Real time prototyping of physical lighting based on goniometric light sources

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Abstract

The quality and aesthetic values of computer graphics, to the greatest extent, are determined by the used lighting model. The basic elements of such model are the light sources. Complex lights are rarely used in real-time systems, restricting their differentiation to the ideal diffuse point sources, directional sources and spot lights. In this paper we present a technique which simulates the light sources of any directional characteristics. This type of lights, called goniometric light sources, can represent physical luminaries with the linear or spatial characteristics. The photometric correctness of the luminaire model is provided through the use of HDR images. We present the usage of the goniometric light sources in the real time rendering systems with dynamically changing intensity, colour, and characteristic of the light. We evaluate the possibilities of using this system in the lighting design, taking into consideration limitations of the local lighting model.

1 Introduction

Lighting design is a rapidly growing area of industry which is mainly used in branches such as architecture or entertainment. It involves designing the scene in such a way that the lighting is capable of providing an additional value. Such values may be mood creation, maintenance of efficiently illuminated work environment, exposure of representative areas and concealment of areas which are not representative at all.

For generating realistic images accurate lighting simulation is necessary. However many rendering systems still use simple light models, especially for real-time graphics synthesis. This approach greatly limits the quality of produced images. Simple light sources like point, directional or area lights are idealised simplifications and can not be found in real world. On the other hand, global illumination systems offer much more capabilities. Systems like Radiance support goniometric light sources nowadays. Goniometric light sources could also be found in full-scale modelling software, like Autodesk 3ds Max or Maya.

Lighting simulation systems used in light design are based on global illumination models. Examples include the use of radiosity method in the *Relux* system [1]. However, it is still difficult to find a real-time software which would support the lighting design. The main problem is local lighting model used in such systems, which makes it impossible to calculate the correct lighting. On the other hand, real-time based systems can offer interactive rendering. And the ability to dynamically change the lighting is an essential aspect of efficient and easy lighting designing. Substitute of such solution is the *VIVALDI* model [2] of a plug-in distributed together with *Relux Suite*. In this solution images of light sources, previously generated with the help of a global illumination technique, are saved to HDR (High Dynamic Range) files for further manipulation with image processing and blending methods.

In this paper, we propose the use of a real-time graphics system extended with goniometric light sources support for lighting design purposes. This type of a light source bases upon the description of a specific physical lamp's light emission characteristics. Therefore this lighting system improves the local lighting model, which originally uses only idealised light sources, by adding the complex light sources which are close to the actual emitters. These real-life emitters are called luminaire. The solution certainly does not provide photometric correctness of global illumination renderings, but in many applications the rendering quality will be sufficient.

In our solution the light source characteristics data is read from industrial standard files IES-LM63-95 (see Sect. 3). The data from the files are converted to Light Distribution Textures [13]. And finally the values from these textures are applied to object fragments by shader programs. We also provide the ability to change the intensity and colour temperature of subsequent luminaires.

In Sect. 2 we describe the basic concepts associated with light models used in real-time computer graphics, extended by goniometric models. We also describe the principal ideas of lighting design. In Sect. 3 the rendering process using physical light source characteristics derived from Light Distribution Textures is presented. The 4 section contains various LDT use case renderings and performance considerations.

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2 Background and related work

Light source characteristics have a decisive influence on the photometric and perceptual correctness of a rendered scene. The use of lighting models which are close to the actual physical lighting improves the quality of the rendering and allows the use of synthesis methods for physical stage lighting simulation [12].

2.1 Light sources used in real-time computer graphics

In computer graphics four types of light sources are commonly used. These are point lights, directional lights, area lights and spotlights. Point lights emit light uniformly in all directions. It is the simplest light source to be used, and could be compared to an ideal light bulb. A *point light* is represented by an infinitely small light source, which has a certain position in space. Point lights are mainly used to simulate light sources such as lamps, ceiling lights or street lights. A *spotlight* simulates light radiating from an infinitely small point, like point light. The difference between these light sources is direction, in which the light is emitted. In spotlights, light direction is limited by a spotlight cone of illumination, and has a defined focus direction. Spotlights can also be controlled by a drop-off angle determining softness of the cone's edge. These light sources are mainly used in computer graphics, because of large control and adjustments abilities. Spot light could be used for simulating light sources as desk lamps, torches and scene lamps. Point lights and spot lights are local light sources and are usually placed close to the observer. These light sources are also affected by attenuation. A *directional light* is sometimes called an infinite light, because this light source is assumed to be at an infinite distance from the scene. According to this assumption, objects are illuminated by parallel rays, approaching each fragment of the scene at the same angle. This direction vector can be precomputed for each light source. This leads to the improvement in rendering performance by decreasing the amount of computations at a single vertex. Directional lights are mainly used to simulate very distant light sources such as the Sun. An *area light* source is described by a two-dimensional shape, such as a rectangle or disc, simulating the luminaire's spatial characteristics. One of the main advantages of this approach is the ability to scale light source area, which leads to the decrease or increase of its illumination. Larger areas also improve the quality of generated soft shadows. Area light sources are usually simulated by large amount of point light sources, or by using rough approximations such as *PCSS* [7]. The usage of area lights leads to large computational overhead, but turns out to provide a very good quality of rendered images.

Simple light sources used in scan line methods are not sufficient to provide realistic results, therefore we are providing a sufficient method of generating goniometric light sources.

2.2 Goniometric light sources

Photometric distribution of luminaire might be expressed as *goniometric data* - quantised light intensity function of the vertical angle [4]. The three-dimensional diagram extension, called the *photometric solid*, expands function dependency to a second parameter - horizontal angle [14]. A typical photometric file contains intensity values in many different directions, which means it is perfect to provide data to simulate realistic light sources.

There are a few standards of photometric data storage, like ELUMDAT or IESNA. The format which we are using in this paper is IES-LM63-95, proposed by the Illuminating Engineering Society of North America (IESNA) [6]. IES-LM63-95 file provides data as candela values for vertical and horizontal angles, ballast and multiplying factors or input watts. The IES file is *de facto* an industry standard in North America, and it is also widely used in Europe. Photometric file data is used in many industry areas as lighting designing for architectural purposes. It allows calculations to be made on how many luminaries are needed to achieve the desired illumination in a specific installation.

2.3 Lighting design

Real world scenes are illuminated by *lamps*. There are many types of lamps, e.g. incandescent-filament, gaseous discharge, and mercury blended light lamps. The physical equipment which contains the lamp is called a *luminaire*. It controls the light emitted by a light source, protects the source from mechanical damage, and provides a fixture of appearance. The light distribution from a luminaire can be presented in polar coordinates.

In architecture lighting, the design phase takes place at the stage of room designing [11]. Through this process the investor can get a room which is illuminated exactly in the correct and expected way. Light fixtures are selected driven by lighting project before room realisation work starts. Total light amount which reaches specific place is well known, not random, and therefore can be suited to specific norms and expectations. Entertainment industry is another very popular branch which uses lighting design. Effect of light designers work can be seen on theatre stages, music concerts and art or corporative presentations.

The lighting design is driven mostly by two forces: lighting quality and energy efficiency [5]. To provide advanced, high quality projects three aspects have to be considered: what to illuminate, how to illuminate and what to illuminate it with. Deciding what to illuminate can be considered in the context of task, accent and ambient lighting. Key elements of the second aspect are where to place the luminaires, and how many luminaries have to be used in the specific application. The third aspect covers determining specific light sources which are best for each aspect of the project. At this step desired light distribution, colour appearance and rendering, as well as maintenance costs, are considered.

To provide realistic projects, simulation has to be done. In non-real time issues, global illumination methods such as Radiosity are commonly used [3, 8]. These methods generally have high rendering times and are hard to use in the real time applications.

3 Goniometric light sources for real-time lighting design

In this section we describe the use of physical light source models in real-time based rendering systems.

3.1 Light distribution textures

Light distribution texture (LDT) [13] is a high dynamic range texture which stores the light distribution of a luminaire. It stores pixels in RGBE image format [9] - as one byte each for red, green, and blue values with a one byte shared exponent - so that the pixel values have the extended range and precision of floating point values. The intensity of light is read from a photometric file (from IES-LM63-95 files in our case) and mapped onto such a texture using two-dimensional polar coordinates.

In IES-LM63-95 the photometric data are given as series of candela measurements in polar coordinate system. LDT stores normalised candela values as pixel intensity to provide control of intensity outside the image. The vertical angles are defined along the radius from 0 - centre of texture, to 180 - the border. The horizontal angle is represented by azimuthal angle. Candela values are normalised to provide control of the intensity. A different approach to LDT parametrisation is also described in [13].

In Fig. 1 the LDT and goniometric diagram corresponding to the same data stored in a photometric file are presented. Content of this file is included in Appendix. The data stored in the IES-LM63-95 files depict only the intensity of light, so it could be converted to a single channel texture. However, it is possible to create colourful LDT, which may represent luminaires generating light with specific patterns. In this case, all texture channels will be used.

3.2 Light temperature

The colour temperature of a light source is the temperature of an ideal black body radiator that emits light of a comparable hue to that of the light source. Cooler light is used to improve concentration at the corporative buildings, while warmer is often used to provide homely mood in flats and apartments.

Our solution allows the ability to change the colour temperature of the light source by multiplying light intensity derived from LDT by the values corresponding to individual white points.

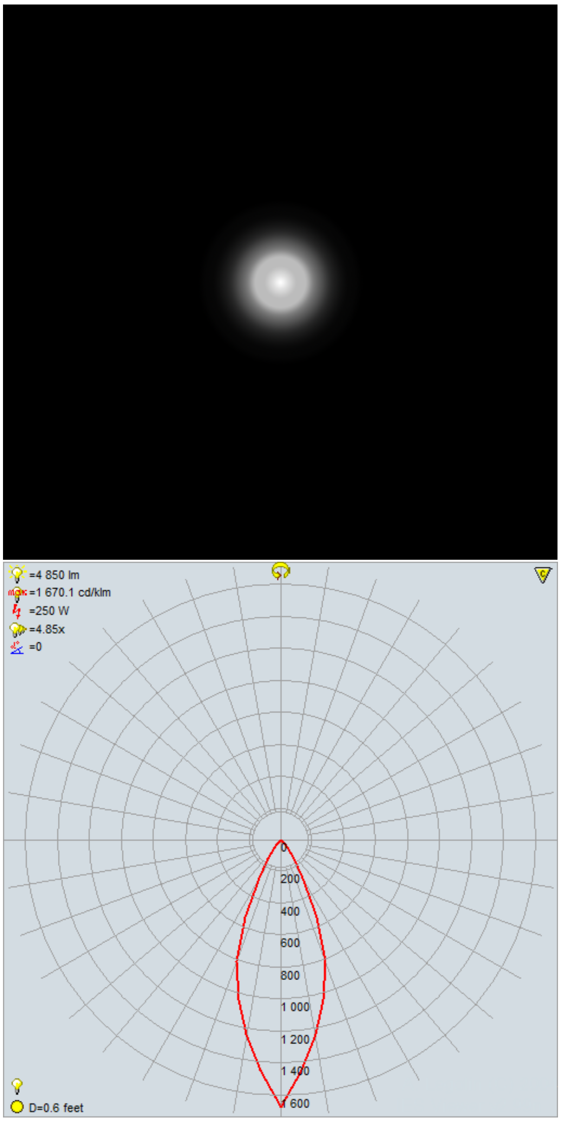

Figure 1: IES-LM63-95 based Light Distribution Texture and photometric diagram (250W frost downlight Kurt Versen T-4 FR MC).

3.3 Rendering

In Fig. 2 the processing pipeline in our real-time renderer with the goniometric light sources is presented.

First of all, the Light Distribution Texture must be created. Through the HDR image storage, this process can be done programmatically by mapping photometric values onto the image, or by simply painting the luminaire shape and intensity in graphics editing software such as Adobe Photoshop. This is a great advantage for prototyping lighting design. Secondly LDT must be loaded into an OpenGL texture object and passed to the fragment shader. While evaluating the lighting equation, the constant light intensity is multiplied by sampled light intensity read from the LDT. For dynamic colour temperature control each component must be additionally multiplied by a colour tem-

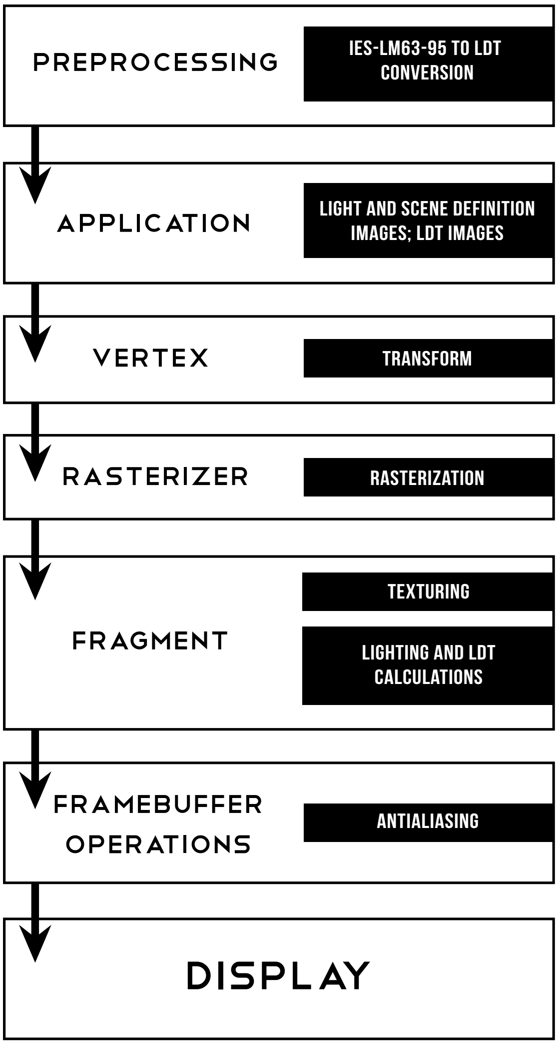

Figure 2: The rendering pipeline.

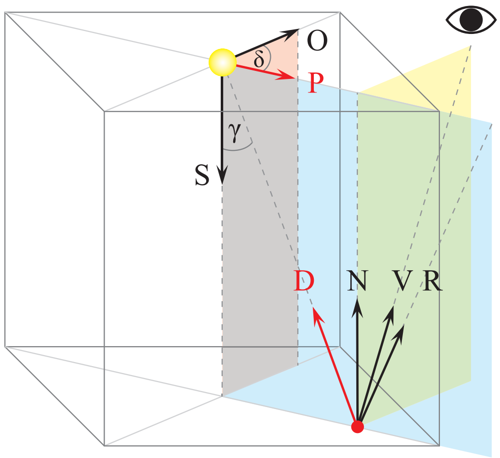

Figure 3: Texture mapping.

perature coefficient.

To orientate the light source in the three-dimensional space we provide an additional vector $\mathbf{O}_m$ (see Fig. 3) besides standard spot light direction vector $\mathbf{S}_m$. This vector $\mathbf{O}_m$ combined with spot direction $\mathbf{S}_m$ defines the plane onto which the horizontal angle γ is mapped. The vertical angle is defined as angle δ between the plane and spot direction vector $\mathbf{S}_m$ reduced by a 45 degree angle.

Data from the LDT are used as an extension of Phong shading:

$$I_p = \frac{k_a i_a + \sum_{m \in \text{lights}} (i_t k_d (\mathbf{D}_m \cdot \mathbf{N}) i_{m,d} + i_t k_s (\mathbf{R}_m \cdot \mathbf{V})^{\alpha} i_{m,s})}{d^2}. \tag{1}$$

Each light source intensity is defined as diffuse i_d and specular i_s component. The ambient lighting is defined as single ambient i_a component. Materials are defined using ambient k_a, diffuse k_d and specular k_s reflection constant. Each material has also the shininess α constant. $\mathbf{D}_m$ is the direction vector from point being calculated to the light source position. $\mathbf{R}_m$ is reflected direction vector at the calculated surface point. $\mathbf{V}$ is the view vector from calculated point to the viewer. Finally $\mathbf{N}$ is the normal at this point.

We extend this model by adding the light distribution multiplier $i_t(s_m, t_m)$ obtained from LDT by sampling this texture using texture coordinates:

$$s_m = \frac{(\mathbf{P}_m \cdot \mathbf{O}_m)\frac{arccos(-\mathbf{D}_m \cdot \mathbf{S}_m)}{\pi} + 1}{2}, \tag{2}$$
$$t_m = \frac{\| \mathbf{P}_m \times \mathbf{O}_m \| \frac{arccos(-\mathbf{D}_m \cdot \mathbf{S}_m)}{\pi} + 1}{2}.$$

To access the light intensity from LDT one has to calculate the coordinates for a given direction vector $\mathbf{D}_m$. To calculate the coordinates it is necessary to retrieve vertical and horizontal angle first. The vertical angle is the angle between spot direction $\mathbf{S}_m$ and direction vector $\mathbf{D}_m$. The horizontal angle is the angle between additional light orientation vector $\mathbf{O}_m$ and the direction vector mapped onto luminaire plane $\mathbf{P}_m$.

The last step in the rendering pipeline is multiplication by inverse square of distance $\mathbf{d}$ between light source position and current shading point position, according to the Inverse Square Law. The resulting image is rendered to the floating point frame buffer to provide high dynamic range quality.

4 Results

In this section the images rendered using our method are presented. We compare the results to the images obtained using standard lighting used in real-time computer graphics. Example 3D scenes of a room and a car are used to simulate typical tasks of the lighting design. We show renderings for different physical light sources, the capabilities of dynamic modification of luminaire parameters and the light temperature. Finally we discuss the impact of the goniometric light sources on the rendering performance.

Point vs. goniometric light sources

The typical Phong shading for a point light describes the light reflection as a combination of the diffusion factor of rough surfaces and the specular reflection factor of shiny surfaces. In this model we can change the scene appearance by providing different light and material parameters such as ambient, diffuse and specular components. Final result varies on these parameters, vertex normal and location relative to the light source and the observer's eye. Through the use of LDT we can enhance the control of dependency between a light source and the material parameters by introducing an additional variable - the light intensity. As a result, generated image becomes more close to the real scene. In this approach the use of a large amount of light sources is not necessary. In Fig. 4 the results for eight light sources are presented.

Figure 4: Typical point light model (top) and rendering based on goniometric light sources (bottom).

Colour temperature

Figure 5 presents images of the same scene, rendered with the same LDT but with different colour temperatures. The system allows changing the colour temperature interactively and individually for each luminaire.

LDT for physical light sources

Figure 6 presents images of the same scene, rendered with different light characteristics.

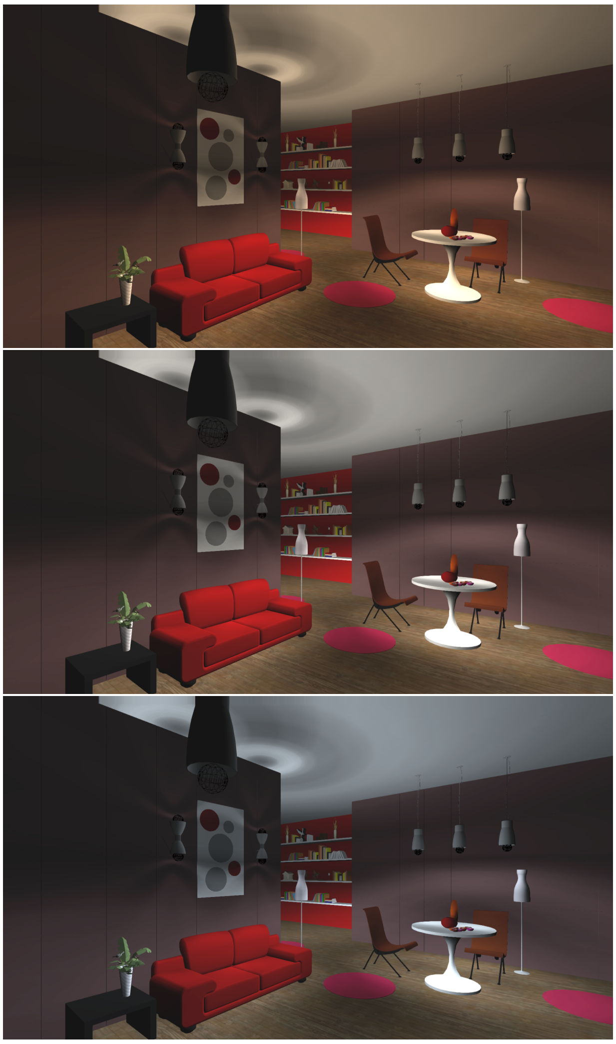

Figure 5: The same LDT with various colour temperatures (respectively from top to bottom image: 2850 K, 6000 K, 7000 K).

Dynamic lighting

Through the fast scan line real-time rendering process the designer gains the ability to move, rotate, turn on and off specific light sources, change their colour temperature, or even replace whole light sources intensity distribution function by simply replacing the LDT. In Fig. 7, the top image presents the reference rendering. Fig. 7 presents the ability to turn on and off individual lights.

Performance

Performance of this model is very close to the point lights rendered with Phong shading. The only additional overheads are the computation of texture coordinates and the LDT texture lookup. For the sample scene containing 103379 triangles the frame rate is 56 frames per second for point lights and 50 frames per second for our approach. The test was conducted with ATI Mobility Radeon HD

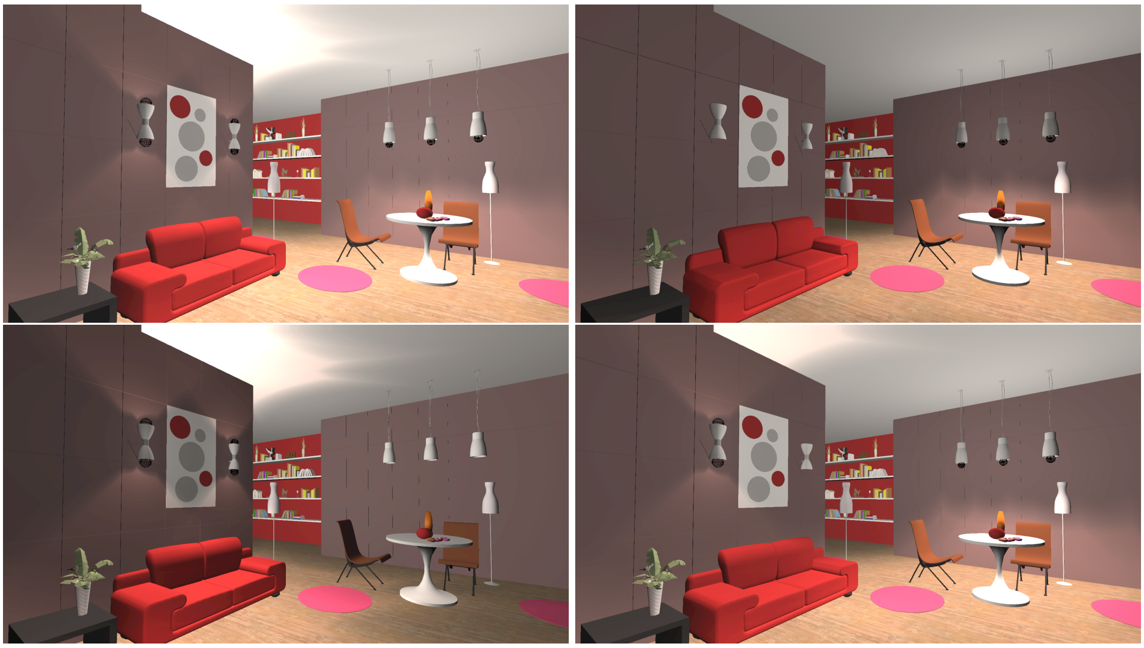

Figure 7: Each light source can be switched on or off dynamically. In the upper left image all light sources are switched on. In the upper right image all lights above the sofa are switched off. In the bottom left image all lights above the table are switched off. In the bottom right image the rightmost light above the sofa is switched off.

4670 graphics card, Intel Core2 Duo T6600 2.20 GHz processor and Hyundai DDR3-1066 4096 MB RAM memory.

One of the factors influencing the rendering quality is the chosen filtering function. Through the use of texture filtering, missing photometric values can be interpolated. In this work we are using bilinear filtering, which is appropriate for most practical applications. Small number of samples, as well as the irregularity of the distribution may cause too large generalisations and distortions in the results (see Fig. 8).

5 Conclusions and future work

We presented a method which allows the use of a real-time based system for lighting design purposes. We introduced the goniometric light sources represented by LDT textures for extending standard lighting model. These light sources allowed us to generate visual results which are closer to the reality.

While designing the texture sampling formula we took into consideration the ease of creating new Light Distribution Textures. Through this approach, fast light distribution prototyping is possible and could be made by generating textures containing photometric values in a simple and easy way with the help of common graphics processing software. Colour temperature can be derived from the LDT, as well as can be provided directly to the fragment shader. The only computational overhead comparing to traditional lighting models, is the calculation of texture coordinates and the actual LDT texture lookup. Therefore, this method can be successfully used in real-time systems. Future applications can include interactive real-time renderers with luminaire selection decision support system based on the search for the most similar image to the user-prepared LDT in a luminaire database.

Due to the use of a local illumination model, the proposed solution does not generate correct results in the terms of photometric correctness. It would be an interesting project of developing a system for lighting design based on a real-time global illumination renderer, for example using the OptiX library [10].

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Appendix

Radiometry and photometry of the light sources

Visible light is an electromagnetic wave which wavelength is in a very narrow band of the whole spectrum. The wavelength for visible light spans from about 380 nanometers to about 740 nm, which is between the invisible infrared and invisible ultraviolet. These wavelengths are visible to human eye and are responsible for the sense of sight.

Figure 6: Renderings for different LDTs (shown in bottom right corner).

Light sources with shorter wavelengths and higher frequencies have a higher energy than those with longer wavelengths. Although it is possible to limit the band to a specific range by the usage of special sources or filters. Lights with short band have a single colour and are called monochromatic.

The science of measuring light is called photometry. Light can be measured in many ways. The rate at which the light energy flows from the source is called the luminous flux. It is measured in lumens which represent the energy per second. While it has the same dimension as watt unit, it is incorrect to convert photometric values to energy quantities, because radiant energy depends on its wavelength.

The brightness of a source is measured in candelas, the unit of luminous intensity. Candela is the light energy distributed in one steradian.

For measuring the result of illumination on the illuminated surface, the illuminance term was introduced. It is luminous flux falling on a unit area of the surface.

Figure 8: Images rendered with 2048x2048 pixels (top) and 128x128 pixels (bottom) LDTs.

The luminance of an illuminated surface in a given direction is defined as luminous intensity per unit area coming from the surface in the particular direction.

The relation between luminous intensity and illumination is known as the Inverse Square Law of illumination. The light illuminance is inversely proportional to the square of the distance between the light source and the measured point. This law can be extended to the Lambert Cosine Rule - the illumination of the surface also depends on the cosine between the light source and the point.

IES-LM63-95 file format

The file format specification for the IES-LM-63-1995 photometric file format variant:

```
Id Description
00 IESNA:LM-63-1995
01 {Keyword 1}
02 {Keyword 2}
03 ...
04 {Keyword n}
05 TILT={file-spec} or {INCLUDE} or ...
05 {NONE}
06 {lamp-to-luminaire geometry}
07 {# of pairs of angles ...
07 and multiplying factors}
08 {angles}
09 {multiplying factors}
10 {# of lamps} {lumens per lamp} ...
10 {candela multiplier} ...
10 {# of vertical angles} ...
10 {# of horizontal angles} ...
10 {photometric type} {units type} ...
```

```
10 {width} {length} {height}
11 {ballast factor} {future use} {input watts}
12 {vertical angles}
13 {horizontal angles}
14 {candela values for all vertical ...
14 angles at first horizontal angle}
15 {candela values for all vertical ...
15 angles at second horizontal angle}
16 ..
17 {candela values for all vertical  ...
17 angles at nth horizontal angle}
```

Example IES-LM-63-1995 file:

```
IESNA:LM-63-1995
[TEST]2863-B
[MANUFAC]KURT VERSEN
[LUMCAT]C7394
[LUMINAIRE]DOWNLIGHT
[LAMPCAT]T-4 FR MC
[LAMP] 250W FROST
TILT=NONE
1 4850 1 19 1 1 1 -.6 0.00 0
1 1 250
0 5 10 15 20 25 30 35 40 45 ...
50 55 60 65 70 75 80 85 90
0
8100 6998 5999 4995 3938 2574 ...
1328 698 306 189 54 5 0 0 0 0 0 0 0
```

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