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ORIGINAL PAPER

Energy Harvesting Floor Tile Using Piezoelectric Patches for Low-Power Applications

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Abstract

Purpose One of the sustainable energy sources derived from kinetic energy is human footsteps. This research sought to find a substitute for conventional power sources to lessen dependence on them. As a result, a floor tile excited by human footsteps was demonstrated and presented to generate usable electrical power.

Methods Piezoelectric patches, hot melt glue sticks, wood plates, and foam plates are just a few of the commercially available materials used in the suggested technique, making it suitable and practical. In addition to the components, uncomplicated circuits like a voltage multiplier and rectifier with a capacitance filter were employed for the electrical power capture. The proposed prototype has a length of 455 mm and a width of 405 mm.

Results Two LEDs were effectively illuminated as an actual load using electrical energy collected from human footsteps. The maximum useful power that could be harvested successfully via the proposed floor tile (one tile) was 246 mW, with an approximate cost of $10.2.

Conclusions Designing an array of footsteps-based energy harvesting tiles covering broad areas to maximize the harvested power could be considered as a future work. Moreover, the number of pedestrians variable can be also studied for the proposed design of this study in a real excitation environment such as a railway station, subway station, street, discotheque, and wedding festival hall.

Keywords Energy harvesting · Floor tile · Piezoelectric patch · Schottky diode

Introduction

The use of wireless devices, sensors, and electrical systems has expanded rapidly. Most of them are driven by batteries that wear out relatively quickly and are difficult to replace or replenish. Batteries remain an essential component of many products. Even a little input from green energy resources can help alleviate the effects of climate change. Consequently, there has been a rise in interest in energy harvesting techniques and devices in recent years. It is important to integrate energy harvesting technologies with wireless networks. These technologies can support solutions like powering a vast array of wireless health monitoring devices or optimizing the energy consumption of various innovative city applications [1].

One renewable energy source that derives from the environment is kinetic energy. Kinetic energy is converted into electricity by devices that capture energy from pressure and vibration. The most prevalent techniques for kinetic energy harvesting are piezoelectric energy harvesters [2, 3],

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electromagnetic energy harvesters [4, 5], electrostatic energy harvesters [6, 7], and inertial energy harvesters [8, 9]. Microwatts or milliwatts of electrical power could be produced via pressure-based MEMS power generators. Considering the characteristics of the excitation source, pressure energy harvesters ought to be able to function at low frequencies. The ability to produce as much energy as is feasible is another requirement for energy harvesting devices.

Human movement may be one of the most effective nontraditional renewable energy sources. Since they include energy in both kinetic and potential modes, human footsteps can generate electrical energy [10]. It has been proposed to create power from human footsteps using an energy-harvesting floor that employs a rotating electromagnetic approach [11]. This system had two critical components: the power management electronic circuit and the electromagnetic generator. Another method was developed by [12] and is constructed from two square-sized tile construction pavers. Two fluid bags are connected by flow control devices such as unidirectional valves and mini-hydro generators, which convert mechanical energy from people into electricity through fluid movements.

Piezoelectric energy harvesters have gained attention due to their high energy density, ability to convert mechanical energy to electrical energy, and compatibility with a wide range of applications. Recent studies show that piezoelectric energy harvesting can be developed using MEMS technology. When mechanical stress is applied to a material, the direct piezoelectric effect causes electricity to be generated. Creating an electric current from wasted vibrations is the distinctive property of piezoelectric materials. Hence, an unlimited energy source might be provided by using the special piezoelectric material features [13, 14]. In this regard, many piezoelectric-based solutions were shown by [15–20] to produce power from human footsteps. A two-stage piezoelectric cantilever-based energy harvesting floor tile was introduced in [15]. The resonance frequency of the cantilever was 14.08 Hz. Moreover, as described in [16], a heel charger employs a multilayered levered piezoelectric system coupled with a nonlinear mechanically synchronized switching on the inductor interface. This design makes the most of the user's weight to maximize the deformation of multilayer piezoelectric patches while amplifying footstep displacement. A floor tile that harvests energy using unimorph PZT piezoelectric cantilevers was introduced in [17]. The frequency up-conversion achieved with the results has a resonance frequency of 10.54 Hz. The device was scaled up with the addition of 24 unimorph PZT cantilevers. Each cantilever was linked to a full-wave bridge rectifier, and eventually, all cantilevers were connected in parallel. In [18], a piezoelectric-based-tile was fabricated and utilized based on the PVDF polymer nano-fibers and PZT composites to construct the energy harvester. A rectifier circuit was attached to convert AC to DC and a charging circuit was used to charge a lithium battery. The energy harvested from the pedestrian footsteps could power an LED light fixture. In [19] a tile consists of an upper plate that had to be footstepped, a piezo-installed layer containing piezoelectric units attached to the upper plate. A bottom plate is supported and joined to the upper plate by four springs was presented. The piezoelectric energy harvesting tile used the PZT-PZNM ceramic with a stainless steel substrate. The incident frequency was in the range of 20 to 25 Hz. A theoretical analysis of the optimization of PZT-based tiles for energy harvesting was presented in [20], the tile prototype was designed and experimentally analyzed with different connections of sensors for maximum power harvesting. That study concluded that the tapping frequency, number of sensors, sensor fixation, sensor connection, and direction of applied force are significant factors for maximizing harvested power.

The main goal of this study is to utilize the direct piezoelectric effect of pressure from human movements to achieve the energy harvesting purpose using a simple and cheap design, as illustrated in Fig. 1, which shows the proposed footsteps energy harvesting system starting from the excitation pressure source, piezoelectric patches array, circuit to extract the usable DC power, and finally, the system's output could be connected to feed the load.

The proposed system can be used to power various IoT devices, including sensors, actuators, and communication modules. This system can enable the deployment of self-powered IoT systems, eliminating the need for battery replacements or wired power sources, thus reducing maintenance costs and environmental impact. The system can also provide power redundancy to critical IoT applications, ensuring continuous operation and reliability. Moreover, the proposed energy harvesting system can be integrated with energy storage devices, such as batteries or supercapacitors, to provide backup power during periods of low foot traffic. The integration of the energy harvesting system with IoT devices can lead to a more sustainable and efficient IoT ecosystem, enabling the development of smart cities. The system offers a friendly solution for

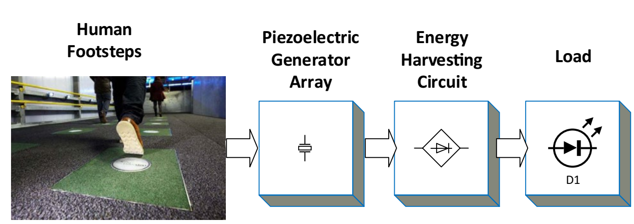

Fig. 1 Piezoelectric-based footsteps energy harvesting system

powering various IoT applications, such as street lighting, traffic signals, wireless sensor networks, micro-devices, and so on. Thus, this research could open new avenues for the development of sustainable IoT systems, leading to a greener and more connected future.

In this work, two light-emitting diodes (LEDs) were utilized as a load to simulate the power consumption of powering various smart city applications. The rest of this article is structured as follows: Section Methods and Experimental Validation presents the "Methodology and experimental configuration," Section Results and discussions introduces the "Results and discussions," and Section Conclusion covers the "Conclusion" of this study.

Methods and Experimental Validation

In fact, several variables have to be studied, such as the geometric distributions of piezoelectric patches' on the plate, inserting springs into the mechanical structure, the number of piezoelectric patches that can be utilised in the floor tile, the topology of the energy harvesting circuit, and testing the proposed design in a real environment. However, due to the time limits, studying the effect of such variables on the energy harvesting system's performance will be conducted in a future study. This study focused on introducing a simple and economical design able to generate power from the wasted pedestrians of people using the available materials in the market. The target is to use hundreds of floor tiles to build an energy harvesting system in a real environment, such as a railway station.

The experimental setup for the introduced energy harvesting system includes two sections: mechanical and electrical design.

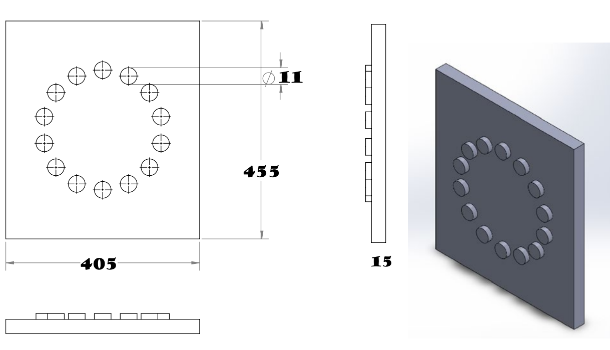

Fig. 2 Dimensions of wood plate No. 1 in mm (**a**) Different views and (**b**) 3D wood plate

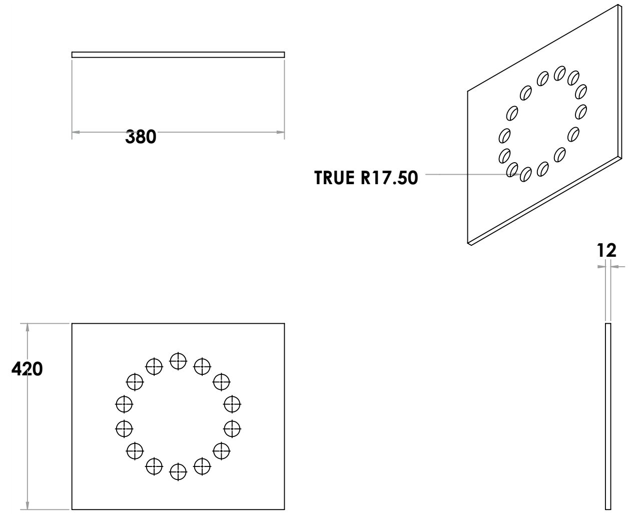

Fig. 3 Different views of foam plate No. 3 (Dimensions are in mm)

Mechanical System Design

The mechanical part consists of three plates arranged in the configuration of a sandwich. Plate No. 1 represents the front plate, with dimensions 455 mm × 405 mm × 15 mm, as shown in Fig. 2. Plate No. 2 represents the substrate plate, which has dimensions of 455 mm × 405 mm × 3 mm. Between plates 1 and 2 plate No. 3 is positioned with dimensions 420 mm × 380 mm, 12 mm, as shown in Fig. 3.

Plate No. 3 was placed on plate No. 2 because plate No. 2 acted as the design structure substrate. On plate No. 3, fourteen holes with depths of 12 mm and diameters of 35 mm were drilled. Inside each hole, a piezoelectric patch was fixed to a foam plate, the piezoelectric patches have the same size as the intended opening. The fourteen perforations were evenly spaced on a 300-mm disc.

Furthermore, fourteen hot melt glue sticks with 10 mm lengths were placed on plate No. 1 with equal spaces on a circle with a circumference of 300 mm, as depicted in Fig. 2. The hot melt glue sticks were employed to provide direct pressure to each piezoelectric patch in the cavity when any human footsteps applied on the floor tile. Hot

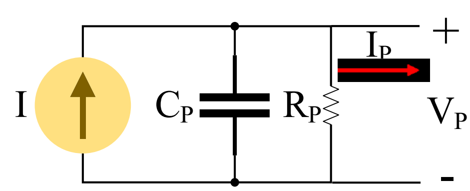

Fig. 4 Piezoelectric equivalent circuit

Fig. 5 Experimental setup of the proposed footsteps energy harvesting system (**a**) Wood plate No. 1, (**b**) Mounted piezoelectric elements on the foam and wood substrate plates, and (**c**) 3 plates

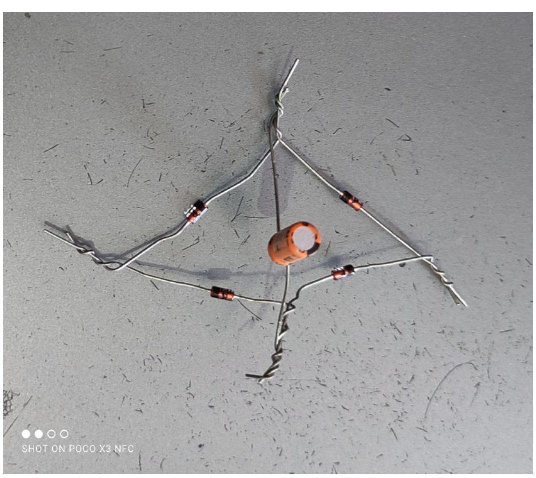

Fig. 6 Prototype of a bridge rectifier circuit + filter

melt glue sticks and foam materials were employed in the system designed to withstand high pressures because of their flexibility. Materials that have flexibility were adopted during the design process, such as hot-melt glue and foam, to avoid piezoelectric patches being damaged by hard materials. Moreover, the proposed design is just a prototype that was designed with available and cheap materials to prove the energy harvesting concept. Besides, studying the effect of using different materials on energy harvesting performance as a variable can be considered an individual study. Hence, to convert the prototype into a commercial design, we look for materials that have the best characteristics for optimal energy harvesting performance. On the other hand, the proposed design using such materials is made up of individual sections rather than a single block, which makes it simple to repair a broken portion during maintenance. The way of experimenting is summarised as follows: When pressure is applied to the floor tile by a pedestrian, the hot melt glue will create instant pressure on the mounted piezoelectric patches

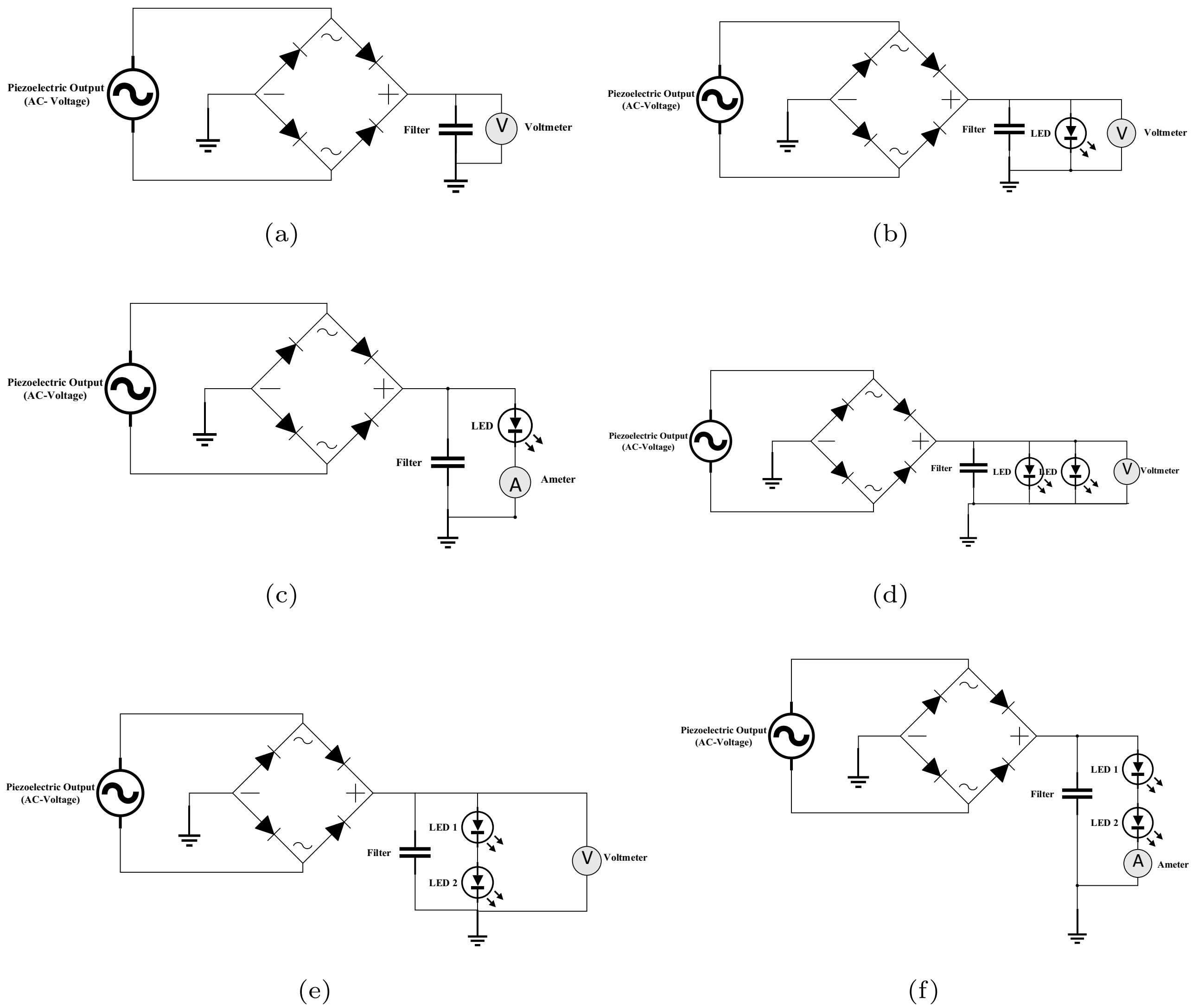

Fig. 7 Bridge rectifier circuit measurement conditions (**a**) Open loop voltage measurement, (**b**) Single load voltage measurement, (**c**) Single load current measurement, (**d**) Two parallel loads voltage measurement, (**e**) Two Series loads voltage measurement, and (**f**) Two Series loads current measurement

Table 1 1N60P Schottky diode specifications

Symbol	Parameter	Condition	Value		Unit
			Typ	Max	
VRRM	Repetitive peak reverse voltage		45	–	V
I_F	Forward continuous current	$T_A = 25°C$	50	–	mA
V_F	Forward voltage	I_F=1mA	0.24	0.5	V
I_R	Reverse current	V_R=15V	5	10	μA
C_J	Junction capacitance	V_R=10V F=1MHz	6	–	pF

on the plate. Repeating dynamic pressure on the tile will generate a continuous electrical output voltage. Otherwise, applying static pressure to the floor tile will generate an instant voltage, and then this voltage disappears.

Electrical System Design

This application requires a large number of piezoelectric patches to be inserted inside the floor tile; hence, the cost is a critical parameter that should be taken into account.

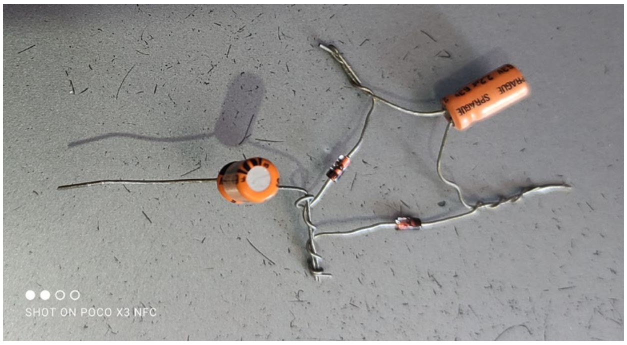

Fig. 8 Prototype of a voltage doubler circuit

Accordingly, circular piezoelectric patches available on the market with a low cost ranging from \$0.13 to \$0.20 per patch were utilised. Furthermore, these piezoelectric patches are suitable for energy-harvesting floor tiles since such patches receive direct pressure from pedestrians, which means low-sensitive piezoelectric patches fit with this application. Energy harvesting from vibrations and acoustic waves requires highly sensitive piezoelectric patches.

The equivalent circuit for a piezoelectric patch is illustrated in Fig. 4. The piezoelectric current (I_P), and voltage (V_P) are given by (1) and (2), where J indicates to the imaginary part due to the internal capacitance of the piezoelectric patch; R_P, C_P, and ω are piezoelectric resistance, piezoelectric capacitance, and angular frequency, respectively.

$$V_P = I \cdot \frac{\frac{1}{J\omega C_P} \cdot R_P}{\frac{1}{J\omega C_P} + R_P} = I \cdot \frac{R_P}{1 + J\omega C_P R_P} \tag{1}$$

$$I_P = I - V_P(J\omega C_P) - \frac{V_P}{R_P} \tag{2}$$

From Fig. 2, the equivalent current (I_{P14}), and voltage (V_{P14}) of the 14 piezoelectric patches connected in the parallel are given by (3) and (4).

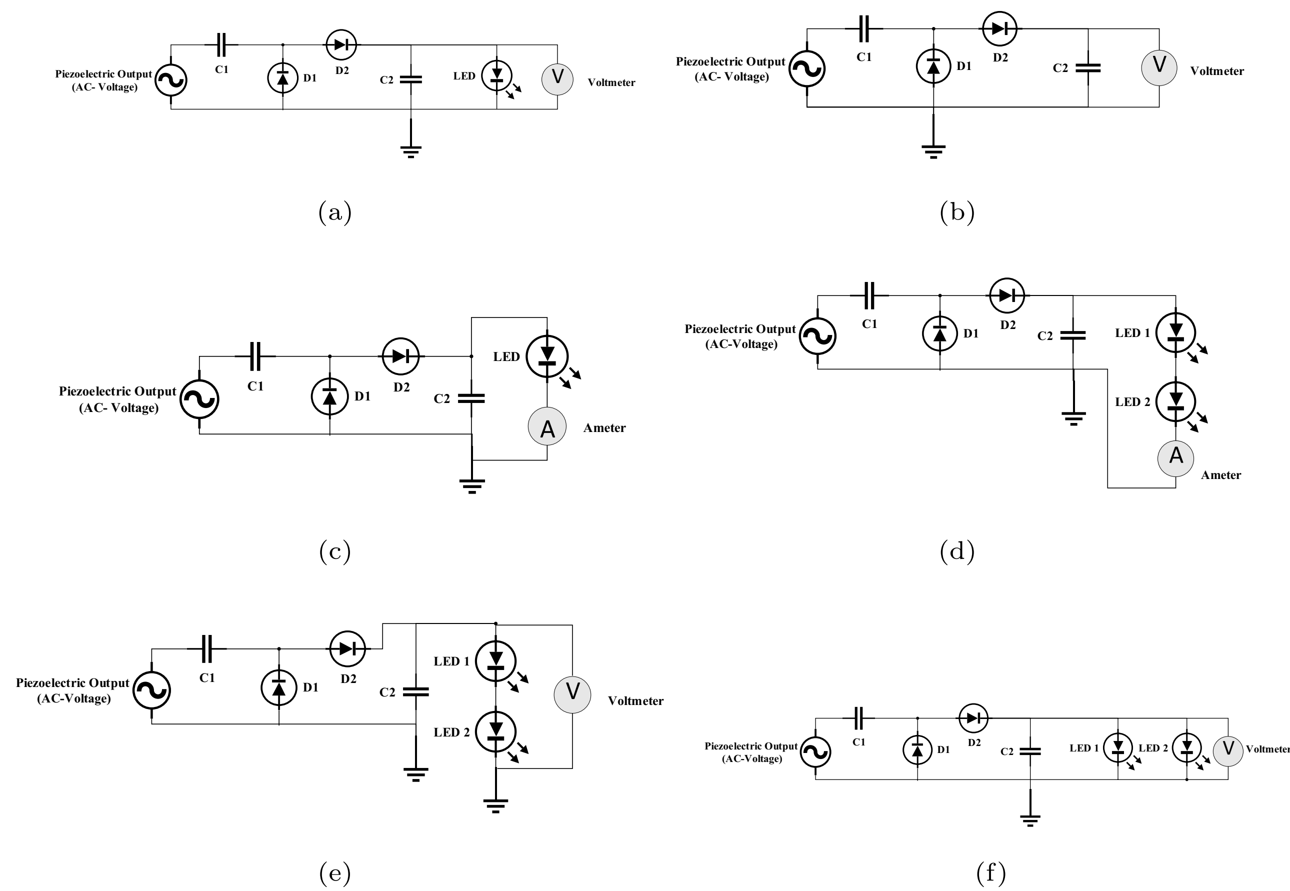

Fig. 9 Voltage doubler measurements (**a**) Open loop voltage, (**b**) Single load voltage, (**c**) Single load current, (**d**) 2 parallel loads voltage, (**e**) 2 Series loads voltage, and (**f**) 2 Series loads current

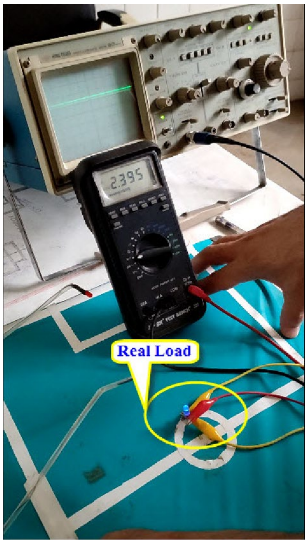

Fig. 10 Real load measurement (single load) connected to the voltage doubler circuit by Avometer and Oscilloscope

Table 2 Measured results of one footstep pressure on the tile via the two circuits

Circuit test condition		Quantity measured	Value	Unit
Bridge	Open loop condition	Output voltage	33.7	V
	1 LED as a load	Output voltage	2.4	V
	1 LED as a load	Output current	0.079	*A*
	2 series LEDs as a load	Output voltage	4.8	V
	2 parallel LEDs as a load	Output voltage	2.4	V
Doubler	Open loop condition	Output voltage	31.8	V
	1 LED as a load	Output voltage	2.4	V
	1 LED as a load	Output current	0.066	*A*
	2 series LEDs as a load	Output voltage	4.8	V
	2 parallel LEDs as a load	Output voltage	2.3	V

$$V_{P14} = 14I \cdot \frac{\frac{1}{J\omega(14C_P)} \cdot \frac{R_P}{14}}{\frac{1}{J\omega(14C_P)} + \frac{R_P}{14}} = I \cdot \frac{R_P}{1 + J\omega C_P R_P} = V_P \quad (3)$$

$$I_{P14} = 14I - V_P(14J\omega C_P) - \frac{14V_P}{R_P} \quad (4)$$

As illustrated in Fig. 5, the piezoelectric harvesters are distributed along the rectangular floor tile.

Two electrical circuits were adopted in experiments. The first was the bridge rectifier circuit, whereas the voltage multiplier was the second circuit. 1N60P Schottky diode was used to build the two circuits due to its low forward voltage of 0.24 V at low current conditions compared to silicon diodes. The most significant parameters of the 1N60P Schottky diode are presented in Table 1.

In the first rectifier circuit, four Schottky diodes of the 1N60P type are connected with a filter capacitor of 2.2 µF, as shown in Figs. 6 and 7.

The rectified output voltage (V_{out}) is given by (5). The average voltage (V_{avg}) and the average load current (I_{avg}) are given by (6) and (7).

$$V_{out} = V_P sin(\omega t); 0 \le \omega \le \pi \quad (5)$$

$$I_{avg} = \frac{2I_m}{\pi} \quad (6)$$

$$V_{avg} = \frac{1}{\pi} \int_0^{2\pi} V_P sin(\omega t) d(\omega t) \quad (7)$$

where t is the time. The instantaneous power(P(t)) and average power (P_{avg}) for the bridge rectifier circuit are given by (8), (9).

$$P_{out} = \frac{V(t)^2}{R_L} \langle \quad (8)$$

$$P_{avg} = \frac{1}{R_L} \cdot \frac{1}{T} \int_0^T P(t) dt \quad (9)$$

After inserting a filter capacitor (C_F) with the bridge rectifier, the expected DC output voltage (V_{dc}) across the load (R_L) and the harvested power (P_{dc}) are given by (10) and (11).

$$V_{dc} = \left[1 - \frac{1}{2fR_L C_F}\right]\left[\frac{V_m}{2} - 0.7\right] \quad (10)$$

$$P_{dc} = \frac{V_{dc}^2}{R_L} \quad (11)$$

where *f* is the frequency. The voltage multiplier circuit was built with two Schottky diodes (1N60P) and two 2.2 µF capacitors as shown in Figs. 8 and 9. During the negative half cycle, the voltage across the first capacitor (V_{C1}) is given by (12).

$$V_{C1} = V_P - V_{D1} \quad (12)$$

where V_{D1} is the voltage drop across D_1. After that, during the positive half cycle, we get equation (13):

Table 3 A comparison between the proposed work and the literature

Ref	Piezoelectric Dimensions	Tile Dimensions	Number of generators	Power extraction circuit	Load type	P_{out} & V_{out}	cost
[15]	71 mm ×25.4 mm × 0.76 mm cantilever	NR	1	NR	Resistive Load 50KΩ	119.2 Vp.p and 0.82 mW at 14.08 Hz	NR
[18]	50×35×0.2 cantilever	400 mm ×400 mm × 70 mm	4	Bridge rectifier + charging circuit	Resistive Load (15kΩ) and LED light fixture	4.5 mW and 6.8 V	NR
[19]	47×32×0.2 cantilever	150 mm ×150 mm	4	NR	Resistive Load (500kΩ)	36.63 mW and 33.18 V at 25 Hz	NR
[20]	40 mm circular diameter	300 mm ×300 mm cardboard sheet	36	Voltage multiplier	Battery	3.626 mW	NR
[21]	71 mm×25.4 mm× 0.76 mm cantilever	450 mm×450 mm× 58 mm	44	Bridge+Filter Capacitor	Resistive Load 1KΩ	35mW	NR
This work	35 mm circular diameter	455 m×405 m	14	Bridge+Filter Capacitor	2 series LEDs	189.6mW and 33.7V	$10.2
This work	35 mm circular diameter	455 m×405 m	14	Voltage Doubler	2 series LEDs	249.6mW and 31.8V	$10.2

NR: Not Reported

$$-V_{C2} - 2V_P + V_{D1} + V_{D2} = 0 \tag{13}$$

V_{D2} is the voltage drop across D_2. Since D_1 and D_2 used in the circuit are symmetric, the voltage drop across each diode is expressed as V_D; hence, the total output voltage is given by (14), as follows:

$$V_{out} = V_{C2} = 2V_P - 2V_D \tag{14}$$

Finally, the harvested power via the voltage doubler circuit can be obtained by (14).

$$P_{out} = \frac{V_{out}^2}{R_L} \tag{15}$$

Results and Discussion

The pedestrian of one person was adopted in this study. The obtained results are primary results, which can be enhanced in future work. The number of pedestrians can be considered in real environments such as railway stations, subways, streets, or wedding festival halls. The average adopted speed was that one person pressed the wooden plate at a rate of 85 times per minute.

The generated voltage and current were recorded under various circumstances for bridge rectifier and voltage multiplier circuits. Table 2 displays the most significant results. In the open-loop state, the bridge rectifier and voltage doubler circuits generate a high output voltage due to the high internal resistance of the Voltmeter measurement device, as shown in Table 2. The bridge rectifier caught the maximum voltage of 33.7 V. Furthermore, when the LED was used as a real load, whether with one LED (a single load) or two LEDs (two series loads or two parallel loads), the generated voltage that showed on the load's terminals was equivalent to the LED's operating voltage, whereas, in the case of connecting one LED, the recorded voltage was between 2.3 V and 2.4 V. For the two parallel LEDs, the voltage noticed was also between 2.3 V and 2.4 V, which agrees with the parallel connection roles regarding the voltage. Moreover, the voltage measured across the two series LEDs was 4.8 V, which agrees with the series connection role regarding the voltage. Generally, the voltage produced by the energy harvesting system was sufficient to power the single and two loads.

Based on the findings in Table 2, it is possible to infer that the results of the bridge rectifier and voltage doubler circuits are convergent. Figure 10 depicts the real load measurement (single load) connected to the voltage multiplier by a digital multimeter and oscilloscope. Both circuits could be utilized successfully in the implementation of human footsteps.

A comparison between the proposed work and the literature is presented in Table 3, showing the reported designs and the obtained findings of the proposed design in this study. Studies such as [15, 18–21] introduced the design in detail regarding the system design and performance; however, they neglected the actual cost of their reported designs, which is a critical point concerning institutions or foundations planning to adopt and apply this energy harvesting technique in the real environment.

The simplicity and low cost of the proposed design had no negative impact on the system performance, which offered a good and acceptable performance.

Compared to [20, 21], our design utilised fewer piezoelectric patch numbers with higher harvested power. [20] employed 36 patches and recorded a harvested power of 3.626 mW, whereas [21] used 44 patches and recorded a harvested power of 35 mW.

Referring to [18, 20, 21] as illustrated in Table 3, it can be noticed that the occupied floor area by such studies is similar to the floor area of this study; however, the harvested power of the proposed floor area is significantly higher. Finally, the adopted energy harvesting system costs around $10.2 for one tile.

Conclusions

An energy harvesting system that depends on human footsteps was designed using piezoelectric patches. Wood plates, foam plates, hot melt glue sticks, and piezoelectric patches were employed. A bridge rectifier circuit produced the highest output voltage of 33.7 V. Two LEDs were effectively lit by the proposed prototype, which has a length of 455 mm and a width of 405 mm. Designing an array of footsteps-based energy harvesting tiles covering broad areas to maximize the harvested power is soon future work. Moreover, the number of pedestrians variable can be also studied for the proposed design of this study in a real excitation environment such as a railway station, subway station, street, discotheque, and wedding festival hall to determine clearly the impact of the pedestrians' numbers on the floor tile energy harvesting performance.

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Data availability The data presented in this study are available in this article.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

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