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Artificial Intelligence-Driven Smart Home Systems: Technologies, Applications and Future Challenges

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Abstract. With the continuous development of artificial intelligence (AI) technology, smart home systems have gradually evolved from traditional automated control modes toward intelligent systems with environmental perception, autonomous decision-making, and proactive service capabilities. However, existing smart homes still face problems such as a single mode of interaction, insufficient intelligent proactivity, and limited scene adaptability. Based on relevant research results in recent years, this paper systematically reviews the application progress of AI technology in the smart home field, focusing on key directions such as the Internet of Things (IoT) architecture, multimodal interaction, intelligent decision-making, edge computing, and data security. The review shows that AI technology has effectively improved the perception, interaction, and decision-making capabilities of smart home systems. Among these technologies, large language models (LLMs) enhance natural language understanding and user interaction capabilities, edge computing improves the real-time response efficiency of the system, and technologies such as blockchain provide new solutions for data security. At the same time, smart homes still face challenges in privacy protection, model reliability, cross-device collaboration, and standardization. In the future, modern smart home systems should be further integrated with artificial intelligence technologies, change traditional basic interaction modes, and promote the development of smart homes toward greater intelligence, security, and adaptability.

Keywords: smart home, artificial intelligence, large language model, blockchain, edge computing

1. Introduction

Compared with early smart home systems reliant on basic automation, today's systems are evolving toward greater intelligence and autonomy. As Internet of Things (IoT) technology matures and spreads, device connectivity has improved significantly, communication protocols have converged toward unified standards, and edge computing has enhanced systems stability [1]. Smart devices now span lighting, appliances, environment, water use, health, and energy, making a qualitative leap in both interaction methods and sensing capabilities [2]. Meanwhile, user expectations have shifted from manual control to demand for proactive, context-aware services [3].

However, traditional systems still rely on apps or fixed rules for control, which leads to inefficient workflow, broken task continuity, and inflexible responses. To address this, artificial

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intelligence (AI) is transforming smart homes from passive responders into proactive systems capable of perception, reasoning, and adaptive decision-making. For example, large language model agents enable accurate intent inference [4]; neural network-based controllers improve appliance control accuracy while cutting sensor energy use [5]; and DeepSeek-powered appliances enhance perception, decision-making, and problem solving [6].

Based on the above discussion, this paper first proposes the following research questions: How does AI improve the autonomy of smart homes? How does multimodal interaction improve user experience? What security and application challenges do current systems face? This paper systematically summarizes the development status and application integration of smart home systems driven by artificial intelligence technology, serving as a reference for readers.

2. Background and related work

2.1. Traditional smart home systems and IoT architecture

Modern smart home systems are usually built on an IoT architecture, and the overall system can be divided into a perception layer, a transmission layer, a decision layer, and an execution layer [7]. As the information collection entry point of the system, the perception layer mainly obtains environmental state and user behavior data through sensors and converts physical signals into digital information. With the development of sensor fusion technology, smart home systems can comprehensively utilize multidimensional data (temperature, images, sound, human activity, etc.) to improve environmental perception capabilities [7]. The transmission layer is responsible for data communication between devices and between devices and cloud platforms, establishing information transmission channels through wireless communication protocols such as Zigbee and Wi-Fi [1]. The decision layer is the core control module of the system, responsible for data processing, state analysis, and control strategy generation, usually relying on cloud computing or edge computing to achieve rapid response and intelligent control [1, 2]. The execution layer is responsible for executing digital decisions in the physical world, completing environmental regulation and device management through intelligent devices, such as smart lighting, smart access control, and environmental monitoring [2].

The core advantage of traditional smart homes lies in automation control based on preset rules, with clear operational logic and predictable behavioral outcomes, which facilitates system maintenance and troubleshooting. However, the limitations of this model are also obvious: it mainly relies on manually set rules and lacks the ability to understand environmental changes, user behavior, and complex scenarios. Therefore, traditional systems still have deficiencies in personalized services, proactive response, and dynamic environmental adaptation, making it difficult to meet users' ever-increasing demands for intelligent services.

2.2. Evolution toward AI-based smart home systems

With the increasing complexity of home environments and the growth of user demand for personalized services, the simple automatic control of traditional smart homes can no longer meet people's needs. The introduction of AI technology has promoted the transformation of smart home systems from rule-driven modes to data-driven and autonomous decision-making modes, enabling systems to perceive, analyze, and generate strategies based on multi-source information.

At present, AI-driven smart homes mainly rely on key technologies such as deep learning, large language models, and AI agents. Among them, deep learning models are mainly used for

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environmental perception, behavior prediction, and pattern recognition, and can extract high-dimensional features from historical data and sensor information and optimize device control processes [5]. Large language models enhance the natural language understanding and semantic reasoning capabilities of smart home systems, enabling users to express their needs in a more natural way and transforming vague instructions into executable tasks [6]. In addition, AI agents further integrate perception, reasoning, and execution functions, achieving more autonomous task management through large language models and intelligent algorithms. For example, the HomeMind agent based on large language models can improve autonomous interaction capabilities in smart home environments [4].

Overall, the integration of these three technologies promotes smart home systems from automated tools that passively respond to rules to autonomous service entities that actively perceive, dynamically decide, and continuously evolve.

2.3. Multimodal interaction in smart home

While artificial intelligence technology is gradually introduced into the decision layer and the system becomes increasingly intelligent, the interaction modes between users and smart homes are also evolving from traditional single-command input to multimodal integrated interaction. Because a single interaction mode is insufficient to fully express user needs, multimodal interaction improves the naturalness and accuracy of human-computer interaction by integrating different information sources [8].

Among interaction modes, voice interaction usually handles contactless intention expression and semantic command input; visual interaction relies on computer vision and visual sensors to perceive user posture; in addition, physical feedback is used to establish a more personalized, emotional, and immersive interaction experience, and voice and text interaction is constructed through WeChat chatbot architecture [9, 10].

The advantage of multimodal interaction lies in the mutual complementarity of different information sources, which improves the robustness of the system in complex environments. For example, when voice input is disturbed by environmental noise, visual and tactile channels can assist the system in understanding user intent. At the same time, however, multimodal smart home systems still face challenges such as cross-modal information fusion, context understanding, privacy protection, and real-time response. How to further improve the accuracy and naturalness of multimodal interaction remains an important direction for future research [9].

3. Key technologies of AI-driven smart home systems

3.1. AI-based perception and context awareness

The perception layer is the foundation for smart home systems to understand the external environment and user states, and the introduction of AI technology further improves the system's ability to analyze multi-source data and understand context. AI-based perception technologies enable smart home systems to shift from simple data collection to environmental understanding and behavior prediction, providing a cognitive foundation for proactive services.

In AI-driven smart home systems, the perception layer is usually composed of various IoT terminals such as temperature and humidity sensors, photometers, and gas sensors and is responsible for quantitatively collecting environmental state and user behavior information [2]. Through IoT communication technologies, these multi-source data can be transmitted to computing platforms,

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where deep learning models are used for feature extraction and temporal analysis to identify user behavior patterns and environmental change trends from continuous data streams, and inference engines are used to map context-aware data to device control services to achieve automatic system control [3, 5, 8].

3.2. Intelligent decision-making and automation

After completing environmental perception and context understanding, smart home systems need to further transform information into autonomous, real-time, and optimal control strategies. AI-driven decision-making mechanisms, by combining machine learning, large language models, and deep learning methods, enable systems to dynamically generate control plans according to environmental changes and user needs.

Among them, machine learning models often learn and summarize patterns from users' long-term historical behavior records, and thereby predict user behavior, infer user behavioral intentions, and provide proactive services. Large language models often generate control strategies and rules based on users' semantic meanings. For example, HomeMind is an LLM agent system for automatically generating smart home scene rules, with capabilities including temporal feature extraction, sequential decision coordination, data preprocessing, context inference, user intent inference, and rule generation [4].

Deep learning models can further optimize the control process by continuously learning user behavior and environmental changes, thereby improving the accuracy of device control and energy utilization efficiency. For example, neural networks can be periodically trained through edge computing technology to realize automatic control of smart home devices; adaptive data collection frequency calculation methods can be used to reduce the energy consumption of smart home and sensor devices; at the same time, DeepSeek can be deployed in smart home appliances to further enhance their capabilities in perception, decision-making, and problem solving [5, 6].

3.3. Secure data management and privacy protection

As AI technology enhances the deep perception and autonomous decision-making capabilities of smart home systems, the scale and sensitivity of the data that systems need to process also continue to increase, making data security and privacy protection critical challenges. Smart home devices can continuously collect information about user behavior, home environments, and living habits. Once data leakage occurs, the consequences can be extremely serious.

Traditional centralized architectures usually rely on a single trusted entity for data management and permission control. When the central node is attacked, the entire system may face security risks. Therefore, blockchain technology has been gradually applied to smart home security management, enhancing data integrity, access control, and system reliability through distributed storage and decentralized authentication mechanisms [11].

However, blockchain technology still faces problems such as high storage costs, transaction latency, and insufficient real-time performance in smart home applications. To address these limitations, research has proposed a dynamic trusted lightweight security authentication mechanism based on blockchain (DTL) to improve authentication efficiency and meet the real-time interaction needs of smart homes [11]. In addition, combining blockchain with the InterPlanetary File System (IPFS) can reduce the pressure of on-chain data storage while improving data management efficiency [12].

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4. Applications of AI-based smart home systems

The integration of the three major technological pillars discussed above—perception, decision-making, and security—has demonstrated a transition from functional automation to proactive services in specific application scenarios. The following sections illustrate the implementation forms of AI-driven smart homes from three dimensions: energy management, healthcare and elderly assistance, and lifestyle automation, using specific examples.

4.1. Energy management

In the field of energy management, AI-driven smart homes are far superior to timed modes based on simple automated control. Through fine-grained management and control based on behavior prediction and dynamic optimization, the energy consumption problem of smart homes can be greatly optimized. Among energy consumption issues, the first to be addressed is the most common fixture in modern homes—the lighting system.

To address this problem, Wang Hongshui proposed an intelligent lighting system based on artificial intelligence and wireless communication technologies. The system adopts AI technologies such as speech recognition and image recognition, as well as wireless communication technologies such as WiFi, Bluetooth, and ZigBee, to realize intelligent lighting control. This control system greatly reduces unnecessary losses in traditional lighting systems and achieves more efficient, energy-saving, and comfortable lighting effects [13]. In addition, AI technology has been gradually applied to scenarios such as household energy load forecasting, air-conditioning temperature optimization, and equipment operation scheduling, reducing unnecessary energy consumption by predicting user needs.

4.2. Healthcare and elderly assistance

For elderly people or those with limited mobility, smart home systems can provide safer and more convenient life assistance services through continuous perception and intelligent analysis. In this application scenario, AI perception, multimodal interaction, and behavior analysis technologies play important roles, enabling the system to identify user states and provide personalized support.

For example, Li Minbo et al. proposed a context modeling method based on an object-attribute graph model, which can intelligently perceive user preferences and habits, thereby performing behavior identification and monitoring for elderly people and greatly improving their lives [3]. Wang Yun et al. discussed tactile interaction that can improve interaction naturalness and user comfort, optimizing the smart living experience of elderly users [9].

4.3. Intelligent lifestyle automation

As user demand for proactive services from smart homes increases, lifestyle automation has gradually become an important application direction of AI-based smart homes. This is especially true for lighting, home appliances, and security systems, which are the most frequently used and most important smart home devices in modern home environments, and users expect to strengthen the proactivity of these smart home systems.

In response to this demand, Yang Wentao et al. proposed a smart home system based on a WeChat chatbot, allowing users to control smart homes through WeChat, which is the most frequently used application in daily life [10]. Liu Liwei et al. proposed HomeMind, an LLM agent system for

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automatically generating smart home scene rules, thereby greatly improving the accuracy of large language model intent inference tasks in modern home environments [4].

5. Challenges and future trends

5.1. Privacy and security risks

As mentioned above, a high degree of intelligence means that a large amount of user privacy data is entrusted to intelligent control systems. Therefore, the vulnerability of privacy leakage and the susceptibility of smart home systems to external attacks remain major deficiencies of current smart home systems.

To address this issue, existing studies have proposed various security protection schemes. For example, Zhang Yinghui et al. proposed a fine-grained secure remote data update scheme with privacy protection for smart homes, and Zhang Zhujun et al. proposed a lightweight blockchain authentication mechanism for smart homes. Both address this problem, but more research is still needed to further mitigate this deficiency [11, 12].

5.2. Device compatibility and standardization

Today, the smart home field can be described as flourishing and growing rapidly, which also makes compatibility and standardization among different smart home products, sensors, and actuators a major problem. In actual smart home environments, attention should be paid to how various sensors coordinate with each other; for example, conflicts should be avoided when multifunctional modules are assembled together [2].

5.3. Human-centered AI and personalization

Generative artificial intelligence has indisputably become the core of modern smart home systems. Therefore, how to further optimize large language models, how to further strengthen the inference of user intent, and how to further deploy large language models in smart homes have become urgent issues to be addressed next [4, 6].

6. Conclusion

This paper systematically reviewed the key technologies, application scenarios, and future challenges of AI-driven smart home systems. The main conclusions are as follows. First, the integration of deep learning, large language models, and AI agents has reconstructed the system decision layer, achieving a leap from passive rule execution to proactive cognitive decision-making. Second, multimodal interaction through voice, vision, tactile, and WeChat robot channels realizes semantic complementarity among sensory channels, improving the robustness and naturalness of interaction in real environments. Third, blockchain, smart contracts, and encryption technologies constitute a decentralized and tamper-resistant security architecture that can effectively address the structural deficiencies of centralized trust models.

The main limitation of this paper is the lack of original empirical experiments and quantitative analysis, with challenges such as multimodal fusion latency and blockchain consensus overhead discussed only qualitatively. Future improvements can include systematic horizontal benchmark evaluations and extend to emerging directions such as federated learning and edge-cloud collaborative inference.

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