Design of Intelligent Home Lighting System Based on Digital Twin Technology

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Abstract. This article proposes an innovative design concept for lighting systems using digital twin technology. The proposed system utilizes digital twins to construct virtual models and rapidly develop and improve lighting solutions in simulated environments. In addition, digital twin technology can monitor and predict the operational status of analysis systems in real time, thereby improving reliability and security. This article provides an overview of the architecture design of a digital twin lighting system, detailing the design of each module, and providing insights into the experimental results of optimizing system performance. The experimental results clearly emphasize the significant improvement in efficiency and overall performance of smart homes through the application of digital twin technology in lighting systems.

Keywords: Digital Twin, Intelligent Home, Lighting System, Application.

1. Introduction

With the rapid development of the Internet, a large number of new technologies and applications have emerged. It is worth noting that the Internet of Things (IoT) and smart homes have attracted great attention. The Internet of Things represents a technology centered on the Internet, which facilitates intelligent connections between objects and between individuals and objects. And smart home represents the practical application of Internet of Things technology in the residential field, realizing that home devices can interact with cloud platforms through IoT technology support, and achieve various controls and management. The combination of the Internet of Things and smart homes can bring us a smarter, more convenient, and more environmentally friendly way of life.

By connecting physical fields with digital modeling systems, digital twin technology can help smart home systems better control and manage homes, and improve their insight and predictive ability towards real-world events. For example, by using digital twin technology, smart home systems can regularly observe and analyze the current state of the entire family, and automatically adjust settings and functions based on the scene and lifestyle habits. By using digital twin technology, the entire household system has been fully monitored.

In summary, digital twin technology has great potential in improving the intelligence, environmental friendliness, and comfort of smart homes. Smart home systems based on digital twins are particularly adept at customizing smarter connections and settings to meet the needs and usage habits of different households.

2. Smart Home Systems and Digital Twin

The foundation of smart homes lies in the intelligent integration of home devices, utilizing advanced technology and the internet to facilitate functionalities such as visual depiction, intelligent control, and automated coding, thereby improving the efficiency and simplicity of home management. The complexity of the smart home lighting system is rooted not only in the selection of various bulb types and fixed devices, but also in its capability to seamlessly toggle between application configurations, precisely modify brightness and color, and provide automated control.

Digital twin technology signifies a sophisticated technological advancement, facilitating precise simulations and predictions based on the physical surroundings. Through the amalgamation of sensors, immediate data, and advanced modeling methods, this procedure transforms the configuration, operation, and behaviors of physical objects, systems, or processes into a digital format. Employing digital twin technology facilitates continuous collection and juxtaposition of real-time data against existing models. This feature's real-time functionality enables the monitoring, improvement, and prediction of complex real-world systems.

Consider smart homes as a case in point, in which digital twin technology precisely reflects the structure, equipment, and environmental condition of the home. The system has the ability to mimic and predict various scenarios, encompassing energy consumption, temperature fluctuations, and safety risks. The effectiveness of virtual testing and simulation matches. By altering the digital twins, we gain the ability to predict and track the results of various strategies and decisions, thereby assisting in making decisions and resolving issues. Employing digital twin technology acts as a powerful tool to improve design, simplify procedures, and increase total efficiency, simultaneously nurturing a smarter, efficient, and safe living environment for families (Figure 1).

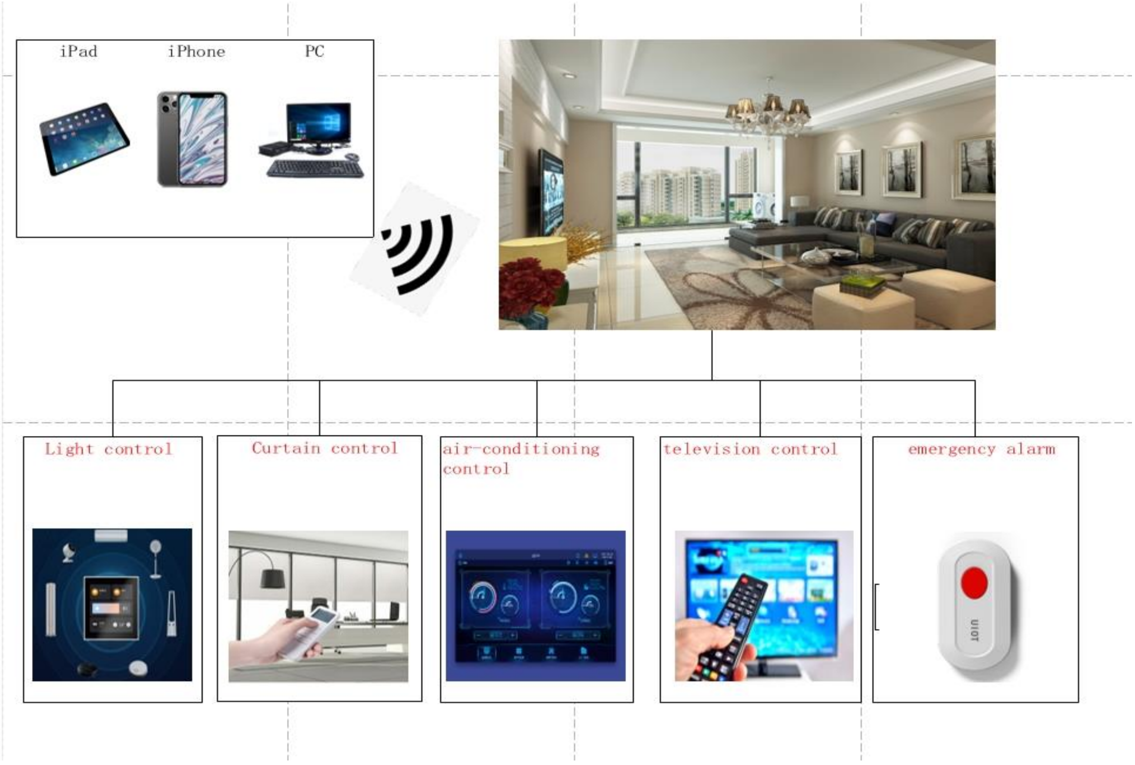

Fig 1. Schematic diagram of smart home.

Essentially, digital twin technology replicates real-world objects, systems, and processes digitally, offering a broader, more sophisticated, and accurate approach for comprehending, observing, and forecasting reality. This feature enables smart home lighting systems to better supervise and control the home environment, enhancing overall life quality. As a result, the array of practical applications and commercial prospects presented by digital twin-based smart home lighting systems is extensive.

3. Structural framework

Digital twins are about creating precise virtual models that reflect the real world. Smart home backgrounds can simulate interior lighting in real scenes and achieve intelligent control.

For smart home lighting systems based on two digital foundations, 1) adjust the lighting conditions: brightness and color can be adjusted to improve the interior comfort and well-being for any household. 2) Customize lighting for specific scenes: Adjust brightness, color temperature and lighting direction to improve interior aesthetics. 3) Intelligent detection: The system can automatically control lighting based on factors such as availability, outdoor lighting and weather, thereby improving daily comfort. 4) Unique Scenarios: Digital bio-industrialization technology enables different scenarios, such as movies, meetings, reading, etc., to improve the overall quality of life.

In short, digital twin technology will significantly improve the comfort, aesthetics and comfort of smart homes, ultimately improving the quality of life of residents as a whole.

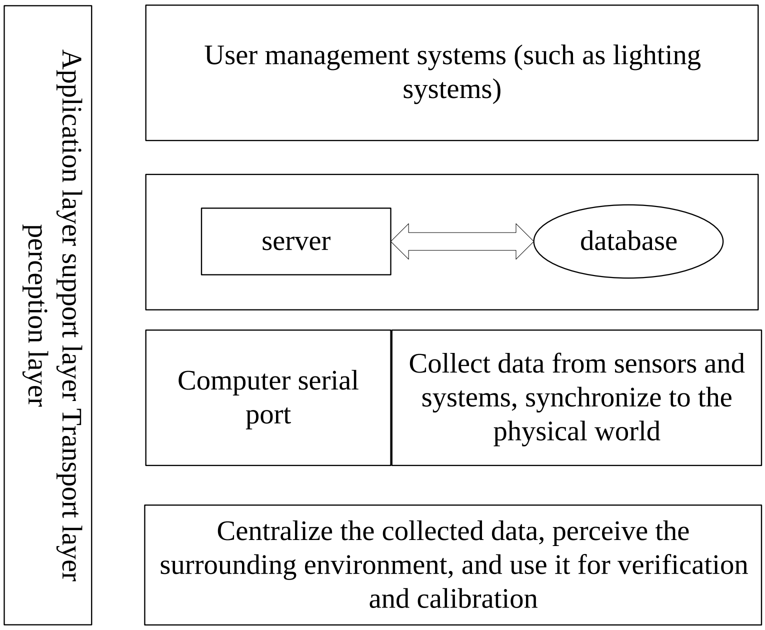

Fig 2. The framework of the proposed intelligent lighting system.

The application layer is the interface for users to interact with digital twins. Provide users with a graphical interface, user interface, command input and a way to communicate with digital twins. The application also provides data analysis, reporting and problem solving capabilities to help users understand data and make informed decisions (Figure 2).

The support layer provides the backend support required for implementing digital twins. It includes functions such as data management, database management, security and privacy, user management, system and device management, etc. The support level also provides technical support for data processing, data storage, algorithm optimization and model training.

Data transmission and intercom component communication are handled by the transport layer. It offers transmission protocols, data interfaces, and communication protocols for data and information transfer in digital twins. Cloud platforms, IoT communication, data networks, etc. can all be considered components of the transport layer.

The real-world state and data of objects or systems are observed, recorded, and tracked using the perceptual layer. The sensor layer gathers environmental data for the digital twin system through a variety of sensors, gadgets, measuring tools, cameras, detecting systems, and other systems. To update and synchronize the data of digital twins, the perception layer transmits real-time data to the transport layer.

3.1. Modeling

The process of turning real-world physical locations and things into computer representations is known as digital space modeling. Computer-aided design (CAD), building information modeling (BIM), LiDAR, and photogrammetry are some of the techniques it uses.

In reality, CAD is extensively utilized in industries like electronics, machinery, and architecture. Drawings and models are designed, altered, and optimized with the use of computer software.

Specifically, engineers can deepen their comprehension of smart home lighting systems' intricacies by employing CAD for an accurate depiction of the system's operation and structure. Through CAD tools, designers have the ability to create and alter system models, select optimal design options, and evaluate the impact of these decisions on system efficiency and user experience.

Integrating digital twin technology with CAD enhances the simulation and forecasting of lighting system efficiency. CAD software is capable of generating simulated lighting models and replicating various lighting patterns. Adjusting the necessary data for practical models is achievable through diverse experiments on this model.

Techniques in Building Information Modeling (BIM), LiDAR, and photogrammetry share a close connection with digital twin lighting systems.

Digital twins' lighting setup is interconnected with BIM, enhancing the precision and dependability of lighting designs. Utilizing LiDAR technology for gathering geometric information on building surfaces enables the creation of digital twin building models, capable of simulating light distribution in real-time under various lighting scenarios, thus enhancing lighting impacts. Furthermore, the use of photogrammetric techniques enhances the accuracy of digital twin building models by amassing additional geometric information via image measurements.

3.2. Data analysis

Digital twins are crucial to the analysis of data. They are able to convert real-world entities, procedures, or systems into data models. We can more effectively collect the necessary data, show data changes more clearly, and conduct intuitive analyses thanks to digital twins.

First and foremost, we must gather and document statistical information on the lighting system, including the frequency, length, and brightness of light changes. Sensors or user interface devices in lighting systems can be used to gather this data, which can then be stored on cloud platforms or central databases for processing that can be done centrally.

Next, we can use algorithms to examine and process the obtained data to identify patterns and usage trends of lighting systems. By analyzing the most typical usage patterns in these data, we can better understand user habits and preferences in lighting, and then allow the model to self-optimize to the state that best suits user habits.

In addition, time series analysis will also be applied to lighting system data to identify light usage trends over time, which helps the model identify specific situations, such as nighttime lighting.

Machine learning technology is crucial for digital twins in data analysis. Train algorithms by learning historical data, such as decision trees, vector machines, or neural networks. We can create user preference models for lighting, which can automatically adjust lighting settings based on the user's historical habits.

In practical applications, the choice of data analysis methods depends on requirements and specific environments. For example, in the lighting system, if the user wakes up regularly at 6 o'clock every morning, the system can make predictions based on historical data and actively turn on the lights. However, considering the personal preferences of users, they can also manually intervene and control the system when interacting with it, so that they can enjoy a comfortable and personalized lighting system.

3.3. System optimization

Incomplete or inaccurate data: When creating a digital twin model, it is necessary to collect and integrate multiple data points, such as color, brightness, and light source position, which are key factors determining the authenticity and quality of the digital twin model. Digital twin models can be significantly impacted by missing or erroneous data in terms of authenticity and accuracy.

Data transmission and synchronization: Digital twin models are virtual models created based on real lighting systems, but they cannot accurately reflect all characteristics of the real environment, such as network latency, data loss, or synchronization issues. Therefore, when using IoT technology for remote control of digital twin models, it is necessary to ensure continuous data output and synchronization between the lighting system and the digital twin model. Only by understanding the changes in these data and evaluating and modifying them as needed, can data transmission be ensured.

Limitations of simulation: As it is a simulation model, some small changes in the interaction between light can easily be ignored when calculating the transmission and reflection of light, so the expected results of the model may not be the same as reality.

The effectiveness of algorithms and controls: When controlling the lighting of digital twin models, careful consideration must be given to the efficiency of the algorithms used. Different algorithms will produce different results in different situations, so it is necessary to optimize and debug the algorithms appropriately when facing lighting systems to meet the requirements of the required operations.

4. An Example of Intelligent Lighting System

This specific case study demonstrates the benefits of applying digital twin technology in smart home lighting systems. This technology can customize lighting settings to ensure accuracy in brightness and color control, and enhance user happiness and comfort. Smart home lighting systems can also improve indoor space aesthetics and automatically adjust lighting based on historical data recorded by sensors and specific conditions, making the lives of family members easier. In summary, the application of digital twin technology in smart home lighting systems can significantly improve the quality of life for users (Figure 3).

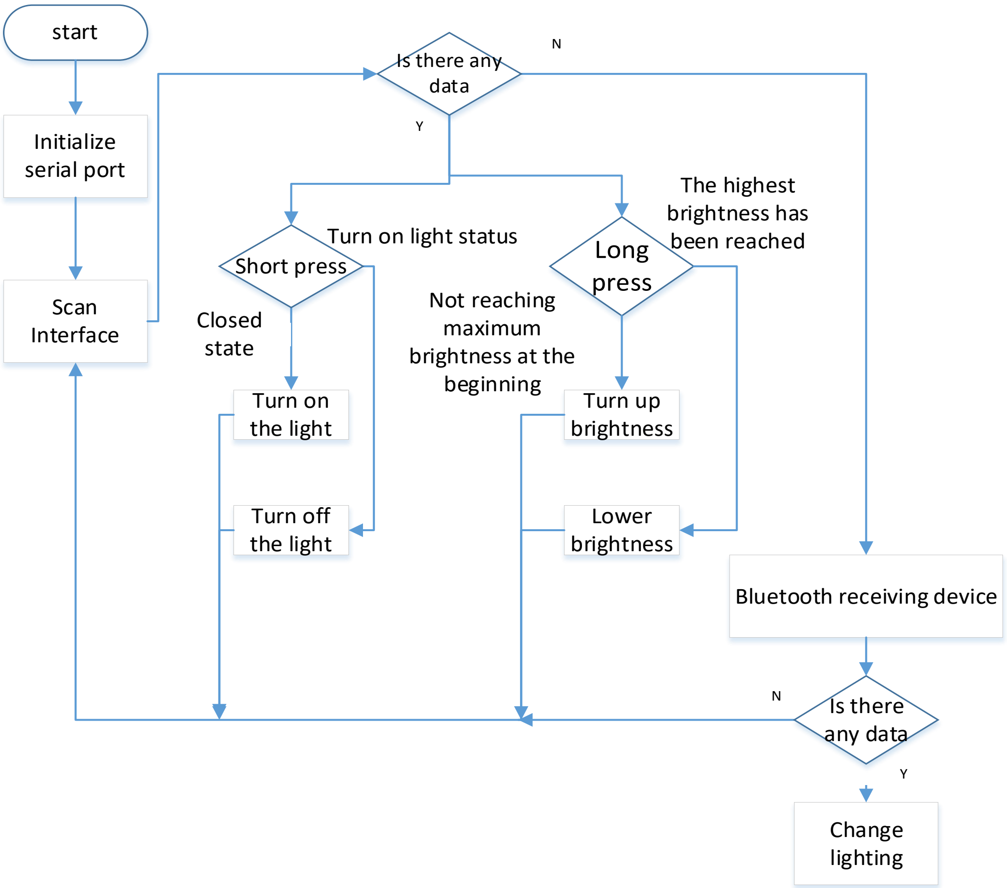

Fig 3. The flowchart of a digital twin lighting system.

Firstly, we need to develop a digital, which is a virtual comparison of actual lighting systems in virtual reality. For this, we can use some modeling software such as CAD to design and model some parts.

Set the digital twin model's lighting modes, hue, and brightness to replicate the behavior of light. To simulate the propagation and reflection of light as it happens in the real world, use a physics engine in the virtual environment. You can observe in this virtual environment how the scene is affected by varying light elements and positions.

Control Algorithms and Data: Leverage a range of algorithms and data to control the lighting within the digital twin model. Employ machine learning algorithms to autonomously adjust brightness and color based on environmental conditions and user preferences, achieving intelligent lighting control.

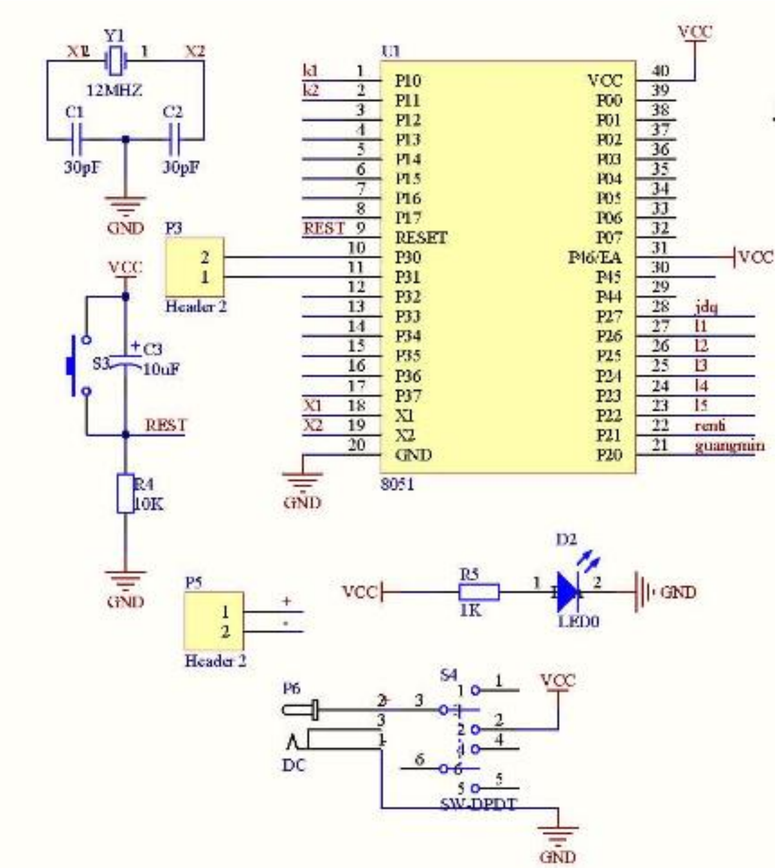

Fig 4. Information exchange among the lighting system by Bluetooth.

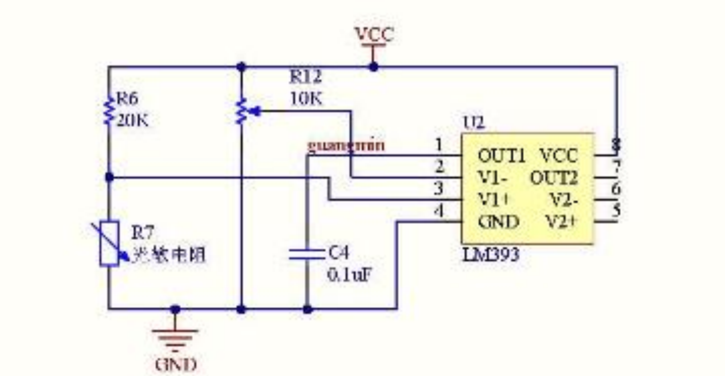

Fig 5. Bluetooth design diagram.

As depicted in Figure 4 and Figure 5, information exchange is facilitated among the lighting system components via Bluetooth. When the first component receives a signal, it can relay this information to the second component, enabling it to execute the switching function.

The system initially requires the collection of real-world data, encompassing parameters of lighting equipment, light intensity, energy consumption, environmental conditions, and more. This gathered data must be transmitted via a network or other means to the digital twin system for processing and analysis, either within a local server or a cloud environment. Within the digital twin system, the collected data serves as the foundation for constructing a virtual lighting system model. This model comprises lighting equipment parameters, system topology, light propagation models, and related physical and energy consumption models.

The simulation and analysis results are then presented in an understandable manner by the digital twin system. This visualization, which can be displayed in graphical reports, 3D models, dynamic demos, and other forms, can assist users in having a complete understanding of the system's performance and operating state.

5. Conclusion and Future Work

This article provides an overview of the application of digital twin technology in intelligent lighting systems, as well as relevant experimental results. It also summarizes the advantages and disadvantages of digital twins in intelligent lighting systems, and provides future research paths and expansion opportunities.

In the future, many research topics should be studied. Firstly, digital twin modeling technology can improve the accuracy and reliability of system predictions. Secondly, research the best method to incorporate external environmental data into digital twin models to better adapt to the actual operating environment of intelligent lighting systems. Finally, a particularly interesting research area is to optimize the control strategies of intelligent lighting systems by using deep learning and reinforcement learning techniques to improve lighting effectiveness and energy efficiency.

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