Research Statement

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Background

With the advancements in low-power and miniature electronics, the last decades have witnessed the unprecedented prosperity of wearable technology. Various wearable devices (smartphone, smartwatch, wireless earbuds, etc.) have been employed as a computing platform for human-centered sensing, which, in turn, facilitates the understanding of human physiological behaviors, cognitive states, health conditions, etc. However, many practical issues, such as energy efficiency, robustness to interference, unknown correlation between behaviors, etc., hinder the large-scale real-world deployment of these systems. My research focuses on wearable computing, aiming to design practical, efficient, and intelligent wearable sensing systems. The methodologies and tools used in my research include theoretical modelling, machine learning, in-the-wild measurement and experimentation, as well as system design, instrumentation, and optimization.

Research Areas

- **Audio-based Human Sensing with Earables**

Recent years have witnessed a rapid growth of wireless earbuds in the wearable market. People wear them for various purposes like entertainment (listening to music) and fitness activities (e.g., running) in daily life, which makes earbud a promising platform for human sensing. However, the small form factor and lightweight requirement of earbuds pose challenges in integrating multiple specialized sensor on the device. Thus, we investigate sensors (more specifically, the in-ear microphones) that have already existed in most of the current wireless earbuds. We demonstrated that with the use of a phenomenon known as occlusion effect, in-ear microphone can be leveraged to achieve multiple human sensing applications. In details, the occlusion effect can amplifie the low-frequency bone-conducted sound in the ear canal when the orifice is sealed. As a result, vibrations induced by various human movements can be detected.

Activity Recognition: when human foot hit the ground, a vibration will be generated and then propagates across human body via bone conduction. When it reaches the occluded ear canal, the vibration will be amplified and picked up by the in-ear microphone. Consequently, we can achieve step counting and human activity recognition [7].

Gesture Recognition: every finger-tapping on human face will also generate a vibration signal which would be amplified in the ear canal. Since the propagation paths from different tapping spots are distinct, the vibration signal shows unique pattern for each location, resulting gesture-based interaction [7]. Moreover, such design transforms human face into the input interface for better user experience.

User Authentication: identifying the earbud's wearer allows personalized audio delivery and perception. We devised two mechanisms using the in-ear microphone for user authentication. First, the walking-induced signals captured by the in-ear microphone not only show the gait information but also reflect the unique skeleton of the user [8]. Second, given that the occlusion effect is determined by the unique ear canal geometry, the sounds captured by the in-ear and out-ear microphones exhibit a unique correlation [11, 16]. Both mechanisms have been demonstrated to achieve excellent user authentication performance.

Heart Rate (HR) Estimation: heart beat induced sound can also propagate to the in-ear and be amplified, thereby achieving HR estimation using the in-ear microphone. However, human walking and running generate much stronger vibration than heart beat, affecting the estimation performance. We devised a deep neural network to suppress such interference and achieved accurate HR tracking [12].

Speech Enhancement: human speech captured by the in-ear microphone is more robust to external noise due to the occlusion effect and the attenuation of earbuds. However, it lacks the high frequency speech information, thereby sounds unnatural. To enhance human speech in noisy conditions, we proposed the joint use of the in-ear and out-ear microphones, and designed a suit of techniques to effectively fuse the two signals [14].

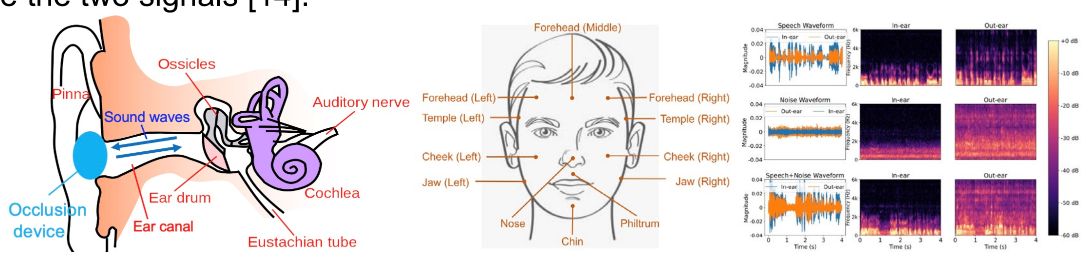

Fig.3 Illustration of ear canal anatomy and the occlusion effect (left), the designed face-tapping gestures (middle), and the comparison of in-ear and out ear speech/sound (right).

Breathing Mode Monitoring: Running is a popular and accessible form of aerobic exercise and breathing, which fuels our bodies with oxygen and expels carbon dioxide, is crucial to improving the efficiency of running. We presented the first breathing mode monitoring system that identifies four types breathing modes (oral inhale, oral exhale, nasal inhale, nasal exhale, as in Fig. 2) during running. It leverages the in-ear microphone on earbuds to record breathing sounds and combines the out-ear microphone on the same device to mitigate external noise and achieves 98% accuracy in quite condition [15].

This thread of work pioneers accurate yet robust audio-based human sensing on earables and exhibits the potential to breed a variety of sensing applications such as tooth clenching detection, dietary monitoring, etc. Moreover, since no hardware modification is required, these applications can be easily commercialized by simply implementing a software update.

- **On-device Computation**

The above research primarily focuses on exploring the feasibility of sensing applications based on specific sensing principles or improving sensing performance through advanced signal processing and deep learning. Therefore, although the data is collected from wearable devices, the actual processing (e.g., deep learning inference) is typically executed on powerful computing platforms (e.g., CPU and GPU) after data offloading, which often raises concerns related to privacy and latency. An intuitive solution is to perform on-device computation; however, this presents challenges due to the extremely limited computing resources available on wearable devices (at the microcontroller level). My research in this area targets two directions: (1) achieving accurate and efficient on-device inference with strict memory constraints, and (2) enabling adaptive on-device inference in dynamically changing conditions. In [16], we proposed a novel selector-classifiers framework, where multiple small classifiers with complementary expertise are connected to a compact selector model. During inference, each input sample is first pre-processed by the selector to identify its characteristics, and then routed to an appropriate classifier for classification. The diversity in classifier's expertise guarantees the accuracy of the framework, while inference using a single classifier per sample minimizes memory and computation overhead. To effectively train such a framework, we developed multiple strategies from the perspective of data preparation, model architecture, and training scheme. This work was awarded the Best Paper Award at PerCom'24. Generally, a pre-trained model experiences performance degradation when deployed in dynamically changing conditions due to distribution shifts in incoming data compared to the training data. As a result, it is essential to continuously adapt (fine-tune) the pre-trained model to maintain performance, a process known as test-time adaptation (TTA). Previous works have focused on adapting the model for every incoming batch of data to ensure optimal performance; however, in practice, latency and energy consumption are often more critical, particularly for battery-powered wearable systems. Therefore, we introduced an on-demand TTA framework that adapts the pre-trained model only when necessary. We proposed novel and lightweight strategies to detect distribution shifts for triggering adaptation, select the appropriate source model for more effective adaptation, and perform memory-efficient adaptation using small batch sizes.

- **Ultra-low-power Sensing with Energy Harvesting Wearables**

Wearable devices are usually powered by batteries with a limited energy budget. Frequent recharging or battery replacement poses burdens on users, increases the cost, and restricts long-term sensing and monitoring. To extend the battery lifetime, my research innovates in two dimensions by integrating energy harvesters into wearable devices. Specifically, the energy harvester not only serves as an extra power source (by harvesting energy from human activities or surrounding environment) but also works as an energy-free sensor to sense human behaviors.

The following describes two threads of work that realize the proposed idea on different wearables with different energy sources.

Kinetic Energy Harvester based Human Activity Sensing: Since human daily activities (e.g., walking and running) contain fruitful kinetic energy, we utilize the piezoelectric energy harvester to acquire the energy. In the meantime, the electrical output of the energy harvester is used as the sensing signal to infer human activities, based on the rationale that energy generation is actually resulted from human movements. With this principle, we explored and demonstrated multiple applications including human activity recognition [1], transportation mode detection [2], short-range acoustic communication [3], and gait recognition [4-5]. One step further, we optimized the system hardware design and proposed a suite of signal processing techniques to achieve simultaneous energy harvesting and sensing. This work was published at IEEE IoTDI 2018 [4] and IEEE TMC [5], and its corresponding demonstration received the Best Demo Runner-up Award at IoTDI 2018.

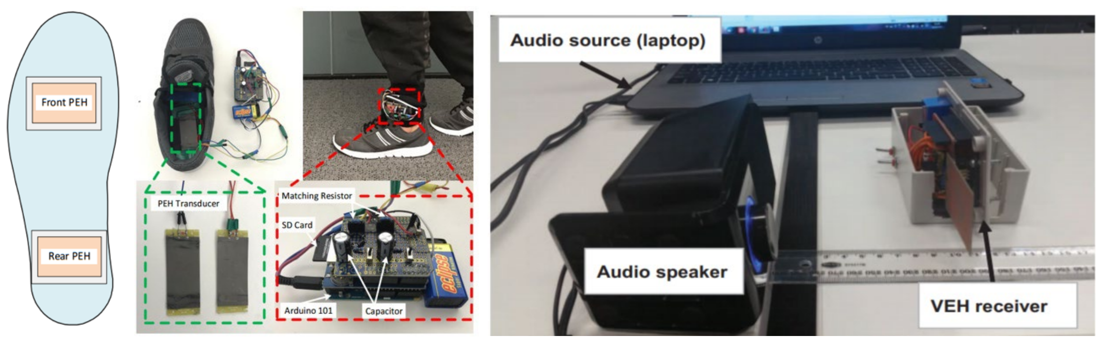

Fig.1 Energy harvesting prototype for human activity recognition and gait authentication (left), and for acoustic communication (right).

Solar Cell based Hand Gesture Recognition: besides human motions, the environment is another viable energy source for wearable devices. Solar energy harvesting is a promising direction due to the omnipresent availability, high energy density, and cost-free nature of light/sunlight. However, conventional silicon solar panels are opaque and rigid, making their adoption on wearables problematic in both integration difficulty and impairment on device appearance. To obviate this issue, we built organic transparent solar cells (looks like clear glass), which can transform the screen of electronics into an energy harvesting surface. Moreover, we achieved gesture recognition with solar cells, where the key insight is that each gesture interferes with incident light rays on the solar cell in a unique way, leaving its distinguishable signature in the harvested photocurrent. We further developed a 2x2 solar cell array to extend the number of gestures into fifteen with a recognition accuracy of 95%. The initial work was published at ACM MobiCom 2019 [6] and its extension was published at TMC [9]. Later, we also demonstrated that solar cells equipped on self-powered IoTs can be used for indoor localization [10].

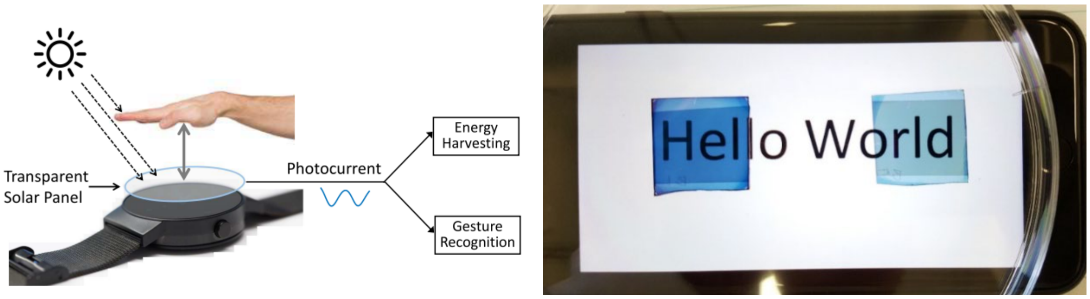

Fig.2 Solar cell based energy harvesting and gesture recognition (left), and the developed solar cells (right).

Although these works are established on wearable devices only, the proposed ideas are general and can be easily extended to the full spectrum of IoT systems. For instance, kinetic energy harvesters can gather energy from wind while estimating its speed and strength in environment monitoring applications or harvest energy from bridge/railway vibrations while performing structural health monitoring. Solar cells can be integrated into outdoor vending machines to collect energy from sunlight and allow gesture-based interaction/purchasing, or be equipped on smart home IoTs that support gesture control.

- **Future Research Agenda**

In the past few years, I have designed and demonstrated new sensing mechanisms that enrich the context sensing toolset for IoTs. I plan to continue this adventurous and exciting journey of exploring innovative and pioneering sensing modalities in future research. However, building upon my interdisciplinary research experience in mobile systems and machine learning, I intend to diversify into broader domains that can push the practical adoption and deployment of IoT systems in the real world. Specifically, I will dive into the following two research avenues:

Healthcare with Earables. Earables have been envisioned as the dominant device in the wearable market in the next few years. Serving as a computing platform, earables own great potential for future human-centric sensing compared to traditional wearables due to (1) earables are worn in the upper part of the body, which not only complements the sensing scope of smartphones/smartwatches, but also is more robust to intensive body artefacts (e.g. hand swing) during motion detection; (2) the human ear is an ideal position to capture various neurological, cardiovascular, and dietary signs, which promises great sensing potential for health monitoring. I have explored the use of audio signals for human activity detection, while there are a bunch of sensing modalities (such as EEG, EMG, PPG) that are critical for healthcare applications. Consequently, I plan to explore the usage of such modalities in different health monitoring, disease detection and intervention applications. Moreover, given the context of healthcare, I would shift more attention to the robustness and reliability of the system.

Tiny Machine Learning on IoTs. Machine learning or deep learning has become a disruptive technology in almost all fields of modern science, yet with an essential requirement of advanced computation power. However, the fundamental characteristic that differentiates IoTs from other electronics (e.g., phones, laptops, and data centers) is the extremely constrained computation and storage resources. To feast the power of deep learning in real-world IoT systems, substantial customization and adaptation of existing deep learning techniques should be made. Our preliminary work has investigated efficient frameworks of integrating deep learning into wearable sensing [13]. Next, I plan to work on several aspects of tiny machine learning, including novel inference frameworks design, heterogeneous model design, collaborative task execution, and in-the-wild implementation.

Overall, I am excited to conduct interdisciplinary research on sensing, systems, and artificial intelligence in the IoT world. I believe pervasive, intelligent, and efficient IoT systems would have a significant impact on shaping the cyber-physical world.

Selected Publications and Outputs

[1] G. Lan, D. Ma, W. Xu, M. Hassan, and W. Hu, “Capacitor-based activity sensing for kinetic-powered wearable IoTs”, in ACM Transactions on Internet of Things (TIoT’20), vol. 1, no. 1, pp. 1–26, 2020.

[2] G. Lan , W. Xu, D. Ma, S. Khalifa, M. Hassan, and W. Hu, “EnTrans: Leveraging kinetic energy harvesting signal for transportation mode detection”, in IEEE Transactions on Intelligent Transportation Systems (TITS’20), vol. 21, no. 7, pp. 2816–2827, 2020.

[3] G. Lan, D. Ma, M. Hassan, and W. Hu, “HiddenCode: Hidden acoustic signal capture with vibration energy harvesting”, in Proceedings of the IEEE International Conference on Pervasive Computing and Communication (PerCom’18), 2018.

[4] D. Ma, G. Lan , W. Xu, M. Hassan, and W. Hu, “SEHS: Simultaneous energy harvesting and sensing using piezoelectric energy harvester”, in Proceedings of the ACM/IEEE International Conference on Internet-of-Things Design and Implementation (IoTDI’18), 2018. [Corresponding demo received the Best Demo Runner-up Award at IoTDI’18]

[5] D. Ma, G. Lan , W. Xu, M. Hassan, and W. Hu, “Simultaneous Energy Harvesting and Gait Recognition using Piezoelectric Energy Harvester”, in IEEE Transaction on Mobile Computing (TMC’20), 2020.

[6] D. Ma, G. Lan , M. Hassan, W. Hu, M. B. Upama, A. Uddin, and M. Youssef, “SolarGest: Ubiquitous and battery-free gesture recognition using solar cells”, in Proceedings of the ACM Annual International Conference on Mobile Computing and Networking (MobiCom’19), 2019.

[7] D. Ma, A. Ferlini, and C. Mascolo, “OESense: Employing Occlusion Effect for In-ear Human Sensing”, in The 19th ACM International Conference on Mobile Systems, Applications, and Services (MobiSys’21), 2021.

[8] A. Ferlini*, D. Ma*, R. Harle, and C. Mascolo, “EarGate: Gait-based User Authentication with Earables”, in Proceedings of the ACM Annual International Conference on Mobile Computing and Networking (MobiCom’21), 2021. [Co-primary Authors]

[9] D. Ma, G. Lan , M. Hassan, W. Hu, M. B. Upama, A. Uddin, and M. Youssef, “Recognizing Hand Gestures using Solar Cells”, in IEEE Transaction on Mobile Computing (TMC’22), 2022.

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[11] Hu C, Ma X, Ma D, and Dang T, "Lightweight and Non-invasive User Authentication on Earables", in the Twenty-fourth International Workshop on Mobile Computing Systems and Applications (HotMobile'23), 2023.
[12] Butkow K J, Dang T, Ferlini A, Ma, D, Mascolo, C, "hEARt: Motion-resilient Heart Rate Monitoring with In-ear Microphones", in IEEE International Conference on Pervasive Computing and Communications (PerCom'23), 2023.
[13] Pham, N., Jia, H., Tran, M., Dinh, T., Bui, N., Kwon, Y., Ma, D., Nguyen, P., Mascolo, C. and Vu, T. "PROS: an efficient pattern-driven compressive sensing framework for low-power biopotential-based wearables with on-chip intelligence", in Proceedings of the 28th Annual International Conference on Mobile Computing and Networking (MobiCom'22), 2022.
[14] Dong Ma, Ting Dang, Ming Ding, Rajesh Balan. "ClearSpeech: Improving Voice Quality of Earbuds Using Both In-Ear and Out-Ear Microphones.", The Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies (IMWUT'23), 2023.
[15] Changshuo Hu, Thivya Kandappu, Yang Liu, Cecilia Mascolo, and Dong Ma. "BreathPro: Monitoring Breathing Mode during Running with Earables." Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies (IMWUT'24), 2024.
[16] Changshuo Hu, Xiao Ma, Xinger Huang, Yiran Shen, and Dong Ma. "LR-Auth: Towards Practical Implementation of Implicit User Authentication on Earbuds." Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies (IMWUT'24), 2024.
[17] Xiao Ma, Shengfeng He, Hezhe Qiao, and Dong Ma. "DiTMoS: Delving into Diverse Tiny-Model Selection on Microcontrollers." In 2024 IEEE International Conference on Pervasive Computing and Communications (PerCom'24), 2024.