NIGHTTIME OUTDOOR LIGHTING ENVIRONMENT DESIGN SYSTEM USING WEB-BASED MIXED REALITY TO REDUCE LIGHT POLLUTION

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Abstract. In nighttime outdoor spaces, light pollution due to excessive artificial lighting, particularly from lighting emitting diode (LED) displays direct light, is a recognized issue. Mitigating light pollution necessitates a careful consideration of the impact of large-scale LED displays during the design phase. Therefore, it is crucial to accurately assess the luminance of direct light and its effects on the environment during the design phase through simulation. This study aims to realize a lighting simulation system targeting LED displays, which are prone to contribute to light pollution, as a lighting environment design system for nighttime outdoor spaces. The proposed system utilizes web-based mixed reality (MR) to simulate direct light accurately. We also conduct a comparative verification between the real LED and the model. With this system, design simulations using mobile devices become feasible at the spatial design stage of LED displays in the intended location. Additionally, adjustments to the luminance and size of the LED display model and the visualization of color and luminance in the real world are possible. Consequently, it is anticipated that this system will contribute to the reduction of light pollution from both landscape design and lighting engineering perspectives.

Keywords. Lighting Simulation, Nighttime Outdoor Space, LED Vision, Luminance, Web Real-Time Communication.

1. Introduction

The emergence of excessive artificial lighting in nighttime outdoor spaces has raised concerns about light pollution. Light pollution is recognized as a factor contributing to environmental degradation, impacting not only human health but also the ecosystems

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 3, 459-468.

and natural lighting. Among the artificial lightings in nighttime outdoor spaces, particular attention must be given to the placement of direct light, which enters the eyes directly and is prone to causing light pollution. In this context, lighting emitting diode (LED) displays with exposed light sources and large display areas are prevalent sources of direct light in outdoor spaces at night. To mitigate light pollution, it is essential to consider the distribution, display area, and luminance of direct light in the design phase of such outdoor spaces.

To assess direct light, it is necessary to accurately understand the luminance of direct light and its impact on the surrounding environment through lighting simulation. When conducting lighting simulations, capturing images of the surrounding landscape concurrently is crucial. Mixed reality (MR) technology, as proposed by Milgram and Kishino (1994), enables the real-time overlay of virtual models onto the real space. This allows for the superimposition of actual-size 3D models onto the buildings and lighting environment of the real space, facilitating design considerations in a synthesized scene of the surroundings and the model. Recently, Web-based Mixed Reality (Web MR) has been developed, which is executable in web browsers without software dependencies. This advancement enables landscape simulations for outdoor spaces using laptops and mobile devices. However, within outdoor landscape simulations, challenges persist in representing the 3D model of LED displays, which emit direct light, and visualizing luminance in MR simulations.

This study aims to achieve lighting simulations using MR targeting LED displays that are particularly prone to causing light pollution in nighttime outdoor spaces. The goal is to comprehend luminance and its impact on the surroundings. The study begins by creating a 3D model of the LED display using a game engine. Subsequently, parameters are set to allow users to interactively modify the luminance and size of the LED display. The simulation results from the game engine hosted on a server are then displayed in MR on the client's web browser. In the system developed in this study, the client-side involves acquiring real-world camera imagery through a mobile device and displaying MR, while the server-side entails creating and placing a 3D model of the LED vision, as well as synthesizing it with real-world imagery. The resulting streaming video, synthesized in real-time on the server, is presented as MR on the client's mobile device. Importantly, the visual content of the 3D model is not pre-downloaded on the client side but is transmitted in real-time between the client and server using web real-time communication (WebRTC) technology. This system not only facilitates MR visualization on LED vision displays but also allows for real-time display of changes in LED vision rendering resulting from parameter adjustments made on the MR display screen of the mobile device. Through validation testing, this Web MR system enables the display of LED displays and the rendering of models based on user-defined parameters, along with the visualization of luminance distribution.

This system facilitates mobile device-based design simulations at the spatial design stage of LED displays in the intended location. The envisioned use of MR in this study is illustrated in Figure 1. When a mobile device is directed towards the designated area for LED vision design, a simulation model of the LED vision is displayed at the designated location. Within the display screen, a remote controller with adjustable parameters is positioned to allow user control. Additionally, false color representation is employed for luminance visualization.

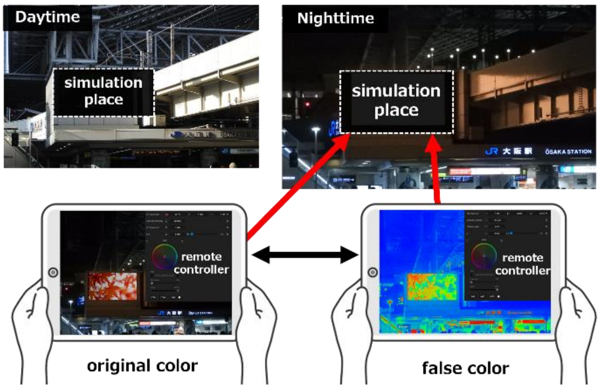

Figure 1. Envisioned usage of MR System

2. Previous Research

2.1. LIGHT POLLUTION AND THE IMPACT ON THE HUMAN BODY

Light pollution is an environmental issue related to outdoor lighting fixtures that emit lighting, causing adverse effects in the surrounding area due to excessive luminance or unnecessary light leakage in undesirable directions. The environmental issues caused by light pollution are varied. From an astronomical and ecological perspective, reports indicate degradation of human perception of the night sky and behavioural changes in organisms due to light pollution (Longcore and Rich 2004). Moreover, the ecological impact of artificial lighting on outdoor facades at night has been investigated as light pollution, involving the measurement and quantitative analysis of various indicators such as the spectrum, luminance, and color chart (Wu et al. 2023). Furthermore, the impact of outdoor lighting on the environment has been reported in connection with the Sustainable Development Goals (SDGs) (Tavares et al. 2021).

Direct light, which is affected by light pollution, has a high attractiveness, while its impact on the human body has been reported. The influence of direct light on the human circadian rhythms and daily routines is being investigated and analysed concerning lighting distribution and intensity (Walker et al. 2022). Furthermore, it has been reported that direct light can lead to a decrease in contrast sensitivity function in the human retina, thereby impairing visual function (Feng et al. 2023).

These investigations reveal that the distribution and intensity of direct light can have adverse effects on the human body. Therefore, it is imperative to consider the impact of direct light in the design phase of lighting to avoid negative consequences on the human body. In this study, we conduct simulations to visualize the effects of direct light at the design stage.

2.2. LIGHTING SIMULATION SYSTEM

In the realm of lighting simulation in virtual environments, there have been proposals for simulation methods utilizing game engines (Scorpio et al. 2022). Moreover, in virtual reality (VR) focused on indoor spaces using game engines, visualization of lighting conditions (illuminance) employing techniques like false color has been accomplished (Natephra et al. 2017).

However, in virtual environments, it is currently not feasible to conduct simulations concurrently with the surrounding landscape of real-world spaces. Therefore, the use of MR, which enables overlaying real-world landscapes with virtual models, is deemed effective. To conduct lighting simulations in MR, it is imperative to model the state of light and display it within the MR environment. Furthermore, the realization of simulations in outdoor spaces, where carrying a computer with installed software is challenging, poses a significant challenge. Hence, this study aims to develop an MR system capable of simulating light in outdoor environments.

2.3. MR SYSTEM

By leveraging MR technology, it becomes possible to overlay true-to-scale 3D models onto existing structures and lighting environments in the real space without the need to create virtual landscape models (Crolla and Goepel, 2022).

Furthermore, Web MR, which has been developed in recent years can be utilized on mobile devices such as laptops and smartphones with web browsers, making outdoor landscape simulations accessible even to non-experts (Zhou and Zhou 2023). However, in Web-based system, compared to using dedicated applications, there are limitations on data capacity, and the available libraries may be restricted. Furthermore, when displaying MR content over the network, the size of data that can be transmitted and received is limited compared to the application (Qiao et al., 2019). Therefore, in this study, server-side configurations and computations for necessary libraries are conducted, allowing the client side to display streaming videos. This approach enables Web MR visualization without restricting the libraries required for displaying simulation results.

Moreover, within outdoor landscape simulations, addressing the realistic representation of 3D models, especially those depicting nighttime direct light, and achieving luminance visualization in MR simulations pose challenges. Therefore, in this study, we aim to create a realistic representation of the targeted direct light, specifically an LED vision, and implement MR visualization capable of displaying luminance distribution.

3. Proposed Method

An overview of the system is shown in Figure 2. In this study, we propose a system where users can simulate the overlay of real-world space and an LED vision model using MR through mobile devices. This system operates on a web browser, eliminating the need for specialized software knowledge.

In the system, the tracking is initiated by aligning the mobile device's camera with the light serving as a marker placed in the real-world space. The user utilizes a mobile device to capture real-world space through the camera, sending the captured video feed to the server. Next, the server performs position and pose estimation of the camera image, reflects it onto a virtual camera placed in the game engine, and conducts tracking by transmitting the LED vision model images corresponding to changes in the camera's position and pose to the client side. Finally, the video feed of the LED vision model is synthesized into the real-world space and displayed as MR.

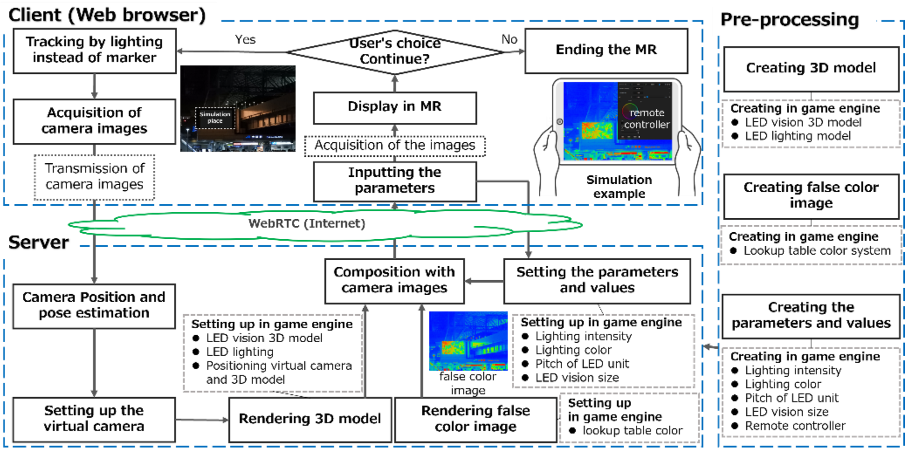

Figure 2. System overview

3.1. PROCESS OF DISPLAY AND OPERATION IN MR

Here, we illustrate the process of acquiring real-world imagery, creating an LED vision model, and synthesizing real-world and model imagery. To create the LED vision model for display in MR, the game engine is employed. In the game engine, the creation, generation, and placement of the LED vision panel components are conducted. Furthermore, to enable interactive user adjustments of parameters such as the size and luminance of the model created on the MR display screen, these settings are configured within game engine to facilitate MR interactions. Additionally, a remote controller is created for adjusting parameters, and the association with parameters is established.

For presenting the created model overlaid onto the real-world space in MR, the introduction of Web MR is implemented. In the Web MR system, the process begins with capturing real-world space imagery through the camera of the client's mobile device. The captured video data is then transmitted to the server via the internet using WebRTC. On the server side, position and pose estimation is performed based on the received camera imagery, and these calculations are reflected in a virtual camera. The virtual camera captures the video feed of the LED vision model corresponding to the perspective from the real-world space and incorporates adjustments based on parameters received from the client side. Synthesizing the received real-world spatial images with an LED vision model as the background, streaming video is transmitted to the client side via the internet using WebRTC. This allows for displaying MR on the client's mobile device.

3.2. PROCESS OF LUMINANCE VISUALIZATION

We present a system that incorporates a game engine for luminance visualization. To visualize the luminance of the LED vision as a luminance distribution (false color), a look-up table (LUT) color is employed. LUT is a reference table that associates output color data with input color data, allowing for instantaneous color transformation across the entire image. Using LUT, the display of the false color representing luminance distribution is achieved. In game engine, a 256x16 3D LUT is available.

The process for creating the LUT is illustrated in Figure 3. The neutral color LUT is obtained from game engine and imported into image editing software. In the software, luminance values ranging from 0 to 5000 cd/m² are transformed into a gradient from blue (#0000FF) to red (#FF0000), resulting in the false color LUT. This created LUT is then imported into game engine to display the luminance distribution.

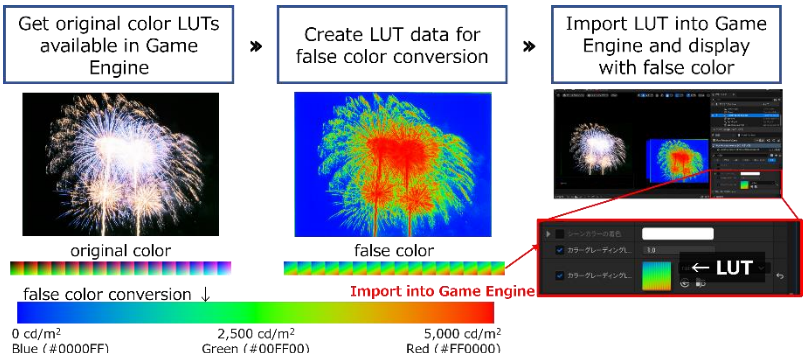

Figure 3. The process for creating the LUT

4. Verification

In this section, we validated to assess the proposed method in our study. In Section 4.1, the accuracy of the LUT used for luminance visualization in the proposed method was compared and verified. In Section 4.2, a comparative evaluation of the LED vision was conducted, and in Section 4.3, the operational verification of the MR was performed.

4.1. LUT ACCURACY VERIFICATION

The LUT used for luminance visualization is based on proprietary data. It is necessary to compare and verify its accuracy by ensuring it can accurately display false color like lighting analysis tools commonly used in lighting design. In this validation, we compared histograms of RGB values. For ground truth data, images displaying false color using the pseudo color exposure control feature of 3ds Max's lighting analysis tool are employed. The comparative LUT display is conducted using UE5. In this process, a lighting model is set up in 3ds Max, the same lighting 3D model is imported into UE5, and False color images are output under identical conditions. Histograms for each channel (RGB) are created for the two output images, and a comparison verification of image similarity based on the correlation coefficient is conducted for the R, G and B histograms. The histograms are plotted with pixel values on the x-axis and pixel frequency on the y-axis. The calculation of the correlation coefficient was performed using the histogram comparison method in Python OpenCV 4.5.5. The function employed for this purpose is HISTCMP_CORREL. The definition formula (1) is as follows. H1 represents the values of the histogram in 3ds Max, while H2 represents the values of the histogram in UE5.

$$d(H_1, H_2) = \frac{\sum_I (H_1(I) - \overline{H_1})(H_2(I) - \overline{H_2})}{\sqrt{\sum_I (H_1(I) - \overline{H_1})^2 \sum_I (H_2(I) - \overline{H_2})^2}} \tag{1}$$

The similarity for each histogram is illustrated in Figure 4. The results indicate a high degree of similarity for the R, G and B values, with correlation coefficients approaching 1.

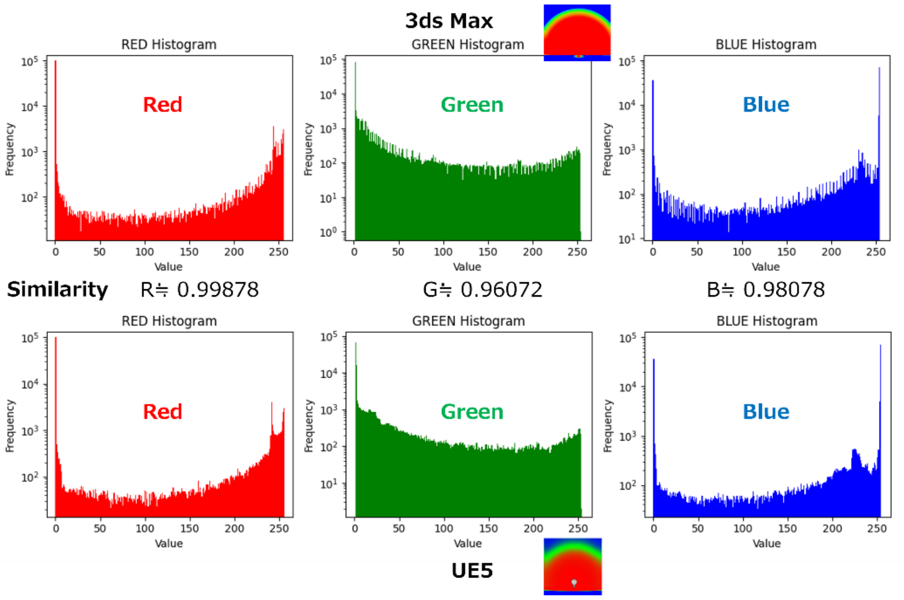

Figure 4. The similarity for the histogram (false color)

4.2. COMPARISON AND VERIFICATION OF LED VISION

We compare whether a model representing a real LED vision in MR can achieve similar expressions. The real LED vision used for comparison employs a panel of HUB75E type with a maximum luminance of 5000 cd/m² and a resolution of 64x64 dots. The panel's luminance is confirmed using a luminance meter (Konika Minolta LS100) to be 5000 cd/m² at 1 m from the front of the panel. To illuminate the panel, an Arduino Uno and a DC 5V power supply, as shown in Figure 5, were utilized. A program for illuminating all points was created using the Arduino IDE, and the panel is lit with a white color (#FFFFFF) light.

The images used for comparison include the model of the LED vision set to a luminance of 5000 cd/m² in UE5 and images captured using a mobile device (Google Pixel 7a: F8, 1/30) for the real LED vision in MR display. Similarity verification using the histogram comparison method in Python OpenCV 4.5.5 and correlation coefficient is performed, like the precision verification of the LUT. The histograms set the pixel values on the horizontal axis and the frequency of pixel values on the vertical axis. For comparison, images representing luminance values using a LUT are used to assess whether the luminance is accurately represented.

The similarity of each histogram is shown in Figure 5. As a result, similarity values above 0.9 were obtained for all R, G, and B values. However, there is an error due to differences in the representation of ambient scattered light.

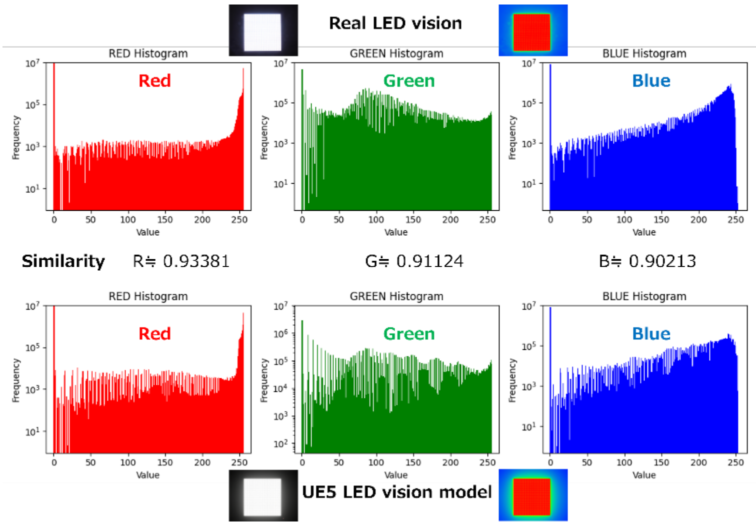

Figure 5. The similarity for the histogram (LED vision)

4.3. VERIFICATION OF THE PROPOSED METHOD

The performance verification of the MR system is conducted in an indoor environment, assuming nighttime outdoor conditions, with an average illuminance set below 25 lux (Pollard et al. 2017). An android 14 is utilized as the mobile device for the performance verification. The web browser that connects to the MR system utilizes browsers installed on android. To perform the verification, the designated URL is entered, and access to the MR page is initiated over the internet, initiating the MR experience.

Figure 6 illustrates the display screen of the MR during the performance verification, showing the LED vision displayed as MR on the real wall. Additionally, the representation of false color, introduced for luminance visualization, is visible. Furthermore, a remote controller is incorporated within the MR display screen, allowing for adjustments to parameters such as the size and luminance of the LED vision. Examples of parameter modifications are presented in Figure 6.

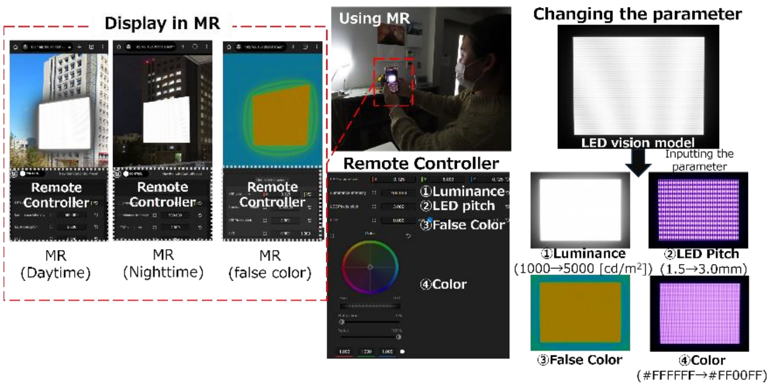

Figure 6. MR simulation and examples of parameter modifications

5. Discussion

As a result of the verification of the false color representation accuracy in the LUT, a highly significant correlation, with a similarity exceeding 0.9 and approaching 1, was observed between the image derived from the lighting analysis results of 3ds Max (considered as the ground truth) and the image applying the LUT in UE5. This suggests a strong correlation and affirms that the LUT accurately visualizes luminance.

As a result of the comparative validation between the real LED vision and the UE5 model, a similarity of 0.9 or higher was confirmed. This suggests that the model created in UE5 can represent visuals closely resembling the real-world counterpart. Additionally, a notable difference between the model and the real LED vision is identified in the rendering of diffused light in the surroundings. To achieve a more realistic representation of light, it is believed that improvements in the quality of rendering for light scattering and diffused light are necessary.

The results of the MR system's performance verification show that accessing the MR display screen from the web browser of an Android smartphone is achievable. In an environment with insufficient luminance at night, it was confirmed that the MR effectively displays a composite of the surrounding landscape captured by the mobile device's camera and the LED vision image. Furthermore, the capability to present false color on the MR display screen was verified. Additionally, the remote controller placed on the MR screen enables the modification of parameters such as the size and luminance of the LED vision, and these changes are reflected in the MR.

In summary, the simulation of lighting using web-based MR as an outdoor lighting environment design system at night has been successfully achieved. However, a potential issue lies in the current MR system's reliance on internet transmission for video exchange. In cases of weak internet connectivity, the smooth operation of MR may be compromised, leading to potential interruptions. While deploying MR in locations with stable internet environments can address this concern, attention to signal strength remains essential.

In this study, verification was conducted only for the actual LED vision's maximum luminance of 5000 cd/m² to confirm whether UE5 models are rendered correctly. However, in the future, it is necessary to create a new program to systematically vary the luminance of the LED panel from 0 to 5000 cd/m² and conduct verification at multiple luminance levels. Additionally, it is crucial to reveal differences in verification results caused by variations in camera exposure settings during the capture process.

6. Conclusion

In this study, we achieved a design simulation using web-based MR with mobile devices for LED vision as an outdoor lighting environment design system during the night. The proposed system demonstrated the capability to display MR, overlaying LED vision on the real environment, even in dark nighttime conditions. Additionally, a remote controller placed on the MR screen allowed users to adjust parameters such as the luminance and size of the LED vision.

Furthermore, by implementing LUT for luminance visualization, the system enabled the visualization of the LED vision's appearance (true color) and luminance values (false color) while considering the surrounding lighting conditions. This MR system provides an efficient means to understand the status of the designed LED vision at a glance, contributing to the improvement of PSE for users during the design stage. Thus, the system presented in this study can contribute to both landscape design and lighting engineering aspects for optimizing direct light towards reducing light pollution.

Through the proposed method, simulation in MR has become possible. However, enhancing the realism of MR requires addressing the challenge of achieving photometric registration with the real lighting environment, specifically in terms of uniform luminance perception with surrounding light. Currently, we are in the process of developing a program that estimates the ambient lighting environment from the camera of a mobile device and incorporates it into the LED vision model. This is a crucial step for improving the optical coherence between MR and real-world lighting conditions.

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