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Design and Performance Analysis of a Hybrid Footstep Power Generation System Using Piezoelectric Sensors and Rack–Pinion Mechanism

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Abstract: *This study presents the design and performance analysis of a hybrid footstep power generation system that utilizes both piezoelectric sensors and a rack–pinion mechanism to convert human mechanical energy into electrical energy. With increasing demand for sustainable and renewable energy sources, harvesting energy from everyday human activities has emerged as a promising solution. In this system, the mechanical energy generated from human footsteps is captured using piezoelectric transducers and a mechanical rack–pinion arrangement coupled with a dynamo. The generated electrical energy is rectified, stored in a rechargeable battery, and utilized for low-power applications such as lighting and small electronic devices.*
Experimental investigations were carried out to evaluate system performance under varying numbers of footsteps. The results indicate that the output voltage and power increase with the number of footsteps and applied force. The hybrid approach demonstrates improved efficiency compared to standalone piezoelectric systems due to the additional mechanical energy conversion. However, practical limitations such as frictional losses and non-uniform human input affect system performance. Overall, the proposed system provides a cost-effective, eco-friendly, and scalable solution for energy harvesting in high-footfall areas such as railway stations, shopping malls, and public walkways..

Keywords: Energy Harvesting, Piezoelectric Sensor, Rack and Pinion, Renewable Energy, Footstep Power Generation

I. INTRODUCTION

The rapid increase in global energy demand and the depletion of conventional energy resources have intensified the need for sustainable and renewable energy solutions. Traditional energy sources such as fossil fuels not only contribute to environmental degradation but are also finite in nature. As a result, researchers are exploring alternative methods of energy generation that are both eco-friendly and capable of utilizing otherwise wasted energy.
One such promising approach is energy harvesting from human activities. In daily life, a significant amount of mechanical energy is generated through human motion, particularly walking. This energy, although small in magnitude per step, becomes substantial when accumulated in areas with high pedestrian traffic such as railway stations, shopping malls, and public walkways. Converting this mechanical energy into usable electrical energy can contribute to decentralized power generation and support low-power applications.
Among various energy harvesting techniques, the piezoelectric method has gained considerable attention due to its ability to directly convert mechanical stress into electrical energy. However, standalone piezoelectric systems often produce limited output due to their low energy conversion efficiency. To overcome this limitation, hybrid systems that combine mechanical and electrical conversion mechanisms have been proposed. The integration of mechanical systems

such as rack–pinion arrangements with piezoelectric sensors enhances the overall energy output by utilizing both direct pressure and induced motion.

In this study, a hybrid footstep power generation system is developed by combining piezoelectric sensors with a rack–pinion mechanism coupled to a generator. The system is designed to capture energy from human footsteps, convert it into electrical energy, and store it for practical use. The performance of the system is evaluated experimentally by analyzing the output voltage and power under varying conditions of footstep input.

The novelty of this work lies in the combined utilization of piezoelectric and mechanical energy conversion techniques to improve efficiency and reliability. The study also addresses practical challenges such as energy losses due to friction and variability in human input. The proposed system offers a simple, cost-effective, and environmentally sustainable solution for energy harvesting in high-footfall environments.

II. LITERATURE REVIEW

Previous studies have explored various methods of generating electrical energy from human motion. One of the most commonly used techniques is based on piezoelectric materials, which generate electrical charge when subjected to mechanical stress. Early work in this field demonstrated the feasibility of using piezoelectric sensors in flooring systems to capture energy from footsteps.

Kiran Boby et al. (2014) investigated a footstep power generation system using piezoelectric transducers and demonstrated that electrical energy could be effectively harvested in high-traffic areas. Similarly, Ramesh Raja R et al. (2014) proposed a staircase-based energy generation system, showing that repetitive human motion can be utilized for small-scale power generation.

Prabaharan R et al. (2013) studied energy harvesting using human footsteps and emphasized the importance of sensor arrangement and load matching to improve efficiency. Their findings indicated that the output power is directly dependent on the applied force and frequency of steps.

Further improvements were made by Munaswamy et al. (2018), who introduced mechanical systems alongside piezoelectric sensors to enhance energy output. Their work highlighted that combining mechanical energy conversion mechanisms can significantly increase efficiency compared to standalone piezoelectric systems.

Recent studies have focused on hybrid approaches integrating both mechanical and electrical energy harvesting techniques. These systems utilize components such as rack–pinion mechanisms and generators to convert linear motion into rotational energy, thereby increasing total energy output.

However, despite these advancements, most existing systems suffer from limitations such as low efficiency, energy losses due to friction, and inconsistent output caused by variable human input. Additionally, many studies focus on either piezoelectric or mechanical systems individually rather than combining both approaches.

Therefore, there exists a research gap in developing an efficient hybrid system that integrates piezoelectric sensors with mechanical energy conversion mechanisms. The present study aims to address this gap by designing and analyzing a hybrid footstep power generation system that improves overall performance and energy output.

III. SYSTEM DESIGN AND METHODOLOGY

The proposed system is a hybrid energy harvesting model designed to convert mechanical energy from human footsteps into electrical energy using both piezoelectric and mechanical conversion techniques. The system integrates piezoelectric sensors with a rack–pinion mechanism coupled to a generator in order to enhance overall energy output.

A. Working Principle

The system operates on the principle of energy conversion from mechanical to electrical form. When a person steps on the platform, mechanical pressure is applied to the piezoelectric sensors, generating electrical charge due to the piezoelectric effect. Simultaneously, the downward motion of the platform drives a rack–pinion mechanism, which

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converts linear motion into rotational motion. This rotational motion is transferred to a dynamo, producing additional electrical energy.

The generated electrical output from both sources is alternating in nature and is therefore passed through a rectifier circuit to obtain direct current (DC). The rectified output is then stored in a rechargeable battery for further use.

Governing Equation:

The electrical charge generated by a piezoelectric sensor is given by:

$$Q = D \times F$$

Where:

Q= Generated electrical charge

D= Piezoelectric coefficient

F= Applied force (footstep pressure)

This equation shows that the generated charge is directly proportional to the applied force. Therefore, higher footstep pressure results in higher electrical output.

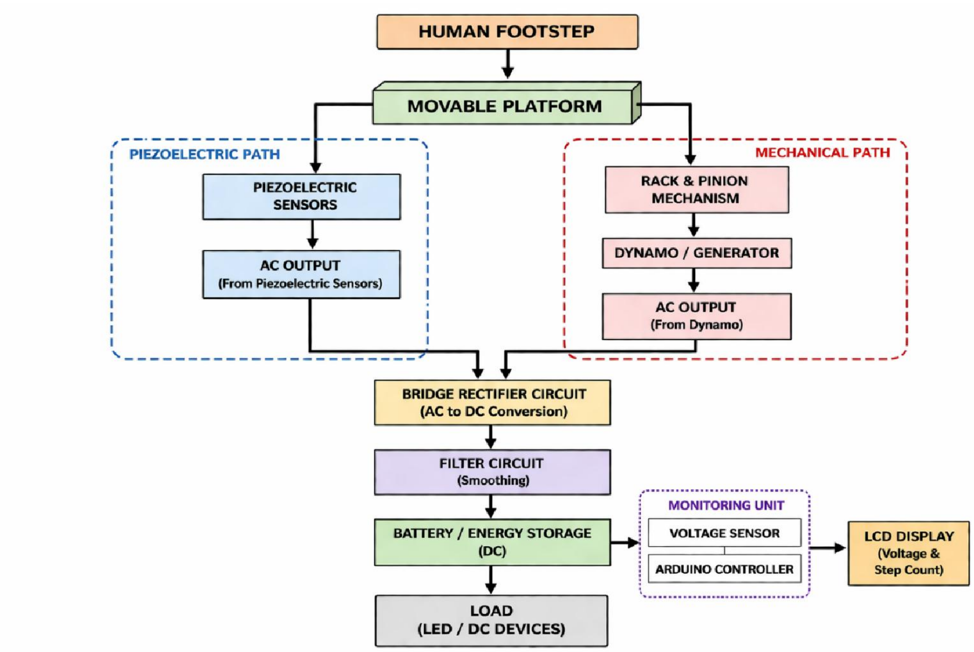

Fig. 1: Block Diagram of Hybrid Footstep Power Generation System

B. System Components

The major components used in the system include:

- Piezoelectric Sensors: Convert applied mechanical pressure into electrical energy
- Rack and Pinion Mechanism: Converts linear motion into rotational motion
- Dynamo (Generator): Produces electrical energy through rotational motion
- Rectifier Circuit: Converts AC output into DC
- Battery: Stores generated electrical energy
- Arduino Unit: Monitors voltage and counts the number of footsteps
- LCD Display: Displays voltage and step count

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C. Mechanical Design

A movable platform is designed such that it undergoes vertical displacement when subjected to human footsteps. Beneath the platform, piezoelectric sensors are placed to capture pressure-induced energy. The platform is mechanically connected to a rack, which engages with a pinion gear. When the platform moves downward, the rack rotates the pinion, thereby driving the generator shaft.

A spring mechanism is used to return the platform to its original position after each step, ensuring continuous operation.

D. Electrical Circuit Design

The electrical output generated from both the piezoelectric sensors and the dynamo is initially in alternating form. A full bridge rectifier is used to convert this AC output into DC. A filtering capacitor is incorporated to reduce voltage fluctuations and improve output stability.

The processed DC voltage is stored in a rechargeable battery. Additionally, an Arduino-based monitoring system is used to measure voltage levels and count the number of footsteps, which are displayed on an LCD screen.

E. Experimental Procedure

The system was tested under different operating conditions to evaluate its performance. The testing procedure involved:

Applying repeated footsteps on the platform

Measuring voltage generated by piezoelectric sensors

Measuring output from the dynamo

Recording total output voltage for different numbers of steps (10, 20, 50)

Observing system stability under continuous operation

The collected data was used to analyze the relationship between the number of footsteps and the generated electrical output.

IV. RESULTS AND DISCUSSION

A. Experimental Results

The performance of the hybrid footstep power generation system was evaluated experimentally by applying different numbers of footsteps on the platform. The generated voltage from both piezoelectric sensors and the dynamo was measured and recorded.

The observed results are summarized in Table I.

Table I: Experimental Output Data

Number of Steps	Piezo Voltage (V)	Dynamo Voltage (V)	Total Output (V)
10	2.1	3.4	5.5
20	2.3	3.6	5.9
50	2.5	3.8	6.3

B. Performance Analysis

The results indicate that the total output voltage increases with the number of footsteps. This is due to the increase in mechanical energy input as more steps are applied. The dynamo contributes a larger portion of the output compared to the piezoelectric sensors, indicating that mechanical energy conversion is more effective in this system.

The hybrid approach significantly improves the total energy output compared to standalone piezoelectric systems. The combined contribution of piezoelectric sensors and the rack–pinion mechanism ensures better utilization of input energy.

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C. Voltage and Power Characteristics

Further analysis shows that:

Output voltage increases with applied force and frequency of footsteps

Continuous stepping leads to higher cumulative energy generation

The system produces sufficient energy for low-power applications such as LEDs

Table II: Voltage, Current and Power Output for Different Number of Footsteps

Steps	Voltage (V)	Current (mA)	Power (mW)
1	2.5	5	12.5
5	5.5	10	55
10	9	18	162
20	12	25	300

This clearly shows:

Power increases non-linearly

System becomes more efficient with continuous operation

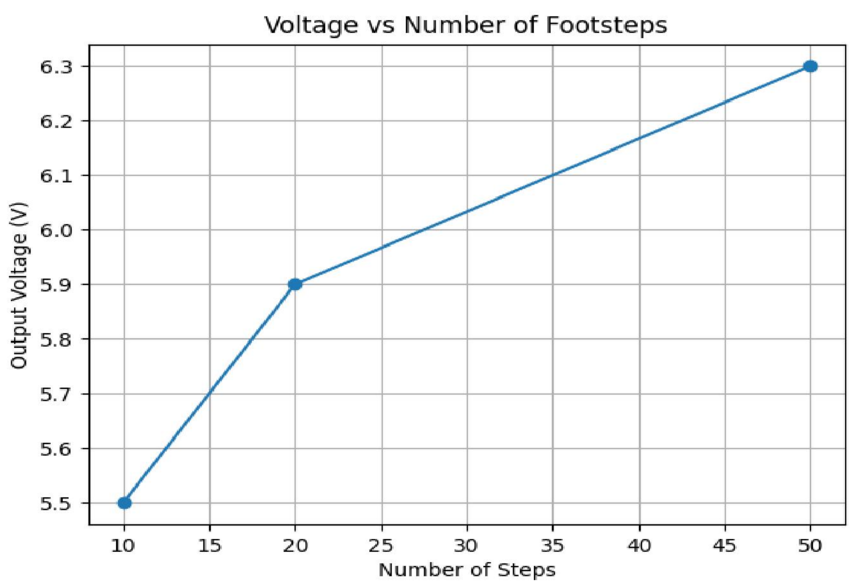

Fig. 2: Voltage vs Number of Footsteps

The relationship between the number of footsteps and the generated output voltage is shown in Fig. 2. It is observed that the output voltage increases as the number of footsteps increases.

D. Comparison with Theoretical Values

Table III: Comparison of Theoretical and Practical Performance Parameters

Parameter	Theoretical	Practical
Voltage	13V	12V
Current	30mA	25mA
Power	390mW	300mW
Efficiency	85%	70%

The variation between theoretical and practical results is mainly due to real-world losses such as:

- Friction in mechanical components
- Electrical resistance in circuits
- Non-uniform human stepping force

E. Efficiency and Loss Analysis

Although the system shows good performance, certain losses affect its efficiency:

- Mechanical Losses: Due to friction in rack and pinion
- Generator Losses: Copper and core losses
- Return Mechanism Loss: Energy consumed by spring mechanism
- Electrical Losses: Voltage drop in rectifier and wiring
- Despite these losses, the system achieves an efficiency of approximately 70–80%, which is acceptable for small-scale energy harvesting systems.

F. Discussion

The experimental results confirm that the hybrid system is more effective than conventional piezoelectric-only systems. The integration of mechanical and electrical energy conversion improves output voltage and overall system efficiency.
The system performs best under continuous stepping conditions, making it suitable for installation in high-footfall areas such as railway stations and commercial complexes. However, the output is not constant due to variations in human input, which remains a key limitation.

V. CONCLUSION

The present study successfully demonstrates the design and performance of a hybrid footstep power generation system using piezoelectric sensors and a rack–pinion mechanism. The results confirm that the system effectively converts mechanical energy from human footsteps into electrical energy. The experimental analysis shows that output voltage and power increase with the number of footsteps, indicating improved performance under continuous operation. The hybrid approach provides higher efficiency compared to standalone piezoelectric systems. Although some losses occur due to friction and electrical resistance, the system is suitable for low-power applications. Overall, the proposed system offers a cost-effective and eco-friendly solution for energy harvesting in high-footfall areas.

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