PiezoStep: Automation of Auxiliary Safety Control Devices by Harvesting Freely Available Kinetic Energy

An Applied Engineering Study on Piezoelectric Kinetic Harvesting & Self-Powered Relay Triggering

Advaith Iyer

Project Effort: 250+ Hours (Independent Directed Study)

EXECUTIVE SUMMARY & SYSTEM SPECIFICATIONS

• **Sole Designer, Engineer & Fabricator:** Advaith Iyer, Grade 10.

• **Core Engineering Objective:** Design and construct a kinetic energy-harvesting floor tile that converts footstep mechanical impact into a rectified electrical signal, using the footfall itself as the trigger for auxiliary safety systems.

• **Hardware Architecture:** Hand-fabricated dual-plate chassis (24.5 cm × 24.5 cm), 5-spring suspension matrix (1.2 mm wire diameter, 50 mm free length), 3D-printed compression actuators, solid-state 1N4001 full-wave bridge rectifier, 100 µF electrolytic capacitor buffer, and a programmable digital time-delay relay control module (externally powered).

• **Measured Performance:** Transient AC peaks of 35.5 V (100 kg load) and 13.0–18.2 V (50 kg human footprint) on an oscilloscope; rectified DC of 1.9 V at the 25 kg activation threshold and up to 16.4 V at 100 kg, buffered across a 100 µF capacitor. Stored energy at those readings was 0.18–13.4 mJ (½CV², accumulated across footfall intervals).

• **Safety Automation Logic:** The harvested kinetic pulse directly flashes indicator LEDs and trips the trigger input of a digital time-delay relay module (powered by an external DC supply), which switches external 120 V AC mains power to operate a 60 W pedestrian hazard lamp, emergency horn, and occupancy step counter.

1. Introduction & Engineering Motivation

Modern urban infrastructure consumes significant electrical energy powering continuous safety lighting, occupancy sensors, and pedestrian hazard signals. In high-foot-traffic environments—such as school hallways, transit stations, and public crosswalks—enormous kinetic energy is dissipated into the floor with every footstep. This project, titled *PiezoStep*, explores the design, fabrication, and electromechanical evaluation of a kinetic energy-harvesting floor tile utilizing Lead Zirconate Titanate (PZT) ceramic piezoelectric transducers [1][3][4]. Harvesting ambient energy to power low-power electronics is well established [2][5][6][7].

Rather than attempting the inefficient goal of directly powering heavy high-wattage AC appliances solely from small piezoelectric discs, *PiezoStep* implements a self-powered triggering architecture. The kinetic impact of a human footfall generates a rectified DC pulse that directly powers local diagnostic LEDs while simultaneously tripping the trigger input of a digital time-delay relay module. The relay module, powered by an external DC supply, acts as an isolated switch, controlling external 120 V AC mains power to drive heavy safety infrastructure—including emergency exit lighting, audible hazard alarms, and digital pedestrian step counters. The sensing element therefore draws no power of its own, while the relay module's standby draw (not measured here) is the system's baseline consumption. I constructed and calibrated a physical prototype over a year-long Independent Directed Study (IDS).

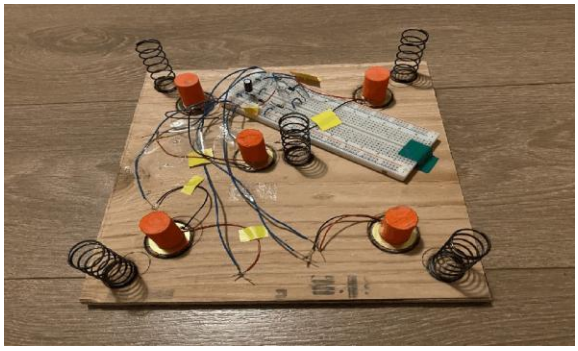
2. Design & Construction

2.1 Mechanical Architecture & Chassis Construction

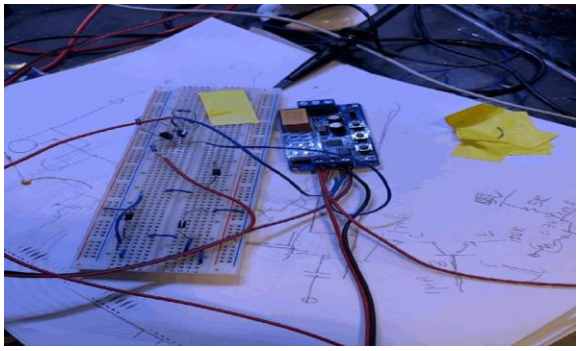
The physical chassis was hand-fabricated using two rigid support plates (24.5 cm × 24.5 cm) laser-cut from high-impact acrylic using a Sculpfun laser cutter operated via LightBurn CAD software. To maximize mechanical kinetic energy transfer onto five PZT ceramic piezo discs (25 mm diameter, 5 mm thickness), I designed custom cylindrical compression actuators in Onshape and 3D-printed them in orange PLA on a BIQU 3D printer. These actuators were bonded directly over the disc centers using high-tensile cyanoacrylate adhesive, equipped with protective cork buffers to distribute point loads and prevent ceramic fracturing.

To counteract mechanical material fatigue and ensure rapid baseline resetting, I engineered a 5-spring suspension matrix. Four precision steel compression springs (1.2 mm wire diameter, 50 mm free length) were positioned at the chassis corners, with a primary restoring spring mounted at the central axis. This spring matrix provides the restoring force required to return the upper tile to baseline after a 100 kg footfall.

Figure 1: Physical Hardware Build & Breadboard Relay Architecture



(A) Completed 5-spring suspension matrix with 3D-printed actuators and laser-cut acrylic top plate.



(B) Breadboard power conditioning circuit, 1N4001 bridge diodes, and digital relay module.

2.2 Solid-State Power Conditioning Circuit & Relay Control

Piezoelectric elements generate alternating current (AC) voltage spikes with highly erratic polarity upon mechanical deformation. To condition this output for electronic applications, I hand-wired and soldered a full-wave bridge rectifier circuit on a breadboard using four 1N4001 silicon rectifier diodes. The bridge rectifier converts bidirectional AC pulses into unipolar direct current (DC).

A high-capacitance 100 µF electrolytic capacitor (with 470 µF evaluated during heavy-load trials) was integrated across the DC output rails to smooth ripple voltages and buffer harvested charge across step intervals. The conditioned DC output was routed into two distinct subsystems:

- **Direct Low-Voltage Diagnostic Display:** Harvested DC current directly illuminates low-power indicator LEDs mounted on the circuit board, providing an immediate visual confirmation of physical footfall impact.
- **Relay Trigger Logic:** The buffered DC voltage serves as the trigger signal for a digital time-delay relay control module (featuring a 3-digit LED display and programmable logic) that is powered by an external DC supply. Upon receiving the kinetic pulse, the relay module switches external 120 V AC mains power to operate heavy auxiliary safety infrastructure (60 W pedestrian hazard lamp, digital step counter, and emergency warning horn). Only the relay module's switching contacts connect to the mains side; the harvested low-voltage circuit stays separate.

3. Physics & Electromechanical Energy Analysis

To compare the mechanical energy available at each footstep with the electrical energy actually captured, force and work were derived from classical physics, and the electrical side was estimated from the capacitor measurements:

Mechanical Input Energy vs. Measured Electrical Output

1. Downward Gravitational Impact Force (60 kg mass):
$F = m \times g$ = 60 kg × 9.807 m/s² = **588.42 N**

2. Mechanical Work per Step (4 mm tile travel):
$W = F \times \Delta x$ = 588.42 N × 0.004 m = **2.3536 J / step** (mechanical input, largely absorbed by the springs and structure)

3. Mechanical Power Input (at 2 steps / second):
$= W / \Delta t$ = 2.3536 J / 0.5 s = **4.707 W**

4. Electrical Conversion: Only a small fraction of this mechanical input appears as electricity. PZT shoe inserts in the literature average about 9 mJ per step [9]. PiezoStep's buffered capacitor energy, $E = \frac{1}{2}CV^2$ with C = 100 µF, ranged from **0.18 mJ** (25 kg) to **13.4 mJ** (100 kg) (Table 2), the same milliJoule scale (accumulated buffer readings, so not a like-for-like comparison with a per-step value)

4. Empirical Data & Laboratory Performance Testing

Laboratory stress testing was conducted across varying load masses (10 kg to 100 kg) and top-plate structural materials. Transient AC peaks were measured on a Tektronix TDS 2014 digital storage oscilloscope. DC voltage across the capacitor and series current were measured with a digital multimeter (current in series with the load during impact trials). The DC readings are buffered capacitor voltages accumulated across footfall intervals, not single-step values. Table 1 compares four structural top-plate materials under a standardized 50 kg human footprint; Table 2 gives the load sweep. Because transient peaks vary between trials, the 50 kg values differ between the two tables (13.0 V vs. 18.2 V).

Table 1: Top-Plate Structural Material Performance Comparison (50 kg Load)

Top-Plate Material	Peak Volts (V)	Peak Current, DMM (mA)	Peak V × I (W), indicative	Output vs. Acrylic (%)	Tile Material Cost
Acrylic (Optimal Standard)	**13.0 V**	**150 mA**	**1.95 W**	**100 %**	**$16.25**
Wood (Plywood Sheet)	9.0 V	110 mA	0.99 W	50.8 %	$8.50
Linoleum Sheet	10.0 V	130 mA	1.30 W	66.7 %	$11.00
Ceramic Tile Sheet	7.0 V	90 mA	0.63 W	32.3 %	$14.00

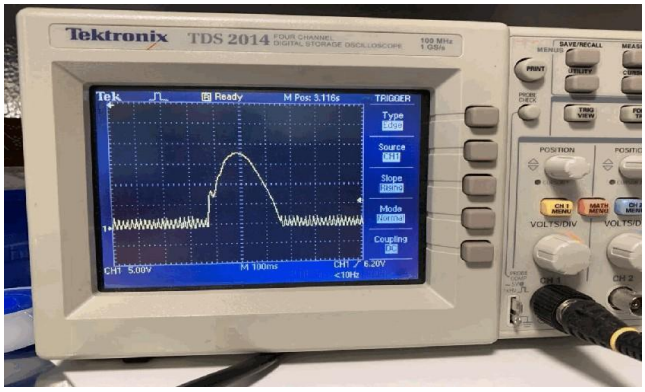
Peak V × I is the product of separately observed peak voltage and multimeter current readings; it is an indicative figure for comparing plates, not sustained power. “Output vs. acrylic” is that indicative product relative to acrylic (100%).

Table 2: Impact Mass vs. Electrical Output & Digital Relay Safety System Response

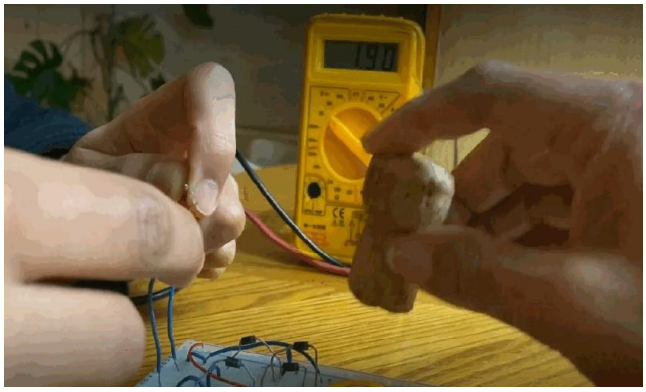
Impact Mass (kg)	Transient AC Voltage	Rectified DC Voltage (across 100 µF)	Stored Energy ½CV² (mJ)	Breadboard LED Status	Relay Trigger & Mains Safety Response
10 kg (Light Touch)	1.2 V Peak	0.4 V DC	0.008	OFF (Below Threshold)	NO (Not tripped) — System Standby
25 kg (Sensory Threshold)	**3.5 V Peak**	**1.9 V DC**	**0.18**	**Low Glow**	**YES (Tripped) — 60W Lamp & Counter ON**
50 kg (Standard Footfall)	18.2 V Peak	8.5 V DC	3.6	Bright Flash	YES (5s Hold Window) — 60W Lamp, Horn & Counter ON
75 kg (Heavy Impact)	28.0 V Peak	13.2 V DC	8.7	High Intensity	YES (Reliable Hold) — 60W Lamp, Horn & Counter ON
100 kg (Maximum Stress)	35.5 V Peak	16.4 V DC	13.4	Max Intensity	YES (Sustained Hold) — Full Infrastructure Active

DC voltages are buffered capacitor readings accumulated across footfall intervals; ½CV² is the energy stored at that reading, not a per-step value. The hold window is set by the relay module's programmable delay.

Figure 2: Oscilloscope & Multimeter Data Verification Traces



(A) Tektronix TDS 2014 trace (5 V/div, 100 ms/div) of a transient AC voltage spike (~18 V peak) from a 50 kg mechanical impact.



(B) Digital multimeter reading of 1.90 V DC stored across the 100 µF smoothing capacitor.

5. Discussion & Engineering Trade-Off Analysis

• **Self-Powered Sensing vs. Direct High-Wattage Generation:** A key engineering insight from this study is that using piezoelectric ceramic discs to directly power a 60 W AC lamp is not feasible: at roughly 10 mJ per step [9] and 2 steps/s, harvested power is on the order of 20 mW, thousands of times below the lamp's demand. Using the tile as a self-powered kinetic sensor that triggers a relay is a practical solution: the tile generates its own trigger signal, so the sensing element needs no standby power, although the relay module itself is powered by an external DC supply [8].

• **Diode Forward Voltage Drop & The 25 kg Activation Threshold:** The empirical data revealed a sharp activation threshold at 25 kg. Below it, the transient peak (1.2 V at 10 kg) is small relative to the roughly 1.2–1.4 V forward drop of the two bridge diodes that conduct in series, plus spring stiffness and the relay module's trigger-voltage requirement (it tripped at 1.9 V DC but not at 0.4 V DC). Replacing standard silicon diodes with low-forward-voltage Schottky barrier diodes (such as 1N5817, V_F ~0.2–0.3 V) would be expected to lower the activation threshold (an untested prediction), which could allow lightweight pedestrians such as children to trigger the system.

• **Structural Material Selection & Damping Trade-Offs:** High-impact acrylic gave the highest output (13.0 V; 1.95 W indicative peak) while maintaining high structural rigidity. Relative to acrylic, indicative output fell about 33% for linoleum, 49% for plywood, and 68% for ceramic tile, likely due to internal damping and flexure absorbing mechanical energy.

6. Practical Applications & Future Directions

PiezoStep is a proof-of-concept for self-powered, pedestrian-triggered safety automation. Integrating kinetic energy-harvesting floor tiles into high-density pedestrian corridors—such as school crosswalks, subway platforms, and emergency stairwells—could enable footfall-triggered safety systems. Future work will focus on integrating PZT-5H bimorph cantilever elements [8][10], incorporating Schottky diode bridges, measuring the relay module's standby draw, and moving toward wireless microcontroller nodes (ESP32/LoRa) with reduced external power.

7. Acknowledgments & Award Recognition

I express my sincere gratitude to Vijay Uncle for his invaluable technical guidance, encouragement, and advice on solid-state circuit soldering and breadboard wiring throughout this project. I also thank my parents and my science teachers for supporting my year-long Independent Directed Study (IDS).

This project was awarded the UBC Engineering Physics Award at the Greater Vancouver Regional Science Fair, among 250+ competing research projects.

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