Abstract  Daylight simulation problem is a difficult problem in computer graphics due to the complexity of daylight itself. Based on the purposes of simplifying the traditional simulation process and improving the realism at the same time, this paper proposes an image-based daylight simulation method in which color temperature is used to describe daylight. This method can simulate various daylights at different color temperature realistically by using only one general image. The main idea of this approach is using a spectra database, called SOCS, to generate a spectral reflectance image from a general image. The experimental results illustrate the efficiency of this approach.

Key words : Daylight Simulation, Color Temperature, Spectral Database, Image-based Daylight Simulation

1. Introduction

Daylight simulation has been one of the difficult problems in computer graphics. The apparent movement of the sun with time yields an illumination, which changes throughout the day, the year, and with differing terrestrial locations. The illumination due to the sky changes not only with the motion of the sun but also with atmospheric conditions and weather conditions. These make the daylight as a hemispherical source of illumination, which exhibits spatial variation in brightness and spectral composition. In about 20 years, by the efforts of the researchers, the daylight simulation problem had been achieved many progresses in both process speed and realism. However, even now in which CPU speed becomes much faster, and memory becomes much cheaper, the problem of daylight simulation is still a difficult problem in CG due to that the generated image lacks of realism, and its speed cannot satisfy real time rendering.

With the advance of computer vision, image-based modeling and rendering, we realize that image-based method is a possible and prosperous approach to daylight simulation. Some researches try to get the light information or object surface reflectance information from image. All of these works illustrate that the pixel value in an image reflects the interaction of object surface and daylight, and makes image-based daylight simulation possible. However, to our knowledge, there are still the following problems in the daylight simulation:

1. Lacks of realism. Though some algorithms proposed to extract surface reflectance and light information from images, but the rendering process is still based on computer graphics.

2. Too many parameters are required to simulate daylight. Therefore for general users it is difficult to master how to adjust these parameters to get a satisfied result.

3. Modeling work or many reference images are required, which is a heavy burden.

Focus on the above three problems. This paper proposes an approach called spectra database based daylight color temperature simulation. In our approach, color temperature is used to describe the spectral composition feature of different daylight condition, which is very simple even for nonprofessional user. The purpose of this paper is based on only one digital image to simulate its scene illuminated by different color temperature daylights.

The daylight color temperature simulation has a wide application. Besides of the general virtual reality systems, such as driving or flight simulation, it is also required in digital image editing systems. Users often hope to change an image taken in the noon to an image looks like taken in the sunrise/sunset or vise versa. By
adjusting the daylight color temperature, to make the original image looks more satisfied is the function that all users hope the image editing system should have. The study of daylight color temperature simulation is meaningful to this point of view.

A spectra database called SOCS is taken used in this paper for converting an RGB image to a multispectral image, and estimating its illumination spectrum. By the approach proposed in this paper, a spectral reflectance image can be generated, and with it various daylightings described by color temperature can be simulated.

The paper is partitioned into the following sections. The daylight spectrum defined by color temperature is explained in Section 2. In Section 3, our approach of spectra database based daylight color temperature simulation is described intensively. The experimental results and discussion are given in Section 4. Finally, the conclusion and future work are described in Section 5.

2. Daylight and Color Temperature

2.1 Color Temperature

Though usually the daylight is thought to be white, but in fact it is going from reddish to bluish white. Physically speaking, this means that white sunlight is a mixture of several electromagnetic rays with different wavelengths. Every color corresponds to a wavelength. The complete visible light spectrum ranges from 380 nm to 780 nm.

In this case light source could be described by two metrics, one is its spectrum, and the other is its intensity. In this paper, only the effect of spectrum is studied, and described by color temperature, expressed in degrees Kelvin (K), a temperature scale with zero point at, or absolute zero. The link between temperature and color is made by a theoretical light source called a blackbody radiator whose emitted colored light depends on its temperature. Therefore correlated color temperature is a metric that is used to quantify the tone of the light being used for viewing. As color temperature varies, the relative power distribution is also varies. The advantage of using color temperature and intensity to quantify daylight is that only two independent metrics are needed and the instruments needed to measure color temperature and intensity are much less expensive and easier to use than a spectroradiometer. Therefore, in this paper, daylight is described by color temperature.

2.2 Daylight Spectrum Defined by Color Temperature

The color temperature of daylight actually varies greatly, due to the time of day, the amount of haze or smog in the atmosphere, and the geographic longitude and latitude. Because of its angle to the earth in the early morning and late afternoon, sunlight must travel longer through the earth’s atmosphere. Generally, the color temperature of the daylight is shifted toward red, which accounts for the red in sunrises and sunsets. The concept of color temperature is widely used in photographing and film printing areas.

The color temperature of daylight alternates from 2000 K to 20000 K. Deane proposed an algorithm for calculating daylight spectrum of any color temperature. For color temperature $T$, its daylight spectrum $S(\lambda)$ can be determined by the following:

\[
x = \begin{cases} 
-4.6070 \times 10^6 \frac{1}{T^3} + 2.9678 \times 10^6 \frac{1}{T^3} + 0.09911 \times 10^3 \frac{1}{T} \\
+0.244063, 4000 K \leq T < 7000 K \\
-2.0054 \times 10^6 \frac{1}{T^3} + 1.9018 \times 10^6 \frac{1}{T^3} + 0.2478 \times 10^3 \frac{1}{T} \\
+0.237040, 7000 K \leq T < 25000 K
\end{cases}
\]  

(1)

![Fig. 1 Daylight spectrum at color temperature 4100 K, 6000 K and 8000 K.](image-url)
Here the $S_0$, $S_1$, and $S_2$ are coefficients which can be found in the paper. Fig. 1 shows the daylight spectrum calculated by equation (1) and (2).

3. Spectral Based Daylight Simulation

The color appeared when a nonluminous opaque object being viewed is produced by light which has come from some source, fallen on the object and been reflected to our eyes. When light strikes a surface, it is reflected if the object is opaque, and transmitted if it is transparent. Different objects differ in the percentage of the light that they reflect or transmit. This is the property that makes objects when seen in uniform illumination appear lighter or darker than other objects. Objects also differ in the percentage of light on different wavelengths that they reflect or transmit. This is the property that makes them appear with different colors.

This feature of object can be characterized by spectral reflectance. The spectral reflectance is at each wavelength in the visible spectrum (380 nm~830 nm), the proportion of incident light and the surface reflects at that wavelength.

Suppose the spectral distribution of a point in an image $I$ is $M(\lambda, x)$, its reflectance function at $x$ is $R(\lambda, x)$, and the spectral distribution of light source is $L(\lambda)$. Assuming lighting is uniform across the investigated part of the image, then the relationship among the spectrum of reflected light $M(\lambda, x)$, spectral reflectance $R(\lambda, x)$, and spectrum of light $L(\lambda)$ is the following:

$$ M(\lambda, x) = R(\lambda, x) \cdot L(\lambda) $$

From equation (3), we can see that if the spectral reflectance is known, then the color under new daylight could be obtained easily.

Fig. 2 shows the overview of our proposed approach. The basic idea is using a spectra database to generate a multispectral image from a general image first. Specifically speaking a general RGB image is converted into a multispectral image by using a spectra database. Then estimate the illumination spectrum of this image, and extract the spectral reflectance for each pixel. This is the second step, and its result is the Spectral Reflectance image, as shown in Fig. 2. Based on the spectral reflectance, new multispectral image under the desired daylight (Desired light spectrum, shown in the Fig. 2) can be generated. This is the third step. Finally, by converting the new multispectral image to RGB image, the whole simulation procedure is finished.

3.1 Conversion of RGB to Spectrum

Today, true multispectral imaging is only used in a few application areas such as remote sensing. The vast majority of color images are, however, stored in one of the three-dimensional color systems such as RGB. Therefore, the technique of converting an RGB color...
space to the spectral domain is required. But this is an ill-defined problem since many different spectra will correspond to the same RGB vector in an RGB coordinate system, a phenomenon known as metamerism.

To solve this conversion problem, a spectra database that consists of spectrum of typical colors in the world is used in this paper. One simple method is to compute the RGB-coordinates for all elements in the spectra database and chose the element whose RGB vector is the nearest to the RGB vector to be converted. This is unreliable due to the non-Euclidean structure of the RGB-space. Therefore we used the method proposed by 15) to alleviate the intensity influence.

At first, the RGB vector is converted to XYZ coordinates using the linear transformation specified by CIE-1931 RGB and XYZ systems10). For each spectral datum in the database, compute its XYZ vector using CIE primary stimuli of X, Y and Z. Then from the (X, Y, Z) vector the chromaticity vector (x, y, z) is computed as the following:

\[
(x, y, z) = \frac{(X, Y, Z)}{(X + Y + Z)}
\]

(4)

Denote \( C_i = (x_i, y_i, z_i) \) and \( C_d = (x_d, y_d, z_d) \) as the chromaticity vector of the RGB vector and the chromaticity vector of the database spectrum element respectively. The following three distances are defined between \( C_i \) and \( C_d \).

1. The distance in the \( l^1 \) norm of the (x, y) part between \( C_i \) and \( C_d \) are defined as the following:

\[
dist_1(C_i, C_d) = |x_i - x_d| + |y_i - y_d|
\]

(5)

2. The distance in \( l^1 \) norm of the (u, v) space between \( C_i \) and \( C_d \) are defined as the following:

\[
dist_2(C_i, C_d) = |u_i - u_d| + |v_i - v_d|
\]

(6)

Where \( u, v \) are defined as

\[
u = \frac{4X}{X+15Y+3Z}
\]

(7)

\[
v = \frac{9Y}{X+15Y+3Z}
\]

3. The distance in \( l^1 \) norm of (a, b) space between and are defined as the following:

\[
dist_3(C_i, C_d) = |a_i - a_d| + |b_i - b_d|
\]

(8)

Where \( a, b \) are defined as

\[
a = 500(X^{1/3} - Y^{1/3})
\]

(9)

\[
b = 200(Y^{1/3} - Z^{1/3})
\]

The coordinates of each element in the spectra database is computed in the coordinate system described above in advance. Then for a RGB vector, its corresponding spectrum is estimated in the database, so that the sum of the three distances between the spectrum and the RGB value is the smallest.

### 3.2 Illumination Estimation

For a general digital image, by the conversion algorithm proposed in last subsection, its multispectral image can be obtained. That is, in equation (3) \( M(\lambda, x) \) is known. In order to obtain \( R(\lambda, x) \), the illumination spectrum \( L(\lambda) \) has to be estimated first.

Taking the logarithm, equation (3) becomes the following:

\[
m(\lambda, x) = r(\lambda, x) + l(\lambda)
\]

(10)

Where,

\[
m(\lambda, x) = \ln(M(\lambda, x))
\]

\[
r(\lambda, x) = \ln(R(\lambda, x))
\]

\[
l(\lambda) = \ln(L(\lambda))
\]

Expressing function \( m(\lambda, x), r(\lambda, x) \), and \( l(\lambda) \) in the same coordinate system spanned by some basis functions \( b_k(\lambda) \), equation (10) can be expressed as

\[
m(\lambda, x) = \sum_{k} \mu_k(x) b_k(\lambda)
\]

\[
r(\lambda, x) = \sum_{k} \rho_k(x) b_k(\lambda)
\]

\[
l(\lambda) = \sum_{k} a_k b_k(\lambda)
\]

(12)

Here \( N \) is the basis function number. Replacing (12) into equation (10), the following is obtained:

\[
\mu_k(x) = \rho_k(x) + a_k
\]

(13)

The above equation means that the effect of the illuminant on the \( k \)th expansion coefficient of the logarithm reflectance function is a location independent, i.e. constant shift \( a_k \). The problem of illumination estimation is in fact to estimate coefficient \( a_k \) for each basis function \( b_k(\lambda) \) in equation (13). The estimation of illumination spectrum is based on the following fact that the space of electromagnetic spectra that is relevant to human color vision can be described by a set of representative colors up to the order of thousands16). In addition for a natural scene image, the distribution of the reflection coefficients \( \rho_k \) in equation (13) has the same modes as the coefficients computed from the spectra database. This means that the probability distributions of the coefficients \( \mu_k(\lambda) \) and \( \rho_k(\lambda) \) can be considered as relating by the shift coefficient \( a_k \).

For each \( b_k(\lambda) \), the distribution of its coefficient \( a_k \) in an image and the database are known, and the mode (the most probable value) for each coefficient can be estimated. For each, \( b_k(\lambda) \), comparing the modes of the distribution of image and database, their shift can be considered as \( a_k \). Thus the illumination spectrum of this image can be estimated.
3.3 Spectral Reflectance Image Generation

Spectral reflectance image is an image whose pixel records the spectral reflectance vector. After the light spectrum has been estimated, according to equation (13), the parameter of reflectance $\rho_k(\lambda)$ can be deduced for each pixel of an image. Thus the spectral reflectance image is obtained.

3.4 Computation Cost

The cost of the whole approach can be classified into two parts: preprocess cost and online process cost. The preprocess includes the conversion of RGB image to spectrum, the illumination estimation, and spectral reflectance image generation. While, the online process is the simulation procedure of different color temperature.

1. Preprocess cost:
   a. The conversion of RGB to spectral
      As described in Section 3.1, the cost of this process is the searching time, and determined by the size of image and the size of spectral database. In fact the $(x, y)$, $(u, v)$, and $(a, b)$ values of each spectral datum are calculated in advance therefore suppose the size of the image is $N$ pixels, and there are $M$ data in the database, the cost calculation can summarized as $O(N)t_1 + O(N\cdot M)t_2$. Here $t_1$ is the addition/subtraction time, $t_2$ is the multiplication/division time.
   b. Illumination estimation and spectral reflectance image generation
      As described in Section 3.2 and Section 3.3, the cost of the two processes is mainly dependent on the image size. The cost is $O(N)t_3$.

2. Online process cost
   The cost of this part is mainly on the image size. Suppose the dimension of each spectral datum is $P$. The calculation cost is
   \[ C_{online} = P^2 \cdot N \cdot t_4 \]  

4. Experimental Results and Discussion

As shown in Fig. 2, daylight color temperature can be simulated by four steps:

1. Convert a digital RGB image to a multispectral image.
2. Generate the spectral reflectance image from the multispectral image obtained in step(1).
3. Generate daylight spectrum at desired color.
4. Generate new image under desired daylight color temperature by multiplying the spectral reflectance image with daylight spectrum.

In this approach, a spectra database is needed, and its gamut and representatives are very crucial to the simulation result. There are some well-known color appearance systems, such as the Munsell system\cite{17} and the Natural Color System (NCS)\cite{18}. But in this paper, the Standard Object Color Spectra database for color reproduction evaluation (SOCS)\cite{19} is chosen because this database collects much more color data, and consequently has larger gamut than that of Munsell or NCS.

The basis functions of SOCS are determined by singular value decomposition\cite{20}. The first five basis functions in log-spectral space are shown in Fig. 3. The coefficient distribution of the log-spectral basis functions of SOCS database is shown in Fig. 4, and their modes are listed in Table 1.

4.1 Results

Using SOCS spectra database the following experiments are done. First, the efficiency of illumination estimation method is tested.

Fig. 5(a) is a general JPEG image of $640 \times 480$ taken by Epson CP-500. Each pixel of this image is converted to a spectral data by the method described in Section 3.1. Next, the operation of multiplication with a known light source D 65 is performed point-wise, and gives a simulated multispectral image. This simulated multispectral image is converted to a RGB image again, and is shown in Fig. 5(b). From this RGB image, the

![Basis Function of log SOCS](image)

Fig. 3 Five basis functions of log-spectral space of SOCS.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Modes of SOCS database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eigenvector number</td>
<td>1</td>
</tr>
<tr>
<td>Mode of SOCS</td>
<td>$-7.140$</td>
</tr>
</tbody>
</table>

The illumination spectrum is estimated by the approach described in Section 3.2. Fig. 5 (c) shows the original daylight D 65 and the estimated daylight spectrum. This figure illustrates the error of estimated illumination is small.

The second experiment is using SOCS database to simulate the daylight in term of color temperature. Fig. 6 is a general digital image taken in the afternoon. The estimated daylight spectrum is shown in Fig. 7. By using the proposed method, images under daylight with color temperature at 4100 K, 5100 K, 6000 K, 7000 K, 8000 K, and 9000 K are generated and shown in Fig. 8.

From these two experiments, the following facts could be realized. First, from only one general image, its illumination could be estimated. Second an image can be transformed to different daylight in term of color temperature. Fig. 8 shows that under low color temperature, the color appearance looks red, and when the color temperature goes higher, color appearance becomes blue.

4.2 Discussion

From the experimental results, the following advantages of this approach could be listed:
1. One reference image is enough. From a general image, without knowing its photographing time, camera parameters and geometrical information...
of the scene, new images under novel daylight described by color temperature can be simulated.

2. Daylight is described by color temperature. The specification of daylight becomes much simpler by using color temperature because users can describe daylight by using only one parameter.

3. Any daylight spectrum can be simulated. Though only the daylight described by color temperature is simulated in this paper, in fact, this method can simulate various daylights only if the spectral distribution is known.

4. The large numbers of SOCS database is the assurance of the effectiveness and correctness because according to equation (3), only if we can ensure to get correct reflectance $R(\lambda)$, the simulated result is correct. While the extraction of reflectance is determined by what kind of spectra database.

While one thing deserves to mention. The estimation of the modes of the $\rho_k$ will be deviated from true value

![Fig. 6 A general digital image.](image)

![Fig. 7 Estimated daylight of the image in Figure 6.](image)

![Fig. 8 Experimental result of image-based daylight color temperature simulation. New images at color temperature 4100 K, 5100 K, 6000 K, 7000 K, 8000 K, and 9000 K respectively.](image)
largely if there are only a few number of color in the reference image. For example, there is only sky or tree in an image. A simple way to compensate the different probabilities of the colors is to count each color only once. The estimated illumination spectrum, spectral reflectance, and the final estimated color under new daylight are not physically accurate. This is because this approach is based on the assumption that the distribution of image reflectance has the same distribution of the database taken use of, and the illumination estimation procedure is executed by statistical method.

5. Conclusion and Future Work

The simulation of the daylight in spectral space is the main idea of this paper. If describe the multi-dimension of spectral space by several basis functions, and convert them into logarithm space, the effect of the illuminant on the th expansion coefficient is a location independent, i.e. constant shift. This fact is taken use of to simulate daylight color temperature in this paper.

To perform in spectral space, first the RGB value is converted into spectral data because the digital images that we can get in our daily life are almost recorded in RGB values. Though this problem is an ill-defined problem, by using a huge spectra database SOCS, a RGB vector can be converted to an approximate spectral data. The illumination spectrum is estimated by comparing coefficient distribution of image and database. Then, the spectra reflectance of each pixel is abstracted, and the final estimated color under new daylight temperature in this paper.

Because of its efficient result, this approach would be very useful in digital image editing system. In order to let this approach be used widely, there are also some work required to be studied further. First the relationship between the spectral database and the obtained result should be studied. Second, typical daylight spectra database needs to be built. Lastly, a friendly user interface is urgently required.

12) http://colorpro.com/info/data/daylites.html