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CASE STUDIES OF A THREE-DIMENSIONAL EXPRESSION OF COLOURED LIGHT FLOW USING VOLUME PHOTON MAPPING

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Abstract

Considering the light distribution in an interior space is an important aspect in the process of architectural design. In most settings, the surface-bound illuminance/luminance distribution provides general cues describing the lighting environment. However, visualising the flow of light in three-dimensional space, similarly to thermal air-flow, can guide designers by providing an overview of the light field which surrounds people in the space, thus promoting advances in human centred lighting design. In this paper, we will propose a new method to depict the coloured light flow using the volume photon mapping algorithm and report the application results of this method for two case studies.

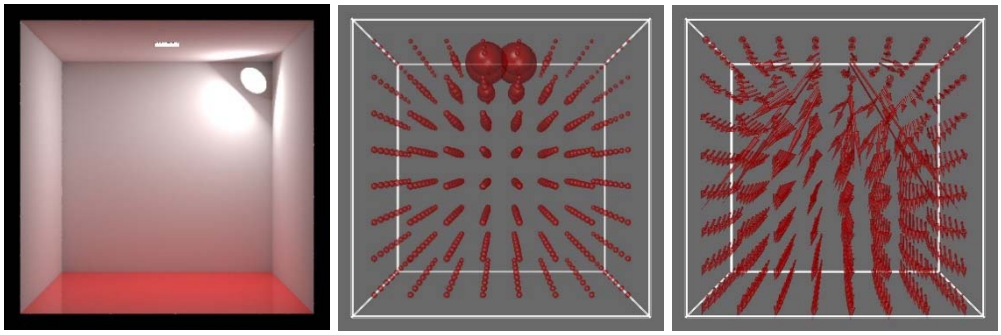
Keywords: Light flow, Volume photon mapping, Radiance, Three-dimensional expression

1 Introduction

The spatial light field inside the architecture has been recently becoming more complicated due to the increase of individually-controllable LED luminaires or the diversification of architectural facade design for daylighting, etc. In the current process of architectural design, the surface-bound illuminance/luminance distribution provides general cues describing the lighting environment. These data represent only the final stage of light transport in the space, therefore, it is sometimes difficult for designers to directly grasp the process where light spreads out after emitting from light sources and affects the visual environment.

Furthermore, as Kartashova et al. pointed out in their paper that *"human observers have consistent impressions of the light field, though not exactly corresponding to the physical truth…"*, light environment surely gives a certain three-dimensional impression to observers: however, the conventional surface-bound illuminance/luminance distribution could not always explain well this spatial impression.

Spatial illumination metrics, such as scalar illuminances and illumination vectors, as shown in Figure1, are the classic methods for describing three-dimensional light distribution in lighting engineering. These metrics are easily calculated by using up-to-date lighting simulation programmes: however, they have some drawbacks. Description with illumination vectors could differ greatly depending on the grid spacing of measurement points. If the spacing is wider than



(a) (b) (c)

Figure 1 – Spatial illumination metrics: Scalar Illuminance and Illumination Vector
(a) Rendered image, (b) Scalar illuminance, (c) Illumination Vector

an appropriate value, there is a possibility that the characteristics of the light field could not be described well. Besides, when there are multiple light sources in the space, it is generally difficult to read the light flow from the illumination vectors, because all the vectors are synthesized ones.

In this paper, we will propose a new method to depict the light flow using the volume photon mapping algorithm. This visualisation can be effectively reinforced by complementing it with colour information, indicating the spectral interaction of the light with the space (e.g. colour bleeding from walls). We will also report the application results of this method for two case studies: the “Kimbell Art Museum” designed by architect Louis. I. Kahn, and the “Villa Müller” by Adolf Loos. Visualising the flow of light in three-dimensional space, similarly to thermal air-flow, can guide designers by providing an overview of the light field which surrounds people in the space, thus promoting advances in human centred lighting design.

2 Methods

2.1 Photon mapping algorithm

Photon mapping is a Monte-Carlo raytracing algorithm for global illumination consisting two passes: the first pass, as indicated in blue lines in Figure2, emits packets of energy called photons from the light sources via forward raytracing and stores them in the photon map when they hit surfaces within the scene. Each photon is characterised by its hit point position and energy (Luminant or radiant flux). After generating the photon map data structure, the final image is rendered, as indicated in red lines in Figure2, using a standard backward raytracing algorithm that performs a nearest-neighbour lookup for photons around the area of interest; the illuminance is then proportional to the local photon density, as each photon contributes a fraction of the flux distributed throughout in the scene.

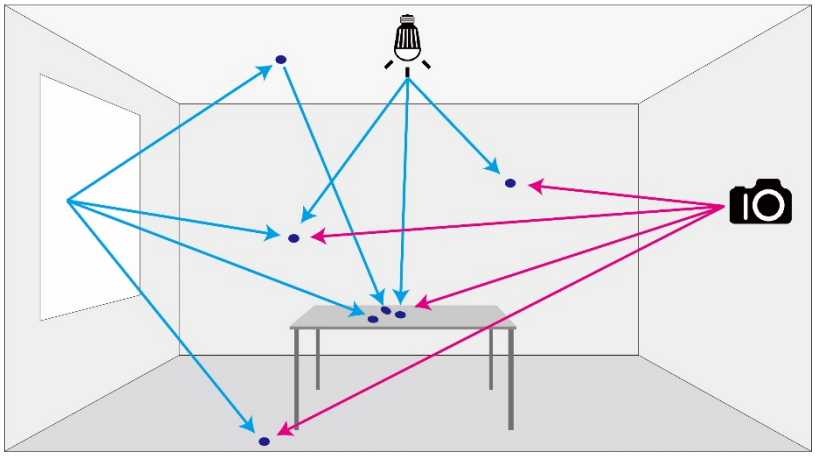


Figure 2 – Overview of photon mapping algorithm

Although photon mapping is technically decoupled from the scene geometry, it is generally used in a surface-bound context; photons are deposited on the surfaces they hit, and the reconstructed illuminance is only valid for surface points.

2.2 Applying volume photon mapping algorithm

Volume photon mapping algorithm is a rendering method that the influence of participating media such as dust and particles in the model can be taken into account. The proposed method uses the volume photon mapping extension and “mist” participating medium material implemented in the RADIANCE rendering and lighting simulation system. The RADIANCE photon mapping module was first developed by R. Schregle in 2002 and supports H. W. Jensen's volume photon map originally published in 1998. This method captures photons in three-dimensional space as they are emitted from the light sources by simulating their interaction with a participating medium between the surfaces in the room. This results in an efficient and intuitive representation of the three-dimensional light flow.

In a first step, the entire model is enveloped with a “mist” material with a Henyey-Greenstein scattering eccentricity of g=1, implying forward scattering to prevent modifying the photon paths. The prepared scene is then passed to the volume photon tracing tool, which records each photon's position and flux colour as it interacts with the participating medium in the space. Theoretically, the density of photons approximately equals the scalar illuminance at each point.

2.3 Coloured light flow

In addition to describe the light distribution by photon's density, we also attempted to express the light flow more impressively by applying actual light colour to each photon. Since the radiance of photon is described by the RGBE format for HDR images, tone mapping was applied to convert each RGB component value representing this absolute radiance to an 8-bit RGB values. These data are written in the point cloud data format, including information on coordinates (x, y, z) and colours (R, G, B), and displayed as point clouds using a three-dimensional modelling tool such as Autodesk’s ReCap, CloudCompare, Revit, Rhinoceros, etc.

Figure3 shows the coloured light flow in the same room as Figure1 (a). We can distinguish the light flow from a ceiling luminaire and a spotlight on the right corner, and read the light flow tinted with red after reflected on the red floor.

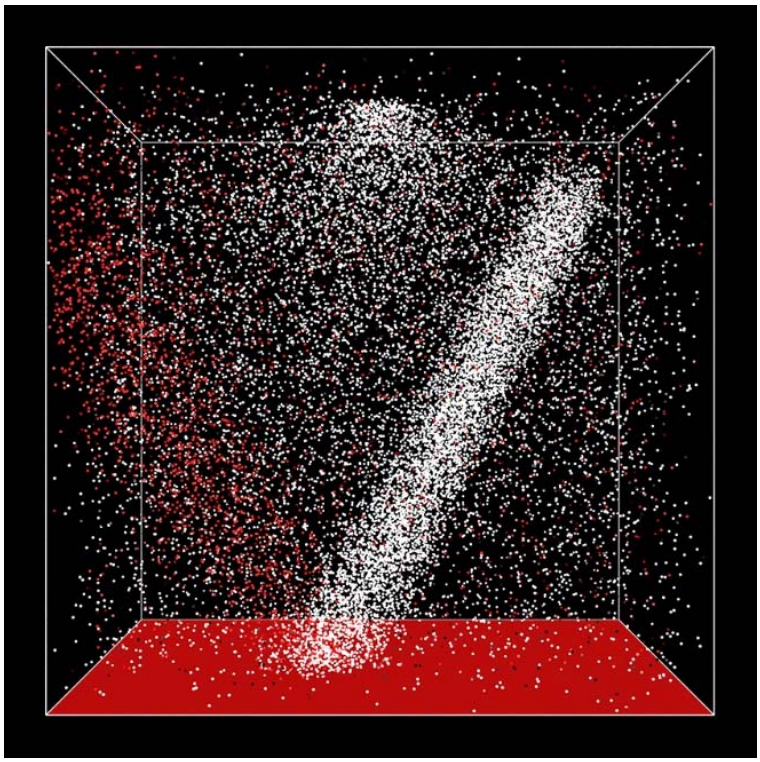


Figure 3 – Photon flow in the same space as Fig. 1

3 Case studies

3.1 The Kimbell Art Museum

3.1.1 An overview of the architecture

The Kimbell Art Museum was built in 1972 in Fort Worth, Texas, designed by architect Louis I. Kahn. One of the greatest features of this architecture is the introduction of daylight in a unique way. Kahn placed a reflector called "Lunette" under the skylight of the vaulted ceiling and introduced daylight to the ceiling surface to appear silver.

3.1.2 Simulation result

FIG. 4 shows the result of analyzing the change of the light distribution inside the museum on December 22. The gray lines in each image indicate the outline of the architecture, and the vertical yellow line on the left side indicates the wall on which paintings are displayed. Due to the effect of the reflector, introduced daylight is distributed mainly near the vault ceiling throughout the day, and most of the daylight does not reach the paintings on the wall except around noon. This result coincides with the report by Cuttle in his literature (2007) that in the Kimbell Art Museum required illuminance for paintings are almost given by artificial spotlightings, and this characteristics is really important for assuring the quality of the museum daylighting.

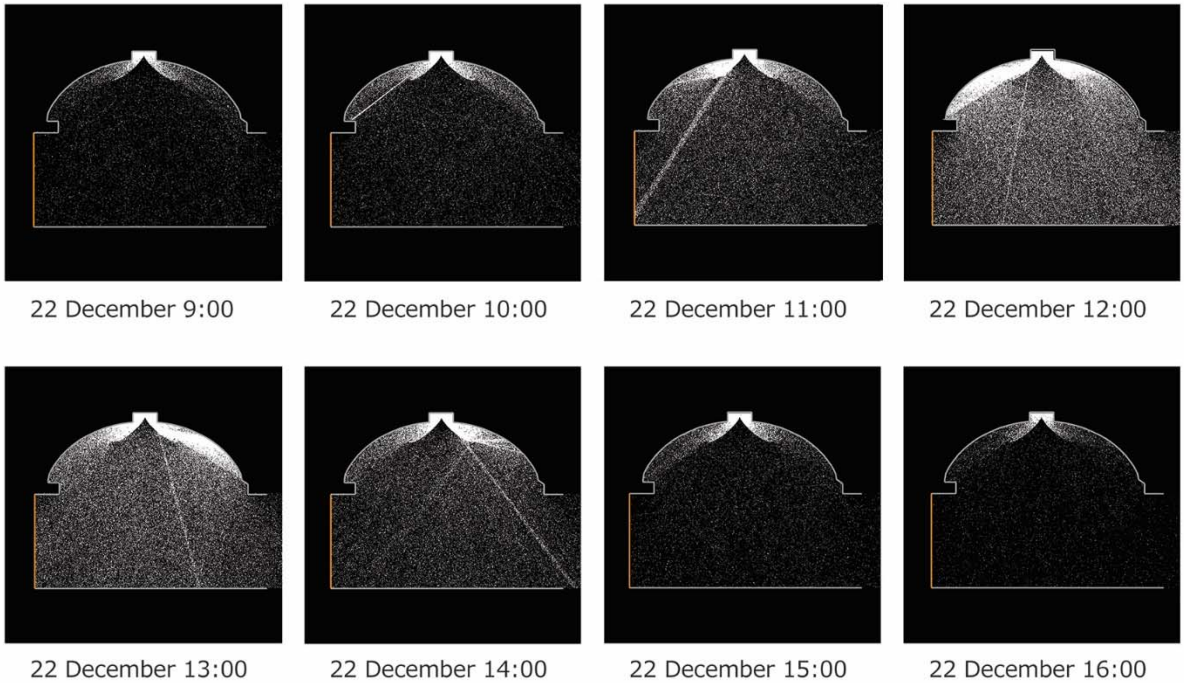


Figure 4 – Hourly changes in the light environment of the Kimbell Art Museum

3.2 The Villa Müller

3.2.1 An overview of the architecture

The Villa Müller was built in 1930 in Prague, designed by the architect Adolf Loos based on the concept "Raumplan" advocated by him. “Raumplan” is a three-dimensional planning method that departs from the traditional method using two-dimensional floor plans. Using this method, the complicated and highly diverse spaces with different ceiling heights and various windows are produced. Another feature of Villa Müller is the use of completely different interior materials in each room. Interconnected continuous spaces and coloured light in the house provide a unique experience to visitors.

3.2.2 Simulation result

Figure 5 (A) shows the positional relationship between the main hall and the dining room where the interior materials are unified with glossy brown wood. Figure 5 (B) shows the result of analysis of photon flow at 11:00am on August 31 in this space. The physical properties of the material used in this analysis was determined with reference to the data measured by ourselves. The photon flow shows the reddish light was produced after daylight reflecting the brown surfaces in the dining room and it tinted white walls and pillars with red, and some of them spread out into the main hall.

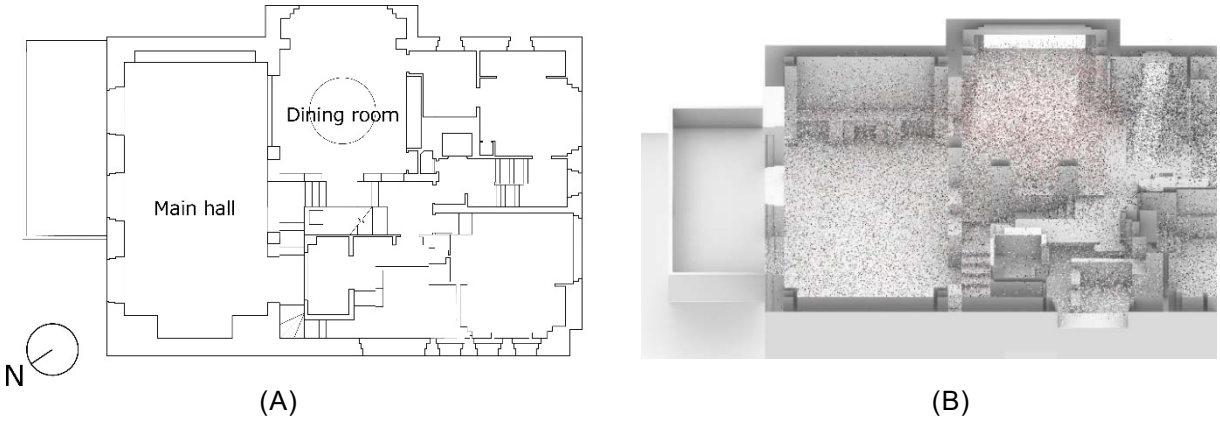


Figure 5 – Drawing and the photon flow inside of the Villa Müller

Figure 6 shows the photograph taken on August 31, 2018 (left) and the photon distribution calculated by Radiance using the proposed method (right). The yellow framed part in (a) and (b) on the photograph has the same reflectance and colour(white), but (b) on the right wall looks reddish due to the colour of light in the dining room. From the photon distribution in Figure 6 (right), it can be read that red-coloured points are gathered around the right wall.

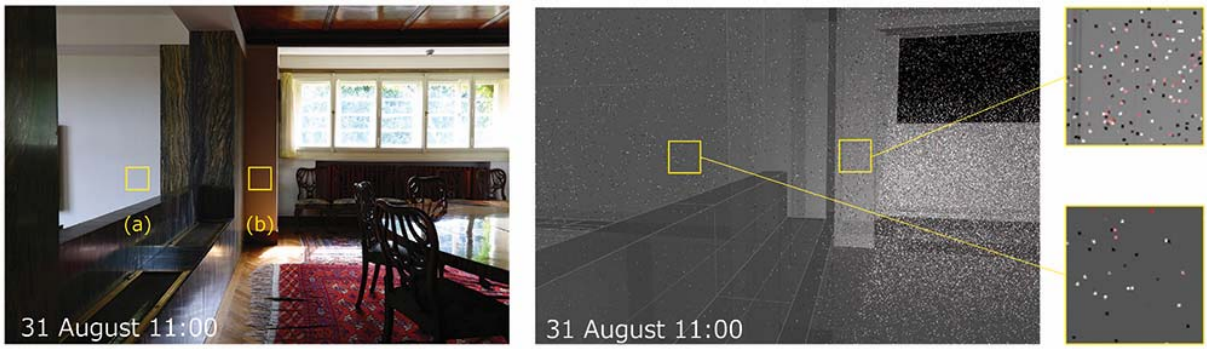


Figure 6 – Comparison of analysis results of photon distribution with actual photograph

4 Conclusion

The new method to depict the coloured light flow using the volume photon mapping algorithm was proposed in this paper. It becomes possible to express the behaviour of the light in the scene in an easy-to-understand way. As shown in the analyses of the Kimbell Art Museum and the Villa Müller, designers can directly grasp the light flow from a complex shaped lighting device and understand the effects of subtle coloured light on the space and objects.

Further improvements are necessary to represent the light intensity from the apparent density of the photon particles. Besides, the relationship between visual light field and this method will be examined in future studies.

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