The Simulation of Building Lighting Systems

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Abstract

This paper describes a recently developed, multi-chromatic lighting simulation model, known by the acronym DIM (Digital Illumination Model). DIM accepts a description of a zones geometry, surface finishes, contents and natural and artificial light sources. A multi-chromatic raytracking scheme is then employed to obtain the surface spectral luminance distribution corresponding to each light source. Outputs from the model include data on planar illuminance and coloured perspective images. The paper also describes the interaction between DIM and the ESP model for the simulation of a building's energy systems. In particular, the range of lighting control options, as implemented in ESP, are described. Finally the developments now underway to transform DIM into a polished design tool are outlined.

Introduction

Traditionally, the building design profession has employed analytical methods to appraise the performance of a building's lighting sub–system against a range of sky luminance distribution assumptions and electric light proposals. Unfortunately, such methods suffer from several deficiencies which will restrict their use in a real design context.

For example, the level of sophistication is often low: a room might be limited to an orthogonal form or the assumption of Lambertian surfaces (perfectly diffusing) might be made. Often the inter–reflection of light between surfaces is crudely modelled or surface reflectance is assumed to be constant regardless of the wavelength of the incoming light. In most cases, the method is constrained to the mono–chromatic case with no account taken of the spectral composition of the light sources; the assumption being made that the light flux is uniform over the visible spectrum – that is white. In other words, the qualitative aspects of light are omitted.

At the theoretical level, such methods are often simplified and abstract: using the integrating sphere theory to handle surface reflections for example; or the split flux method to account for externally reflected light; or the lumen method for artificial lighting design; or relying on an analytical solution valid only for certain limiting geometries or sky luminance distributions.

As a consequence of these deficiencies, the treatment of specular reflections, movable window features, intra–zone obstructions, arbitrarily positioned light sources and switching regimes – in short realism – is not possible. And few models provided the capability of experiential outputs in which a three point, coloured perspective is displayed.

The objective of the DIM project was to develop an entirely new approach capable of representing complex geometries, with internal obstructions included, embodying the range of surface response models – from the diffusing case through off–specular to specular – and equipped to handle luminaires of different spectral emission, located arbitrarily within an enclosure. A second objective was to tailor the DIM software for a Unix[TM] workstation environment so that a run–time link could be achieved with the ESP system for the simulation of the energy sub–system.

The DIM System: An Overview

The system comprises 4 program and 3 database modules:

The first program module – DIMdis – accepts user data which describes a zone's topography and topology. The objective of DIMdis is to transform this continuous zone model to a discrete numerical equivalent by a 'surface and radiosity finite element' technique (as explained below). The output from DIMdis is a data structure of rays representing the total number of possible light flow–paths.

The second program module is DIMray. This accepts the output from DIMdis and the user's specification and positioning of luminaires extracted from the fittings' database. In this database luminaire photometric data is represented as a number of vectors corresponding to a fitting's three dimensional intensity distribution. These vector–sets are then assumed to exist at several mono–chromatic wavebands to represent the luminaire's spectral characteristics. The computational mission of DIMray is to process each vector through the list of rays representing the total inter–reflection possibilities. The output from DIMray is a database giving, for each surface finite element and luminaire, the spectral luminance distribution.

DIMout is the analysis module which allows the recovery and presentation of this performance data. It has two capabilities. The first allows the performance data to be integrated by fitting and by surface. This yields, for any mix of fittings, surface illuminance or luminance. The second capability concerns the transformation to terminal RGB to enable, via a scan–cell algorithm, the production of an enhanced, coloured image.

The final module, DIMdbm, is a database manager for the luminaire and surface property databases. It allows the display of existing entities and the insertion of new fittings and surface finishes as required.

Problem Specification

DIM is a full three dimensional model which treats a room as a collection of bounding planar polygons – to represent the walls, ceiling, floor, windows, doors and surface features such as blinds, pictures, etc. – with a second class of polygons to represent any internal obstructions.

Once this data is entered DIM is equipped to perform a range of basic geometrical operations. This includes area and volume computation, polygon gridding, diffuse black body view factor determination for all combinatorial polygon pairings, and hidden line, three point perspective view generation.

Discretisation

Fundamental to DIM is the concept of surface radiosity on a finite element grid. The objective is to transform the continuous system into a discrete ray equivalent in a manner which respects the spatial relationships but minimises the processing scheme. This is done as follows.

Firstly, a user–specified finite element grid is applied to each polygon.

A unit hemisphere is then generated and, by slicing this equally in the horizontal and vertical planes, its surface is represented as a set of finite patches, each subtending an equal solid angle at the base centre point. When placed over a polygon cell, these surface patches then represent the cell's discrete radiosity field to a user controlled level of accuracy.

The 'patched' unit hemisphere is then placed over each bounding and obstruction polygon grid cell in turn and a number of rays formed by connecting the cell's centre point with the centroids of each hemispherical patch. Each ray is then projected to locate the point of intersection with another polygon grid cell. In this way each projection gives rise to a ray, and each ray has a source and sink cell.

The technique makes allowance for the relationship between the source/sink separation distance and the spread of light due to the solid angle effect. Consider the following. Because of the spread of light effect, the number of illuminated cells arising from one exit ray increases as the distance to the point of intersection increases. The radiosity technique (as opposed to simple combinatorial cell connection) represents this phenomena while minimising the number of rays for processing. For any given level of radiosity representation (hemisphere patch subdivision), it guarantees a distribution of rays which best represents the spatial relationships. For example 10 polygons, each divided into 100 grid cells, and using a unit hemisphere with 50 patches, gives rise to 50,000 rays (10 polygons times 100 cells times 50 patches). If, instead, each polygon cell is joined to all the others, the total combinatorial pairings is 450,000 rays ! $[n(n-1)100^2/2]$ where n is the number of polygons; 10 here. The latter case is computationally unacceptable and contains many redundant rays since whole clusters of rays will have identical point view factors and so could be replaced by one representative parent ray. This is, in effect, the result of the radiosity technique employed in DIM.

The next step is to group all un-hit cells and mark them as family members of some parent ray. These family members are never processed at ray tracking time but, instead, inherit the illuminance properties of their parent. To determine family members the following technique is employed. An un-hit cell is connected to the centre point of the initial polygon cell: this is equivalent to a back projection. This gives the point of intersection with the hemispherical surface, indicating the associated patch. All back projections associated with the same patch are then marked as family members of the source/sink ray which was initially processed for this patch and polygon cell.

At the end of this discretisation process a number of rays exist, each one with a distinct source and sink cell. These comprise the discrete equivalent of the initial continuous zone and are the only rays processed. The secondary rays, grouped together as family members, are then represented by these parent rays and are not processed at simulation time.

Modelling of Light Sources

Three entities are of importance in light source representation: the geometry of the source; its intensity distribution; and its spectral power distribution. In DIM all light sources, whether artificial or natural, are treated in the same numerical manner: as a discrete set of vectors representing intensity and spectral power distribution.

Artificial Sources

Normally luminaire geometry is differentiated into point, linear and area sources. In DIM all light sources are discretised and treated as a collection of point sources. The spatial distribution of luminous intensity – as represented by manufacturer's candel power distribution data – is then made discrete and processed as a collection of vectors.

The relative energy emitted from a light source at each wavelength in the visible spectrum is given by a spectral energy distribution curve. DIM treats this spectrum as a number of mono-chromatic wavebands.

Natural Sources

Dim is able to operate in conjunction with separate daylight prediction models – such as SUPERLITE (2) for example – which offer a range of sky luminance distributions and a representation of building geometry including facade obstructions. A window in DIM is then treated as an area light source with the predicted intensity distribution.

Ray Tracking

This is the kernel of DIM. The starting point for a given luminaire is to determine, for each waveband, the direct illuminance of each polygon cell after taking account of visibility.

The luminous flux of a light source is radiant flux in the visible range (390 to 780nm) weighted according to a visual response as specified by a spectral luminous efficiency function. The unit of luminous flux is the lumen (lm); defined as a radiant flux of $\frac{1}{683}W$ at a wavelength of 555nm in air. Therefore the elemental luminous flux associated with a spectral radiant flux $\varphi_{e\lambda}$ over an elemental range $d\lambda$ is

$$d\lambda_v = 683V(\lambda)\varphi_{e\lambda}d\lambda \qquad (1)$$

and the total luminous flux, φ_v, is obtained by integrating over the visible range:

$$\varphi_v = 683\int V(\lambda)\varphi_{e\lambda}d\lambda \qquad (2)$$

Now, the luminous intensity – the luminous flux per steradian – emitted in a given direction is given by

$$I = \frac{d\varphi}{d\omega} \qquad (3)$$

The spectral luminous intensity is determined from the spectral energy distribution function:

$$I(\lambda) = IF(\lambda) \qquad (4)$$

where $F(\lambda)$ is the spectral weighting factor, defined as the fraction of luminous energy contained in a mono-chromatic band $\delta\lambda$ at some wavelength λ. It is found from

$$F(\lambda) = \frac{\sum S(\lambda)\delta\lambda}{\sum\delta\lambda} \qquad (5)$$

where $S(\lambda)$ is the relative spectral energy distribution function.

With reference to figure 1, the direct illuminance of a sink cell of elemental area dA is

$$E_d = I\frac{d\omega}{dA} \qquad (6)$$

and since $d\omega = \frac{dA\cos\vartheta}{r^2}$, then

$$E_d = I\frac{\cos\vartheta}{r^2} \qquad (7)$$

Combining equations 4 and 7 gives the final expression for the direct illuminance due to a mono-chromatic waveband as

$$\delta E(\lambda) = \frac{IF(\lambda)\cos\vartheta}{r^2} \qquad (8)$$

In this way a light source vector is 'locked' onto the discrete ray equivalent of the specified zone. Then, a surface reflection model is invoked which depends on the reflection properties of the surface – diffusing, off-specular or specular. This gives one or more exit or reflected rays and the light intensity of each. The intensities are written to the output database and the rays are inserted in a ray stack for onward processing. In order to minimise the size of the stack, the procedure of DIMray is to then process the last ray in the stack. The next reflection point is reached, the reflection algorithm is invoked as before, and the new exit rays are appended to the stack. The process continues until, eventually, new exit rays can be discarded because their intensity has diminishes below some threshold value. In this way the ray stack is processed until exhausted. The next light source vector is then processed.

Surface Reflection

For fully diffusing surfaces, the reflected rays are equal in number to the number of initial hemispherical patches, with an intensity obtained directly from the average wavelength dependent reflectance assigned to the polygon cell in question. With specular and off-specular surfaces, the number of exit rays is greatly reduced.

DIM employs the biangular reflectance technique of Torrance and Sparrow (3)). This is defined as the reflected radiance in the direction (ϑ_r, ξ_r) divided by the incident radiant flux from the direction (ϑ_i, ξ_i); where ϑ and ξ are the azimuth and altitude angles in polar coordinates. Thus, the biangular reflectance ρ is given by

$$\rho(\vartheta_i, \xi_i; \vartheta_r, \xi_r) = \frac{I_r(\vartheta_r, \xi_r)}{I_i(\vartheta_i, \xi_i)\cos\vartheta d\omega_i} \qquad (9)$$

Biangular reflectance data can be obtained by experiment or analytically. In the former case the directional reflectance characteristics are measured using either gonionic reflectometers or luminance meters. The decomposition of the specular and diffuse components can also be made through the use of polarising glass on luminance meters. But because of the large number of combinations of incoming and outgoing directions, a major problem exists with the size of the data set for even a single material. For this reason the analytical approach is often favoured. This entails the theoretical determination of material reflectance based on geometrical optics. In the approach the biangular reflectance is expressed as a specular and diffuse component

$$\rho = k_s \rho_s + k_d \rho_d \tag{10}$$

where $k_s + k_d = 1$.

While the diffuse reflectance data are generally available as measured values, the specular component requires a mathematical model and several such models can be found in the literature. For example, Cook and Torrence have proposed that

$$\rho_s = \frac{F\ D\ G}{\pi \cos\vartheta_l \cos\vartheta_v} \tag{11}$$

where F is the Freznel reflectance, D is a distribution function for the micro–facets comprising the surface, G is a geometric attenuation factor arising from micro–facet shadowing and masking, ϑ_l is the angle of the light source vector and ϑ_v is the angle of the viewing vector.

The Freznel reflectance is found from

$$F = \tfrac{1}{2}\left[\frac{\sin^2(\varphi - \vartheta)}{\sin^2(\varphi - \vartheta)} + \frac{\tan^2(\varphi - \vartheta)}{\tan^2(\varphi - \vartheta)}\right] \tag{12}$$

where $\sin\vartheta = \frac{\sin\varphi}{\eta}$ and η is the index of refraction of the reflecting surface.

The geometric attenuation factor is a function of the angular relationship between the incident light and the surface facet geometry:

$$G = 1 - \frac{m}{l} \tag{13}$$

And Torrence and Sparrow have proposed the following distribution function

$$D = c_l e^{-(\delta/m)^2} \tag{14}$$

where c_l is an arbitrary constant and m is the root mean square of the micro–facets.

This allows a surface to approach a diffuse distribution at short wavelengths and a specular distribution at long wavelengths. The difficulty of the technique is in securing the reflectance data for a representative number of input/exit ray pairs.

Model Output

The output from DIMray is a database containing, separately for each initial light source vector and waveband, the reflected flux distribution for each polygon cell.

The use of this data to produce a coloured image requires a display driver possessing a subjective and terminal colour mapping operation. For any given eye and focus point, a perspective transformation is applied to each polygon cell before terminal display. When combined, as in DIM, with a visibility priority algorithm (such as z–depth sorting), this rise to a perspective image. Note that if the initial polygon cells are set small enough, then the technique becomes equivalent to scan–line pixel addressing.

The reproduction of surface colour from the calculated spectral luminance distributions is based on the CIE chromaticity system (4). The first step is to weight the calculated surface spectral luminance distribution. This is done by using three CIE colour–matching functions which represent the contribution of a unit amount of energy at each wavelength. This gives rise to the following tri–stimulus value

$$\delta X = x(\lambda) L(\lambda) \delta\lambda \tag{15a}$$

$$\delta Y = y(\lambda) L(\lambda) \delta\lambda \tag{15b}$$

$$\delta Z = z(\lambda) L(\lambda) \delta\lambda \tag{15c}$$

where $x(\lambda), y(\lambda)$ and $z(\lambda)$ are the CIE colour matching functions for the theoretical primaries X, Y and Z; and $L(\lambda)$ is the luminance of a surface at a mono–

chromatic band $\delta\lambda$.

The final theoretical primaries are obtained by integrating the elemental tri–stimulus values over the entire visible spectrum. That is $X = \sum \delta X$ and so on. The CIE chromaticity coordinates of a colour comprised of X, Y and Z primaries is then derived by normalising the tri–stimulus values such that

$$x = \frac{X}{X + Y + Z} \tag{16a}$$

$$y = \frac{Y}{X + Y + Z} \tag{16b}$$

$$z = \frac{Z}{X + Y + Z} \tag{16c}$$

The relationship between these theoretical colour coordinates x, y and z and the R, G and B primaries of a colour terminal is found by solving the following system of simultaneous colour matching equations:

$$X = x_r R + x_g G + x_b B \tag{17a}$$

$$Y = y_r R + y_g G + y_b B \tag{17b}$$

$$Z = z_r R + z_g G + z_b B \tag{17c}$$

where the three sets of coefficients $(x_i, y_i, z_i); i = r, g, b$ are the x, y and z coordinates of the red, green and blue primaries of a given terminal.

The luminance range of typical terminals – of the order of 1 cd/m^2 – is somewhat inadequate when compared to the luminance variation encountered in the real world; between 1 and several thousand cd/m^2 for example. It is therefore necessary that the foregoing luminances should be scaled down to the range manageable by the terminal. In this context it is normal to assume that when the brightness ratio is held constant, the perception of relative brightness in the model will approximate to the real world.

Firstly, the computed surface luminance values are transformed into apparent brightness values as perceived by the human eye. A luminance to brightness rationship has been proposed by Stevens and Stevens as

$$b_i = k(L - L_o)^c \tag{18}$$

where b_i is the brightness at location i, L is the surface luminance, L_o is the thres–hold luminance of the human eye and c and k are correlation coefficients.

The maximum monitor brightness can also be determined from equation 18:

$$b'^{max} = k(L'^{max} - L_o)^c \tag{19}$$

where b'^{max} is the maximum monitor brightness and L'^{max} is the maximum monitor luminance.

The luminance of the surface in terminal space is then determined from

$$b'_i = (b_i / b_{max}) b'^{max} \tag{20}$$

And finally, from the terminal brightness, the luminance of the terminal is determined through the inverse of the luminance/brightness function.

Unfortunately it has not been possible to reproduce high quality coloured images within these proceedings. Such images can be obtained from the author on request.

DIM and ESP

DIM has been designed to operate in conjunction with the ESP system for building energy simulation (5). Within ESP there exists a user–orientated control facility which enables system states to be modified as a function of time or state variable tests. Stated briefly the user defines a control loop comprising:

- A sensor to sense the property of interest – for example time, temperature, enthalpy or, in this context, illuminance.
- An actuator to allow some system state to be changed over time – for example zone flux input, boiler valve position or electric lighting status (on or off in whole or part).
- And a controller to generate the actuator signal based on the sensed condition.

To interface DIM and ESP it was therefore necessary to develop a new sensor (an illuminance meter), an actuator (a switch) and several control laws to represents control characteristics (on/off, proportional dimmer, step–down control, etc.) and occupant response. It was also necessary to arrange that the DIM results could be transferred to ESP as a 'zone lighting level' file. In the absence of such a file, ESP will resort to the use of an in-built algorithm based on hourly global and diffuse shortwave flux.

For each of the potential light sources – the direct solar beam, the clear sky portion and the overcast sky portion – an empirical efficacy factor is applied as follows.

For the clear sky portion, the efficacy, L_{cs}, is assumed constant at 144 Wm^{-2}.

For the overcast sky portion the efficacy K_{os} is given by

$$K_{os} = (91.2+0.702\varphi_s - 0.1163\varphi_s^2)(1.22-7.96e^{-4}\Delta+7.96e^{-7}\Delta^2) \quad (21)$$

where Δ is given by

$$\Delta = \frac{I_g}{\sin(\varphi_s \times \frac{\pi}{180})} \quad (22)$$

And for the direct solar beam:

$$K_d = 17.72+4.4585\varphi_s - 8.7563\times E^{-2}\varphi_s^2 + 7.3948\times E^{-4}\varphi_s^3 - 2.167\times E^{-6}\varphi_s^4 - 8.4132\times E^{-10}\varphi_s^5 \quad (23)$$

The internal illuminance at any point, E_p, is then found as a weighted summation of the three possible components:

$$E_p = I_{dn}K_s F + C(I_{fh}K_{cs})df + (1-C)I_{fh}K_{os} \quad (24)$$

where I_{dn} is the direct normal irradiance, I_{fh} is the diffuse horizontal irradiance and C is the cloud cover (evaluated as I_{fh}^2/I_g^2 where I_g is the global horizontal irradiance); F is a geometric factor which dictates whether or not the point can see the sun; and df is the daylight factor.

In addition to conventional lighting switching strategies, ESP also offers a probabilistic model (6) in which the effects of occupant psychology are considered. This model, which is based field data, gives the probability of lights being switched on as a function of the minimum daylight illuminance on the working plane. A probability index φ is given by

$$\varphi = \frac{-0.0175+1.0361}{1.0+EXP(4.0835\times\log E_m)-1.8223} \quad (25)$$

where E_m is the minimum daylight illuminance on the working plane.

This index is then constrained to $0.0 \leq \varphi \leq 1.0$ and compared to a random number generated within the same range. If the lights are already off and the switching probability is greater than the random number then the lights are switched on.

Present and Future Work

At the present time a follow-on project is underway to refine DIM in terms of its user interface and to validate its output. This work is being undertaken in collaboration with Philips International and the University of Technology at Eindhoven. In support of the validation work, Philips have established a configurable test room which allows surface and light source characteristics to be varied. This facility is then used to test the realism and predictive accuracy of DIM.

Conclusions

A prototypical lighting simulation model has been developed which is able to model complex geometries when subjected to a number of light sources. Account is taken of the distributions and spectral composition of light. Output from the model is the usual contours of surface illuminance or a screen image produced by a mapping to terminal RGB.

A follow-on project is now in progress which aims to further refine the model in terms of its validity and usability.

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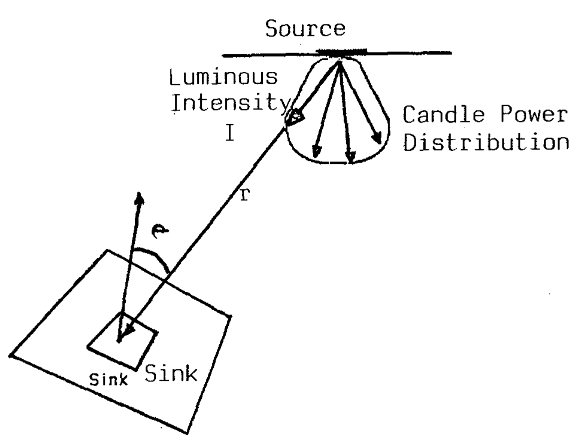

Figure 1 Direct Illumination of a Surface Element