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DESIGN AND IMPLEMENTATION OF A PIEZOELECTRIC PEDESTRIAN-POWERED ENERGY HARVESTING SYSTEM FOR SUSTAINABLE URBAN INSTALLATIONS

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ABSTRACT

This project proposes integrating a pedestrian-powered system into a public installation to create a renewable energy source in urban environments. The system utilizes piezoelectric sensors embedded in the sidewalk to convert mechanical energy from footsteps into electrical energy, which is then used to power lights and display kinetic movement in the art installation. The main goal of this project is to provide a participatory, environmentally friendly, and sustainable solution in the form of an interactive artwork, while reducing dependence on conventional energy sources. Test results show that the greater the applied load, the higher the generated voltage. The lowest voltage recorded was 11.76 mV at a weight *of 50 kg, while the highest voltage reached 315.16 mV at a* weight *of 90 kg, with an average voltage of 168.46 mV for the load range of 50–90 kg. These findings demonstrate that piezoelectric technology has great potential as an energy harvesting system in public areas, as it can provide power for energy-efficient devices while enhancing the aesthetic quality and awareness of sustainable energy in urban spaces.*

Keywords: *pedestrian energy harvesting; piezoelectric sensors; sustainable art installations; renewable energy.*

1. INTRODUCTION

Urban areas face increasing sustainability and energy consumption challenges, especially in public spaces with high pedestrian traffic. Traditional energy systems, which rely heavily on non-renewable sources, contribute significantly to environmental degradation and rising energy costs. As urbanization accelerates, the need for more efficient and sustainable energy solutions has never been greater. Urban areas face significant sustainability and energy challenges due to an increasing population and reliance on non-renewable energy sources. Transitioning to low-carbon, resilient cities requires reducing energy consumption and shifting to cleaner energy sources, with city-integrated renewable energy being a promising strategy. Several challenges must be overcome to achieve this transition [1][2]. The research investigates the potential of piezoelectric, triboelectric, and hybrid systems to convert pedestrian foot traffic into electrical energy, addressing challenges such as efficiency, durability, scalability, and integration with existing infrastructure [3].

Footstep power generation is a renewable energy solution for high-traffic urban areas, potentially improving sustainability and energy efficiency in public spaces [4]–[6]. One underutilized source of renewable energy is the kinetic energy generated by pedestrians. Millions of people walk through parks, streets, and public spaces daily, exerting mechanical force with each step. This mechanical energy can be harnessed and converted into electrical power, reducing dependence on traditional energy sources and offering a clean and sustainable solution. Renewable energy systems enhance urban sustainability by improving energy efficiency, reducing greenhouse gas emissions, and promoting energy security [7].

Piezoelectric sensors offer a promising way to capture energy from mechanical stress or pressure, providing a renewable and sustainable energy source, but face challenges such as low power output and environmental sensitivity [8]–[12]. These sensors are ideal for use in high-foot-traffic areas, where energy generation can be maximized by embedding them in walkways or public installations. Previous research has demonstrated the effectiveness of footstep power generation using piezoelectric sensors. These systems have been shown to power low-energy devices, such as streetlights and public charging stations, and can be integrated into urban infrastructure to promote sustainability.

Although several previous studies, such as those by Kamboj et al. [13] and Ali et al. [14], have highlighted the potential of piezoelectric sensors for harvesting energy from human motion, most of these investigations have been limited to laboratory-scale setups or portable applications [15]–[17], such as wearable devices and small-scale floor prototypes. Research integrating piezoelectric energy harvesting within urban public spaces—where human interaction, city infrastructure, and interactive artistic systems coexist—remains relatively scarce. Moreover, there is still a lack of comprehensive evaluation regarding energy conversion efficiency, durability, and performance consistency under varying pedestrian traffic conditions.

This study aims to address these gaps by exploring the feasibility and effectiveness of piezoelectric-based energy harvesting systems in public environments, particularly to power interactive kinetic installations and public lighting, contributing to smarter and more sustainable urban spaces.

2. METHODS

This section details the methodology used to design and implement the pedestrian kinetic installation, focusing on the components, system design, and data acquisition process.

2.1. System Design and Components

The stages of system design and components in this research can be seen in Figure 1.

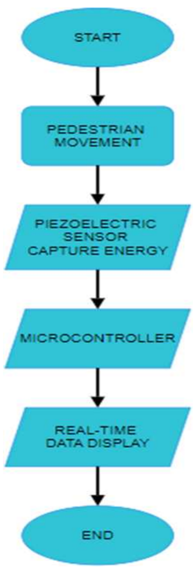

Figure 1. Flowcharts illustrating the process and design of system operations

Figure 1 illustrates the process and design of system operations. The system was designed to convert kinetic energy from pedestrian movement into usable electrical energy, leveraging piezoelectric sensors embedded in the sidewalk. The system comprises several key components, including piezoelectric sensors, load cells, microcontrollers, and IoT platforms for data acquisition and real-time monitoring.

The core components of the pedestrian kinetic installation include the piezoelectric sensors, load cells, microcontroller, and an IoT platform for data acquisition. Piezoelectric sensors are crucial in this system, as they convert mechanical energy from foot traffic into electrical energy [18] [19]. This project used 15 piezoelectric ceramics (50 mm in diameter) embedded beneath the pedestrian walkway. These sensors are selected for their ability to convert the pressure from footsteps into electrical signals efficiently.

Load cells measure the force exerted by pedestrians on the system. Four load cells are installed in the setup, with each cell connected to a strain gauge to detect even slight variations in the weight of pedestrians. The data from the load cells allows for a more accurate analysis of the energy generated by foot traffic, as it provides insight into the force applied at different steps.

The system's central processing unit is the microcontroller, specifically the ESP8266. It collects the data from piezoelectric sensors and the load cells, processes it, and transmits it wirelessly to a cloud-based platform for real-time monitoring and storage. The ESP8266's Wi-Fi capabilities make it an ideal choice for this project, ensuring that data can be transmitted seamlessly to an IoT platform.

The IoT platform used in this system is Thinger.io, which allows for real-time monitoring and visualization of the data generated by the system. Thinger.io supports data acquisition, providing an interface where users can view live data, including voltage output from the piezoelectric sensors and the force readings from the load cells.

2.2. Data Acquisition

Research data collection includes pedestrian input, piezoelectric sensor, microcontroller and IOT/Monitor output, as shown in Figure 2.

Figure 2. Block diagram for data acquisition

Figure 2 shows the data acquisition process begins with the piezoelectric sensors generating electrical voltage in response to the mechanical stress of pedestrians walking on the surface. The voltage output from these sensors is minimal, so it is first amplified using an HX711 amplifier to make the signals readable by the microcontroller. This process ensures that the microcontroller receives accurate data, crucial for assessing the system's efficiency.

Once the voltage signals are amplified, they are transmitted to the ESP8266 microcontroller. The microcontroller is programmed to read and record the data from the piezoelectric sensors and load cells. In addition to capturing voltage, the microcontroller also records the force applied to the load cells, which helps determine the energy generation efficiency at different pressure levels.

The data collected is then sent wirelessly to the Thinger.io platform via Wi-Fi. Thinger.io serves as a cloud-based data storage and analysis tool, where real-time data can be monitored through a dashboard. This platform also allows for long-term data logging, so trends in energy generation can be analyzed over time. Using Thinger.io, the system ensures continuous data collection and enables remote monitoring of the system's performance.

2.3. Experimental Procedure

The experimental procedure involves testing the piezoelectric sensors under varying pedestrian weights to measure the output voltage and the corresponding force readings. For each test, a set of known weights was applied to the system to simulate pedestrian foot traffic.

Five different weights were chosen for testing, ranging from 50 kg to 90 kg, based on expected pedestrian traffic in urban areas, shown in Table 1. Each weight was applied in a controlled manner, and the system was allowed to stabilise before measurements were taken. The corresponding voltage outputs from the piezoelectric sensors and the force measurements from the load cells were recorded.

Table 1. Experimental weights

Number	Weight (Kg)
1	50
2	60
3	70
4	80
5	90

The voltage readings for each weight were measured at 5-10 seconds to ensure accuracy. The data was then transmitted to the ESP8266 microcontroller, processed, and sent to the Thinger.io platform for real-time monitoring.

The experimental setup was repeated three times for each weight to ensure consistency and reliability of the results. The data was analysed to determine the correlation between the applied weight and the voltage output from the piezoelectric sensors, providing insights into the system’s efficiency in converting mechanical energy into electrical power.

2.4. Project Design

Figure 3 shows the design of this project focuses on creating a pedestrian-powered energy harvesting system using piezoelectric sensors. The primary objective is to capture the mechanical energy from pedestrian foot traffic and convert it into electrical energy, which can power small devices such as lighting or interactive displays in public spaces.

The system comprises several key components: piezoelectric sensors, load cells, a microcontroller, and an IoT platform for data acquisition and monitoring. The piezoelectric sensors are placed beneath the pedestrian walkway and are connected to load cells to measure the force exerted by pedestrians. These components work together to generate electrical energy and collect real-time data on energy production.

The piezoelectric sensors are selected for their efficiency in converting mechanical energy from foot traffic into electrical power. The load cells, connected to the sensors, measure the force pedestrians apply, allowing for more accurate data collection and analysis of the system's energy generation capabilities.

The microcontroller (ESP8266) plays a central role by processing the data from the piezoelectric sensors and load cells. It transmits the data wirelessly to the Thinger.io platform for real-time monitoring and visualisation. This platform allows users to track energy production and optimise the system's performance.

The system is designed to be modular and scalable, meaning additional sensors and load cells can be added to accommodate varying levels of pedestrian traffic. The design is also focused on durability, with the sensors and load cells being housed in protective casings to ensure long-term functionality in outdoor environments.

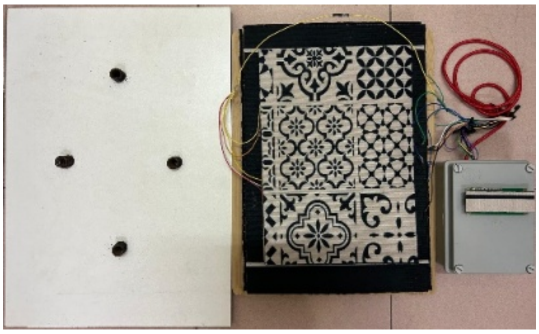

Figure 3. Project design

3. RESULTS AND DISCUSSION

The results of this project demonstrate the effectiveness of the pedestrian kinetic installation in generating electrical energy from foot traffic using piezoelectric sensors. The data collected from the system reveals the relationship between the applied force (from pedestrians) and the output voltage generated by the piezoelectric sensors.

The output voltage generated by the piezoelectric sensors was measured under varying weights, ranging from 50 kg to 90 kg. The results indicate a direct correlation between the applied weight and the generated voltage, with higher weights resulting in higher voltage outputs.

3.1. Weight

Table 2 shows the recorded voltage data for the 50 kg-90 kg weight variation, where the lowest voltage occurred at 2.19 mV at the 50 kg weight and the highest voltage value at 315.16 mV at the 90 kg weight. This indicates that the resulting voltage increases significantly as the load increases.

The output voltage for a 50 kg weight was initially low, with the voltage increasing progressively as the applied load was transferred to the piezoelectric sensors. This behavior indicates that the generated voltage is directly proportional to the mechanical stress applied to the piezoelectric material, as greater force produces a higher electrical response due to increased deformation of the crystal lattice. The test results demonstrated a consistent rise in output voltage as the applied weight increased, confirming the sensitivity and responsiveness of the piezoelectric elements under compressive loading. Table 2 presents the detailed measurement results for weights ranging from 50 kg to 90 kg, showing a clear correlation between applied force and voltage generation, which validates the system's effectiveness in energy harvesting applications for pedestrian-powered installations.

Table 2. Output voltages for 50 kg-90 kg

Date/Time	Weight (Kg)	Load cell (Kg)	Force (N)	Voltage (mV)
6/4/2025, 10:41:24 PM	50	50.99	500.25	2.19
6/4/2025, 10:45:44 PM		52.69	516.93	3.25
6/4/2025, 11:14:53 PM		55.42	543.67	29.84
6/4/2025, 11:16:43 PM	60	62.75	615.60	50.15
6/4/2025, 11:22:28 PM		66.71	654.42	144.62
6/4/2025, 11:27:25 PM	70	72.08	707.08	172.46
6/4/2025, 11:29:16 PM		77.21	757.41	182.03
6/4/2025, 11:53:25 PM	80	80.19	786.69	236.34
6/4/2025, 11:56:20 PM		80.37	788.42	245.15
6/4/2025, 11:08:49 PM	90	92.94	911.775	315.16

3.2. Load Cell (Kg) Versus Piezoelectric Voltage (V)

Figure 4 the graph below shows the correlation between the applied weight (measured in kilograms) and the voltage generated by the piezoelectric sensors. As the load increases, the voltage increases proportionally, demonstrating the system's sensitivity to mechanical pressure.

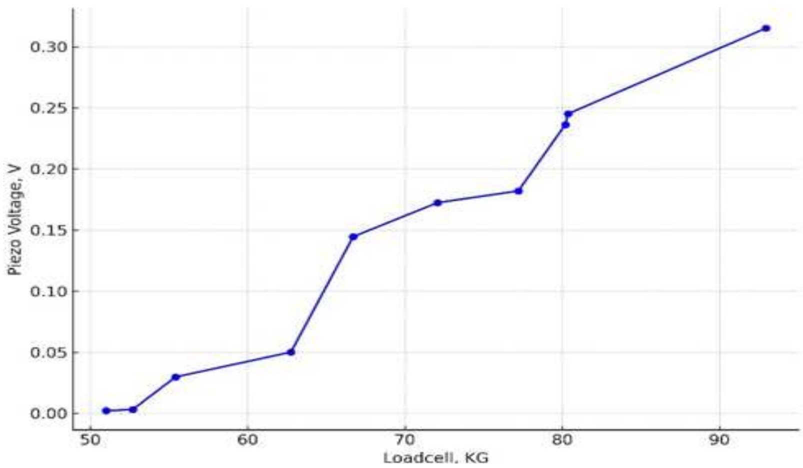

Figure 4. Load cell (Kg) vs voltage (V)

Figure 4 shows that as the load increases, the voltage produced increases. The average voltage from a 50-90 kg weight is 168.459 mV. The data from this graph illustrates that the system's energy generation efficiency increases with higher pedestrian traffic, which is crucial for large-scale implementation in public spaces [20].

3.3. Force (N) Versus Piezoelectric Voltage (V)

Figure 5 shows the relationship between the applied force (measured in Newtons) and the voltage output generated by the piezoelectric sensors. As the applied force increases, the voltage generated by the sensors rises significantly.

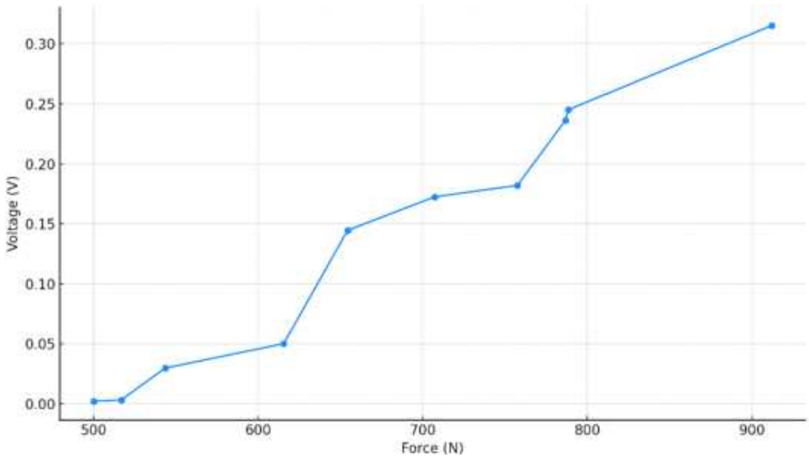

Figure 5. Force (N) vs voltage (V)

Figure 5 shows a graph of the relationship between force and the resulting voltage—generally, the greater the force, the greater the voltage produced. The lowest voltage was generated at a force of 500.25 N, at 11.76 mV. The highest voltage was generated at a force of 911.775 N, at 315.16 mV. This indicates that the piezoelectric sensors are highly responsive to varying levels of force, which can be critical for monitoring pedestrian traffic and optimising energy harvesting in urban environments [21].

3.4. Comparison with Previous Research

The results obtained in this study are consistent with previous research on footstep-based piezoelectric energy harvesting systems. Similar to the studies reported by Kamboj et al. [13] and Ali et al. [14], these findings confirm that the electrical output of the piezoelectric module increases proportionally with pedestrian load and traffic frequency. Both studies emphasize that greater applied force and higher footstep rates result in higher voltage output, validating the fundamental relationship between mechanical stress and electrical potential in piezoelectric materials. The experimental results in this study reaffirm this principle, demonstrating that pedestrian-induced mechanical energy can be effectively converted into electrical energy for low-power urban applications.

However, this study goes beyond previous research in several important respects. Previous studies have primarily focused on laboratory-scale evaluations or single-sensor analysis, which are often limited to controlled environments. In contrast, this study explores the potential for real-world integration of piezoelectric systems in pedestrian walkways, emphasizing system robustness, sensor arrangement, and power management under repeated dynamic loading. This practical approach enhances understanding of how such systems can be scaled up and implemented as functional energy harvesting installations in public spaces. Furthermore, consideration of urban environmental factors—such as varying pedestrian traffic densities, load distribution, and surface design—provides additional insights not thoroughly addressed in previous research.

The significance of this research lies in its interdisciplinary contribution, which bridges renewable energy harvesting technologies with sustainable urban design and public interactivity. Unlike conventional renewable systems such as solar or wind energy, piezoelectric-based installations harness human kinetic activity as an alternative energy source. This approach is particularly advantageous in densely populated metropolitan areas where space and aesthetics limit the implementation of conventional energy infrastructure. Therefore, the proposed system aligns with global efforts to develop sustainable smart cities and diversify environmental energy sources.

In terms of progress, this research presents an applied demonstration of a pedestrian kinetic installation that generates measurable electrical output while maintaining structural robustness. The proven correlation between applied mechanical force and voltage generation suggests the feasibility of large-scale implementation in areas with high pedestrian density [22], [23]. Furthermore, this study introduces a participatory perspective by integrating renewable energy generation with public engagement-transforming routine pedestrian movement into an environmentally friendly, interactive energy source.

In summary, while these findings corroborate the general conclusions of previous studies, the novelty of this study lies in its applied scope, system integration strategy, and contextual adaptation to a real-world urban environment. Therefore, this research provides a valuable step forward in realising sustainable and interactive urban infrastructure powered by human kinetic energy.

4. CONCLUSION

The results of this study demonstrate that a piezoelectric sensor-based pedestrian kinetic system effectively converts mechanical energy from human footsteps into electrical energy. Experimental testing demonstrated a direct correlation between the applied load and the output voltage: the lowest voltage recorded was 11.76 mV at a weight of 50 kg, while the highest voltage reached 315.16 mV at a weight of 90 kg, with an average output voltage of 168.46 mV in the 50–90 kg range. These findings confirm the feasibility of using piezoelectric transducers as an energy harvesting mechanism in urban environments, providing a sustainable and environmentally friendly power source for low-power applications.

For real-world implementation, the developed system could be embedded beneath pedestrian paths, public plazas, or transportation hubs where heavy pedestrian traffic ensures sustainable energy generation. The generated power could be harnessed to operate energy-efficient systems such as LED street lights, environmental monitoring sensors, or interactive public installations, thereby reducing reliance on conventional power sources. The integration of power management circuits and energy storage modules—such as supercapacitors or rechargeable batteries—will improve energy stability and enable consistent operation during periods of low pedestrian activity. This implementation strategy not only promotes sustainable urban infrastructure but also increases public engagement and awareness regarding renewable energy utilization through visible and participatory technology implementation.

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