A STUDY OF DAYLIGHT ENVIRONMENTS WITH SPHERICAL MIRRORS

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Abstract. A spherical mirror has the ability to record all information of the surrounding environment and its map offers an ideal 2D picture to study 3D environments. This paper tries to study the daylight environment by using spherical mirror maps, which can be acquired from photography or computer simulation. Both quantitative and qualitative evaluations of daylight in architecture are discussed and applications of spherical mirror maps in daylight design are proposed.

1. Background

In his paper "On mapping the world in a mirror", Michael Benedikt (1980)studies the reflection of various small and very convex mirrors, which can create images of the whole visual world around themselves. Benedikt discussed the characteristics of several kinds of convex mirrors, analyzed the geometry of the images created by them and proposed that the characteristics of spherical mirror map (SMM) make it an ideal tool to study the environment around it. Benedikt gives the equation of mapping an arbitrary point p(d, φ, θ), onto the coordinate of spherical mirror images p'(ρ, θ). For Figure 1, we have:

$$\phi_{sph} = \arctan\frac{l}{z} + \arcsin\frac{r\sin(\phi/2)}{d}$$

$$= \arctan\frac{l}{z}, \text{ for d » a} \quad (1)$$

$$\phi_{sph} = r\sin(\phi/2); \quad (2)$$

Benedikt points out that SMMs provide an ideal approach to record and analyze the environment in daylight studies because of two characteristics. The first is that SMM has the ability recording all visual information of the environment around it except the area behind the spherical mirror, which will be blocked by the spherical mirror. With the assumption that the size of the spherical mirror is far smaller than the dimension of the environment to be studied, it can be safely ignored. The second characteristic is that SMMs preserve the solid angles of surfaces subtended at the given point.

In daylight studies, the SMMs make it possible to project the three-dimensional space on to a two-dimensional image, which makes our analysis easier to proceed with. A spherical mirror or hemispherical mirror provides a simple but applicable approach to record the environment and a clear basis for a standard mathematical and computational treatment of the maps.

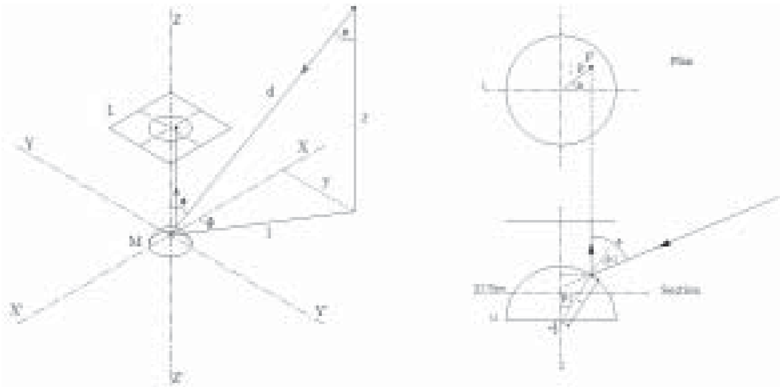

Figure 1. Coordinate system of spherical mirror projection.

2. Acquiring Spherical Mirror Maps

Basically, there are two methods of acquiring SMMs: by photography and by computer simulation. A small stainless steel ball which has perfect roundness works as an ideal spherical mirror. Regular digital cameras and tripods are good enough to take photos of spherical mirror.

Figure 2. SMMs, left: by photography, right: by computer.

Compared to the traditional photography, computer-generated SMMs have obvious advantages. They can be widely used in design process to study a virtual environment. Both the “spherical mirror” and the “camera” can be precisely placed in any desired positions. The SMMs are free of any flaws. To improve the quality of daylight study, a prerequisite of the computer-generated SMMs is that global illumination algorithm such as radiosity or ray-tracing must be used to compute the illumination.

3. Daylight Analysis in SMMs

3.1. SUNLIGHT

Sunlight is an abundant source of light. However, direct summer sunlight is often expected to be excluded from rooms to reduce overheating and visual discomfort. In the winter of cold regions, the presence of direct sunlight in rooms is often welcomed by occupants for its warmth and brightness. Without knowing the position of the sun through days, the shades, louvres and blinds may not take effect in warm regions while windows of rooms in cold regions might not gather enough sunlight and heat SMMs offer an alternative method to study sunlight: projecting sun path on to the SMMs.

Figure 3 shows the sun path projected on the SMMs. To study the sun's position in an architectural space by the maps, a sun-path graph can be generated and overlapped onto SMMs that reflected the space to be studied.

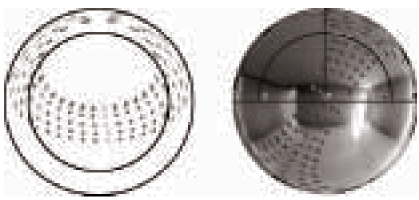

Figure 3. Sun path projected on SMMs.

3.2. SKYLIGHT AVAILABILITY

Excess direct sunshine in the room will cause discomfort both in visual and thermal aspects. The diffused light from the sky is more welcomed by people as the natural source of illumination.

To evaluate the skylight in a space, we use the concept of "apparent sky visibility". In traditional daylight factor method, the ratio of area of windows to the total area of room surfaces can only estimate the average illuminance of skylight. On the other hand, "apparent sky visibility" is a factor presented by solid angle. With SMMs, it is convenient to perform a supplicated study of distribution of skylight in a given space.

Figure 4. Distribution of skylight.

3.3. INDIRECT LIGHT

When we take a photo and digitize it to obtain a two-dimensional array of "brightness" values, these values are rarely true measurements of relative radiance in the scene because the limitation of the brightness range of a raster image and the nonlinear in mapping of photographic process.

Paul and Malik (1997), "Recovering High Dynamic Range Radiance Maps from Photographs" presents a method of recovering high dynamic range radiance maps from photographs taken with conventional imaging equipment. In this method, multiple photographs of the scene are taken with different amounts of exposure. Debevec's algorithm fuses the multiple photographs into a single, high dynamic range radiance map whose pixel values are proportional to the true radiance values in the scene.

Figure 5 is the analysis of HDR information of the whole environment provided by SMMs processed by a Java program. The upper is the horizontal distribution created by adding the brightness of pixels in surround the centre of the SMMs. The bottom of Figure 5 is the vertical distribution of the illumination of spherical mirrors from 0 to π.

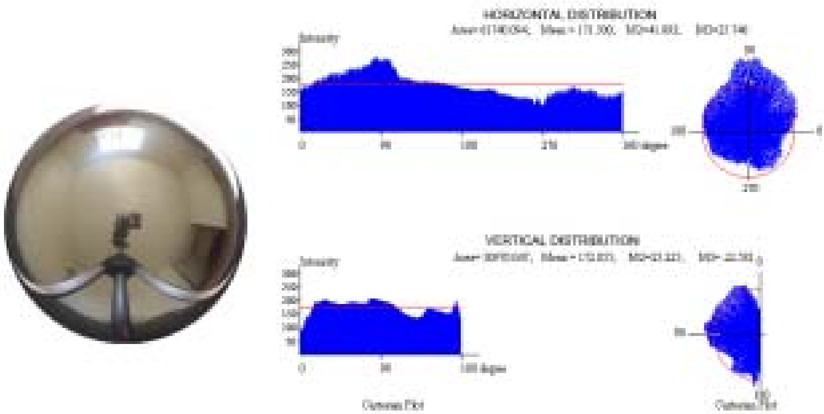

Figure 5. Analysis of illumination in SMM.

Statistic methods are used to analyze the distribution and characteristics of the illumination to perform a qualitative study. The measures of the distribution graphs include:

1. The *area* of the distribution measures the global illumination of the whole environment. A larger area value indicates a higher intensity of illumination.
2. The *mean* value of distribution. Mean value is used to evaluate the subject perception. A higher mean value of distribution indicates that the room appears brighter to the occupants in the point.

The mean value also provides a measure to analyze the character of surfaces. In distribution graphs, the parts beyond the mean value line can be regarded as light sources and parts below the mean value line can be regarded as light receivers. Besides the light from the window and sunlight patch, Figure 5 shows that the reflected light from the ceiling can also act as a light source. The high reflectance of the ceiling makes it reflect light from window and distribute it into the room.

3. The *variance M2*, which is a measure of how spread out a distribution is, is computed as the average squared deviation of each number from its mean.

$$M_2 = \sqrt{\frac{\Sigma(X - M)^2}{n}}; \tag{3}$$

The variance can measure the contrast of illumination in a given environment. A higher value of variance indicates that the environment has sharper contrasts in illumination. On the other hand, a low value of variance indicates that the overall distribution of illumination in the given environment is quite even.

4. The *skewness* of the distribution *M3*

$$M_3 = \sqrt{\frac{\Sigma(X - M)^3}{n}}; \tag{4}$$

Compared to variance, the skewness can have positive value or negative value. A large positive value of *M3* implicates that the light sources in the given environment are concentrated in a small area but provide a high intensity of illumination. On such occasions, the discomfort glare might happen. A negative value of *M3* implicates that a small area might be much darker than other area.

4. Possible Applications of SMMs in Architectural Design

SMMs have versatile applications in dynamic design. These applications are still being studied and developed including typological study of architecture, glare prediction, panorama virtual reality, etc.

4.1. SIMULATION OF DAYLIGHTING ENVIRONMENTS

To simulate an existing daylighting environment in computer model and create photo-realistic computer graphics has been studied by a lot of researchers. Paul Debevec in his paper “Rendering Synthetic Objects into Real Scenes: Bridging Traditional and Image-based Graphics with Global Illumination and High Dynamic Rang Photography”, 1998, proposes a method that uses an HDRI-based model of the scene, rather than synthetic light sources, to illuminate the new objects. However, this approach has several disadvantages. Mapping the photos on to a box cannot restore the precise orientation of those points in the original environment. Moreover, current devices of generating HDRI cannot record very high radiance easily, such as the clear sky and sunlight.

SMMs with HDRI have the ability to offer a simple, efficient and practical process with precise results in those simulations. A virtual sphere mapped by an unwrapped SMM processed by Java program is used to simulate the environmental lighting. Synthetic lights are used to simulate the sunlight and skylight. The results have proved to be precise not only in simulating global illumination, but also in generating shadows and reflections.

Figure 6. Simulation of Daylighting Environment with SMMs.

4.2. DYNAMIC DESIGN WITH SMMS

SMMs provide a simple approach to evaluate the whole 3D environment by 2D images. If one can also make design modification with SMMs, the design and evaluate processes can be performed in the same environment, so that the design or modification will be more efficient and precise. This approach will be beneficial in designing geometric daylight control elements such as windows, openings and shades, etc.

A single SMM cannot reveal the depth of information of its mapped points. If a single point is specified in two SMMs, its 3D position can be found at the intersection of two linear functions in space. The process has been tested successfully in a Java Program. The work in the future is to reduce the error and integrating the process with current CAD software.

References

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