MULTI-POINT SIMULTANEOUS ILLUMINANCE MEASUREMENT WITH HIGH DYNAMIC RANGE PHOTOGRAPHY

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ABSTRACT

Daylight illuminance uniformity is a common criterion when assessing the performance of fenestration and solar control. To evaluate a design according to this requirement, a grid of horizontal illuminance readings for a given time is required. In simulation based assessments, this can be calculated by defining sensor points at working plane level and running a simulation for a single time step, or an annual simulation to assess the uniformity for a typical year. Backing such predicted assessments with measured data has been a task involving installation and calibration of sensors, cabling and data acquisition systems, which typically render the assessed space unusable for the time of assessment. Using sequential readings from handheld devices as a convenient alternative ignores the dynamics of daylight, as the sky conditions cannot be assumed constant during the time required to record the illuminance at the required amount of locations.

We propose instantaneous image-based measurements of horizontal illuminance for assessments of daylight uniformity. Instead of cabled sensors, near-Lambertian reflectors are placed at working plane level in the assessed space. High Dynamic Range (HDR) images of the working plane with markers are taken and the luminance of the marker surfaces is extracted from the corresponding pixel values. These luminance values can be used to calculate horizontal illuminance for each marker location, assuming Lambertian reflection. As direct sunlight at working plane is considered to exceed the range of acceptable illuminance for uniformly lid spaces, only readings below a threshold of 3000 lm/m2 are considered.

Keywords: Illuminance, daylight, Lambertian diffuser, Goniophotometry, high dynamic range imaging

INTRODUCTION

Horizontal illuminance requirements have been related to tasks and have been established for planning with artificial and natural light. Handheld devices for point-measurements of horizontal illuminance are available and commonly found in practice. National and international standards however impose requirements of horizontal illuminance over the occupied area of buildings. LEED IEQ8.1 e.g. requires horizontal illuminance in an acceptable range for at least 75% of the occupied space [1]. Daylight uniformity as a separate metric addresses the spatial distribution and is credited e.g. in the BREEAM rating system as a minimum uniformity ratio Emin/Emax of 0.4 [2]. The distribution of horizontal illuminance however cannot be evaluated using measurements for only one point due to the uneven distribution of illuminance in typical environments. Handheld illuminance meters, which are not suitable for simultaneous measurements, could be used for sequential measurements at given locations. However, the dynamics in daylight would heavily affect the results of such measurements. The effort to equip a space with wired sensors and a data acquisition system, which typically limits the usability of the assessed space, is hardly acceptable to occupants especially for extended assessment periods.

Researchers have investigated the usage of digital cameras as commonly available devices for luminance measurements [3]. Stacked exposures of low dynamic range images, as captured by the image sensors of typical consumer cameras, have been assembled into HDR images to cover the dynamic range of daylight environments [4, 5]. The dynamic range of the resulted HDR image is mostly limited by the number of images that can be taken in a short time. The time span available for the image series is determined by the variability of the lighting conditions, which are assumed as constant in the assembly process. Research has shown that HDR techniques are an accurate method for luminance measurements [6, 7, and 8].

For perfectly Lambertian diffusion, luminous flux through transmissive objects can be calculated from observed luminance if the diffusor is placed between a calibrated camera and a light source. The method has been demonstrated for assessment of luminous flux through fenestration systems and light pipes, and also as a method to capture total-horizontal and diffuse-horizontal illuminance [9]. The almost perfect Lambertian bidirectional scatter distribution function (BSDF) for transmission through paper allows its application in flexible and low-cost measurements within an accuracy range reasonable for daylighting applications.

We extend the method of using paper as a diffusor for illuminance calculations using HDR imaging techniques to illuminance calculations from luminance measured on the reflecting side of the diffusor. While the deviation from an ideal Lambertian BSDF is higher for reflection than for transmission, this allows the application of the method for multipoint illuminance measurements, addressing the lack of measured data backing requirements for daylight uniformity. Markers made of low-cost paper are placed on existing surfaces. The area covered by the markers included in the measurement is limited only by the view angle of the camera lens and the image resolution, as wide angle lenses lead to lower pixel resolutions for each marker. Besides allowing a simultaneous measurement of illumance at many locations, potentially over an extended time span, the resulting images contain relevant information for documentation such as marker locations, changes in the setup and shadowing effects.

METHOD

A Lambertian diffuser [10], with its perfect diffuse reflection properties, has a constant luminance independent of the viewing direction. A marker made of a Lambertian diffuser would be ideal for our method. Regardless the location of the marker in the field view of the luminance acquisition camera, illuminance E on an ideal diffuser could be calculated as

$$E = \frac{1}{\rho} * \pi L \qquad (1)$$

where ρ is the reflectance of the diffuser and L is the luminance from the viewing direction.

Acquisition of luminance maps

The camera used in this project, the “LMK mobile advanced” by Technoteam, is a luminance acquisition system based on a calibrated Canon EOS 5500 DSLR. A proprietary software reads in raw image data and applies the calibration data for the combination of lens and camera as supplied by the manufacturer. This results in luminance maps that can be processed and exported in a tabular format of pixel coordinates and corresponding luminance. These luminance values were used to assemble HDR images in Radiance RGBE format using the *pvalue* program as part of Radiance.

Selection of the Marker

The marker for the presented method should have properties as close as possible to those of a Lambertian diffuser. To obtain illuminance values at multiple positions in a scene, a number of markers are required so it must be inexpensive and easy to attach to surfaces. Industry diffuse standards, typically made of Polytetrafluoroethylene (PTFE) such as used in integrated spheres would be much too expensive. Hence, an alternative material needs to be found that still presents desired reflection property.

To quantify how close the reflection of a real material comes to that of the Lambertian diffuser, a Goniophotometer is used. A Goniophotometer measures the light that is reflected off and/or transmitted by surfaces and materials (optical scatter) at any point in space [11]. In addition, the angle of the light that is incident on the surface or material can be varied from the standard normal (perpendicular to the sample plane) to very oblique angles (up to 85°) to quantify the optical scatter as a function of the incidence angle. The outgoing angles are defined by an orbital mesh around the sample with an angular resolution of less than 0.1°. The characterization follows the format of Bidirectional Scattering Distribution Function (BSDF), in which light intensities for each angle of incidence are measured for all outgoing angles (direct-to-direct reflection/transmission). In this paper, only reflectance property is investigated, therefore the term Bidirectional Reflectance Distribution Function (BRDF) is used instead of BSDF. The results were presented in polar plots as shown in Figure 1. The polar plots show the BRDF in common logarithmic scale for the scatter plane (Φ_i=0°). Each polar plot shows the scatter of the sample in reflection. The logarithmic scale is marked by concentric rings whose values represent a ratio of the power of light leaving a unit area of the sample in a given direction to the power of light incident on that area.

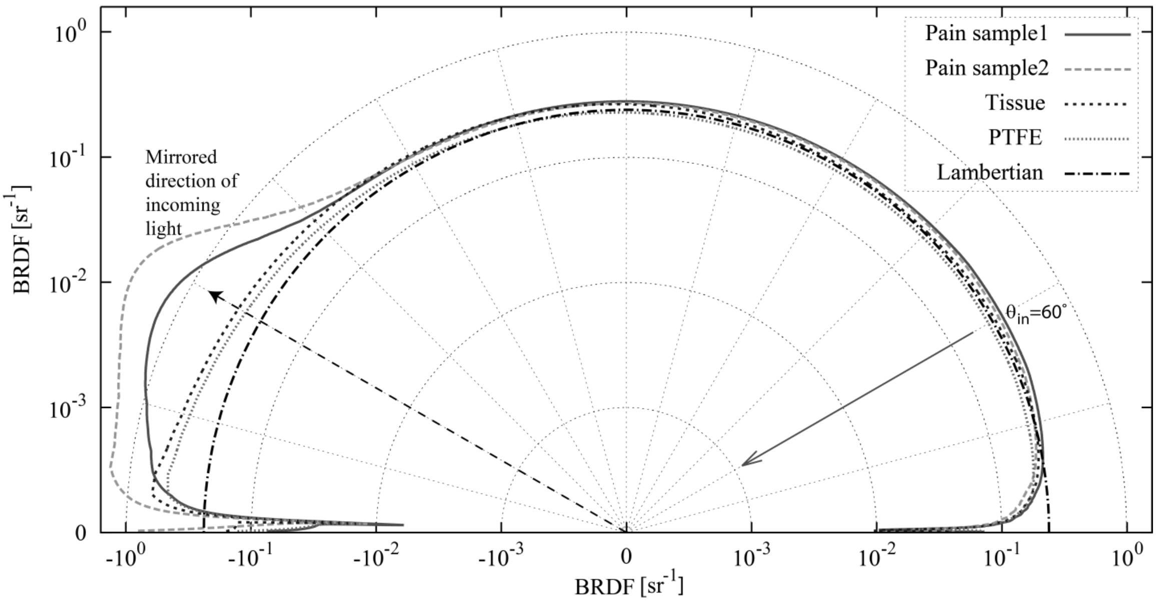

Figure 1: Polar plot showing the reflection properties of two pain samples, tissue paper and PTFE at 60° incident angle compared to a theoretical ideal diffuse reflection of a Lambertian surface with reflectance the same as PTFE.

Eight materials were measured including two spray matt pains, four kinds of matt paper, tissue paper and Polytetrafluoroethylene (PTFE). The PTFE sample is a reflectance standard for optical experiments which has nearly ideal diffuse reflection properties over a wide range of wavelengths from UV to infrared (250 – 2500 nm). All materials were measured with Goniophotometer at incident angle (θ_i) equals to 0°, 15°, 30°, 45° and 60°. Results for 60° are shown in polar plots comparing to the theoretical Lambertian diffuser (Figure 1). All materials expect paint sample 2 present reflection properties that are very close to the theoretical Lambertian surface when incoming light is close to the normal of the material surface. However, when incoming light is at a more oblique angle (θ_i = 60°) the reflection pattern of all the materials become asymmetrical along the surface normal. Among all the materials, PTFE shows the closest result to the theoretical Lambertian diffuser follows by the tissue paper. The four matt paper samples have similar reflection pattern and shows larger value near the mirrored direction of incoming light. The two pain samples show bulging along the light exit angle which suggests strong directional diffuse components in their reflection properties. As shown in the above results, tissue paper, with its desired reflection property, was selected as the material for the diffuse marker.

Validation and error analysis

The directional diffuse component in the reflection property of a marker leads to the errors in the presented method. This error is dependent on light incident direction and viewing angle. With directional light at oblique angle, the error is considerable as shown in Figure 1. However, the presented method is proposed for useful daylight monitoring. As the highly directional sunlight which always result illuminance values exceeding the desired range, it need not to be quantified for this method. In order to validate the method in diffuse daylight conditions for various incident light direction, a marker was placed one meter away from a façade with French windows. The marker was made of tissue paper pasting on an opaque rigid corrugated-core sandwich panel. The panel ensured the flatness of the tissue paper and it could also maintain the reflection property of the marker independent from the background. With a movable blind next to the windows, the façade working as a diffuse light source could be changed for its elevation angle to the marker. With a correction factor *f* introduced to equation 1, the difference between the calculated illuminance from a HDR image and the illuminance from a lux meter could be quantified. As shown in Figure 3 left, the factor remains in a limited range which implies that under diffuse daylighting condition, the luminance value reflected from the marker can be considered independent from the direction of incident light.

$$E = \frac{1}{\rho} * \pi L * f \qquad (2)$$

For a fixed set up of the camera and markers, the factor *f* could be calculated for each marker to correct the error from viewing direction. Using the same setup with the blind fully open, a series of HDR images of the marker were captured with half hour step. During the entire process, the weather was dominated by overcast sky. The illuminance values calculated from the HDR images was compared to the illuminance value recorded with lux meter (Figure 3 right). With the same camera-marker position, the factor *f* was applied to correct errors result from the viewing angle in this set up. The difference between the image and lux meter is within 12% for the sequence expects the value recorded at 15:45 which is 19%. The error is beyond the 10% range which is acceptable for daylighting monitoring. The experiment will be repeated for further investigation.

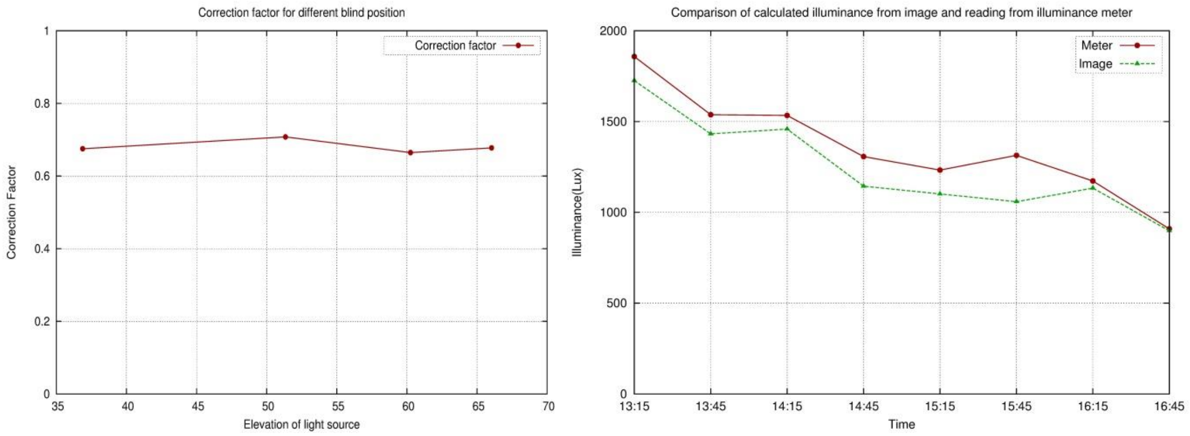

Figure 2: Left: Correction factor calculated for different blind positions. Right: Comparison of calculated illuminance from images and readings from illuminance meter.

CASE STUDY: OFFICE SPACE

The presented method was applied to capture daylight distribution in an occupied office (Figure 3 left). Ten markers in two rows were equally spaced along the working plane away from the façade. The camera position and direction was fixed to take a series of images. A correction factor for each marker was calculated and applied to the readings from the images. Two rounds of photo shoot were taken place in the office with one hour step. Each round consists of two images taken one minute apart to capture instant daylight variance. The results are shown in Figure 3 Right. It is clear that daylight level on the working plane decrease gradually with the distance from the façade. For the first round, the daylighting condition kept constant and there is a 10% variance of illuminance level in the second round. With an extended assessment period, the set up could be used as a daylighting monitoring system for the office space.

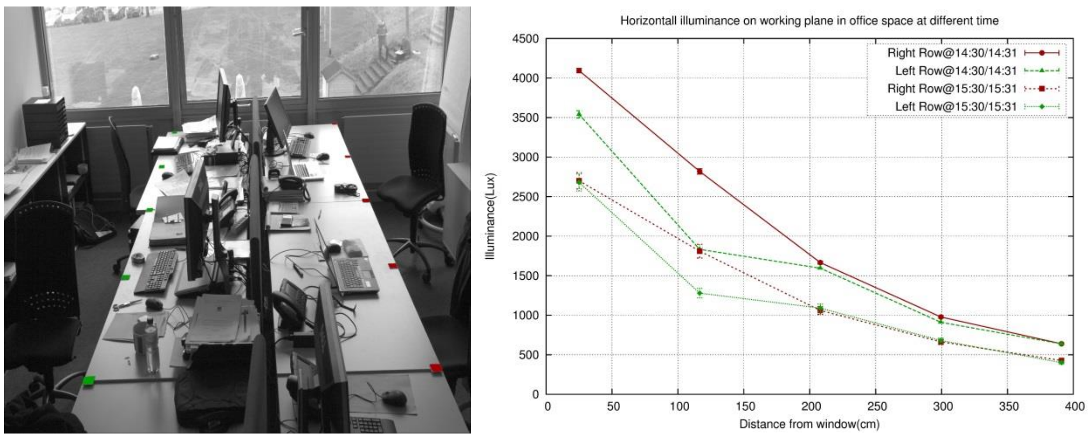

Figure 3: Left: Experiment set up in an occupied office space with 10 markers on the working plane. Right: Daylight distribution in office space at different time using the presented method.

CONCLUSION

This paper addresses the lack of measured data backing requirements for daylight uniformity by introducing a method for measuring daylight illuminance at many points simultaneously. The method uses HDR techniques to capture the luminance of markers located at the measurement points.

A Goniophotometer was applied to identify a marker material that exhibits nearly Lambertian diffuser properties allowing the calculation of illuminance from the luminance values captured in HDR images.

Inexpensive tissue paper is found to be a suitable material for the markers, presenting reflection properties very close to those of perfect Lambertian diffusers. The deviation from a perfect Lambertian diffuser is corrected by a factor for each marker in the set up. The highly directional sunlight is not covered, as areas receiving direct sunlight would not contribute to a uniformly daylight space and thus do not need to be quantified. The non-Lambertian reflection occurs only for extreme incident angles and can be neglected for predominantly diffuse lighting conditions. Within this scope, relevant for assessments of daylight uniformity, the presented method has potential to provide sufficient accuracy to be used for simultaneous multi-point illuminance acquisition of daylight in buildings. We believe, that digital photography could become an integrated capturing and display system for luminance, illuminance and surface material properties of an architectural scene and as such helps lighting planners/engineers in quantifying and visualizing the lighting milieu of a scene.

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