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APPLICATIONS OF IMAGE BASED RENDERING IN LIGHTING SIMULATION: DEVELOPMENT AND EVALUATION OF IMAGE BASED SKY MODELS

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ABSTRACT

This paper demonstrates the use of High Dynamic Range (HDR) fisheye images of the sky dome in lighting simulations. The objective is to improve the accuracy of simulations with site specific sky conditions. The luminance information stored at a pixel level in an HDR photograph is used to light the simulated environment through an Image Based Rendering (IBR) technique. The results show that image based sky models can provide a more accurate and efficient method for defining the sky luminance distributions and the impact of surrounding urban fabric and vegetation as compared to generic CIE sky models and explicit modeling of surrounding urban fabric and forestry.

INTRODUCTION

The accuracy of lighting simulations depends on the physically based modeling of the building and site properties, as well as the algorithmic reliability of the computational tools. Despite many developments in lighting simulation in the past decades, faithful representation of the sky luminance distributions at a specific location and time continues to be a challenge.

Daylight availability and sky luminance distributions vary spatially and temporally depending on geography, weather, climate, and other local conditions. Substantial amount of data is accumulated from long term measurements in various parts of the world (IDMP, 2008) through sky scanners. These devices (such as the Krochmann sky scanner) typically measure luminance at 145 points. The accumulated data is used to establish generic predictive sky models in the form of mathematical formulae. Currently, International Commission on Illumination (CIE) has identified 15 generic sky models that cover conditions varying from overcast to cloudless skies (CIE, 2003). Lighting simulation software utilize standard sky models (most commonly available models are the CIE overcast sky, clear sky and intermediate sky). However, these generic models do not represent actual sky conditions specific for any location; thus create high levels of uncertainty in the simulation and software validation processes. Moreover, due to the limited number of measurement points, the generic models do not have enough resolutions to adequately represent luminance variations, such as the rapid changes around the boundaries of clouds in an actual sky. The CIE sky models do not also include the spectral variations in the sky dome (Chain et al., 2001; Navvab, 2005). These shortcomings hinder the predictive power and the fidelity of the simulation results. Therefore, there is a need for the development of sky models that encompass high resolution data to acquire the spatial variability within the sky dome.

Previously, a number of researchers have utilized photography to derive empirical sky models (Spasojevic and Mahdavi, 2007; Uetani et al., 1993). The common approach in these studies is to capture the sky through a single photograph using a calibrated camera. The manual calibration process is tedious and camera dependent. Moreover, single image approach provides a limited dynamic range of luminance values. The acquired photograph is used to derive a customized mathematic model, and it is not used as a direct simulation input.

The technique utilized in this paper draws from two recent developments in the field of Computer Graphics: High Dynamic Range (HDR) Photography and Image Based Rendering (IBR). In HDR Photography, multiple exposure photographs are taken to capture the wide luminance variation within a scene (Debevec and Malik, 1997; Reinhard et al., 2006). The camera response function is computationally derived through a self calibration algorithm; and then it is used to fuse these photographs into a single HDR image, where pixel values can correspond to the physical quantity of luminance.

Image Based rendering (IBR) is a visualization technique that utilizes captured HDR images as light sources in the rendering process (Debevec, 2002). This paper demonstrates the use of 180° HDR images of the sky dome in lieu of the CIE sky models. Actual sky conditions at a place and time are captured through HDR photography technique. The luminance information stored at a pixel level is used to light the simulated environment. IBR is not specifically developed for lighting simulation purposes. Although few applications have been developed for architectural visualizations (Torres, 2003; Debevec, 2005; de Valpine, 2006), there is a need for a comprehensive evaluation to determine the appropriateness of the technique for lighting simulation.

The goal of this research is to develop advanced lighting simulation techniques to empower researchers and practitioners with better predictive capabilities. The specific objectives include (i) development and utilization of high resolution data acquisition techniques to collect image based sky luminance information; (ii) demonstration of the utilization of the image based sky models in lighting simulations; and (iii) evaluation of image based sky models as accurate sky luminance distribution representations in lighting simulations.

METHODOLOGY

The research consists of 4 main tasks:

- HDR images of the sky dome are captured at different times and under different sky conditions.
- Simultaneously, HDR images of a daylit office interior are captured to measure the luminance properties of the office under current sky conditions.
- Physically based Rendering (PBR) and IBR techniques are used to simulate the same office with CIE sky models and captured sky images, respectively.
- Captured and simulated lighting conditions are compared. Uncertainties in the simulation, accuracy, expected errors, applicability, limitations, and advantages of the techniques are discussed.

High Dynamic Range Photography

Capturing a luminous environment with HDR photography is a straightforward task. Multiple exposure photographs of static scenes can be taken with a commercially available digital camera to capture the wide luminance variation within the scenes. The camera response function is computationally derived, and then used to fuse the multiple photographs into an HDR image. This approach has been validated for lighting measurement purposes (Inanici, 2006). Laboratory and field studies show that the pixel values in the HDR photographs can correspond to the physical quantity of luminance with reasonable precision and repeatability (within 10% error margin).

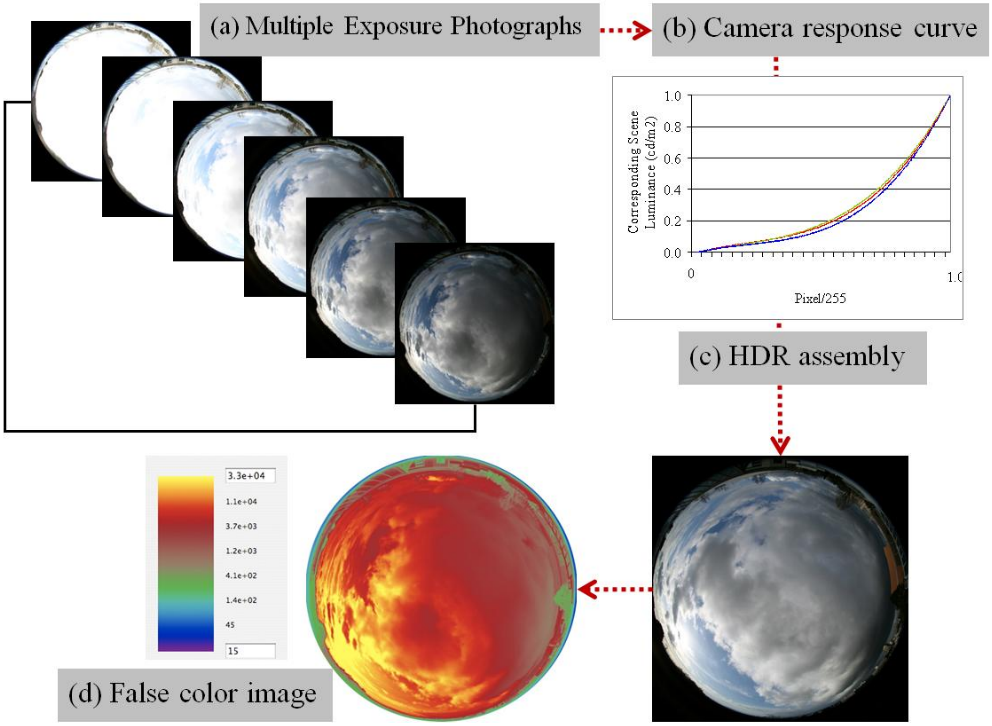

Figure 1 Multiple exposure photographs (a) assembled into an HDR image (c) using the camera response function (b); false color image (d) shows the luminance distribution patterns.

HDR images of the sky dome are captured at the roof of the Architecture Hall at the University of Washington in Seattle during the month of January. A commercially available digital camera (Canon EOS 5D) and fisheye lens (Sigma 8mm F3.5 EXDG that has 180° angle of view and equi-angle projection properties) are mounted on a tripod and used to capture the multiple exposure photographs. White balance and ISO settings are kept constant (daylight and 100, respectively) for achieving consistent color space transitions. Photographs are taken with a fixed aperture size (f/5.6), and varying only the shutter speed in manual exposure mode. Simultaneously, HDR images of a west facing office interior are captured in the second floor of the same building. These photographs are captured with a Canon EOS 30D camera and Canon EF 20mm f/2.8 lens. Each multiple exposure sequence is fused into an HDR image (Figure 1) using a software called Photosphere (Ward, 2005). The assembly process succeeds the calculation of the camera response functions of both cameras, which were performed automatically through a built-in self calibration algorithm within the software.

Fisheye lenses exhibit noticeable vignetting, i.e. light fall off for the pixels far from the optical axis. Although vignetting effects are negligible in the center of the image, there are increasing errors towards the peripheral pixels. This discrepancy is significant in capturing the sky luminance. The vignetting function of the fisheye lens is determined through laboratory measurements done in 5° intervals and this function is used to devise a 'digital filter' to compensate for the luminance loss (Figure 2). Vignetting is strongly dependent on the aperture size, so the function is generated for an aperture size of f/5.6, which is used for capturing the multiple exposure sequences. The maximum loss caused by the vignetting effect is around 40% at the periphery. The digital filter is an image that has the same resolution as the fisheye image, and it is applied as a post process to compensate for the vignetting effect based on the pixel location.

During the image capturing process of the sky dome, horizontal illuminance is measured at the camera level (Minolta T-1H illuminance meter). A single luminance value of a gray target is measured from the camera viewpoint during the image capturing process of the office interior (Minolta LS110). The calibration feature of Photosphere is used for fine tuning the luminance values within each scene.

Simulation

Radiance Lighting Simulation and Visualization system (Ward, 1994) is used to simulate the office space both with the CIE skies and captured images. Radiance is widely accepted as the most reliable lighting software and it is validated (Mardaljevic, 1995). IBR technique was also originally developed using the Radiance software (Debevec, 2002).

It is necessary to create accurate (physically based) modeling of the environment for performing a real-world lighting analysis. Dimensions of the office space are measured on site (3.6m x 4.4m x 4.5m) and a 3D model is created (Fig. 3). The color and reflectance of the materials are determined using a GretagMacbeth ColorChecker© Color Rendition Chart and the Radiance Macbethcal program (Ward, 1997). To determine the chromaticity and reflectance properties of the materials, two subsequent photographs are taken under stable lighting conditions: Macbeth chart is photographed in front of the material in question, and then the chart is removed to photograph the material sample. Radiance Macbethcal program is used to compute a linear transformation function from the measured color space into the standard Radiance color space based on the six neutral (grayscale) color patches in the Macbeth chart, and this function is used to calibrate the material samples. The RGB values in the calibrated sample images determine the chromaticity and the average hemispherical diffuse reflection properties. Some of the calculated diffuse reflectance values are provided here: concrete wall (29%), plaster wall (62%), ceiling tiles (75%), floor (15%), desktop (17%). The specularity and roughness properties of sample materials are approximated.

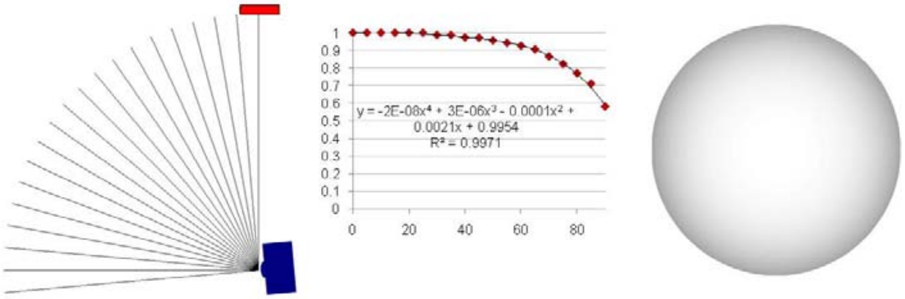

Figure 2 Vignetting function of the fisheye lens is determined as the camera is rotated in 5° intervals away from the target (left), the camera response function is determined as a polynomial fit (middle), and used to create a digital filter (right) that is applied as a post process to compensate for the light fall off.

In a Physically Based Rendering (PBR) system, daylight availability is defined through a sun description (distant light source) and a sky model (skylight). Direction and intensity of sunlight is calculated based on latitude, longitude, date and time. The sky geometry is defined through an invisible hemisphere. Luminance distribution patterns over the hemisphere (i.e. sky dome) are calculated based on latitude, longitude, CIE sky type, and turbidity.

Figure 3 3D model and simulation of the office space with CIE overcast sky

In an IBR system, the fisheye image of the sky dome is used in place of the mathematical definitions of the sun and the sky. By definition, a fisheye image is a parallel projection of a hemisphere onto a circle, and therefore, the circle (fisheye image) can be projected back onto a hemisphere (Figure 4). For the rendering process, the mathematical model of the sun and the CIE sky are removed from the simulation input; and the HDR image of the sky dome is included in form of an invisible, light emitting hemisphere. Pixel values in the HDR image correspond to the physical quantity of luminance (cd/m^2), therefore, each pixel ‘glows’ with its luminance value providing a source of illumination. Individually, each pixel represents the luminous intensity in a given direction per unit area; direction is determined by the position of the pixel (patch) in the sky dome. Collectively, pixels form the entire sky dome (sunlight and skylight) that provide real world lighting conditions, under which any built/natural environment can be simulated.

EVALUATION AND DISCUSSION

Evaluation of the IBR technique with image based sky models are done in two categories: The first category is a theoretical validation, where the objective is to study the accurateness of the IBR technique in comparison to PBR. The second category includes the empirical evaluation of the IBR technique, where the objective is to compare the IBR results with real world measurements.

Theoretical Validation

For the theoretical validation, the interior office space is first simulated under standard CIE skies for Seattle, 47.6° North 122.3° West (refereed as the ‘PBR technique’). Then, a fisheye image of the sky dome is simulated for the same time and location. Theoretically, if an ideal CIE overcast sky was occurring and captured using an HDR photograph, this photograph would be identical with the image of the sky generated within the Radiance program.

Both HDR photographs and physically based renderings saved in HDR image formats (i.e. .hdr, a.k.a. Radiance .pic) allow us to collect and generate visual and numerical lighting information in i) high resolution; ii) dynamic range that covers the total human visual range from starlight to sunlight; and iii) large field of view. Therefore, it is possible to generate an image of the sky using the Radiance software and use it as an image input in the IBR technique. Note that although the sky is the same, it is defined through a mathematical model in PBR, and in the form of an image in the IBR technique.

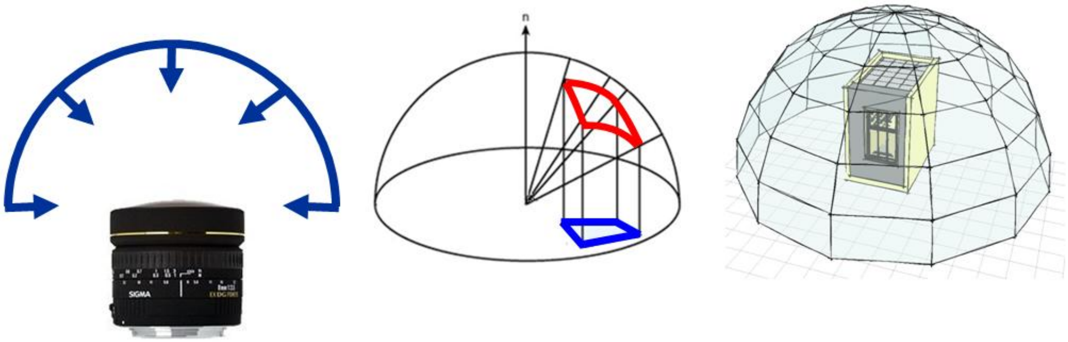

Figure 4 Fisheye projections and application of a fisheye image as a light emitting hemisphere

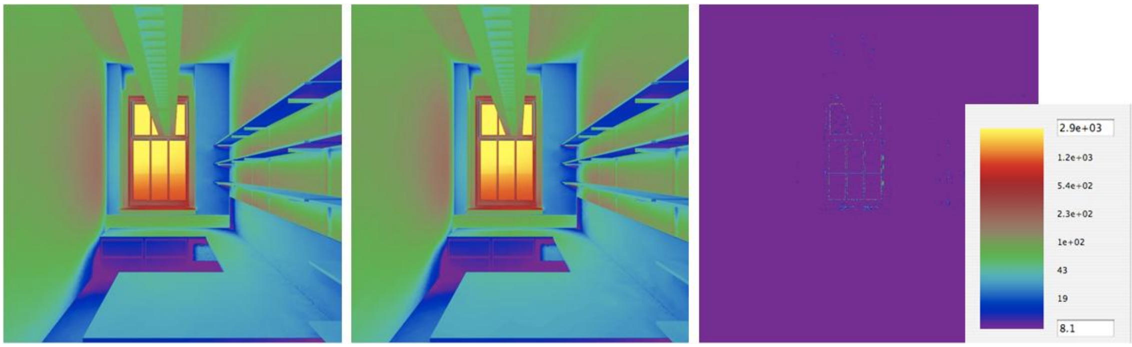

Figure 5 False color (luminance) comparison of a scene simulated with a CIE intermediate sky: the left scene utilizes a mathematical model of the CIE sky (PBR), the middle scene utilizes the image (IBR) of the CIE sky generated based on the mathematical model; the right image displays the differences between the two approaches.

Radiance software uses a hybrid deterministic / stochastic (Monte Carlo) technique, where direct lighting components are computed with rays traced to random locations on the light sources (Ward, 1994; Ward and Shakespeare, 1997). In PBR approach, the sun and sky are defined as apparent light sources. Sun is explicitly defined as a source with 0.5° arc, and unobstructed sun is computed with the deterministic ray tracing algorithm: i.e. a single sample ray is sent from the camera position towards the sun and its contribution is calculated based on the known size and luminosity of sun. In IBR approach, sun and the sky are embedded within the HDR image. This image is processed through Monte Carlo ray tracing algorithm which is based on random sampling. The premise of this technique is that photons in the physical world bounce randomly, and collectively they provide stable lighting conditions (Ward, 1994). Obviously, these are two different approaches for lighting calculations. In IBR technique, sun is not explicitly modeled as a concentrated light source, and it is calculated as part of the indirect calculation through random sampling. It is a possibility that concentrated light sources (such as the sun) may be overlooked in the random sampling process. The objective of this part of the research is to study whether both approaches yield similar results.

Two sets of simulations are generated. In the first set, luminance distribution patterns are compared with the two techniques under a CIE intermediate sky for March 21st at noon. Figure 5 shows false color images of the setting simulated under CIE intermediate sky, where the sky models are defined with a mathematical model (PBR) and an image (IBR) generated based on the mathematical model, respectively. There are minor differences between the images at the pixel level due to algorithmic differences, but overall, the differences are insignificant for lighting analysis purposes. The average luminance level difference between the two scenes is calculated as 1.6%. Note that the rendering parameters are set to high quality (ambient resolutions and divisions are set to 128 and 256) to improve the accuracy of indirect calculations.

In the second theoretical evaluation set, illuminance levels across a grid are studied and compared with the two techniques under a CIE clear sky for June 21st at noon. Figure 6 demonstrates the results from this study. The illumination levels are very similar and the average difference between the two simulation methods is 3%.

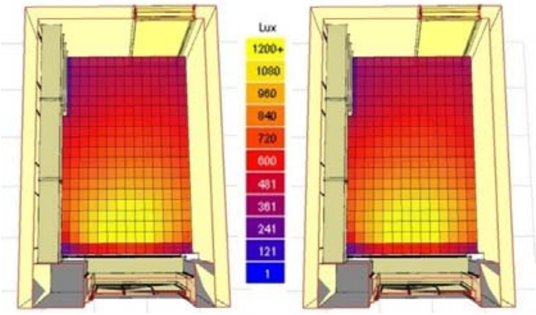

Figure 6 Illuminance values are represented in a grid as a comparison of the same scene simulated with a CIE Clear sky model for June 21 with PBR and IBR techniques, respectively.

Empirical Evaluation

For the empirical evaluation, the interior office space is simulated using the HDR images of the sky dome that were collected at the roof of the building. Simulation results are analyzed in comparison to the HDR images of the same office that were captured simultaneously at the same time with the sky images. Multiple data sets were collected. Three sets are presented here (Figure7):

- Cloudy sky: The horizontal illuminance was measured as 17,976 lux.
- Partly cloudy sky: The horizontal illuminance was measured as 24,757 lux.
- Mostly clear sky: The horizontal illuminance was measured as 34,445 lux.

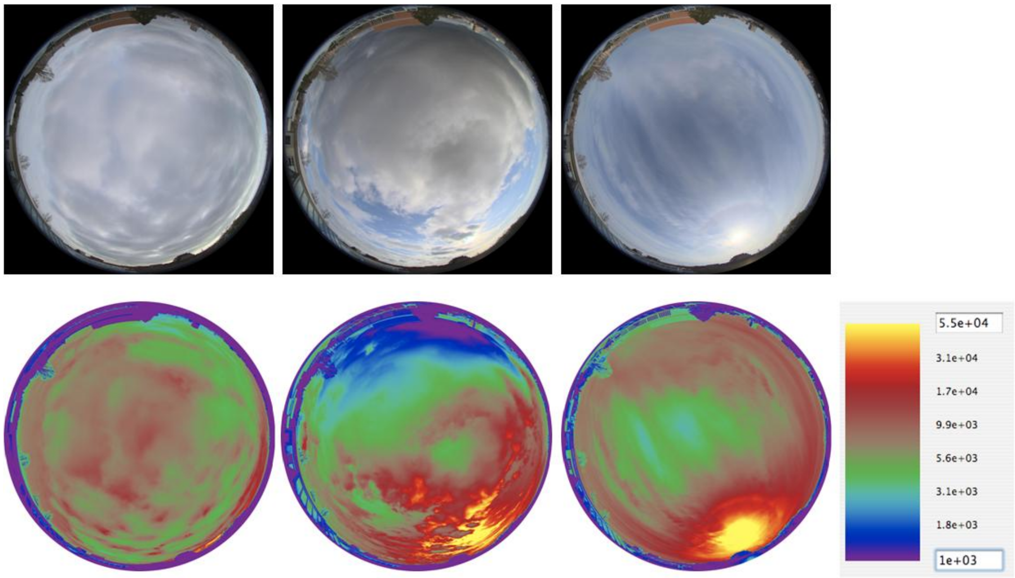

Figure 7 Captured sky images

Figure 8 demonstrates the captured HDR photograph and the simulated IBR scene with the partly cloudy sky. As seen from the scene outside the window, there are differences between the simulated and captured scenes. The sky dome was captured at the roof level and it does not include the surrounding objects that are below this level (such as the trees and low buildings seen from the office window).

Figure 8 Photograph and simulated image of the office under partly cloudy sky

One of the most important advantages of using an IBR technique is that the input image, not only contains the sky, but also the surrounding structures and vegetation. Therefore, it is site specific. Neighboring structures block portions of the sky, and they reflect light based on their material properties. Although it is possible to digitally model the surrounding and include it in the simulations, there are known challenges: Modeling neighboring structures and vegetation can be computationally expensive, especially in dense urban or forestal areas. Trees are particularly difficult to model, and they filter light in a complex manner that is not straightforward to approximate. It is possible to model the surrounding buildings, but it is not feasible to determine the reflectance properties of all building materials at an urban level. Depending on the site, the impact of the surrounding on lighting quantity and quality can be substantial. An HDR image captures the amount of light reflected from all of the neighboring structures towards the camera; therefore, it eliminates the need to digitally model the geometry, physically based material properties of the surrounding, and to compute the interreflections between these outside surfaces. This technique works well for simulation and analysis of un-built projects, where the building site is empty and HDR images taken close to the ground level include the entire surrounding environment.

Although per-pixel comparisons can be made between the captured and simulated images, it is neither realistic nor useful to expect luminance values to match at a pixel level due to unavoidable uncertainties and simplifications in the input, measurement, and simulation processes (Rushmeier et al., 1995). It is also acknowledged that although absolute errors are not major concern for most lighting designers, relative errors can have great consequences in the design decisions (Navvab, 2003). Therefore, the comparison should focus on the spatial luminance distributions and relative differences in the whole image as well as on critical task surfaces. False color luminance images of the simulated and captured office interior under the cloudy, partly cloudy and mostly sunny skies demonstrate that although the absolute values may not match, the luminance distributions are comparable.

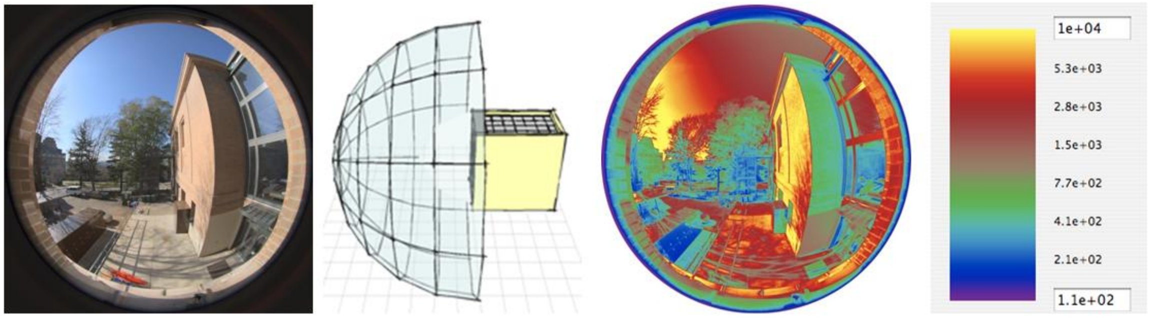

Figure 9 Vertical fisheye image taken outside the window of the office is used as the lights source in the IBR technique to simulate the office interior

For existing structures that have unilateral windows, a better simulation method is to capture a vertical fisheye projection and use the image to provide side lighting from the window (Fig. 9). This method has been proposed by Torres (2003). In this method, a fisheye image taken outside the window captures the sky and surrounding as seen from the window. The first simulation is performed with the vertical fisheye image as the only light source in the environment. In the second simulation, a CIE clear sky for the same time and location has been used through a conventional PBR technique. Figure 10 demonstrates the false color analysis of the simulated and captured images. The interior surface luminance values are similar between simulation and measurement results. IBR technique incorporates the appearance of outside structures and vegetation as well as the reflected light from the surrounding, therefore, improves the accuracy of luminance predictions over the window surface.

CONCLUSION

The paper has demonstrates that image based sky models can provide a more accurate and efficient method for defining the sky luminance distributions and the impact of surrounding urban fabric and vegetation as compared to generic CIE sky models and explicit modeling of surrounding urban fabric and forestry. Theoretical validation results attest that accurate results can be achieved in IBR technique with adequate indirect lighting calculation parameters. Empirical evaluations reveal that for un-built projects, sky models can be captured at the site and close to the ground level for best results. For existing structures, simulation accuracy can be improved for unilaterally side lit spaces through using vertical fisheye images for the simulation.

Increased accuracy of simulations is needed to develop better performance analysis tools, techniques, and metrics. IBR technique is particularly useful for visual comfort and performance metrics, where interior luminance ratios and accurate depiction of window luminance distributions are critical.

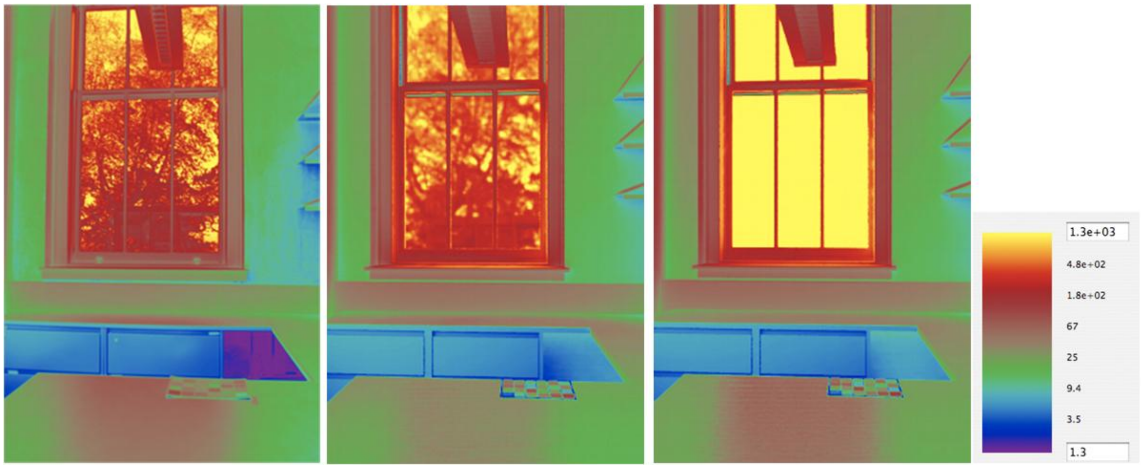

Figure 10 False color images of the office from a) HDR photograph, b) simulation using the IBR technique and vertical fisheye image as the light source, and c) simulation using CIE clear sky as the light source

Possible luminance values from starlight to sunlight range between 10^{-8} to 10^{6} cd/m^2. During the data collection period in Seattle, the maximum sun altitude angle was around 20°. For higher altitude angles and higher sky luminances, a previous study (Stumpfel et al., 2004) suggests using neutral density filters to record the extreme values in the capturing process and using a directional light source as the virtual sun in the simulation process. Further research will be done during the summer months to collect data under higher solar altitudes and luminance values.

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