PhD Forum Abstract: Ubiquitous Sensing System for Activity and Gesture Recognition via Optical and Energy-Harvesting Technologies

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ABSTRACT

This research focuses on ubiquitous sensing systems for activity and gesture recognition through novel optical sensing and energy harvesting technologies such as triboelectric nanogenerators (TENG), solar cells, and visible light communication (VLC). The primary goal is to address the limitations of existing sensing systems by creating a low-cost, energy-efficient, comprehensive solution that enhances sensor integration and communication. Thus, this study utilizes TENG for contact sensing, solar cells for non-contact sensing, and VLC for spatial sensing. The applied methodologies achieve activity and gesture recognition, with accuracies up to 99.4% and 97.3%, respectively. This work has potential applications in smart home automation, health monitoring, and intelligent control by providing a more sustainable and user-friendly approach to ubiquitous sensing.

KEYWORDS

Ubiquitous Sensing, Optical Sensing, Energy Harvesting, Human-Computer Interaction

1 INTRODUCTION

In the era of the Internet of Things (IoT) and intelligent buildings, the significance of ubiquitous sensing technologies and energy-harvesting systems cannot be overstated [10, 4]. These technologies are pivotal in advancing the modern technological landscape, enabling the seamless integration of digital and physical worlds. However, despite their potential, existing systems face considerable challenges, including limited energy supply, integration difficulties, and inefficiencies in communication. These limitations hinder the widespread adoption and functionality of ubiquitous sensing systems, underscoring the need for innovative solutions.

The primary objective of this research is to develop ubiquitous sensing systems for activity and gesture recognition that address the above limitations. Specifically, the study aims to create a low-cost, energy-efficient system by integrating novel technologies and devices such as triboelectric nanogenerators (TENG) [3, 5], organic solar cells [1], and visible light communication (VLC) [7, 9, 2]. This approach not only promises to overcome the energy supply challenges but also enhances the integration and communication efficiency of the sensors. Moreover, by leveraging these advanced sensing technologies for precise activity and gesture recognition, the research seeks to contribute to smart human-computer interaction, thereby improving user experiences and system autonomy.

The research adopts a technical route that involves the design of new sensor structures, the development of data acquisition chips, and the construction of integrated systems. These methods are chosen to enhance ubiquitous activity and gesture sensing by offering more integrated, efficient, and self-sufficient solutions. Potential applications include intelligent home automation, health monitoring, and security surveillance. Integrating energy-harvesting capabilities with advanced sensing technologies can create more sustainable and user-friendly systems for the next generation of smart interconnectivity.

2 METHODOLOGY

This research employs TENG, ultraflexible organic solar cells, and VLC as direct embodiments of contact, non-contact, and spatial sensing, respectively, to enhance indoor ubiquitous sensing. The approach is designed to comprehensively capture human activities and hand gestures, aiming for intelligent and energy-efficient sensing in indoor environments. Advanced data analysis with a design data processing chip further enhances the system's efficiency and accuracy, offering an edge computing solution for energy-efficient ubiquitous sensing.

Based on the triboelectric effect, TENG generates electricity through the contact and separation of two different material surfaces [4]. In this research, TENG is utilized to develop a novel sensor for low-energy consumption and high efficiency to enhance the energy autonomy of ubiquitous sensing systems. Through meticulously designed structures, these sensors can capture the minimal energy produced by human motions and convert it into electrical power for self-sustaining the sensor's operations, representing an advancement in contact sensing. Exploring ultraflexible organic solar cells, this study leverages their dual function for energy harvesting and optical sensing, enhancing both energy efficiency and sensing stability [1]. When light is obstructed, the electrical current generated by the cells changes, enabling the detection of movements or alterations in the environment. The ultraflexible design allows for adaptability to various installation environments and effective operation under low-light conditions, providing a reliable energy supplementation source for the system and advancing non-contact sensing capabilities by harnessing ambient light. VLC employs light waves from LED sources for data transmission, offering a secure and efficient alternative solution to the increasingly congested radio frequency spectrum [8]. Beyond its capability for high-speed data communication, VLC can also be utilized for sensing purposes. This is achieved by analyzing the changes in light

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intensity caused by objects or movements within the environment, allowing for the detection of spatial patterns and interactions.

3 CURRENT WORK

The work starts with the development of a floor-based sensing system utilizing TENG [3, 5]. The TENG-based sensor, characterized by its low fabrication cost and flexibility, adeptly transforms gait movements into electrical signals, thereby eliminating the need for external power. Enhanced sensitivity of the TENG sensor units, combined with the deployment of a deep learning network, enabled us to achieve accuracies of 97.9% in activity recognition and 99.4% in user identification. An extension of this work into fitness exercise monitoring demonstrated its capability to accurately differentiate between standard and non-standard activities with a 97.2% success rate, suggesting its applicability in diverse fields such as smart homes and healthcare monitoring. Further investigations led to the development of SolareSkin, a system integrating ultraflexible organic solar cells for better energy harvesting and visible light sensing [1]. This dual-functional e-skin system not only efficiently captures light signals but also demonstrates commendable gesture and activity recognition capabilities, achieving accuracies of 97.3% for finger gestures and 96.7% for body activities. Its advanced system integration and application of machine learning models underscore its utility in wearable human-centric sensing. Subsequently, we addressed accurate indoor health monitoring through a system based on VLC technology [7]. This non-intrusive system combines VLC with an efficient signal analysis chip to passively monitor human postures and activities, ensuring user privacy and convenience. With accuracies exceeding 90%, this spatial sensing approach shows potential for broad applications in smart homes and healthcare facilities, offering a privacy-preserving and convenient solution for real-time health monitoring.

For sustainable human-computer interaction, we introduced SolarSense, a self-powered gesture recognition system utilizing solar cell arrays [6]. This system exemplifies a shift towards sustainable interfaces by combining energy harvesting with gesture sensing, achieving an accuracy exceeding 97%. This work broadens the scope of applications in industrial contexts, providing a sustainable and non-intrusive alternative to traditional gesture recognition technologies. Lastly, we explored the potential of VLC for non-contact gesture recognition within human-computer interaction [9]. By leveraging a cost-effective VLC setup optimized for indoor environments and supported by a comprehensive signal processing framework, we attained a gesture recognition accuracy of 95.7%. This achievement underscores the effectiveness of VLC as an interface in smart environments, enhancing the user experience through more intuitive and responsive interactions.

4 CONCLUSION AND FUTURE WORK

The utilization of TENG, solar cells, and VLC has demonstrated potential in enhancing ubiquitous sensing for intelligent human-computer interaction. Achievements include high recognition accuracies in both activity and gesture recognition. Future research will focus on further optimizing the energy efficiency and increasing the accuracy of these systems, exploring their integration into a wider array of applications, such as sleep monitoring, health parameter monitoring, home automation, etc. By continuing to advance these sensing technologies, we aim to unlock new possibilities for seamless interaction between humans and the digital world.

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REFERENCES

[1] Jiarong Li, Changshuo Ge, Jun Tao, Jingyang Wang, Xiaomin Xu, Xinlei Chen, Weihua Gui, Xiaojun Liang, and Wenbo Ding. 2023. Solareskin: self-powered visible light sensing through a solar cell e-skin. In *Adjunct Proceedings of the 2023 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2023 ACM International Symposium on Wearable Computers*.

[2] Jiarong Li, Chenxin Liang, Zixuan Xie, Xiaojun Liang, Wenbo Ding, Jian Song, and Xiao-Ping Zhang. 2024. Poster: real-time material and texture recognition using visible light communication. In *Proceedings of the 22st Annual International Conference on Mobile Systems, Applications and Services*.

[3] Jiarong Li, Zihan Wang, Zihao Zhao, Yuchao Jin, Jihong Yin, Shao-Lun Huang, and Jiyu Wang. 2021. Tribogait: a deep learning enabled triboelectric gait sensor system for human activity recognition and individual identification. In *Adjunct Proceedings of the 2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2021 ACM International Symposium on Wearable Computers*, 643–648.

[4] Jiarong Li, Changsheng Wu, Ishara Dharmasena, Xiaoyue Ni, Zihan Wang, Haixu Shen, Shao-Lun Huang, and Wenbo Ding. 2020. Triboelectric nanogenerators enabled internet of things: a survey. *Intelligent and Converged Networks*, 1, 2, 115–141.

[5] Jiarong Li et al. 2023. A triboelectric gait sensor system for human activity recognition and user identification. *Nano Energy*, 112, 108473.

[6] Jiarong Li et al. 2024. Demo: solarsense: a self-powered ubiquitous gesture recognition system for industrial human-computer interaction. In *Proceedings of the 22st Annual International Conference on Mobile Systems, Applications and Services*.

[7] Jiarong Li et al. 2024. Indoor health monitoring with vlc-based passive posture monitoring. In *2024 PhotonIcs & Electromagnetics Research Symposium (PIERS)*.

[8] Chenxin Liang, Jiarong Li, Sicong Liu, Fang Yang, Yuhan Dong, Jian Song, Xiao-Ping Zhang, and Wenbo Ding. 2023. Integrated sensing, lighting and communication based on visible light communication: a review. *Digital Signal Processing*, 104340.

[9] Xiaojun Liang, Jiarong Li, Chihan Xu, Zixuan Xie, Chaobo Zhang, Wenbo Ding, and Weihua Gui. 2024. Gesture recognition and control based on visible light communication. In *2024 43rd Chinese Control Conference (CCC)*.

[10] Zihan Wang, Jiarong Li, Yuchao Jin, Jiyu Wang, Fang Yang, Gang Li, Xiaoyue Ni, and Wenbo Ding. 2021. Sensing beyond itself: multi-functional use of ubiquitous signals towards wearable applications. *Digital Signal Processing*, 116, 103091.