Smart Home Security System Based on Digital Twin Technology

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Abstract. This paper proposes a digital-twin-based smart home security system aimed at addressing key security challenges in modern households. By constructing a digital replica of the home environment, the system enables continuous, precise, and real-time monitoring of various indoor conditions. It details the system architecture, digital modeling methods, data processing, and the integration of anomaly detection algorithms, which significantly enhance detection accuracy and responsiveness. As smart home technologies become increasingly widespread, users demand higher security performance, yet existing solutions still face issues such as delayed threat detection, limited interoperability, and unreliable event judgement. To overcome these limitations, this paper proposes a novel digital-twin-enabled system design that offers improved intelligence, coordination, and effectiveness in safeguarding residential environments.

Keywords: Digital twin, smart home, security system, Internet of Things.

1. Introduction

As an emerging field that has risen rapidly in recent years, the Internet of Things smart home [1] [2]is showing vigorous development vitality. The market scale continues to expand, and consumers' acceptance and usage rate of smart home products continue to rise - from the early smart door locks and smart speakers, gradually expanding to an all-round smart home system covering lighting, home appliance control and other scenarios. In terms of industry layout, Haier, Midea, Xiaomi and other leading enterprises have joined one after another. At the same time, a number of emerging start-ups have emerged with digital twins' [3] technological innovation and product differentiation. With the maturity of 5G, artificial intelligence and other technologies, the variety of products is getting richer and richer, and the functions are also more suitable for user needs: users can realize convenient operation and remote management of home equipment through mobile phone APPs, voice assistants and other ways.

The key technologies supporting the development of smart home mainly include communication technology [4] with WiFi, Bluetooth and 5G as the core, which realizes data transmission and real-time interaction between devices, which is the basis for connection. Artificial intelligence technology focuses on voice recognition, image recognition, face recognition [5] and other applications - voice recognition allows users to use natural language Command control equipment to improve operation convenience; image recognition can monitor family activities in real time and enhance security; more importantly, AI can allow devices to independently learn user behavior patterns and realize personalized services. Sensor technology [6] [7]: covers a variety of types such as temperature and humidity, light, human infrared, etc. By monitoring the home environment and user status in real time, the device can respond quickly and adjust automatically to achieve "perception is service".

Digital twins are the digital representation of physical entities (or processes, systems) in virtual space. It builds a digital model that fully corresponds to physical entities by integrating physical models, sensor data, running history and other information. It is not a static "photo", but a continuously updated "live screen". It is not an isolated 3D model, but a "live" model that injects data, can be simulated, analyzed and predicted. Digital twin technology is particularly important in today's smart home development. The real-time virtual digital model created by digital twin technology can instantly reflect the changes in the state of physical space. For example, when there is an abnormal person breaking in at home, the model can be presented instantly, so that the system can quickly issue

an alarm and greatly improve the real-time detection of threats. Digital twin technology can integrate various equipment data into a virtual model, comprehensively analyze personnel activities, equipment operation and other information, accurately judge the nature of the event, and effectively avoid misjudgment. In addition, digital twin technology takes the virtual model as the core, and processes all device data centrally, so that all devices can work closely around the model. When a device detects an abnormality, the model can quickly allocate other devices to work together to deal with security incidents. The accuracy and speed of the fingerprint recognition module of the smart door lock have been significantly improved. 3D structure light face recognition technology can effectively defend against two-dimensional attacks such as photos and videos, and can achieve high-precision recognition in dim light and even at night (through the infrared night vision module), and can also adaptively learn the user's facial features (such as wearing glasses, masks, etc.)). Palm vein identification has begun to be applied in high-end markets because of its higher anti-counterfeiting and accuracy. Infrared sensors, sound sensors, temperature and humidity sensors, light sensors and other sensing elements, combined with AI algorithms, can more accurately judge real threats (such as abnormal intrusion, elderly falls), and effectively reduce the false alarm rate. Smart door locks and cameras can identify abnormal stay in front of the door, tailing, prying locks, multiple password trial and errors and other behaviors, and actively capture and send alarms. AI object recognition, for example, sweeping robots can accurately identify and avoid obstacles at home.

Modern home security is no longer a single soldier, but emphasizes integration and linkage. Intelligent linkage between devices: intelligent door locks, surveillance cameras, door and window sensors, alarms, lighting systems (such as smart lights), and even household appliances (such as air conditioners and range hoods) can be linked based on the scene. Mainstream security devices are usually compatible with smart home platforms such as Apple HomeKit, Google Home, etc., allowing users to manage all devices through an App or voice assistant [8]. The privacy function design allows users to turn off monitoring at a specific time or area by providing physical occlusion (camera lens cover), privacy area setting and other functions. And the pet care function. When the owner goes out, he can remotely observe the pet's condition through the camera, and even interact with voice or feed it. Instant teleworking can also be remotely video intercomed, which is convenient for receiving express delivery or receiving temporary visitors and generating temporary passwords. Due to the continuous growth of the market, the market scale of core security equipment such as wireless surveillance cameras [9] intelligent door locks [10] continues to expand. The consumer-level surveillance camera market is growing steadily.

2. Smart Home System and Digital Twin

In smart home, the multi-sensing integrated intelligent security and environmental monitoring system achieves all-round coverage of home safety and environmental perception. The system is deployed in key areas such as balconies, bedrooms and kitchens, and the specific distribution is shown in Figure 1. In the second bedroom area, smoke detectors and temperature sensors can quickly identify fire hazards, and alarms can issue warnings in time when there is an abnormality; on the balcony of the master bedroom, smoke detectors and light sensors can monitor smoke and light changes, and alarms, monitoring, sound sensors, door and window sensors work together to ensure regional safety, It can also perceive the environment and the state of doors and windows; in the kitchen, smoke detectors and temperature sensors can keenly capture the fire risk during cooking, and sound sensors and monitoring equipment can assist in monitoring abnormal sounds and pictures; the living room balcony and surrounding areas are also integrated with corresponding sensing and monitoring equipment to build a solid core activity area of the family. Security defense line. Through the linkage of various sensors, monitoring equipment and alarms, the system realizes the comprehensive monitoring of home safety (fire, intrusion, etc.), environment (light, temperature, smoke, etc.) and sound dynamics, so that users can grasp the home situation in real time. Once an abnormality occurs,

it can respond quickly to create a safe and intelligent environment for the family. The living environment.

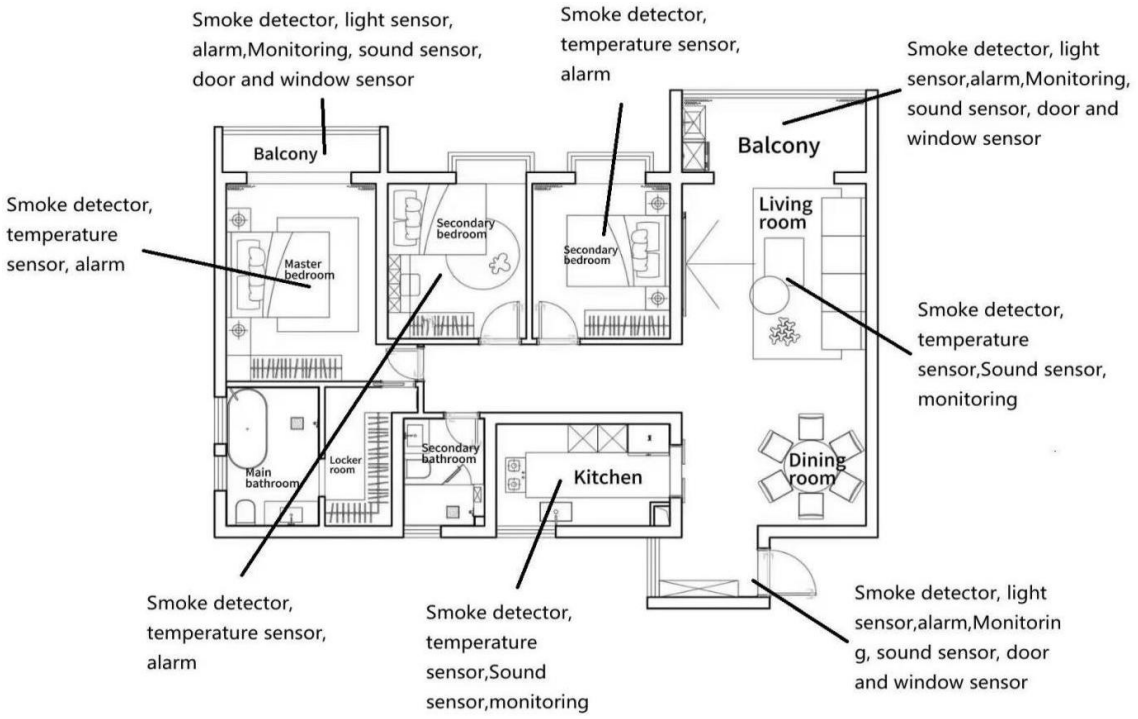

Figure 1. Smart home application scenario

3. DT-based Smart Home System Framework

Figure 2 shows the architecture of an intelligent system, which is divided into four levels: data layer, model layer, application layer and management.

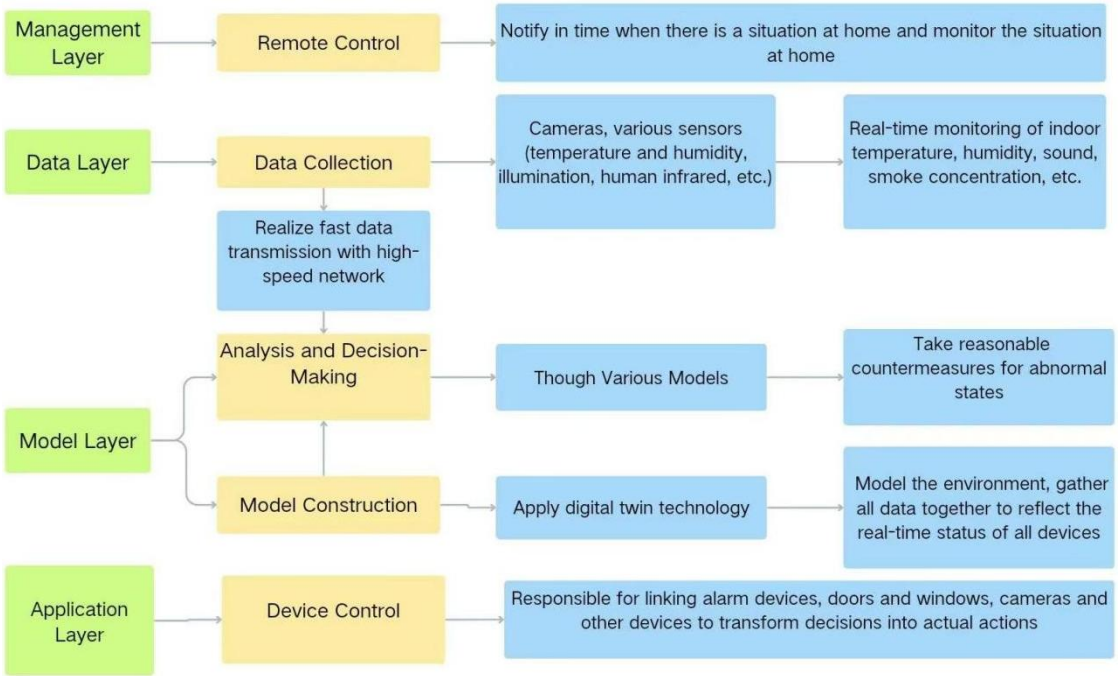

Figure 2. System architecture diagram

Management, through the "remote control" link, timely notification and remote monitoring of the home situation can be realized. Data layer, through the "data collection" link, cameras, temperature and humidity sensors, light sensors, human infrared sensors and other devices are used to monitor

indoor temperature, humidity, sound and smoke in real time. Concentration and other data, and then realize the rapid transmission of data through the high-speed network. Model layer, including two links: "model construction" and "analysis and decision-making". "Model Construction" uses digital twin technology to model the real-time state of the environment and all equipment and gather all data; "Analytical Decision-making" makes reasonable countermeasures for abnormal states through various models. Application layer, Through the "device control" link, it is responsible for linking alarm devices, doors and windows, cameras and other equipment, and transforming the decision-making of the model layer into practical actions.

4. Modeling

In the smart home security system, digital space system modeling can build accurate virtual models, so as to realize real-time monitoring of home security status, intrusion behavior prediction and intelligent device linkage. The modeling methods that can be adopted include system dynamics modeling, data-driven modeling, discrete event modeling, physical modeling, multi-intelligent body and other methods. Among them, the multi-intelligent body modeling method simulates an intelligent body with independent decision-making ability and its collaboration mechanism. Each intelligent body represents a functional entity in the system, such as door and window sensors, face recognition cameras, emergency alarm devices, etc. Each intelligent body makes independent decisions based on preset strategies and real-time environmental information, and exchanges information and behavioral coordination with other intelligent bodies through communication networks, so as to achieve accurate simulation of complex security scenarios. For example, when an abnormality is detected, the intelligent experience immediately activates the regional camera for visual verification and sends a risk assessment request to the central controller. The intelligent alarm will decide whether to start sound and light alarm or remote notification according to the comprehensive threat level. The user terminal intelligence can receive system alerts and provide a human-computer interaction interface, and support remote confirmation or emergency dispatch. This distributed decision-making architecture has significantly improved the adaptability of the system to multi-source threats. It can be described by the following formula:

$$\text{Action} = \pi(\text{InternalState}, \text{EnvironmentalInput}) \tag{1}$$

Among them, Internal State includes the internal state of the intelligent body (such as power state, signal strength, working mode), and Environmental Input covers environmental input (such as motion detection signals, sound characteristics, time context).

System dynamics modeling is mainly used to describe the timing evolution of various elements in the home security system. This method depicts the dynamic characteristics of key variables such as intrusion risk level, device response delay, environmental interference factor and so on by constructing a system of ordinary differential equations. The system realizes real-time deduction and early warning of abnormal events by establishing home security digital twins.

Figure 3 shows the System flow chart.

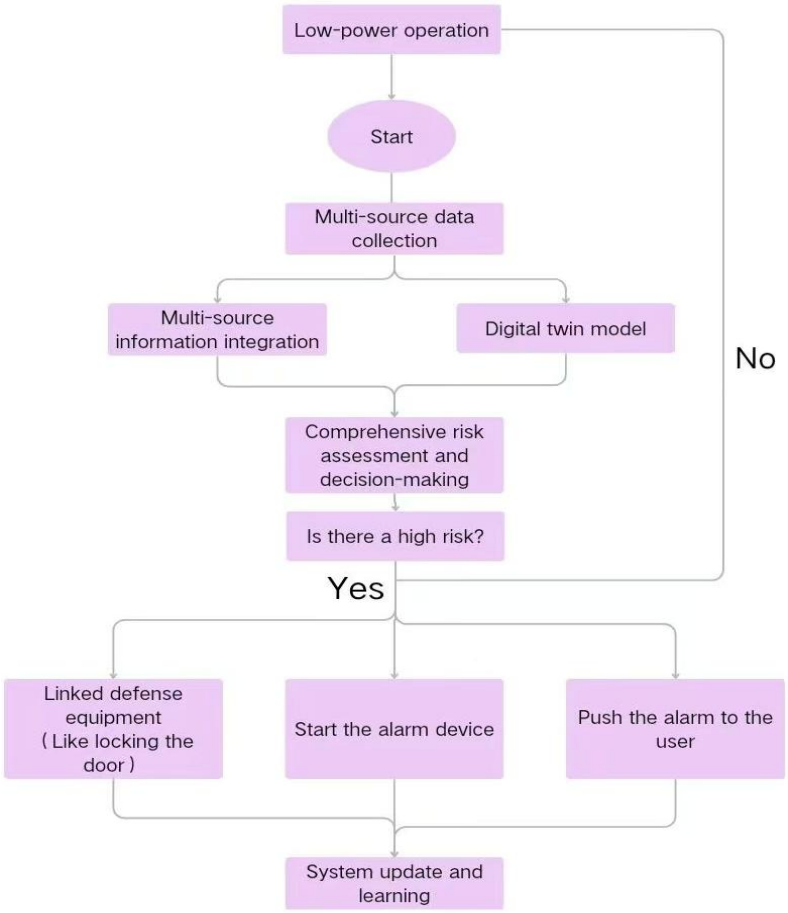

Figure 3. System flow chart

5. Intelligent Computation

Use threshold-based detection to set reasonable thresholds for various sensor data. For example, the normal state of the door and window sensor is off (the state value is 0). If the state value is detected to be 1 (that is, the door and window are open) and the system is in a defensive state, an abnormal alarm will be triggered. When the smoke sensor detects that the smoke concentration exceeds the preset safety threshold (such as 50ppm), it is judged as an abnormal situation. It is suitable for situations where there is a clear safety range for specific indicators, such as detecting abnormalities that obviously deviate from the normal range, such as smoke and temperature. Collect sensor data for a period of time and calculate its average and other statistics. Take the personnel activity in the camera monitoring area as an example, if the number of personnel or activity frequency detected at a certain moment significantly deviates from the historical mean (such as exceeding 3 times the standard deviation), there may be an abnormal situation. This method assumes that the normal data distribution conforms to certain statistical laws. It is suitable for situations where the data has relatively stable statistical characteristics, such as places where the entry and exit rules of daily personnel are relatively fixed, which can effectively detect abnormal behaviors that deviate from the conventional pattern.

6. System Optimization

According to the actual use scenarios and needs, reasonably arrange hardware equipment such as sensors and alarms. For example, increase the density of the sensor in the position of doors and windows that are prone to intrusion to improve the detection accuracy; choose devices with better performance and lower power consumption. Choose devices that support encrypted transmission and strong anti-interference ability, and avoid using old models that are easy to crack; give priority to the

camera with night vision function, reasonable layout and coverage to ensure that the door There is no dead angle on the window sensor, and the camera covers key areas such as the door and balcony to avoid monitoring blind areas. In areas with weak signals, the stability of the equipment network should be ensured. Optimize the algorithm of the control center to improve data processing efficiency and system response. (Figure 4)

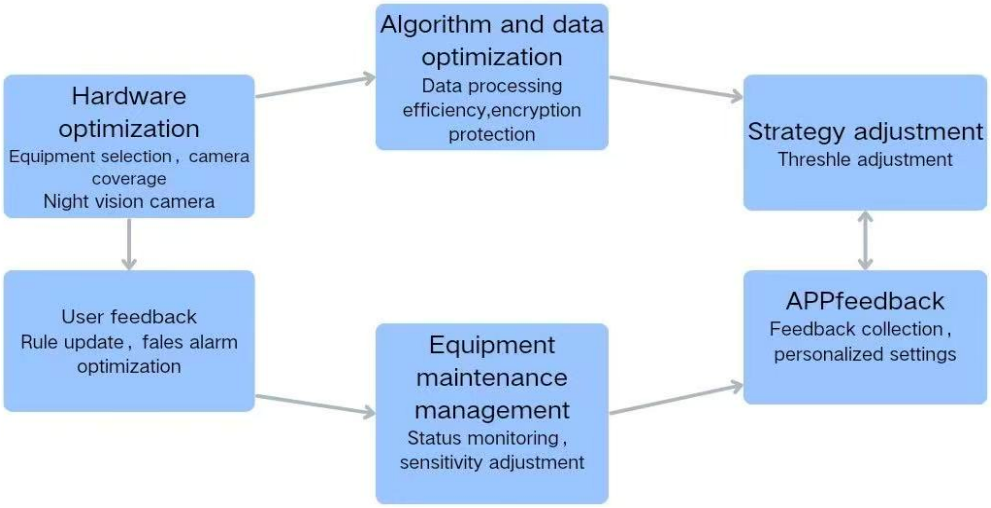

Figure 4. System optimization chart

7. Fire alarm system

For fire prevention, the house is equipped with smoke detectors and heat detectors.

For smoke detectors, the principle of photoelectricity can be used to detect smoke, which is suitable for ordinary families and can detect the smoke generated by the combustion of a variety of substances. The heat detector adopts a constant temperature to trigger the alarm when the ambient temperature reaches a specific threshold, which is suitable for the scene of abnormal temperature rise. In addition, the detector has a multi-level alarm mechanism, a built-in high-decibel buzzer (the volume can reach more than 85 decibels) and flashing LED lights to ensure that it can be clearly perceived in noisy environments. And send SMS, phone or App push to users through smartphone applications or smart home systems, so that they can keep abreast of the fire even if they are not at home.

The temperature threshold of fire alarms in different places is different. For places with high daily temperatures such as kitchens, garages, etc., the temperature point is 57℃ (135℉), while for living rooms, bedrooms and other places, the temperature point is 68℃ (155℉).

When an abnormal situation is detected, it quickly links with other home systems at home through the digital model to automatically close the gas valve when a fire is detected to prevent the fire from spreading. Start the sprinkler system and cooperate with the automatic sprinkler fire extinguishing system to carry out local sprinkler at the beginning of the fire to control the fire. And turn on the smoke exhaust equipment, link the smoke exhaust machine, positive pressure fan and other equipment, and quickly exhaust the smoke to create conditions for escape. (Figure 5)

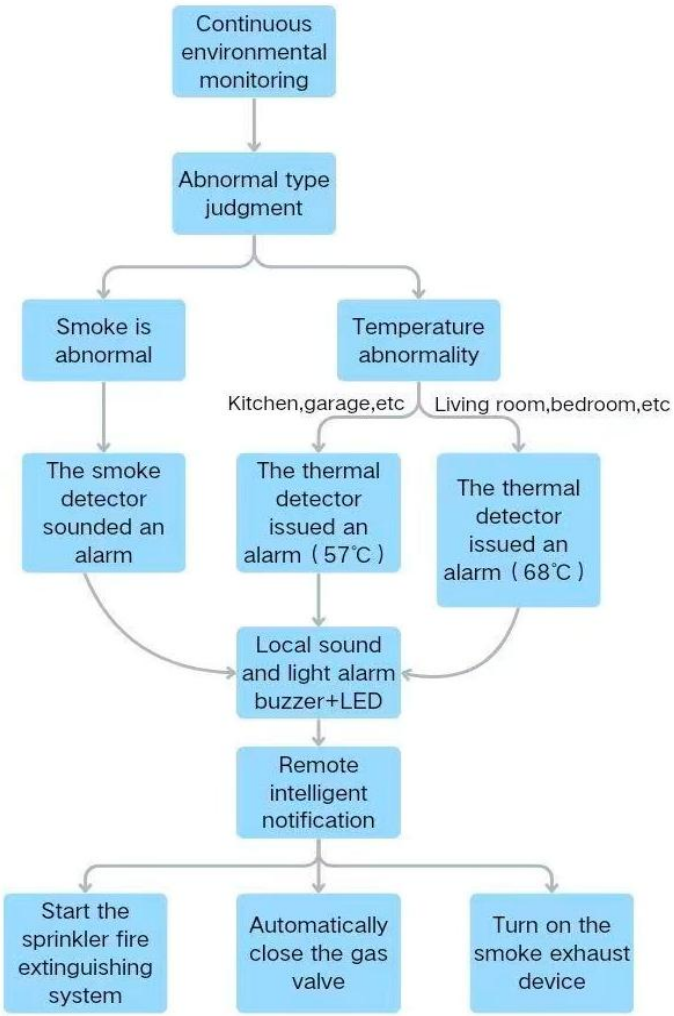

Figure 5. Flow chart of fire alarm

8. Conclusion

In summary, integrating digital twin technology into smart home security systems greatly enhances household safety and environmental monitoring capabilities. The adopted modeling techniques and intelligent computing methods improve real-time monitoring and anomaly detection performance. Through targeted optimization of hardware deployment—such as strategic sensor placement to eliminate blind spots—and functional design enhancements, including multi-level alarm mechanisms and fire-linked automatic gas valve shutoff, the system significantly improves threat detection responsiveness, event judgment accuracy, and device coordination. Although current technologies enable smart home systems to deliver basic security functions, substantial opportunities for further advancement remain. Future work may focus on improving modeling accuracy and efficiency by exploring more advanced AI-driven dynamic modeling methods, leveraging deep learning to optimize real-time model updates and simulation capabilities, and better adapting to complex and evolving home environments. In addition, customized safety strategies should be developed to meet the needs of different age groups, such as children and the elderly. Ensuring data privacy will require stronger encryption mechanisms and more robust security protocols. Finally, enhancing cross-platform compatibility will be critical for enabling seamless integration with a wider range of devices and further expanding the system's development potential.

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