From Body Heat to Behavioral Horizons: Spatial Sensing Intelligence with Thermal Arrays

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Abstract

While humans spend most of their lives indoors, our built environments remain largely *blind* to their behavior. My research establishes **Spatial Sensing Intelligence**, leveraging low-cost, passive thermal arrays for non-intrusive, privacy-preserving human perception. To overcome the limited spatial resolution of passive heat signals, I develop physics-informed deep learning frameworks that transform 2D thermal maps into high-fidelity 3D body representations. These geometric representations directly unlock diverse applications, including fine-grained around-device control, sleep monitoring, and fall detection, validated by a 256-day real-world campus deployment. Moving forward, I extend this vision through interpretable modeling and multi-modal sensing, paving the way for natively human-aware indoor spaces.

CCS Concepts

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

Keywords

Spatial Intelligence, Human Sensing, Thermal Array.

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1 Motivation

Humans spend 80–90% of their lives indoors, yet built environments remain fundamentally *blind* to their occupants. While *digital twins* digitize static infrastructure, the lack of continuous human perception creates vulnerabilities in safety, efficiency, and health. My research establishes *Spatial Sensing Intelligence*, which enables buildings to continuously and privately infer human posture, motion, and interaction. Concretely, this enables always-on, privacy-preserving sensing for applications such as occupancy-aware energy control, safety monitoring (*e.g.*, fall detection), and health/behavior tracking (*e.g.*, sleep monitoring) without cameras or wearables.
Design Requirements: To realize this vision at scale, a sensing modality must satisfy four stringent criteria: (1) Non-contact (embedded in the built environment; no wearables); (2) Low-cost (building-scale deployment); (3) High-utility (capturing complex body geometry); and (4) Privacy-preserving (suitable for sensitive spaces). Together, these requirements ensure practical deployability while preserving trust in everyday living and care environments.

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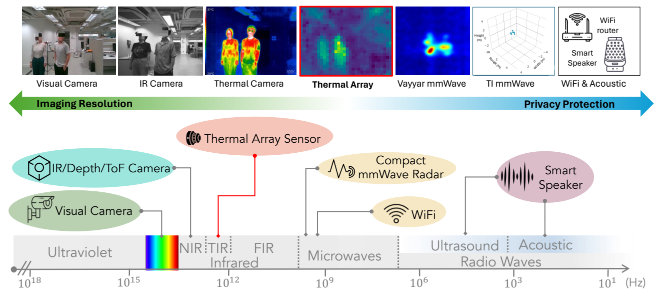

Figure 1: Non-contact human sensing modalities. Thermal arrays strike an optimal balance between imaging resolution and physical-layer privacy.

Why Thermal Arrays? As Fig. 1 shows, conventional modalities face fundamental bottlenecks. Visible light and ToF cameras offer high utility but fail strict privacy requirements. Conversely, LiDAR and radar provide privacy but are prohibitively expensive or suffer from low spatial resolution at the edge. WiFi and acoustic sensing lack the boundary definitions required for fine-grained body geometry. I identify *low-cost thermal arrays* as the optimal pathway. They balance imaging resolution and privacy, offering: (1) Passive, 24/7 perception: harnessing naturally emitted body heat (8–15 μm) without active signals; (2) Inherent privacy: capturing unidentifiable heat signatures; and (3) Multiphysics richness: naturally encoding temperature, emissivity, and spatial cues.
The Core Challenge: The central bottleneck is the limited 3D spatial resolution and noisy nature of passive heat signals. My research overcomes this by recovering fine-grained 3D geometry from sparse heat distributions, scaling from foundational algorithms to full systems and cross-modal extensions (Fig. 2). The key idea across my work is to treat heat propagation and radiative physics as structured constraints, combining them with learning-based priors to recover depth, shape, and dynamics from sparse, noisy measurements.

2 3D Geometry from Heat

To translate 2D thermal pixels into actionable spatial awareness, my research first tackles the fundamental depth deficiency of heat signals. I began by developing TADAR [8], the first system capable of multi-user ranging using only passive thermal radiation. By recovering range information from sparse heat distributions, TADAR

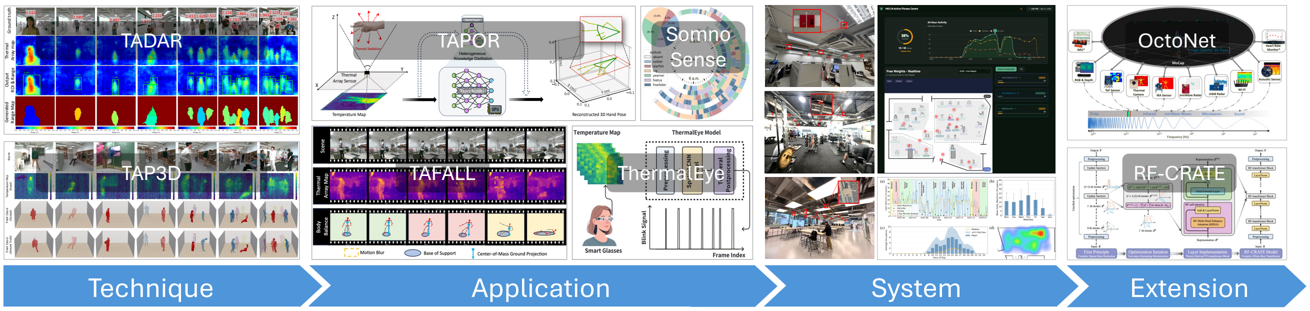

Figure 2: Overview of thermal-array-based Spatial Sensing Intelligence. My research spans core techniques, edge applications, long-term system deployments, and multi-modal extensions.

successfully transforms flat 2D thermal maps into 3D spatial coordinates, achieving a ranging accuracy of 20.1 cm and thereby establishing a robust, privacy-preserving alternative to active RF sensing. Building upon this foundational localization, I critically extended this capability beyond simple coordinate tracking toward full-body digitization with TAP3D [5]. TAP3D reconstructs dense 3D human point clouds directly from low-resolution heat signatures by employing a novel physics-informed architecture that integrates forward thermal radiation models with geometric perspective fusion. By effectively disentangling multiple users and suppressing environmental thermal interference, this progression from point-level localization to dense 3D reconstruction enables complex downstream spatial tasks, including continuous indoor tracking (21.86 cm MAE) and fine-grained human mesh recovery (4.87 cm error).

3 Applications at the Edge

Building on these geometric foundations, I expanded thermal sensing to diverse IoT, mobile, and healthcare applications spanning (i) around-device interaction, (ii) privacy-critical healthcare monitoring, (iii) ambient safety, and (iv) wearable form factors. To push the limits of thermal resolution for around-device interaction, I developed TAPOR [6], which formulates 3D hand pose estimation as a retrieval task. By applying heterogeneous knowledge distillation, it reduces computational overhead by 377×, enabling complex gesture control on resource-constrained edge devices. Beyond interaction, I adapted these spatial principles for privacy-critical monitoring. SomnoSense [3] fuses thermal arrays with low-cost dToF sensors for continuous, non-contact sleep monitoring, effectively overcoming blanket occlusion to achieve 96.1% posture recognition accuracy. For ambient safety, TaFall [2] detects falls by estimating pose-driven biomechanical balance dynamics, achieving a 98.26% detection rate. Finally, ThermalEye [1] demonstrates the modality's extreme scalability by integrating a miniature 12×16 thermal array into smart glasses for robust, fully passive eye-blink detection.

4 Real-World System Deployment

To validate long-term robustness as ubiquitous infrastructure, I deployed these systems across three real-world environments (an office, student activity center, and gym) for up to **256 days**. Continuous passive sensing successfully uncovered macro-level human rhythms, capturing distinct temporal signatures—from the stable, routine-driven usage of the office to the volatile, event-driven spikes of the student activity center and gym. These multi-month deployments confirm that thermal arrays can reliably capture institution-scale spatial dynamics while strictly preserving individual privacy.

5 Future Horizons

Moving forward, I am extending Spatial Sensing Intelligence toward interpretable and cross-modal architectures. As an early exploration into interpretable human sensing models, I developed RF-CRATE [7], a mathematically transparent white-box transformer that addresses the black-box limitations of current deep wireless sensing. Furthermore, to unlock "thermal+X" synergies, I introduced OctoNet [4], a large-scale dataset capturing 67.72 million synchronized frames across 12 heterogeneous modalities to drive the next generation of multimodal spatial intelligence. Ultimately, by converging thermal physics with advanced machine learning, my research reframes body heat as a rich signal that continuously encodes human geometry and motion. I envision a future where our built environments intuitively understand and adapt to human dynamics.

6 Short Biography

Xie Zhang is a fourth-year Ph.D. candidate at the University of Hong Kong, supervised by Prof. Chenshu Wu. He also serves as the Chief Scientist of the startup SenseAI Tech.

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