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Development of a Sustainable Walkway System and Its Performance Analysis of Voltage, Current, and Power Output

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Sustainable walkway, piezoelectric materials, performance analysis.

Abstract

This project designs a sustainable walkway using piezoelectric materials to capture energy from pedestrian movements. It converts human mechanical energy into electricity with piezoelectric tiles. The study involved developing these tiles, choosing materials, and measuring power output. Results indicated that an array of twelve piezo discs generated up to 128.74 mW, highlighting their significant potential for renewable energy applications in urban areas. This system supports sustainable urban development and highlights the feasibility of using piezoelectric technology in urban infrastructure. Future work could expand applications and integrate with other renewable energy systems.

1. Introduction

In the contemporary global landscape, sustainable energy generation and intelligent infrastructure are becoming increasingly important due to the persistent environmental impacts of conventional energy sources [1],[2]. The project "Development of a Sustainable Walkway System and Its Performances Analysis of Voltage, Current, and Power Output" investigates harnessing electrical energy from human foot movement to enhance safety and functionality in public areas [3], [4]. Piezoelectric energy harvesting offers significant advantages, including being an environmentally friendly and sustainable energy source that reduces dependence on finite resources and mitigates carbon emissions [5], [6]. Additionally, LED lights powered by harvested energy improve pedestrian safety by illuminating routes, particularly in low-visibility areas [7]. This project aims to conceptualize, create, and assess a system that captures and utilizes mechanical energy from pedestrian movement on engineered paths using piezoelectricity, which generates electric charge from mechanical strain [8], [9], [10]. In urban settings, there is a critical need for sustainable energy solutions due to the inefficiencies of conventional power sources and the untapped potential of human-generated kinetic energy in public spaces [1],[2]. This project addresses these issues by utilizing piezoelectric technology to convert unused kinetic energy into electrical power, aligning with global trends towards environmentally conscious and technologically advanced urban environments [9],10). The research objectives are to investigate an energy harvesting system for pedestrian movement, design optimal configurations for energy harvesting, and analyze the efficiency of the piezoelectric materials used [10]. The scope includes understanding the impact of foot traffic patterns, selecting effective piezoelectric materials, and developing and evaluating the energy harvesting system from simulation to prototype to ensure efficient energy conversion [2].

2. Literature Review

The materials of piezoelectric are classified or distinguished based on chemical composition, structure, and physical characteristics.

2.1 Single Crystal

In terms of crystal classes, there are a lot of different kinds of crystals that are piezoelectric, and different chemical compounds can be categorized as piezoelectric single crystals as shown in **Fig. 1** [11]. Nonetheless, there are notable differences in the degree of piezoelectric behaviour's depending on the chemical composition and crystal structure [12]. Examples of piezoelectric single crystals are quartz (SiO2), lithium tetraborate (LiB4O7), lead zirconate niobate / lead titanate (PZN-PT), lead magnesium niobate / lead titanate (PMN-PT), and lithium niobate (LiNbO3) [13].

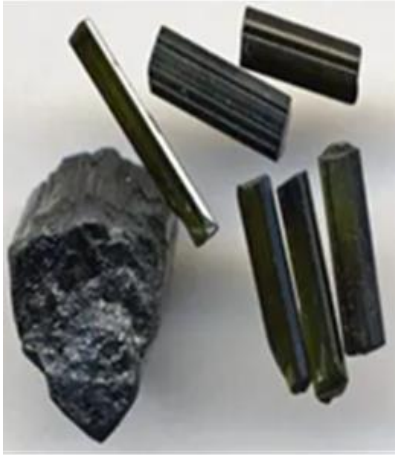

Fig. 1 *Tourmaline Single Crystals*

2.2 Polymers

In [13], Ferroelectric polymers are the top choice for piezoelectric materials due to their excellent conduction qualities. Their piezoelectric properties come from charge accumulation around molecular dipoles in the polymer chain. These materials offer benefits like flexibility, low environmental impact, and mechanical resilience. Examples include poly (vinylidene fluoride) (PVDF) and poly (vinylidene fluoride-co-trifluoroethylene) (PVDF-TrFE). Polymer composites, made from ceramic nanoparticles and polymers like poly (dimethyl siloxane) (PDMS), also have piezoelectric qualities.

2.3 Ceramics

Lead zirconate titanate (PZT) as shown in **Fig. 2**, for example, is one of the piezoelectric metallic oxides that can be converted into piezoelectric ceramics by carefully controlling the heat treatment process [14]. The ceramic piezoelectric sensors, which use any of the known piezoelectric ceramic materials as their primary sensory component, are straightforward detection devices for measuring mechanical variables. The ceramics' piezoelectric behavior is influenced by external variables such as temperature [15]. A wide variety of behaviors can be displayed by piezoelectric ceramic materials under a variety of conditions due to their multifunctional nature [15].

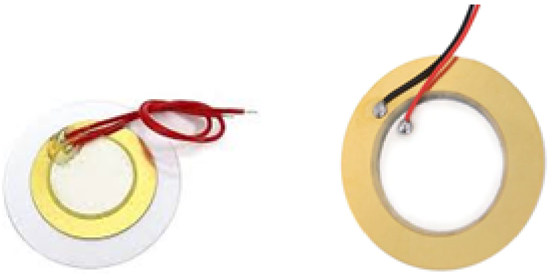

Fig. 2 *Piezoelectric Ceramic*

3. Methodology

3.1 Material Selection for Piezoelectric Sensors

Piezoelectric materials encompass a wide range of substances, such as Polyvinylidene Fluoride (PVDF) as a polymer, PZT as a ceramic, as well as single crystals and composites. PZT is the predominant material utilized in piezoelectric energy harvesting systems. When selecting materials, the primary factors considered are the piezoelectric coupling coefficient, piezoelectric charge constant, and piezoelectric voltage constants. PZT exhibits a higher coupling coefficient, indicating its ability to efficiently convert input mechanical energy into electric energy. Additionally, PZT has a larger charge constant, resulting in a greater power output compared to PVDF. However, it is worth noting that PVDF possesses greater flexibility. After taking these aspects into account, the decision was made to choose PZT as the piezoelectric material.

3.2 Conceptual Design

The energy harvesting system is designed with two plates forming a sandwich-like structure. Plate No. 1 is the front plate and Plate No. 2 is the back plate, as illustrated in **Fig. 3**. The piezoelectric element is arranged and attached to Plate No. 2. Additionally, hot melt glue sticks are mounted on each piezoelectric element. These glue sticks ensure direct and balanced pressure on all piezoelectric transducers, preventing significant voltage drops during human footsteps on the floor tile. An acrylic sheet is used to distribute pressure uniformly. Cardboard is utilized on both sides of the piezo disc in the design because its high deformation leads to increased electricity generation.

(a) **(b)**

Fig. 3 *Conceptual design (a) Conceptual design for array of piezoelectric disc; (b) conceptual side view design of a piezoelectric disc array*

3.3 Electrical Pressure Energy Harvesting System Design

A series connection of the disc array is used to optimize voltage output and ensure continuous power generation. This configuration, shown in Fig. 4, maximizes efficiency by amplifying voltage cumulatively. The series setup is balanced carefully to enhance voltage while maintaining the integrity of the energy harvesting system, ensuring effective power storage and utilization. This approach supports the project's goal of creating an efficient and sustainable walkway system using piezoelectric energy harvesting technology.

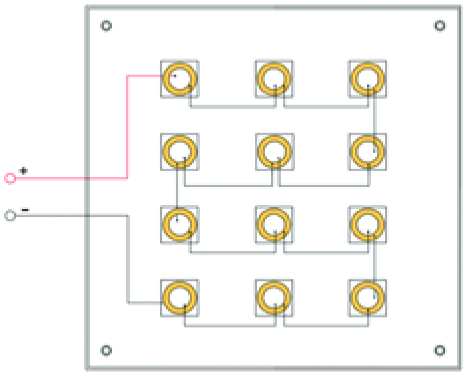

Fig. 4 *Conceptual framework for connecting piezoelectric discs*

3.4 Hardware Implementation

During the project, prototypes of piezoelectric tiles were created using twelve piezo discs as shown in Fig. 5. Two acrylic sheets, each measuring one square foot and eight millimeters thick, were used. Crystalline acrylic, known for its weather resistance, strength, clarity, and versatility, was chosen. This material ensures even weight distribution and allows visibility of the circuitry due to its transparency. The piezo discs were connected in series to maximize output efficiency. Corrugated cardboard was placed underneath the piezo surface to enhance flexibility and deformation capabilities. It was observed that uneven surfaces increased voltage and current output compared to flat surfaces. The cardboard also acted as a spring, contributing to the prototype's functionality.

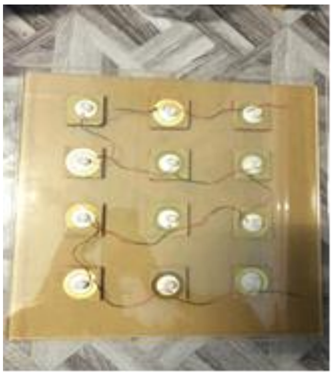

Fig. 5 *Series connection of 12 piezoelectric discs*

4. Results and Discussions

4.1 Power Output from A Single Piezo Disc

The study aimed to assess the power generation capability of a single piezo disc. Table 1 shows multiple measurements of voltage and current outputs, with typical readings being 2.35 volts and 0.0067 mA, respectively. The maximum power output of the piezo disc, calculated using the basic power equation P = V * I, was found to be 0.016 mW. These initial tests provide essential foundational data on the energy conversion potential of the piezo disc and guide future project research.

Table 1 *Voltage, current, and power from an individual piezo disc*

Voltage, V	Current, mA	Power, mW
2.35	0.0067	0.016

4.2 Output Voltage from Various Quantities of Piezo Disks

The peak voltage observed from a single piezo disc was 2.35 volts. As more piezo discs were added, the peak voltage increased proportionally. With twelve piezo discs working together, the peak voltage reached 13.41 volts as mentioned in Table 2.

Table 2 *Output voltage from various quantities of piezo disks*

Number of piezo discs	Voltage, V
1	2.35
2	3.50
4	4.75
6	6.59
8	9.50
10	11.55
12	13.41

Initially, a maximum voltage of 2.35 volts was recorded using one piezo disc. **Fig 6** demonstrates a proportional increase in voltage with the number of piezo discs in the setup. This scalability indicates that combining multiple piezo discs can yield higher voltage outputs, offering valuable insights for improving piezo-based energy harvesting systems.

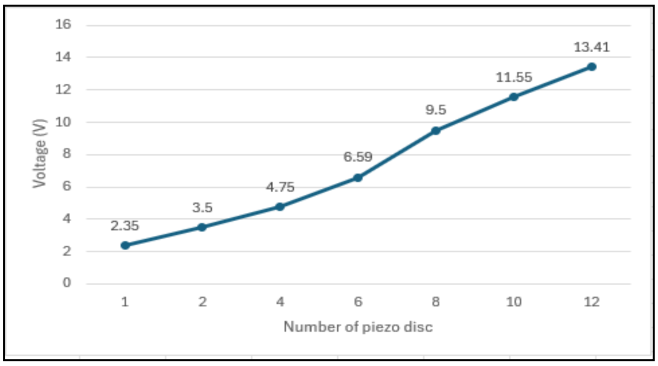

Fig. 6 *Voltage output from different numbers of piezo disc*

4.3 Current Output from Different Numbers of Piezo Disc

The multi-meter data show that as the number of piezo discs increases, both the current and voltage rise. Although the current values are modest, the clear upward trend with more discs indicates that piezo-based devices can be scalable and generate more power. The tabular data in Table 3 highlights the performance characteristics of the piezo disc array.

Table 3 *Output current from various quantities of piezo disks*

Number of piezo discs	Current, mA
1	0.0067
2	0.0075
4	0.0079
6	0.0081
8	0.0090
10	0.0093
12	0.0098

As the piezo disc array grows, the current increases, as shown in Fig 7. Initially, one piezo disc generates 0.0067 mA, and with twelve discs, the peak current reaches 0.0098 mA. The graph demonstrates a clear trend of increasing current levels as more piezo discs are added, despite the initially low values.

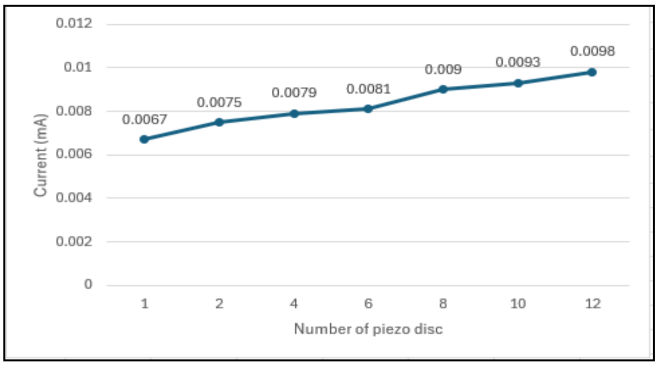

Fig. 7 *Current output from different numbers of piezo disc*

4.4 Power Output from Varying Numbers of Piezo Discs

The voltage and current values were measured, and the system's power output was calculated. These power values are shown in Table 4. This comprehensive approach allows for evaluating power generation efficiency based on the recorded voltage and current, providing valuable insights for further research and system improvement.

Table 4 *Output power from various quantities of piezo disks*

Number of piezo discs	Power, mW
1	14.1
2	23.56
4	33.43
6	56.49
8	82.60
10	105.11
12	128.74

The power output increases with the number of piezo discs as shown in Fig. 8. A single piezo disc produces 14.1 mW, while twelve discs generate 128.74 mW. This trend indicates that adding more piezo discs enhances the system's ability to convert mechanical energy into electrical power.

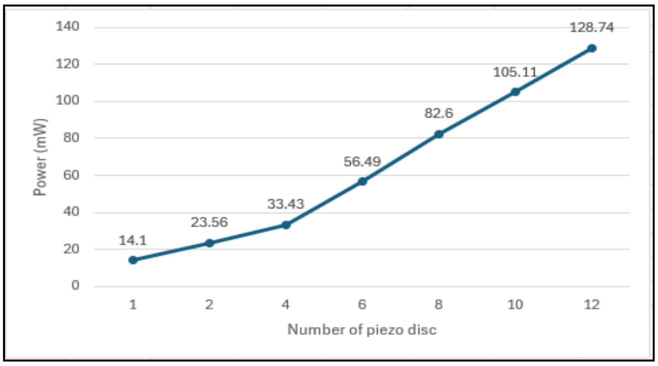

Fig. 8 *Power output from different numbers of piezo disc*

4.5 Time, Steps, and Battery Voltage Measurement Data

Table 5 shows a piezoelectric energy harvesting experiment where battery voltage and steps taken were measured over time. Starting at 11.5 volts with no steps, the voltage increased steadily with more steps: 11.52 volts at 50 steps (10 minutes), 11.54 volts at 122 steps (20 minutes), 11.56 volts at 183 steps (30 minutes), 11.58 volts at 245 steps (40 minutes), and 11.60 volts at 311 steps (50 minutes). From 60 to 90 minutes, with steps ranging from 347 to 525, the voltage remained at 11.62 volts. By 100 minutes and 574 steps, the voltage reached 11.70 volts. This demonstrates the effectiveness of piezoelectric energy harvesting in converting mechanical energy from walking into electrical energy to gradually charge a battery.

Table 5 *Time, steps, and battery voltage measurement*

Time, minutes	Number of steps	Battery voltage, V
0	0	11.5
10	50	11.52
20	122	11.54
30	183	11.56
40	245	11.58
50	311	11.60
60	347	11.62
70	410	11.64
80	460	11.66
90	525	11.68
100	574	11.70

5. Conclusion

The main goal of this work was to explore the use of piezoelectric devices to generate electrical energy from mechanical stress. The experiments showed that piezoelectric materials could convert mechanical energy into electrical energy, producing significant voltage spikes despite generating little current. However, the limited number of devices used in the experiment meant it took a long time to charge a battery, highlighting the need for more piezoelectric elements to increase energy output. Future improvements could involve connecting more devices in series and parallel configurations to boost current and voltage, as well as optimizing mechanical designs to enhance energy conversion efficiency.

To maximize energy production, placing piezoelectric tiles in high-traffic areas such as sidewalks and corridors is recommended. Using levers, pressure plates, supercapacitors, and boost converters can further improve energy harvesting and storage efficiency. Real-time monitoring and adaptive systems can optimize performance based on observed mechanical stress patterns. The project demonstrated the potential of piezoelectric energy harvesting, and future research should focus on scaling up installations, enhancing material durability and efficiency, integrating with other renewable energy sources, and conducting practical pilot projects. These steps can accelerate the adoption of piezoelectric energy harvesting as a sustainable and versatile energy source.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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