ViPSN-OMS: A Battery-free Occupancy Monitoring System Using A Time-of-flight Sensor

Shengqi Gao, Jiacong Qiu, and Junrui Liang*
School of Information Science and Technology
ShanghaiTech University, Shanghai, China
Email: {gaoshq2023, qiujq, liangjr}@shanghaitech.edu.cn

2025 IEEE Workshop on Signal Processing Systems (SiPS) | 979-8-3315-9831-0/25/$31.00 ©2025 IEEE | DOI: 10.1109/SiPS66314.2025.11261259

***Abstract*—This paper introduces ViPSN-OMS, a battery-free occupancy monitoring system. The system detects and processes time-of-flight (ToF) information. It consists of four components: a small amorphous photovoltaic (PV) cell, a low-power ToF sensor, an energy management unit (EMU), and a system on chip (SoC). This study analyzes the charge budgeting process in detail. The process aims to balance PV input and total system consumption. When the storage capacitor accumulates sufficient charge, the system powers up autonomously. It then executes a round of operation. The operation includes two steps: measuring distance and sending the result via Enhanced ShockBurst (ESB). Laboratory experiments were conducted. Under 99.1 lux illumination, the system completed one test round in approximately 87.4 seconds. The test consumed 1.0293 mC of accumulated charge. A field test was also performed. The battery-free device was deployed on a student's office bench. It continuously monitored occupancy for 1.26 hours. With a vision-based benchmark as reference, the proposed battery-free system achieved an accurate estimation of human presence. Meanwhile, it maintained a certain level of privacy. This system features easy installation and convenient maintenance. As a sustainable solution, it has broad application prospects in the smart home domain and multiple industrial scenarios.**

***Index Terms*—Ambient IoT, energy harvesting, edge sensing and computing, time-of-flight (ToF), occupancy monitoring.**

I. INTRODUCTION

In the context of the industrial 4.0 era [1] as well as in smart-home applications, there is a substantial demand for occupancy monitoring for security enhancement, equipment status monitoring, elderly care, and other aspects [2], [3]. Conventional occupancy monitoring systems are powered either by mains electricity or batteries. The expenses associated with wiring, battery replacement, and subsequent maintenance are relatively high, which confines their extensive application in massive, sparse, and long-lasting scenarios.

Unlike the conventional mains-powered or battery-powered systems, the emerging battery-free solutions, which realize energy self-sufficiency by harvesting energy from ambient energy sources, are promising for their environmentally friendly feature. They also require relatively lower costs in both initial installation and later maintenance. Several battery-free methods have been proposed for occupancy monitoring. Existing designs use optical ultra-low-power cameras and RF backscatter [4], radio frequency identification (RFID) [5], [6], accelerometers [7], or passive infrared (PIR) [8] sensors. These existing solutions have their limitations. For example, camera-based systems may raise privacy concerns and require good lighting conditions for reliable operation; the reading distance of RFID is rather limited; PIR sensors can only detect dynamic targets. In addition, some of these sensors also suffer from other challenges, such as complex installation, inaccuracy, large power consumption, and high cost.

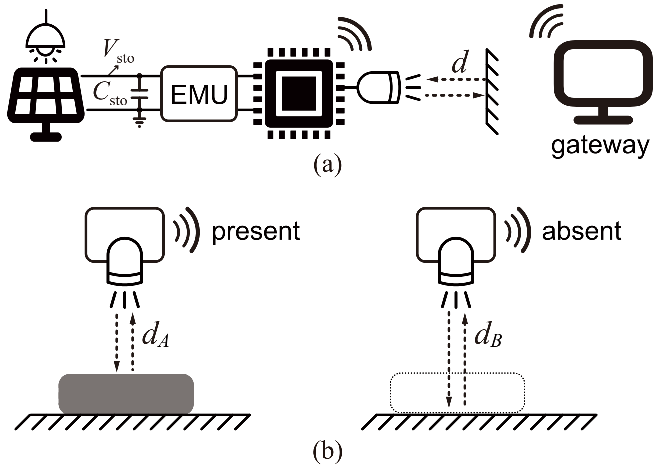

Fig. 1. Proposed ViPSN-OMS using a ToF sensor. (a) System configuration. (b) ToF measurements toward occupancy monitoring.

This study proposes a battery-free and wireless time-of-flight (ToF) sensing system, named ViPSN-OMS, for realizing low-cost occupancy monitoring. The low-power ToF sensors offer good cost-effectiveness for they possess several advantages, e.g., privacy protection, lower power consumption, high accuracy, and reasonable detection range.

II. WORKING PRINCIPLE

A. System Configuration

The system configuration of ViPSN-OMS is shown in Fig. 1(a). This compact setup, comprising a small amorphous photovoltaic (PV) cell, a low-power ToF sensor, an energy management unit (EMU), and a system-on-chip (SoC), offers notable advantages. The amorphous PV cell enables energy autonomy by harnessing indoor ambient light, reducing reliance on batteries, and lowering long-term maintenance costs. The low-power ToF sensor, paired with the EMU's smart energy regulation, ensures efficient operation even in low-light conditions, extending the system's operational lifespan significantly. The SoC consolidates key embedded computing and ESB wireless functions into a single component, minimizing size and enabling real-time, on-device data processing to reduce latency and bandwidth usage. Together, these elements create a self-sustaining solution ideal for remote or hard-to-access deployments where reliability and energy efficiency are critical. Fig. 1(b) depicts the results with or without the occupancy of a detecting object.

B. ToF Measurement

An integrated ToF ranging module (VL53L0X, STMicroelectronics Inc.) is utilized for distance measurement. It consists of a 940 nm vertical-cavity surface-emitting laser (VCSEL) emitter and a ranging sensor to capture the reflected light. An avalanche photodiode (APD) is commonly used as the receiver. APDs operate under a high reverse bias voltage, enabling an internal gain mechanism through the avalanche multiplication process.

The integration of precise timing circuitry and highly sensitive photodetection in VL53L0X enables ToF sensors to offer accurate and real-time distance measurements. The distance d can be computed by utilizing the speed of light c and the measured round-trip travel time Δt as follows

$$d = c \cdot \Delta t / 2 \tag{1}$$

Due to the compact and energy-efficient design of an integrated ToF ranging sensor, it is appropriate for use in battery-free wireless systems. An SoC can establish communication with the VL53L0X through the I2C protocol. The SoC writes to a register of the ToF sensor to initiate a measurement and subsequently reads the result from the register once it is available. The distance information obtained from the sensor is transmitted wirelessly to the host server via ESB. The operation procedures of the system are summarized in Algorithm 1.

Algorithm 1: Working logic of the SoC controller.

1 Initialize the RF SoC. Power on the ToF sensor.
2 Wait for the sensor to complete data acquisition.
3 Establish communication with the sensor using the Inter-Integrated Circuit (I2C) protocol.
4 Perform data packaging for wireless transmission.

C. Charge Buffer-release Design

The crucial technique for enabling self-powered operation lies in appropriately managing the trickling energy derived from ambient sources to provide a regulated voltage to power digital electronics [9].

Ambient energy existing in the environment is often weak, sparse, and in different physical or chemical forms. It can be collected and utilized through various technologies. For example, electromagnetic energy can be captured from radio frequency (RF) signals, thermal energy can be extracted from temperature differences, or kinetic energy can be obtained from mechanical vibrations. These energy harvesting methods each have their preferred applicable scenarios.

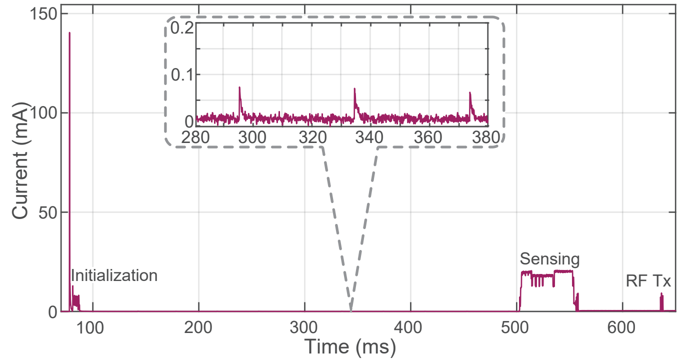

Fig. 2. Current trace during a single ToF measurement and transmission at a constant voltage of 3.3 V.

Among various environmental energy harvesting technologies, photovoltaic energy harvesting, although a relatively traditional technical approach, exhibits targeted advantages in the specific scenario focused on in this research. It can provide a relatively stable and continuous energy output under indoor lighting conditions, which highly matches the energy demand characteristics of the research scenario. Based on this feature, this study selects a PV panel as the energy harvester to provide reliable transient power for the system.

Due to the limited power output of the PV panel in the indoor environment, it cannot directly power the sensing system in real-time. Instead, an energy management circuit is employed to accumulate charge from the photovoltaic panel and release it once a specific voltage threshold is reached. This ensures the energy-neutral operation in the long run.

As shown in Fig. 2, the current of this low-power system is impulsive. The consumption includes two major parts. During the system initialization (the former sharp peak) and the scheduled ToF measurement (the latter plateau). This system uses a low-dropout regulator (LDO) for voltage regulation. Given the charge-conservation feature of an LDO, it is more suitable to consider the supply-demand balancing issue in terms of charge, rather than energy.

Given the I-V feature of most PV cells, the output current in the small voltage region is rather constant, approximately equal to the short-circuit current i_{sc}. The input or harvested charge in an interval of T is calculated as follows

$$Q_{\mathrm{in}} \approx \int_T i_{\mathrm{sc}}(t)\,\mathrm{d}t. \tag{2}$$

The harvested charge is accumulated in the storage capacitor C_{sto} for later release. The amount of charge is formulated as follows

$$Q_{\mathrm{out}} = \Delta V_{\mathrm{sto}} C_{\mathrm{sto}}, \tag{3}$$

where ΔV_{sto} is the voltage difference before and after a round of energy release. Sufficient Q_{out} is necessary to cover the total consumption of a round of operations, including system initialization, sensing, and transmission. From Fig. 2, we can do a numeric integral and summarize that the total charge for a round of operations is about 1.0293 mC.

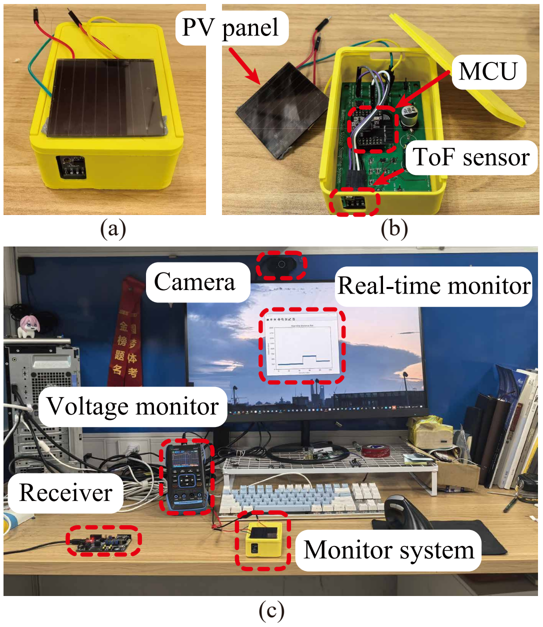

Fig. 3. Prototype and experimental setup. demonstration. (a) Assembly. (b) Printed circuit board assembly (PCBA). (c) Field test setup.

TABLE I
PARAMETERS AND COMPONENTS OF THE PROTOTYPE.

Parameter/Component	Value/Type
V_{oc}	4.90 V
I_{sc}	300 μA
C_{sto}	1650 μF
V_{on}	3.36 V
V_{off}	2.12 V
LDO	HT7333, Holtek Semiconductor Inc.
RF SoC	nRF-52832, Nordic Inc.
ToF sensor	VL53L0X, STMicroelectronics Inc.
Illuminance	99.1 lux
Host device	nRF52832, Nordic Inc.
Test range	20 mm to 1800 mm

TABLE II
NUMBER OF SAMPLES COLLECTED IN 10 MINUTES.

Illum. (lux)	28.7	34.4	63.9	192.3	246.1	304.5	357.2
Sample No.	1	5	10	14	16	20	24

When sufficient charge is accumulated and ready to be released, the energy management circuit automatically delivers power at a regulated digital voltage to the embedded system. An RF SoC nRF-52832 is used as the microcontroller. The power supply of the ToF ranging sensor is provided by a general-purpose input/output (GPIO) pin, so as to cut the power consumption of the sensor in other non-sensing periods.

Once the system starts, the charge stored in the storage capacitor gradually depletes, causing the voltage to drop. Once the voltage falls below a predefined V_{off} threshold, the energy management circuit disconnects the whole embedded system from the storage. The SoC is shut down and waits for another active cycle after sufficient charge is accumulated again.

III. EXPERIMENTS

Fig. 3(a) and (b) show the experimental setup for the lab evaluation. Fig. 3(c) presents the field test for a battery-free occupancy detection application. The experimental conditions were set as listed in Table I.

A. Lab Evaluation

The illumination level has a significant impact on the output characteristics of PV panels. Table II lists the number of received samples within 10 minutes under different illumination levels. In such an experiment, a dark illuminance as low as 28.7 lux (dark condition) can power the system to sample in 10 minutes. When the illuminance is above 63.9 lux, it is sufficient for the system to sample once within one minute.

B. Field Test

A field test is conducted to assess the occupancy detection system within a student workplace. The battery-free occupancy-monitoring prototype is installed at chest level to mitigate the risk of laser exposure to the user's eyes. When an individual enters or exits the sensor's field of view, the ToF unit records a corresponding measured distance. This distance serves as a reliable indicator of the presence or absence of the person. Subsequently, these distance measurements are wirelessly transmitted to a host system. The host system receives and processes each ToF update, thereby demonstrating the viability of this approach for low-power, intermittent communication in battery-free sensing applications. In the meantime, to benchmark the real-time occupancy situation, a camera monitors human presence in front of the workplace. It takes a picture every 60 seconds. All of the pictures are then processed by RetinaFace [10] for face detection, a component within the InsightFace project. It performs face recognition by extracting high-dimensional features from images to tell whether there's a human. The experiment setup is shown in Fig. 3.

During the 1.26-hour experimental period, 53 valid data packets were received, with an average inter-arrival time of 87.4 seconds (min: 67.7 sec, max: 233.3 sec, caused by illumination variation due to human body coverage or obstruction). Such a result is reasonable according to Table II.

To estimate human occupancy around the desktop, a distance threshold is applied to the result of the distance of the ToF sensor measurement. When a person is present, the distance between the individual's chest and the ToF sensor is relatively short. On the contrary, in the absence of a person, the measured distance is significantly larger. In this study, an empirical threshold of 0.5 meters is selected. Specifically, distances shorter than 0.5 meters are classified as occupied. Distances exceeding this threshold are considered unoccupied.

In parallel, reference data is obtained by capturing images every 60 seconds and applying face detection algorithms to determine human presence.

As shown in Fig. 4, when comparing two results, the experimental results demonstrate a good agreement between

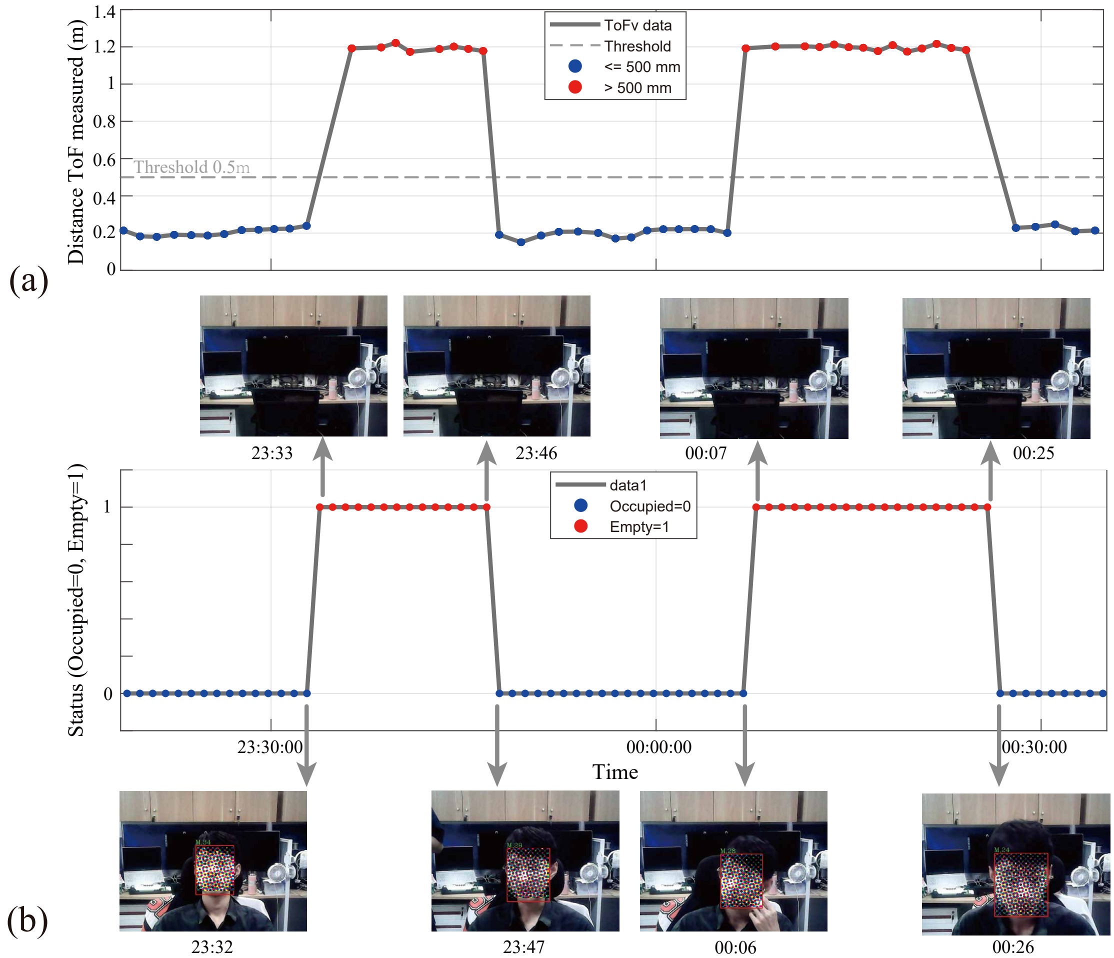

Fig. 4. Field test and experimental result. (a) Measured distance by the battery-free ToF occupancy sensing system. (b) Real-time occupancy detection by Insightface as the benchmark, which processes pictures every 60 seconds from a camera.

the proposed self-powered ToF-based method and the vision-based approach. It indicates that the proposed system achieves high accuracy and reliability in human occupancy detection.

Likewise, besides human, other sensing units can be easily installed to monitor the presence of valuable instruments, such as to ensure their proper placement and security.

IV. Conclusion

This study showcased a practical battery-free occupancy monitoring system that utilizes time-of-flight (ToF) sensing and indoor photovoltaic energy harvesting. By obviating the requirement for batteries, the system decreased maintenance costs and was in line with the increasing demand for sustainable IoT solutions. This work highlighted the potential of battery-free ToF sensing as a low-cost, low-maintenance solution for sustainable ambient intelligence in smart buildings and industrial settings. Future efforts will focus on three aspects: first, enhancing the efficiency of energy harvesting; second, tailoring sensing intervals to ambient conditions; third, integrating complementary sensing modalities. These enhancements may broaden the system's applicability to more dynamic and complex environments.

Acknowledgment

This work was supported by the National Natural Science Foundation of China under Grant 62271319 and Grant U21B2002.

References

[1] A. G. Frank, L. S. Dalenogare, and N. F. Ayala, "Industry 4.0 technologies: Implementation patterns in manufacturing companies," *International Journal of Production Economics*, vol. 210, pp. 15–26, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0925527319300040

[2] Z. Chen, Y. Gao, and J. Liang, "Lopdm: A low-power on-device predictive maintenance system based on self-powered sensing and tinyml," *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1–13, 2023.

[3] G. Maselli, M. Piva, and J. A. Stankovic, "Adaptive communication for battery-free devices in smart homes," *IEEE Internet of Things Journal*, vol. 6, no. 4, pp. 6977–6988, 2019.

[4] P. Franco, J. M. Martínez, Y.-C. Kim, and M. A. Ahmed, "Iot based approach for load monitoring and activity recognition in smart homes," *IEEE Access*, vol. 9, pp. 45 325–45 339, 2021.

[5] D. C. Ranasinghe, R. L. Shinmoto Torres, A. P. Sample, J. R. Smith, K. Hill, and R. Visvanathan, "Towards falls prevention: A wearable wireless and battery-less sensing and automatic identification tag for real time monitoring of human movements," in *2012 Annual International Conference of the IEEE Engineering in Medicine and*

Biology Society. San Diego, CA: IEEE, Aug. 2012, pp. 6402–6405. [Online]. Available: http://ieeexplore.ieee.org/document/6347459/

[6] T. Wang, S. Dai, Y. Liu, and T. T. Ye, "Battery-Less Sensing of Body Movements Through Differential Backscattered RFID Signals," *IEEE Sensors Journal*, vol. 22, no. 9, pp. 8490–8498, May 2022. [Online]. Available: https://ieeexplore.ieee.org/document/9739718/

[7] Y. Zhao, A. LaMarca, and J. R. Smith, "A battery-free object localization and motion sensing platform," in *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. Seattle Washington: ACM, Sep. 2014, pp. 255–259. [Online]. Available: https://dl.acm.org/doi/10.1145/2632048.2632078

[8] S. Stirapongsasuti, S. Misaki, T. Matsui, H. Suwa, and K. Yasumoto, "Batterfly: Battery-free daily living activity recognition system through distributed execution over energy harvesting analog pir sensors," in *2021 17th International Conference on Distributed Computing in Sensor Systems (DCOSS)*, 2021, pp. 54–56.

[9] X. Li, L. Teng, H. Tang, J. Chen, H. Wang, Y. Liu, M. Fu, and J. Liang, "ViPSN: a vibration-powered IoT platform," *IEEE Internet Things J.*, vol. 8, no. 3, pp. 1728–1739, Feb. 2021.

[10] J. Deng, J. Guo, J. Zhou, and S. Zafeiriou, "Retinaface: Single-shot multi-level anchor-free face detection in the wild," in *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, 2020, pp. 5203–5212.