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The Design of Environment Monitoring Systems Based on Digital Twins in Smart Home

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Abstract: *Nowadays, Digital Twins (DT) and Smart Home are both hot points. As the recent new idea, the former one has received great attention. And after few years developing, the latter one is gradually maturing. In principal, in a typical smart home, there should be numerous devices and systems which most can be networked. Using various sensors and actuators, these system could collect the data from the real world and influence the real world. In fact, DT can also be used in these systems. By using DT, we could cheek not only the current states of the system, but also the history of the data for learning. Therefore, it could be the connection between smart home and AI. This article firstly introduces the development status of smart home and DT. Then it analyzes the possibility of connecting smart home and DT. Finally the article pays attention to the framework and design for the whole system and introduces the modeling methods, the computing methods and system optimization. Finally, the article makes a conclusion and draw the picture of the comprehensive application of DT at the social level.*

Keywords: *Digital Twins, Smart Home, Environment Monitoring, System Modelling*

1. Introduction

With the popularization of 5G technology, the continuous improvement of cloud computing technology and Artificial Intelligence, the realization of Internet of Things (IoT) as a technology and its widespread application have become possible and are gradually maturing. By using IoT technology, controllers can execute commands by entering commands into a client device, such as a PC, tablet or cell phone, to instantly control one or more remote ports [1]. IoT technology has a wide range of application scenarios. It will have a profound impact on many industries or sectors, such as transportation, energy, healthcare, education, and so on [2]. Along with the development of IoT technology and the arrival of 5G communication technology, IoT technology can be applied to a wider range of fields, especially in the area of smart home. Smart home is the most direct way for people to enjoy high-tech life. The continuous upgrade and iteration of communication technology has created the possibility for the realization and application of smart home [3]. The implementation and application in the field of smart home has become a popular project [4]. However, the realization of the smart home requires multiple technical support as electronics, software, sensors, actuators and network connectivity that enable these objects to collect and exchange data.

Digital Twins is a technology that connects the real physical world with the virtual simulation world. By simulating in the virtual world what might happen in the physical world, it enables a one-to-one mapping of any possible situation to its response strategy. Virtual models can collect data from physical sensors to obtain the state of the real physical world and process and analyze the data for prediction, estimation, and simulation. The DT will build a closed loop between the physical and virtual worlds [5-7]. The DT can be applied to the smart home, enabling multi-complex situation response solutions through virtual world simulation and data analysis. This paper will focus on how to apply DT in the field of environment monitoring in smart homes and design the basic structural architecture as well as modular functions. The safety of smart home is ensured by using DT in temperature and humidity detection, environmental alarm detection, and gas leak detection.

The following parts of this paper are as follows. Section 2 introduces the smart home application scenario and the specific implementation method and conceptual structure diagram. Section 3 introduces the architecture of smart home system based on DT, and the functions of each module or level in the

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architecture, including mathematical modeling methods, data analysis methods, and system optimization schemes. A basic implementation case is given in Section 4. Finally, conclusions and future works are summarized in Section 5.

2. Smart home System and Digital Twins

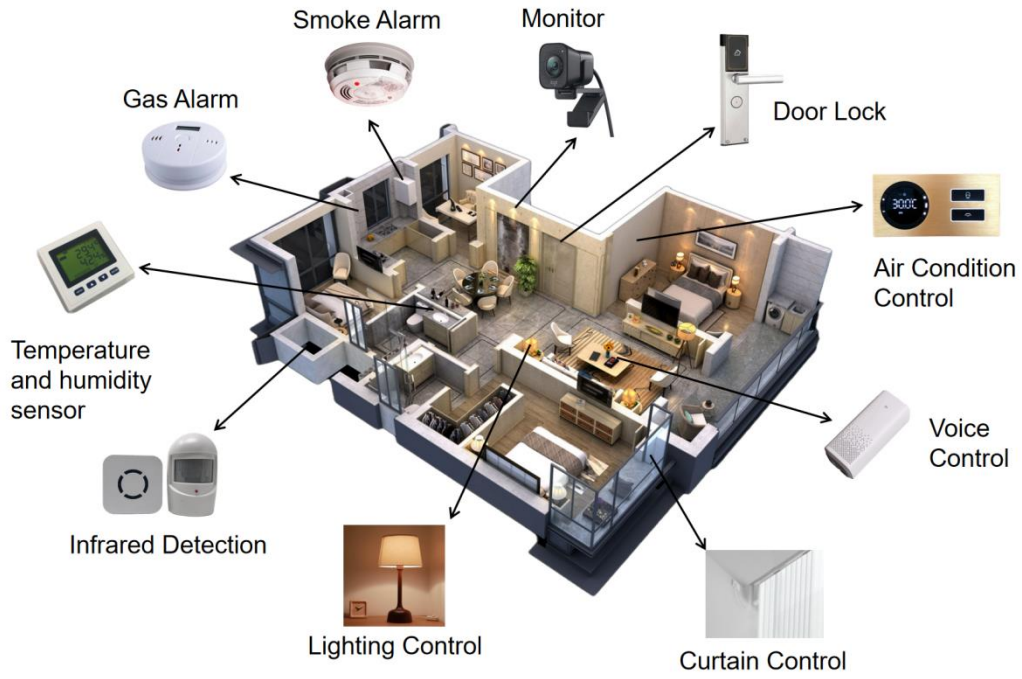

Figure 1: A general view of a smart home system

As shown in Fig.1, the whole smart home basically consists of smoke alarm, monitor, smart door lock, air conditioner controller, voice controller, curtain controller, light controller, infrared detection, temperature and humidity sensor, gas alarm, smoke alarm and other basic sensors and control system. The most important system is the voice control system, which consists of a voice receiving unit that can receive, recognize and transform the voice information of the house owner, and realize the central control of voice by communicating with other control unit systems in the house such as air conditioning control system, lighting control system, etc. through specific protocols. The one-to-many communication also allows other control systems to eliminate the need for a separate voice recognition module.

The voice center collects the voice information of the house owner as well as other complex information such as heart rate at the time of giving the command, time of giving the command, etc. and uploads it to the cloud using the Internet. The cloud collects the data and uses mathematical methods to analyze the data and combine it with big data to try to summarize more potential information such as user preferences, user habits, etc. In the virtual space built based on the DT, simulated experiments are conducted and the results are sent back to the voice control center of the house. The voice center receives the command from the cloud and then digitizes the command and sends analog signals to other control systems to achieve intelligent control.

3. DT-based Smart Home System Framework

This part will introduce the technology framework of the system for the digital twin for smart home. The technology framework has four layers, which are the physical layer, data layer, modelling layer and application layer.

(1) Physical Layer

Physical layer corresponds to the physical entities. The devices in physical layer can be divided into sensors and actuators. Sensors include temperature sensors, humidity sensors, and infrared detector. It is clear that sensors are used to collect data. And the actuators are used for operating the order. Typical

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actuators are air conditioner, light, and lock. At this layer, the system achieves most functions in reality such as, operate different devices and use sensors to collect data.

(2) Data Layer

Data layer is responsible for finishing all the data including collecting data, dealing with data, and transporting data. At this layer, the system could finish the connection and transformation between the input and the output. The input comes from the data collected by various sensors and detectors. After computing, the results will be send to the output. (The detailed calculation method will be introduced later).

(3) Modeling Layer

At modeling layer, the system will use various methods to finish the modeling task. The construction of DT model mainly includes conceptual model and model implementation method. The front one, conceptual model describes the structure and system of DT at large scales. And the latter one, model implement methods focus on the modeling language and the development of related tools [8]. The process of building the model has five steps: 1.conceptual modeling 2.framework design 3.model design 4.model implementation 5.integration [9].

(4) Application Layer.

At application layer, system will finish detecting, predicting, and make the final decisions. All the decisions and the results of predicting are based on the huge number of historical data to confirm the accuracy of the decisions. After combining the DT, the system could complete the process of reasoning, analysis, and replying. Based on the results of modeling layer, application layer will make the final decisions. Based on this decision, it could decide whether to turn on certain actuators and their working conditions. For example, application layer can decide whether open air conditioner and the degrees of setting. So, at this layer, the system will finish learning and make adjustment by itself. Because of this feature, DT is treated as the connection and bridge between many real senses and the intelligent manufacturing.

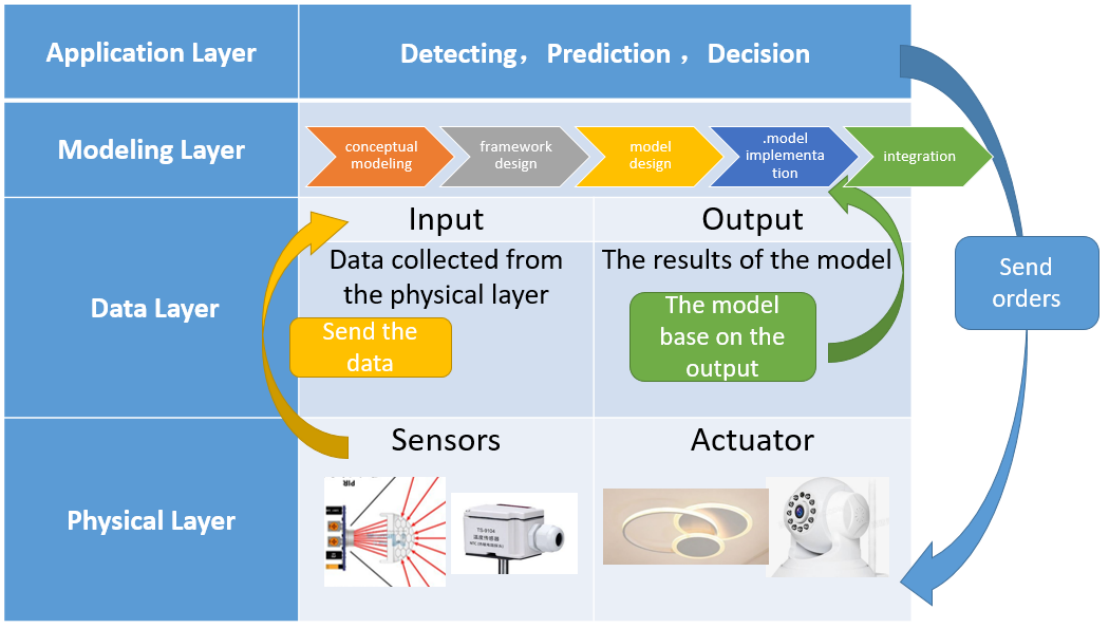

Figure 2: The structure of the proposed DT-based environment monitoring system.

This part introduces the usage framework of the system for the DT for smart home. Nowadays, with the development of computer technology and modeling methods, DT has been used in various fields, such as aerospace, factory layout, military deduction and so on. Using the DT in the smart home could help solve the problems of environmental monitoring, system operation and the system reply. Based on the definition and the feature of the DT, the system could finish the design for serval frameworks of typical applications such as adjust indoor temperature, adjust the indoor humidity, and control the indoor brightness. By these frameworks of typical application, the system achieve the detecting and simulating of indoor environment, the working conditions of indoor equipment, the use of different equipment, and the prediction of the users' habits. Then base on the results of modeling and simulating, the system could

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make decisions about different conditions which include normal conditions and emergency. Under normal circumstances, the system just collect the data and makes the predictions and then follow it.

For example, if the resident always set the air conditioner when the indoor temperature is higher than 35 degrees. When emergency happens, the system should record and identify this condition. Just following the front example, when the indoor temperature is higher than 35 degrees, the system open the air conditioner automatically. However, at this time the resident just close the air conditioner for serval reasons. For the smart home system, it could be treated as an accident and emergency, because it is totally different from the prediction. At this time, the system should try to analyze the reasons by comparing other data and find out what other factors cause this result. This is only an example of how the system control the indoor temperature. Adjusting the indoor humidity and brightness is similar to it. The single difference of these process is the data subject changes from the indoor temperature to indoor humidity and brightness.

3.1 Modeling

Modeling is the most important part in the whole system. Under normal conditions, modeling means copying or reconstructing the layout and structure of the house. Modeling here means building a digital model to help system make decisions and prediction. The basis of building this model is the related historical data collecting from users habits. After serval years' development, there are various modeling methods and they should be used in different occasions.

According to whether the data is regular, it can be divided into two occasions. If the data is regular and the law is easy to find, the digital model is easy to build. Taking temperature control as an example, if we only consider the environment temperature and air condition using conditions (on or off, recorded as 0 or 1), we just need to find the relationship between these two variables. So, the aim is to find the fit indoor temperature to open the air conditioner. Under this circumstance, we could use Fuzzy Model to deal with this problem [10]. Fuzzy model can solve problems which its background and relationship is unclear.

However, in the reality, the conditions are more complicated and there are more factors need to be considered. Also taking temperature control as an example, if temperature is not the only factor, the ambient humidity, the healthy condition of residents and many factors could make differences. Under this circumstance, there may be not an accurate and clear digital model. So, some complicated modeling methods are considerable. One of this is BP neural network model. The process could be summarize that performing nonlinear operation on the input samples, and then performing linear superposition to get the result. If the result is inconsistent with the expected value, the output error will be inversely transmitted, and the two processes keep cycling.

In fact, there are many modeling methods can be used in smart home. For example, the BP neural network based on the neural network algorithm could be used for fire prediction and warning [11]. And Hussein also pointed out a smart home system which use RNN (Recursive Neural Network) and BP neural network model [12]. Furthermore, there are many deep learning model which could be updated and revised. A new model based on the LSTM was proposed in [13], which could revise and update itself when occasions are different.

3.2 Intelligent Computation

Firstly, we should be clear that the intelligent computation has a close relationship with modeling, but they are different ideas. Algorithm is the method of building the model and how to deal with massive data. However, the model is the results of the algorithm running on the training data. Because of the development of related technology, some algorithms and AI technology has been used in some IT companies which have massive data collected from users [14]. In fact, some of these algorithms could be used in the DT based on smart home system. Because they have the same aim, providing more smarter and personalized service for users. One of these algorithms is machine learning algorithm. Machine Learning is an algorithm used to analyze data, keep learning, and make prediction and judgement. Some of the typical machine learning algorithms are also correspond to the modeling methods mentioned above. For example, Logistic Regression could be used in binary classification problems [15]. Just like the example of air-conditioning mentioned earlier, the working condition of the air conditioner is binary opposition (on and off, 0 and 1). So, using this algorithm could the predicted result. Naive Bayes is also typical machine learning algorithm. Because of its using condition, two factors are independent, Naïve Bayes could only be used in some special occasions. Besides machine learning algorithm, deep learning

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algorithm is also a good choice. Deep learning algorithm is similar to machine learning algorithm, but they still have some differences. Deep learning algorithm can extract features by itself. The typical deep learning algorithm is neural network. Furthermore, ANN (artificial neural network) is commonly used in predicting and analyzing data [16]. Both the RNN model and BP neural network model which mentioned before are based on this algorithm. No matter deep learning algorithm or machine learning algorithm needs plenty of data. The application scenario of smart home happens to provide a large amount of data which could reach the requirement.

3.3 System Optimization

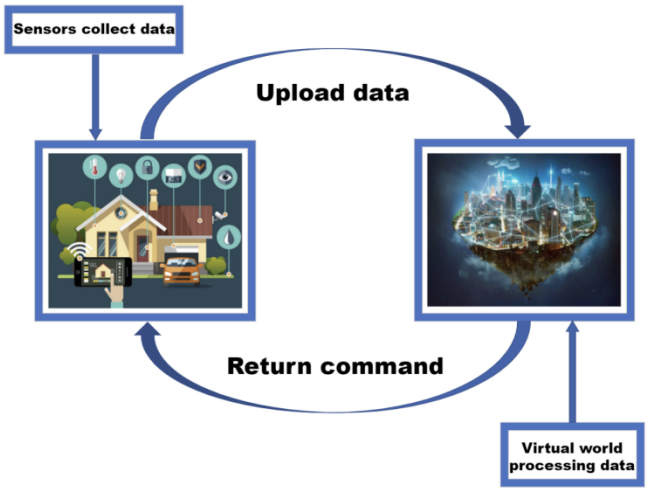

Figure 3: Optimization between virtual and physical system.

Smart home systems can be optimized by using digital twin technology. After receiving data from sensors inside the house, the house control system can collect and upload the information to the website for statistics and organization. The processed data will be transferred to the cloud, where it will be processed and fed directly into a space generated using digital twin technology, where the data will be recognized and processed by the computer to simulate the real physical world in which the data resides. In this virtual space, which is based on the real physical world data, the computer can simulate any possible scenario and make the most reasonable calculation to achieve the optimal solution for these scenarios.

The whole optimization system is a closed-loop structure. As the user's usage time grows, the amount of data will become larger and larger, and the virtual space constructed using digital twin technology will become more realistic and closer to the real physical world scenario. In addition, homeowners can regularly give feedback on their experience and evaluate the optimal solution of the virtual space to help the virtual space better simulate the real world and achieve a high degree of personalization. This closed-loop optimization update system perfectly realizes the feedback adjustment, which can greatly improve the intelligence of smart home and user satisfaction.

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4. An Environment Monitoring system based on Arduino technology

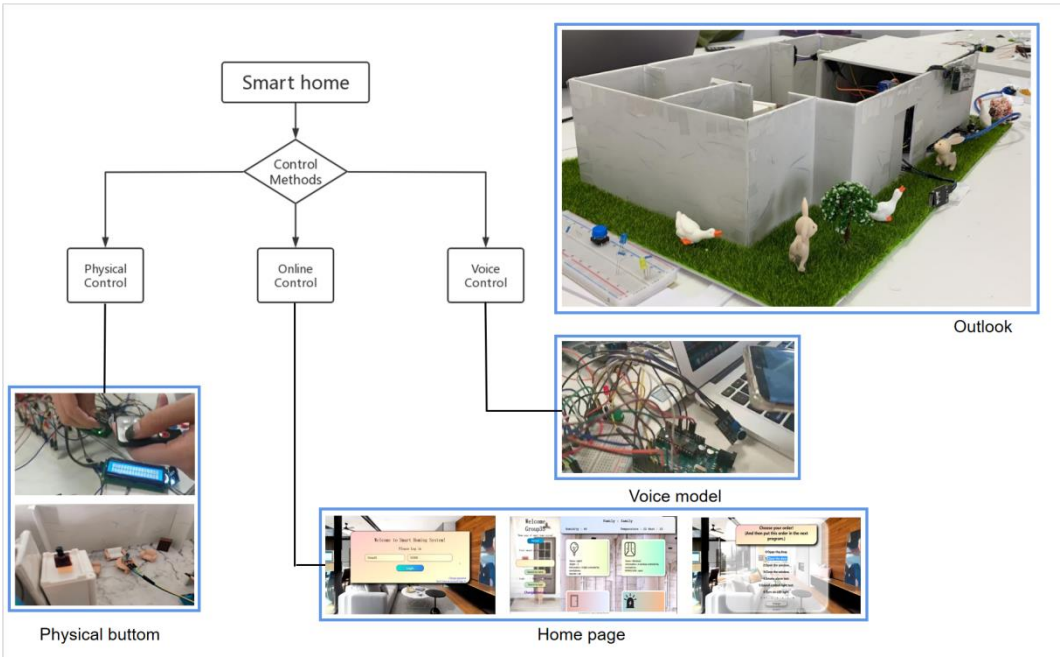

Figure 4: A smart home example based on Arduino technology

The above picture shows a smart home based on Arduino technology, with built-in smoke alarm, temperature sensitive resistor, temperature and humidity sensor and other basic sensors to realize the digital house information such as temperature and humidity, and open and close the doors and windows status and other functions. After the code is written and transferred to the UNO board, the voltage output of the interface inside the UNO board is controlled by the change of external physical buttons and switches or the state adjustment of the web site, thus realizing the control of electronic devices. By connecting to MySQL database, the information is stored and sorted together, and in cooperation with Bluetooth module and infrared sensor module, it can obtain the room information and control the house remotely from the web. Finally, the alignment of the house will be standardized, and the control panel will be sealed in an area to achieve encapsulation to make the smart home more simple and beautiful.

Our smart home case implements three basic controls, physical control, web-side control, and voice control. Among them, the voice control module realizes the feedback for voice, and more intelligent voice judgment needs more technical support. Our case realizes the simulation of the physical end as well as the digitalization of the smart home, which has positive implications for the future implementation of the smart home. The case shows the feasibility of smart home and the aspects that can be improved, such as the nesting of complex functional modules and the intelligent decision-making functions constructed by the virtual world. Cloud computing technology and DT will really make the smart home take shape.

5. Conclusions and Future Work

Nowadays, with the development of AI, big data, and integration of new technologies and new ideas, DT could be used in wilder field. In the previous part of this article, it has introduced the design for the DT system and mentioned several applications of DT for smart home. However, that parts focus on the control of family internal factors. In fact, it could connect with many external factors. For example, by using DT, we could achieve the control of temperature or humidity such things. If we can also implement the external links, the whole system could finish more complicated tasks such as automatic contact hospitals, automatic maintenance, and automatic warning. For instance, if an elderly person has an acute disease at home, the system can not only detect and analyze the elderly person's healthy conditions, but also can contact the hospital immediately.

What's more, DT could be used in the design of the whole city. Using DT can better realize resource regulation and allocation which is helpful to the management of the whole city. Nowadays, many Chinese cities are trying to achieving the smart city by using DT. Nanjing tries to use DT to achieve efficient

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deployment of express delivery. Smart governance center of Chengdu also tries to build the cyber city to deal with possible accidents in the future. Although, many aims can't be achieved immediately, DT will be more mature in the future.

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