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Design, simulation and experiment of a novel high efficiency energy harvesting paver

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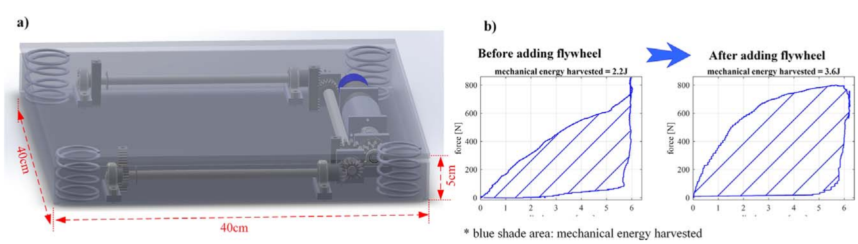
HIGHLIGHTS

- A novel energy harvesting paver is designed to harvest energy from human footstep.
- A dynamic model is built with consideration of Coulomb damping and viscous damping.
- The system parameters (flywheel and electrical load) are analyzed and optimized.
- 75% of all the theoretically available potential energy is harvested mechanically.
- The paver experimentally harvests 1.8 J electrical energy per step, peak power 12 W.

GRAPHICAL ABSTRACT



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ABSTRACT

Harvesting energy from pedestrians can be used to power sensors in smart infrastructure, monitor structural health, and provide environmental sensing data. This paper presents a novel paver that efficiently harvests energy from human walking. Within the paver, a permanent magnetic motor is used as an electric generator. Racks, pinions, gears and a one-way-clutch are employed to convert the up-and-down motion of the paver's top panel to the unidirectional rotational motion of the electric generator. A flywheel is attached to the electric generator to take full advantage of the theoretically available potential energy during human walking. A dynamic model is developed with the consideration of Coulomb friction, electrical damping and mechanical damping. Based on the model, parameters of the energy harvesting paver are analyzed to optimize the harvested energy from human walking. The experimental results show that, during typical human walking, the energy harvesting paver can produce an average electrical power of 3.6 W, with a peak value of 12 W. The average harvested energy is 1.8 J per step. The roles of the flywheel and electrical load in changing the amount of harvested energy are discussed. The flywheel's influence to energy harvesting in walking, fast walking and running conditions are compared and discussed. The energy harvesting paver has potential applications in high-volume pedestrian paths and areas such as sport arenas, airports, railway stations, shopping malls, offices and apartment blocks.

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1. Introduction

Developments and deployment of smart infrastructure and the global expansion of digital interconnectivity have been increasingly shaping our day-to-day activities. This is particularly evidenced by the Internet of Things where connectivity has extended to everyday objects, enabling them to send and receive data. Ubiquitous sensing is key to the Internet of Things [1]. However, powering the sensors can be a problem, especially in far and remote places. Running long wires or replacing batteries to power sensors can be costly, inconvenient or even impractical. Harvesting energy from the ambient environment could be a key source for providing off-grid power supply for sensors used in smart infrastructure, structural health monitoring, and environment sensing [2–4]. As sensors and communication systems require less and less power, energy harvesting becomes more promising. Both piezoelectric [5–8] and electromagnetic [9–13] transducers have been used at small-scale, mid-scale and large-scale energy harvesting.

Energy harvesting from the human body and human motion has many applications, including powering portable and wearable devices [14]. Rome et al. [15] designed an energy harvesting backpack by using an electromagnetic generator to harvest kinetic energy from human walking. They experimentally obtained a maximum output power of 5.6 W. Donelan et al. [16] designed an electromagnetic energy harvester based on the motions of knees and legs. Their experiments demonstrated that an average power of 5 W can be harvested from these motions, while causing little extra human effort. Researchers have long been focusing on harvesting energy from the interaction between the human foot and the ground. MIT Media Lab's energy harvesting shoes proved capability of harvesting average 1.3 mW from PVDF stave, 8.4mW from PZT unimorph and 250 mW from electromagnetic generators [17,18]. Fu et al. designed energy harvesting shoes based on footstep-induced airflow and harvested 6 mW from pedestrians [19]. Wu et al. came up with an electromagnetic wearable 3-DoF resonance human motion energy harvester and harvested 2.3 mW [20]. Hsu et al. devised a novel ultra-high power density energy harvesting method based on reverse electro-wetting [21]. They fabricated small lightweight energy harvesting devices capable of producing a wide range of power for application of energy harvesting shoes.

Energy harvesting pavers have received attention because of multiple potential applications that include powering infrastructure sensors, ambient lighting fixtures and nearby communication systems [22]. Zhao et al. [23] designed a cymbal-based piezoelectric energy harvester embedment in asphalt pavement to harvest energy from automobiles. Their numerical simulation results showed a potential maximum power output of 1.2 mW from passing vehicles. Xiong and Wang [24] installed a piezoelectric energy harvester on a public roadway and demonstrated the ability to harvest an average output power of 2–3 mW and a peak power of 100 mW from passing trucks. Sharpes et al. [25] presented the concept of a piezoelectric tile energy harvester that is placed below the floor surface. They showed that the output energy from footsteps could be used for building automation or control in smart buildings. Yao et al. [26] used triboelectric material to design a triboelectric nano-generator. They were able to harvest 0.5 mW of power from human steps. Although these different approaches used to harvest energy from pavers are interesting and meaningful, they do not take full advantage of the potential energy. For this reason, the amount of energy harvested is still in the mW level.

Another approach to harvest energy from footsteps is the electromagnetic-based energy harvesting paver. Pavegen has commercialized electromagnetic-based energy harvesting pavers that convert the floor's up-and-down motion to rotational motion of an attached generator to produce electricity [27]. Taliyan et al. [28] designed a footstep energy-harvesting device that uses a DC generator. Their experimental results show that 3–5 J of electrical energy can be generated from each step. However, the paver top panel displacement is 3 cm, which is not only uncomfortable for pedestrians, but also would not conform to the Americans with Disabilities Act (ADA) [34,35]. This act limits the amount of the vertical height difference between pavement joints. Bhatia et al. [29] designed an energy harvesting paver using rack and pinions. They were able to harvest 0.36 W average power. The displacement of the device's top panel varied between 13 and 38 mm, which incurs the same comfort and regulatory code issues as the Taliyan paver [28]. Furthermore, their overall efficiency, which is less than 20%, is still low. Another company, Waydip came up with an energy harvesting paver called "*Waynergy*" that can harvest 0.3–0.6 J of energy per step. Considering the energy potential, their overall efficiency is 13.6% [30].

In summary, the overall efficiency of existing research on energy harvesting pavers is less than 20%. The energy output is far below the available potential energy during human walking. This paper presents a novel design of energy harvesting paver that efficiently harvests energy from human walking and makes them more useful in real-world applications. A DC generator is used to convert kinetic energy into electricity. A one-way-clutch is placed between the gears and the shaft to extend the energy harvesting period. Based on the action of this clutch, energy harvesting continues even after the top panel reaches its displacement limit. The period of energy harvesting is further enhanced by using a flywheel that is attached to the electric generator rotor. A complete dynamic model is developed with the consideration of the Coulomb damping, electrical damping and mechanical damping. Based on this model, system parameters are analyzed to optimize energy harvesting performance. The roles of the flywheel and the load resistance are analyzed and discussed. Experiments are carried out to verify the dynamic model. The experimental results match well with numerical simulations. The experimental results show that the energy harvesting paver can produce an average power output of 3.6 W over 0.5 s of step time, with a peak power of 12 W. The output electrical energy is 1.8 J per step. It is shown that 75% of the theoretically available potential energy during human walking is transmitted to the energy harvesting paver. This exceeds values in the published research work by significant margin. The flywheel's influence to energy harvesting in walking, fast walking and running conditions are compared and discussed.

The rest of this paper is organized as follows: Section 2 describes the working principle, design, and fabrication of the proposed energy harvesting paver. In Section 3, the dynamic model of the energy harvesting paver is developed and analyzed. The electric load and flywheel are optimized to harvest more energy with high efficiency. The tests and results of the proposed energy harvesting paver are presented in Section 4. Conclusions are provided in Section 5.

2. Concept, design and fabrication

2.1. Working principle

According to literature [31,32], human walking induces a 500–1000 N dynamic force on the ground. In this section, the conceptualization and design of the proposed paver to harvest human motion energy efficiently are discussed. The idea is that when a pedestrian steps on the paver, it gently shifts 6 mm downwards and harvests the work done by this motion. Compared with the pedestrian's height and stride length, a displacement of 6 mm is small. This motion likely has a negligible effect on the human effort of walking. Although seemingly slight, this displacement can be used to generate electrical energy. Importantly, the 6-mm displacement also falls within the range recommended by the Americans with Disabilities Act [34,35].

The working principle of the proposed energy harvesting paver is shown in Fig. 1. The pinion gear rotates counter-clockwise when the step force acts on the rack. The shaft rotates with the pinion gears. The one-way-clutch is engaged and the gears between the shaft and the generator rotate and drive the generator to rotate clockwise. As shown in Fig. 1(b), when the displacement of the rack reaches its limit or the