Shader Technology based on Physical Rendering

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Abstract. In the development of space mission simulation system, the fidelity of real-time scene rendering is one of the key indexes of simulation system. This paper presents a new shader technology based on physical rendering. The technique was validated by rendering tests in the engine. The simulation results show that the method can effectively improve the fidelity of scene rendering and provide technical support for the development of high-fidelity space mission simulation system.

Keywords. Shader technology, physical rendering, unreal engine, simulation

1. Introduction

In recent years, with the application of PBR rendering technology, we have experienced more and more realistic effects such as corroded metal, heavy leather, fine texture, in 3D real-time rendering of games, simulation systems, etc. It shows more and more real world in front of you, and constantly refresh people's understanding of the quality of real-time rendering pictures.

PBR refers to Physically Based Rendering[1]. It is an interactive process that includes scene lighting, model material input, and rendering shading algorithms. It contains a collection of rendering technologies based on the physical principles of the real world. Physics-based rendering uses a more physics-based method to simulate lighting, so this rendering method is more realistic and effective than the Phong or Blinn-Phong simplified lighting algorithm[2]. In addition to looking more realistic, because it is very close to the description of physical properties, you can directly write surface materials based on physical properties, making material editing and adjustment more convenient. At the same time, writing materials based on physical parameters has greater adaptability to lighting conditions, ensuring a more realistic and stable rendering output under different lighting conditions.

2. Illumination analysis in nature

2.1. The process of light transmission on the surface of material

First, we analyze the interaction between materials and light in nature. There are two situations when the light hits the surface of the object, reflecting or continuing to refract. The refracted light is absorbed or scattered. The act of absorbing light does not occur on the surface but on the subsurface. Absorption will reduce the intensity of the light and absorb light of a certain spectrum. The color of the remaining light changes, but the direction remains unchanged. After discretization, the direction changes and the intensity does not change. For insulators and conductors, the interaction between the two and light is completely different, as shown in Figure 1.
The reflectivity of insulators, that is non-metals, is generally very low, generally around 2%-8%, most of the light is refracted, part of the refracted light is absorbed, and the rest is scattered. The light absorption rate of this part of the refraction is related to the brightness of the material. The dark absorption is more and the bright absorption is less; the color of the scattered light also depends on the surface color of the object.

For metal conductors, the reflectivity is generally very high, reaching 70%-100%, so most of the light will bounce back in the form of specular reflection. A small part of the light is completely absorbed after it is refracted, and different metals absorb light of different wavelengths, causing the light reflected by the mirror to be colored.

2.2. Standard lighting model

In 1975, Bui Tung Phong proposed the basic concept of the standard lighting model, and based on this, he realized the abstraction of the lighting process. This lighting model mainly focuses on direct lighting, which refers to the light that enters the camera after being reflected from the object surface once after being emitted from the light source. Its basic method is to divide the light entering the camera into four parts: diffuse reflection, highlight, self-illumination and ambient light, and each part uses a separate method to calculate the contribution.

The self-illumination is directly set according to the self-illumination color in the object material, and the ambient light is set to a global constant to approximate the indirect lighting. The following focuses on the modeling of diffuse reflection and specular reflection in standard lighting.

Diffuse reflection in nature is the expression of light being refracted. The light enters another medium from one medium, and returns to the original medium from the approximate position of the incident point after multiple scattering inside. During the diffusion process, in addition to the discrete light rays, they are also absorbed and converted into heat energy. If the light does not enter the medium deeply, the difference between the entry point and the exit point can be ignored. The standard lighting model further believes that diffuse reflection is completely random, the same in any reflection direction, independent of the angle of view, but related to the angle of incident light. Specifically, the model believes that diffuse reflection conforms to Lambert’s law: the intensity of the reflected light is proportional to the cosine of the angle between the surface normal and the direction of the light source. The calculation method is as follows:

\[
C_{\text{diffuse}} = (C_{\text{light}} \cdot M_{\text{diffuse}}) \max (0, \hat{n} \cdot \hat{l})
\]

(1)

Among them, \(C_{\text{diffuse}}\) refers to the diffuse reflection part of the light, \(C_{\text{light}}\) is the color of the light source, \(M_{\text{diffuse}}\) is the diffuse reflection color of the material, \(n\) is the surface normal, and \(l\) is the unit vector pointing to the light source.

Specular reflection in the standard lighting model is an empirical model, which only calculates the light reflected in the direction of complete specular reflection, and does not fully conform to the specular reflection phenomenon in the real world. Four vectors of surface normal, viewing angle direction, light
source direction and reflection direction are used in the calculation process. The reflection direction can be calculated by the surface normal and the direction of the light source. The formula is as follows:

$$\hat{\mathbf{r}} = 2(\hat{n} \cdot \hat{l})\hat{n} - \hat{l}$$  \hspace{1cm} (2)

Among them, $\hat{n}$ is the surface normal, and $\hat{l}$ is the pointing light source Unit vector.

The formula for calculating specular reflection is as follows:

$$C_{\text{specular}} = (C_{\text{light}} \cdot M_{\text{specular}}) \max(0, \hat{v} \cdot \hat{r})^{m_{\text{gloss}}}$$  \hspace{1cm} (3)

Among them, $C_{\text{specular}}$ refers to the highlight part of the light, $M_{\text{specular}}$ is the highlight color of the material, $\hat{v}$ unit vector of the viewing direction, and $m_{\text{gloss}}$ is the glossiness of the material.

The standard lighting model is only an empirical model and does not fully conform to the lighting phenomenon in the real world. However, due to its ease of use, computing speed and acceptable rendering effects, it is still widely used. However, this model also has many limitations, and there are many lighting phenomena that cannot be expressed, such as fresnel reflection and anisotropic reflection. These characteristics are relatively common in the light performance of metal and hair. The following introduces a more complex model to reflect the interaction of light and objects more comprehensively and realistically.

3. Implementation of PBR

3.1. Illumination calculation model in Unreal Engine

In order to better simulate the light transmission process in the natural world, the Unreal Engine uses physical-based rendering technology (PBR) to make an approximate abstraction and approximation of real-world lighting. The illumination calculation model considers and solves three important problems, such as the surface model based on microfacet[3], the conservation of energy, and the diffuse refraction model based on physics.

Among them, the micro-surface theory is based on the reality of this subtle irregularity on the surface of the object. It doesn't abstracts the colored plane into a perfect reflection plane, but imagines it to be composed of more tiny reflection planes. During the interaction with light, these incident angles are different, the angle after bounce is also different, and some places are blocked, some places will produce shadows, and visually will produce blurred reflections. In this way, the specular reflection will show different results according to the roughness of the object surface. Regardless of the smoothness and roughness, the total energy reflected is the same, and the intensity of the light after reflection is unchanged, which is more in line with the interaction process of light in nature.

The Unreal Engine uses the BRDF (Bidirectional Reflectance Distribution Function)[4] to describe the incident radiance in a given incident direction and the outgoing radiance distribution in the reflecting direction to achieve the PBR lighting calculation process. Experiment and application results prove that this function also provides a relatively accurate calculation method.

$$\text{FinalColor} = \left\{ \begin{array}{l}
\text{DiffusePart} \times \text{BaseColor} \\
\text{SpecularPart} \times \text{GeometricOcclusion} \times \text{Fresnel} \\
\times \text{LightColor} \times \text{LightDir} \times \text{Normal} \\
\end{array} \right\}$$  \hspace{1cm} (4)

In the formula, the integral part represents the superposition of multiple light sources; the diffuse part is relatively simple, considering the proportion of diffuse reflection in the process of interaction between the material and light, and directly multiplies the base color of the texture to express the diffuse color. The specular highlight is relatively complicated, and a series of light source angles, normal directions, observation angles, and roughness need to be considered comprehensively.

The problem is analyzed in detail below.

$$\frac{\text{Specular} \times \text{GeometricOcclusion} \times \text{Fresnel}}{\text{\langle viewDir \cdot normal \rangle} \times \text{\langle lightDir \cdot normal \rangle}}$$  \hspace{1cm} (5)
The highlight calculation part is also called Cook-Torrance's BRDF lighting formula. The meaning of the three coefficients on the molecule is as follows:

1. The Specular is a normal distribution function with parameters (normal, viewDir, lightDir, roughness). Like the traditional BlinnPhong highlight model, the intermediate vector \( h \) of viewdir and lightdir is used, and the normal multiplication of dots to calculate the highlight brightness.

2. Geometric occlusion is a geometric function with parameters (normal, viewDir, lightDir, roughness), which is a feature that other traditional lighting models do not have, and reflects the loss of light when reflected on the rough surface of the object.

3. The Fresnel equation is generally used in water bodies before, because the water body has low roughness and strong reflection ability, but it is not a metal, and it is the most obvious object of the Fresnel effect. The greater the angle between the normal and the line of sight (the closer the line of sight is to the horizontal), the higher the brightness of the reflected light. This is the Fresnel effect that all objects have.

4. The denominator is the balance coefficient:

\[
\frac{4(\text{viewDir} \cdot \text{normal}) (\text{lightDir} \cdot \text{normal})}{(\text{normal} \cdot \text{lightDir}) (\text{normal} \cdot \text{viewDir})}
\]  

(6)

3.2. Material design and rendering effects

Based on the above rendering algorithm, Unreal Engine has designed corresponding attribute definition entries in the material. Through simple parameter configuration, it can be used to distinguish the reflection characteristics of different types of materials in the engine and render high-fidelity graphics effects. The material abstract model of Unreal Engine is shown in Figure 2.

![Material Model](image)

Figure 2. material model in Unreal Engine

3.2.1. Base Color

The Base Color of the material model in Unreal Engine defines the overall color of the material. It receives Vector3 (RGB) values, and each channel is automatically limited to between 0 and 1.

In Figure 3, the right part shows the input of color parameters after using the Unreal Engine icon and blue modulation in the material editor, and the left shows the final rendering effect of the material applied to the cube.
3.2.2. Roughness

Roughness describes the roughness that actually controls the material. Compared to smooth materials, rough materials scatter the reflected light in more directions. It can also be determined according to the blur or sharpness of reflection or the breadth or intensity of specular highlights. Roughness parameter 0 is specular reflection, while roughness 1 is completely matte or completely diffuse. The effect of the adjustment of roughness parameters in rendering non-metallic and metallic materials is shown in Figures 4 and 5.

![Figure 4. roughness performance of non-metallic materials](image1)

![Figure 5. roughness performance of metallic materials](image2)

3.2.3. Metallic

The metallic input actually controls how much the surface looks like metal. Non-metal has a metal property value of 0, and metal has a metal property value of 1. For pure surfaces such as pure metals, stones, plastics, this value is not 0 or 1, not any value between them. When creating mixed surfaces that are corroded, dusty, or rusty metals, consider setting a value between 0 and 1. The performance of the adjustment of the metal degree parameter in the material rendering process is shown in Figure 6.

![Figure 6. performance of metallic parameters](image3)

3.2.4. Specular

Specular is used to adjust the current amount of specular reflection on non-metallic surfaces. It has no effect on metals. Under normal circumstances, the highlight input setting is not required. In most cases, it should be left at the default value of 0.5. In Figure 7, in the left and right material inputs, the highlight parameters are set to 0 and 1, respectively, and the right material contains more specular highlights in the rendering of the cube.
Finally, in the Unreal Engine material editor, through the material input interface introduced above, three common materials for the simulation environment of stone, wood and blue brick were set respectively, and the PBR rendering technology was applied. The final rendering effect is shown in Figure 8. Experiments show that, compared with the traditional simplified lighting model, the application of PBR rendering technology can achieve more realistic picture quality in the simulation system.

Figure 7. specular parameter performance

![Specular Parameter Performance](image)

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![Stone Material](image)

![Wood Material](image)
4. Conclusion

This paper analyzes and studies the popular high-fidelity PBR rendering technology in recent years, analyzes the propagation mechanism of light after contact with natural objects from a physical point of view. And then further analyzes and summarizes the advantages of the PBR lighting model by comparing with the traditional standard lighting model. On this basis, the BRDF function and related algorithms for solving the PBR lighting model in the Unreal Engine graphics engine are further analyzed, and then the material design and corresponding input interface in the engine are introduced, and the rendering effect comparison based on single parameter adjustment is given. Finally, through the setting of the material parameters in the engine, the final rendering results of the three natural materials of stone, wood and blue brick are given. The results show that the physics-based rendering technology can greatly improve the fidelity of the 3D real-time rendering scene performance. It is of great significance for the development of three-dimensional simulation system.

5. References

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