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Piezoelectric Energy Harvesting Using a 10 × 10 Sensor Matrix with Integrated Circuit Design for Pressure Control

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Abstract

This project aims to create a system that generates energy using piezoelectric technology, designed as a rectangular tile platform. The platform has two layers of sensors arranged in a 10 × 10 grid, connected in a mix of series and parallel setups. The top layer acts as a surface for external forces, like footsteps, while springs connect the layers to control pressure and maximize energy generation. A rectifier ensures the energy output is stable, and capacitors store the collected energy for later use. Tests show the system is effective at turning pressure into usable energy, with the springs helping it reset after each use. This study primarily aims to evaluate how viable and efficient piezoelectric energy harvesting systems are as a consistent power source for low-power electronic devices. It also seeks to expand knowledge about the environmental sustainability and impact of these systems, supporting the broader goal of advancing renewable energy technologies for a more sustainable future. This innovative design is scalable and sustainable, making it ideal for powering small electronic devices and promoting eco-friendly energy solutions.

Keywords: Piezoelectric sensors, full-wave rectifier, rechargeable battery, load

INTRODUCTION

In recent years, low-power electronic devices have become more common, making our daily lives easier. However, to meet society's increasing energy needs and protect the environment, it is important to develop energy sources that are eco-friendly, efficient, and renewable. This need has sparked a renewed interest in finding alternative sources of energy. Moving towards sustainable energy is essential for creating a cleaner, healthier world and addressing issues like climate change.

This work investigates using piezoelectric sensors to generate energy for low-power devices. Piezoelectric materials produce an electric charge when they are stressed, making them a great way to harness energy from vibrations and movements in the environment [1, 2].

Evaluating the viability and efficiency of piezoelectric energy harvesting systems as a dependable energy source for low-power electronic devices is the primary objective of this study. The study also intends to advance knowledge of the sustainability and environmental impact of such systems, which is in line with the larger objective of developing renewable energy technology [3–7].

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LITERATURE RIVEW

Using the piezoelectric effect, the project produces electricity using 36 piezoelectric sensors positioned on a transducer pad. To maximize current production, the sensors were linked in parallel using a half-wave rectifier because a series connection generated less current. It converts the AC output of the transducer plate to DC and stores it in a battery. Using a buck converter allows for efficient control and powering of required loads [8].

The project's goal was to maximize power generation when walking or running by designing a flexible insole with 20 piezoelectric transducers placed in a three-part configuration. The insole's flexibility was assessed after it was 3D printed using polylactic acid (PLA) after being modeled using computer-aided design (CAD) software. Based on their characteristics, ceramic PZTs (lead zirconate titanate) were chosen, and different circuit configurations were examined to maximize power production. Alternating power was converted to direct using a full bridge rectifier, and the accuracy and charging capabilities of the system were tested using a Ni-MH (nickel–metal hydride) battery [9].

Materials can convert mechanical loads into electrical reaction thanks to the 1880 discovery of the piezoelectric phenomenon. It has been discovered in a variety of materials, including wood, ceramics, polymers, and crystals like quartz. Piezoelectric characteristics are significant in perovskite crystals. The effect has a mathematical description and is related to electrical and mechanical fields. For ferroelectric materials, piezoelectric coefficients are crucial and are influenced by crystal symmetry. Phase boundary effects and domain wall are examples of extrinsic contributions that enhance the inherent lattice-induced polarization. Piezoelectricity is essential in many industries, including consumer goods, transportation, healthcare, the military, and energy, due to its adaptability [10].

Polyester, copper, PZT, stainless steel, and polyimide layers are layered on top of a PPA1001 substrate to create a multi-layer piezoelectric harvesting floor structure. To effectively transform footsteps into electrical power, the structure is made up of four levels of simply supported beams. The strain at the 2-mm deflection is close to the allowed limit, according to calculations. Considering human weight and gait, 104.6 beams are advised with a permissible force of 8.282 N. A four-layer interdigitated structure with a 4-mm stroke and 2-mm deflection per layer is used for efficient energy collecting [11]. Piezoelectric energy transducers efficiently convert vibrations into electricity but face durability challenges. Thanh Huyen Pham et al [12]. addressed this by designing a flexible sensor with indirect touch points and a protective spring, significantly improving durability and efficiency in energy-harvesting systems.

METHODOLOGY

A piezoelectric-based energy-harvesting platform that efficiently converts mechanical vibrations into electrical energy is shown in the study. The system is based on a rectangular plate that has 50 piezoelectric sensors arranged in 10 sensor rows, connected in series within a row and in parallel between rows. If a sensor is damaged, this series-parallel arrangement maximizes energy collection while reducing the chance of circuit failure (Figure 1).

The alternating current (AC) generated by the piezoelectric sensors is transformed into direct current (DC) via a full-wave rectifier to efficiently use the energy that has been gathered. The rectification process has guaranteed a consistent and dependable power source for rechargeable batteries or low-energy gadgets that are powered directly. After that, the rectified output is kept for later use in a rechargeable battery or capacitor. To better optimize the energy harvested, voltage boosters are strategically added.

A design based on cantilevers: The foundation material's mechanical qualities are carefully considered to get the best possible flexibility and durability. Similarly, springs of the right strength are used to install the top plate, which allows the platform to rebound after supporting external weights while maintaining enough pressure on the sensors (Figure 2).

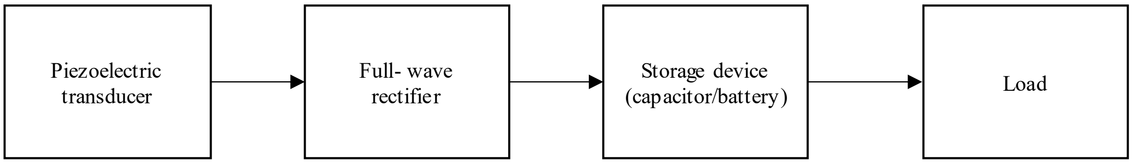

Figure 1. Block diagram of working principles.

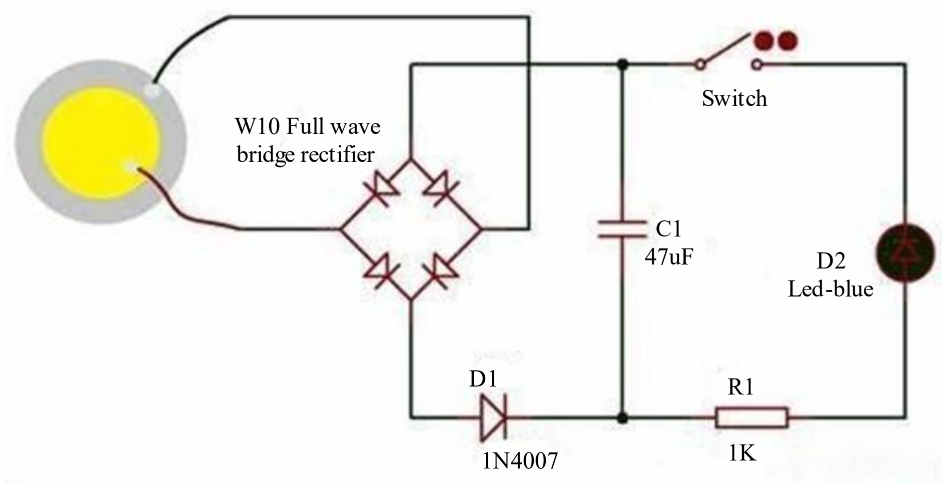

Figure 2. Footstep power generation circuit using piezoelectric sensor.

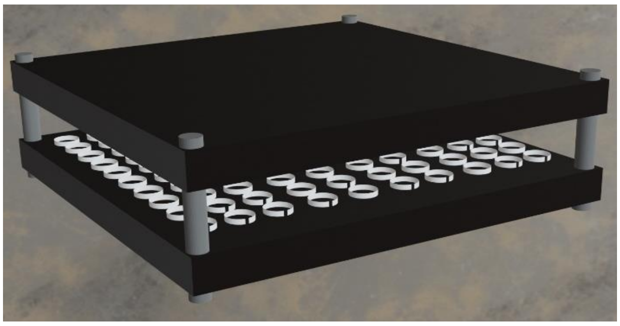

Figure 3. Two-dimensional (2D) view of piezoelectric sensors implemented.

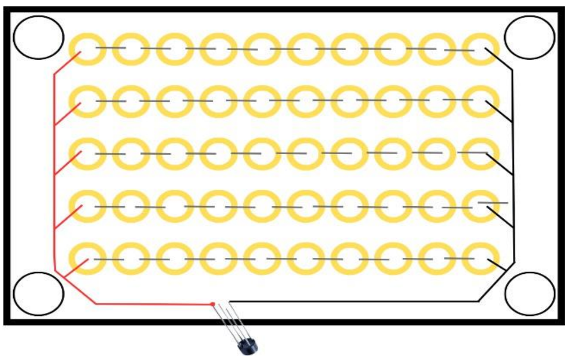

Figure 4. Three-dimensional (3D) view of piezoelectric sensors implemented.

Advanced materials for the base and top plate should be investigated in future research to enhance overall system performance, taking durability, flexibility, and weight into account. Enhancing the platform's reactivity to mechanical vibrations through spring design optimization may further boost energy harvesting effectiveness (Figures 3 and 4).

External forces are imparted to the platform's top layer, such as vibrations or footsteps. By deforming the piezoelectric sensors, the applied pressure creates an electric charge via the piezoelectric effect. The 10x10 matrix of piezoelectric sensors is set up with each row coupled in parallel and series arrangements to maximize energy gathering. To provide controlled pressure application and platform recoil following deformation, springs are incorporated between the layers.

The produced AC voltage is rectified to create a controlled DC output that can be used to power or charge electrical devices. Utilizing gathered energy efficiently is made possible by the integration of capacitors for energy storage (Figure 5). The energy output of a piezoelectric material depends on the material's properties, the mechanical stress that is applied, and the system design. Calculating the energy generation of a piezoelectric material with an area of x cm^2 requires considering the following factors.

Piezoelectric Material Properties

Among the distinctive properties that each piezoelectric material has are the piezoelectric coefficient and capacitance. The ability of the material to convert mechanical stress into electrical energy is based on these properties.

The piezoelectric coefficient, also referred to as *d*, expressed in coulombs per newton (C/N), indicates how sensitive a material is to mechanical stress. An increase in *d* values signifies a higher efficiency of energy conversion.

Applied Mechanical Stress

Putting mechanical stress on the piezoelectric material is a significant part of energy production. Stress can be generated by a variety of methods, including vibrations, deformation, and pressure. Energy output depends on the frequency and magnitude of applied stress. More energy may be produced, for instance, when stress frequencies and amplitudes increase.

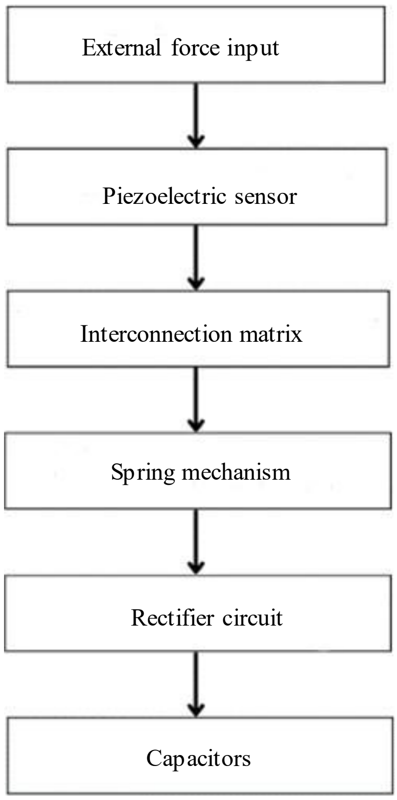

Figure 5. Key components and the flow of energy within the piezoelectric-based platform for energy harvesting.

Design and Configuration

Energy production is also significantly impacted by the system design that employs piezoelectric material. The quantity and arrangement of components, the size and shape of the piezoelectric element, and the system's overall efficiency all influence the energy output. Additions of rectifiers, energy storage devices, and amplifiers may be necessary to optimize the conversion and utilization of the generated energy.

A more accurate estimate can be obtained by doing practical testing or by consulting the datasheet for the piezoelectric material. The datasheet should specify the piezoelectric coefficient. Additional testing should be conducted to ascertain the energy output under different stress levels that are relevant to your application.

Be aware that the energy output of a single piezoelectric element may be quite low. To get greater energy output for real-world uses, many components are typically combined and increased in size. Determine the applied stress to compute the energy produced by a single footfall on a 2000 cm^2 piezoelectric panel while taking a 50-kg person into account.

THEORETICAL CALCULATIONS

a. *Piezoelectric effect*: The fundamental relationship describing the piezoelectric effect is given by:
$Q = d \times F$,
where:
Q = induced charge
d = piezoelectric charge coefficient, and F = applied force.

b. Calculation of Energy Generation:
The energy generated by a piezoelectric material can be estimated using the formula:

$\text{Energy} = 0.5 \times d \times A \times S^2$,
where:
d indicates the material's piezoelectric coefficient (C/N),
A is the area of the material (m^2),
S is the applied stress (N/m^2 or Pascal).

The factor of 0.5 is a result of the integration and simplification process when relating the strain energy to the piezoelectric coefficient and applied stress.

Convert the area to square meters:
Area = 2000 cm^2 = 2000/10,000 m^2 = 0.2 m^2. Calculate the force applied by the person's weight:
Force = mass × acceleration due to gravity = 50 kg × 9.8 m/s^2 = 490 N.

Calculate the stress applied to the piezoelectric panel:
Stress = force / area = 490 N / 0.2 m^2 = 2450 N/m^2 or 2450 Pascal (Pa)

Determine the piezoelectric coefficient (d):
Depending on the material, the piezoelectric coefficient (d) has a specified value. Please consult the manufacturer or the datasheet to get the correct value.

Considered hypothetical value of d = 0.01 C/N. Now, we can substitute the values into the formula:
$\text{Energy} = 0.5 \times d \times A \times S^2$
$= 0.5 \times 0.01\ \text{C/N} \times 0.2\ m^2 \times (2450\ N/m^2)^2$
= 0.000245 joules or 0.245 millijoules (mJ)

c. Based on the assumptions and calculations provided, a single footfall on a 2000 cm^2 piezoelectric panel can produce roughly 0.245 mJ of energy.

The integration and simplification process that links the strain energy to the piezoelectric coefficient and applied stress results in the factor of 0.5.

RESULTS AND DISCUSSION

The results of the experiments using the piezoelectric-based energy harvesting platform were encouraging. Electrical energy was efficiently produced by the 50 piezoelectric sensors and stored in a 12-V rechargeable lead-acid battery (see Table 1). The voltage levels in the power generation were noteworthy; they ranged from a minimum of 17 V each step to maximum of 62 V per step. The experiment showed that to boost the battery charge by 1 V, about 300 steps were needed. It was estimated that approximately 3600 steps were required for a complete recharge. It would take about 60 minutes to fully recharge in a heavily populated region where an estimated 2 steps per second could be attained. The viability and potential effectiveness of the suggested piezoelectric energy harvesting device in real-world applications are demonstrated by these outcomes.

Particularly in settings with high foot traffic or mechanical vibrations, the piezoelectric-based platform for energy harvesting offers a lot of potential for real-world applications. To gather energy from foot traffic, the platform might be incorporated into pavements, dance stages, or walkways as part of smart infrastructure. Following that, this energy might be used to light lamps, operate sensors to keep an eye on the surroundings, or even charge devices. To capture energy from vibrations generated during operation, the platform might also be integrated with machinery or other equipment in an industrial setting. Sustainability efforts would be supported and the need for external power sources would be lessened. Due to its versatility and scalability, the platform may be widely used in both urban and industrial settings, making it a versatile option for a variety of energy collecting applications.

For Lead-Acid Rechargeable Batteries (12 V)

It is well knowledge that piezoelectric sensors generate energy, which is then stored in a battery. In the experiment, 50 piezoelectric sensors were used (Figures 6 and 7). Because the power produced by piezoelectric sensors varies in small increments, we were able to determine that the maximum output voltage was 62 V. The minimum output voltage is 17 V with about 20 steps at a time, without interruption.

Table 1. Voltage generated per 20 steps.

S.N.	Weight (in kg)	Voltage Generated (in V)
1.	40	23.7
2.	50	36.2
3.	60	48
4.	70	57
5.	80	62.8

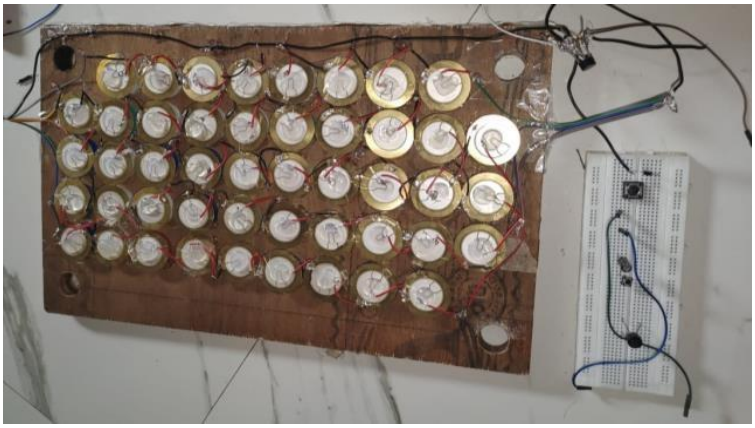

Figure 6. Physical implementation of 50 piezoelectric sensors.

Figure 7. Mechanical stress was provided on transducer pad.

CONCLUSION

Mechanical vibrations are converted into electrical energy with efficiency thanks to the piezoelectric energy harvesting platform. Together with a full-wave rectifier and voltage boosters for improved output, the series-parallel sensor design guarantees dependability. Durability and responsiveness are enhanced by thoughtful material selection and spring adjustment. To improve system performance, further study should examine sophisticated spring designs and cutting-edge materials. This platform shows great promise for real-world application and offers a workable option for sustainable energy applications.

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