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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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ABSTRACT
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. Maximizing the access of daylight for an interior space in a dense urban environment has thus become a priority in lighting design. Digital lighting simulation using high dynamic range imaging for image-based lighting can provide accurate daylight simulation of an interior luminance distribution. However, the method of generating a high-dynamic range light probe image is limited to the setting of a flat landscape with an unobstructed view. This paper presents an innovative system that is implemented using a lightweight smartphone camera equipped with a fish-eye lens on a customized unmanned aerial vehicle (UAV). The system can be remotely controlled to loiter, recording multiple images in a horizontal direction. The captured images can then be assembled into a high dynamic range light probe image to be used as the image-based lighting source for interior spaces with one-directional access to daylight. The pilot test proved that the light probe images generated with the constructed prototype and system provide reasonable accuracy in daylight simulation.

KEYWORDS
Image-Based Lighting; HDR; remote sensing; drone; lighting simulation

1. Introduction

Two types of artificial and natural lighting sources can provide illumination for an interior environment. Artificial lighting uses a variety of luminaire and electric lamps to provide lighting that can be precisely controlled. On the other hand, natural lighting relies on daylight, and thus, the interior illumination depends upon the ever-changing sky conditions through the constructed openings. Although artificial lighting can provide the necessary illumination alone, it comes with the cost of energy consumption. In contrast, freely available daylight is proven to have positive influences on the inhabitants' productivity and mental health [1] [11]. Therefore, maximizing the highest possible daylight for a built interior environment becomes an important consideration for lighting design, especially for living spaces in urban environments, where daylight is often obstructed by over-crowded high-rise buildings.

The natural lighting for a constructed room can be only passively controlled through devices like mini blinds to reduce, or reflectors to enhance. Moreover, the amount of control is limited to the physical dimensions of the constructed openings. To develop a daylight design strategy for an interior environment in a dense urban context, it is thus important to first accurately simulate real world natural illumination surrounding the openings. Various lighting simulation tools and metrics are available to analyze different aspects of daylighting [8]. The daylight factor, or daylight autonomy, is based on the illuminance, reporting the ratio of illuminance on an interior working plane contributed by the outdoor daylight; and the percentage of the year when the interior illuminance meets the varied minimum illumination with daylight alone [9]. These illuminance-based metrics can be calculated or simulated using standard sky models based on past averages, and provide useful feedback for the possible savings on artificial lighting in the schematic design process. Luminance study, on the other hand, presents the daylight distribution of an interior environment for specific times. The luminance study of critical dates and times, therefore, provides good indications for the perceptual aspect related to daylighting, such as perceived brightness and glare problems, that can be factors influencing the inhabitant's psychological response.

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

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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 [10]. For specific time and location, the technology of image-based lighting (IBL) can be used [4].

Image-based lighting is a digital technique built and based on the related techniques of environmental mapping and high dynamic range imaging. This technique often uses an omnidirectional image that has been captured in the real-world, which then is projected onto a dome in a virtual scene. When the projected image is a high dynamic range image, which encompasses the captured luminance distribution, the mapped image can provide real-world illumination in a virtual scene. However, the light probe image, which used to be projected onto the dome in a virtual scene, can now be acquired by photographing a mirrored sphere or by using a fish-eye lens [7]. 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].

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, as illustrated in Fig. 2, 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.

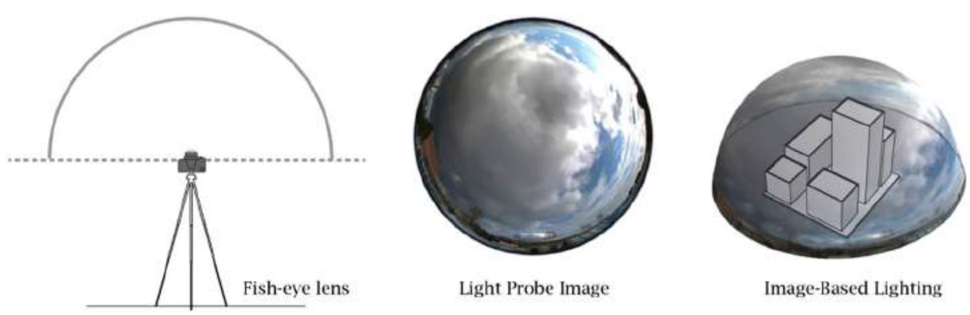

Figure 1. Using fish-eye lens to generate the light probe image for image-based lighting.

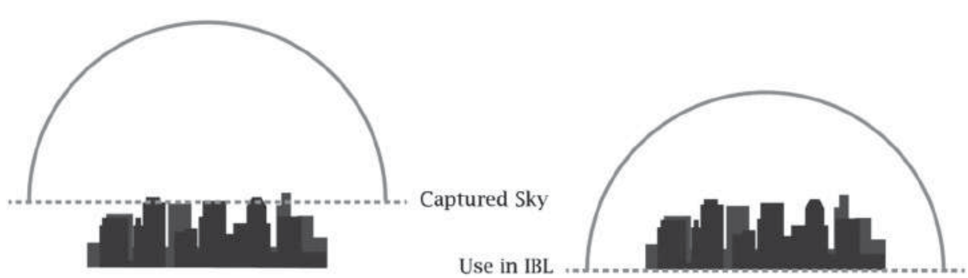

Figure 2. Problem of image-based lighting simulation of lower level living environment in a dense urban context with the light probe image captured on the building rooftop.

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 smartphone 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.

2. Method

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 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 fish-eye lens camera, the body of the drone will appear in the field of view of the captured image, thus causing unwanted obstructions, as illustrated in Fig. 4. 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. Fig. 5 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 0 cm, 10 cm, 20 cm, and 30 cm away from the camera. The five HDR light probe images were used as

Figure 3. A typical illumination environment for a window of high-rise buildings in a dense urban context.

Figure 4. Unwanted obstruction caused by the body of drone in the image taken with fish-eye lens.

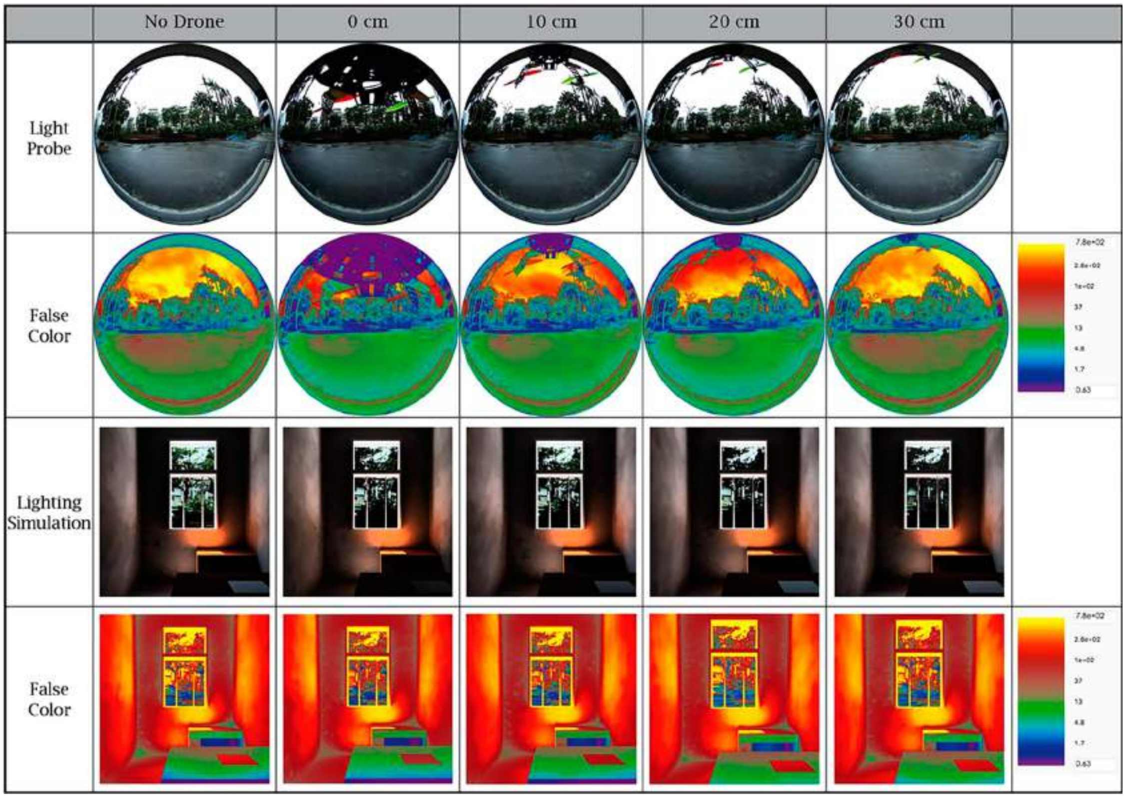

Figure 5. Lighting simulations with IBL sources generated with different conditions of drone location.

an image-based lighting source to simulate the luminance distribution of an interior scene.

Fig. 5 illustrates the comparison between the captured probe images and their applications in interior lighting simulations. False color studies that use color to represent the range of luminance, demonstrate that the luminance distributions of the simulated scenes do not differ significantly. 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 Fig. 6. 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%.

This preliminary 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.

Instead of installing a digital camera on the vertical axis of the drone, we developed an alternative solution of installing a lightweight smartphone 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 smartphone allows the developer to create an application to further specify tasks to perform remotely.

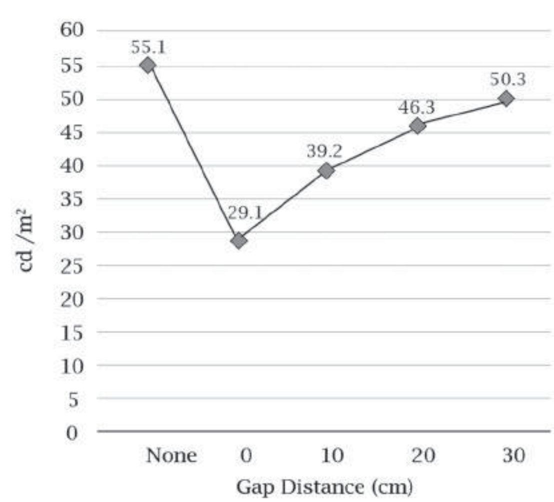

Figure 6. Impact of the gap distance between drone and camera on simulation result.

3. Prototype design

3.1. Alternative image capturing system

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 smartphones such as the iPhone 5. In our prototype, we used the Izawaopt KSW-4 fish-eye lens. It is a circular fish-eye lens with 185° angle. A comparison of lighting simulations between the full-frame Canon Mark 5D II system with the Sigma fish-eye lens and iPhone 5 with the KSW-4 fish-eye lens is shown on Fig. 7. As our intent is to develop a system that can capture the light

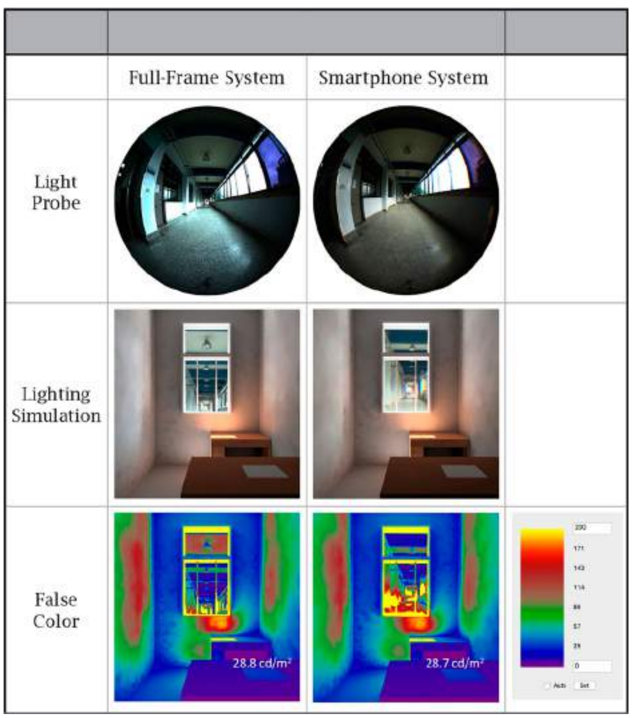

Figure 7. Comparison of the alternative system of iPhone with full-frame digital camera on image-based lighting simulation.

probe image between dense urban buildings, we chose a scene without direct sunlight for the evaluation. The simulations demonstrate that the alterative system provides reasonable matching results for this particular setting.

3.2. Integrated system of Drone and HDR image capturing device

The first working prototype called “HDRone” was constructed with a digital fabrication technology and implemented with an iPhone 5 equipped with a fish-eye lens on a drone. Fig. 8 illustrates the physical configuration of the HDRone. The main frame of the HDRone was constructed with the commercially available DJI Flame Wheel F450 ARF drone kit. It consists of an ArduPilot Mega (APM) autopilot system, a Hobbywing 20A Electronic Speed Controller (ESC), four 10 inch propellers, 930 kv brushless DC motor, and a 2200 mah battery. The ArduPilot Mega is based on the Arduino Mega board, which can be programmed with the open source software Arduino IDE. This autopilot system is embedded with GPS, 3-axis gyro, high-performance barometric sensor, 6 degrees of freedom accelerometer, and electronic compass, which allows us to use a 433 Mhz remote to localize the drone in three-dimensional space, takeoff, and landing. It can also switch to loiter mode at a specific location to allow the camera to take photos.

A customized camera cradle head was manufactured with 3D printing technology. It can hold the body of the iPhone 5 with the attached fish-eye lens. On the opposite side, a weight balance was created and installed, in which weights can be added or subtracted for balance. The cradle head consists of two parts of a damping platform equipped with four anti-vibration rubber shock absorber balls to assist in stabilization; and a camera holder that allows the iPhone to slide in and out. The camera holder is removable, thus allowing the system to accept different camera holders for different smartphone types. The entire camera cradle head and camera with

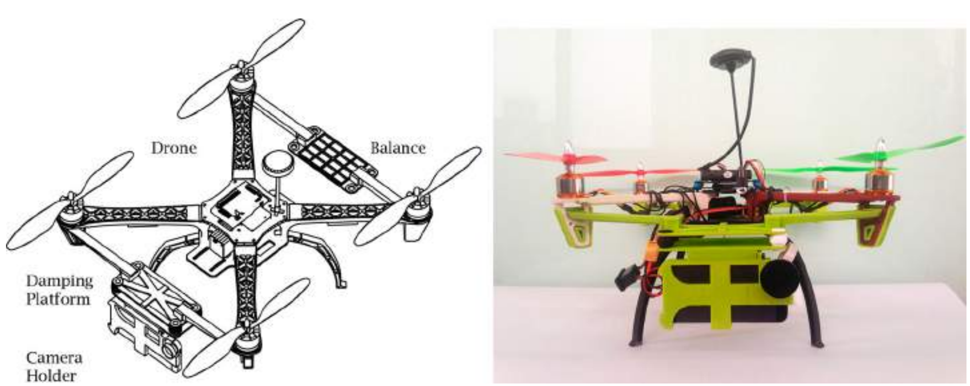

Figure 8. Physical configuration of the HDRone.

lens weighs about 225 kg, which can be balanced with added metal weights on the opposite side.

3.3. System framework

Fig. 9 illustrates the system framework for the process of utilizing the HDRone to generate the light probe image for image-based lighting simulation. The 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 smartphone through the Internet. In the field, we start with initializing the APM autopilot system, then use a wireless remote control to initiate the flight of quadcopter. Next, we use GPS to position the longitude and latitude, and the barometric pressure sensor to detect the height. We then loiter at the specific location in three-dimensional space. While loitering, we use the second smartphone to instruct the airborne smartphone 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.

4. Evaluation

To validate the drone's reliability of recording an illumination environment for image-based lighting, we conducted a preliminary 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

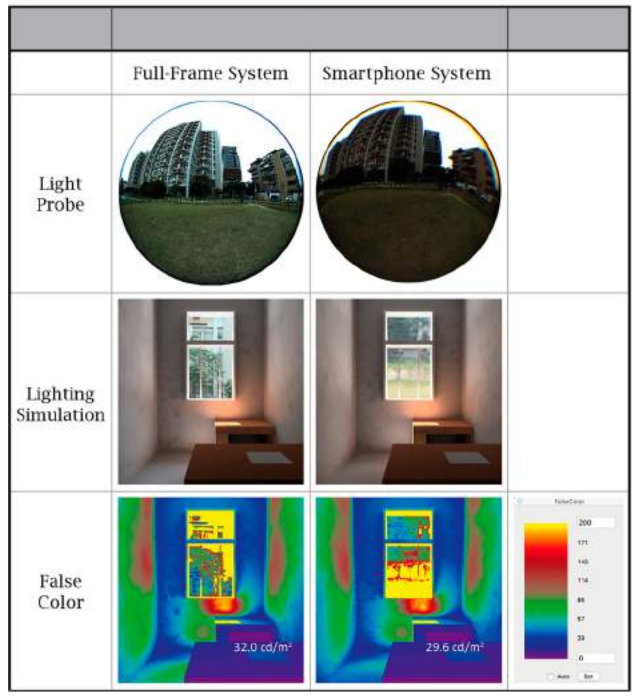

Figure 10. Comparisons of the light probe images generated by HDRone and full-frame digital camera on image-based lighting simulation.

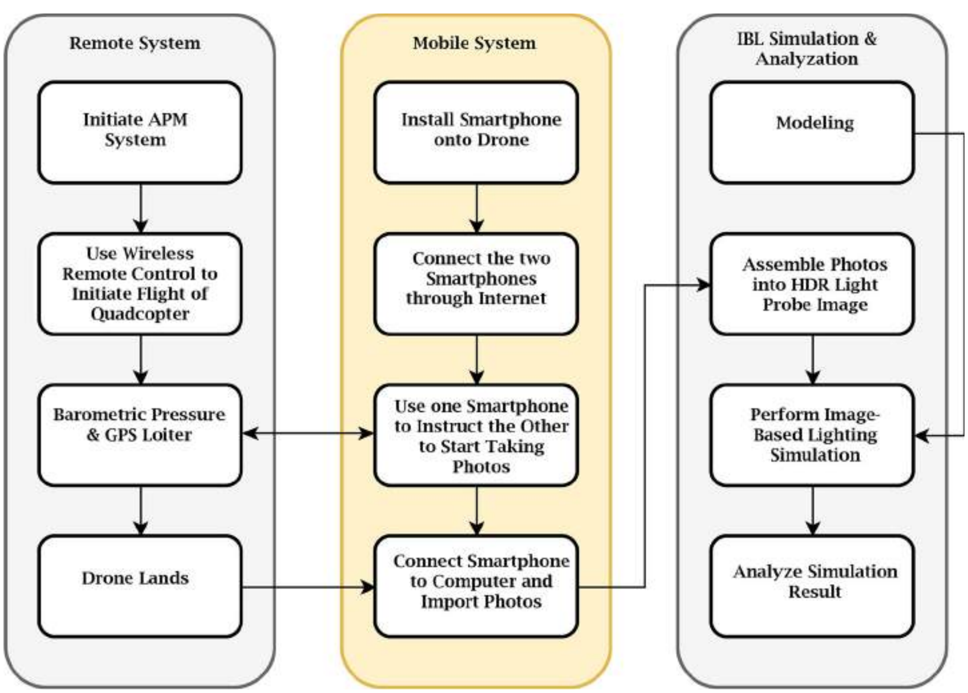

Figure 9. System framework of using HDRone to create light probe image for image-based lighting simulation.

approximately the same location, to create a light probe image. Fig. 10 compares the simulation results using the light probe image generated from the full-frame system and HDRone. The luminance value 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.

5. Conclusions and future works

This paper presents an innovative system consisting of a remote-controlled UAV and smartphone equipped with a fish-eye lens that can record natural illumination for building openings that accesses daylight from a horizontal direction. The current prototype has accomplished the following goals: 1) the customized body frame design of the drone can accept different smartphone types with different types of add-on lens to take photos in a horizontal direction to avoid the obstruction of the drone body; 2) the mobile system that connects the two smartphones can use an application to instruct the system to take multiple images at a loitering position. However, although the preliminary test shows some promising simulation accuracy results with the light probe image generated by the prototype, those pilot tests were limited to certain situations and thus, cannot account for all illumination environments. Therefore, many future works are required to further develop the proposed system to be a practical tool that can contribute to daylighting simulations for dense urban environments. First, continued development of the mobile application is needed to examine whether the captured photos cover the entire dynamic illumination range, this will ensure the generated light probe image can faithfully record the natural illumination. Second, the possibility of using visual localization technology on vertical surfaces should be investigated to evaluate whether or not it would allow for more stable loitering, and its use at higher locations in narrow vertical alleyways between high-rise buildings.

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