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SECTION 5
Artificial Intelligence and Cognitive Systems

The Development of Physically Correct Reflectance Model Based on Logarithm Function

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Abstract—**The purpose of this work is to develop the physically correct reflectance model based on logarithm function, which allows to increase the realism level of objects visualization.**

***Keywords*—reflectance model, bidirectional function, logarithm function, physically correct model, symbolic regression, energy conservation law, normalizing coefficient.**

I. Introduction

The main requirements to objects visualization [1] are the high speed and enough level of realism. The high speed of objects visualization is provided through using effective surface shading methods [2] and simple forms of light reflectance models. In order to achieve high realism level of objects visualization the surface microfacet division [3] and wave-particle dual theory can be used depending on the task. Realistic light reflectance models [4] should comply with the energy conservation law and Helmholtz reciprocity principle. The Helmholtz reciprocity principle [5] lies in the possibility of swapping the income and outcome light direction. The energy conservation law [6] means that the amount of light scattered over the surface can't be bigger than the amount of incident at surface light.

The reflectance models that comply with the energy conservation law are called physically correct [7]. Therefore, the development of new physically correct light reflectance models is necessary.

II. Literature Analysis

The two main approaches to scene rendering are rasterization and ray tracing.

The essence of ray tracing method [8] is that the light ray is directed from the camera through the image pixel, the pixel color intensity is calculated when the ray intersects with the scene point. This method is used only for the tasks of highly realistic graphics. The method is very laborious so it's not widely used for the tasks of dynamic graphics.

The rasterization method is more productive and lies in transforming the three-dimensional scene model into two-dimensional image. The geometrical primitives of surface are shaded, and the visibility of points is taken into account.

The optical characteristics of surface during the shading are described by bidirectional reflectance distribution functions [8] (BRDF). BRDF [9] show the ratio of reflected light radiance in the direction $\vec{V}$ to irradiance in incident light direction $\vec{L}$ (Fig. 1).

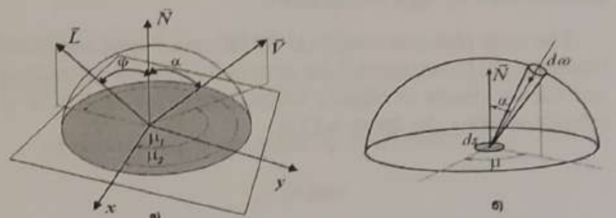

Fig. 1. The data for BRDF calculation

Bidirectional reflectance distribution functions are calculated using the formula [6]

$$\frac{\mathrm{d}\,I(\vec{V}_i)}{I(L_i)\cos\alpha_i\,\mathrm{d}\,\omega_i},$$

where $\mathrm{d}\omega$ – differential solid angle, $I(\vec{V}_i)$ і $I(L_i)$ – light intensity in the reflected light direction and incident light direction respectively.

The light intensity in given direction is calculated using formula

$$I=\frac{\mathrm{d}\,\Phi}{\mathrm{d}\,s\cos(\alpha)\,\mathrm{d}\,\omega},$$

where $\mathrm{d}s$ – area of light incidence, Φ – the radiant flux value.

The main two types [10] of BRDFs are theoretical (physically accurate) and empirical.

The theoretical BRDFs are used for modelling the surface light reflection with exact consideration of physical laws. BRDFs of this type are computationally expensive, so they are rarely used in highly productive computer graphics systems. In the theoretical reflectance models the surface roughness is described using a big number of microfacets. Among such models the Ward and Cook-Torrance BRDFs.

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Ward BRDF is based on using the mean facet orientation deviation m. For the BRDF calculation the formula is used [10]

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

where $\vec{N}$ – vector normal, $\vec{H}$ – half-vector between $\dot{L}$ and $\vec{V}$.

For the Cook-Torrance BRDF [10] calculation the Beckmann microfacet distribution D, Fresnel factor F (describes the reflection from the microfacet), the geometrical attenuation factor G (describes the shadowing of facets) are used. The function is calculated using the formula

$$\frac{D\cdot F\cdot G}{\pi(\vec{N}\cdot\vec{L})(\vec{N}\cdot\vec{V})}.$$

The empirical BRDFs approximately represent the surface reflectance characteristics, therefore they are characterized by high productivity.

The most common empirical BRDFs are Phong and Blinn functions [11], considering the simplicity of their calculation and decent results of objects visualization. Phong BRDF is calculated using the formula [12]

$$\cos(x)^n,$$

where n is surface specularity coefficient (shows the surface reflection degree), x – the angle between light reflection vector to viewer $\vec{V}$ and specular light reflection vector $\vec{R}$.

Energetically correct Phong model [6] includes normalizing coefficient calculation using formula

$$(n+1)/2\pi.$$

Blinn BRDF [13] modifies the Phong BRDF using the angle between normal and vector $\dot{H}=(\dot{L}+\dot{V})/|\dot{L}+\dot{V}|$. This angle [13] shows the value of surface deviation from maximum specular direction.

When the surface specularity coefficient reaches big values, the calculation complexity of Blinn and Phong functions is starting exponentially increasing.

Schlick BRDF [14] is the first degree approximation of the Blinn-Phong BRDF. Schlick BRDF is calculated using the formula

$$\frac{\cos(x)}{n-n\cdot\cos(x)+\cos(x)}.$$

The disadvantage of function is not enough level of glow's attenuation zone reproduction realism.

The modified Schlick BRDF, which was developed by article authors, is calculated using the formula [15]

$$\frac{2\cos(x)}{(1.25)(n-n\cdot\cos(x)+1.25\cos(x))^2}.$$

The modified Schlick function is more accurate in the attenuation zone of glare.

Gauss BRDF [10] is a function based on angle calculation between vectors. This BRDF provides the accurate glare reproduction but the angle calculation is a computationally complex operation. The function is calculated using the expression

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

The logarithm function based Blinn-Phong BRDF approximation is characterized with low computational requirements and high precision glow's epicenter and attenuation zones reproduction. The function is calculated using the formula [10]

$$(1-0.5\cdot\log_2(1-n\cdot\log_2(\cos(x)))).$$

Let's mark logarithm function based BRDF as F_{log}, Blinn-Phong BRDF as F_B, Schlick BRDF as F_s.

Fig. 2 shows the plots of F_{log}, F_B, F_s when $n=20$.

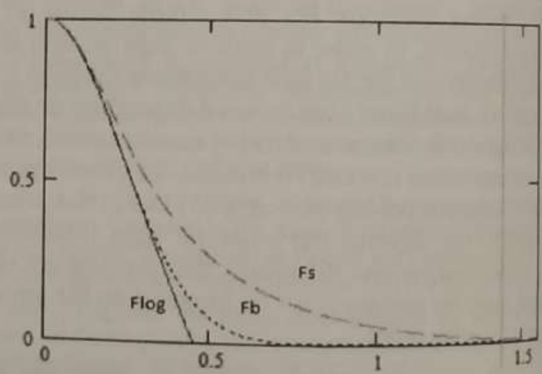

Fig. 2. F_{log}, F_B, F_s plots when $n=20$

Fig. 3 shows the plots of maximum relative errors δ between F_{log}, F_s and F_B at the interval $n\in[1;1000]$ in the glow's epicenter zone.

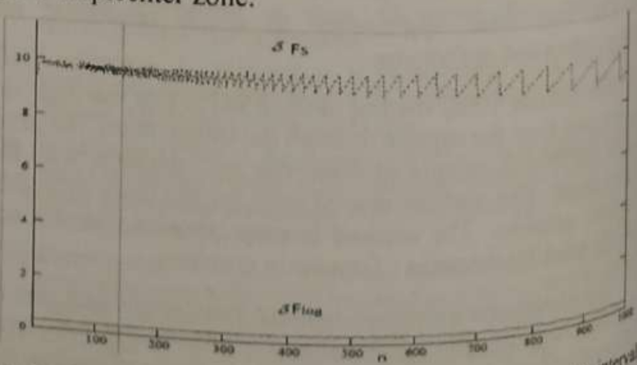

Fig. 3. The plots of maximum δ between F_{log}, F_s and F_B, at the interval $n\in[1;1000]$ in the glow's epicenter zone

... maximum δ between F_{log} and F_g at the interval ...[1;1000] in the glow's epicenter zone is 0.3%.

Fig. 4 shows the plots of maximum absolute errors Δ between F_{log}, F_s and F_g at the interval $n \in [1;1000]$.

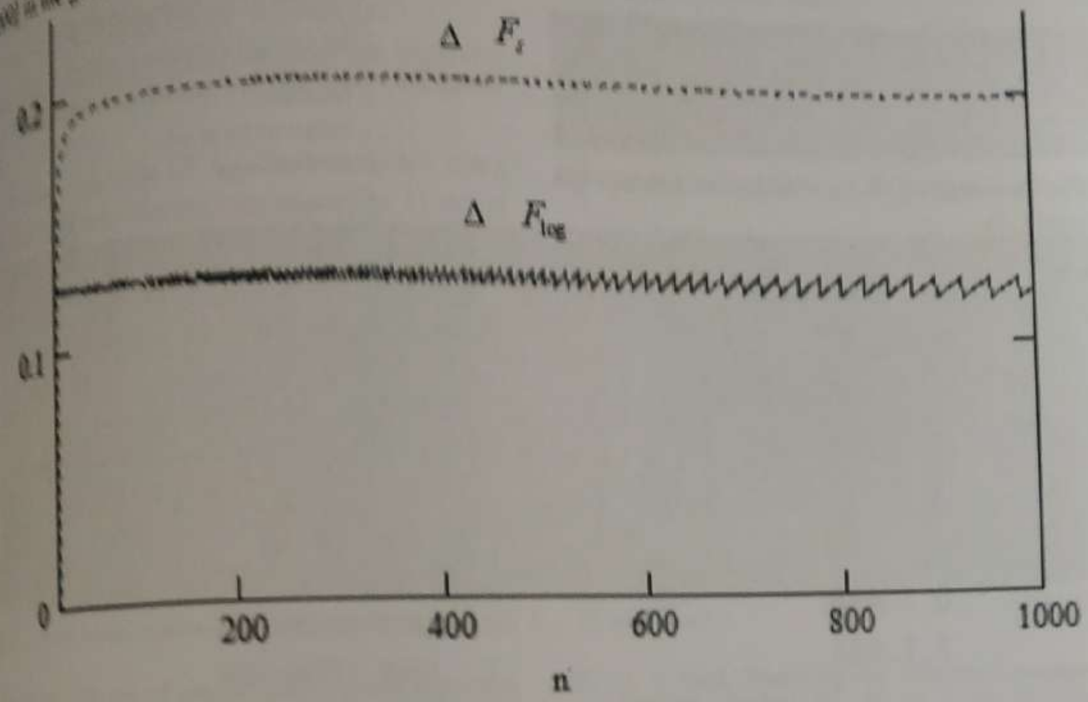

Fig. 4 The plots of maximum Δ between F_{log}, F_s and F_g at the interval $n \in [1;1000]$

The maximum Δ between F_{log} and F_g at the interval $n \in [1;1000]$ is 0.12, the maximum Δ between F_s and F_g is 0.2.

Therefore, F_{log} in comparison with F_s provides more precise F_g approximation in glow's epicenter and attenuation zones.

The disadvantage of F_{log} is non-compliance with the energy conservation law. So the calculation of F_{log} normalizing coefficient is needed.

III. Normalizing Coefficient Search For The Logarithm Function Based Reflectance Model

The surface light reflectance model should comply with energy conservation law. This is expressed mathematically by the condition [15]

$$\int_{\Omega} f_r(\omega,\omega_o)\cdot\cos(\theta)\,d\omega \le 1,$$

where $d\omega = \sin(\theta)\,d\theta\,d\varphi$, $f_r(\omega,\omega_r)$ – bidirectional reflectance distribution function.

We enter the normalizing coefficient $coef(n)$ for F_{log} in order to ensure its compliance with energy conservation law. From the condition of energy maximization we obtain the equation

$$coef(n)\int_{\Omega} f_r(\omega,\omega_r)\cdot\cos(\theta)\,d\omega = 1,$$

where $coef(n)$ is normalizing coefficient.

The $f_r(\omega,\omega_r)$ is replaced by F_{log} formula. We move to spherical coordinates. The equation takes the form

$$coef(n)\int_0^{2\pi}\int_0^{gran(n)}(1-0.5\cdot\log_2(1-n*\log_2(\cos(\theta))))\cdot$$
$$\cdot\cos(\theta)\sin(\theta)\,d\theta\,d\varphi = 1.$$

The limit value of F_{log} argument $gran(n)$, at which the function reaches zero, is calculated using the formula

$$gran(n) = acos(e^{\frac{-2.08}{n}}).$$

After the integration of left part by $d\varphi$ the equation takes the form

$$coef(n)\cdot 2\pi\cdot\int_0^{gran(n)}(1-0.5\cdot\log_2(1-n*\log_2(\cos(\theta))))\cdot$$
$$\cdot\cos(\theta)\sin(\theta)\,d\theta = 1.$$

The integral expression is replaced by the $Int(n)$

$$Int(n) = \int_0^{gran(n)}(1-0.5\cdot\log_2(1-n*\log_2(\cos(\theta))))\cos(\theta)\sin(\theta)\,d\theta.$$

Then the normalizing coefficient coef(n) is calculated using formula

$$\text{coef}(n) = \frac{1}{2\pi \cdot \text{Int}(n)}.$$

The values of coef(n) were calculated depending on $n \in [1,1000]$. The sample of 50 n, coef(n) pairs was saved in the text file (Fig .5).

```
n, coef(n)
1,0.483
2,0.665
3,0.855
4,1.048
5,1.243
6,1.438
7,1.634
```

Fig. 5. The saved in the text file sample of n, coef(n) pairs

The data of text file were used for the coef(n) formula selection using the software tool TuringBot (Fig. 6).

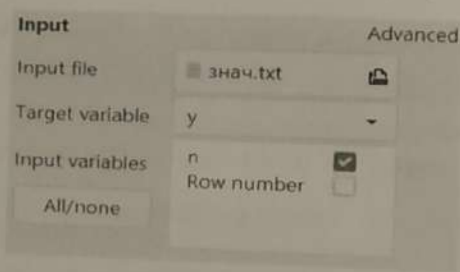

Fig. 6. Making the choice of text file for coef(n) formula selection in TuringBot

The root mean square error (RMS) was chosen as the error metric. Among the possible operations of formula the addition, multiplication and division were chosen (Fig. 7).

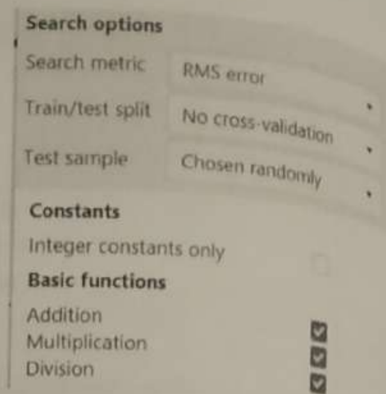

Fig. 7. The setting of error metric and possible formula operations in TuringBot

The set of possible coef(n) formulas was received (Fig. 8). The second last formula was chosen from the list taking to account its simplicity and low error value.

Size	Error	Function
1	62.583411	58.7142
3	0.183519	0.197639*n
5	0.006839	0.197244*(n+1.27235)
9	0.006503	(0.197234-(-1.39266e-08*n))*(n+1.2752)
10	0.001128	0.197253*((0.224161/n)+1.2449+n)
12	0.000280	0.197254*(n+1.23891)+(0.0681339/(0.641677+n))
18	0.000273	0.197254*(n-(0.242046/((-0.680778+(-0.00838297*n))*n-0.475525)-1.24...

Fig. 8. Set of possible coef(n) formulas in TuringBot

So, coef(n) for F_{log} .is calculated using the formula

$$0.197(n+1.24)+\frac{0.068}{0.64+n}.$$

Fig. 9 shows the plot of absolute errors Δ between the expression coef(n)$\cdot 2\pi \cdot$Int(n) and 1 depending on $n \in [1,1000]$.

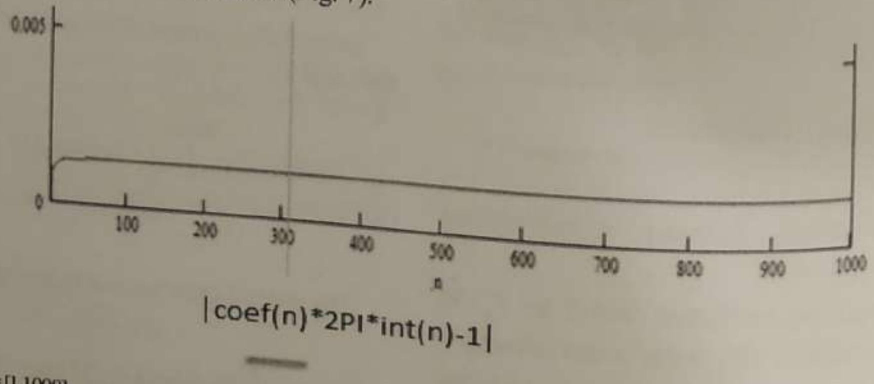

Fig 9. Δ depending on $n \in [1,1000]$

The maximum Δ value at the interval $n \in [1,1000]$ is [illegible].

IV. Practical Use of the Results

For the visualization of use of the modified logarithm function based reflectance model the web tool OneShader was used.

Fig. 10 shows the code of F_{log} implementation using GLSL (Graphics Library Shading Language). Fig. 11 shows the visualized spheres using the energetically correct logarithm function based model, original logarithm function based model, Schlick model.

```
float specLog=min(max((0.197*(n+1.24)+0.068/(0.64+n))*
(1.0-0.5*log2(1.0-n*log2(dot(N, H)))),0.0),1.0);
```

Fig. 10. Code of energetically correct F_{log} implementation using GLSL

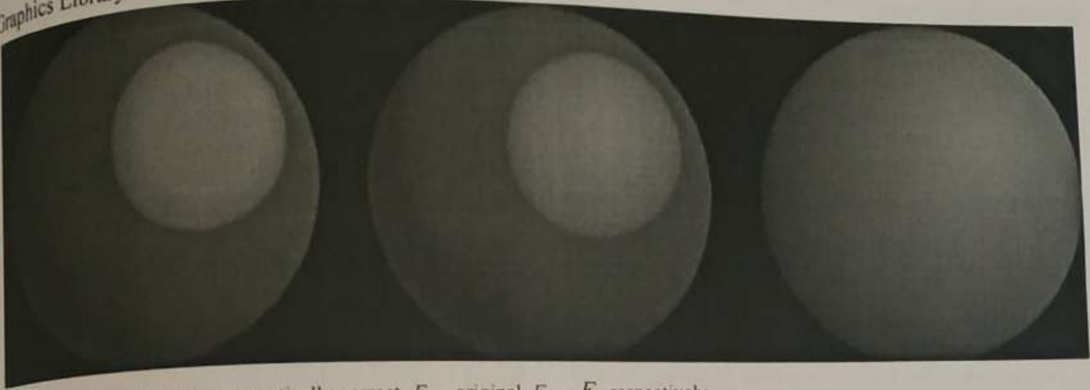

Fig. 11. Created spheres images based on energetically correct F_{log}, original F_{log}, F_s respectively

Summarizing, the use of energetically correct logarithm function based model allows more precise glow's epicenter and attenuation zones reproduction in comparison with F_s and original F_{log}.

V. Conclusions

In the article the energetically correct surface reflectance model based on logarithm function was developed. The logarithm function based model compared to the Schlick model allows approximating the reference Blinn-Phong model with considerably smaller absolute and relative errors.

The original logarithm function based reflectance model was modified by introducing the normalizing coefficient. The calculated with the usage of symbolic regression normalizing coefficient formula provides compliance with the energy conservation law and energy maximization condition.

Using GLSL shading language the visualization realism level was compared for the Schlick model, the original and energetically correct models based on logarithm function. It was found that the proposed model among the considered ones provides the most accurate specular color component reproduction.

The developed surface reflectance model can be used for the tasks of highly realistic computer graphics.

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