

Enhancing the Scalability of LED Control Systems through Virtual Reality Technology Integration

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Abstract

This study aims to develop a VR technology-based LED control interface. The objective of the study is to provide an intuitive user experience and improve efficiency in smart home lighting environments. For this, it designed an algorithm and interface to control LED lighting installations utilizing VR technology. VR technology was utilized to allow users to intuitively control LEDs in a virtual reality space, and a spatial coordinate-based input method was used to enable more precise control. It also implemented pulse width modulation (PWM) technology to control LED color temperature and brightness. This enables real-time control and synchronization of LED installations, and the system is designed to allow multiple users to share and visualize control data on a network basis. By establishing a multi-participatory LED control environment, this study presented various application possibilities such as media art, education, and experiential content. It also added vibration feedback to user input to enhance immersion, and optimized the algorithm to prevent data loss and ensure real-time operation. This study expects to make an innovative contribution to the development of smart home lighting systems and extended reality content.

Keyword : VR, LED Control, Smart Lighting, Multi-User Synchronization, Intuitive Interface

1. Introductions

Modern LED (Light Emitting Diode) lighting technology is becoming an important technology for improving energy efficiency and user experience in smart home environments. LEDs are widely used around the world due to their low power consumption and long lifespan compared to traditional lighting systems. In recent years, they have evolved beyond simple lighting to smart lighting technologies that control color, brightness, and timing. In particular, the convergence of virtual reality (VR) technology and the Internet of Things (IoT) is further expanding the possibilities of LED lighting systems. VR technology enables users to connect real and virtual spaces in real time in order to give them more intuitive control over their lighting environment. This offers the potential to revolutionize the user

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experience. VR-based LED control technology provides users with an immersive lighting control experience, unlike traditional control methods. While traditional wall switches and dimmers only allow for simple brightness adjustments, VR technology allows users to precisely adjust the color and brightness of LEDs based on coordinates in space. This goes beyond simple control and allows for creative lighting environments. Beyond simple ease of use, VR-based LED control has potential applications in a variety of industries. It can be utilized as a tool to deliver immersive content in media arts, performances, exhibitions, and education. In particular, with advances in user interface design and data processing technology, these systems are becoming more intuitive and accessible to users.

In this regard, this study focuses on developing a VR technology-based LED control system and examining its potential applications. In doing so, it aims to enhance the user experience and offer new possibilities to support more efficient energy management and creative lighting design in smart home environments. The main objectives of the study are to design an intuitive and real-time interface for controlling LED lights, develop algorithms including color and brightness control of LEDs, and integrate them with a virtual reality environment to allow users to control them in real time. In this process, spatial coordinate-based data processing techniques are utilized to effectively process the user's intuitive input [1].

The purpose of this study is to maximize the user experience by introducing VR technology to the LED control system and explore the possibility of integration with the smart home ecosystem. In particular, it provides a technical basis for realizing LED control in a multi-user environment through combination with IoT technology. Thus, it aims to realize creative and immersive user experiences that existing LED control technologies have not been able to provide. In particular, the design of intuitive interfaces that can effectively control LEDs in large-scale installations or public lighting environments remains a significant challenge. To meet this technical need, this study designs and develops a system that can control LED lights in real-time using a VR technology-based controller. In addition, various tests are conducted in an experimental environment to verify the effectiveness of such a system, and the obtained results are analyzed. In conclusion, this study explores how LED control systems utilizing VR technology can be applied in smart homes and commercial environments. In doing so, it expects to open up new directions for expanding the potential of LED technology and enhancing the user experience.

2. Developing an LED control system based on VR technology

The VR technology-based LED control system is designed to provide users with more intuitive and

and gestures in real time and converts them into spatial coordinate data. This allows the user to select the exact location of the LEDs in the virtual space, adjust their color and brightness, and more.

As shown in [Fig. 2], the user interface was designed utilizing virtual reality development tools such as Unity. The interface has a user-friendly design and supports multiple input methods including buttons, gestures, and voice commands [3]. For example, users can use hand gestures to change the color of the LEDs or adjust their brightness. This intuitive interface contributes to reducing the user's learning curve and increasing system usability [4]. Spatial coordinate-based algorithms utilize data input from the HMD controller to control the LEDs. The user's movements are converted into 3D spatial coordinates, which are associated with the position of the LEDs based on this coordinate data. For example, when the user moves the controller to a specific location, the LED at that location is selected and controlled. This algorithm ensures high accuracy and responsiveness, and greatly improves the user experience. PWM is an essential technology for controlling LED lighting, which precisely adjusts the current and voltage of the LEDs to achieve smooth, flicker-free lighting. The system generates the appropriate PWM signal for the LED driver based on the user's input data. These signals dynamically control the brightness and color of the LEDs and can meet different lighting conditions [5]. A synchronization mechanism is designed to prevent data conflicts when multiple users use the system simultaneously, and to ensure that each user sees the LEDs in the same state. Real-time synchronization is achieved by utilizing a network-based data transmission method, which is especially important in smart home environments and public lighting environments.



[Fig. 2] LED Control User Interface Using HMD Controller

3. Applications of LED Control Systems

A case study of a smart home environment is analyzed to evaluate the effectiveness of a VR technology-based LED control system. The analysis is conducted to measure the technical performance

and user experience of the system, and to examine its various application possibilities. The user in the test wears an HMD and uses the LED control system to manipulate the interface, such as adjusting a specific light or selecting a desired location [6]. In the tests, the system responded very quickly and accurately when it came to adjusting the brightness and color of the LED lights. Lighting control utilizing PWM technology provided smooth light changes and resulted in flicker-free, stable lighting. The ability to see the status of the LEDs in real-time in the virtual reality space allowed participants to intuitively understand the adjustment process. In particular, participants found the spatial coordinate-based control method to be simple and intuitive to use, with a short learning curve for effective control.

Testing results in a multi-user environment were also positive. Even when multiple users were using the system simultaneously, there were no data conflicts, and all users were able to see and adjust the same LED status. This demonstrates the reliability and efficiency of the network-based synchronization mechanism. The system demonstrates that it can offer strong advantages, especially in public lighting systems or environments where collaborative work is required.

The system has the potential to be utilized in a variety of fields. In media art and exhibitions, it can provide an immersive experience that interacts with the audience through lighting. For example, in an exhibition space, audiences can select specific colors and brightnesses of lighting through a virtual reality space and experience the immediate changes that are applied to the physical exhibition space [7]. This allows light itself to be used as a medium for artistic expression, and can dynamically transform an otherwise static exhibit. In education, VR can be used to help students learn how light works and experiment with creative lighting designs. In particular, in space design or architecture classes, immersive simulations utilizing LED lighting can be a powerful learning tool for students.

In a smart home environment, the system can provide customizable lighting and contribute to energy efficiency. Through VR technology, users can control all the LED lights in their home at once, and adjust them through voice commands or simple gestures. For example, a user can turn off the lights in every room without getting out of bed. This system has the potential to become a tool that combines ease of use with energy savings. However, the system does have some limitations. The current prototype has been validated in a small-scale environment and needs further testing before it can be applied to larger installations or complex public lighting systems. In addition, the interface needs to be further improved to make it more accessible to users with less technical skills. For example, simplifying the UI or adding voice-based help is needed to make it intuitive for users of different ages and skill levels. The development of sophisticated gesture recognition technology is also needed to improve the accuracy and efficiency of the system. Current systems recognize basic gestures, but higher resolution sensors and

sophisticated algorithms are needed to accurately detect detailed gestures. For example, if a user can fine-tune the color of an LED with the slightest movement of a finger, the user experience will be richer. It is also possible to leverage artificial intelligence technology (AI) to analyze user behavior and automatically optimize lighting. This would allow the lighting to automatically adjust to the user's habits and environment without the user having to make any settings. For example, if a user prefers to dim the lights in the evening, the system can automatically work to reduce the light level during that time.

4. Scalability of multi-participant LED control systems

One of the keys to a VR technology-based LED control system is to realize a multi-participant control environment where multiple users can collaborate simultaneously in a virtual reality environment. This system is a departure from the traditional control approach centered on a single user, and offers new possibilities for multiple users to interact with each other to adjust lighting and reconfigure spaces [8]. The multi-participant LED control system adopts a server-client network structure to support real-time data exchange between users. The server collects input data from each user, processes it, and transmits it to the clients so that all users can see the same lighting status. This structure is essential to prevent data loss while maintaining synchronization of LED control. The virtual reality space provides a variety of visual and interactive elements that allow users to get direct feedback on the lighting. For example, when a user selects an LED in a particular area, that LED is highlighted and its selected state is shared with other users in real time. This visual feedback effectively supports multi-user collaboration to design or adjust lighting.



[Fig. 3] Examples of Multi-user collaboration

In addition to network-based data synchronization, the system incorporates multisensory elements such as vibration feedback to enhance the user experience. When a user selects or adjusts an LED, the HMD

controller communicates the accuracy of the selection to the user through subtle vibrations. This feedback complements the user experience in a virtual reality environment where there are no physical buttons or switches. Multi-participant systems also have applicability in a variety of scenarios where virtual reality-based collaboration is required. For example, in the performing arts, stage designers and lighting designers can work together in real time to set up stage lighting as shown in [Fig. 3]. As one user adjusts colors and brightness, the other can make additional adjustments in other areas of the space to optimize the overall stage lighting. This real-time collaboration provides flexibility and creativity that is difficult to achieve with traditional methods. In educational environments, multi-participant LED control systems can support learner-centered, immersive learning environments. For example, students can work in teams to design or coordinate LED lighting in a virtual reality space. In the process, students can deepen their understanding of spatial design and lighting technology, and cultivate collaboration skills. The system also extends its educational utility by including the ability for teachers to monitor students' work in real time and provide feedback.

In a smart home environment, it allows multiple users to control lighting simultaneously in order to provide a personalized lighting experience that can meet the needs of each family member. For example, parents can set the lights in the living room to bright, while children can dim the lights in their rooms to read or relax. Such multi-user control greatly enhances the flexibility of smart home systems and contributes to the satisfaction of family members [9]. Multi-participant LED control systems can also be useful in public environments. At large exhibitions or fairs, multiple managers can simultaneously adjust the lighting in different exhibition areas to ensure overall harmony and consistency. Smart lighting systems in cities can also leverage this technology while opening up the possibility for multiple users to control and optimize city lighting.

However, multi-participant LED control systems also present some challenges. First, the bandwidth and processing speed required to keep data synchronized in a network-based system increases, especially when a large number of users participate simultaneously, and the system needs to be optimized to minimize delays in data processing and transmission. To address this, using a mix of local and cloud-based servers can be used to distribute data processing. In addition, the interface and algorithms need to be more sophisticated to accurately process user input data. If users select or adjust LEDs in similar locations at the same time, there is a possibility of data conflicts, which requires a prioritization algorithm to prevent them. For example, data conflicts can be mitigated by prioritizing the data entered first and keeping the rest of the data in a waiting state.

5. Discussion

This study presents new possibilities for smart lighting technology through the design, implementation, and validation of an LED control system based on VR technology. The convergence of VR technology and LED lighting technology shows that lighting control can be transformed from a mere functional tool to a medium that provides an immersive and creative user experience. This demonstrates that LED lighting technology can play an important role not only in smart home environments, but also in education, art, public lighting, and many other areas.

The VR technology-based LED control system is designed to allow users to precisely adjust the brightness, color, and timing of LEDs through an intuitive and easy-to-use interface. The system utilizes pulse width modulation (PWM) technology to provide flicker-free, stable lighting and respond to user input in real time. In particular, the system maintains seamless synchronization without data conflicts even in a multi-user environment. It demonstrates the potential for network-based cooperative lighting control. In testing, the VR technology-based LED control system demonstrated high accuracy and fast response time in order to greatly enhance the user experience. Participants were able to intuitively control the LEDs in the virtual reality space while viewing their status in real time, and provided positive feedback on the responsiveness and ease of use of the system. In particular, the multi-participant control environment proposed a new way of interaction where multiple users can collaborate to set or adjust the lighting. The system's potential applications were identified in several areas including media arts, education, smart homes, and public lighting. In media arts and exhibitions, the system offers the possibility of using light as a means of artistic expression, while in education, it provides an environment for students to experiment with light and engage in creative learning. In smart home environments, it showed promise as a tool to achieve both customizable lighting and energy efficiency.

6. Conclusion

In conclusion, this study demonstrates that a VR technology-based LED control system integrates virtual reality technology and the Internet of Things (IoT) to enhance user experience and open up new possibilities for smart lighting technology. This system goes beyond simple lighting control to provide a user-centered, creative, and immersive lighting experience, and redefine the role of lighting in smart environments. The VR technology-based LED control system developed in this paper demonstrates the

potential for innovative improvements in user experience and energy efficiency through the combination of VR and IoT technologies [10]. This expands the application range of LED technology and sets a new benchmark for providing a customized lighting environment.

However, this study has some limitations. The system was tested in a small-scale environment, and its performance in larger installations and complex environments requires further validation. Future research directions include the development of sophisticated gesture recognition technology and artificial intelligence-based lighting control systems. This will allow users to make more fine-grained lighting settings, and the system will be able to automatically adjust to user behavior and environmental conditions. Integration with smart technologies will also expand the scope of applications to include home appliances, public facilities, and smart city lighting systems. In addition, future research can be done to integrate this system with various smart technologies to develop it into a more comprehensive smart solution. For example, it could be extended to work with HVAC (heating, ventilation, and air conditioning) systems to synchronize lighting and temperature, or to integrate with appliance controls to manage the entire smart home. Such integration offers the potential for efficient and user-centered systems in smart urban environments [11].

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