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A step towards an inclusive future via piezo generators

Dr. Bala Maheswaran, Northeastern University

Bala Maheswaran, PhD College of Engineering 367 Snell Engineering Center Northeastern University Boston, MA 02115

Catherine Costa
Minnah Uddin
Ms. Morgan Mica Williams, Northeastern University
Ingrid Alikaj

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Bala Maheswaran, Catherine Costa, Minnah Uddin, Ingrid Alikaj, and Morgan Williams
College of Engineering
Northeastern University

Abstract

Around the world, technology is advancing faster than ever before. As we strive towards the future, we cannot forget those who cannot take this step forward. Lack of accessibility is a widespread problem, especially for those living in cities where high-rise buildings are prevalent. To address this issue, we created a sustainable way for buildings with heavy foot traffic to implement solutions for those with mobility challenges. We wanted to develop a way for the mechanical stress of walking to be converted into an electrical output that could be stored via batteries and used to power elevators and other accessible technologies for those who need them. Our prototype will use the unharnessed mechanical energy of foot traffic within buildings rather than drawing on pre-existing, expensive, and often non-sustainable energy sources. This paper explores a cost-effective solution to our problem, using piezoelectric sensors in a pressure pad to convert mechanical stress to a voltage output. With this solution, we hope to incentivize businesses to implement accessible options, such as elevators, for those with physical impairments.

Introduction and Background

The Americans with Disabilities Act of 1990 (ADA) revolutionized accessibility by mandating that public spaces be usable by all people, including those with disabilities. Though there has been progress since the passage of the ADA, private building designs often do not prioritize accessibility. Much of America's existing infrastructure was built before legislation like the ADA, making it expensive to update and implement accessible infrastructures like elevators and escalators.

Hefty price tags have halted recent efforts to revolutionize American infrastructure. In Boston, the cost to make public transit alone more accessible would be 477 million dollars [1]. Although costly, this investment is necessary; 26% of Americans have a disability, 14% of which are disabilities that hamper mobility, making it hard to walk up and down stairs [2]. One of the main contributors to the price tag of these projects is the increased draw from the power grid to power elevators and escalators. The cost of installing and powering an elevator year-round ranges from $30,000 to $55,000; our team sought to find a way to offset these costs by eliminating the need to outsource power for these machines [3]. By creating a prototype with piezoelectric sensors, the mechanical stress of people walking could be used as a direct, local power source, thus removing the need for external power.

These sensors make use of the piezoelectric effect: the ability of certain crystals to generate an electric charge under mechanical stress. Piezoelectric sensors apply this effect and enable the creation of circuits that generate electricity when mechanical stress is acting on the sensors [4]-[5]. As more advancements make use of piezoelectric technology, these sensors have evolved as an efficient way to harness vibrational energy in human-powered applications. They require no voltage source to run and generate more energy than other comparable generators [6].

This prototype aims to prove that we can generate a substantial electrical output from the mechanical stress of walking that, on a larger scale, could be stored in batteries and used to power elevators, escalators, and other accessible technologies.

Design Approach and Methods

We decided on the sustainable solution of using piezoelectric sensors to convert the mechanical stress of walking into an electrical output that can be stored in a capacitor and later used to power an elevator, escalator, or other accessible technology. Piezoelectric sensors are inexpensive, thereby providing a viable option for creating a voltage output that aligns with our goal of creating a cost-effective way to address accessibility issues.

To create the prototype, we considered two basic options for the pressure pad mechanism. In both potential solutions, the user would step on the pressure pad, but with the first option, the piezo elements would start in a convex position with the ends fixed, and once force is applied, it would be pushed flat. In our second potential solution, the pressure pad starts in a flat position and ends in a concave position after the application of force, again with the ends fixed. We wanted this technology to be durable and did not want to impede the user's ability to walk on the pads, so we decided the most feasible option for our prototype was the one that would result in a concave position after force was applied. We figured this design would be easier to maintain when not actively in use and would enable us to make a thinner pressure pad that would result in a more normal walking experience.

To optimize space on a large scale, we designed a three-layer, five-inch octagonal tile so each tile could fit right next to another. Cardboard was the best material for the middle layer with the piezoelectric sensors because it would move with the applied force, which would produce more of a voltage output than using a rigid material with the piezoelectric sensors. We also realized that the corrugation of cardboard would allow us to embed the piezo elements in the material and secure them in place. To maintain durability while still creating a thin prototype, we used ⅛" wood pieces for the top and bottom layers.

Design Details

We created the initial designs for the middle layer of the pressure pad where the sensors would lie in AutoCAD (Figure 1). The design has ten 0.95" x 0.51" cutouts for the piezoelectric sensors, which are slightly smaller than the sensors to be embedded in the cardboard without slipping out.

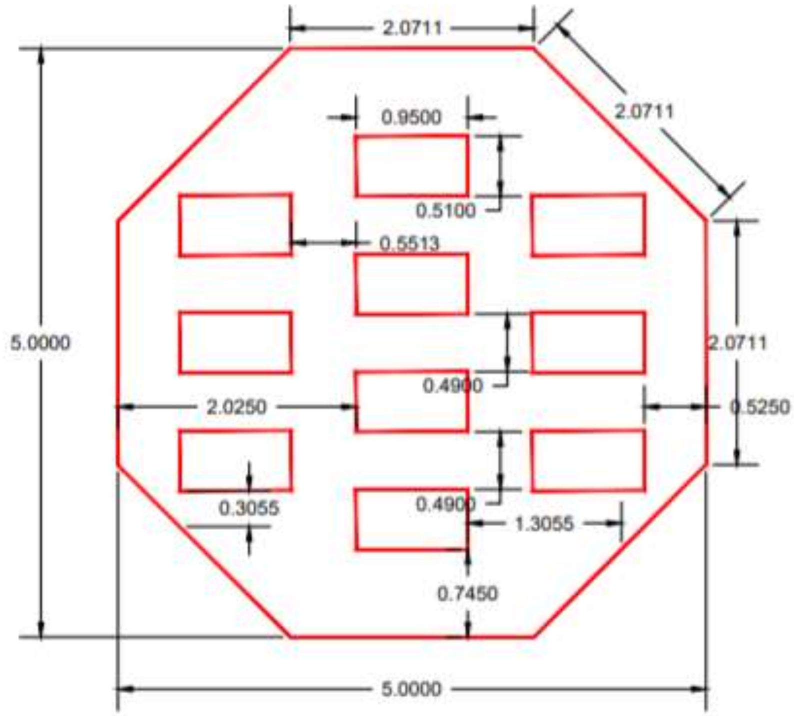

Figure 1: AutoCAD Model of Middle Layer of Pressure Pad

We then utilized SolidWorks to assemble the entire pressure pad with springs between the middle and bottom layer (Figures 2a and 2b). We then added the two pieces of wood going the length of the octagon to prevent the springs from breaking or detaching from the pad under the force of the user walking on the tile.

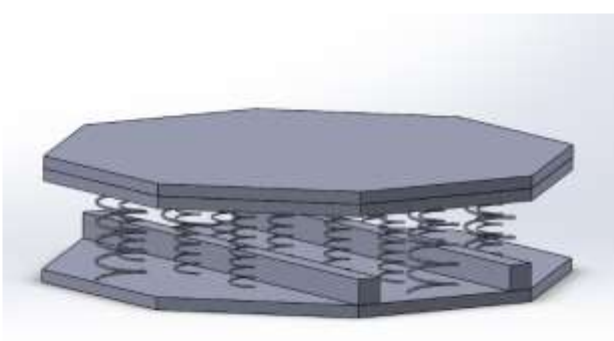

Figure 2a: SolidWorks Model of Final Pressure Pad Design

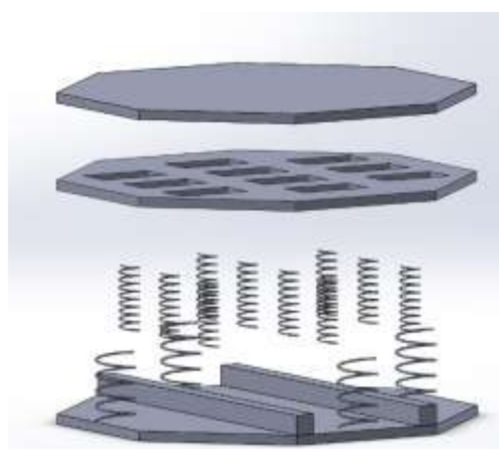

Figure 2b: SolidWorks Exploded View of Model Prototype

Initially, we wanted to store the energy from the pressure pad in a battery or capacitor. However, due to time constraints, we could only wire the sensors to calculate the voltage output, which we graphed as a function of time (Figure 3). After finalizing our physical design, we laser-cut the middle layer from cardboard with cutouts for the sensors and the two ⅛" thick pieces of wood with the same octagonal shape but with no cutouts to be the top and bottom layers of the tile.

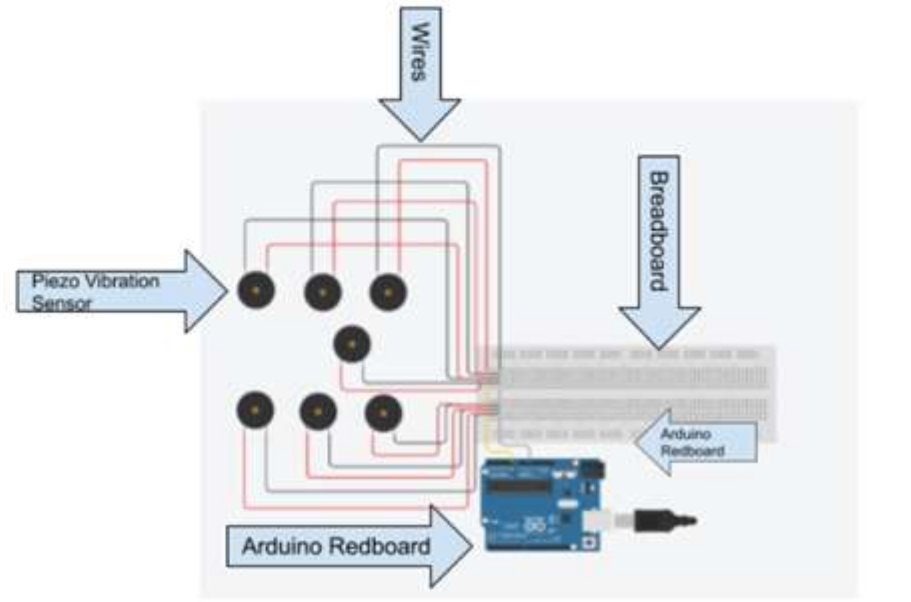

Figure 3: Piezoelectric Circuit

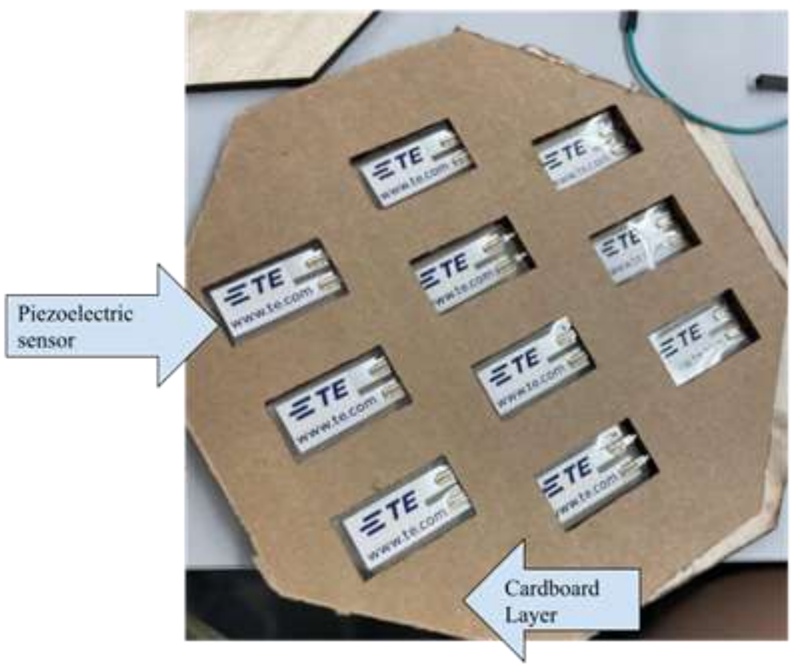

Figure 4: Ten Piezo Sensors in the Cardboard Layer

For our final assembly, we started with ten sensors and checked their positioning in the cardboard piece to ensure that everything fit properly (Figure 4). Then, to connect the sensors, we had to solder them. This method was flawed because the sensors were so small, less than 1” x 1”, that it was challenging to wrap wire around them (the two gold points) and solder them without melting the plastic on the rest of the sensor. Three of the sensors melted, rendering them unusable (Figure 5). Rather than let this challenge set us back, we used it as a learning experience and accounted for the sensitivity of the sensors in the future. With this in mind, we decided that it would be most effective to wire our sensors in parallel rather than series to prevent the entire prototype from failing if one sensor were to fail (Figure 3).

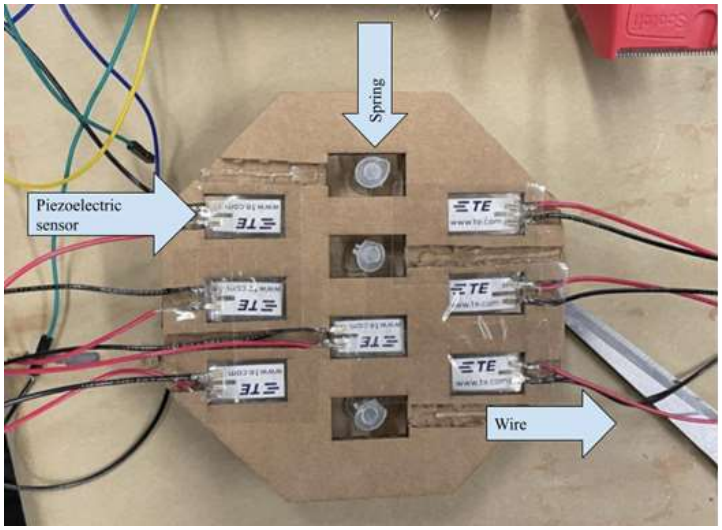

Figure 5: Seven Piezo Sensors Wired in the Cardboard Layer

Once we wired all the sensors, we collected data. We originally wanted to power a mini elevator to mimic the intended application of this technology; however, due to time constraints, we were unable to do so. After much consideration, we agreed that a digital display of the electrical output would be sufficient. To do so, we utilized the analog input pins of our Arduino RedBoard and a MATLAB Code (see Appendix) to graph and display the output voltage.

After our prototype was entirely assembled and we had a method for data collection, we began our testing. To test our prototype, we first used a CPR method to press on the sensor manually, then tested it while stepping on the tile to apply force at a constant rate for 45 seconds.

Results

The initial testing of our proof of concept involved plugging the piezoelectric sensors into a RedBoard and reading the voltage from a multimeter. To stimulate footsteps, we wiggled the sensors and read the subsequent output, which was lower than the output generated by the prototype — about 0.8 Volts (Figure 6). We used the initial testing to indicate if these sensors would be a viable option to use in our pressure pad.

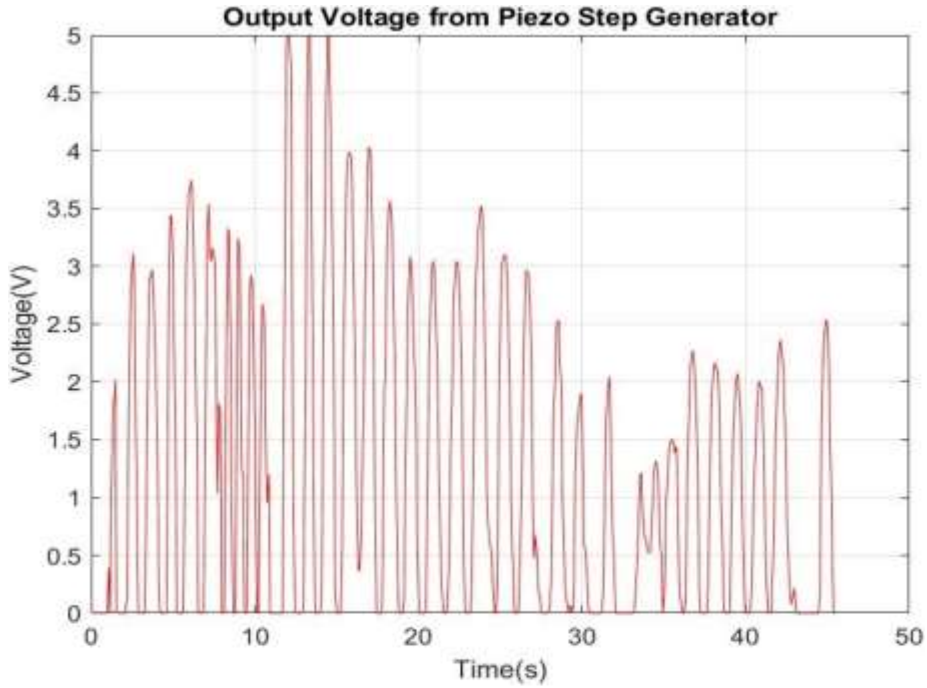

Figure 6: Output Voltage Recorded for 45 Seconds with Hands Using CPR Method

We tested our prototype by exerting mechanical stress with our hands, using the CPR Test method, which involved placing as much pressure as performing CPR requires. We ran the test for 45 seconds and recorded the output using the analog input pins on our RedBoard and a MATLAB code that formatted it into a graph. Each spike represents a moment of applied pressure or a footstep. With the CPR Test method, each footstep recorded 2.5 Volts on average, with some footsteps spiking up to 5 Volts.

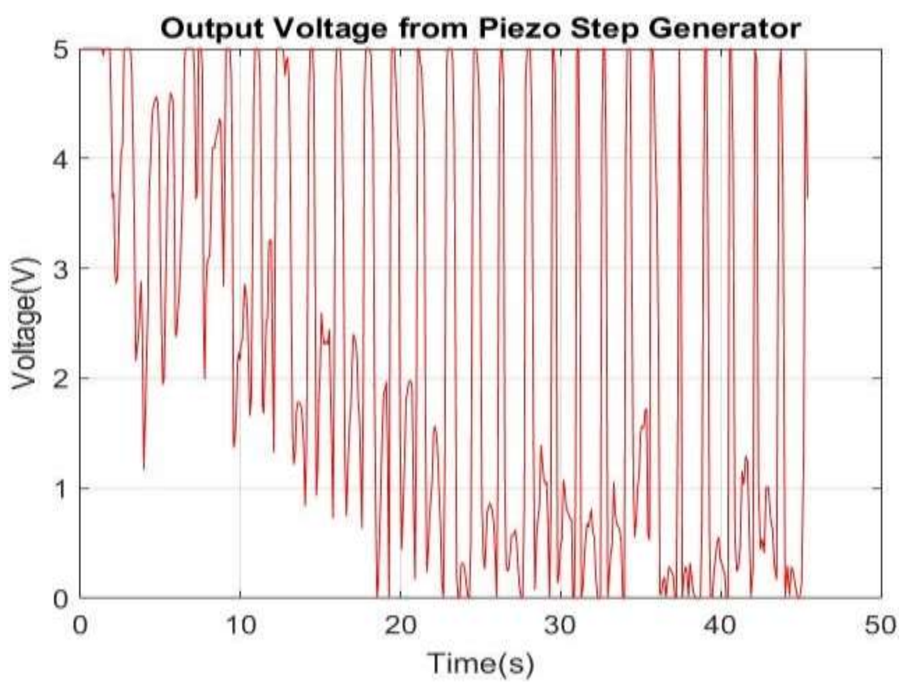

Figure 7: Output Voltage Recorded for 45 Seconds of Consistent Stepping

Our second test involved stepping on the prototype. This method created more mechanical stress than the previous method, resulting in a higher voltage output (Figure 7). Unfortunately, we were unable to record electrical outputs above 5 Volts due to limitations of the Arduino Analog pins. As a result, if any outputs were above this threshold, they were not recorded and graphed as such. Given that every step was at least 5 V, we inferred that with consistent stepping on the prototype, our prototype could produce at least, and more than, 5 Volts.

Discussion

Using data from initial testing, we estimated that the maximum output of each sensor was ~0.8 V. Operating under the assumption that a step on the ten-sensor tile produces 8 V, we made calculations about the power produced per square foot of tile. Using the equation Electrical Power (Watts) = Current (Amps) * Voltage (Volts), with current being 0.04 A from the Arduino input pins and voltage being 8 V, we estimated the power output of the tiles to be ~0.32 W.

Each spike with compression of the pressure pad lasts for about 1 second (Figures 6 and 7). Hence, our pressure pad produces ~0.32 Watt seconds. In one hour or 3600 seconds, our pressure pad would output 0.32 x 3600 = 1152 watt-hours.

Our tiles are 5” x 5”, and the average stair size is about 35” x 10”, so we could fit fourteen tiles on one stair (Figure 8) [7]. The average urban building has around 14’ walls and 22 steps per floor, so 308 pressure pads could fit on a staircase [8].

Although about 14 pressure pads could fit on one stair, one footstep would only cover about two pressure pads so that the power output would be ~2304 watt-hours (2 x 1152 watt-hours) per step.

An average elevator requires about 3600 watt-hours for a four-floor run [9], so approximately 3.1 of our pressure pads could power one elevator trip, assuming they produce around 8 V with each step. However, there are further limitations because, in its current state, our design does not store the energy generated. To store the electrical output of our pressure pad in a battery, we would have to account for energy transfer losses. Therefore, we assumed that the compression of about 4 or 5 tiles could produce 3600 watt-hours and power one four-floor elevator trip.

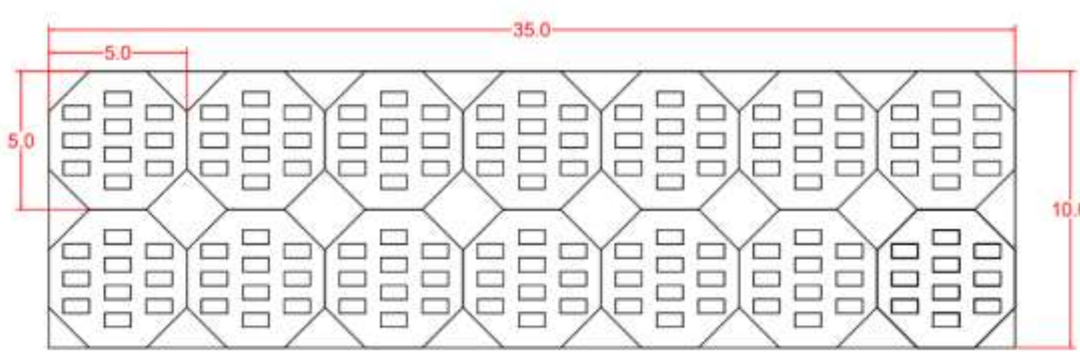

Figure 8: Piezoelectric Tiles on an Average Staircase

With 22 stairs in a staircase and only 4-5 required for the energy to power a four-floor trip, one person taking a trip up one staircase could power the elevator for about 5.5 trips (22 stairs/4 stairs needed per elevator trip). With the installation of our technology in a building with heavy foot traffic, the pressure pads will produce sufficient energy to power an elevator consistently. Moving forward with this project, we would include a battery in our design to store excess energy to power the elevator when there is no one walking on the tiles.

Another key advantage of our design is the cost-effective aspect. Each of our tiles cost about $55: $5 for each sensor x 10 = $50, $4 for wood, $12 for a pack of springs, and $0.84 for each tile. For one staircase of 308 sensors, the total cost would be $16,940.

A wide variety of factors determine how long it would take different companies to break even and see a return on investment after installing our technology. Some of these factors include local energy costs, elevator use, stair traffic, and the number of sensors they would need to install to power all the accessible technology they have implemented. Rather than providing an estimate for a 'standard' building, we figured that an equation to calculate the break-even point would be more helpful and informative for companies considering utilizing our technology.

$$\frac{B + 55P}{C} = T \qquad \frac{A + B + 55P}{C} = T$$

B = *Cost of Batteries*

A = *Cost of accesible technology*

C = *Cost to power accesible technology per year without the piezo pressure pads*

T = *Time (in years) to break even*

P = *Number of pressure pads needed to power accesible technology*

Given some initial data points from our client - dependent upon their current infrastructure, resources, local energy costs, and indoor foot traffic - we could easily calculate how quickly they would see a return on their investment. Return on energy investment alone is an important data point to provide to our clients; however, we know that many potential clients may implement our technology only when they do not already have accessible technology in place. Thus, we have also provided a way to calculate the break-even point that takes the cost of the accessible technology into consideration, which will undoubtedly yield a higher break-even point. However, we feel it is essential to be transparent with our clients and give them all the details of their investment upfront. Although this equation would need to be tweaked with improvements to our innovation, we view it as a helpful tool that would help incentivize clients to utilize our technology and add accessible technology to their buildings.

Conclusion

Although the electrical output of our piezoelectric pressure pad may seem low given the comparatively large force of people walking up stairs, our prototype serves as a glimpse into a more inclusive and accommodating future. Applying the basic concepts of our piezoelectric pressure pad design on a larger scale with some improvements to maximize efficiency and minimize costs, we could achieve the necessary energy requirements to power the accessible technology within urban buildings. We could find larger and more cost-effective piezo sensors that could produce a greater electrical output in adapting our design. We could also find cheaper building materials were we to buy in bulk.

The journey of identifying and generating a potential solution to improve the accessibility of America's dated infrastructure was not an easy one. With a limited amount of time and a rigid set of goals, constraints, and user needs to consider, we frequently had to step back from our work and reassess how our prototype compared to all these requirements. This iterative process prevented us from straying too far away from our ultimate goals and taught us a great deal about the importance of sticking to our values and always considering the needs of our users. The result of this work is our prototype, which demonstrates a proof of concept accompanied by a method for applying this technology to solve our targeted problem and incentivize companies and building developers to implement accessible technology.

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Appendix: MATLAB code for reading, graphing, and storing voltage from piezo pressure pad

```
%Set up and establish arduino and counter varaibles
a = arduino('COM8', 'uno');
end_time = 0;
ticker = 1;
user_time = 0;
x = 0;
```

Input from the user.

```
%Request user input to determine how long to test voltage for
user_time = input('Enter time to test voltage for (seconds): ');
fprintf('\nRunning, please be patient...')
```

Counts down before reading volatge.

```
%Count down to instruct user when to begin stepping on pressure pad
%generate for loop to run throuh 4 times (3,2,1,0)
for cDwn = 3:-1:0
    %output the number of seconds until testing begins
    fprintf('\nTest in %0.0f seconds...',cDwn)
    %if the countdown variable of the for loop is at 0 instruct the user to
    %begin testing
    if cDwn == 0
        fprintf('Begin testing!')
    else
        pause(1);
    end
end
```

Start timer to control when the while loop will end.

```
start = tic;
% Loops until user-defined time.
while end_time <= user_time
    voltage_output = readVoltage(a, 'A0');
    v = voltage_output;
    % Arrays for the voltage output and time
    voltage_val(ticker,1) = voltage_output;
    t(ticker,1) = toc(start);
    % This is to draw a graph live.
    figure(1)
    x = [x,v];
    plot(x,'b-')
    title('Voltage - FOR REFERENCE ONLY')
    xlabel('t (20 ms)')
    ylabel('Voltage(v)')
    grid;
    drawnow;

    % Controls the looping of the function
    ticker = ticker + 1;
    end_time = round(toc(start));
end
% Converts voltages and outputs to a graph
voltage_val = voltage_val;
figure(2)
plot(t,voltage_val,'r-')
grid;
xlabel('Time(s)'); ylabel('Voltage(V)');
title('Output Voltage from Piezo Step Generator');
```

Exports Data to Excel File

Remember to change name of the file as not to overwrite previously written data.

```
for row = 1:1:length(voltage_val)
    TV(row,2) = voltage_val(row,1);
    TV(row,1) = t(row,1);
end
xlswrite('voltage_time_data_X.xlsx',TV);
```