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Optimised Light Source Modelling and Simulation to Match Physical Intensity-Angle Light Profile

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Abstract
One of the key elements in an optical simulation including design and utilisation of a virtual instrument is to optimise the light source model to match the physical intensity-angle light profile. To have such a matched virtual light source model within a Blender environment, multiple spotlight source models with different power parameter values can be utilised at the same point. The overall intensity angle profile corresponding to this light source is then obtained within the Blender environment. A mathematical formulation is proposed to estimate the parameters of each light source such that the overall intensity angle profile match that of the manufacturer's given curve. Results demonstrate that using the proposed approach, it is possible to make the light source model follow the actual intensity-angle light profile given by the light source manufacturer. Inspired by the results obtained in this paper, the proposed light source model will be used within the virtual instrument for a multi-illumination dome system to perform precision simulation within this environment.

Light source modelling, Intensity-angle light profile, virtual instrument, optical simulations

1. Introduction

Reflectance transformation imaging (RTI) is a measurement technique to characterise surface texture through the estimation of surface normal [1]. Some of the applications of the surface normal characteristics are extracting defects in steel [2], wood [3], and liquid crystal displays [4], and texture analysis and documenting for cultural heritages including numismatic material [5]. Relighting is another application of RTI, in which the surface texture under a different lighting condition can be estimated using existing images in a certain lighting condition [6]. A typical RTI setup is composed of a camera and multiple light sources which are turned on sequentially, providing different illumination conditions to estimate the surface normal after applying an estimation technique including least squares [7], robust least squares [8], and polynomial texture mapping [9]. However, it is required to design the light source models such that they match the manufacturer's given characteristics [10].

The four main components of a RTI system include an object, lighting, camera, and environmental conditions. To analyse an RTI system in a virtual environment, test the performance of the estimation process, and perform optimisation, it is required to simulate its elements in the virtual environment. The realism of the images taken in the virtual instrument is therefore dependent upon the accuracy of the virtual components representing the RTI system [11]. In this paper, one of the main components of a virtual instrument, light source characteristic optimisation, is considered. The appearance of an object under different illumination conditions depends on an accurate model of soft shadow, light power, multiple reflections, and light patterns due to refraction or reflection [12]. The virtual instrument is developed in a Blender environment. Blender environment is an open-source, comprehensive and versatile software which benefits from a wide range of optical components. It is further possible to design three-dimensional (3D) components within this environment directly using its mesh capabilities [13] or by importing a mesh from another 3D design software [14, 15]. This software is supported by a community which continuously add objects and features to it [16]. This software benefits from a Python API to import and modify components including changing their parameters, or changing their position, and orientation directly through the API to provide programmable design, and optimisation within the Blender environment [16].

There exist four types of light source models within Blender environment: point light, sun light, spotlight, and area light (as explained in more details in the next section). Each of these light sources benefit from multiple parameters, some of which are specific to the light source model. In this paper, to have a more realistic virtual light to match the intensity angle profile of a physical light source, multiple light sources are utilised. Using multiple light sources, it is possible to define more complicated geometry for a light source than a regular spherical shape one. However, to match the intensity versus angle characteristics of overall light source with a physical light source, an accurate parameter assignment procedure is required.

In this paper, multiple spotlight sources are used simultaneously to match the intensity angle characteristics of a single physical light source. To perform this task, an optimisation process is designed. First the light sources are added to the scene. To estimate the optimal power parameter value for each light source, a mathematical formulation is considered. Solving this mathematical formulation, the best power value for each spotlight source is calculated. Then, by using the estimated power values for the spotlight sources, the intensity angle profile of the combination of all light sources in the virtual environment is measured virtually. It is shown that the characteristics of the combination of the light source are close to that of manufacturer's data.

2. Existing light source models in Blender

There exist four types of light source models within Blender environment: point light, sun light, spotlight, and area light. The details of these light sources, their characteristics, and their parameters are given in this section.

2.1. Point light source

This type of light source is an omnidirectional light source which emits light in all directions. This type of light source is illustrated in Blender environment with the shape given in Fig. 1. The main parameters of a point light source are energy, color, and radius. The corresponding position of point light source can be assigned using the corresponding parameters within Blender environment. The parameter color is a common parameter within all different types of light source and specifies the color of the emitted light.

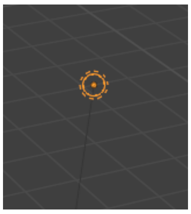

Figure 1. Point light source illustration in Blender

The power parameter is another common parameter for all types of light sources. The power parameter is given in Watts. Negative values can be given for each light source within simulation environment which can cancel the effect of positive light sources. Another common parameter is soft falloff which is used to avoid sharp edges when light geometry intersects with other objects. The radius parameter defines the radius of the sphere from which light is emitted. This value can be equal to zero which indicate a single point light source. If it is larger than zero, sphere is created within the Blender environment for the point light source.

2.2. Sun light source

This type of light source is used to model a light source with a constant intensity emitted from an infinitely far light source. A sun light source is presented by a sun symbol with a line which illustrates the direction of the light.

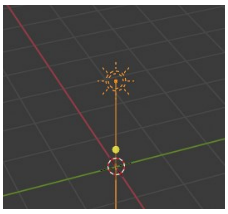

Figure 2. Sun light source illustration in Blender

The parameters of a sun light source are strength and angle. The parameter strength is given in Watts per square meter. The angle parameter is the size of sun light according to its angular diameter as seen from earth. The color parameter is used in a similar way as in point light source.

2.2. Area light source

Area light source is another type of virtual light source which simulates a surface light source such as a TV screen, a neon light source, etc. the shape of the light source can be in the forms of a rectangle, square, disk, and ellipse. Each of these forms have their own 2-dimensional size values. Similar to point light source, and sun light source, this type of light source has color and power parameters. The 3D position of the light source, and its orientation can also be specified within the Blender environment. This type of light is illustrated with its shape in Blender as in Fig. 3 in which two different area light shapes, square and ellipse, are given.

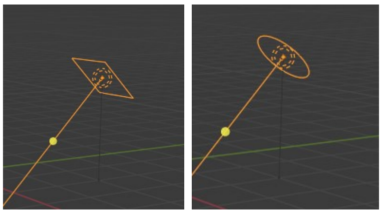

Figure 3. Area light source illustration in Blender

2.4. Spotlight source

Spotlight source is another type of light source which is represented by a cone in the Blender environment (see Fig. 4).

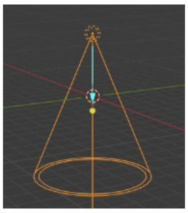

Figure 4. Area light source illustration in Blender

Using spotlight source, it is possible to have a limited light angle for the light source. This feature makes spotlight source a special choice for simulating light sources. The parameters power, radius, and color are among the common parameters of spotlight source which have similar function for spotlight source as for other light sources as well. However, this type of light source benefits from beam shaping features through assigning appropriate parameters to size and blend parameters as well. The parameter size specifies the angle of the cone within which light rays are emitted ranging between 1 degree to 180 degrees. The effect of this parameter within the light beam shape is illustrated in Fig. 5. As can be seen from this figure, the angle of the beam can be easily assigned using this parameter.

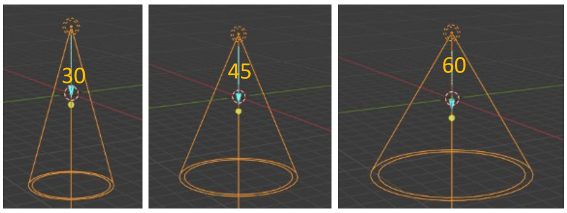

Figure 5. Effect of choosing different size parameters in an area light source

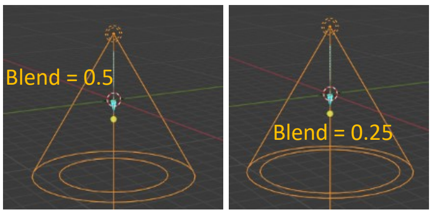

Figure 6. Effect of choosing different blend parameters in an area light source

On the other hand, the parameter blend can accept any value between zero and one and it controls the volume of the inner cone. As can be seen from the Fig. 6, the shape of the inner cone within spotlight source varies as different values are assigned to the parameter blend.

In conclusion, considering the fact that the intensity of the physical light source used in this study is limited, to model the intensity versus angle of the given physical light source, spotlight source is chosen. Multiple spotlight sources are therefore inserted within Blender environment with some initial parameter values (see Fig. 7). A mathematical procedure is then used to estimate the parameter values of all spotlight sources to make the overall intensity versus angle graph follow that of manufacturer given graph. Having an accurate intensity angle model close to that of manufacturer's given one allows high fidelity simulations to be carried out within the virtual instruments.

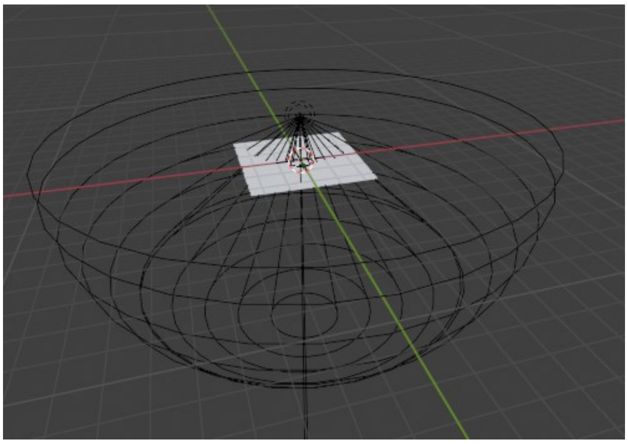

Figure 7. Multiple light sources used to simulate the physical light source

3. Optimisation process

Considering the fact that spotlight source is the only light source available within Blender with limited beam angle, this type of light source is selected to model the physical light. The combination of multiple spotlights with increasing spot size is considered to model the light sources. The spot size values are increased by $2°$ for each individual light source spanning the whole $100°$ matching the manufacturer's given intensity angle profile range. It is therefore desirable for the overall intensity angle curve for the light sources to follow the manufacturer's given intensity angle characteristics. To obtain a match between the two curves, it is required to tune the energy parameter value of each of the light sources.

For this purpose, the intensity versus angle of the overall light combination is formulated mathematically as a function of each spotlight source power. The intensity values of the multiple spotlights which are stacked on top of each other are summed up within their effective region. Therefore, the following set of equations hold.

$$DI(i) = \frac{\sum_{j=i}^{N} Power(j)}{\sum_{j=1}^{N} Power(j)}, i = 1, \ldots, N \qquad (1)$$

where $DI(i), i = 1, \ldots, N$ values are the desired normalised intensity values in an increment of $2°$ given from the manufacturer intensity angle curve. Then the equation (1) is solved for all light power values as follows.

$$Power(j) = Power(N)\frac{DI(i) - DI(i+1)}{DI(N)}, i = 2, \ldots, N$$

$$Power(1) = Power(N)\frac{1 - DI(1)}{DI(N)} \qquad (2)$$

where $Power(N)$ is a free parameter which provides a gain for power values of all light sources within the light source model. Using this parameter the overall brightness of the light source model can be changed. To measure the intensity versus angle characteristics of the light source, the light source is maintained in close range to the surface and a camera perpendicular to the surface on top of the light source is added. Figure 8 illustrates the intensity angle characteristics of combination of the designed light source. As can be seen from the figure, the two curves match each other. The root-mean-squared-error value for the two curves resampled at an interval of $1°$ is 0.0371. Using the obtained parameter values, the images taken to characterise the combination of the light sources within virtual instrument is given in Fig. 9. As can be seen from the figure, for larger angle values, the pixel intensity values become darker.

Remark 1. It is to be noted that (1) needs to be solved twice once for angles less than 90 degrees and another time for angles larger than 90 degrees.

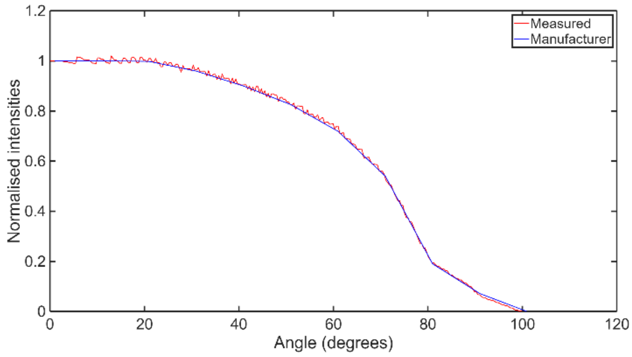

Figure 8. Manufacturer given intensity - angle curve for the physical light source

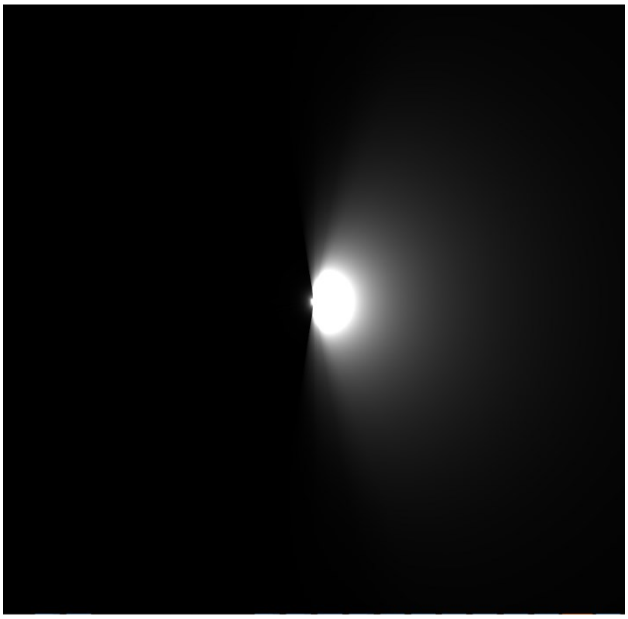

Figure 9. Image taken from the camera within virtual instrument to estimate intensity angle profile of the light source

Remark 2. To have intensity values for angles larger than 90 degrees, a light source is added with its direction opposite the main light source. The spot size for this light source is considered as equal to 180 degrees. Then a light source with negative power and spot size of $180 - 2d$ degrees is added in the same direction to have a light span of d on the opposite direction of the main light source.

4. Conclusions

This paper presents a model for the light sources which benefits from multiple spotlight sources. The intensity angle characteristics for the light source combination is obtained by placing the light source within a close proximity (less than $1mm$ in this simulation) to the surface and adding a camera perpendicular to the surface on top of the light source. To match this characteristic with that of the manufacturer's given characteristics, a mathematical formulation is considered. The mathematical formulation is based on the fact that the normalised intensity values of multiple light sources are added up together and are divided by the maximum intensity in the zero angle. By solving this mathematical formulation, appropriate energy values for each individual spotlight source are obtained. Inspired by the results obtained using the mathematical modelling, in a future paper, optimisation of the light source including more parameters of the spotlight such as size, and blend parameter is considered to improve modelling error. Improving light source model may result in more realistic simulations within a virtual instrument.

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