ABSTRACT

This paper demonstrates an image-based lighting analysis procedure and tool called Virtual Lighting Laboratory. Virtual Lighting Laboratory is a computer environment, where the user has been provided with matrices of illuminance and luminance values extracted from high dynamic range digital images. The discussions mainly refer to the flexibility of capabilities within a virtual laboratory environment to handle various lighting design and analysis problems. Conception and utilization of virtual lighting meters and per-pixel lighting analyses are demonstrated through architectural examples.

IMAGE GENERATION AND ANALYSIS

It is crucial to generate digital images with reasonably accurate photometric data in absolute values and physical units. Physical accuracy in lighting context depends on plausible modeling of light sources, light transportation, and light reflections. It is important to note that every simulation is a simplification. Validation studies should be referred to assess the accuracy of the rendering algorithms.

The physical units of photometric data are HDR quantities. The dynamic range of luminance values from starlight to sunlight extends to 14 logarithmic units (Ferwerda et al., 1996). Rendering software internally use floating-point representations for these quantities. However, the storage of floating point numbers is not very feasible. Therefore, the data is usually clipped into 24 bit/pixel integer values, which allows a dynamic range of about 2 logarithmic units. This solution is efficient in terms of disk space, but the lost information is irrecoverable in terms of extracting absolute photometric information and performing operations outside the dynamic range of the stored values. RGBE and SGI Logluv are two image formats that enable the storage of HDR quantities (Ward, 1991; Ward, 1997).

RGB is often used as the basis of color computation in computer graphics. Basically, RGB combinations are metamers in virtual environment for the spectral power curves of light in real world. The rendering software internally defines the CIE chromaticity coordinates of the RGB values. CIE XYZ data for each pixel can be quantified from RGB through a series of conversions that involve the sampling of the spectral curve using the CIE 1931 (2° observer) color matching functions (Hall, 1989; Hall, 1999). Operations such as gamma correction and exposure that might alter the stored pixel values should be
reversed before CIE XYZ conversion. CIE Y is the luminance value in cd/m².

VIRTUAL LIGHTING LABORATORY
Through the application of the guidelines listed above, digital images can be utilized as lighting laboratory settings. VLL is a computer environment, where the user has been provided with matrices of illuminance and luminance values extracted from HDR images (Figure 1). The underlying idea is to provide the ‘laboratory’ to the designer/researcher to explore various lighting analysis techniques instead of imposing limited number of predetermined metrics.

The images utilized in this paper are generated with Radiance (http://radsite.lbl.gov/radiance/home.html), which is a physically based lighting simulation and visualization software. Radiance images are composed of HDR pixel values that correspond to the physical quantity of radiance. The RGB color space is computed from the radiance value in three channels as floating point numbers and stored in RGBE format. RGB value of (1,1,1) is equal to a total energy of 1 watt/steradian/m² over the visible spectrum. Since the standard luminous efficacy of equal-energy white light is 179 lumens/watt, 1 watt/steradian/m² is equal to a photopic luminance of 179 cd/m² (Ward and Shakespeare, 1997).

LIGHTING ANALYSIS
Mathematical operations and statistical analysis can be performed with the computed quantities. Per-pixel lighting data is invaluable information for analysis, but it might also be an extensive amount of knowledge to process. The rest of the paper provides a general span of the architectural lighting analysis capabilities and procedures within the VLL.

PIXEL ANALYSIS
The first example is an office building located in Ann Arbor, Michigan. The base case has a south facing clear window (Figure 2). Within a generic scenario, three visual tasks have been specified for optimum performance:

- The first task involves computer; such as reading a text displayed on the screen and recognition of letters on the keyboard;
- The second task is reading a text on a document placed at a normal reading distance close to the computer;
- Thirdly, outside is the source of attraction, where the occupant will be looking at frequently.

The exact position of the occupant is important for lighting analysis, since the focus is mostly on the amount of light reaching the eye. It is useful to generate hemispherical fisheye images from the view of the occupant. A hemispherical fisheye is a half sphere projected on a 2D plane such that each differential area corresponds to the product of original area and the cosine of polar angle. Subsequently, illuminance is equal to the product of π and the uniform sampling of luminance over the projected hemisphere (Ward and Shakespeare, 1997). Moreover, hemispherical fisheye projections cover the total human vision with view angles that can be as wide as 180° vertically and horizontally.

Figure 2 The office space used as an example in VLL

Figures 3.a-c are generated from occupant’s point of view while performing the visual tasks. They are used to study the characteristics of light that reach the eye. The next two images, pc-view and paper-view, (Figures 3.d-e) demonstrate the volume seen by the illuminance meter, if physical measurements were to be taken. Four more images (Figures 3.f-i) are generated to simulate vertical illuminance meter on paper for four cardinal orientations. These images (Figures 3d-i) are used to study the characteristics of the light on the tasks. The amount of light reaching the eye or tasks can be derived from these images.

Figure 4 shows the illuminance values for December 21, 9:00 a.m. The dynamics of the amount of the illuminance reaching the eye is also studied throughout the day (Dec 21) when the occupant is performing the visual tasks (Figure 5).
In lighting practice, it is common to compare luminance ratios on task and certain architectural elements such as wall, ceiling, surround and etc (CIE, 1986; IESNA, 2000). The scene in Figure 6 is decomposed into elements. The computer screen and paper has two parts; black and white representing the text and background, respectively. The other elements identified in this image are the wall behind the task, table, and the window. Minimum, maximum, and mean luminance values, luminance range and ratios are identified. The variations can be studied within one element or between the elements and surrounding.

Luminance contrast is calculated for the paper and screen. Contrast on screen is the quotient of the background to foreground luminance (B&K, 1984). Contrast on paper is the quotient of the difference between foreground and background luminance values and the background luminance (IESNA, 2000). Figure 7 shows the dynamics of the screen and paper contrast throughout the day.
As an extension of the study, the scene is dissected into the specific regions of the visual field, i.e., foveal, binocular, and peripheral vision (Figure 8). The total human vision is 180° horizontally and 130° vertically. The central 120° forms the combined binocular vision, which is the overlap of two monocular fields. Fovea is the central 2° visual field on visual axis (IESNA, 2000).

The response to light is not the same over the human retina. The photoreceptors, rods and cones, are unevenly. Cones are concentrated on the fovea. Rods rapidly peak outside the fovea, but then they decrease towards far periphery. Rods and cones have different spectral and absolute sensitivities to light. Rods reach peak spectral sensitivity at approximately 505 nm whereas cones peak at approximately 555 nm (IESNA, 2000).
Photopic luminous efficiency function pertains to cone vision and luminance levels higher than 3 cd/m². Scotopic luminous efficiency function applies to rod vision, and luminance levels between $10^{-5}$ and $10^{-3}$ cd/m² (IESNA, 2000). Study of the photopic and scotopic variations within the field of view in relation to the placement and number of photoreceptors in the human eye might be helpful for better understanding of vision and adaptation. Figure 9 shows the luminance differences in different parts of the visual field when the occupant is looking at different tasks. These images allow studying the luminance transition occurring when the user switches among different visual tasks.

Design decision-making requires adequate information, performance evaluation criteria, and systematic comparison. The impact of each design choice can be studied in VLL in many different ways. Computed quantities can be utilized in various luminous environment indicators such as illuminance and luminance distribution, luminance contrast, glare indices, contrast sensitivity, visual acuity, and visibility on threshold and supra-threshold lighting levels.

Figure 10 illustrates the office space for the same date and time with three different window systems: clear glass without any light control device, fritted glass, and clear glass with horizontal blinds. Different design decisions affect the average luminance in the total field of vision (Figure 11). Clearly, the excessive brightness of the clear window is reduced by fritted glass and horizontal blinds. Figure 12 is used to study the contrast variation on the computer screen. Contrast on the screen is calculated as the quotient of the background to foreground luminance (B&K, 1984). Therefore, lower value indicates higher contrast.

It is important to note that the examples demonstrated here are chosen to provide a general span of the capabilities and procedures within the VLL to establish its flexibility. Therefore, they are illustrated with a singled out sky condition and/or time. Obviously, actual analysis and design decision making processes would require assessing different sky conditions and different times of the day/year.

VIRTUAL METERS
Virtual meters are built within VLL for conducting complex lighting studies. Contrast Rendering Factor (CRF) analysis is used to exemplify two virtual meters: contrast meter and integrating sphere.
CRF is an index to study the effects of veiling reflections in reducing task contrast. Task contrast is measured by the contrast meter and calculated by comparing the contrast in the setting with the contrast in a reference environment, i.e. isotropic conditions of an integrating sphere (IESNA, 2000).

Researchers have studied CRF through full-scale photometric measurements (Siminovitch et al., 1992; Siminovitch, 1993). Various lighting and furniture configurations have been used to determine the luminance contrast variation on the task plane as a function of luminaire position. The task station is composed of a table and full-scale body shadow profile. This station is positioned relative to a single fixture mounted on the ceiling and 11 different source-task geometries have been obtained by moving the task station relative to the luminaire. For each fixture position, measurements have been done by an adjustable Breul & Kjaer (B&K) luminance contrast meter. Additionally, horizontal and vertical illuminance values have been measured for determining contrast potential (CP). CP is defined as the quotient of the difference between the horizontal and vertical illuminance measurements and horizontal illuminance. CRF and CP values are analyzed to identify effective task-source geometry.

This study has been replicated in VLL (Figure 13). Surface geometries, materials, light source, body shadow profile, and the contrast meter are modeled. The virtual contrast meter mimics the physical one: It consists of black and white surfaces, representing the task and background. The entire surface is coated with a glass layer to allow specular reflections. The camera, corresponding to the user eye, is tilted to obtain 25° viewing angle on the task plane, which is the CIE recommendation (CIE, 1986). The simulation is repeated for all the different fixture positions.

Figures 13 a-c illustrate the veiling reflections from occupant’s point of view. In Figure 13.a, the glass layer is totally washed by the light so it is not possible to see the black and white circles under the glass. If the task were a glossy magazine, it would not be possible to read the text. In Figure 13.b, there are some veiling reflections. Visibility is totally restored in Figure 13.c.
In general, forward positioning of the luminaire relative to the viewer reduces luminance contrast by causing veiling reflections (Siminovitch et al., 1992; Siminovitch, 1993). The results indicate that similar dynamics has been obtained using the physical and virtual measurements in terms of identifying effective source-task geometries (Figure 14). The advantages of VLL over full-scale models can be listed as follows:

- It does not require physical space and expensive equipments;
- It does not require laborious measurements, especially to map the contrast variation across the table, because it is possible to achieve several measurements from one rendering;
- The measurements are free from operator, who could screen off the parts of the environment during measurements.

Figure 14 CRF and CP variation with respect to source position in physical and virtual environments

Integrating sphere is a hollow sphere coated with a diffusing material with uniform nonselective reflectance. It creates an isotropic luminous environment that is universally used for lighting measurements (IESNA, 2000; Walsh, 1958). The virtual integrating sphere is created in VLL as the reference environment for CRF calculations. The surfaces are modeled as lambertian emitters with a luminance of 100 cd/m².

Having a virtual integrating sphere turns out to be a very rational approach not only economically but also theoretically:
- Integrating spheres are expensive equipment and they are available only in some national laboratories and few research universities.
- While high reflectance diffuse materials are used for sphere interiors, no material / coating in real life exhibits the ideal properties of perfect diffusivity and spectral nonselectivity (Walsh, 1958). Simulating the perfectly diffuse materials is one of the most powerful features of the current computer graphics algorithms.

- There are practical problems associated with the physical integrating spheres. For instance, sphere has to be perfectly empty in order not to interfere with the reflected flux distribution by the presence of objects within the sphere. However, physical requirements, such as the existence of a light source, necessary shields and baffles, and aperture in the sphere wall for the measurement purposes, are violation of this condition to a certain extent (Walsh, 1958). In virtual integrating sphere, neither cause disturbance. The walls are constructed as self emitted, so there is no visible light source. There is no need for an aperture for the measuring equipment. There is no need to worry about accessories such as tools to hold sample material, since gravity is not an issue in virtual integrating sphere.
- The size of the virtual integrating sphere can be easily determined, whereas the size of a physical integrating sphere is fixed. The initial cost of the physical integrating sphere grows significantly with the size; and adequate physical space is need.

REMARKS
Advanced lighting analysis requires substantial amount of information, which is cumbersome and expensive to achieve through physical measurements. The resolution of the information through physical measurements is usually limited by the number and type of the equipment available. The measurement grid may be too coarse to do thorough analysis. Physical measurements are restricted to the existing buildings and full / scale models. More importantly, feasible methods of measuring some of the lighting indicators have not been developed outside laboratory conditions. Therefore, these indicators are inaccessible to majority of the lighting professionals.

Physically based rendering tools generate high quality images that embeds enormous amount of visual and numeric information in a very fine resolution. However, the displayed images have limited dynamic range that hampers the reliable display of the computed data. Most of the current software provides false color images and iso-contour lines to overcome this shortcoming. More informative solution is to extract the lighting data from the images.

This paper demonstrates an image-based lighting analysis procedure / tool. It proposes transformations in utilization of digital technology in architectural lighting research. The strength of VLL is derived by the high-resolution lighting information that originates from a flexible laboratory environment, where the user possesses high control and manipulative power over a variety...
of data including geometric, photometric, climatic, and material properties.

VLL can incorporate various virtual laboratory equipments depending on the capabilities, restrictions, and assumptions of the algorithms. Virtual meters can substitute expensive physical lighting equipment with virtual ones and support the transformation of complex indices from laboratory environments to real architectural applications.

The examples given in this paper refer to utilization of this data in available lighting indices and indicators. An ongoing study investigates per-pixel data analysis that can facilitate exploration of new indices by processing the high-resolution lighting data. Single quantities such as luminance, illuminance, reflectance, transmittance, glare indices, S/P ratio, CCT, CRI may not be very informative about the quantity and quality of light in the entire space. Pixel information is appropriate to study variations within an environment. Per-pixel quantities are used for detailed study of the temporal and spatial dynamics within an environment. Lighting variability has been investigated and correlations have been established among different architectural surfaces.

In summary, VLL provides full autonomy over the luminous data, acknowledging the idiosyncratic nature of each design that might require different lighting analysis techniques. Having access to a high resolution visual and numerical environment provides rich information to the designer. The degree that VLL is useful to architect, lighting designer and consultant depends on the person’s ability to relate the analysis results with the design. However, VLL provides many numerical and visual means to endorse this relationship.

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REFERENCES