Sensor systems

Battery-Free Wireless Floor Tile for People Counting

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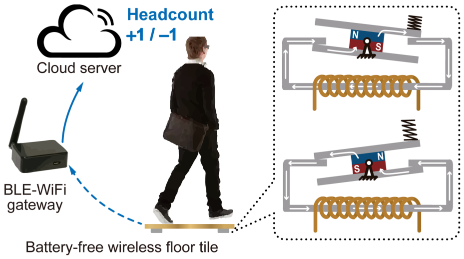
Abstract—People counting constitutes a crucial application of Internet of Things (IoT) technology. It offers valuable information for crowd management, security, and public health purposes. However, the majority of the current people counting sensors are powered either by batteries or by mains electricity. These power sources involve intricate installation procedures that frequently necessitate redecoration and arduous maintenance. This letter introduces a novel battery-free wireless floor tile sensor system for people counting. The floor tile terminal is composed of four quasi-static-toggling electromagnetic motion-powered switches. The foot traffic data transmitted are received by a gateway and subsequently forwarded to a cloud platform for analysis. The battery-free wireless floor tile is convenient to install. The entire system is capable of monitoring the number of people and their flow direction in real time. A prototype system is manufactured and installed at the entrance of the authors' laboratory for a field test. It achieves a 94.8% accuracy in walking directional identification and people counting. It is energy autonomy, low cost, and easy deployment. This study establishes a sustainable model for long-term indoor occupancy monitoring and crowd management. The design aligns with the current trend of eco-friendly, battery-free ambient IoT.



Index Terms—Sensor systems, battery-free (BF) Internet of Things (IoT), electromagnetic, energy harvesting, people counting, sensor application.

I. INTRODUCTION

The Internet of Things (IoT) is revolutionizing data-driven decision-making in smart environments, enabling real-time monitoring and automation across various domains, including industrial, commercial, and public sectors. IoT systems integrate passive sensing, edge computing, and cloud analytics to inform spatial dynamics. This is especially true for occupancy monitoring and crowd flow optimization. Core applications, such as people counting, are critical infrastructure. They support safety assurance, energy efficiency, public health management, and spatial resource optimization. However, existing solutions face bottlenecks in sustainable deployment and scalability, primarily due to power dependence and installation complexity.

Vision-based systems are highly accurate in analyzing crowd density. But they perform badly in low-illumination areas and are restricted in privacy-sensitive areas [1]. They also demand heavy computation and continuous grid power. Battery-powered infrared sensors, by contrast, need frequent maintenance, invasive wiring, and often structural modifications. These include wall penetration for cables and battery replacement. Such changes raise more safety concerns [2] and environmental issues [3]. Gate machines work well at controlled access points but create physical barriers, causing peak-hour bottlenecks. This balance between precision, privacy, and practicality is a big problem. It hinders long-term, large-scale deployment. Recent studies point out a key unmet need: energy autonomy. Over 95% of commercial IoT nodes run on batteries [4], and none solved the issue of seamless floor-integrated installation.

To address these challenges, floor-embedded sensing has emerged as a promising alternative. Researchers have explored artificial intelligence of things-enabled triboelectric nanogenerator-based floors for trajectory recognition [5]. They have also studied mechanical electromagnetic systems for energy harvesting [6]. However, these solutions lack wireless capabilities and deliver insufficient power for sustained operation. Commercial capacitive sensing floors, such as SensFloor [7], offer high resolution but are costly and wired. These gaps highlight the need for a self-sustaining, wireless, maintenance-free floor system that integrates with IoT infrastructure.

In this letter, a battery-free (BF) wireless floor tile system is introduced. It employs four quasi-static-toggling (QST) electromagnetic switches, whose working principle was previously introduced by Liu et al.'s research group [8]. A QST switch harvests kinetic energy from footstep-induced excitation. This energy suffices to power Bluetooth low-energy (BLE) packet transmission for real-time entry/exit reporting. Without utilizing any external power source, the system enables *put-and-play* and *deploy-and-forget*, i.e., easy and sustainable deployment. Its design includes the following three key features.

1) *Self-powered edge terminals (floor tiles)*: Each QST switch used in BF floor tiles is capable of generating a sufficient amount of energy on each click/step action to support a round or several rounds of BLE beacon broadcasting.
2) *Edge-cloud synergy*: The broadcast BLE data, which incorporate precise timestamps via the gateway, are relayed to a dedicated cloud platform, where they undergo directional identification processing.
3) *Easy installation and low maintenance cost*: Modular BF and wireless floor tiles eliminate the need for wiring or reconstruction, thereby minimizing deployment costs when compared with camera-based or other floor-based alternative solutions.

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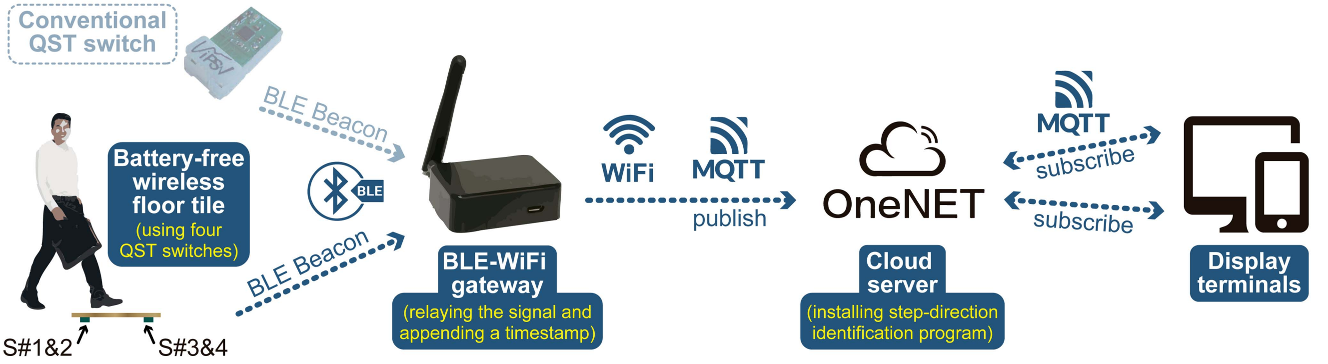

Fig. 1. System configuration. The implementation uses four QST switches locally and a step-direction identification program on the cloud.

II. KEY COMPONENT: MOTION-POWERED SWITCH

QST motion-powered switches are key components for BF tile end devices in this system. Each switch is powered by a QST electromagnetic energy harvester (EMEH). The harvester converts kinetic energy from pedestrian footsteps into electrical energy. A low-cost energy conditioning circuit handles rectification and regulation. The processed energy delivers a stable digital voltage to drive a low-power BLE system-on-chip (SoC).

A. QST Mechanical Energy Harvester

The QST mechanical energy harvester, whose configuration is shown in Fig. 2, transduces energy across mechanical, magnetic, and electrical domains. Its detailed working principle is elaborated in the literature [8]. This technology generates sufficient energy to power a BLE wireless switch or button. It works even under ultra-low-speed mechanical excitation. Quasi-static motion means extremely low-speed motion. Its triggering dynamics mimic the snap-through behavior of a bistable system. Each excitation cycle includes pressing and releasing phases. It produces two sharp voltage pulses with opposite polarities. Each excitation cycle yields approximately 0.7 mJ of energy. The energy is conditioned by a power electronic circuit. It can then power an advanced low-power Bluetooth SoC for a short duration.

B. Energy Conditioning Circuit

The energy conditioning circuit used in this study is shown in Fig. 3. A depletion-mode n-type MOSFET is used as a low-cost regulator. Compared with using a low-dropout regulator or a switch-mode dc/dc converter to provide a stable digital voltage, such a solution is simple and eliminates quiescent current consumed by using a commercialized regulator [9]. When the QST EMEH is excited, the energy associated with the two voltage pulses is rectified by the bridge rectifier and temporarily stored in the filter capacitor. The generated pulses are very sharp, with an interval of one millisecond and an amplitude of 20 volts. The regulation carried out by the MOSFET starts almost immediately after the generation. No additional electrical buffer-release mechanism is needed for handling the necessary burst-mode operation in this QST case [8]. The energy conditioning circuit used here follows that introduced by Teng et al.'s research group [9].

C. BLE SoC

The SoC utilizes harvested energy to transmit BLE beacon signals. In this work, an nRF-52832 SoC (by Nordic Ltd.) is used as the embedded microcontroller. It was shown that the amount of harvested energy in only one click can support the successful transmission of three BLE iBeacon packets [10].

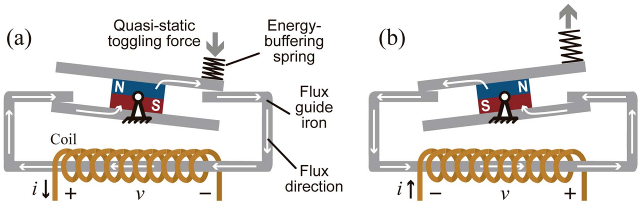

Fig. 2. QST EMEH. (a) One stable state with a clockwise magnetic flux. (b) Other with a counterclockwise magnetic flux [8].

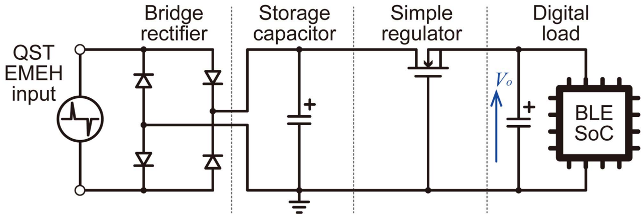

Fig. 3. Energy conditioning circuit for QST energy harvester.

The BLE broadcasting power level is set to 0 dBm in this design. These signals are receivable within 10 m by our customized gateway. The gateway decodes the signals, appends corresponding timestamps, and relays the decoded data to cloud servers via a WiFi network. The cloud server performs centralized processing. It decrypts gait phases. It also aggregates people-counting results.

III. SYSTEM-LEVEL SYNERGY

A. Hardware Assembly

Fig. 1 shows the proposed floor tile system, developed with a novel system-level integration of motion-powered switches. The floor tile system comprises four interconnected modules: motion-powered floor tiles, edge computing nodes, a cloud server, and remote visualization terminals. As shown in Fig. 4(a), each floor tile integrates four BF BLE switches. These switches are embedded in a wooden substrate. They are powered by QST energy harvesters. The harvesters convert kinetic energy from pedestrian footsteps into local electricity. A low-cost energy management circuit performs rectification and voltage regulation. This enables the unregulated and impulsive harvested energy to power

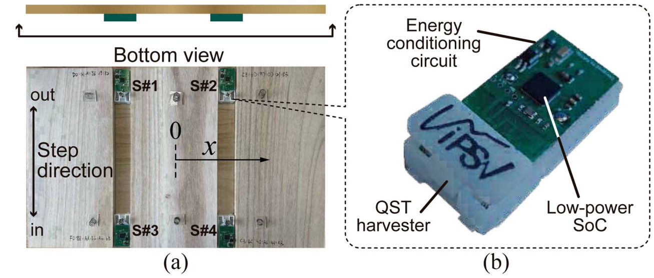

Fig. 4. Floor tile configuration. (a) Bottom view. (b) Enlarged view of a QST motion-powered switch.

a BLE SoC. The switches broadcast BLE packets with a temporal difference. This difference is inherently associated with the phases of a pedestrian's gait during walking.

B. Gateway and Cloud

The gateway conducts periodic scanning. It captures BLE packets from all four motion-powered switches. It transmits an immediate data packet, including its timestamp, to the cloud via WiFi links. The cloud server identifies walking direction by analyzing the IDs and timestamps of received BLE packets. It first identifies device-specific signatures, then executes local processing algorithms. The cloud server maintains two-way communication with edge nodes. This communication supports configuration updates. Both historical and real-time data are stored in the cloud server. They can be visualized on remote terminals, including PCs and smartphones. The data are structured in a lightweight exchange format, e.g., JSON. This ensures interoperability with downstream applications.

C. Step-Identification Logic

The step-direction identification program, which is run on the cloud server, is detailed in Fig. 5. The system adopts strict dual-packet sequential detection logic to identify pedestrian step phases. The finite state machine is presented in Fig. 5(a). For outdoor-to-indoor walking, front (S#1 or S#2) and rear (S#3 or S#4) modules activate sequentially [see Fig. 5(b) and (c)]. In the opposite direction, S#3 or S#4 activates first. This is illustrated in Fig. 5(d) and (e). The gateway records an entry or exit event only when it receives packets from both groups in proper spatio-temporal orders. This dual-packet validation drops false positives caused by incorrect steps.

IV. EXPERIMENTS

A. Success Rate of a Single Device

To better quantify step-direction detection robustness, in terms of success rate, controlled tests are conducted on a 5-m path with a central floor tile and a 0.5-m buffer. Subjects walked at three speeds: running ($t < 2.5$ s), fast walking (2.5 s $< t <$ 3.5 s), and slow walking ($t > 3.5$ s).

Fig. 6 presents the identification success rate in the experiment when the stepping positions differ. The parameter x denotes the transversal distance from the tile center [see Fig. 4(a)]. The system achieves an average 97.4% success rate in daily scenarios (slow and fast walking) across all footstep positions x on the tile. Even under running excitation, it maintains an average 92.6% success rate. Errors primarily occur in marginal cases, where footsteps fail to trigger adjacent modules in a logical sequence.

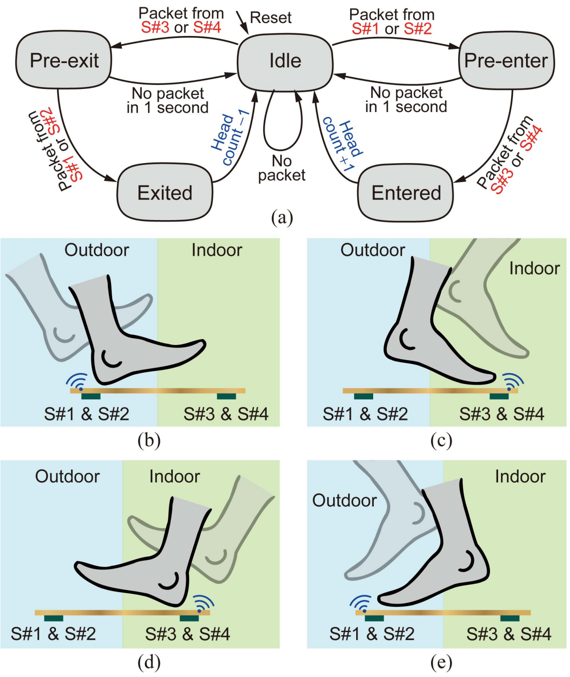

Fig. 5. Step-direction identification logic. (a) Finite-state machine. (b) Pre-enter state. (c) Entered state. (d) Pre-exit state. (e) Exited state.

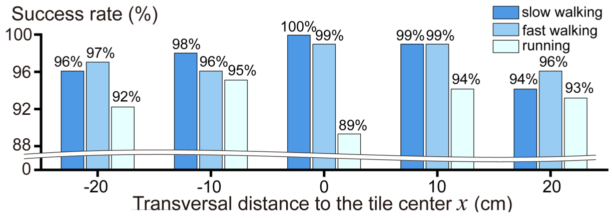

Fig. 6. Success rate in step-direction identification in experiment.

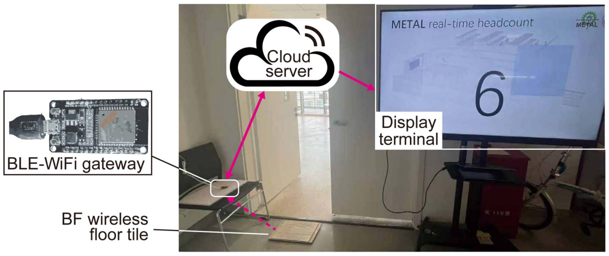

Fig. 7. Field test setup.

B. Field Test

To further evaluate long-term performance, the proposed system is deployed at the entrance of the Mechatronics and Energy Transformation Laboratory, ShanghaiTech University.[1] It conducted continuous monitoring for 120 h, i.e., five days. As shown in Fig. 7,

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[1] This setup is only for prototyping and testing at this stage. It cannot count a large number of parallel pedestrians right now. In practical application scenarios, to count people individually, this floor tile must be installed along a narrow aisle. This installation method is similar to the configuration of existing turnstile gates, and its purpose is to prevent pedestrians from walking side-by-side.

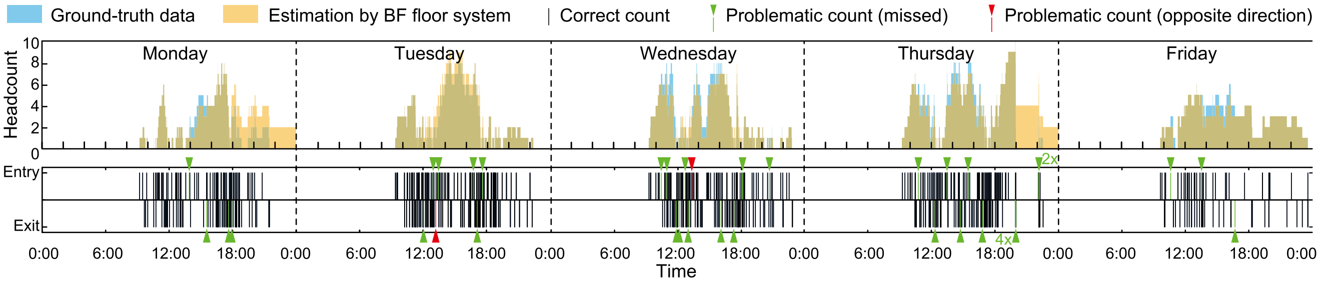

Fig. 8. Recorded data in a five-day field test.

the tile is installed in the lab entrance, whose width is 90 cm. The tile (40 cm × 25 cm) integrates four BF QST switch modules (4.5 cm × 2.5 cm), as shown in Fig. 4(a). Its mechanical structure includes six restoring springs that support a wooden tile plate. When a pedestrian foot-strike applies a 1-mm stroke–an amplitude even shorter than the heel deformation of a typical shoe–each module harvests a certain amount of energy. This energy is adequate to support the initialization and transmission of three BLE beacon packets. The stroke can be further reduced by using the lever structure. It causes no strong imbalance when a person steps on it. The transmission uses an nRF-52832 SoC. The SoC consumes 201 μJ per BLE packet.

A BLE-WiFi gateway is developed using the ESP32 (by Espressif Systems Ltd.). It samples BLE beacon signals at 100 Hz. Timestamp synchronization is achieved at the microsecond scale via Network Time Protocol. OneNET (by China Mobile Ltd.) is selected as the cloud platform. Upon detecting footsteps, the ESP32 gateway receives sequenced beacon packets transmitted by BF switches. It sends data to the server via the Message Queuing Telemetry Transport protocol. The cloud server analyzes the entry or exit condition and counts the number of people in the room. The total number of people and historical data can be remotely obtained in real-time from the cloud server via the Internet.

A five-day field test validates the robust performance in a real-world application. The system records the entry and exit times to the laboratory with a time accuracy of milliseconds. Fig. 7 shows the experiment setup. Fig. 8 illustrates the number of people in the laboratory over the five days. The lower part of Fig. 8 presents the raw data. A positive pulse indicates an entry event, while a negative one represents an exit event. Instances of a missed count are marked in green. Opposite counts are marked in red. Throughout the five days, it records 5372 BLE packets, among which the system identified 714 correct counts, 35 missed counts, and two opposite counts. It leads to a 94.8% success rate in direction identification, compared with the ground-truth record obtained from video analysis. Failures mainly occur during high-traffic periods. Fast foot strikes might be confused due to the limitation of a 100-Hz scanning frequency. Marginal steps account for a major reason for these misclassifications.

V. CONCLUSION

This letter introduced a low-cost, high-success-rate, and easy-deploy motion-powered wireless floor monitoring system for IoT-based people counting. It integrates QST EMEH with an edge-cloud synergetic design. The edge device, i.e., the tile, runs entirely on motion energy. The major contributions are threefold. 1) The QST motion-powered mechanism converts extra-low-frequency excitations from foot strikes into sufficient energy to drive BLE broadcasting. 2) Step direction can be identified with a high success rate via dual-packet sequential validation logic at the cloud server. 3) Deployment and scalability are ensured by modular tiles that require no structural modifications, thus reducing labor costs for initial installation and future maintenance. In a field test, it demonstrated a 94.8% success rate in step-direction identification. The system overcomes key limitations of vision-based and battery-dependent alternatives. In summary, this study pioneers a sustainable paradigm for long-term indoor people counting and occupancy analytics.

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