZ to deflect for detection in FEA.

16. Conclusion and Future Work

The final design will be a tile system that utilizes a dual layer of PZ elements to detect whether a pedestrian is crossing or if a vehicle is moving through the intersection. An isolated detection system will be powered by the energy harvested from the PZ elements and send a bluetooth signal to the warning system when a pedestrian is crossing. The warning system will be housed in the ramp of the cross walk and use solar panels to power flashing LEDs. Testing was conducted on an Instron to determine the optimal housing for the PZ elements and the maximum allowable deflection. The results of the testing were used to determine the number of PZ elements per layer required to optimize power generation and the ideal shape of the housing.

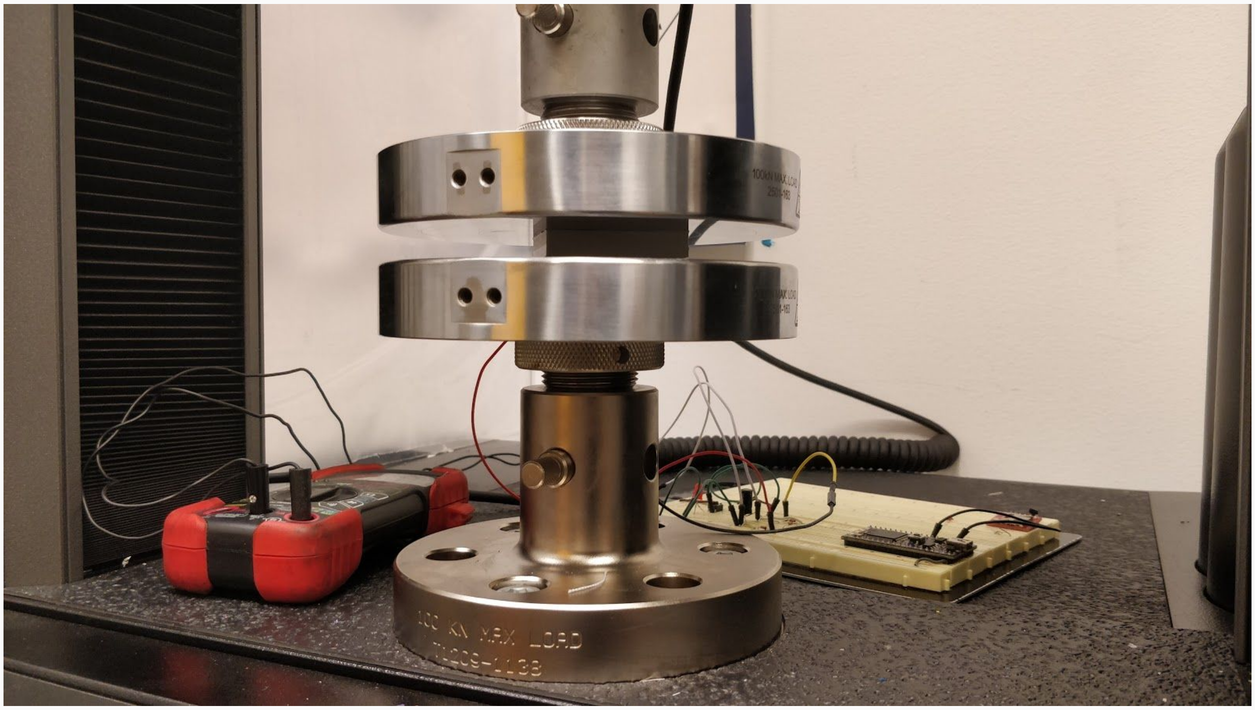
The electronics with the tile prototype only worked some of the time, and more experimentation and testing will be required to validate a final circuit design. At best, the detecting microcontroller was able to detect a press on the tile prototype and sends a signal to the receiving microcontroller and flash an LED. It appeared that the capacitor used was too large and the signal would continue to be sent even after the press. The receiving microcontroller would also time-out and stop receiving and flashing after a certain amount of time.

Next steps for electronics will be to investigate and test a battery charger circuit with the tile prototype. The detection of a pedestrian was validated, energy generation is important to the system, and the many PZ elements not required for detection will be used for energy generation. They can be wired in parallel to a single rectifier as no interference was detected when all of the PZs are pressed at the same time. In the coding space, the microcontrollers currently send and receive only, so the next functionality that should be added is the low power mode when not sending the signal. This was investigated, but not implemented in the prototype. When the circuit design is finalized, a printed circuit board should be designed to fit in the space below the PZ layers within the tile.

Full production of a mechanical model is recommended as the next step, since it provides dedicated room for additional electronic components as may be required by future experimentation. Simulation results suggest the mechanical model as designed will satisfy all operational requirements, but physical testing is highly recommended. Such testing should include compressive load testing, temperature sensitivity analysis, and cyclic loading testing.

Appendix A: Instron 3330 Test Procedure

Background:

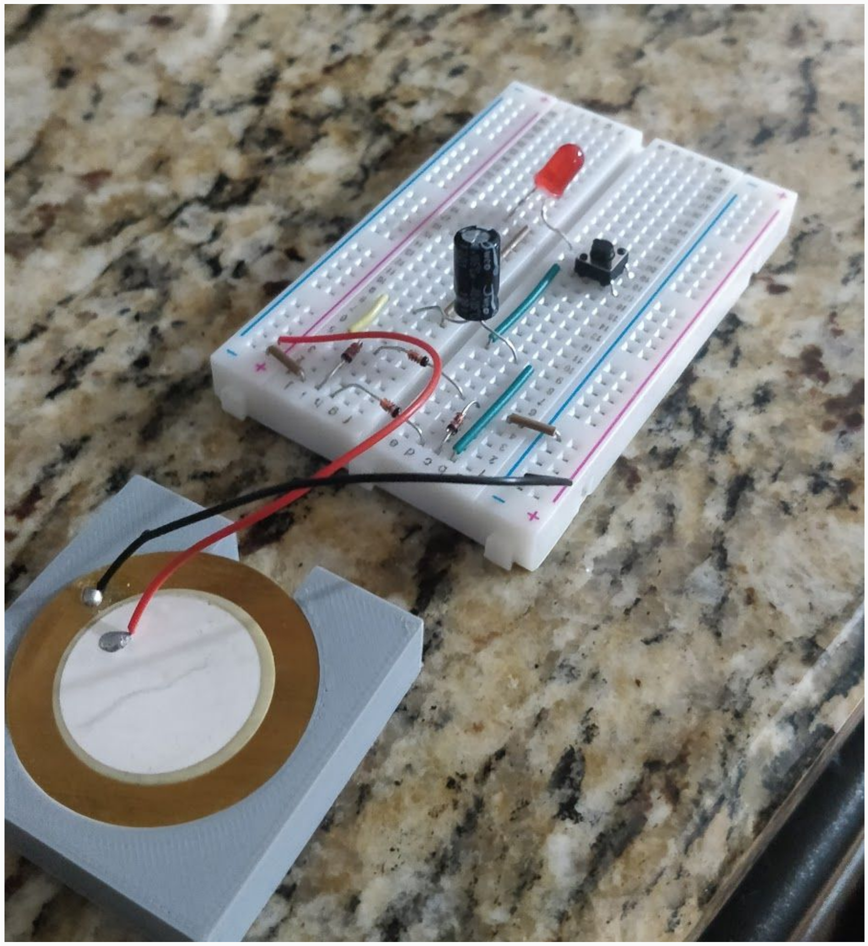


The Instron is a mechanical testing frame capable of testing materials under tensile, compressive, and 3-point-bending modes. This machine is equipped with a 30 Kilo-Newton load cell. It can be configured to deflect sample specimens according to user-specified criteria including force, displacement, and time.

In this procedure, Piezo-electric elements (PZs) will be evaluated in a number of configurations to determine their ability to produce energy. The elements will be placed in various 3D-Printed 'forms', which will hold the PZs, and alter the manner of their deflection based upon the shape of the form. The Instron machine will exert compressive force on the molds, deforming the piezos to a magnitude specified by the operator. The PZs will be electrically connected to a bridge rectifier and capacitor set-up. The capacitor voltage will be monitored in order to determine the power generated throughout the procedure.

Specific Test Procedure:

1. Strip the ends of the leads from the PZ to expose a length of wire, approximately 1 cm. Connect the leads to the nodes of the bridge rectifier as shown



2. Place the PZ in the base mold, and cover with the top mold, ensuring the soldered points on the PZ will not be directly acted upon by the mold
3. Lower the Instron until it has just made contact with the top mold case. Zero out the Instron Displacement and Force measurements
4. Set the desired displacement of the Instron. This is the magnitude to which the machine will deflect the PZ. Set the rate of this displacement such that the entire process is completed in 0.65s, the approximate period of a footstep. Set the number of cycles to 15 so that the machine completes 15 compression actions.
5. Attach the leads of a multimeter to the capacitor terminals.
6. Record the initial voltage of the capacitor, and start the machine. Record the highest voltage registered by the capacitor.
7. Press the button on the breadboard to drain the capacitor back to a smiliar initial voltage as you saw in step 6.
8. Repeat steps 4 through 7 for different magnitudes of deflection and mold forms.

Analysis:

The results of the test procedure are shown at this link.

Of particular importance is the Energy Generated per Deflection Column, which is the average amount of electrical energy injected into the capacitor with a single deflection of the PZ element. It is derived by the following:

$$\Delta E_{capacitor} = \tfrac{1}{2} C \Delta V_{capacitor}^2$$

Limitations:

The results yield conservative figures for the Energy Generation per Deflection, as the capacitor has some leakage current that reduces its voltage even as the test is ongoing. This leakage current is defined in the datasheet as a function of maximum capacitor charge, 25V. As this maximum charge was not approached, it is inappropriate to assume this leakage current is the same as what was experienced in the test procedure.

Appendix B: Instron Testing Results

Piezo Deflection Testing Results

Capacitance (indicated):	0.0001	Farads
Capacitance (measured):	0.0001	Farads

Run	Piezo #	Form Shape	Deflection (in)	Period (s)	Rate of Deflection (ipm)	# of Deflections	Initial Voltage (V)	Final Voltage (V)	Delta Voltage ^2 (V^2)	Total Energy Generated (mJ)	Energy per Deflection (mJ)	Max Force (lbf)
1	1	U-Channel, Low	0.03	0.65	5.54	15	1.61	2.48	3.5583	0.1779	0.01186	2.5
2	1		0.04	0.65	7.38	15	1.61	2.8	1.19	0.2624	0.01749	6
3	1		0.05	0.65	9.23	15	1.61	2.89	1.28	0.2880	0.01920	9.5
4	1		0.06	0.65	11.08	15	1.61	3	1.39	0.3204	0.02136	20
5	1	U-Channel, Mid	0.03	0.65	5.54	15	1.65	2.48	0.83	0.1714	0.01143	2.5
6	1		0.04	0.65	7.38	15	1.65	2.94	1.29	0.2961	0.01974	6
7	1		0.05	0.65	9.23	15	1.65	3.01	1.36	0.3169	0.02113	9.25
8	1		0.06	0.65	11.08	15	1.66	2.51	0.85	0.1772	0.01182	10
9	1		0.04	0.65	7.38	15	1.65	2.15	0.5	0.0950	0.00633	6
10	2		0.04	0.65	7.38	15	1.68	2.38	0.7	0.1421	0.00947	6
11	2		0.06	0.65	11.08	15	1.65	2.6	0.95	0.2019	0.01346	
12	3		0.04	0.65	7.38	15	1.68	2.91	1.23	0.2823	0.01882	8.25
13	3		0.06	0.65	11.08	15	1.67	2.81	1.14	0.2554	0.01702	14.5
14	3		0.04	0.65	7.38	15	1.67	2.68	1.01	0.2197	0.01465	8
15	3	U-Channel, High	0.03	0.65	5.54	15	1.67	2.58	0.91	0.1934	0.01289	5.75
16	3		0.04	0.65	7.38	15	1.65	2.75	1.1	0.2420	0.01613	9
17	3		0.05	0.65	9.23	15	1.67	2.79	1.12	0.2498	0.01665	10
18	3		0.04	0.65	7.38	15	1.66	2.75	1.09	0.2403	0.01602	9
19	3	Deep U-Channel, High	0.03	0.65	5.54	15	1.66	2.51	0.85	0.1772	0.01182	1.65
20	3		0.04	0.65	7.38	15	1.66	2.91	1.25	0.2856	0.01904	2.4
21	3		0.05	0.65	9.23	15	1.66	3.23	1.57	0.3839	0.02559	4.5
22	3		0.06	0.65	11.08	15	1.67	3.33	1.66	0.4150	0.02767	9.75
23	2	Deep Dish, Mid	0.03	0.65	5.54	15	1.65	2.35	0.7	0.1400	0.00933	3.1
24	2		0.04	0.65	7.38	15	1.65	2.59	0.94	0.1993	0.01329	6
25	2		0.05	0.65	9.23	15	1.64	2.69	1.05	0.2273	0.01516	8.5
26	2		0.06	0.65	11.08	15	1.65	2.49	0.84	0.1739	0.01159	8.75
27	2	Deep Dish, Mid w/ Upside Down Piezo	0.04	0.65	7.38	15	1.65	1.83	0.18	0.0313	0.00209	2
28	2		0.04	0.65	7.38	15	1.59	1.79	0.2	0.0338	0.00225	2
29	2		0.04	0.65	7.38	15	1.67	1.83	0.16	0.0280	0.00187	2
30	3	Deep U-Channel, High	0.05	0.65	9.23	150	1.75	4.2	2.45	0.7289	0.00486	3.5

Appendix C: FEA Figures, Tables, Equations, and Code

Figures:

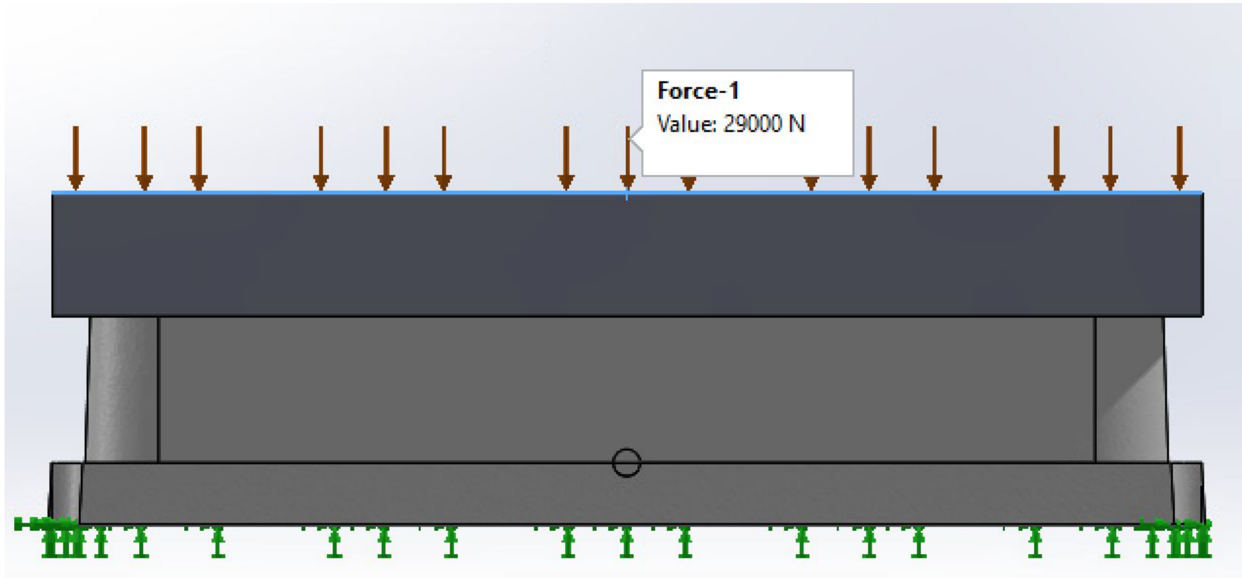


Figure 1: Fixtures and Loads

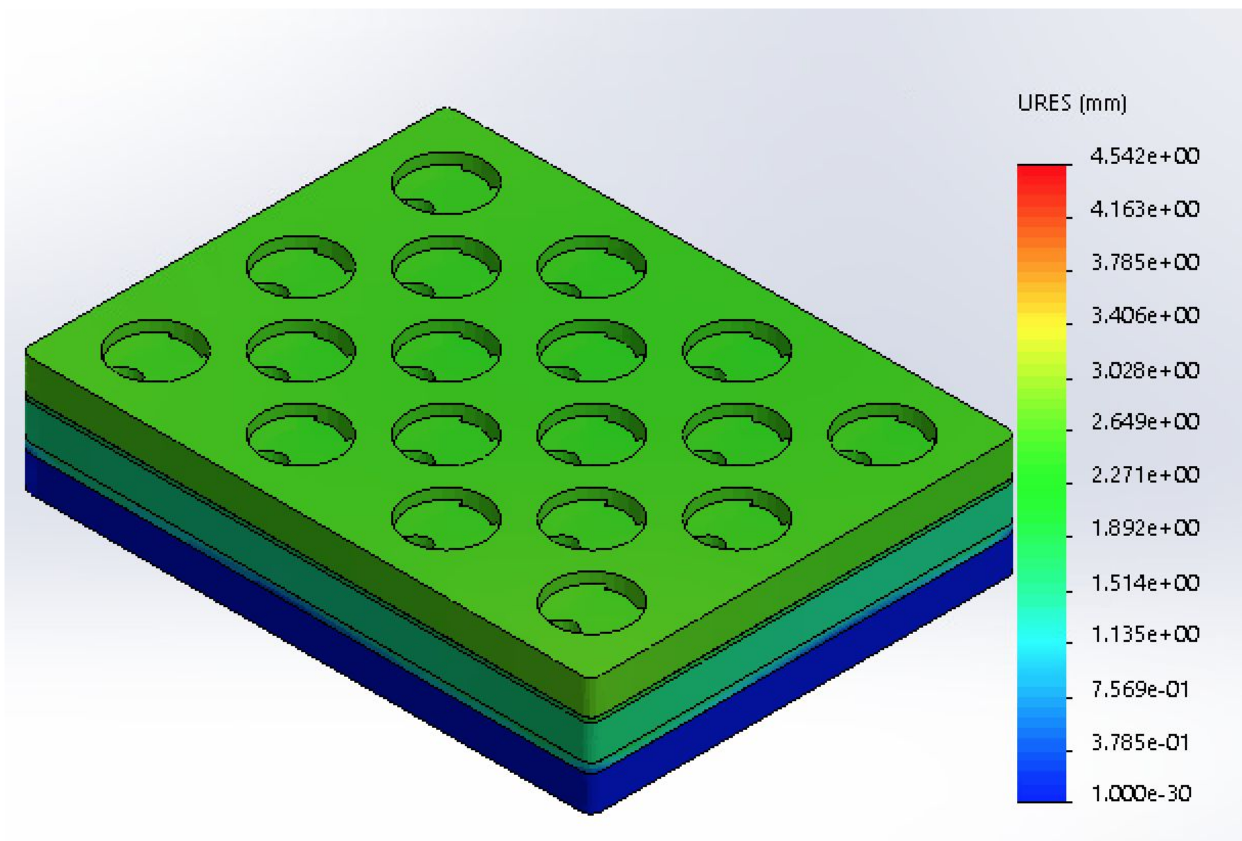


Figure 2: Displacement of Internal Components with Maximum Loading

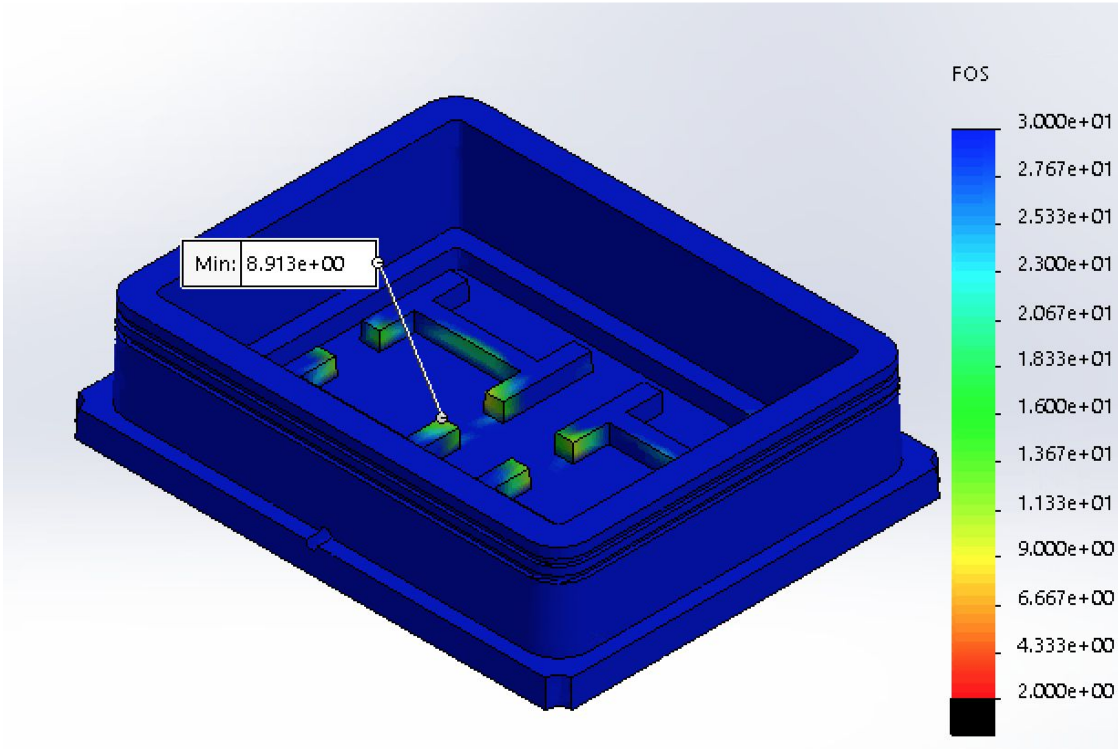


Figure 3: Basin FOS

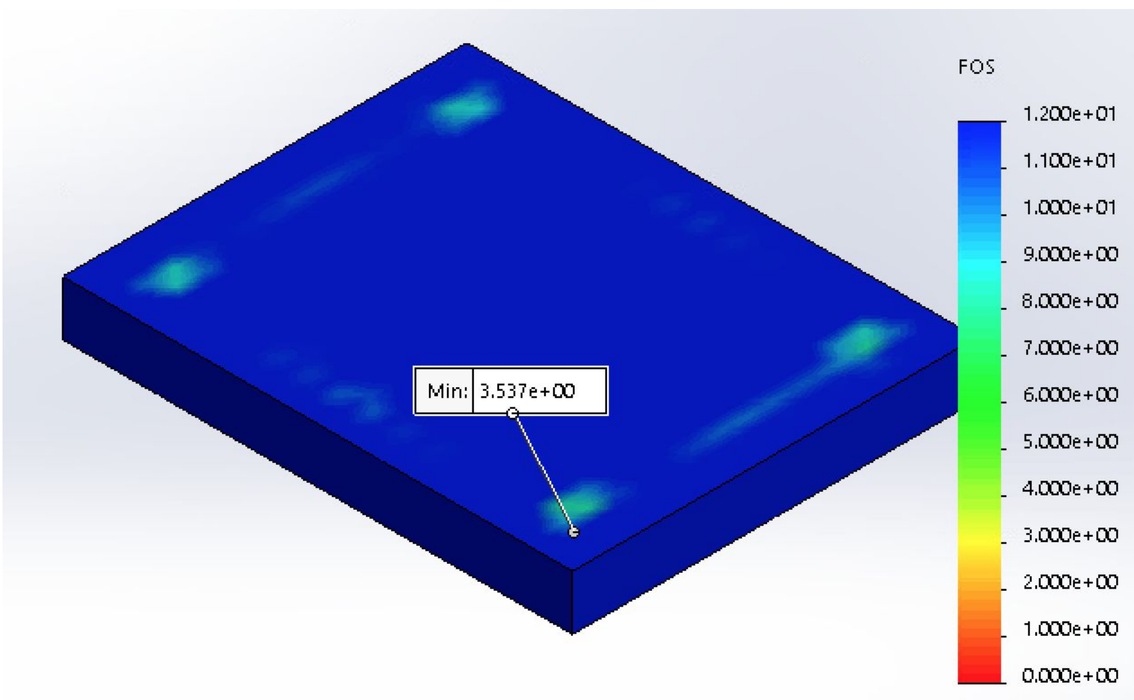


Figure 4: Top FOS

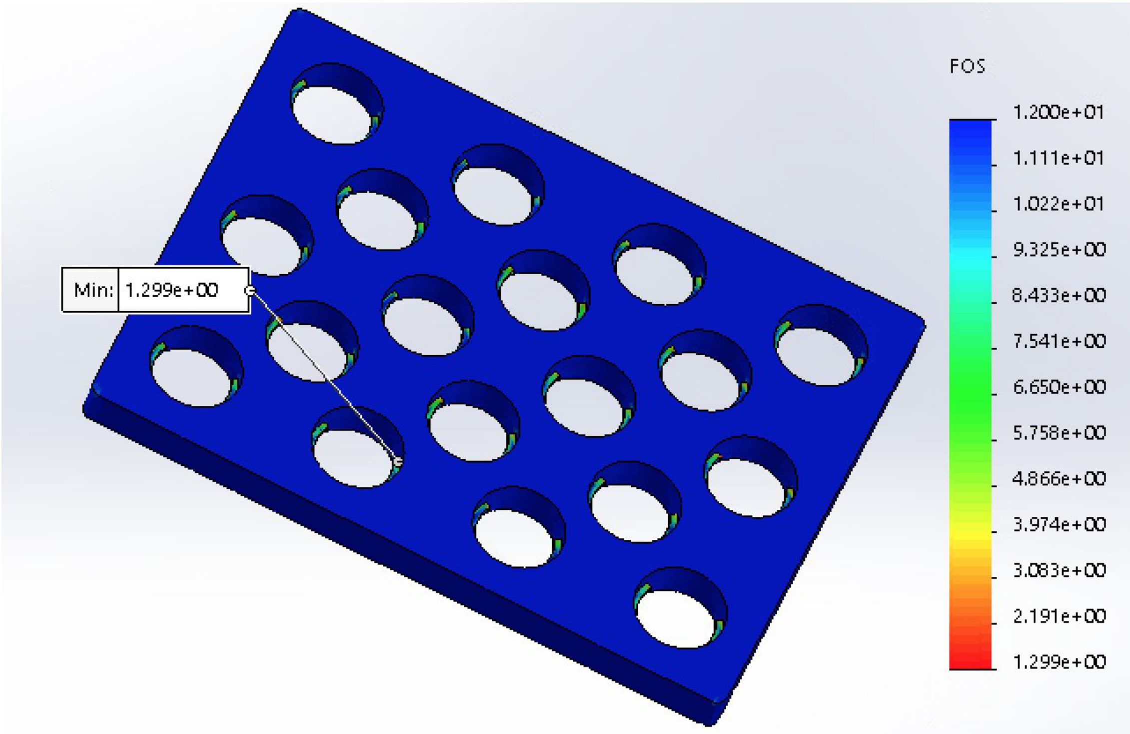


Figure 5: Holster FOS

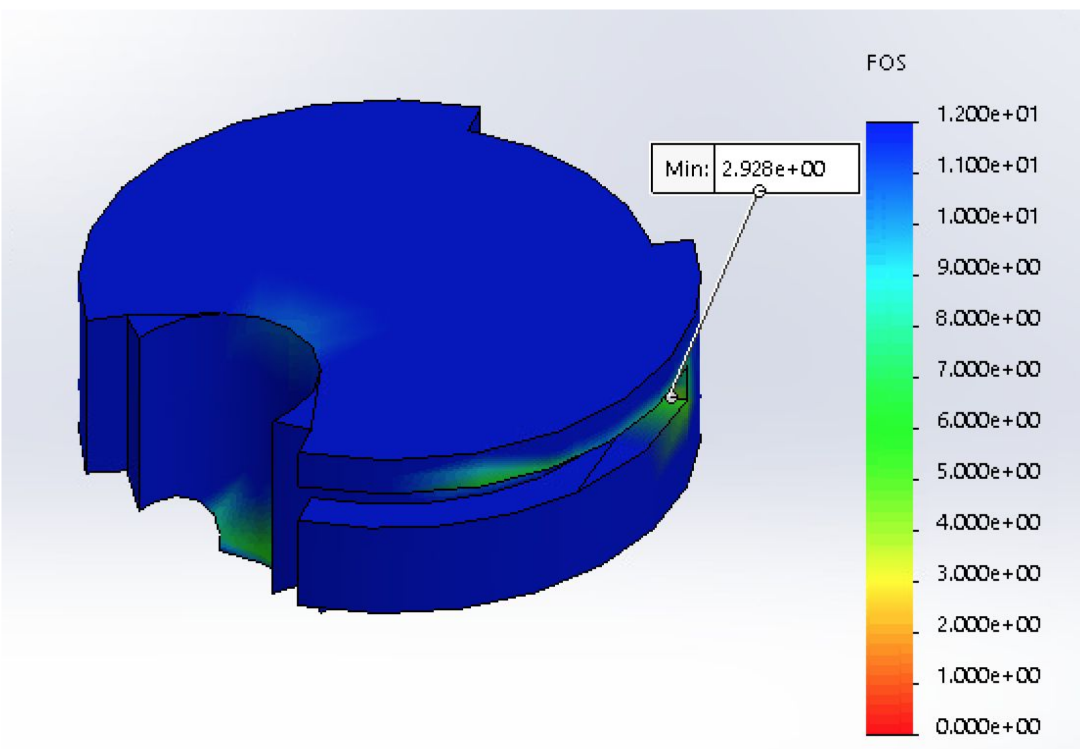


Figure 6: Press Insert FOS

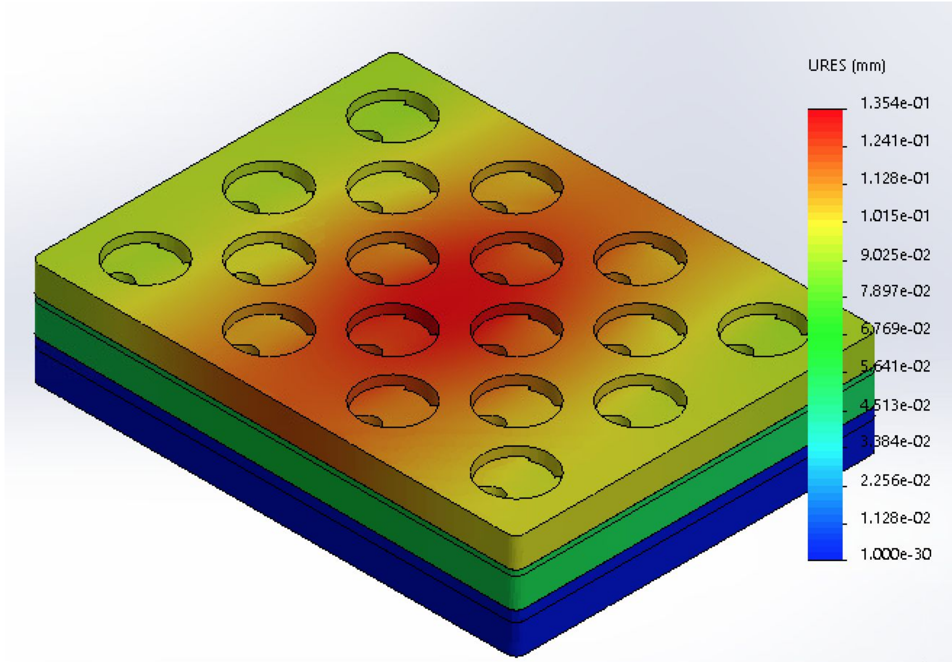


Figure 7: Displacement of Internal Components with Human Weight

Tables:

Component	Material	Young's Modulus (N/m^2)	Poisson Ratio	Density (kg/m^3)	Yield Strength (N/m^2)
Top Cap	ABS Sheet	2.90E+10	0.41	1200	35163262
Holster Plates	PA66 30% Carbon Fiber	2.40E+10	0.328	1301	330258875
Press Insert	PEEK 30% Carbon Fiber	4.00E+10	0.47	1470	268895535
Layer 1 Rubber	40A Neoprene	1.35E+06	0.48	1230	10342136
Layer 2 Rubber	70A Neoprene	2.73E+06	0.48	1230	10342136
Basin	Concrete	3.00E+10	0.235	2600	55000000

Table 1: Final Materials

Material	Young's Modulus (N/m^2)	Poisson Ratio	Density (kg/m^3)	Yield Strength (N/m^2)
ABS Filament	2.90E+09	0.35	1040	45000000
ABS Sheet	2.90E+10	0.41	1200	35163262
Casting Resin	1.51E+08	0.48	1150	34500000
Foam	1.00E+07	0.3	35	119969
High Strength Neoprene Shore 30	1.07E+06	0.48	1230	8273708

High Strength Neoprene Shore 40	1.35E+06	0.48	1230	10342136
High Strength Neoprene Shore 50	1.71E+06	0.48	1230	10342136
High Strength Neoprene Shore 60	2.16E+06	0.48	1230	10342136
High Strength Neoprene Shore 70	2.73E+06	0.48	1230	10342136
Impact & Chemical Resistant PVC	2.07E+09	0.4	1384	38610639
Multipurpose Neoprene Shore 30	1.07E+06	0.48	1230	6205281
Multipurpose Neoprene Shore 40	1.35E+06	0.48	1230	6205281
Multipurpose Neoprene Shore 50	1.71E+06	0.48	1230	6205281
Multipurpose Neoprene Shore 60	2.16E+06	0.48	1230	6205281
Multipurpose Neoprene Shore 70	2.73E+06	0.48	1230	6205281
PA66 30% Carbon Fiber	2.40E+10	0.328	1301	330258875
Peek 30% Carbon Fiber	4.00E+10	0.47	1470	268895535
PLA Filament - PRO	3.50E+09	0.33	1240	60000000
PLA Filament - standard	3.50E+09	0.33	1240	37000000
Polycarbonate	2.52E+09	0.41	1210	68878625
Polycarbonate Carbon Fiber mix	2.00E+10	0.331	1381	131689864
Polycarbonate PET 30% Glass	6.82E+09	0.356	1481	110316117

PTMEG	1.51E+08	0.48	1150	50000000
Quikrete DOT	3.00E+10	0.235	2600	55000000
Ultra High Performance Concrete	5.00E+10	0.235	2610	200000000
Ultra Strength Neoprene Shore 50	1.71E+06	0.48	1230	17236893
Ultra Strength Neoprene Shore 60	2.16E+06	0.48	1230	17236893
Ultra Strength Neoprene Shore 70	2.73E+06	0.48	1230	17236893

Table 2: Materials Used Throughout Simulations

Equations:

1. $k_{(PZ,\, Rubber\ 1,\, Rubber\ 2,\, Holster,\, Press)} = (A * E)/L$
2. $Shore\ to\ Young's\ Modulus : E = e^{(0.0235*(Shore-0.6403))} * 10^{6}$
3. $k_{\ internal} = 1/(2 * (\frac{1}{9*k_{PZ}}) + (\frac{1}{k_{Rubber\ 1}}) + (\frac{1}{k_{Rubber\ 2}}) + 2 * (\frac{1}{k_{Holster}}) + 2 * (\frac{1}{9*k_{Press}}))$
4. $I = \frac{bh^3}{12}$
5. $k_{(top,\, basin)} = \frac{48*E*I}{L^3}$
6. $\delta = F/\,(k_{\ internal} + k_{\ top} + k_{\ basin})$

Code:

```
%% Dimensions

% Rubber 1: 8.6x11.5x.125

% Rubber 2: 8.6x11.5x.25

% Holsters: 8.6x11.5x.7

% Press: r = .75 height = .73 width of press piece = 0.47

% Tile Base: 10.10x13x3.4

% Tile Top:11.1x14x.5


c = 25.4; %conversion to m
```

```
%% Stiffness Estimates

%PZ Elements - AB3526B-LW100-R
d1 = 35e-3; %m
t1 = .25e-3; %m
a1 = (pi*d1^2/4);
E1 = 7.2e10;
k1 = 9*a1*E1/t1;

%Pedestrian Rubber
w_p = 8.6*c*10^-3; %Width of cross sectional area
t_p = (.125)*c*10^-3; %thickness of cross sectional area
l_p = 11.5*c*10^-3; %length of trigger
a_p = w_p*t_p; %cross sectional area of rubber
Shore = 40; %A
E_p = exp(.0235*Shore-.6403) * 10^6; %Youngs Mod Pa
k_ped = a_p*E_p/l_p;

%Vehicle Rubber
w_v = 8.6*c*10^-3; %Width of cross sectional area
t_v = .25*c*10^-3; %thickness of cross sectional area
l_v = 11.5*c*10^-3; %length of trigger
a_v = w_v*t_v; %cross sectional area of rubber
Shore = 70; %A
E_v = exp(.0235*Shore-.6403) * 10^6; %Youngs Mod Pa
k_veh = a_v*E_v/l_v;

%Press
w_pr = .47*c*10^-3; %Width of cross sectional area
t_pr = .73*c*10^-3; %thickness of cross sectional area
l_pr = 1.5*c*10^-3; %length of trigger
a_pr = w_pr*t_pr; %cross sectional area of rubber
E_pr = 2.4e10; %Youngs Mod Pa
```

```
k_pr = (a_pr*E_pr/l_pr)*9;

w_h = 8.6/c; %Width of cross sectional area
t_h = .7/c; %thickness of cross sectional area
a_h = w_h*t_h; %cross sectional area of rubber
l_h = 11.5/c; %length of trigger
E_h = 4e10; %Youngs Mod Pa
k_h = a_h*E_h/l_h;
% I_h = (t_h^3) * w_h /12;
% k_h = (48*E_h*I_h)/(l_h^3);

%%Equivalent Spring Constant of Trigger System
k_eq = 1/(2*(1/k1)+(1/k_ped)+(1/k_veh)+2*(1/k_h) + 2*(1/k_pr));

%% Beam Stiffness
E_s = 3e10;
t_s = .7/c; %thickness of surface
w_s = 10.10/c; %width of tile
l_s = 13/c; %length of tile
I = (t_s^3) * w_s /12;
k_beam = (48*E_s*I)/(l_s^3);

E_s = 2.07e9;
t_s = .5/c; %thickness of surface
w_s = 11.1/c; %width of tile
l_s = 14/c; %length of tile
I = (t_s^3) * w_s /12;
k_beam2 = (48*E_s*I)/(l_s^3);

F = 29000;
disp1 = F/(k_eq+k_beam2+k_beam) * 10^3 / c

F2 = 800;
```

```
disp2 = F2/(k_eq+k_beam2+k_beam) * 10^3 / c
```

Appendix D: Social Impact Assessment Tables

Objective of Assessment	Design Function	Functional Unit	Lifecycle Stages Considered	Associated Activities
Assess social impacts of piezoelectric crosswalk	Develop crosswalk system powered by piezoelectric components	1 crosswalk tile	Manufacturing	Assembly of tile
			Product Use	Deployment of tile
				Pedestrian use of crosswalk
			End of Life	Recycling
				Disposal of components

Table 1: Goal and Scope

Product Lifecycle Stage	Stakeholder Group	Social Impact Category	Impact Indicators
Manufacturing	Workers	Health & Safety	# of injuries while working
	Local Community	Local Employment	% of workforce hired locally
			% of spending on locally-based suppliers
Product Use	Local Community	Local employment	% of workforce hired locally
		Safe & Healthy Living Conditions	% of pedestrian fatalities

	Workers	Health & Safety	# of injuries while working
End of Life	Consumer	End of life responsibility	Extent to which consumers are informed about the possible end-of-life options of the product

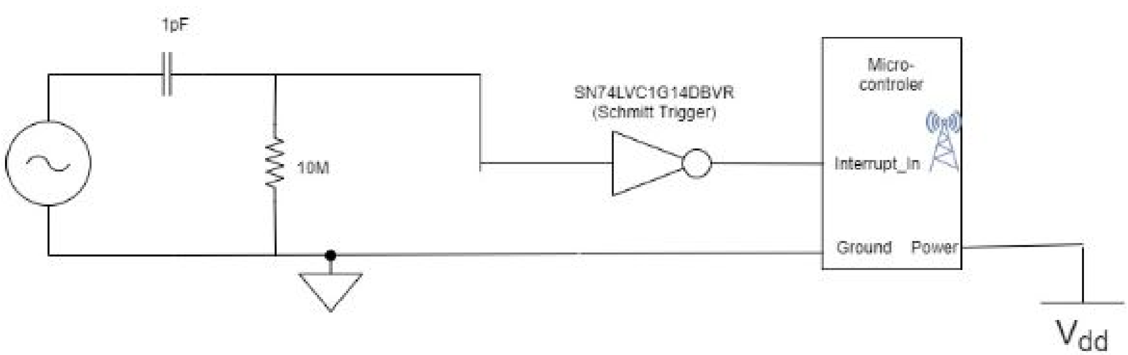
Table 2: Inventory Analysis

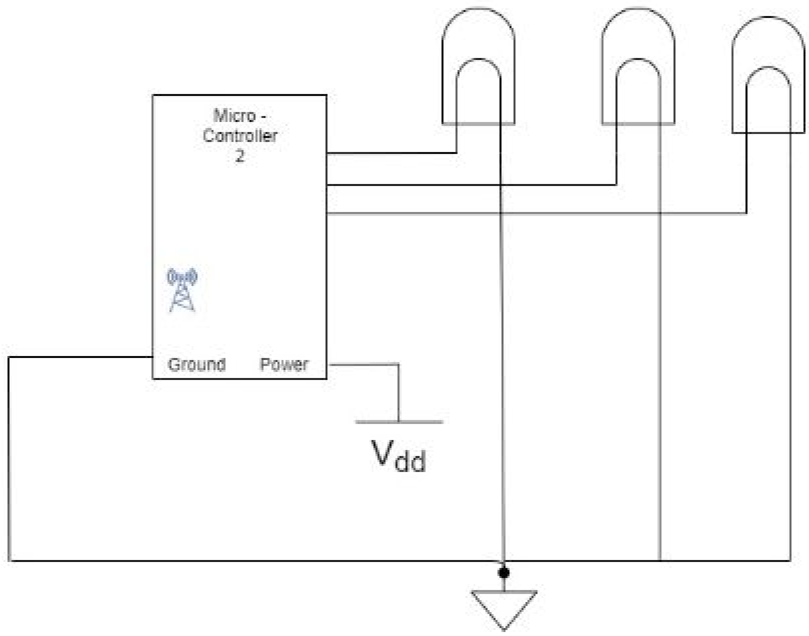
Appendix E: Failure Mode and Effect Analysis

System	Piezoelectric Crosswalk	Potential Failure Mode and Effects Analysis (Design FMEA)	FMEA Number 1
Subsystem	Tile		Prepared By
Component			FMEA Date
Design Lead		Key Date	Revision Date
Core Team			Page 1 of

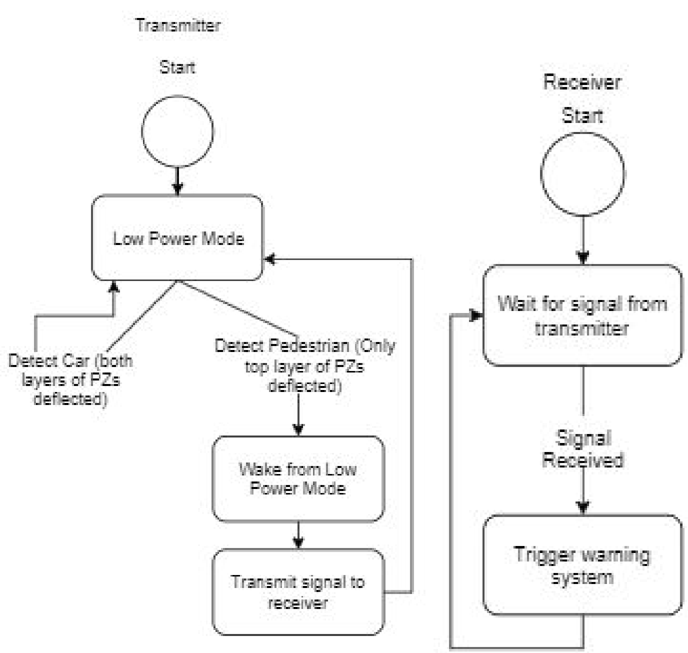
Item/Function	Potential Failure Mode(s)	Potential Effect(s) of Failure	Sev	Potential Cause(s)/ Mechanism(s) of Failure	r r o	Current Design Controls	Det	RPN	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	New Sev	New Occ	New Det	New RPN
											Action Results				
Packaging System - Tile															0
Package system surface	Cracked Packaging	Damaged Electronics - water intrusion, debris,	8	Overpressure	1	FEA analysis of materials under loading	1	**8**							0
			8	Fatigue	1	FEA analysis of materials under loading	1	**8**							0
			8	UV Degradation	3	Selection of material/ UV resistant sealant	3	**72**							0
Sealing	Seal degrades over time	Damaged Electronics - water intrusion, debris,	8	Material Selection/ Groove for o ring	3	Design of o ring groove, stretch of o ring, compression of o ring	3	**72**							0
	Seal not compressed enough	Damaged Electronics - water intrusion, debris,	8	O ring sizing	2	O ring sizing selection	3	**48**							
Connection - Tiles	Tiles come loose from system	Trip hazard, damage to tiles from cars,	10	Connection type	4	Asphalt screws to attatch to road and other tiles	2	**80**							0
Road Attachment	System comes up from road	Trip hazard, system could catch under car, system could break	10	Method of attaching to road	4	Asphalt screws to attatch to road and other tiles	2	**80**							0
Electronics -															0
Piezoelectric Element	Cracked Piezoelectric Element	Pedestrian crossings not recognized; LED do not activate	8	Overpressure; bumper system failure	7	Hard stop on piezo plate - checked in FEA	4	**224**			Redesign on piezo plate to remove hard stops	8	3	3	72
	Piezoelectric Element does not deflect	Pedestrian crossings not recognized; LED do not activate	5	Packaging system too stiff	7	Press design & bumper system	3	**105**			Change shore of rubber	5	3	3	45
Battery	Battery does not store any power	LED lights do not function	7	Overcharged battery	3	Battery management system	3	**63**							
Wires	Wiring not connected	Piezos do not sense/generate energy	8	Wiring path	3	Design of piezo plate	3	**72**							0

Appendix F: Circuit Diagrams





Appendix G: State Machine Diagrams



This state machine shows how the code should be implemented in the final system, the low power mode was not implemented in testing and prototyping.

Appendix H: Raw Code

Appendix H.1: Transmitter Code

```
//Transmitter.ino
#include <SPI.h>
#include <nRF24L01.h>
#include <RF24.h>

RF24 radio(7, 8); // CE, CSN
const byte address[6] = "00001";
const int inputSwitch = 2;
int count = 0;
void setup()
{
  Serial.begin(9600);
  radio.begin();
  radio.openWritingPipe(address);
  radio.setPALevel(RF24_PA_MIN);
  radio.stopListening();
  pinMode(inputSwitch,INPUT);
}

void loop()
{
  int temp = digitalRead(inputSwitch);
  int x = 0;
    if(temp == HIGH)
    {
       x = 5;
       count++;
       Serial.println(count);
       radio.write(&x, sizeof(x));
    }
    delay(2000);
}
```

Code Analysis: Using an Arduino Uno platform, this code is designed to read an input signal from pin 2 on the Arduino Uno board(“inputSwitch”). After reading the input signal from the pin which is attached to a Schmitt trigger, a radio signal is sent on the channel “00001” . After the signal is sent, a counter is implemented and printed to the serial port. This counter was designed to analyze the number of times a signal is sent for each compression of the Piezoelectric circuit. Initially, hundreds of signals were transmitted for each compression. In order to optimize this process, the capacitor size was adjusted to a size of 10 pF on the Schmitt trigger so that the charge would dissipate for a shorter period of time. The remaining synchronization issues were fixed by adding a two second delay between signal transmissions.

Appendix H.2: Receiver Code

```
//Receiver.ino
#include <SPI.h>
#include <nRF24L01.h>
#include <RF24.h>
//5
RF24 radio(7, 8); // CE, CSN
const byte address[6] = "00001";
int count = 0;
void setup() {
  Serial.begin(9600);
  pinMode(2,OUTPUT);
  digitalWrite(2,LOW);
  radio.begin();
  radio.openReadingPipe(0, address);
  radio.setPALevel(RF24_PA_MIN);
  radio.startListening();
}

void loop() {
  delay(200);
  if (radio.available())
  {
```

```
    int x = 5;
    radio.read(&x, sizeof(x));
    if (x == 5){
      char text[32] = "Power";
      Serial.println(text);
      digitalWrite(2, HIGH);
      delay(500);
      digitalWrite(2,LOW);
   }
    else
    {
      digitalWrite(2, LOW);
      x = 0;
    }
  }
}
```

Code Analysis: This program listens to radio frequencies on the channel “00001” and sends a signal to pin two on the Arduino Uno board which controls an LED. The serial port is invoked in order to send the text “Power” to the terminal as a means of recording signal transmissions in the presence of an LED malfunction. There is also a delay of 200 ms in the main function loop in order to synchronize transmission times.

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