Title:
Design and Development of an Unmanned Aerial Vehicle to Capture Real-World Illumination for Image-Based Lighting for Dense Urban Environment

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Introduction:
Daylighting not only provides alternative illumination to artificial lighting that can reduce energy consumption, it also can increase an inhabitant's productivity and help to relieve depression [1] [9]. Maximizing the access of daylight for an interior space in a dense urban environment has thus become a priority in lighting design. To study the interior lighting distribution, the conventional method uses heliodons that can project artificial light to simulate a parallel sunray. It can adjust the orientation and angle between the projecting light and scale model to simulate lighting conditions for different dates and times. However, scale physical models often cannot faithfully replicate the forms or materials of the building and site context. Further, artificial lighting cannot simulate actual daylight as it is comprised of sunlight and skylight. Therefore, conventional lighting simulations can provide accurate shadow studies, but may fall short of simulating the actual luminance distribution of an interior space. Developments of related digital technologies of high-dynamic range imaging (HDR) have advanced the accuracy of lighting simulation [7]. CIE (International Commission on Illumination; Commission Internationale de l'Eclairage) standard sky models developed and based on past data can be used in a physically-based lighting simulation program, such as RADIANCE, to provide validated simulation for lighting studies [8]. For specific time and location, the technology of image-based lighting (IBL) can be used [4]. Fig. 1 illustrates the use of HDR photography to generate a light probe image for IBL. This method uses a digital camera fitted with a fish-eye lens on a tripod, capturing multiple exposure digital photos each recording a limited range of luminance data of the skydome. If the captured images cover the entire high dynamic range of real-world illumination, the assembled HDR light probe image could be a reliable lighting source representing the sky illumination for IBL [4] [7].

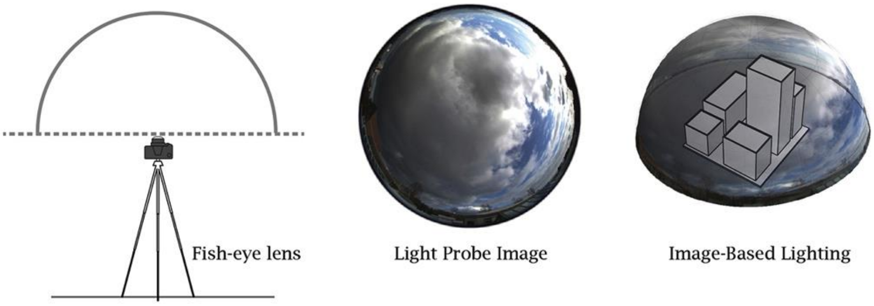


Fig. 1: Using fish-eye lens to generate the light probe image for image-based lighting.

A typical circular fish-eye lens has a view angle of 180 degrees. Thus, it can only capture a hemispherical environment, centered at the camera covering to the horizon in all directions. To capture a complete sky illumination, the camera must be set up on a flat surface with an unobstructed view. In a dense urban context, it is often set up on the rooftop of the building. However, this also means that the building itself, as well as the surrounding neighbor buildings under the horizontal plane of the camera, cannot be included in the field of view. When the assembled light probe image is used as an assumed sky environment, the urban context of buildings that are not included must rely on digital modeling in a virtual environment. Unfortunately, the ignored or approximated details of the urban context modeling can have a significant impact on the daylighting, particularly for the interior lower level living environment in a high-rise building situated in a dense urban context.

In a validation study, Mehlika Inanici compared the lighting simulations of an interior second floor office with a light probe image obtained from an upward pointing fish-eye lens captured from a four-story building roof and a ground floor horizontal pointing fish-eye lens; with an HDR photo of the actual interior environment. As the office had open windows on only one side, the results demonstrated that the light probe images obtained from the horizontal pointing fish-eye lens captured the natural illumination environment closely to the actual environment surrounding the open windows, providing a more accurate simulation [6].

In metropolises, particularly in those that have undergone rapid economic developments, many high-rise buildings have been built on a large scale and too close in proximity, resulting in certain living units with windows on only one side of the building, and thus, unable to receive sufficient daylight. In this study, we adopt the same concept of utilizing the horizontal pointing fish-eye lens to capture the natural illumination outside the windows of a high-rise building. Specifically, we are exploring a practical method that can simulate the daylighting condition for such an interior environment with precision. However, the HDR photography process requires a tripod to maintain stability while taking multiple exposure photos, and is therefore limited to a flat plane, such as grounds, platforms, or roofs. Performing the HDR photography process at higher levels in an urban context becomes the main objective for this study. We present an innovative solution that integrates remote sensing technology and HDR photography. The goal is to design and develop an unmanned aerial vehicle (UAV), implemented with a lightweight smart phone equipped with a circular fish-eye lens camera; and to develop an application that can remotely control the camera in performing the HDR photography process.

Fig. 2: A typical illumination environment for a window of high-rise buildings in a dense urban context.

Main Ideas:

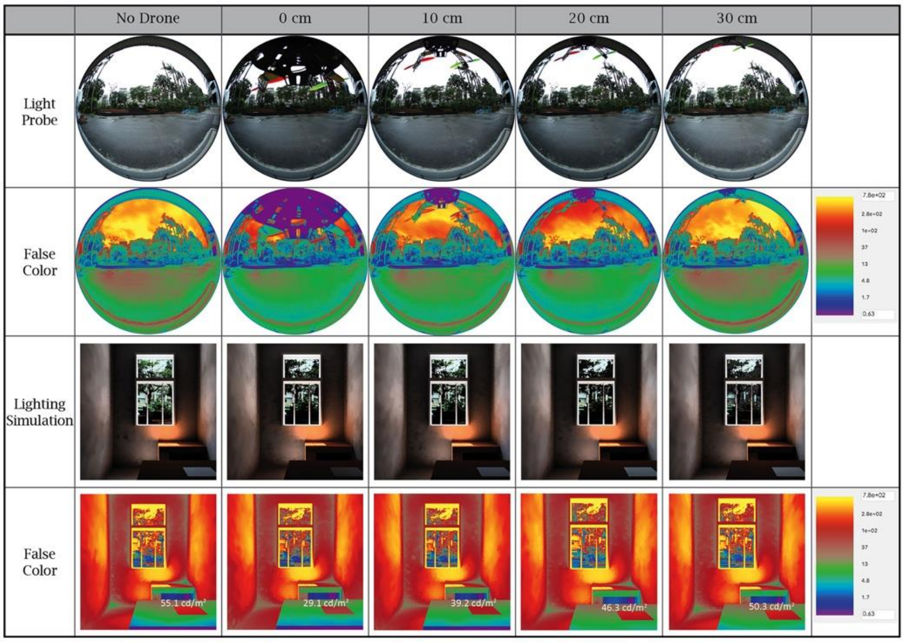
Remote sensing is a technology used to acquire data or information with devices or equipment that can be controlled and monitored remotely [3]. It has a wide range of applications in scientific fields such as ecology or geology, which both use aircrafts or balloons equipped with sensors. Recent developments of UAVs, also known as drones, have allowed applications of remote sensing to become affordable, promoting innovative applications such as the archeological site survey [2]. The commercially available hardware drone kit and open-source software that controls the drone, further allows for remote sensing technology that can be customized for specific scientific research tasks.

Therefore, in this study, we integrated this technology with HDR photography, so that we may develop a system that can record the natural illumination around windows of high-rise buildings.

Most commercially available drones are designed to survey the ground, therefore, their cameras are often pointed downward. However, when recording a light probe image with a horizontal-pointing fisheye lens camera, the body of the drone will appear in the field of view of the captured image, thus causing unwanted obstructions. One solution is to increase the distance of the camera and drone, moving the drone body away from the center of the field of view to reduce its impact on the obstruction. Tab. 1 illustrates the results of a preliminary study investigating the influence of gap distances on daylight simulation. At the entrance of a campus building, a Canon EOS 5D Mark II digital camera, fitted with a Sigma 8mm F3.5 EX DG circular fish-eye lens, was set up on a tripod. Multiple images with different exposures were taken and assembled into a single HDR light probe image with Photosphere software, following the established procedure [5]. The same setting was used to generate different HDR light probe images to investigate the impact of the drone in the field of view on IBL simulation. One HDR image without a drone was generated and then compared with the drone located 0cm, 10cm, 20cm, and 30cm away from the camera. The five HDR light probe images were used as an image-based lighting source to simulate the luminance distribution of an interior scene.

In the interior simulations, a gray piece of cardboard was placed on the table. The average of the luminance of the gray cardboard is illustrated in Tab. 1. With the drone in the field of view without a gap, the luminance dropped from 55.1 cd/m^2 to 29.1 cd/m^2, which is a reduction of about 50%. However, with a gap increase of 30 cm, the influence reduces to about 10%, meaning that a reasonable distance gap can reduce the impact the body of a drone will have in the field of view on the lighting simulation.

This preliminarily study demonstrates that with a reasonable distance gap, it is possible to reduce the impact the body of a drone, in the field of view, will have on the lighting simulation. This suggests that it is possible to use the image capturing system of a full-frame digital camera and circular fish-eye lens previously validated in terms of the accuracy of the light probe image produced. However, full-frame digital cameras and lens can be very heavy and costly. Although there are UAVs capable of carrying objects with heavy weight, the cost can be high and the problem of remotely controlling the image capturing process remains unresolved.



Tab. 1: Lighting simulations with IBL sources generated with different conditions of drone location.

Instead of installing a digital camera on the vertical axis of the drone, we developed an alternative solution of installing a lightweight smart phone with a camera on the side, and added objects with the same weight on the other side for balance. There are two advantages of this affordable, alternative solution: first, it can avoid the drone appearing in the captured field of view; and second, the smart phone allows the developer to create an application to further specify tasks to perform remotely.

An iPhone 5 was selected to replace the heavy weight of the full-frame Canon Mark 5D II digital camera. The operating system that runs the iPhone iOS allows developers to create an application to control the system remotely. In addition, many mountable fish-eye lenses are available for smart phones, such as the iPhone 5. In our prototype, we used the Izawaopt KSW-4 fish-eye lens. The first working prototype called “HDRone” was constructed with a digital fabrication technology and implemented with an iPhone 5 equipped with a fisheye lens on a drone. Fig.3 illustrates it physical configuration. On the other hand, Fig.4 illustrates its system framework. This framework consists of the remote system, mobile system, and post process to perform the image-based lighting simulation. The first step is to install one smartphone with a fish-eye lens to the drone, and connect to a second smart phone through the Internet. In the field, we start with initializing the ArduPilot Mega (APM) autopilot system, then use a wireless remote control to initiate the flight of the drone. Next, we use GPS to position the longitude and latitude, and the barometric pressure sensor to detect the height. We then loiter at a specific location in a three-dimensional space. While loitering, we use the second smart phone to instruct the airborne smart phone to take photos. After landing, we download the captured images to the computer and assemble them into a HDR light probe image. Finally, we use the light probe image in the physically-based lighting simulation program, RADIANCE, to simulate the interior lighting.

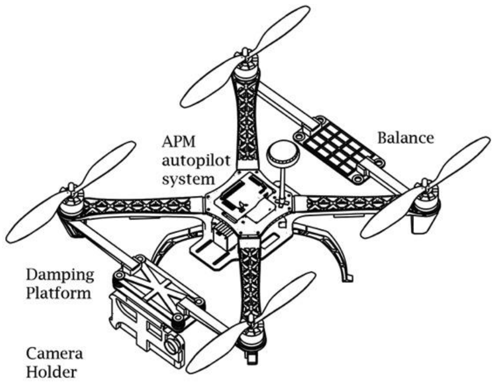


Fig. 3: Physical configuration of the HDRone.

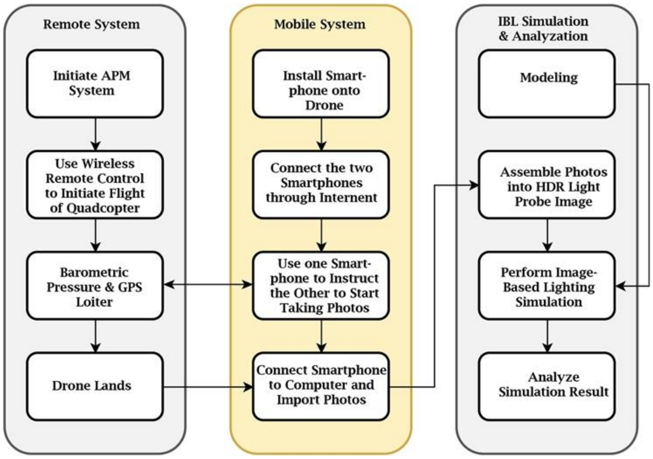
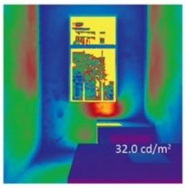
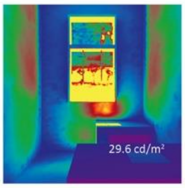
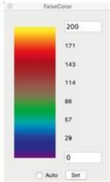


Fig. 4: System framework of using HDRone to create light probe image for image-based lighting simulation.

Conclusions:

To validate the drone’s reliability of recording an illumination environment for image-based lighting, we conducted a preliminarily comparison study. In an open field on campus, we used a full-frame Canon Mark 5D II digital camera with a Sigma fish-eye lens on a tripod to take multiple images, and assembled them into a light probe image. Then, we used the HDRone, loitering at approximately the same location, to create a light probe image. Tab. 2 compares the simulation results using the light probe image generated from the full-frame system and HDRone. The luminance values of the gray cardboard in the interior scenes is 32.0 cd/m^2 using the light probe image from full-frame system; and 29.6 cd/m^2 with the light probe image generated using the HDRone. Therefore, this pilot field test demonstrates that the constructed prototype can maintain stability in air to allow the iPhone 5 to take sequential images and assemble them into an HDR light probe image for an image-based lighting simulation. In addition, the initial test of the simulation results indicates that the proposed system can be reliable for daylight simulation for certain circumstances. Thus, it is concluded that the prototype HDRone can be further developed into a promising remote sensing mobile control system to record the natural illumination for small-scale living units in a dense urban environment.

	Full-Frame System	Smart Phone System	
Light Probe			
Lighting Simulation			
False Color			

Tab. 2: Comparisons of the working prototype of "HDRone" with full frame digital camera on image-based lighting simulation.

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