Self-powered and Self-sensing Floor Tiles and Fall Detection System

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***Abstract*—An increasing number of emerging Internet of Things (IoT) devices are transforming our daily lives in various fields, such as transportation, manufacturing, and home automation. The smart sensing floor offers solutions for tracking and analyzing user movements while maintaining acceptable privacy levels in both public and private spaces. Considering the large number of networked IoT devices on the ground, addressing power supply issues is crucial for efficient installation and convenient maintenance. This paper presents a self-powered and self-sensing smart floor design, with a particular application emphasis on fall detection. The design integrates energy harvesting and information collection, eliminating the reliance on traditional sensors. Each wireless floor tile serves as an integrated self-powered Bluetooth transmitter. It utilizes multiple piezoelectric patches for energy harvesting, a customized energy management circuit to accumulate the generated energy, and a low-power, low-cost system on chip (SoC) for wireless transmission. The signal packets from all tiles are collected and processed through an edge gateway to detect abnormal actions, like falls. A co-design of the piezoelectric array, power management, and transmission circuitry ensures that each step or fall can generate sufficient energy for three rounds of Bluetooth low-energy (BLE) beacon transmission. By receiving immediate data packets from all tiles and conducting specific analyses, the system can effectively identify accidental falls and send timely notifications. A prototype floor composed of 28 tiles and a gateway receiver has been developed. Experiments to test the performance of individual tiles and field tests with the multi-tile floor demonstrate that the system can detect falls reliably.**

***Index Terms*—Battery-free IoT, energy harvesting, fall detection, piezoelectric transducer.**

I. INTRODUCTION

Over the past few decades, the Internet of Things (IoT) has rapidly advanced, serving as a critical bridge between the physical and digital worlds and enhancing the convenience of everyday life. By 2025, the global number of wireless IoT devices is projected to reach 30.9 billion. As IoT devices permeate various sectors, ensuring their stable operation becomes increasingly essential. Currently, chemical batteries are the most common energy source for IoT devices. However, the labor-intensive tasks of charging and replacing these batteries impose significant demands on human resources, while the environmental impact of battery waste presents additional challenges. As a result, power supply limitations significantly hinder the further expansion of IoT applications. The emergence of energy harvesting technology [1], [2] offers a promising solution for powering low-energy IoT devices. This technology harnesses energy from the surrounding environment, enabling devices to achieve energy self-sufficiency. By reducing dependence on batteries, energy harvesting significantly lowers both the maintenance and operational costs associated with IoT systems. Extensive research has focused on harnessing various energy sources, such as solar energy, radio frequency energy [3], wind energy, and magnetic energy. In most studies, the harvested energy is converted into usable power for IoT devices. However, much of the existing research overlooks the implicit information that coincides with the harvested energy and simply treats it as a power source.

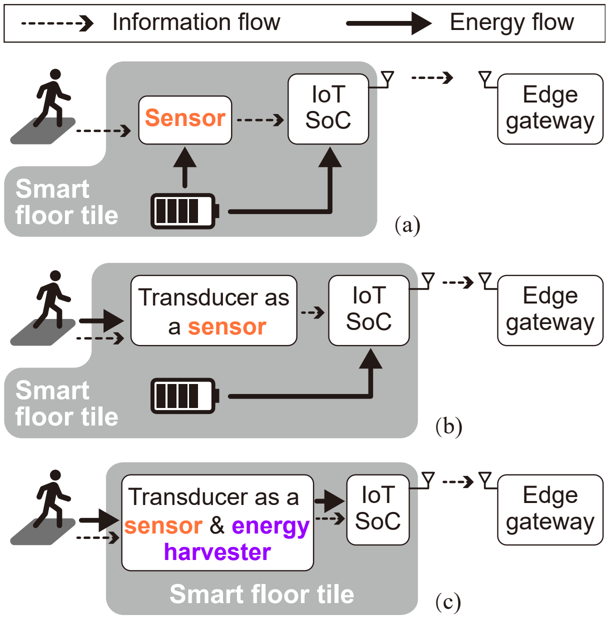


Fig. 1. Configurational comparison of smart floor systems. (a) Conventional embedded system. (b) A system using self-powered sensors. (c) A system using a self-powered and self-sensing scheme.

This study introduces a compact design of self-powered and self-sensing smart floor tile based on piezoelectric energy harvesting. The pavement, which is composed of multiple floor tiles, is designed to detect accidental falls [4] and identify the locations of the falling user. Unlike conventional smart floor tiles [5], [6], [7], which rely on commercial sensors such as accelerometers, force sensors, or optical fibers for fall detection [8], the proposed floor system identifies user

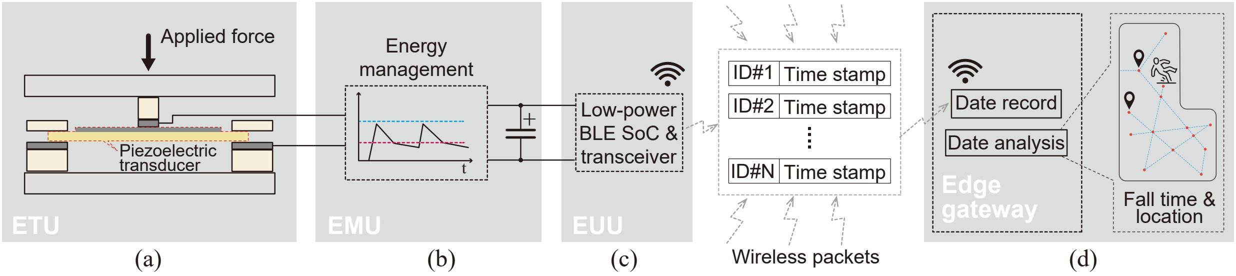


Fig. 2. System overview. (a) Energy transduction unit (ETU). (b) Energy management unit (EMU). (c) Energy user unit (EUU). (d) Edge gateway and computing unit.

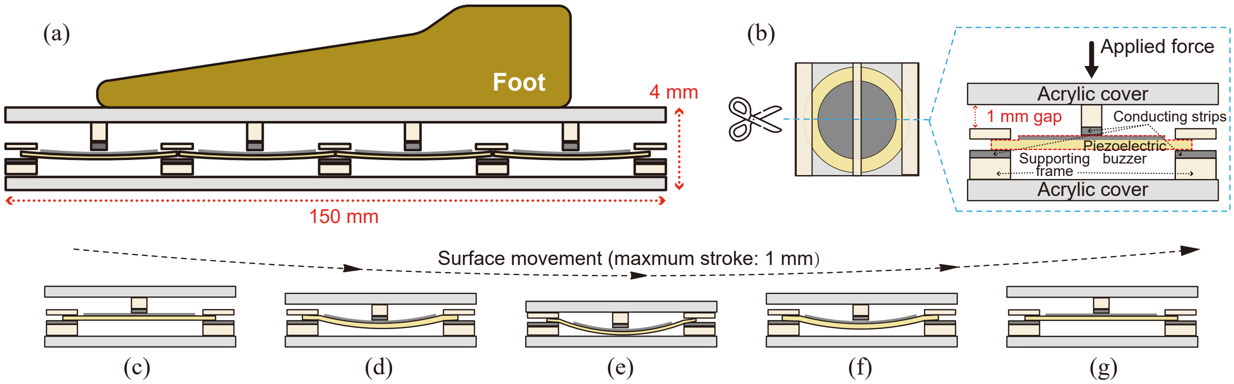


Fig. 3. Configuration and principle of the piezoelectric self-powered floor tile. (a) Structure side view. (b) ETU configuration. (c)–(g) Deformation states.

activities according to the action-related wireless data packets. It enables the collection of action information during the energy harvesting process; therefore, eliminating the need for additional commercial sensors. Fig. 1 illustrates the different configurations among existing conventional embedded smart floors, systems using self-powered sensors, and the proposed self-powered and self-sensing floor system. In conventional fall detection systems, accelerometers or force sensors typically operate at high sampling rates, resulting in significant energy consumption. Maintaining a long-lasting and continuous operation of such sensing methods is challenging for battery-powered IoT systems. In contrast, in the proposed design, the information associated with users' step or fall actions is directly sent out by using the energy harvested during the same action process [9]. Compared with traditional methods, this research greatly reduces module size, cost, energy consumption, and complexity through the ingenious relationship between energy harvesting and information collection.

II. SYSTEM OVERVIEW

The block diagram of the proposed fall detection system is shown in Fig. 2. Fig. 2(a) is an energy transduction unit (ETU), which harvests and converts mechanical energy associated with footsteps into electrical form. The converted electrical energy is conditioned by an energy management unit (EMU) and stored in the buffer capacitor, as shown in Fig. 2(b). When the accumulated energy in the buffer capacitor is sufficient for a specific sensing, computing, transmission function, or any combined task, the EMU, with its customized energy buffer and release circuit, will release the stored energy properly and efficiently to power the IoT tasks. A low-power Bluetooth low-energy (BLE) system on chip (SoC) carries out the control and data transmission tasks. It is regarded as the energy user unit (EUU), as shown in Fig. 2(c). An edge gateway collects the BLE packets from all floor tiles marked with different IDs and carries out higher-level computing tasks, such as the fall detection algorithm, as shown in Fig. 2(d). By processing the broadcasting IDs and their corresponding time stamps, the instant and location of an unexpected fall can be immediately obtained and sent to the cloud. Owing to the specific co-design considering sufficient energy and necessary information, this system, compared with conventional smart floor systems, involves no complicated sampling and pattern recognition procedures.

III. KEY DESIGN

A. Energy Transduction Unit (ETU)

Extensive research has been conducted on piezoelectric materials in the field of energy harvesting [10]. Piezoelectric materials exhibit a positive piezoelectric effect, generating a voltage when subjected to an external force. In this design, multiple piezoelectric buzzers are employed as electromechanical transducers, converting the user's mechanical energy into electrical energy. The configuration and principle of the piezoelectric energy harvesting floor tile module are shown in Fig. 3. As shown in Fig. 3(b), each ETU consists of four major components: acrylic covers, a relatively soft supporting

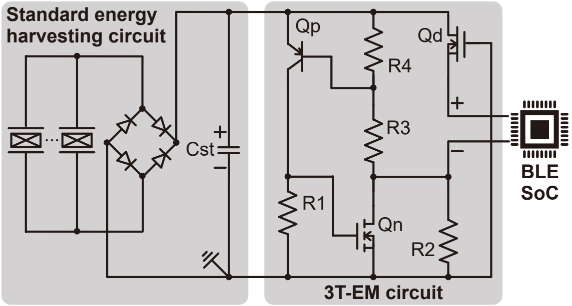


Fig. 4. EMU using standard bridge rectifier energy harvesting circuit and 3T-EM energy management circuit [11].

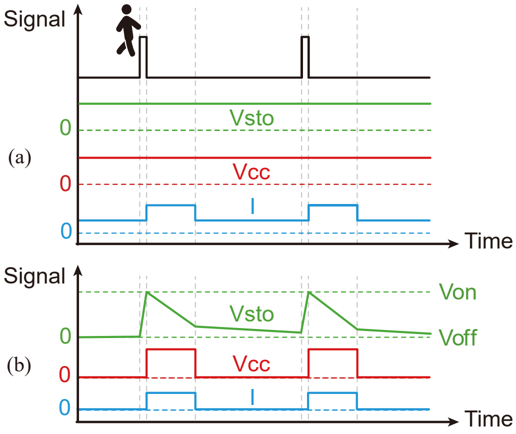


Fig. 5. Operating waveforms of different end devices. (a) Battery-powered one. (b) Self-powered one in intermittent operation.

framework, some conducting strips, and a piezoelectric buzzer. Fig. 3(c)–(g) illustrates a cycle of bending movement of the piezoelectric buzzer when the top cover is pressed down by a vertical force. Therefore, the piezoelectric element works in the 3-1 mode. All top electrodes of the piezoelectric buzzers are connected to a conducting strip, while the bottom ones are connected to another conducting strip. The bending movement of the piezoelectric buzzers induces a voltage difference between the upper and lower electrodes due to the positive piezoelectric effect. To prevent excessive deformation under large force conditions, a stop mechanism is designed. As shown in Fig. 3(e), the top cover will hit the supporting structure at a maximum stroke of 1 mm. Such a design can protect the buzzer structure to operate within a safe and reliable range of elastic deformation. When the user steps off the tile, the buzzer begins to return to its initial state, as depicted in Fig. 3(g). The stepping-off motion generates a negative voltage pulse across the piezoelectric electrodes.

B. Sensing Principle

Conventional smart floor systems rely on high-rate sampling and pattern recognition for picking up useful information. In this design, we take advantage of an energy harvester as a sensor to generate and transmit the coinciding information about the motion source. The integration of energy harvesting

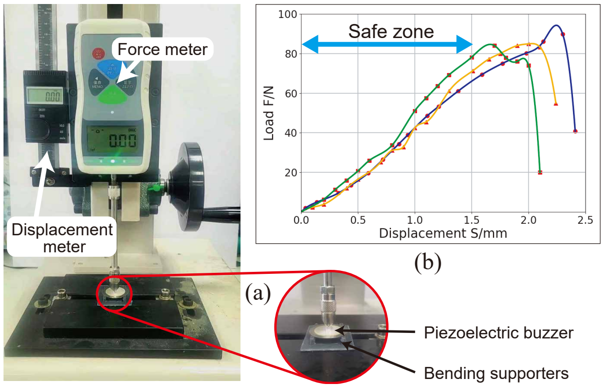


Fig. 6. Single-buzzer test. (a) Setup. (b) Results in elastic tests.

TABLE I
HARVESTED ENERGY IN THIS STROKE-CONSTRAINED TILE DESIGN.

Number of piezoelectric buzzers	**1**	**3**	**8**	**15**
Maximum harvested energy (μJ)	7.04	30.67	100.98	287.23

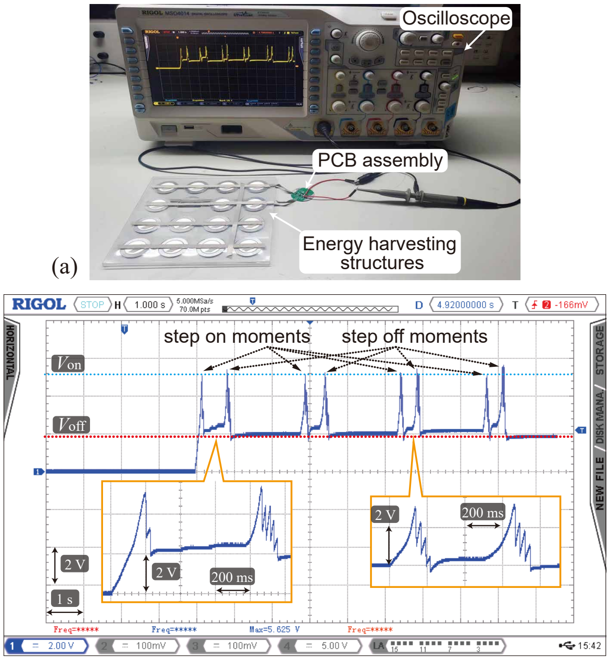
*In this design, the maximum stroke is limited to 1 mm.

and sensing is based on the operational characteristics of motion-driven IoT systems [12], [13].

A 3T-EM circuit, which was developed by the same research group, is utilized to ensure robust intermittent operation [11]. The EMU circuit topology is shown in Fig. 4. Once the energy in the storage capacitor reaches the predefined threshold, the stored energy is released to power the IoT SoC. As we can see from the operational comparison to the conventional battery-powered devices, which is shown in Fig. 5, the 3T-EM circuit outputs an intermittent digital voltage for realizing the energy-driven operation. For example, when energy is insufficient for an atomic operation, the system consumes zero power. Then, when the user steps on the tile, regardless of the force applied, the storage voltage V_{sto} starts to rise. Once V_{sto} reaches the V_{on} release threshold, the BLE SoC is energized to broadcast the corresponding BLE data packet. To ensure an immediate report on a step motion, the generated energy at each step must be designed to be larger than an atomic sensing and transmission requirement. With the ID and time stamp information of all received packets, the edge device can estimate the behavior of the pedestrian users.

C. Tile Module Design

Ensuring energy supply-demand balance is crucial for timely reporting step actions after each excitation. Given a design target of more robust transmission, after the energy buffer process, the released energy must be sufficient for sending out at least three BLE beacon packets without interruption. Some measurements of the harvested energy are carried out when using different numbers of piezoelectric buzzers. In the experiment, a testing subject, whose weight is 65 kg, steps on the tile module. The harvested energy under four sets of piezoelectric buzzers is recorded and listed in Table I. The



(a)

(b)

Fig. 7. Tile module test. (a) Testing setup. (b) Storage voltage V_{sto} characterizing operation processes.

harvested energy is calculated according to the fundamental energy formula of a capacitor, i.e.,

$$E_c = \frac{1}{2} C_{\text{st}} \times (V_{\text{on}}^2 - V_{\text{off}}^2) \quad (1)$$

On the other hand, the energy consumption of the whole atomic function including initialization and BLE broadcasting, which is implemented in an SoC (nRF-52832 by Nordic Co., Ltd.) is about 70 μJ. Based on the measurements on both the supply and demand sides, we selected 15 piezoelectric buzzers connected in parallel for building a single self-powered tile unit, such that the design target of three packets per step can be guaranteed.

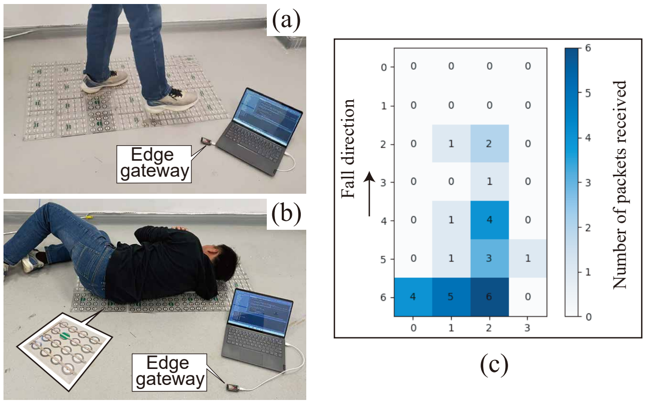
IV. EXPERIMENTS

A. Piezoelectric Element Test

The characteristic of a single piezoelectric buzzer is first tested to ensure the reliable operation of ETU. A key requirement is to keep the deformation of the piezoelectric buzzer within a safe and recoverable elastic range. Fig. 6 shows the testing setup and results of three buzzers. The results show that the buzzers can be safely deformed and recovered within a displacement of 1.5 mm. Therefore, in this floor tile design, we select a maximum 1 mm stroke for making a compromise of sufficient harvested energy and good durability and user experience in natural walking.

B. Tile Module Test

As shown in Fig. 7(a), a prototype of a self-powered floor tile is developed. The recorded waveform of the storage voltage V_{sto} when a 65-kg testing subject stepped on the floor tile four times is presented in Fig. 7(b). At first, the storage voltage starts from zero. When the user steps on the tile, the storage voltage begins to rise. Upon reaching the preset threshold of 4.8 V, the stored energy in the capacitor is released, enabling the BLE SoC to carry out a broadcasting task. The storage voltage increases again when the user steps off the tile. Since the capacitor has some residual energy after the first step-on excitation, the BLE SoC can harvest more energy with a non-zero start-up condition. The broadcast packets can be more as well, as we can see by counting the steep voltage drops in the waveform shown in Fig. 7(b).



	0	1	2	3
0	0	0	0	0
1	0	0	0	0
2	0	1	2	0
3	0	0	1	0
4	0	1	4	0
5	0	1	3	1
6	4	5	6	0

(c)

Fig. 8. Fall test. (a) Normal walking. (b) Fall condition. (c) Received BLE beacon packets at the fall instant.

C. System Test

A floor tile array, which is composed of $4 \times 7 = 28$ tiles, is developed for fall detection purposes. The setup and testing results are shown in Fig. 8. An IoT SoC (ESP32 by Espressif Co., Ltd.) is programmed to be a data gateway.A subject performed 60 rounds of fall and walk motions. Among the 60 recorded samples, 50 were used for machine learning, and the other 10 for inferring. A three-layer convolutional neural network (CNN) with 20 neurons in each layer is utilized to process the data. The model achieves a 90% accuracy in fall identification and 100% in walking. Fig. 8(c) illustrates the activated tiles during a fall event as well as the corresponding numbers of their broadcast packets.

V. CONCLUSION

This paper introduced a self-powered and self-sensing Bluetooth smart floor system for pedestrian tracking and accidental fall detection. By relating the user behavior and its related harvested energy, coincident sensing is realized with a sensor-free scheme. Detailed configurations and considerations are discussed to justify the rations behind this design. Experimental results obtained at element, module, and system levels have validated the reliable operation of the proposed system. Future work will focus on the improvement of real-time algorithms for more efficient and accurate identification of different motions and multiple subjects.

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