A study on computation optimization method for three-dimension scene light field radiation simulation in visible light band

Ligang Li*, Wei Ni, Xiaoshan Ma, Zhen Yang, Xin Meng, Feifei Shen
Key Laboratory of Electronics and Information Technology for Space System, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China

ABSTRACT

The simulation of high accuracy three-dimension (3D) scene optical field radiation distribution can provide the input for camera design, optimization of key parameters and testing of various imaging models. It can benefit for reducing the strong coupling between the imaging models and scene simulation. However, the simulation computation is extremely large and the non-optimization computing method can’t performed efficiently. Therefore, a study was carried out from the algorithm optimization and using high-performance platform to accelerate the operation speed. On the one hand, the visibility of scene was pre-computed which include the visibility from the light source to each facet in scene and the visibility between facets. The bounding box accelerate algorithm was adopted which can avoid a lot of time-consuming computation of occlusion in the light field radiation simulation process. On the other hand, since the 3D scene light field radiation simulation was obtained by a large number of light approximation, the algorithms can be divided blocks and processed parallelly. The GPU parallel framework was adopted to realize the simulation model of light field radiation in visible band. Finally, experiments were performed. The result shown the proposed method was more efficient and effective compared with the non-optimization method.

Keywords: Computation optimization, visible light band, light field, radiation simulation, three-dimension scene

1. INTRODUCTION

The simulation of high accuracy three-dimension (3D) scene optical field radiation distribution can provide the input match the physical world for camera design, optimization of key parameters and testing of various imaging models. It can benefit for reducing the strong coupling between the imaging models and scene simulation. Then the flexibility and expansibility analysis and design tool can be developed.

However, the simulation computation of 3D scene light field radiation distribution in visible light band is extremely large, which can be described as follows: 1) In order to meet the centimeter level high resolution imaging simulation applications, The number of 3D scene facets reaches tens of millions or even billions level. At the same time each facet contains a variety of material types and spectral properties. 2) In order to accurately simulate the incident light field of 3D scene, it need to consider the sun direct light, the whole sky background sampling light and the influence of the mutual reflection between model facets of the scene. Every facet’s incident light field radiation values are calculated using a large number of sampling lights. The block factor, atmospheric attenuation and other factors are also considered in the process. 3) In order to accurately simulate the radiation field of 3D scene in different observation directions, the BRDF model is used. The field radiation value of each facet in scene is calculated according to different sampling observation direction.

For the simulation of high accuracy 3D scene optical field radiation, if we adopt the non-optimization computing method, the computation is too large to perform. Therefore, a study is carried out from the algorithm optimization and using high-performance platform to accelerate the operation speed. We design experiments to prove the correctness and effectiveness of the proposed method. The result shows the proposed method is more efficient than the non-optimization method and has improved more than several hundred times in computation performance compared with the non-optimization method.

*liligang@nssc.ac.cn; phone 86-010-62638746; fax 86-010-62551825

© 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2240631
2. PRINCIPLE OF LIGHT FIELD RADIATION SIMULATION

The concept of light field was first proposed by A. Gershun\(^1\) of the 1930s, which is used to describe the radiation transmission characteristics in 3D space. In 1991, according to the visual perception of external light, E. Adelson and J. Bergen \(^2\) proposed using seven-dimensional function to describe the spatial distribution of the light geometry, which is called plenoptic function. Specific parameters of the formula are described as below.

\[
P(x, y, z, \theta, \phi, \lambda, t)
\]

Where \(P\) is the light intensity, \((x, y, z)\) is the any point of the three-dimensional coordinates in light. \((\theta, \phi)\) indicates the direction of light rays transmission. \(\lambda\) represents the wavelength of light and \(t\) is the time.

Reference to the description of the time, wavelength in all-optical function, we introduced them into a 3D scene light field radiation simulation calculation, in which the incident irradiance field model and zero meteorological range radiation field model are constructed.

2.1 Incident irradiation field model

In order to accurately simulate the scene irradiation field, each facet of the 3D scene models is the basic computation unit. For each facet in scene, we consider the influence of the direct sunlight, skylight and the background reflection. Which can be depicted in Figure 1:

![Figure 1: Composition of incident irradiance field](image)

When the location of facet \(i\) in target is defined as \((x_i, y_i, z_i)\) and the visible light wavelength is denoted by \(\lambda\), then the irradiation on the facet from the direct solar, the skylight and the background reflection are written as Eq.(2), Eq.(3) and Eq.(4) separately.

\[
E_{\text{ss}} = E_0 V_{\text{sun}}(\theta_s, \phi_s, x_s, y_s, z_s) \tau(\lambda) \cos(\theta_s)
\]

\[
E_{\text{sk}} = \int_{\phi_s=0}^{\phi_s=\pi} \int_{\phi_k=0}^{\phi_k=\pi} V_{\text{sky}}(\theta_s, \phi_s, x_s, y_s, z_s) L_{\text{sky}}(\theta_k, \phi_k, x, y, z, \lambda) \cos(\theta_k) \sin(\theta_k) d\theta_k d\phi_k
\]

\[
E_{\text{bg}} = \sum_{j=1}^{N} V_{\text{bg}}(\theta_0, \phi_0, x_0, y_0, z_0) L_{\text{bg}}(\theta_0, \phi_0, x_0, y_0, z_0, \lambda) \cos(\theta_0) S_j / r_j^2
\]

In Eq. (2), \(E_{\text{ss}}^0\) is the exoatmospheric spectral irradiance onto target surface, \(\tau(\lambda)\) is the atmospheric transmission along the sun target path, \((\theta_s, \phi_s)\) is the zenith angle and the azimuthal angle of the sun at the facet \(i\), \(V_{\text{sky}}(\theta_s, \phi_s, x_s, y_s, z_s)\) is the visibility factor from the sun direction \((\theta_s, \phi_s)\) toward the facet \(i\) and the value is in \([0,1]\).
In Eq.(3), we define the skylight irradiation by integration over the hemisphere above the facet $i$. Where $L_d \left( \theta_x, \varphi_x, x, y, z, \lambda \right)$ is the total downwelled spectral radiance reaching the facet $i$ from the $(\theta_x, \varphi_x)$ direction, $V_{\text{sky}} \left( \theta_x, \varphi_x, x, y, z, \lambda \right)$ is the visibility factor from the sun direction $(\theta_x, \varphi_x)$ toward the facet $i$ and the value is in $[0,1]$.

Eq.(4) shows the reflected radiance from a background toward the facet $i$. Where $S_j$ is the area of the facet $j$, $r_j$ is the distance between the facet $i$ and the facet $j$, $L_b \left( \theta_j, \varphi_j, x, y, z, \lambda \right)$ is the reflected background radiation from the background facet $j$ toward the facet $i$ from the direction $(\theta_j, \varphi_j)$, $V_b \left( \theta_j, \varphi_j, x, y, z \right)$ is the visibility factor from the background facet $j$ toward the facet $i$ from the direction $(\theta_j, \varphi_j)$ and the value is in $[0,1]$. So if the simulation time is $t$ and visible light wavelength is $\lambda$, the incident radiation of facet $i$ can be expressed as:

$$E_{ia} = E_{iab} + E_{ikb} + E_{iob}$$ (5)

Through the calculation of all facets in the scene based on formula (5), the incident irradiance light field of 3D scene can be obtained.

2.2 Zero meteorological range radiation light field model.

After three sources of irradiation onto the scene are identified, we begin to build zero meteorological range light field model which is a description of the reflected radiance leaving scene surface. The radiation is closely related to the reflectance properties of the surface material.

In general, the reflectance properties are a function of wavelength, illumination angle, and viewing angle. In order to accurately describe this characteristic, the bidirectional reflectance distribution function (BRDF) is introduced [3].

$$r_{\text{BRDF}} \left( \theta_x, \varphi_x, \theta_y, \varphi_y, \lambda \right) = \frac{L_d \left( \theta_x, \varphi_x \right)}{E_d \left( \theta_x, \varphi_x \right) [sr^{-1}]}$$ (6)

In Eq. (6), $E_d \left( \theta, \varphi \right)$ is the total spectral radiance reaching the target from the $(\theta, \varphi)$ direction, $L_d \left( \theta_x, \varphi_x \right)$ is the reflected radiation into the direction by the orientation angle $(\theta_x, \varphi_x)$. Furthermore, it is often more convenient to describe directional reflectance in a unitless form. This is accomplished by introducing the bidirectional reflectance factor which can be then expressed:

$$r_{\text{BRDF}} \left( \theta_x, \varphi_x, \theta_y, \varphi_y, \lambda \right) = \frac{r_d \left( \theta_x, \varphi_x, \theta_y, \varphi_y, \lambda \right)}{\pi}$$ (7)

Based on the BRDF, the zero meteorological range emergent radiation models with three sources of irradiation are given. If the location of facet $i$ in target is defined as $(x_i, y_i, z_i)$, the visible light wavelength is denoted by $\lambda$, then the sun emergent radiation, the skylight emergent radiation and the background emergent radiation leaving the scene by the orientation angle $(\theta_x, \varphi_x)$ are expressed as Eq. (8), Eq. (9) and Eq. (10) separately.

$$L_{aia} \left( x_i, y_i, z_i, \theta_x, \varphi_x, \lambda \right) = \int_{\theta_i}^{\pi} \int_{\varphi_i}^{\pi} V_{\text{sun}} \left( \theta_x, \varphi_x, x, y, z \right) \cos(\theta_x) d\theta_x d\varphi_x$$ (8)

$$L_{akb} \left( x_i, y_i, z_i, \theta_x, \varphi_x, \lambda \right) = \sum_{j=1}^{N} \int_{\theta_j}^{\pi} \int_{\varphi_j}^{\pi} V_{b} \left( \theta_j, \varphi_j, x, y, z \right) L_{b} \left( \theta_j, \varphi_j, x, y, z, \lambda \right) \cos(\theta_j) d\theta_j d\varphi_j$$ (9)

$$L_{iob} \left( x_i, y_i, z_i, \theta_x, \varphi_x, \lambda \right) = \int_{\theta_j}^{\pi} \int_{\varphi_j}^{\pi} V_{b} \left( \theta_j, \varphi_j, x, y, z \right) L_{b} \left( \theta_j, \varphi_j, x, y, z, \lambda \right) \cos(\theta_j) d\theta_j d\varphi_j$$ (10)
where \( r_{Fr} \) is defined as the bidirectional reflectance factor of facet \( i \), other parameters are referred to the Eq. (2), Eq. (3) and Eq. (4).

So if the simulation time is \( t \) and visible light wavelength is \( \lambda \), the emergent radiation of facet \( i \) by the orientation angle \( (\theta_o, \varphi_o) \) can be expressed as:

\[
L_{x_i} (x_i, y_i, z_i, \theta_o, \varphi_o, \lambda) = (L_{sa} (x_i, y_i, z_i, \theta_o, \varphi_o, \lambda) + L_{sb} (x_i, y_i, z_i, \theta_o, \varphi_o, \lambda) + L_{sc} (x_i, y_i, z_i, \theta_o, \varphi_o, \lambda))
\]

(11)

Through the calculation of all facets in the scene based on Eq.(11), the zero meteorological range radiation light field of 3D scene can be obtained.

3. COMPUTATION OPTIMIZATION PROCESSING

Based on the light field radiation model, simulation computation is performed. But there are still several time-consuming problems need to be considered. Firstly, for high precision 3D geometric scene, each facets need to compute the incident irradiance and emergent radiation, which could be very time-consuming; Secondly, when the background radiation is take into count, every facet need to computer the receiving radiation from other facets in scene and the reflected light source including the sun light and sky light. Thirdly, the radiation computation need to consider the geometric obscure effect between the facets in 3D scene and the computation is very huge. Finally, the atmosphere transmission rate and L-Path radiation need to be considered in computing the incident irradiance and these parameters calculation process is very time consuming. Therefore, in order to optimize the computation efficiency of the radiation simulation in 3D scene, we propose an off-line and on-line combination optimization method which include: 1) For the scene geometric visibility computation, it can be calculated in advance. Because once the scene established, the geometric relationship has been determined. It does not change with inputting simulation parameters variation. 2) For the atmospheric parameters such as atmospheric transmittance rate and path radiation, we can compute them in advance and then establish the lookup table to support on-line radiation computation; 3) On the basis of visibility and atmosphere elements computation, the simulation parameters such as simulation time and atmosphere conditions are inputted, then on-line incident irradiance and emergent radiation are calculated. By this way, the time-consuming can be reduced significantly for on-line radiation computation; 4) Due to the relative independence of each geometry unit calculation, the GPU computation framework is applied in this paper. Through the parallel processing, the computation efficiency can be improved dramatically. The process flow is shown as Figure.2.
3.1 The off-line scene visibility computation and optimization

Light field radiation simulation in 3D scene need to compute the geometry visibility factor from the light source to the facets or from one facet to other facets in scene. There is a method that the light source is equivalent to point light source, which may result in complete block or complete visibility.

Therefore, we adopt a scene visibility processing algorithm based on adaptive shadow map\(^4\), the basic steps are shown as follows:

Step1. For the visibility computation between the light source and the facets, we adopt the orthogonal projection to simulate parallel light; for the visibility computation between facets in scene, multiple light source viewpoints are set to throw light to hemisphere space;

Step2. The scene is rendered from the light source. The rendering input is the geometry index of the model in current scene and the output is the shadow map that saves in depth buffer. Through sorting each pixel in shadow map by depth information, we can get the corresponding visibility facet ID and the visible area ratio;

Step3. According to the statistic of multiple light source visibility in each facet, we can get the visibility factor for every facet in scene finally.

Further, in order to reduce the error generated by the calculation of the shadow map based on the fixed resolution, the algorithm is optimized using hierarchical bounding box (BVH). Each model in the scene is calculated separately for bounding box and adaptive shadow map, which improves the visibility calculation accuracy. Besides, in order to improve the efficiency of scene visibility computation, our algorithm is transplanted into GPU and make full use of the GPU hardware acceleration, which significantly enhance the computation efficiency of visibility.

3.2 Optical field radiation simulation parallel processing based on GPU

Based on the principle of the algorithm, this paper designs a kind of GPU-CPU collaborative computing method using CUDA for the light field radiation computation. The method is to integrate GPU and CPU which are two different architectures processors together to form a cooperative mode of hardware; At the same time, in order to achieve the coordination of GPU and CPU, GPU is designed for the intensive parallel tasks, CPU is designed for scheduling management and used as a GPU data porter to provide a steady stream of data for GPU computation.

The optical radiation simulation in this paper relates to the incident irradianc field simulation and emergent radiation field simulation. Because simulation calculation is carried out using each facet as a unit and the process of each facet is basically similar and independent, so it is very suitable for computing fine-grained data based on parallel GPU\(^6\). In order to realize the simulation of GPU parallelization, a corresponding kernel function is designed which uses the CUDA build-in variable to perform facet process. After the kernel function is written, we can call a serious of CUDA API function to realize the GPU parallel processing.

4. EXPERIMENTS VERIFICATION AND ANALYSIS

Lastly, to prove the correctness and effectiveness of the proposed method, a 3D scene is built which include a terrain model and a sphere model. Where the terrain model contains 20000 facets and the area is 10 meter \(\times\) 10 meter, and the sphere model contains 2400 facets and the radius is 2 meter. The sphere model is suspended on the terrain model.

The simulation parameters are configured as follows: The wavelength is 400nm. The sun zenith angle is 90° and the azimuth is 0°. The skylight zenith angle is from 0° to 90° and the sample interval is 10°. The skylight azimuth is from –180° to 180° and the sample interval is 10°. The background light contains 7 sample direction.

In order to compare the computing performance between CPU and GPU parallel processing, the proposed method is implemented and runs upon the two different platforms which are shown as Table 1. Figure.3 and Figure.4 show the simulation result of incident irradianc and emergent radiation respectively, which uses a 3D scene rendering ways to express the light field radiation distribution according to the computing result.
Table 1. Information of simulation processing platform environment

<table>
<thead>
<tr>
<th>CPU processing environment</th>
<th>GPU parallel processing environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel Core i7-4790(64bit,4core,8thread); Single float-point operation performance :52.07GFlops, Memory:16GB</td>
<td>GeForce GTX 950; Single float-point operation performance : 1850GFlops, Video memory: 2GB</td>
</tr>
</tbody>
</table>

(a) Sun incident irradiance field (b) Skylight incident irradiance field (c) Background light incident irradiance field

Figure 3. the 3D scene incident irradiance distribution

Figure 4. the emergent radiation distribution from different orientation ($\theta_o, \varphi_o$)

To get the result as shown in Figure 3 and Figure 4, we use the proposed method to accelerate the computation speed which include the off-line visibility pre-computation using shadow map and the on-line radiation computation by GPU parallel processing. Here the radiation computation performance comparison between CPU platform and GPU parallel platform is shown as Table 2.

Table 2. The radiation computation performance comparison

<table>
<thead>
<tr>
<th></th>
<th>CPU serial processing</th>
<th>GUP parallel processing</th>
<th>Speed-up radio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incident irradiance field computing time (unit:min)</td>
<td>10140</td>
<td>17</td>
<td>596</td>
</tr>
<tr>
<td>Emergent radiation computing time(3 sample direction) (unit:min)</td>
<td>306</td>
<td>12</td>
<td>26</td>
</tr>
</tbody>
</table>
In Table 2. The computation time of scene visibility is not included in the radiation processing. Because the visibility results have been pre-computed in off-line simulation phase and be computed only once for a fix scene. Besides, In this paper, by using the shadow map method the visibility computation performance has been improved at least ten times compare with the non-optimization method.

From Table 2, we can find that the computer speed of radiation simulation using GPU parallel processing is several hundred times higher than that of using CPU serial processing. The proposed method is valid and we can apply it to the optical radiation field simulation computation, especially for large-scale scene simulation.

5. CONCLUSION

The simulation of high accuracy 3D scene optical field radiation distribution can benefit for camera design, optimization of key parameters and testing of various imaging models. However, the simulation computation is extremely large. Thus, a study is carried out from the algorithm optimization and using high-performance platform to accelerate the operation speed. Experiment is designed to prove the correctness and effectiveness of the proposed method. The result shows the proposed method is more efficient than the non-optimization method, especially for large-scale scene, the method shows obvious advantage. Although we have done some work, there are still some problems in the study of proposed method, such as computation accuracy analysis, the relation analysis between the computation performance and scene scale.

REFERENCES