A Review of Comprehensive Human Sensing Systems for Intelligent Home Automation

Yuheng Zhu[1]

[1]Department of Mechanical Engineering, University College London, London, United Kingdom
zcemhuk@ucl.ac.uk

Abstract. Human presence sensing is essential for enabling intelligent and adaptive control in smart home systems. Traditional single-sensor approaches, such as passive infrared (PIR), millimeter-wave radar, and ambient light sensors, often suffer from specific limitations, including poor performance in detecting stationary individuals, environmental interference, and lack of direct human identification. To overcome these challenges, multi-sensor fusion strategies have been introduced, combining PIR, millimeter-wave radar, and illuminance sensors to form comprehensive sensing systems. These systems improve detection accuracy, reduce false alarms, and enhance energy efficiency by coordinating sensor functions and applying intelligent decision logic. For instance, using PIR for initial motion detection and radar for continued presence recognition balances low power consumption with high detection reliability. Light sensors contribute additional environmental context for smarter lighting control. This paper presents a comparative study of integrated versus traditional sensors, outlines their applications in lighting, HVAC, security, and elderly care, and discusses key challenges such as power management and signal integration. Emerging technologies including WiFi-based sensing, pressure monitoring, and edge computing are also explored as future directions. The findings suggest that comprehensive human sensing offers a promising foundation for next-generation smart home systems.

Keywords: Human Presence Detection, Sensor Fusion, Smart Home, Energy Efficiency

1 Introduction

The rapid evolution of smart home technologies has been driven by increasing demands for comfort, energy efficiency, and automation in modern living environments. At the core of these systems lies the ability to accurately perceive human presence, enabling intelligent control of lighting, HVAC, security, and health-monitoring devices. Without reliable presence detection, these systems cannot provide truly user-centric experiences or respond appropriately to changing conditions.

Traditional presence detection solutions typically rely on single-sensor technologies such as Passive Infrared (PIR) sensors, millimeter-wave (mmWave) radar, or ambient

J. Iqbal (ed.), *Proceedings of the 2025 2nd International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2025)*, Advances in Engineering Research 272,
https://doi.org/10.2991/978-94-6463-821-9_79

light sensors. While each sensor type offers distinct benefits—such as PIR's low power consumption and mmWave's ability to detect micro-movements—each also suffers from specific limitations. PIR sensors cannot detect stationary individuals and are sensitive to ambient temperature changes, while mmWave radars are prone to high power consumption and environmental interference. These drawbacks become particularly pronounced in complex, dynamic home environments, where false detections and missed events degrade both system accuracy and user satisfaction.

To address these challenges, researchers and developers have increasingly turned to sensor fusion approaches, combining multiple sensor modalities into a comprehensive detection system. By integrating PIR sensors, mmWave radar, and illuminance sensors, and enhancing them through AI-powered signal processing, these systems achieve greater accuracy, robustness, and adaptability. Such solutions can not only distinguish between human and non-human motion but also operate effectively under varying lighting, temperature, and spatial conditions.

This paper investigates the structure, functionality, and applications of comprehensive human presence sensor systems in smart homes. It first reviews the principles and limitations of traditional single-sensor solutions. Then, it introduces the concept and working mechanism of integrated sensing systems, highlighting their benefits in various application scenarios such as lighting control, environmental adjustment, security, and healthcare. Furthermore, the paper explores key challenges—including power consumption, data fusion complexity, false alarms, and privacy concerns—and discusses potential optimization strategies and future development directions. Through this analysis, the research aims to support the design and deployment of next-generation human-aware smart home systems.

2 Traditional Single Sensors

2.1 Manuscript formatting requirements

2.1.1 Passive Infrared (PIR) Sensors.

Passive Infrared (PIR) sensors are commonly used for human presence detection and are widely applied in smart homes, security systems, and automatic lighting controls. The working principle is based on detecting changes in infrared radiation emitted by the human body. Humans naturally emit infrared radiation in the wavelength range of 8–14 μm [1]. When a person enters the detection range of a PIR sensor, their infrared radiation alters the thermal distribution in the area, triggering a signal change in the sensor. This signal is processed by a pyroelectric detector and used to control smart devices, such as turning on lights, triggering security alarms, or adjusting air conditioning. This working principle is illustrated in Figure 1, which shows how PIR sensors respond to infrared radiation emitted by the human body.

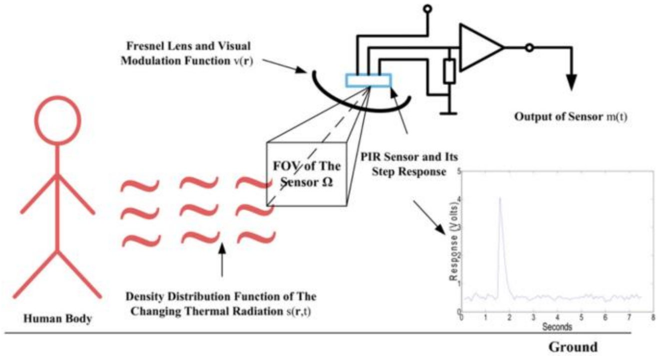

Fig. 1. PIR Sensor Response to Infrared Radiation from Human Body [2].

2.1.2 Advantages of PIR Sensors.

The main advantages of PIR sensors are their low power consumption and cost-effectiveness. Since they only output signals upon detecting infrared changes rather than operating continuously, they are ideal for battery-powered devices such as wireless smart home sensors and standalone security alarms. Additionally, their mature technology and low production cost make them easy to integrate into smart home systems [3]. For example, in hallway lighting control, the lights are triggered when someone enters the corridor and automatically turn off after they leave, saving energy. PIR sensors are also used in door access systems and security alarms to enhance convenience and safety.

2.1.3 Limitations of PIR Sensors.

Despite their widespread application, PIR sensors have several limitations:

1. Inability to Detect Stationary Humans: PIR sensors rely on detecting dynamic changes in infrared radiation. If a person remains still—such as reading, working at a desk, or sleeping—the sensor may misjudge the room as unoccupied, causing lights to turn off or air conditioning to stop, which negatively impacts user experience.

2. Susceptibility to Ambient Temperature: PIR sensors are affected by environmental temperature. In high-temperature conditions (above 30°C), the temperature difference between the human body and surroundings decreases, reducing detection sensitivity [4]. In cold conditions, PIR sensors may falsely detect warm objects like heaters or moving hot air.

3. Limited Detection Range: The typical range is 2–12 meters, depending on the Fresnel lens design and sensor sensitivity [5]. A single PIR sensor may not cover large spaces, leading to blind spots. Multiple sensors may be required in such settings.*1.1.8 Section Headings:* all section heading should be numbered and no more than 3 levels (e.g. 1,1.1 and 1.1.1) of headings should be used.

2.1.4 Typical Applications of PIR Sensors.

Despite their limitations, PIR sensors remain widely used due to their low cost, low power consumption, and ease of deployment. In corridors and stairways, they enable automatic lighting systems that conserve energy. In smart access systems, they provide contactless activation for automatic doors. Additionally, they are used in security systems to detect motion and trigger alarms, enhancing home safety.

2.2 Millimeter-Wave Radar Sensors (mmWave)

2.2.1 Working Principle of Millimeter-Wave Radar.

Millimeter-wave (mmWave) radar is a high-frequency sensing technology, commonly operating at frequencies such as 24 GHz, 60 GHz, and 77 GHz. It detects and analyzes the position and movement of objects based on principles like the Doppler effect, time-of-flight (ToF), and frequency-modulated continuous wave (FMCW) [6]. The radar continuously emits millimeter-wave signals and receives the waves reflected from surrounding objects. By analyzing the frequency shift and time delay of the echoes, the system can determine the distance, speed, and direction of the object.

Unlike passive sensors such as PIR, mmWave radar actively senses its environment. It can not only detect human movement but also pick up subtle physiological activities like breathing and heartbeat, making it well-suited for health monitoring applications. Moreover, it does not rely on ambient light or temperature differences and can function reliably even in dark, smoky, or high-temperature environments, where traditional infrared sensors often fail. Thanks to these advantages, mmWave radar is widely used in applications such as smart lighting, security surveillance, and human presence detection. The underlying working principle and signal flow of a typical 24 GHz mmWave radar system are illustrated in Figure 2.

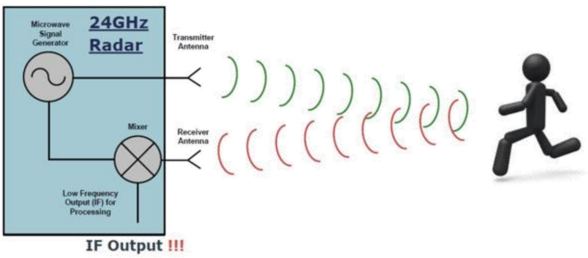

Fig. 2. Schematic Diagram of 24GHz Millimeter-Wave Radar Operation for Motion Detection [7].

2.2.2 Advantages of mmWave Radar.

mmWave radar offers unique advantages in smart home applications. It can penetrate non-metallic materials such as glass and plastic, enabling hidden installations that maintain room aesthetics. For instance, it can be embedded in a ceiling panel to detect room occupancy even with the door closed, allowing for intelligent control of lighting and HVAC systems.

Moreover, mmWave radar can detect stationary individuals by analyzing micro-movements like breathing and heartbeat, ensuring that users who remain still for extended periods are not mistakenly classified as absent [8]. In smart bedroom systems, mmWave radar mounted near the bed can monitor sleep states in real time and adjust temperature and humidity accordingly. In elderly care applications, it can detect falls by recognizing prolonged immobility and abnormal posture changes, triggering timely alerts to caregivers.

Furthermore, mmWave radar is highly adaptable to various environmental conditions and remains effective regardless of lighting, temperature, or smoke. For example, in poorly lit spaces like underground parking lots or tunnels, it can monitor pedestrian movement without degradation in performance.

2.2.3 Limitations of mmWave Radar.

High Power Consumption: Due to continuous signal transmission and reception, mmWave radar consumes significantly more power than PIR sensors. This limits its use in battery-powered devices unless energy optimization strategies are implemented.

Environmental Interference: Reflections from surfaces like walls, glass, and furniture can disrupt radar accuracy, leading to false detections [9]. In open-plan living spaces, furniture placement may cause incorrect readings of human presence. AI algorithms are typically used to optimize signal interpretation and reduce false positives.

False Alarm Rate: Moving objects such as curtains or fans can be mistakenly detected as human movement, triggering unintended system responses. To mitigate this, mmWave radar is often combined with PIR sensors and enhanced by AI algorithms that differentiate between human and non-human motion patterns.

2.2.4 Limitations of Single Sensors.

In complex home environments, the performance limitations of single sensors are increasingly evident. They cannot meet the demands for high precision, low power consumption, and multi-scenario adaptability. Thus, integrating multiple sensing methods into a comprehensive sensor system has become a focal point for both research and engineering practice.

2.2.5 Comparison and Integration of mmWave and PIR.

PIR sensors are quick to respond to moving people and have low power consumption, but they cannot detect stationary individuals and are affected by temperature changes. mmWave radar, on the other hand, can sense micro-movements and penetrate materials, making it suitable for detecting static presence. However, it is more expensive and power-hungry and can produce false alarms in complex environments. The two sensor types complement each other in terms of sensing capability and applicable scenarios, as summarized in Table 1. Integrating their strengths is a promising direction for improving the reliability of smart home systems.

Table 1. Comparative Analysis of mmWave Radar and PIR Sensor in Smart Home Applications

Feature / Metric	mmWave Radar	PIR Sensor
Detectable Targets	Micro-movements, stationary humans, penetrates materials	Only detects moving targets, cannot detect stationary individuals
Environmental Adaptability	Can penetrate some materials, suitable for complex environments	Easily affected by temperature changes, lower adaptability
False Alarm Rate	May cause false alarms in complex environments	Relatively low false alarm rate, limited detection range
Power Consumption	High power consumption	Low power consumption
Cost	Expensive	Low cost
Response Speed	Fast	Fast
Typical Application Scenarios	Static human presence detection, high-precision sensing	Basic human motion detection, energy-saving control (e.g., automatic lighting)
Advantages Summary	High detection accuracy, powerful capabilities	Simple, low-cost, energy-efficient

Disadvantages Summary	High power usage, high cost, prone to false alarms in complex settings	Cannot detect stationary targets, susceptible to temperature changes

3 Comprehensive Human Presence Sensors

3.1 Limitations of Traditional Single Sensors

Traditional single sensors exhibit several limitations in human presence detection, impacting the accuracy of smart home systems and the overall user experience.

Firstly, PIR sensors rely on detecting changes in infrared radiation, making them incapable of sensing stationary individuals [10]. If a person remains still in a room—such as reading or working at a desk—the PIR sensor may misjudge the space as unoccupied. This misjudgment can lead to undesired consequences like lights turning off or air conditioning shutting down, thereby degrading user satisfaction.

Secondly, although mmWave radar sensors offer high-precision detection, including the ability to sense micro-movements such as breathing or heartbeat, their continuous operation consumes substantial power. This restricts their use in battery-powered devices. Furthermore, mmWave radar is prone to environmental interference from dynamic objects like oscillating fans or moving curtains, which may be misinterpreted as human presence, triggering unexpected system behavior [11].

3.2 Composition and Principle of Integrated Sensors

Comprehensive human presence sensors integrate PIR, mmWave radar, and illuminance sensors. By combining sensor fusion with AI-driven optimization, they provide a smart detection solution. This approach offers high accuracy, energy efficiency, and strong resistance to false positives.

Initially, the PIR sensor is used for primary motion detection. Upon identifying movement, it triggers the smart home system to initiate preliminary responses such as turning on lights or adjusting the air conditioning. However, once the person stops moving, the PIR sensor alone cannot maintain reliable status updates.

Next, the mmWave radar sensor is activated to precisely detect stationary individuals. It confirms human presence by analyzing micro-movements like respiration or heartbeat. This ensures that even when users remain still for extended periods, the system continues to recognize their presence, avoiding premature deactivation of lighting or HVAC systems.

Finally, AI-based data fusion technologies optimize the combined sensor outputs. These algorithms analyze signals from PIR, mmWave radar, and illuminance sensors to reduce false alarms and improve detection accuracy. For instance, AI can learn user activity patterns and distinguish between genuine human movements and disturbances from non-human sources like fans or curtains.

In summary, integrated sensors offer significant advantages: improved detection accuracy, reduced false positives, lower energy consumption, and better adaptability to smart home environments. They provide a stable and precise sensing capability essential for next-generation smart systems. The overall control logic and functional workflow of such a multi-sensor fusion system are illustrated in Figure 3.

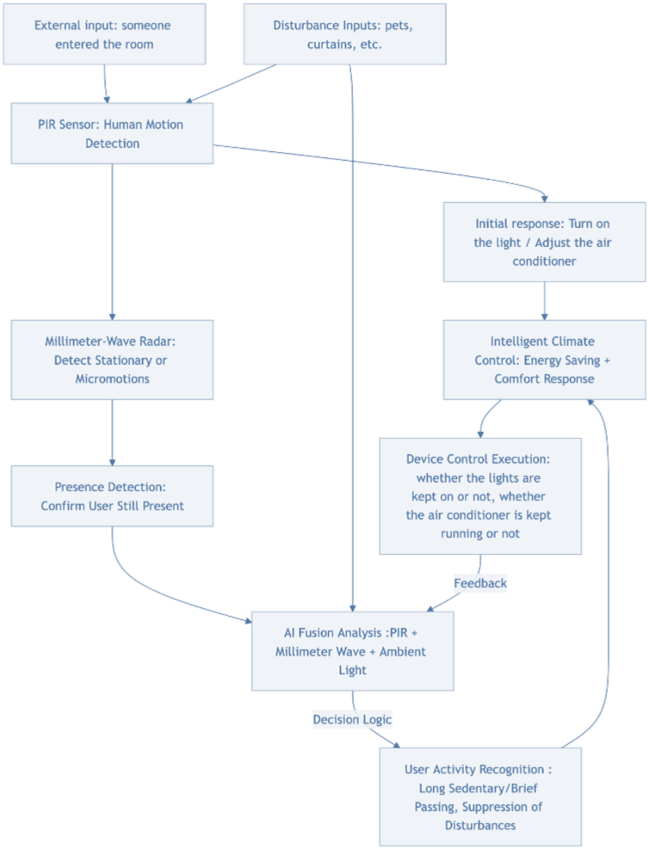

Fig. 3. Flowchart of the Human Presence-Aware Intelligent Control System Based on Multi-Sensor Fusion.

4 Application Scenarios of Integrated Sensors

4.1 Intelligent Lighting Control

In smart home environments, automated lighting control is critical for both energy conservation and user experience. Traditional PIR sensors may misjudge rooms as unoccupied when users are stationary, resulting in unintended light deactivation. Integrated human presence sensors—combining PIR, mmWave radar, and illuminance sensors—allow for more accurate lighting management.

mmWave radar ensures detection of static human presence, preventing lights from turning off when users are sitting or sleeping. The illuminance sensor monitors ambient brightness, enabling the system to adjust indoor lighting based on external light conditions. For example, on a sunny day, the lights may dim or turn off to save energy, while in darker settings, they automatically brighten to improve visual comfort.

4.2 Smart Air Conditioning and Environmental Control

In intelligent air conditioning systems, accurate human presence detection governs the start-stop logic. Since PIR sensors cannot detect stationary individuals, they may cause the air conditioner to shut off unexpectedly. mmWave radar detects subtle movements like breathing, ensuring continuous recognition of users and uninterrupted climate control.

The illuminance sensor also helps manage energy by adjusting curtain states. During daytime, curtains may open automatically to reduce reliance on air conditioning. For instance, in summer, the system may close curtains based on illuminance data to block sunlight and reduce indoor temperatures. If mmWave radar detects absence, the system can lower or disable air conditioning to save energy.

4.3 Security Monitoring

Smart security systems require accurate human presence detection with minimal false alarms. PIR sensors are easily disturbed by environmental changes, such as moving curtains or pets. mmWave radar adds an extra layer of validation by confirming whether the detected target is a real human.

AI-powered data fusion allows the system to analyse signals from all three sensors, improving accuracy. For example, at night, if PIR detects motion but mmWave radar does not identify micro-movements like breathing or heartbeat, the system may determine the source to be non-human and withhold the alarm. Only when both sensors confirm unusual activity will the system notify the user, increasing reliability.

4.4 Health Monitoring and Elderly Care

In elderly care and health monitoring, human sensing technology enables remote surveillance and safety assurance. mmWave radar can monitor breathing and heart rate, while AI algorithms analyze the data for anomalies, such as sleep apnea or irregular heart rhythms.

Furthermore, mmWave radar can detect falls by recognizing long periods of immobility or abnormal posture. When a fall is detected, the system immediately sends alerts through the smart home network to caregivers or family members, enhancing emergency response.

In summary, integrated human presence sensors show great potential across various smart home applications. Through sensor fusion and AI optimization, they not only enhance system responsiveness and user experience but also contribute to energy savings and environmental sustainability. As sensor and data processing technologies continue to improve, their application scope will further expand, driving the advancement of smart home technology.

5 Challenges and Optimization Strategies

5.1 Power Consumption Issues

Due to continuous transmission and reception of high-frequency electromagnetic waves, mmWave radar consumes more power compared to other sensor types. This becomes a significant challenge for battery-powered smart home devices. As smart home systems become more widely deployed, the need for low-power, high-efficiency sensors continues to grow. Therefore, optimizing power consumption is essential for system stability and extended operation.

5.1.1 Wired Power Supply Solution.

A straightforward solution is to use wired power. Since integrated sensors combine key functions such as human presence detection, temperature sensing, and ambient light sensing, typically only one sensor is needed per room. This reduces the number of devices compared to a distributed single-sensor layout, thereby lowering both energy usage and maintenance costs. Most households can accommodate direct power connections for sensors, mitigating the limitations of battery life. For example, the "Xiaomi Human Presence Sensor Pro" combines millimeter-wave radar, infrared sensing, and ambient light detection. It also solves the problem of high-power consumption by being directly powered through a wired connection. A representative product implementing this strategy is shown in Figure 4.

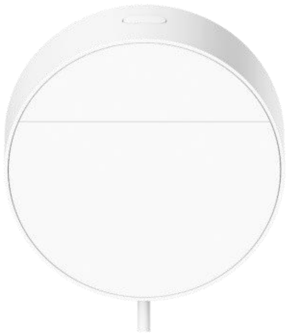

Fig. 4. Xiaomi Human Presence Sensor Pro [12].

5.1.2 Dynamic Power Management.

Another approach is dynamic power management. By leveraging the complementary nature of PIR and mmWave radar, systems can reduce average power usage while maintaining accuracy. For example, mmWave radar only activates in high-precision mode after a PIR sensor detects motion. If mmWave confirms a stationary target, it may lower its sampling frequency to save power. This minimizes unnecessary radar operation and extends device lifespan.

5.1.3 AI-Enabled Energy Optimization.

AI-based power management further reduces energy consumption. By learning patterns of human activity, the system can reduce radar scanning frequency or enter low-power standby mode during long periods of inactivity, especially at night. Once motion is detected again, it resumes normal operation promptly. This ensures real-time responsiveness while minimizing energy usage.

These strategies allow integrated human presence sensors to maintain detection accuracy while reducing power consumption, supporting their widespread adoption in smart homes.

5.2 Sensor Data Fusion

The core advantage of integrated human presence sensors lies in multimodal data fusion—combining inputs from PIR, mmWave radar, and illuminance sensors to improve detection accuracy. However, differences in signal characteristics and processing methods present technical challenges.

5.2.1 Time Synchronization and Alignment.

Synchronizing data from different sensors is essential. PIR sensors respond quickly to motion, while mmWave radar requires more data accumulation. Aligning their timestamps and ensuring consistency in signal interpretation is key to improving system performance.

5.2.2 Handling Signal Conflicts.

Occasionally, PIR may detect motion while mmWave radar fails to identify micro-movements due to stillness. In such cases, how the system determines human presence becomes critical. AI-based fusion algorithms resolve this by learning the behaviour of each sensor and dynamically adjusting their weight to enhance detection reliability.

5.2.3 Deep Learning for Data Fusion.

Deep learning enhances data fusion. Neural networks can be trained on large datasets to learn how each sensor responds under different conditions. For example, in bright environments, illuminance data may be more useful; in darkness, mmWave radar data becomes more important. Neural networks can adjust fusion strategies accordingly.

5.2.4 Bayesian Inference.

Bayesian inference offers a probabilistic approach to data fusion. By analyzing historical data, the system can assess the reliability of each sensor and assign dynamic weights. If radar tends to generate false positives in a specific scenario, its influence on decisions can be reduced in favor of PIR or illuminance data, resulting in a more robust detection system.

These fusion techniques not only improve detection accuracy but also enhance adaptability to complex home environments.

5.3 False Alarms and Environmental Interference

Although integrated sensors use multiple detection methods, they may still experience false alarms due to dynamic non-human elements such as moving curtains, fans, or lighting changes.

5.3.1 Reflection Interference with mmWave Radar.

mmWave radar can be affected by reflections from metal surfaces like furniture or walls, leading to erroneous human presence detection. Background modeling using AI helps distinguish between environmental reflections and real human signals. Multi-frequency radar techniques can also enhance target discrimination.

5.3.2 PIR Sensitivity to Temperature.

PIR sensors are sensitive to environmental temperature. In summer, when ambient temperature nears body temperature, detection performance degrades. Using illuminance sensors to aid in environmental assessment can help adjust PIR sensitivity thresholds dynamically. Temperature compensation techniques using intelligent algorithms can further improve PIR reliability.

5.3.3 Smart Environmental Adaptation.

AI-powered detection can identify typical object movements—like fans or curtains—and exclude them as non-human activity. Dynamic threshold adjustment allows sensors to adapt to changing environments, ensuring stable performance.

In conclusion, using data fusion, AI-based background modeling, and adaptive thresholding, integrated sensors can significantly improve stability and accuracy under complex conditions.

6 Future Development Trends

With the ongoing advancement of smart home technologies, comprehensive human presence sensors are expected to see widespread applications. Future improvements will focus on power efficiency, multimodal sensor fusion, and privacy protection. These enhancements will not only boost sensor adaptability but also improve system safety and user experience.

6.1 Low Power Optimization

The widespread adoption of smart devices demands low-power and high-efficiency sensors to reduce energy consumption and improve battery life. Current systems, particularly mmWave radars operating in continuous scan mode, tend to consume more power. Future optimization strategies will focus on smart energy-saving modes, adaptive standby technology, and low-power hardware design.

6.1.1 Smart Energy-Saving Modes.

These modes rely on user behavior analysis to manage power dynamically. By learning daily activity patterns, sensors can shift to low-power standby during periods of inactivity and resume full operation when human presence is detected, enhancing energy efficiency.

6.1.2 Adaptive Standby Technology.

With AI assistance, sensors can automatically adjust scanning frequencies based on environmental conditions. For example, mmWave radar can lower its scan rate at night to save energy while maintaining accuracy. Additionally, low-power sensor chips and optimized RF modules will reduce energy use and improve battery performance.

6.2 Multimodal Sensor Fusion

Future smart homes will increasingly depend on multimodal sensor fusion to improve accuracy and environmental adaptability. The limitations of single-sensor systems make this a necessary evolution, leveraging complementary sensor types to enhance system reliability.

6.2.1 WiFi Sensing.

WiFi sensing is a promising direction. It utilizes reflected WiFi signals to detect human activity without direct contact. Compared to mmWave radar, WiFi sensing consumes less power and can cover wider areas, making it ideal for large home spaces [13].

6.2.2 Ultrasonic Sensors.

Ultrasonic sensors may also play a key role in enclosed environments, supplementing mmWave radar and overcoming its weaknesses in certain conditions [14].

6.2.3 Pressure Sensor Integration.

Integrating pressure sensors can expand applications further—for instance, detecting whether someone is sitting, standing, or has fallen—enhancing safety and monitoring capabilities [15].

6.2.4 AI-Driven Data Fusion.

AI technologies are critical for coordinating different sensors. Deep learning and data fusion algorithms analyze inputs from multiple sensors to improve human detection accuracy while minimizing false positives. This ensures stable and efficient performance in varied environments.

6.3 Privacy Protection and Edge Computing

As smart home systems become more prevalent, privacy concerns grow. A key future trend is edge computing—processing sensor data locally rather than sending it to the cloud. This reduces the risk of data breaches and lowers latency, improving system responsiveness.

6.3.1 Edge Computing.
Edge computing means that devices like gateways or local units in a smart home can process sensor data directly on-site, instead of sending all the raw data to the cloud [16]. This way, the system only needs to upload statistical results or key events, which helps reduce network load and better protect user privacy. At the same time, processing data locally allows for faster responses—for example, turning on the lights or adjusting the air conditioner immediately when someone enters a room. That's why edge computing is especially suitable for smart home scenarios where both privacy protection and quick system responses are important.

6.3.2 Data Encryption and Secure Storage.
End-to-end encryption and secure storage protocols further protect data, preventing unauthorized access and ensuring sensor data transmission remains safe.

6.3.3 User-Controlled Data.
Smart systems should also offer flexible data management, allowing users to choose whether to store or share their presence data—empowering them with full control over privacy.

7 Conclusion

The introduction of human presence detection technology offers new possibilities for the development of smart homes. Through the collaborative use of PIR sensors, mmWave radar, and other technologies, smart home systems can more accurately identify user activity and optimize the operation of lighting, climate control, and security devices—improving intelligence and user experience.

Compared to single-sensor systems, integrated sensor fusion mitigates individual limitations and enhances the system's ability to detect static individuals, reduce false alarms, and adapt to complex environments. This improves both the reliability and adaptability of smart home systems.

This paper reviewed the mechanisms and limitations of traditional single sensors and explored the architecture and applications of integrated human presence sensors. It also discussed practical challenges including power consumption, fusion complexity, environmental interference, and privacy concerns, offering solutions such as AI-enhanced processing, WiFi and pressure sensor integration, and edge computing.

In the future, as AI and IoT technologies evolve, human presence sensors will become increasingly intelligent, energy-efficient, and accurate. With self-learning, dynamic power management, and multimodal fusion, smart home systems will better understand user behavior and provide more personalized services. However, privacy remains a key issue, requiring careful attention to secure data while enhancing performance.

In summary, continuous improvements in human presence sensing will drive smart homes toward greater efficiency, safety, and human-centric design.

References

1. Li, W., Feng, Y., Wang, Y., et al.: ‘Multimodal non-contact human presence detection using mmWave radar and RGB cameras for smart building applications’, Sci. Rep., 2023, 13, (1), Article 18383
2. Chen, Y., Lu, G., Zhang, Z., et al.: ‘Modeling and analysis of human body infrared radiation for passive human detection’, Sens. & Transducers J., 2013, 161, (11), pp. 134–140.
3. Choi, J., Lee, H., Oh, M., et al.: 'Privacy-aware human detection and localization with passive infrared sensors for ambient assisted living', Scientific Reports, 2024, 14, (1), pp. 1–14
4. IR-TEC, 'PD3 Series - High Performance Ceiling Mount PIR Sensor', White Paper, 2021. Available: https://www.irtec.com/en-ira/upload_images/files/20210326-18225622000.pdf, accessed 21 Mar. 2025.
5. Li, J., Li, X., Wang, H., et al.: 'A review of human activity recognition methods', Sensors, 2018, 18, (2), pp. 604
6. Texas Instruments, 'Understanding and Evaluating PIR Sensor Characteristics', White Paper, 2020. Available: https://www.ti.com/lit/wp/spyy005a/spyy005a.pdf, accessed 21 Mar. 2025.
7. ‘mmWave radar realizes occupancy detection with high precision’, Macnica website, https://www.macnica.co.jp/en/business/semiconductor/articles/infineon/127045/, accessed 25 March 2025
8. Texas Instruments, ‘A Review of mmWave Sensors: Technology, Use Cases, and Advantages’, https://www.ti.com/lit/wp/swra807/swra807.pdf, accessed 25 March 2025
9. Liu, J., Wang, Y., Zhang, H., et al.: 'Design and application of a human presence detection sensor based on multi-source information fusion', Journal of Anhui University of Technology (Natural Science), 2023, 40, (6), pp. 607–614 (in Chinese)
10. Wang, Y., Chen, J., Yang, L., et al.: 'A motion-induced passive infrared (PIR) sensor for stationary human occupancy detection', IEEE Sens. J., 2020, 20, (3), pp. 1409–1419
11. Zhang, J., Wei, H., Zheng, W., et al.: 'Multi-sensor fusion-based real-time human activity recognition using mmWave radar and RGB cameras', Remote Sens., 2023, 15, (13), pp. 3210
12. Xiaomi Corporation: 'Xiaomi Human Presence Sensor Pro', Xiaomi Official Website, https://www.mi.com/shop/buy/detail?product_id=20316, accessed 25 March 2025
13. Hao, Z., Qiao, Z., Dang, X., et al.: 'Wi-Do: A highly robust human motion perception model based on WiFi signals', Journal of Computer Research and Development, 2021, 58, (6), pp. 1202–1214 (in Chinese)
14. Xu, J., Li, M., Yang, X., et al.: 'Application of human activity recognition in smart home environments', Smart City Applications, 2023, 4, (6), pp. 56–63 (in Chinese)
15. Kamiya, K., Kudo, M., Nonaka, H., et al.: 'Sitting posture analysis by pressure sensors'. Proc. Int. Conf. Pattern Recognition (ICPR), Tampa, USA, December 2008, pp. 1–4
16. Gao, L., Luan, T.H., Gu, B., et al.: 'Privacy issues in edge computing', in Privacy-Preserving in Edge Computing, (Springer, Singapore, 2021), pp. 15–34