

The Application and Development Trends of Embedded Temperature Sensors in Smart Homes

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Abstract: The modern living environment has been significantly improved by smart home technologies, with a key role being played by embedded temperature sensors in ensuring comfort, energy efficiency, and safety. These sensors enable smart home systems to achieve real-time temperature monitoring and automatic control of indoor climate. Furthermore, temperature sensors are also crucial for optimizing HVAC (Heating, Ventilation, and Air Conditioning) systems, energy management, and security monitoring functions. However, challenges such as sensor accuracy, power consumption, and data security still exist. This paper explores the technical foundation of temperature sensing in smart homes, focusing on sensor types, working principles, and data processing protocols. Through a literature review and comparative analysis, the performance of different temperature sensors in the smart home ecosystem, their integration strategies, and their influences on system efficiency are evaluated, along with the technical challenges and methods for effective implementation. The results demonstrate that AI-driven temperature control, low-power sensor design, and multi-sensor integration can greatly improve smart home automation. However, ensuring the stability of sensor performance under different environments and ensuring data security remain major obstacles. Tackling these challenges is crucial to further optimize smart home temperature sensing systems and make them more intelligent, efficient, and adaptable to user needs.

Keywords: Smart home, Embedded temperature sensors, Environmental monitoring, Energy efficiency, HVAC systems

1. Introduction

In recent years, smart home technologies have significantly improved the living environment by advancing automation, comfort, and energy efficiency. Temperature sensors, as crucial components, directly influence the performance of Heating, Ventilation, and Air Conditioning (HVAC) systems, energy management, and indoor climate regulation. By providing real-time temperature data, these sensors can serve as the basis for fast-response and adaptive systems to adjust indoor temperature and humidity according to environmental changes and user preferences. Recent studies emphasize the crucial role of temperature sensors in smart home automation, particularly in monitoring indoor temperature, humidity, and air quality through Internet of Things (IoT) integration [1]. Furthermore, research on smart grids and energy management shows that temperature sensors play a key role in controlling home energy use more efficiently [2]. This paper provides a review of the application of embedded temperature sensors in smart homes. Through literature review and comparative analysis,

the working principles, classification, performance attributes, and data communication protocols related to temperature sensors are studied. Moreover, it examines how different types of sensors influence the performance and cost of smart home systems, identifies key technical challenges in implementation, and suggests strategies for optimizing sensor integration in embedded smart home architectures. By investigating these aspects, this study uncovers the advantages, limitations, and emerging trends of temperature sensing technology, offering insights to advance the development of smarter, more energy-efficient smart home systems that better meet user needs.

2. Technical foundation of embedded temperature sensors

2.1. Types and working principles of temperature sensors

Temperature sensors in embedded systems employ various technical principles to deliver precise measurements. Four primary types of sensors that are commonly used in smart homes are identified by Gazis and Katsiri: thermocouples, Resistance Temperature Detectors (RTDs), thermistors, and semiconductor-based integrated circuits (ICs). In contrast to traditional mercury thermometers, each sensor operates on distinct physical principles and offers unique benefits for specific applications [3]. The RTD sensor, primarily made of platinum, operates on the principle of resistance variation with temperature, offering high precision but at a relatively high cost. In comparison, thermistors made of polymer or ceramic materials are cheaper, but their accuracy is also reduced to a certain extent. Thermocouples work by generating a measurable voltage difference between two different metal junctions through the Seebeck effect. They can function over a wide temperature range and have a long service life, making them ideal for smart home devices exposed to high temperatures or outdoor conditions, such as ovens or heating units. Semiconductor-based sensors measure chip temperature through the physical properties of transistors. In practice, the selection of a temperature sensor for a smart home depends on several factors, including accuracy requirements, cost, response time, energy efficiency, and physical size. For example, a smart thermostat may prioritize accuracy and stability and therefore employ an RTD or high-quality thermistor, while a smart fan or lighting controller may use a simple semiconductor sensor to reduce cost and complexity. The diversity of sensing technologies reflects the technological advancements and future needs of modern embedded systems, where factors such as cost, accuracy, and application requirements must be balanced [3]. The choice of sensor type greatly impacts the overall performance and reliability of the temperature monitoring system, with each technology offering distinct advantages in particular scenarios and applications.

2.2. Performance evaluation of temperature sensors

In smart homes, key parameters for evaluating temperature sensor performance include response time, sensitivity, and measurement accuracy across the operating temperature range. Babaie and Masoumi assessed the temperature deviation-error behavior of RTD sensors commonly used in smart home environments, focusing on PT100 type RTDs. These sensors are known for their high accuracy and stability, making them particularly suitable for indoor environmental monitoring and HVAC control. The analysis showed that RTDs maintain a nearly linear and stable relationship between resistance and temperature. Moreover, after calibration, the error typically remains under $\pm 0.15^{\circ}\text{C}$ within the $0\text{-}100^{\circ}\text{C}$ range, with their high reliability making them an excellent choice for smart home applications [4]. However, while RTDs offer higher accuracy, their response time and cost have some disadvantages compared to other sensors. For instance, while RTDs generally have slower response times (1-4 seconds) compared to thermistors, they offer superior stability and longer service life. This makes them especially well-suited for applications that demand accuracy and long-term reliability, such as thermostats. In smart homes, sensor selection criteria also need to consider energy consumption and whether they can be integrated. For example, RTDs, although stable and accurate,

may be replaced by thermistors in low-cost applications such as simple room temperature display devices. In these applications, a certain degree of accuracy can be sacrificed in order to reduce costs and obtain faster response. In smart homes, whether fast temperature response, high measurement stability or low power consumption is required, the choice of temperature sensor must be consistent with the specific functional requirements of the system.

2.3. Data processing and communication protocols in embedded sensor networks

In smart home networks, efficient data processing and transmission protocols play an important role in ensuring accurate temperature monitoring and control. To maintain optimal system performance and efficient resource utilization, selecting the appropriate communication protocol is crucial. The most commonly used protocols in smart home environments are Message Queuing Telemetry Transport (MQTT), ZigBee, and Bluetooth Low Energy (BLE), each offering distinct advantages. MQTT is a lightweight publish-subscribe protocol specifically designed for devices with limited bandwidth. It supports asynchronous communication, making it ideal for real-time temperature monitoring in systems like thermostats or centralized control panels. A study by Shahinzadeh and Azani demonstrated that MQTT can achieve low latency and minimal packet loss, even in networks with high device density, making it especially effective for cloud-connected smart home platforms [5]. In contrast, ZigBee is a low-power, mesh-enabled protocol suitable for multi-room smart home systems. It is more effective for temperature sensors deployed over a larger area because its mesh topology allows devices to relay data to each other, thereby improving coverage and reliability. ZigBee also supports low data rate transmission and has better power efficiency than Wi-Fi, making it suitable for battery-powered temperature sensors embedded in remote or inaccessible locations. BLE is commonly employed for short-range applications, such as wearable temperature sensors or devices within a single room. It offers extremely low power consumption and fast pairing, though it has a more limited communication range. The choice of communication protocol is influenced by several factors, such as network size, power consumption, and response time. For instance, ZigBee is well-suited for distributed room monitoring, MQTT excels in cloud-based integration and mobile applications, while BLE is best suited for short-range applications or localized temperature alarms.

3. The application of embedded temperature sensors in smart homes

3.1. Enhancing HVAC automation with temperature sensors

Temperature sensors are widely used to automate HVAC control in smart homes, optimizing both resident comfort and energy efficiency. In contrast, traditional HVAC systems often operate on fixed schedules or basic thermostatic control. These systems can maintain basic indoor climate conditions, but they often struggle to adapt to changing occupancy patterns, fluctuations in outdoor temperatures, or shifts in user preferences. As a result, they tend to consume excessive amounts of energy. By integrating embedded temperature sensors with intelligent control strategies, smart homes are overcoming these limitations. Real-time temperature data is collected and analyzed using predictive algorithms to enhance the adaptability and efficiency of HVAC systems. Recent studies have shown that combining advanced sensing technologies with machine learning algorithms can optimize HVAC performance. Yun and Won first developed a Zigbee-based wireless sensor system that can collect temperature and humidity data, laying the foundation for machine learning-driven HVAC control systems [6]. Their research demonstrated the importance of temperature sensors in real-time environmental monitoring and control applications. This innovation laid the foundation for later data-driven applications. Recent studies have demonstrated the practical benefits of such systems. Chen and Yin investigated the potential of IoT-based intelligent HVAC control in small buildings by combining temperature sensing with adaptive thermal comfort models. Depending on climate zones

and usage patterns, the simulations showed that occupancy-based control strategies and adaptive set-point temperature regulation could achieve electricity savings between 8.9% and 20.4%. These strategies also resulted in annual reductions in electricity usage intensity by 12.2 to 30.4 kWh/m², while still maintaining comfortable indoor conditions [7]. In addition, Alshammari demonstrated the effectiveness of artificial neural networks in predicting indoor temperatures for automatic climate control. These models helped reduce thermal fluctuations and provided smarter air conditioning control by learning user behavior and environmental patterns [8]. Machine learning algorithms are increasingly being used to enable systems to evolve from static, passive operations to active prediction and response to environmental changes.

3.2. Optimizing energy management with temperature monitoring

Embedded temperature sensors in smart homes are also crucial for managing energy consumption. By using temperature monitoring and control systems, they can greatly improve energy efficiency in households and help reduce environmental pollution. Recent studies highlighted the effectiveness of various technical approaches in achieving such optimization. For instance, Mahindrakar et al. developed a system based on the DHT11 sensor, enabling real-time temperature monitoring and automated fan control. This system laid the groundwork for energy-efficient climate management through predefined operational parameters [9]. Furthermore, Liang et al. designed an advanced Economic Model Predictive Control (MPC) system that intelligently balances energy consumption with user comfort. The system can switch between heating and cooling modes while taking into account price fluctuations and environmental factors [10]. Roessler et al. created a neural network application in which the system learns from both user preferences and sensor data to optimize heating schedules [11]. Through personalized energy management, this application can effectively reduce energy consumption while ensuring user comfort is maintained. The implementation of these technologies demonstrates how smart home systems can effectively minimize energy waste while preserving optimal comfort. From basic sensor systems to complex neural networks, the integration of these different approaches lays the foundation for smart homes to reduce energy consumption and carbon emissions, establishing a comprehensive framework for energy management that adapts to user behavior and environmental conditions.

3.3. Improving home safety through multi-sensor integration

Temperature sensors play a crucial role in enhancing home security by integrating with other smart home sensing systems. Instead of functioning independently, they are often combined with smoke, carbon monoxide (CO), and earthquake detectors to create intelligent, event-driven security systems. And these systems leverage real-time environmental data to detect abnormal conditions and trigger automatic responses, such as activating alarms, shutting down equipment, or initiating ventilation. Hsu et al. developed a smart home system that integrates temperature sensors in multiple rooms with CO sensors, using intelligent fire detection algorithms for environmental monitoring and safety warnings [12]. The system automatically triggers an alarm when CO concentration or temperature exceeds safe levels, thereby improving reliability and responsiveness through this multi-sensor approach. In a similar vein, Khandelwal et al. developed an innovative temperature sensing system (Thingspeak) that integrates wireless data transmission with cloud-based visualization, facilitating real-time temperature monitoring and continuous geographic location tracking through sensor integration [13]. Expanding on this concept, Firmansyah et al. developed a smart home system that integrates temperature control with gas leak detection and safety monitoring via CCTV, effectively mitigating the risks associated with toxic gas leaks [14]. These applications and technical cases highlight the crucial role of temperature sensors in safety prevention within smart home systems

through integration with other devices. By combining different sensing technologies, the accuracy of environmental monitoring is enhanced, while the functionality is expanded, enabling application across a wider range of scenarios.

4. Challenges and future trends

4.1. Current challenges

Despite achieving important results in recent experiments, smart home temperature sensing systems still face major technical challenges, particularly in terms of sensor accuracy and overall system reliability. For example, Mahindrakar et al. highlighted the effectiveness of DHT11 sensors in providing precise temperature and humidity data for automatic fan control, along with integration into the Blynk IoT platform for remote monitoring [9]. Despite its success, this is only a basic implementation, and several technical challenges remain. Specifically, the reliability of sensors under varying environmental conditions, especially extreme temperature or humidity levels, has yet to be fully guaranteed. Another challenge is energy consumption, particularly for battery-powered or wirelessly connected sensors. Many embedded sensors need to balance measurement frequency with energy efficiency, especially during extended operation. Some experts have proposed solutions such as adaptive sampling and the use of thermoelectric or solar sensors to address this issue. In addition, since smart home systems need to collect and analyze users' temperature data and habitual preferences, it is important to protect this information. Cyber attacks and unauthorized access can be a risk. A study by Aldahmani et al. emphasized the increasing security risks in smart home IoT systems and proposed the implementation of a layered IoT security framework to protect sensors and devices from potential attacks [15]. As smart home technology develops and more and more devices are connected to the Internet, it will become more complicated to ensure the security of user data and require continuous technical updates.

4.2. Future development direction

Future development of embedded temperature sensors in smart homes should prioritize improving sensor stability and accuracy across diverse scenarios, alongside enhancing the personalization of the user experience. Achieving intelligent temperature control will heavily rely on AI and machine learning, which will enable systems to learn user preferences and predict environmental changes, ultimately improving comfort and enhancing energy efficiency. At the same time, advancements in sensor materials, such as graphene-based technologies, hold significant potential to produce more accurate and cost-effective sensors, making high-precision monitoring accessible to more homes. Reducing sensor power consumption will also be a critical area of innovation. Researchers can explore low-energy consumption and energy harvesting technologies, allowing sensors to generate energy from heat, light, or vibration, thereby reducing the need for battery replacements. Moreover, as smart homes become more interconnected, security concerns will become increasingly important. Manufacturers must implement enhanced encryption and authentication methods in temperature sensors to safeguard against cyber threats and prevent data breaches. Besides, multi-sensor fusion will further diversify and enhance the functionality and efficiency of smart home systems. For example, temperature sensors working in conjunction with humidity, air quality, and motion sensors will provide more comprehensive indoor environment monitoring and optimization. By enhancing efficiency, security, and intelligence in temperature monitoring, these future developments will ensure smart home systems better meet user needs, foster sustainable development, and improve stability.

5. Conclusion

This study offers an in-depth analysis of embedded temperature sensors in smart homes, examining their technical principles, performance characteristics, and practical applications. And the findings highlight the role of temperature sensors in real-time climate control, HVAC efficiency, and home security, driven by AI, low-power sensors, and protocol-based communication strategies. However, challenges persist in ensuring sensor accuracy across varying environmental conditions, reducing energy consumption, and safeguarding user data. Tackling these issues is crucial for enhancing the stability and accuracy of smart home systems. Although this study offers a comprehensive analysis of temperature sensors in smart homes, it has some limitations. Most of the discussion relies on existing research and theoretical analysis without experimental verification of sensor performance. Future work could involve real-world testing of different sensor types under various environmental conditions to assess their reliability and effectiveness. Additionally, while the article covers various smart home applications, it does not address the cost-effectiveness of different sensor technologies. Since high-precision sensors can be expensive, future research should evaluate the cost-benefit trade-off and explore more affordable temperature sensing solutions.

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