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Combined bidirectional reflectance distribution functions usage for increasing images creation productivity

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ABSTRACT

Modern computer graphics systems are characterized by the requirements of highly-realistic and highly-productive image formation. In order to increase image formation productivity, the improvement of existing light reflectance models and the development of new models are constantly carried out. In the article the development of a combined light reflectance model based on the cosine-power functions is described. The main aspects of surface bidirectional reflectance distribution functions calculation and usage are analyzed. The features of simple empirical models and theoretical models that take into account microfaceted surface representation are described. The disadvantages of existing surface reflectance models are discussed. The cosine-power functions of the fourth and sixteenth degrees are discussed. The necessity of the development of a new surface reflectance model based on two cosine-power functions is justified. The calculation formula of the developed combined surface reflection function is proposed. The formula of the connection point of two cosine-power functions was obtained. The obtained formula was approximated with a simpler formula using Chebyshev polynomials. The plot of cosine-power functions connection point values was built. The plot of productivity gain from combined function calculation relative to the shininess coefficient is given. The average productivity gain value from combined function calculation was found. The plot of relative and absolute errors between the combined function and the Blinn function relative to the shininess surface coefficient is given. The three-dimensional plot of absolute error between the combined function and the Blinn function was built. Using OpenGL shading language the developed model was implemented in the software application Bidirectional Reflectance Distribution Functions Explorer. The teapot visualization results based on the proposed combined function are given. The developed combined model combines the advantages of two cosine-power functions and can be used in highly-productive three-dimensional computer graphics systems.

Keywords: Bidirectional reflectance distribution function; combined function; cosine-power function; phong model; Blinn model

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INTRODUCTION

Three-dimensional computer graphics increases the information perception efficiency [1] through scenes and phenomena rendering. The rendering [1] process includes mesh creation using geometrical primitives [2] and primitives shading. During the shading high productivity and reproducing the surface optical characteristics are important [3, 4]. The choice of surface reflectance model affects the compliance with these requirements.

Necessary characteristics of surface reflectance models include the possibility of providing real-time rendering [5], calculation simplicity, the precise reproducing of glare in epicenter and attenuation zones, the possibility of hardware implementation, physical plausibility [6, 7], the absence of complex operations. Current surface reflectance models don’t always provide the sufficient image creation productivity level. Therefore, the development of new reflectance models is needed.

LITERATURE ANALYSIS

During the surface shading the specular color component calculation is applied. The specular component is used for reproducing glares that occupy about 10 % of the object's surface [8].

For the specular component calculation the bidirectional reflectance distribution function (BRDF) [9] value is used, this value determines the distribution of reflected light with respect to the incident at surface light.

Bidirectional reflectance distribution function is calculated using the formula [10]

$$\frac{dL_r(\theta_r,\phi_r)}{dE(\theta_i,\phi_i)},$$

where E is irradiance; L_r is radiance; θ_i,ϕ_i is zenith and azimuth angles in the direction of incident light respectively; θ_r,ϕ_r is zenith and azimuth angles in the direction of reflected light respectively.

Fig. 1 shows vectors [11] that are used for BRDF calculation.

The vectors $\vec{L},\vec{V}$ are unit vectors to the light source and viewer respectively; $\vec{N}$ is normal vector. $\vec{R}$ is a vector of perfect reflection.

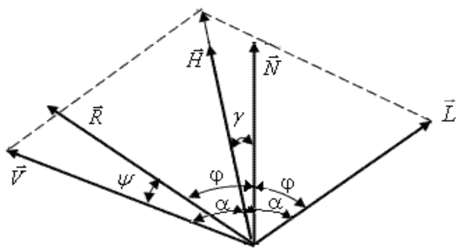

Fig. 1. **Vectors for bidirectional reflectance distribution function calculation**
***Source*: compiled by the [11]**

Bidirectional reflectance distribution functions are divided [12] into theoretical end empirical.

Theoretical BRDFs correspond to wave-particle light theory and have a physical basis. These models have big computational complexity and are used in highly-realistic computer graphics systems. Unfortunately, their usage for dynamic images creation is limited.

Group of BRDFs that take into account faceted surface structure [13] include Ward [14, 15], Torrance-Sparrow [6, 16], Beard-Maxwell [6, 10], [17], Ashikhmin-Shirley [18] models.

Ward model [14, 15] lies in dividing the object's surface into a large number of small specular areas (facets).

Bidirectional reflectance distribution function of such surface is calculated using the formula

$$\frac{1}{\sqrt{(\vec{N}\cdot\vec{L})(\vec{N}\cdot\vec{V})}}\frac{1}{4\pi m^2}e^{\frac{(\vec{N}\cdot\vec{H})^2-1}{m^2(\vec{N}\cdot\vec{H})^2}},$$

where m is mean facet orientation deviation.

Torrance-Sparrow BRDF [6, 16] is used for the microfacet representation of rough surfaces and is calculated using the formula

$$\frac{k_d}{\pi}+\frac{k_s}{4\pi(\vec{N}\cdot\vec{L})}D(\vec{H})\cdot F(\vec{V})\cdot G(\vec{V},\vec{L}),$$

where D is microfacet distribution (usually Gauss or Beckmann [6] distributions are used); F is the Fresnel factor, G is attenuation factor; k_s, k_d are coefficients of specular and diffuse reflection respectively.

Beard-Maxwell BRDF [6, 10], [17] combines two components that represent light reflection from the upper ($f_{r,\sup}$) and interior layers ($f_{r,vol}$).

The component $f_{r,\sup}$ is calculated using the formula

$$\frac{-F(\beta)}{F(0)}\frac{\frac{F(0)D(\vec{H})}{4\cos(\vec{V})\cos(\vec{L})}\cos(\vec{H})^2}{\cos(\vec{V})\cos(\vec{L})}SO(\vec{V},\vec{H},\tau,\upsilon),$$

where D is microfacet distribution; F is the Fresnel factor; β is angle between $\vec{H}$ and $\vec{V}$; SO is component that represents shadowing and obscuration; τ,υ are measured parameters.

The component $f_{r,vol}$ is calculated using the formula

$$\frac{2\rho_v f(\beta)g(\theta_H)}{\cos(\vec{V})\cos(\vec{L})},$$

where ρ_v is surface reflectance when $\theta_L=\theta_V=0,\ f(\beta)=g(\theta_H)=1$.

The complete value of Beard-Maxwell BRDF is calculated using the formula

$$f_{r,\sup}+f_{r,vol}.$$

Ashikhmin-Shirley BRDF [18] is an anisotropic model [19] (depends on object rotation) and is calculated using the formula

$$\frac{\sqrt{(n_u+1)(n_u+1)}}{8\pi}\times\frac{(\vec{N}\cdot\vec{H})^{n_u\cdot cos^2\phi+n_v sin^2}}{(\vec{N}\cdot\vec{L})max((\vec{N}\cdot\vec{V}),(\vec{N}\cdot\vec{L}))}F(\vec{N}\cdot\vec{L}).$$

Empirical BRDFs have considerably smaller computational complexity and became widespread in dynamic computer graphics systems. The main empirical BRDFs are Blinn [20], Phong [21], Lewis [6, 22], [23], Schlick [24] and Gauss [8] models

Blinn BRDF [20] is calculated using the formula

$$cos(\gamma)^n=(\vec{N}\cdot\vec{H})^n,$$

where $\vec{H}=(\vec{L}+\vec{V})/\left|\vec{L}+\vec{V}\right|$, n is shininess.

In Phong BRDF [21] instead of $cos(\gamma)$ $cos(\psi)=\vec{V}\cdot\vec{R}$ is used, where $\vec{R}=2\cdot(\vec{L}\cdot\vec{N})\cdot\vec{N}-\vec{L}$.

Lewis (Lafortune) BRDF [6, 22, 23] is an energetically-plausible Blinn function.

It`s calculated using the formula

$$\frac{n+2}{2\pi}\cos(\gamma)^n.$$

In modern computer graphics systems the Schlick BRDF [24] is widely used, it`s calculated using the formula

$$cos(\gamma)/\left(n-n\,cos(\gamma)+cos(\gamma)\right).$$

The function is characterized by considerably smaller computational complexity compared to Blinn and Phong BRDFs. The disadvantages of function are the presence of division operation and the big difference from Blinn BRDF in glare's attenuation zone.

Gauss BRDF [8] is characterized by high-precision reproduction of glare in epicenter and attenuation zones. The disadvantage of the model is the complexity of inverse functions calculation.

The BRDF is calculated using the formula

$$e^{-\frac{n\cdot(\angle(\vec{H},\vec{L}))^2}{2}}.$$

The analysis of the literature has shown that the Blinn and Phong BRDFs got the most widespread usage in computer graphics systems.

Since these models involve the usage of angle cosine to the power of n, where $n\in[1,1000]$, the lower degree approximation formulas were developed. In particular, this formula was developed [8]

$$(\frac{n}{a}(\cos(\gamma)-1)+1)^a,$$

where a is power of 2 number.

When $a=16$ (let`s denote the function as f_{16}) the highly accurate approximation of Blinn BRDF (f_b) is provided. When $a=4$ (f_4) the approximation is more productive.

Fig. 2 shows the plots of f_{16}, f_4, f_b BRDFs with respect to angle values $\gamma\in[0;0.8]$ and shininess $n=16$.

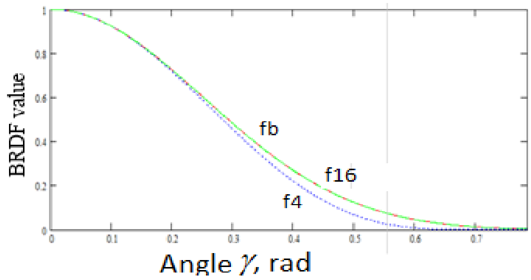

Fig. 2. **Plots of f_{16}, f_4, f_b bidirectional reflectance distribution functions with respect to angle values γ**

***Source*: compiled by the authors**

The function f_{16} requires big amount of computational resources because it's based on raising the polynomial to the 16th degree. In addition, f_4 in the glare's epicenter zone gives similar results. Therefore, it's possible to replace f_{16} with f_4 in the epicenter zone to make the specular component calculation faster.

Among the important features [8] of modern three-dimensional graphics systems are real-time rendering [25] and interactivity [26]. The moving of objects through the scene often depends on the user's actions, so strict time requirements are usually applied to graphics systems.

The present objects visualization methods don`t always comply with the requirements of graphics systems application fields, therefore the increase of three-dimensional scenes rendering systems efficiency is actual.

THE PURPOSE OF THE STUDY

The purpose of the article is the description of the development of combined bidirectional reflectance distribution function based on two cosine-power functions for the three-dimensional rendering productivity increasing.

THE DEVELOPMENT OF COMBINED REFLECTANCE MODEL BASED ON COSINE-POWER FUNCTIONS

The main idea of the method lies in using low-degree BRDF for the glare epicenter and using high-degree BRDF for the glare attenuation zone.

The combined reflectance model based on cosine-power functions (let's denote the function as f_{416}) is calculated using the formula

$$\begin{cases} f_4, \gamma <= merge(n) \\ f_{16}, merge(n) < \gamma <= \lim(n) \\ 0, \gamma > \lim(n) \end{cases},$$

where $merge(n)$ is the point of cosine-power functions connection; $\lim(n)$ is the point where the value of combined function equals 0.

The $\lim(n)$ was introduced because after reach-ing 0 the values of f_{16} begin increasing. $\lim(n)$ is calculated using the formula [27]

$$a\cos(\frac{n-16}{n}).$$

This formula can be approximated using the expression [27]

$$\frac{6}{\sqrt{n}}.$$

Let us find the formula for $merge(n)$ point where $f_4 = f_{16}$. One of the requirements to $merge(n)$ point is its belonging to the interval $\gamma \in (0,\ t_{f\,4=0})$, where $t_{f\,4=0}$ is the point where $f_4 = 0$. The analysis using Mathcad has shown that for the interval $\gamma \in (0,\ t_{f\,4=0})$ the point where $f_4 = f_{16}$ doesn't exist.

Therefore, for the $merge(n)$ we chose the point where f_{16} and f_4 values differ by $\frac{1}{128}$ (this value was chosen experimentally).

We solve the equation

$$\left|(\frac{n}{4}(\cos(\gamma)-1)+1)^4-(\frac{n}{16}(\cos(\gamma)-1)+1)^{16}\right|=\frac{1}{128}.$$

From the equation we find that $merge(n)$ is calculated using the formula

$$a\cos(\frac{n-0.33}{n}).$$

For the calculation simplifying $merge(n)$ was approximated with the piecewise function. $merge(n)$ graph was divided into four intervals: $n \in [1,8], n \in (8,30], n \in (30,150], n \in (150,1000]$. At the first interval $merge(n)$ was approximated with the third-degree polynomial of the form $An^3 + Bn^2 + Cn + D$. At other intervals $merge(n)$ was approximated with the first-degree polynomials of the form $An + B$.

For the approximation the Chebyshev polynomials were used, they are calculated using the formula [8]

$$f(x) \approx \left[\sum_{k=0}^{m-1} c_k T_k\left(\frac{x-0,5(b+a)}{0,5(b-a)}\right)\right] - \frac{c_0}{2},$$

where

$$c_j = \frac{2}{m}\sum_{k=1}^{m} f\left[\cos\left(\frac{\pi(k-0,5)}{m}\right)\cdot 0,5(b-a)+0,5(b+a)\right]\cos\left(\frac{\pi\cdot j\cdot(k-0,5)}{m}\right)$$

$T_0(x)=1$, $T_1(x)=x$, $T_k(x)=\cos(k\cdot\arccos(x))$; $[a,b]$ is interval of approximation; $m-1$ is polynomial degree.

Then $merge(n)$ is calculated using the formula

$$\begin{cases} -0.0039n^3+0.0663n^2-0.3934n+1.16, n\in[1,8] \\ -5.526\cdot10^{-3}\cdot n+0.305, n\in(8,30] \\ -5.567\cdot10^{-4}\cdot n+0.144, n\in(30,150] \\ -3.591\cdot10^{-5}\cdot n+0.059, n\in(150,1000] \end{cases}.$$

The values of $merge(n)$ at the interval $n \in [1,8]$ are intended to be read from graphics system memory. We simplify the formulas for other intervals by representing fractional values as the numbers of power two.

The updated $merge(n)$ formula is defined as

$$\begin{cases} -0.0039n^3+0.0663n^2-0.3934n+1.16, n\in[1,8] \\ -(\frac{1}{2^8}+\frac{1}{2^9})\cdot n+\frac{1}{2^2}+\frac{1}{2^4}, n\in(8,30] \\ -(\frac{1}{2^{11}}+\frac{1}{2^{14}})\cdot n+\frac{1}{2^3}+\frac{1}{2^6}, n\in(30,150] \\ -(\frac{1}{2^{15}}+\frac{1}{2^{18}})\cdot n+\frac{1}{2^4}-\frac{1}{2^8}, n\in(150,1000] \end{cases}.$$

Fig. 3 shows the plots of original ($merge$) and approximated (ap_merge) $merge(n)$ formulas at the interval $n \in [1,1000]$.

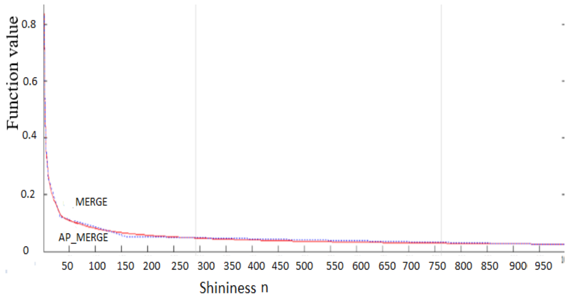

Fig. 3. **The plots of original and approximated formulas of cosine-power functions connection point with respect to shininess n**

***Source*: compiled by the authors**

Fig. 4 shows the plots of f_{416} and f_b when $n=120$ and $\gamma \in [0, 0.55]$.

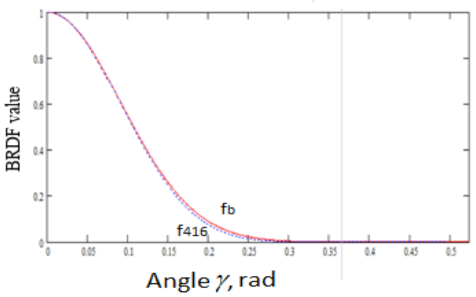

Fig. 4. **The plots of f_{416} and f_b BRDFs with respect to angle values γ**

***Source*: compiled by the authors**

Let us analyze the efficiency gain from the f_{416} calculation. The plot in Fig. 5 shows what percent of the f_{416} curve length is calculated as f_4 for $n \in [1,1000]$.

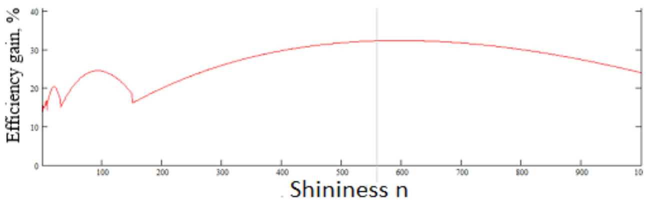

Fig. 5. **The plot of efficiency gain from the combined function calculation with respect to shininess n**

***Source*: compiled by the authors**

The mean value of efficiency gain is 27.3 %.

Fig. 6 shows the plots of maximum relative errors δ between f_{416}, f_{16}, f_4 and f_b in the glare's epicenter zone for $n \in [4,1000]$.

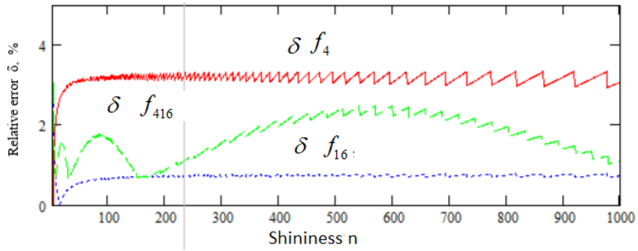

Fig. 6. **Maximum relative errors between f_{416}, f_{16}, f_4 and f_b in the glare's epicenter zone with respect to shininess n**

***Source*: compiled by the authors**

The maximum δ of f_4 from f_b at the interval $n \in [4,1000]$ is 3.3 %. The maximum δ of f_{416} from f_b at the majority of the interval $n \in [4,1000]$ is 2.4 %. Therefore, f_{416} is more precise than f_4 and is quicker to calculate than f_{16}.

Fig. 7 shows the plots of maximum absolute errors Δ between f_{416}, f_{16}, f_4 and f_b for $n \in [4,1000]$. Fig. 8 shows the plot of absolute errors Δ between f_{416} and f_b with respect to $n \in [4,1000]$ and $\gamma \in [0; \pi/2]$.

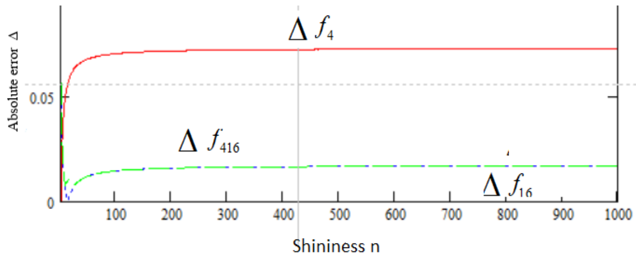

Fig. 7. **Maximum absolute errors between f_{416}, f_{16}, f_4 and f_b with respect to shininess n**

***Source*: compiled by the authors**

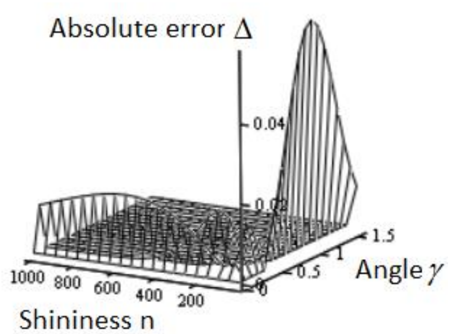

Fig. 8. **Absolute errors between f_{416} and f_b with respect to shininess n and angle γ**

***Source*: compiled by the authors**

The maximum Δ of f_4 from f_b at the interval $n \in [4,1000]$ is 0.07.

The maximum Δ of f_{416} from f_b at the majority of the interval $n \in [4,1000]$ is 0.02.

In the software product BRDF Explorer the teapot was visualized using OpenGL shading language and the proposed f_{416}.

The result of the teapot visualization is shown in Fig. 9.

Fig. 9. **The result of teapot visualization using f_{416}**

***Source*: compiled by the authors**

Therefore, the developed bidirectional reflectance distribution function provides highly-productive and highly-realistic object's glares reproduction.

CONCLUSIONS

The new combined bidirectional reflectance distribution function based on two cosine-power functions was proposed. The proposed function combines the highly-accurate function of the sixteenth degree for the glare`s attenuaton zone and the highly-productive function of the fourth degree for glare`s epicenter.

The connection point between two functions is calculated using the postulated approximated piecewise expression.

The plots that show the advantages of the combined function over the constituent functions were built. The approximation accuracy of Blinn-Phong BRDF in epicenter and attenuation zones was increased compared to the fourth-degree cosine-power function. The productivity of calculation was increased by 27 % compared to the sixteenth-degree cosine-power function.

The developed reflectance function was used for illustrative teapot visualization. To summarize, the usage of proposed bidirectional reflectance distribution function in computer grpahics systems provides the highly-realistic creation of the three-dimensional images.

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Комбіноване використання двопроменевих функцій відбивної здатності для підвищення продуктивності формування зображень

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АНОТАЦІЯ

Сучасні системи комп’ютерної графіки характеризуються вимогами високопродуктивного та високоточного формування зображень. Для підвищення продуктивності формування зображень здійснюється вдосконалення наявних і розробка нових моделей відбиття світла від поверхні. У статті описано розробку комбінованої моделі відбивної здатності поверхні на основі косинус-степеневих функцій. Проаналізовано особливості розрахунку та застосування двопроменевих функцій відбивної здатності поверхні. Описано особливості простих емпіричних моделей і теоретичних моделей відбиття, що враховують мікрофасетне подання поверхні об’єктів. Виділено недоліки наявних моделей відбивної здатності поверхні. Розглянуто косинус-степеневі функції четвертого та шістнадцятого степеня. Обґрунтовано необхідність розробки нової моделі відбивної здатності поверхні на основі двох косинус-степеневих функцій. Запропоновано формулу розрахунку розробленої комбінованої функції відбивної здатності. Отримано формулу обчислення точки з’єднання двох косинус-степеневих функцій. Отриману формулу апроксимовано більш простою за допомогою поліномів Чебишева. Побудовано графік значень формули точки з’єднання косинус-степеневих функцій. Побудовано графік відсотків виграшу від обчислення комбінованої функції відносно значень коефіцієнта спекулярності поверхні. Розраховано середнє значення виграшу у продуктивності від обчислення комбінованої функції. Побудовано графіки відносної та абсолютної похибки комбінованої функції від функції Блінна залежно від коефіцієнта спекулярності поверхні. Отримано тривимірний графік абсолютної похибки комбінованої функції від функції Блінна. За допомогою мови затінення OpenGL реалізовано розроблену модель відбиття у програмному засобі Bidirectional Reflectance Distribution Functions Explorer. Наведено зображення результатів візуалізації чайника на основі запропонованої комбінованої функції. Розроблена комбінована модель поєднує переваги складових косинус-степеневих функцій і може бути використана у високопродуктивних системах тривимірної комп’ютерної графіки.

Ключові слова: Двопроменева функція відбивної здатності; комбінована функція; косинус-степенева функція; модель Фонга; модель Блінна

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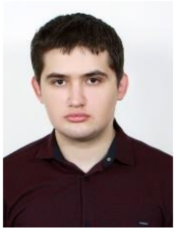

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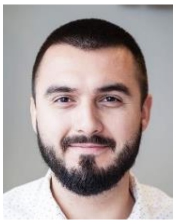

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