A Comprehensive Review of IoT-Based Smart Home Systems: Architecture, Applications, and Challenges

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Abstract. Driven by wireless communication, cloud computing and artificial intelligence, IoT-based smart home systems achieve more efficient and safer household management compared with traditional home modes. This paper systematically reviews their definition, five-layer modular architecture, core supporting technologies, typical application scenarios, unique advantages and prominent industry challenges such as fragmented technical standards, data privacy risks and heavy dependence on networks. Corresponding optimization solutions and future research directions are proposed, providing reliable references for the design and popularization of high-performance, secure and user-friendly smart home products.

Keywords: Internet of Things; Smart Home System; System Architecture; Data Security; Wireless Communication.

1. Introduction

Driven by iterative breakthroughs in wireless communication techniques, progressive optimization of integrated circuit manufacturing craftsmanship, large-scale commercial deployment of cloud computing infrastructure and gradual popularization of artificial intelligence industrialization, core IoT technologies have broken through multiple early-stage technical limitations and achieved large-scale layout and practical application across diversified industries ranging from industrial production, clinical medical services and urban transportation construction to civilian residential consumption fields. Among all practical landing scenarios of IoT technologies, smart home represents the most typical consumer-oriented application product, which has successfully stepped out from the initial developmental stage limited to conceptual hypothesis and laboratory prototype testing and gradually realized large-scale commercial mass production to access the daily lives of ordinary household users. Conventional traditional household operation modes completely rely on manual manipulation to finish switch control of household appliances, doors, windows and indoor lighting equipment, and cumbersome manual operations not only reduce daily household management efficiency but also lead to massive ineffective energy waste caused by long-term standby and idle running of various electrical facilities. Meanwhile, traditional residential space lacks mature supporting safety precaution measures, making it difficult to realize early warning against sudden household hazards such as illegal break-in, gas leakage and indoor fire accidents, resulting in relatively weak overall protection capability for personal property safety of residents. In sharp contrast, IoT-supported smart home systems can break original data barriers existing among home devices of different brands and types by adopting standardized or self-adaptive compatible communication protocols to realize networking interconnection of heterogeneous hardware terminals, collect real-time indoor environmental parameters and operational status data of connected equipment continuously, and complete intelligent data analysis relying on background operational algorithms so as to realize autonomous operation and intelligent centralized management of all household facilities.

The global smart home consumer market has maintained steady expansion momentum over the past decade, and growing market demands in return motivate continuous technological innovation in upstream industrial links of the whole smart home sector, with increasing investment on research and development covering intelligent hardware production, whole-house system integration debugging and optimization of intelligent control algorithms, accordingly speeding up the overall technical iteration rhythm of related subdivided fields. At the same time, numerous universities and research institutions worldwide carry out abundant experimental exploration and theoretical analysis focusing on key research topics such as cross-device communication compatibility schemes for smart homes, construction architecture of user privacy security protection, localized edge intelligent computing and humanized human-machine interaction modes, generating substantial academic achievements for subsequent industrial technical upgrading [1]. Nevertheless, from the perspective of actual industrial landing conditions at present, various technical and non-technical obstacles such as inconsistent industrial product standards, widespread loopholes in information security design and excessively high usage thresholds still severely restrict the comprehensive popularization of smart home products, and the entire industry is still far from realizing the developmental goal of full-scenario implementation and universal civilian popularization. Under such realistic industrial background, compiling a comprehensive and cutting-edge literature review bears vital theoretical significance and practical value, as it can systematically organize latest research progress within the smart home industry and accurately point out feasible research directions and industrial transformation paths for future development. Centered on IoT-driven smart home systems, this paper elaborates relevant content comprehensively following a logical sequence covering layered system architecture, underlying core supporting technologies, diversified practical application scenarios, outstanding advantages compared with traditional household modes, various existing industrial challenges and prospective future developmental trends, sorts out the holistic developmental context of the smart home industry and consolidates theoretical foundations for follow-up relevant academic research and engineering practice. In recent years, governments from multiple countries also introduced preferential industrial policies to encourage the popularization of smart home construction, which further pushes relevant technical research to advance toward higher maturity and practicality.

2. Definition and Hierarchical System Architecture of IoT-based Smart Home Systems

2.1. Definition

From the perspective of academic definition, an IoT-enabled smart home refers to an integrated intelligent management control system which connects scattered household hardware including indoor lighting fixtures, central air conditioning units, multi-functional environmental sensors and full-set household security equipment through standardized communication protocols, allowing all network-accessed devices to complete cross-terminal data exchange [2]. End users or property managers can realize centralized remote control of all household facilities via mobile terminal equipment or wall-mounted central control panels, and the whole intelligent system is capable of automatically issuing corresponding control instructions to complete unattended automatic operation of household equipment according to long-term daily usage habits accumulated from user behaviors and real-time indoor environmental indicators such as ambient temperature and humidity as well as air quality changes. Up to now, the category of smart home terminal hardware has become increasingly enriched, with intelligent surveillance cameras, anti-theft smart door locks, programmable intelligent lighting products and diversified smart white goods and kitchen electrical appliances forming core components of the whole smart home hardware system, and all types of hardware perform differentiated respective functions to jointly support the full-process operation of data collection, instruction receiving and practical action execution of complete smart home systems. With the continuous enrichment of terminal hardware types, newly-emerged wearable intelligent devices are also gradually incorporated into the smart home linkage control scope, further expanding the service boundary of whole-house intelligent management.

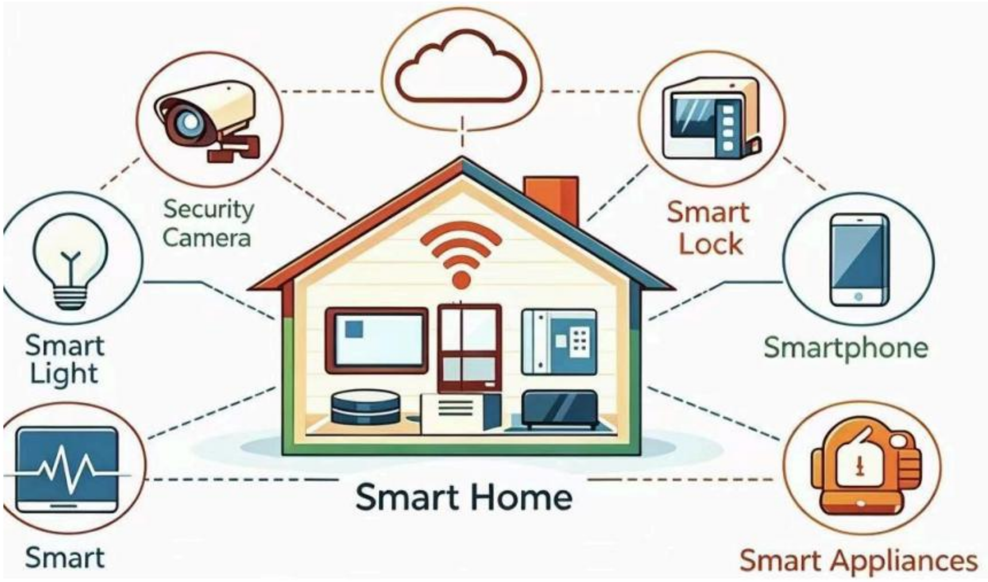

Figure 1. Classification of Mainstream Hardware Terminals for IoT Smart Home.

The classification of mainstream smart home terminal equipment is displayed in Figure 1. This figure intuitively classifies core hardware including smart cameras, smart locks, smart lighting, smart phones and various household appliances, with different hardware undertaking differentiated tasks of data collection, access control security and household control, which constitutes the essential hardware foundation of the whole smart home system.

2.2. System Architecture

Mainstream IoT smart home systems adopt modular layered architectural design in current industrial applications, and the complete system is divided into five mutually connected core functional layers forming an intact closed-loop operational system to fulfill full-link operation ranging from external environmental information collection to final user interactive feedback. Serving as the bottom data source of the entire intelligent framework, the sensing layer undertakes the basic responsibility of collecting full-house environmental data, relying on temperature and humidity sensors, human body infrared detectors, smoke concentration sensors and other microelectronic components to capture key real-time information including indoor temperature fluctuation, air humidity variation, human body movement trajectory, harmful gas leakage and switch status of doors and windows, and all collected original environmental data lays essential data foundation for subsequent intelligent decision-making of upper-layer modules. Raw data obtained from the sensing layer is then transmitted upward to the communication layer, which adopts three mainstream wireless transmission technologies including WiFi, ZigBee and Bluetooth to finish long-distance or short-range data delivery tasks, and different transmission techniques match the data interaction requirements of distinct smart home equipment relying on their differentiated features in transmission speed, power consumption level and effective communication distance[3]. After data arrives at the control layer, built-in computing chips and background operational algorithms inside this layer complete screening, classification sorting and logical analysis of massive original collected data, generating targeted equipment control instructions on the basis of preset operational rules and accumulated user usage preferences. Generated control commands flow downward to the execution layer, where various terminal intelligent equipment such as smart door locks, adjustable lighting products, air conditioning and fresh air systems receive issued instructions and implement specific practical operations including window opening and closing, lamp switch, indoor temperature regulation and automatic door locking. The user interaction layer works as the communication medium connecting human users and intelligent control systems, building effective interactive channels through multiple carriers such as mobile phone application software, voice-controlled smart speakers and wall-mounted central control panels; users can release customized operational instructions to the entire system via manual clicking or voice input and check real-time indoor environmental data as well as running status of connected household equipment anytime and anywhere. These five interrelated layers constitute a closed operational logic following the route of information sensing, data transmission, intelligent decision-making, equipment execution and user interaction to guarantee all-weather stable operation of smart home systems. Some academic literatures simplify the five-layer structural framework into a three-layer division mode consisting of sensing layer, transmission layer and application layer, in which the application layer integrates functional responsibilities of control layer, execution layer and user interaction layer; such two classification standards only differ in internal categorization logic while maintaining consistent overall data circulation links of smart home systems. As smart home integration technology matures constantly, layered architectural design is continuously optimized toward higher integration and lower hardware deployment cost in actual industrial applications.

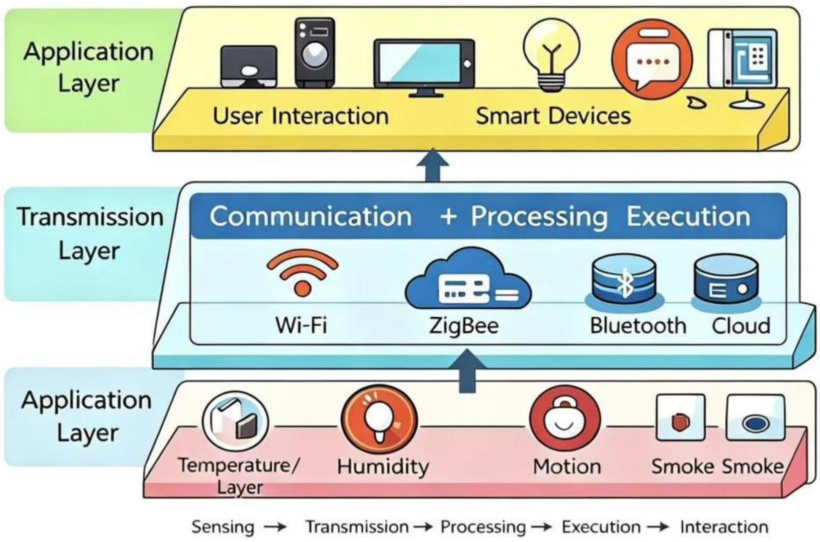

Figure 2. Architecture of IoT-Based Smart Home System.

The three-layer overall system framework is illustrated in Figure 2. The diagram clearly marks sensing layer, transmission layer and application layer, as well as mainstream transmission technologies of WiFi, ZigBee and Bluetooth, completely presenting the closed-loop data circulation of "sensing→transmission→processing→execution→interaction" and supplementing the simplified structural explanation of the five-layer architecture mentioned above.

3. Core Enabling Technologies Supporting Smart Home Operation

Sensor technology functions as the fundamental supporting technique to guarantee practical landing and stable operation of complete smart home systems, and diversified functionalized sensors constitute core hardware for environmental data collection within the sensing layer; different types of sensors can targetedly capture multi-dimensional real-time information covering temperature and humidity variation, indoor human activity track, air quality index, gas concentration and door-window opening-closing state, continuously supplying abundant original data resources for upper intelligent processing modules of the whole system. Without mature and reliable sensing technology as core technical backup, smart home systems cannot accurately perceive dynamic changes of indoor surrounding environment, which means core functional modules such as automatic regulation and abnormal hazard early warning will lose essential preconditions for normal realization. Benefiting from continuous progress of microelectronic manufacturing technology in recent years, household-level sensors keep iterating toward miniaturization, ultra-low power consumption and high measurement precision, effectively improving the detection accuracy and continuous service endurance of environmental monitoring modules in smart home scenarios and indirectly reducing the overall hardware maintenance cost for end consumers in long-term usage cycles. Besides traditional physical parameter detection sensors, biological sensing modules targeting human physical signs have also started to be popularized in high-end customized smart home equipment, further enriching the data collection dimension of modern intelligent residential systems.

Wireless communication technology shoulders the critical mission of realizing internal data interconnection across all devices within smart home ecosystems, and WiFi, ZigBee and Bluetooth represent three most widely-applied mainstream communication protocols in the present smart home industry [3], with obvious discrepancies in transmission rate, energy consumption and effective communication range leading to differentiated applicable practical scenarios [4]. Characterized by high-speed data transmission capability, WiFi is mostly equipped on high-power intelligent surveillance cameras and large-scale smart household appliances requiring frequent transmission of big-capacity streaming data; ZigBee technology stands out for outstanding ultra-low power consumption performance with excellent long-term standby endurance, so it is massively installed on small-sized sensing equipment such as door and window contact sensors and human body induction detectors keeping long-term dormant monitoring status; Bluetooth is mainly used for short-distance point-to-point equipment pairing connection and commonly configured on smart door locks and portable mini intelligent terminals requiring nearby instant manipulation. Complementary matching application of these three typical wireless communication technologies effectively ensures the stability and integrity of internal data transmission among all household smart devices, becoming an indispensable technical prerequisite to realize interconnection of heterogeneous hardware terminals. Along with the emergence of emerging low-power wide-area communication technologies in recent years, partial new-generation smart home products start to introduce novel communication modules to further break the transmission distance limitation of traditional short-range wireless protocols.

Data processing technology mainly relies on collaborative application of cloud computing and edge computing to finish massive operational data analysis tasks generated from daily running of smart home systems [5], and the two computing modes divide processing responsibilities reasonably to form complementary advantages for intelligent data management. Cloud computing depends on remote large-scale server clusters to undertake long-term massive historical data storage of all connected household equipment, large-data statistical analysis and user usage habit modeling work with heavy computational load and prolonged processing period; powerful arithmetic capability supported by remote cloud servers can realize aggregated operational analysis of big data collected from numerous scattered smart home terminals across different residential regions. On the contrary, edge computing transfers partial data processing tasks down to local household gateway equipment and intelligent central control terminals at user premises to complete instant numerical calculation nearby, greatly shortening overall data processing delay and realizing millisecond-level rapid equipment response, which can ensure instantaneous system disposal capacity under emergency scenarios including fire alarm and illegal intrusion reminder. The collaborative operation mode combining edge computing and cloud computing perfectly satisfies dual developmental demands of deep mining of massive historical data based on cloud platform and local low-latency real-time intelligent control of household equipment at terminal ends, gradually becoming the mainstream data processing architectural choice for newly-developed smart home products in the industry.

Continuous popularization and iterative upgrading of artificial intelligence technology steadily promote the overall intelligent level of modern smart home systems[6], and by adopting machine learning, user behavior modeling and other relevant AI algorithms, intelligent control platforms can conduct long-term statistical analysis on daily work-rest schedules and personalized equipment usage preferences of household users to autonomously summarize optimal equipment regulation logic under different living scenarios, getting rid of the operational limitation completely dependent on manually pre-set fixed program parameters. After a period of continuous data learning and model optimization, mature AI-driven smart home systems can automatically adjust indoor ambient temperature, light brightness and startup status of fresh air equipment according to seasonal alternation and indoor personnel presence condition, realizing automatic customized scene operation without human intervention and significantly enhancing the personalized adaptability of intelligent systems matching diversified living habits of different end users. With the rapid development of deep learning technology, intelligent home control algorithms are continuously optimized to improve environmental judgment accuracy and scene switching rationality, further narrowing the gap between artificial intelligent decision and manual optimal operation logic.

4. Typical Practical Application Scenarios of IoT Smart Home

4.1. Smart Security Systems

Intelligent home security constitutes one of the most mature and highest market penetration application directions among all smart home landing fields at present[7], and the whole set of intelligent security system integrates high-definition monitoring cameras, human body infrared detection sensors, door-window magnetic induction components and electronically-controlled smart door locks to finish equipment networking based on IoT data links and construct an all-day uninterrupted residential safety protection system covering indoor and outdoor monitoring areas. Following a fixed five-step standardized operational flow including abnormal target detection, real-time data transmission, background information processing, user notification push and remote emergency disposal, various sensing hardware inside the security system monitors unexpected household hazards all around the clock; once abnormal conditions such as non-standard door opening action, illegal indoor intrusion and domestic combustible gas leakage are detected, relevant terminal equipment immediately uploads early warning information to remote background servers via established communication network, and after systematic risk judgment, warning alerts will be instantly pushed to bound mobile application software of registered users. Under such working mechanism, household owners can receive hazard reminding messages no matter where they stay outdoors, check real-time indoor field situations by remotely activating monitoring cameras, remotely unlock entrance door via mobile terminals or trigger built-in audible and visual alarm devices to deter illegal intruders, and conduct real-time voice communication with visitors outside doors relying on built-in intercom function of intelligent door locks. Although the complete operational process of smart security systems forms a closed-loop safety defense logic, all-round data interaction throughout the whole working procedure highly depends on stable network environment, which inevitably brings prominent network-dependent characteristics to the entire intelligent security module and becomes an obvious restrictive factor affecting stable performance of safety precaution functions. With continuous upgrade of intelligent recognition technology, modern smart security equipment adds human face identification and abnormal behavior analysis functions to further improve early warning accuracy of unexpected safety incidents.

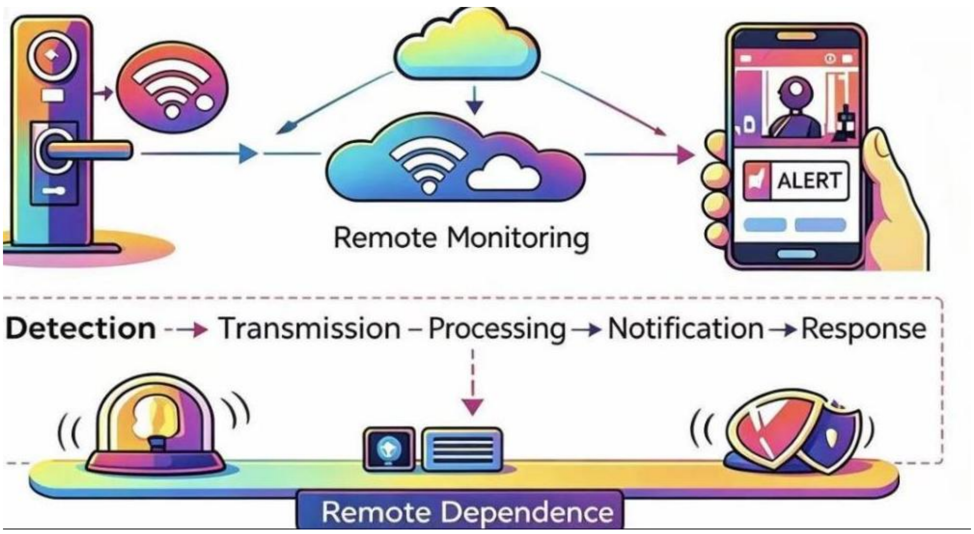

Figure 3. Operation Flow Chart of Smart Home Remote Security Monitoring.

The whole working flow of remote security monitoring is shown in Figure 3. The flowchart sorts out five successive operating steps from abnormal detection to user remote response and also marks the prominent network dependence existing in the whole security system, laying a foreshadowing for the subsequent discussion about network dependency challenges of smart home.

Precision household energy management scenario represents an important industrial landing path for smart home industry to practice nationwide energy-saving and low-carbon development concepts, and core hardware supporting energy control systems include intelligent adjustable curtains, central heating ventilation and air conditioning systems as well as programmable intelligent power sockets. Collecting outdoor sunlight intensity and indoor real-time temperature and humidity data through bottom sensing modules, the whole intelligent system automatically optimizes equipment operational status following pre-set energy-saving control logic to reduce unnecessary household energy consumption. When natural sunlight is sufficient during daytime, intelligent curtain modules automatically expand to make full use of natural ambient light so as to shorten opening duration of indoor artificial lighting lamps; when indoor temperature exceeds preset comfortable threshold value, air conditioning facilities start or shut down automatically for indoor thermal regulation, and intelligent power supply system can cut off power supply of idle electrical appliances synchronously when no resident stays indoors. Through intelligent automatic parameter adjustment of related household equipment, smart home energy management systems effectively eliminate energy waste caused by long-term idle operation and no-load standby of electrical products, minimizing domestic water and electricity consumption under the premise of guaranteeing basic residential comfort level and helping end users cut down daily living expenditure, which conforms to the mainstream green low-carbon development requirement of modern social construction. In recent years, combined with distributed household photovoltaic power generation equipment, intelligent energy management systems can further realize optimal allocation of self-generated clean electricity inside residential space, improving comprehensive utilization efficiency of new energy resources.

Health-oriented customized smart home design has developed into a newly-emerged popular developmental direction within the whole industry in recent years[6], and the core construction of such healthy residential intelligent systems centers on indoor air quality monitoring equipment equipped with carbon dioxide concentration detectors, PM2.5 particulate matter sensors and formaldehyde content detection modules to realize round-the-clock continuous monitoring of multiple harmful air pollutants indoors. Once the intelligent platform detects excessive concentration of toxic gas or suspended particulate matters exceeding national safe standard value inside living space, linkage control instructions will be automatically issued to activate matched air purifiers, whole-house fresh air ventilation systems and electric window openers to replace dirty indoor air continuously, improving overall indoor air environment quality effectively. Targeting senior citizens, infants and crowds susceptible to respiratory system diseases, health-focused smart home systems optimize indoor living atmosphere through automatic intelligent regulation from the perspective of air purification and create safer and healthier residential environments relying on digital intelligent technologies. Apart from air quality monitoring modules, some high-end customized healthy smart home products also introduce environmental humidity adjustment equipment and physical sign monitoring sensors to further expand the health management service scope of intelligent residential systems.

5. Core Advantages Brought by IoT-enabled Smart Home Systems

Compared with traditional fully-manual household management modes, smart home systems supported by IoT technologies display irreplaceable prominent advantages covering operational convenience, energy utilization efficiency, residential safety guarantee and personalized function customization in daily household application. In terms of practical usage convenience, remote equipment manipulation and automatic scene linkage serve as core competitive highlights of intelligent household products; end users no longer need to arrive beside corresponding equipment to finish manual switch operation of lighting, air conditioning and water heater facilities, and real-time remote control can be completed anytime via bound mobile phone application software no matter the geographic location of users. Meanwhile, pre-set fixed intelligent scenes such as all-house power-off mode before going out and sleeping night mode can realize synchronous startup or shutdown of multiple linked household equipment with one-click triggering, greatly simplifying complicated daily household operation flow and saving abundant spare time originally consumed on trivial home management affairs for residents. From the perspective of energy-saving control, intelligent systems optimize equipment running strategies dynamically based on real-time collected environmental data to eradicate unnecessary energy loss caused by long-time burning of idle lamps and no-load operation of household electrical appliances fundamentally, effectively reducing daily domestic water and power consumption in long-term usage cycles to cut down household living cost and fit in with social low-carbon environmental protection development concepts. For residential safety protection, all-weather uninterrupted online monitoring architecture of intelligent security systems can guard household safety day and night, and real-time early warning notification of various unexpected potential hazards makes up for inherent defects of delayed response and lacking risk pre-alarm in traditional household safety defense modes, comprehensively improving residential safety coefficient against theft, indoor fire and combustible gas leakage accidents. In the field of personalized customized service, artificial intelligence self-learning capability enables smart home platforms to formulate exclusive automatic operational scenes matching individual life rhythm for different user groups, so youngsters, elderly residents and families with infants can all obtain optimized intelligent control logic adapting to their unique living demands and break usage limitations brought by homogeneous design of traditional household products to further upgrade overall residential comfort experience continuously. Along with the continuous upgrading of consumer consumption concept globally, the multiple comprehensive advantages of smart homes gradually become core driving force to promote continuous market expansion of the whole intelligent home industry.

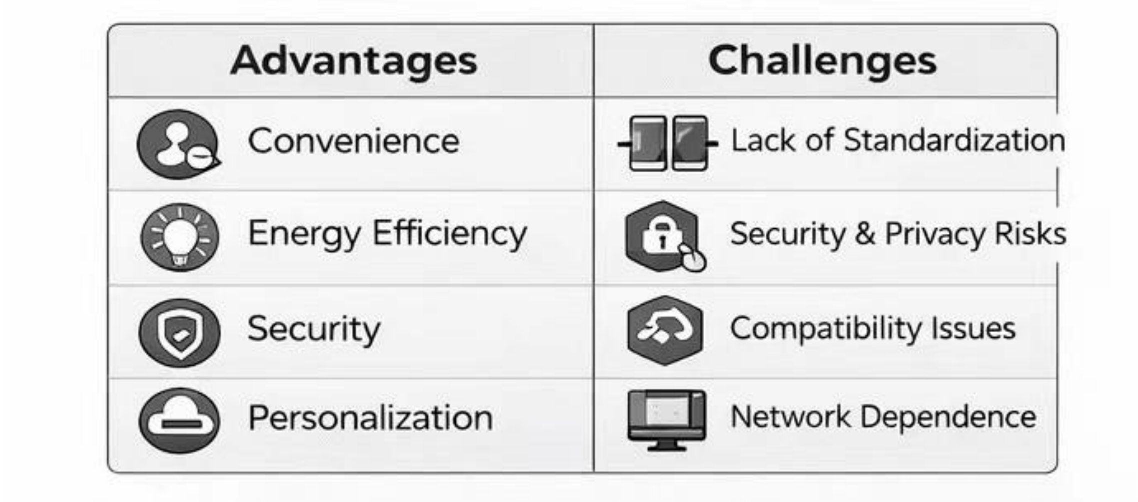

Figure 4. Summary of Advantages and Challenges of IoT Smart Home.

The summarized advantages and existing challenges are summarized in Figure 4. This chart divides the content into two modules of advantages and drawbacks, concisely summarizing four core merits and four major restrictive problems of current IoT smart home products, which can systematically summarize the core viewpoints of the above chapter and the following challenge analysis.

6. Main Existing Challenges Restricting Large-scale Popularization of Smart Home

Despite multiple practical application merits and sustained expanding market scale of smart home industry, four prominent industrial bottlenecks including insufficient unified industrial standardization construction, ubiquitous user privacy and data security risks, excessive operational dependence on stable network environment and inadequate product usability design still hinder comprehensive popularization of intelligent household products among ordinary consumer groups. Lack of unified cross-industry technical standard construction ranks as the primary obstacle facing the entire smart home industrial chain at present[8]; most mainstream manufacturers of intelligent household hardware worldwide independently develop proprietary communication protocols and exclusive equipment docking specifications for self-owned product lines, resulting in serious protocol incompatibility between hardware products produced by different brands and obvious cross-brand interconnection failure problems. When ordinary consumers purchase smart home equipment for home decoration transformation, they have to select full-set supporting products from a single fixed brand to guarantee normal system linkage operation, which not only raises overall household intelligent transformation cost for users but also limits free matching selection space of diversified hardware combinations and obstructs large-scale ecological construction of interconnected whole-house smart home industry. The diversification of technical standards also increases after-sales maintenance difficulty of smart home products and raises long-term operational cost of related after-service enterprises.

User data security and private information leakage hazards constitute long-standing difficult problems unable to be completely eliminated within the whole industry [9-10], as smart home systems collect massive sensitive personal information covering indoor resident activity trajectory, daily living schedule and detailed household environmental data throughout all-day continuous operation. Many small and medium-sized smart home manufacturers fail to build complete information protection mechanism during software and hardware product development, adopting backward data encryption technologies leading to obvious security loopholes in the link of data transmission and cloud-side storage; malicious network attackers can illegally steal confidential user private information by exploiting existing technical vulnerabilities or even remotely take over control permission of connected household intelligent equipment, potentially bringing huge hidden dangers on personal property and life safety of relevant end users. With the increasingly strict global personal information protection legislation in recent years, information security defects of smart home products also bring potential legal risks for relevant equipment manufacturers.

Over-reliance on stable network connection represents another unavoidable shortcoming of mainstream smart home products, because remote control function and automatic multi-device linkage logic of most intelligent household equipment need stable wireless network support to complete normal real-time data interaction. Once unexpected network failures happen such as home broadband outage or router equipment breakdown caused by external factors, numerous intelligent devices will lose remote control access and automatic linkage performance instantly, and partial products directly fall back to original traditional manual manipulation mode, greatly depleting core intelligent usage value of smart home equipment and damaging practical daily usage experience of end consumers under abnormal network conditions. Although partial manufacturers start to increase local offline control function of smart home equipment in newly-developed products, limited local operational functions cannot realize complete offline full-scene intelligent linkage temporarily.

Defective overall product usability is mainly reflected in complicated installation and parameter debugging flow as well as unreasonable human-machine interaction design of existing smart home products; networking configuration of complete whole-house smart home systems requires complex professional parameter setting work with high technical threshold, making it extremely tough for elderly consumer groups to independently finish equipment initialization configuration and subsequent daily functional operation after purchasing intelligent hardware. Meanwhile, excessive redundant functional settings and tedious operating logic of partial commercial smart home products further raise usage learning difficulty for common users, restricting the popularization progress of intelligent household products across all age brackets of consumer groups. Insufficient humanized design fails to consider actual usage habits of senior users and children, becoming an important factor limiting market penetration speed of mid-to-low end civilian smart home products.

7. Prospective Future Research Directions of Smart Home Industry

Targeting various realistic existing drawbacks of current smart home industry, follow-up academic research work and industrial product development within this field need to advance steadily focusing on five core developmental directions including construction of unified cross-industry interoperability standards, technical optimization of edge-cloud collaborative computing framework, upgrading of user private data security protection technology, research and development of inclusive human-friendly interactive interfaces and deep cross-border cooperation among all links of the whole industrial chain[4]. Relevant national industrial regulatory institutions, mainstream smart home equipment manufacturers and professional scientific research organizations need to cooperate closely to jointly formulate unified universal communication protocol standards and cross-brand equipment interconnection specifications covering all categories of smart home hardware; standardized industrial rules can break original technical barriers among different brand manufacturers fundamentally and create favorable market environment for free collocation and arbitrary networking of diversified intelligent household hardware, effectively reducing overall intelligent transformation expenditure of ordinary household users and accelerating the formation of large-scale interconnected smart home industrial ecology.

Continuous optimization of edge-cloud collaborative computing architecture will become another key research focus for future technical iteration of smart home systems, and subsequent research needs to further balance data allocation proportion between local edge processing terminal and remote cloud server, optimize dynamic data shunting algorithm to lower overall system operational delay and reduce unnecessary data transmission volume occupying household network bandwidth resources. By improving synergetic operation efficiency of edge computing and cloud computing, future smart home systems can further promote offline local intelligent processing capacity of terminal equipment and alleviate excessive dependence of intelligent functions on uninterrupted remote network connection. Meanwhile, upgrading of end-to-end data encryption technology and privacy protection algorithm is essential to solve long-standing information leakage risks of smart home industry; researchers need to develop safer confidential storage protocols and dynamic anti-hacking defense mechanisms to enhance overall information safety performance during data collection, transmission and cloud storage process, fully protecting personal private data security of smart home end users and complying with increasingly stringent global personal information protection legal requirements.

Developing humanized and all-age inclusive interactive interface design is also a vital developmental trend of follow-up smart home product upgrading, and R&D designers need to simplify redundant functional operation steps of existing intelligent control terminals, optimize display logic of mobile control application software and develop large-font, voice-dominated easy-operation modes targeting elderly users with poor digital operation ability to lower overall usage threshold of smart home equipment for all-age consumer groups. Depending on comprehensive industrial cooperation among upstream raw material suppliers, midstream hardware manufacturers and downstream system integration service providers can also promote integrated technological innovation of the whole smart home industrial chain, realize resource complementation and technical sharing among different enterprises and accelerate the iterative upgrading speed of new-generation cost-effective intelligent household products. Along with continuous emerging of novel digital technologies such as big data and metaverse-related interaction techniques, smart home research will also combine cutting-edge emerging technologies to expand new intelligent application scenarios and continuously enrich service content of future intelligent residential systems.

8. Conclusion

IoT-based smart home systems have become a major trend of intelligent living, while the problems of inconsistent standards, data security risks, network dependence and poor user experience still restrict its large-scale popularization, and solving these problems is the key to building a comprehensive interconnected smart home ecosystem.

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