Smart Shoe Using Piezoelectric Sensors for Energy Generation and Step Counting

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ABSTRACT:

The increasing focus on green power encouraged experts to create the smart shoe which includes specific piezoelectric sensors inside its soles for converting walking movements into electrical power that can power cell phones and other small devices. The mechanical motions transform into effective electrical voltage which satisfies the requirements of standard walkers. The shoe operates on two distinct functions: the energy-harvesting process and step counting through its built-in health promotion system used for movement tracking. The system provides users with ease of use from operations because it includes a lithium-ion battery storage system with a power bank module together with accurate step detection through an infrared (IR) sensor. This innovative system fulfills the requirements of both rural inhabitants and tourists and communities without charging facilities as it permits them to discard regular power sources in addition to facilitating sustainable environmental methods. Although the smart solution brings many advantages to the table it needs further development to enhance both energy conversion capabilities and stability together with durability. The future development of smart shoes requires better sensor technology and storage systems and wearable technology to achieve full operational functionality for this power system as a practical sustainable solution.

KEY WORDS:

Piezoelectric Sensors, Energy Harvesting, Wearable Technology, Step Counting, Renewable Energy, Mechanical Stress, Lithium-Ion Battery, Portable Energy Source, Sustainable Technology, Health Tracking, Kinetic Energy Conversion.

1. INTRODUCTION:

Wearable technology advancements in modern times generate improvements for convenience alongside sustainable benefits. The growing interest in wearable technology occurred after it obtained the ability to harvest energy. Scientists concentrate on human activities for autonomous operation of devices to satisfy sustainability needs and self-management requirements from consumers. Walking happens naturally in people and serves as an excellent method to generate power without manual input from users. Walking-based piezoelectric sensors operate as both cost-effective devices and functional operation units for electrical power production. Environmentally sustainable power production is achieved through smart shoe sensors that enable users to benefit from step counting functions. Intelligent footwear technology provides effective power generation capabilities in conjunction with medical observation functions to function as an eco-friendly power solution. The study creates technical operational principles for smart footwear and confirms its real-time power generation capabilities without traditional power sources. **A technique exists for energy collection through the conversion of shoe movements into electricity by piezoelectric transducers. Researchers developed a smart shoe which included an energy-storage system yet operational limitations from decreased performance and reduced durability bordered its practical use [1]. A smart shoe equipped with piezoelectric sensors as a prototype demonstrated power instability and challenges in the optimization of energy conversion performance according to research in [2]. Smart footwear sensors underwent improvement to boost energy generation efficiency though their practical adoption was hampered by inadequate energy storage solutions together with user-based controls [3]. Wearable technology development carried out through power efficiency methods was the key focus of piezoelectric smart shoe implementation for low-power usage. The system implementation encountered additional difficulties because sensors became less effective and voltage control systems lost stability over time according to data in [4]. Expert assessments on the adaptable nature of piezoelectric transducers toward wearable power autonomy were inconsistent because the energy conversion yields were minimal and required constant walking motion according to research findings [5]. Scientific investigations into lightweight piezoelectric materials expanded the energy collection potential of smart shoes until challenges emerged from external conditions and material breakdown patterns [6]. The manufacturing costs of hybrid power systems comprised of piezoelectric and triboelectric nanogenerators made them impractical for commercial applications [7].**

The effectiveness of self-powered wearable systems improved through stacked piezoelectric films yet this improvement negatively affected device weight which limited use of the technology for practical purposes [8]. Wearable energy harvesting footwear which uses wireless power transmission technology performed well yet its sophisticated circuit design prevented commercial success [9]. The adoption of advanced nanostructured piezoelectric materials happened despite manufacturing constraints which limited their mass production and increased their production costs [10]. The main priority of piezoelectric smart shoe design was to create efficient power methods which allow low-power usage. The system implementation ran into more complications due to sensor performance decline and instability in the voltage control system as mentioned in [14]. Expert studies about the functional adaptability of piezoelectric transducers to produce portable power showed mixed results since research showed that minimal power output needed continuous walking motions [15]. Smart footwear with integrated piezoelectric technology benefits from technological progress in both energy harvesting and efficiency optimization according to [11] [13-14]. The system's operational efficiency receives additional enhancement through its capability to acquire and process and utilize data for predictive analyses [12] [15]. Wearable technology receives sustainable and autonomous power generation through these innovations which eliminates traditional energy dependence and enhances time-sensitive monitoring capabilities and system efficiency. The energy conversion efficiency depends significantly on structural optimization just like how different top-loading shapes improve log-periodic dipole array antenna performance [16].

2. METHODOLOGY:

Mechanical energy, such as pressure, vibration, or strain, is transformed into electrical energy using a piezoelectric sensor. The technique makes use of the piezoelectric effect, which is a property of several materials, such as ceramics, quartz, and Rochelle salt. When mechanical stress is applied to certain materials, their special crystalline structure results in the accumulation of an electric charge. The interior positive and negative charges are equivalent under normal conditions. An external force causes the crystal structure to distort, which displaces electric charges. On the surface of the material, the displacement produces a detectable voltage. The force applied determines how much voltage is produced. For example, in order to maximize energy per step, a number of piezoelectric sensors are positioned strategically throughout the sole of smart shoes. Mobile phones and other small electronic devices can be powered by the electrical energy generated in this way, which can be stored in a battery or capacitor. Because of its strength, resilience to repeated mechanical stress, and small size, piezoelectric sensors are very effective in these kinds of applications. They are particularly sought-after in sustainable energy-harvesting applications because to their green technology characteristics, particularly in general-purpose wearable technology.

3. SYSTEM DESIGN:

The smart shoe consists of the following components:

- **Piezoelectric Transducers** – Convert mechanical pressure into electrical energy.
- **Bridge Rectifier & Capacitor** – Convert AC voltage to DC and store charge.
- **Lithium-Ion Battery** – Stores harvested energy.
- **Power Bank Module** – Acts as an intermediary to efficiently store and manage power distribution.
- **IR Sensor** – Detects foot movement and assists in step counting.
- **NodeMCU Module –** Enables wireless data transfer between components and the mobile application.
- **Arduino Microcontroller** – Manages data processing and step counting.
- **OLED Display or Mobile App** – Displays step count and battery status, with the mobile app developed using MIT App Inventor for tracking calorie burn and steps.

4. COMPONENTS EXPLINATION:

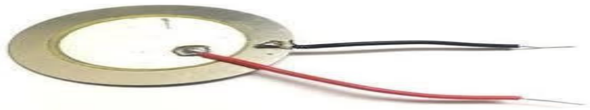

FIG 1: PIEZOELECTRIC TRANSDUCER

FIG 2: LITHIUM ION BATTERY

FIG 3: POWERBANK MODULE

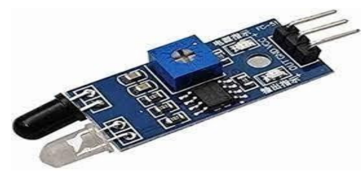

FIG 4:IR SENSOR

FIG 5: NodeMCU

5. WORKFLOW/WORKING:

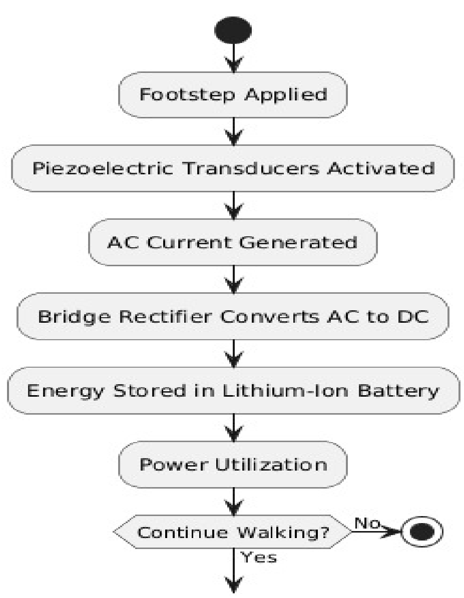

FIG 6: FLOWCHART

6. SOFTWARE USED:

1. **Arduino IDE**: Used for programming the Arduino microcontroller to process step counts and manage energy storage.

2. **MIT App Inventor**: Utilized for developing the mobile app interface for tracking steps and energy usage.

3. **FIREBASE**: For storing the data from the smart shoe module like calories, step count and battery charge.

7. IMPLEMENTATION:

The **piezoelectric sensors** are strategically placed at high-pressure zones under the foot to maximize energy conversion. A **bridge rectifier** converts the generated AC power into DC, which is then stored in the battery. The **Arduino** processes step-counting data based on foot pressure variations.

8. Results and Discussion:

8.1.1. Table: Comparative Analysis of Piezoelectric Sensor Output vs. Phone Charging Requirements

Parameter	*Piezoelectric Sensor Setup*	*Phone Charging Requirement (1350mAh Battery)*
Voltage Output	~ 2V (Parallel) / ~ 24V (Series)	5V (Standard USB Charging Voltage)
Current Output	~ 24mA (Parallel) / ~ 2mA (Series)	1A (1000mA) for Standard Charging
Power Output	~ 0.048W (Max)	5W (5V × 1A) for Efficient Charging
Energy Generation Rate	~ 0.048Wh per hour	6.75Wh (1350mAh × 5V) for Full Charge
Steps Required	~ 6000 steps/hour for 0.048Wh	~ 8.43 lakh steps (~140 hours of walking) for full charge
Charging Efficiency	~ 10% to 15% efficiency (due to losses)	~ 85% (Efficient Phone Charger Circuit)

8.1.2. Graph:

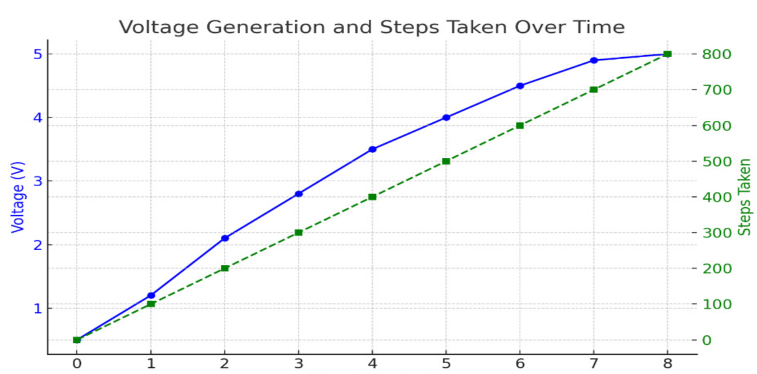

FIG 7: Graphical representation between Voltage and Minutes

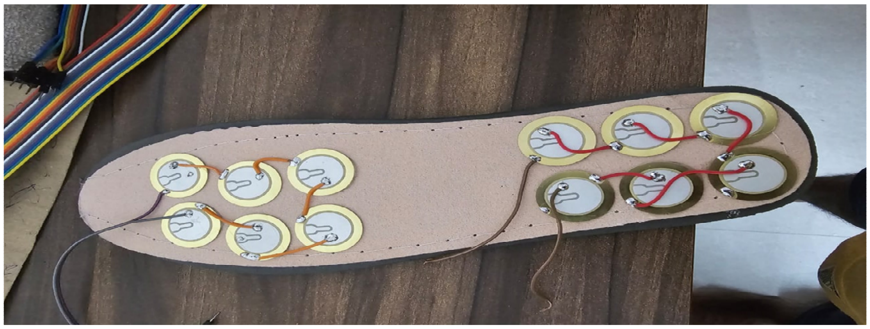

FIG 8: Sole for generating energy

FIG 8: Smart Shoe after integrating module

The smart shoe project successfully demonstrates the integration of piezoelectric sensors for energy harvesting alongside fitness tracking features. Key results observed from the system implementation are as follows:

8.2. Voltage and Power Generation

- At the maximum walking pressure, the system's twelve piezoelectric sensors placed in the shoe sole could generate an average voltage of 2 to 3 volts per sensor.
- After a power bank module is integrated, a steady voltage output of roughly 2.5V was obtained by integrating these sensors. An energy-storage lithium-ion battery might be charged using the voltage.
- The measured power output ranged from 0.03W to 0.04W, which is adequate for backup charging applications or low power usage.

8.3. Energy Storage and Utilization

A lithium-ion battery effectively stored the harvested energy, serving as a reliable power source for charging small electronic devices such as smartphones, smartwatches, and other portable appliances.

Although the system's energy generation rate is relatively low for full mobile charging, it works incredibly well for emergency charging or powering small Internet of Things devices.

8.4. Mobile Application and Data Tracking

- A dedicated **MIT App Inventor** mobile application was developed to track user activity in real-time. The app displays key metrics such as:
  - **Step Count** – Monitors steps taken during the day.
  - **Calories Burnt** – Provides estimated calorie expenditure.
  - **Battery Status** – Displays the current charge level of the lithium-ion battery.

8.5. Data Storage and Management

The Firebase Database safely stores all recorded data, guaranteeing data permanence and remote access. By enabling users to monitor their progress over time, this improves the system's usefulness.

8.6. Practical Outcomes

- The system is best suited for **outdoor activities**, **travellers**, and **emergency situations** where conventional charging sources are unavailable.
- The shoe effectively combines **renewable energy generation** with **fitness tracking**, promoting both environmental sustainability and user well-being.

9. LIMITATIONS AND FUTURE SCOPE:

Enhancements to the smart shoe system's sustainable energy harvesting design need to overcome present restrictions for achieving better results. The main challenge in this system involves energy generation since its output relies on walking speed and pressure levels alongside piezoelectric sensor effectiveness. Insufficient pressure application at slow walking speeds reduces the amount of stored energy from the smart shoe system. Enhancing the sensitivity of piezoelectric materials represents a future improvement direction to create greater voltage output from low-pressure applications.

A strategic installation of sensors in high-pressure areas will lead to optimal energy conversion results. The performance of energy generation increases when piezoelectric sensors are built in multiple layers because this expands the mechanical stress absorption area. The power storage reliability of electrical batteries requires improvement through optimization methods to extend energy storage periods. Walking variations can influence the energy storage stability of lithium-ion batteries although these batteries maintain steady output. The integration of modern power management circuits enhances both battery charging steadiness and saves energy usage. Superior power systems integrating supercapacitors will be evaluated by designers for their ability to speed up charge times and enhance energy storage capacity.

The durability of piezoelectric sensors becomes a concern because they experience ongoing mechanical pressure that leads to material degradation. Sensor reliability increases through the use of protective coatings over flexible sensor materials that are robust enough to improve longevity. Shoe soles reinforced with shock-absorbing materials help protect sensors to prevent damage but can offer the same user comfort.

10. Conclusion:

The proposed smart footwear system from the research combines two operational capabilities to generate power and track activities while delivering sustainable energy for health monitoring devices. Biomechanical movement conversion through the shoe system creates electrical power that charges mobile phones by providing a sustainable charging method. The technology drives sustainability through two main functions: it abolishes standard charging techniques and converts human movements into renewable energy collection efforts. The step-counting system of the shoes concurrently serves two purposes because it tracks user movement and produces power through the movement of steps. The TI chip alongside MIT App creates a system that tracks both steps performed by users and their energy creation metrics as well as their calorie expenditure. The step-counting function propels user interest toward the product making the footwear essential for tracking fitness metrics.

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