Stochastic ray tracing methods in problems of photorealistic image synthesis for augmented reality systems

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The article is devoted to the investigation of stochastic ray tracing methods in problems of photorealistic image synthesis for augmented reality systems and in particular for Head-Up Display (HUD). As a result of the study, we were convinced that the method of forward stochastic ray tracing can be successfully used for virtual prototyping of augmented reality systems. We extended the model of bidirectional stochastic ray tracing by forward ray tracing to simulate image formation in HUD systems without diffuse components.

Keywords: *stochastic ray tracing, photorealistic rendering, image synthesis, augmented reality, head-up display.*

1. Introduction

In computer graphics, photorealistic visualization methods can be used not only to construct images of 3D scenes but also to synthesize images in complex optical systems, such as augmented reality systems, in particular, to synthesize images for the head-up displays (HUD). A large number of articles is devoted to the design of the optical part of the display and evaluation of resulting image quality, for example, [5, 8]. However quality evaluation is commonly reduced to aberration analysis and contrast function calculation, while problem of visual quality evaluation including host analysis or rear projection effect are left behind. This work is focused mainly on visual quality analysis of designed HUD system. A principal scheme of the augmented reality image formation in a typical HUD is shown in Fig.1.

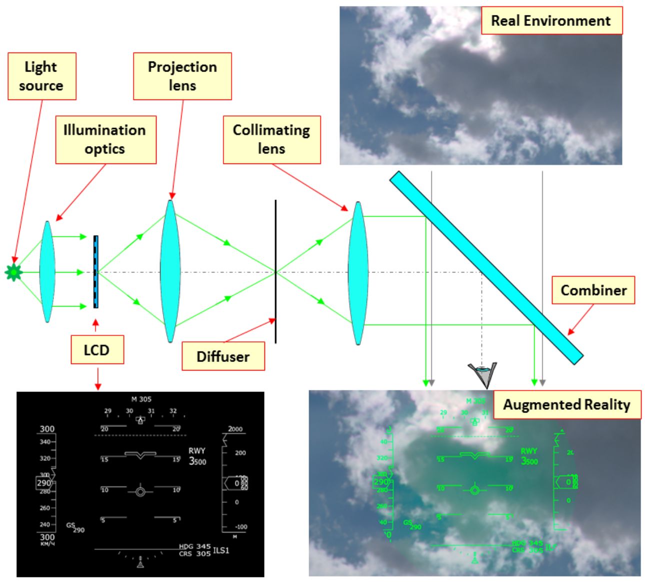

Fig. 1. Principal scheme of HUD with LCD source.

The light source together with the lighting optics illuminates the LCD, which shows some useful information in the form of a transparent slide. The projection lens forms an enlarged image of the slide in the plane of the diffuser. Then collimating optics creates the infinitely distant image of the diffuser. Finally, the beam splitter (combiner) redirects the light from the diffuser in such a way that the image formed on the diffuser and the surrounding reality become visible to the eye simultaneously. Thus, the eye observes the real environment augmented with text or graphic information formed on the LCD.

Using the methods of photorealistic visualization when designing such devices is very important because it makes it possible to build a virtual prototype and to reconcile the luminance of augmented reality objects with the luminance of real environment. Also, it allows choosing the optimal parameters of light sources, illumination optics and a projection lens.

The task of an image formation created by an optical system differs from the classical problem of constructing an image existing in computer graphics. The main difference is that the pinhole camera used in computer graphics forms an image in terms of luminance corresponding to the luminance of the observed scene objects, while in the optical system the image is the illuminance collected from the entire area of the output surface of the optical system. For the visual optical system, the eye is a part of the optical system (its position and pupil size are important components of the visualization system) and the eye retina perceives the illuminance as a luminance. Moreover, the optical system is part of the overall visualized scene and can contain surfaces with both diffuse and specular properties, and all components of luminance (direct vision, primary, caustic and secondary luminance) can be formed both in the observed scene and in the optical system itself. Therefore, the simulation was based on the method of bidirectional stochastic ray tracing, taking into account the caustic and secondary luminance using photon maps. There a large number of methods that allows to synthesize a physically correct image of 3D scene. Starting with Kajiya [4] who presented a solution of rendering equitation with backward ray tracing method a huge number of approaches were invented to numerically solve that equitation. In [10] Veach described the base principles of the photorealistic image synthesis methods. They include stochastic bidirectional ray tracing methods [1, 7], photon maps based methods [2, 6, 9], Vertex Connection and Merging method [3]. However, we should take into account that these methods are used to synthesize an image of scene that have no complex optical system consisting of dozens of specular faced between scene and virtual camera. The use of this method has made it possible to improve the efficiency of image synthesis significantly and take optical and geometric parameters of the elements of the optical scheme of the lens (lenses and mirrors) into account in the synthesis of the image. In addition, the influence of the optical and geometric parameters of the mechanical design of this lens is taken into account.

However, not in all cases, the method based on the bidirectional stochastic ray tracing approach are the most effective. In particular, a decrease in efficiency can occur when using this method for virtual prototyping of the augmented reality systems. Therefore, the aim of this paper is to investigate the methods of stochastic ray tracing, which allow obtaining maximum efficiency when forming physically correct images in the HUD.

2. HUD optical system models

In the scope of this investigation, we used two approaches to the formation of augmented reality image in HUD systems:

- with an intermediate diffuse screen (Fig.2);
- without an intermediate diffuse screen (Fig.4).

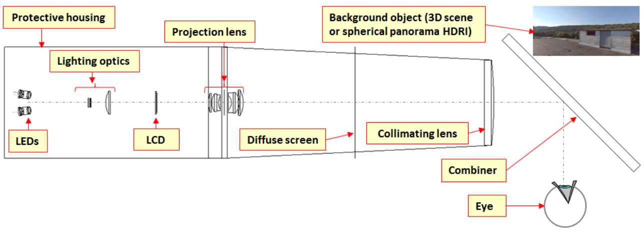

Fig. 2. Scheme with the intermediate diffuse screen.

LEDs with a very small emitting area were used as light sources. The size of the radiating surface is 0.2mm X 0.2mm. Lighting optics provide uniform illumination of the entire LCD surface. A slide with text or graphic information is formed on the LCD (Fig. 3).

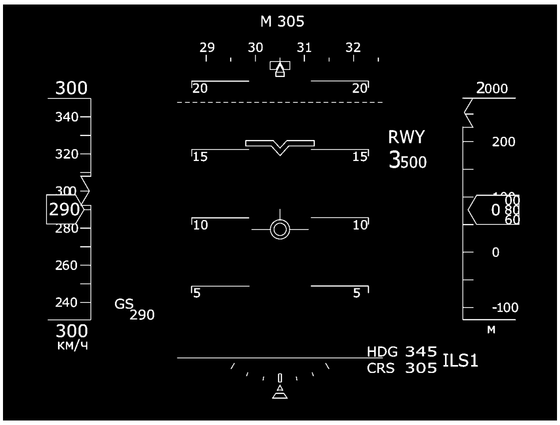

Fig. 3. An example of the image formed on the LCD.

On this slide, all useful information is presented in form of the transparent zones on a black background. However, the black background is not absolutely absorbing. In modern LCD the contrast between absolutely transparent areas and the opaque background is about 300: 1.

The image of the slide enlarged with the projection lens is formed on the diffuser, which is the source of the secondary radiation for the subsequent part of the imaging system in the HUD. The main disadvantage of the first approach is reduced visible luminance of the augmented reality object due to the light scattering on the diffuser.

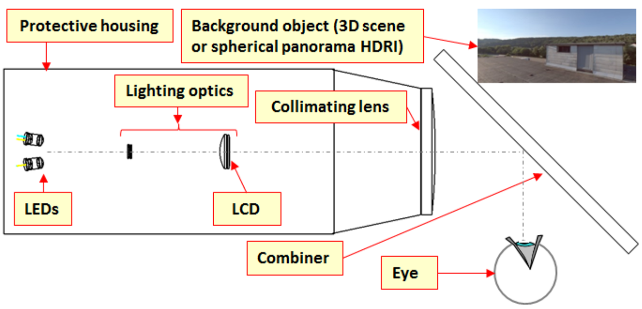

Fig. 4. Direct scheme of HUD image formation.

In the second approach, the lighting optics is the same as in the first one, but in this case, there is no intermediate projection on the diffuse screen. This gives us two important advantages:

- Reduction of the HUD optical system size;
- Reduction of energy loss due to light scattering.

However, together with the above advantages, a problem of the modeling of such systems arises. The problem relates to the choice of the most effective method of stochastic ray tracing.

3. Description of the method

In the case of a diffuse screen, the only source of luminance is the caustic luminance of the diffuse screen, which can be calculated using photon maps. Obviously, for such a scheme, the most effective calculation method is bidirectional stochastic ray tracing using photon maps.

Photorealistic rendering of optically complex scenes reduces to solving the rendering equation [4] for each point of the scene image. The rendering equation allows us to calculate the luminance of the color component *c* on the point $\vec{p}$ and in a given direction $\vec{v}$. For static scenes the rendering equation can be written as follows:

$$L(\vec{p},\vec{v},c)=\tau(\vec{p},\vec{v},c)\begin{pmatrix} L_0(\vec{p},\vec{v},c)+ \\ \frac{1}{\pi}\int\limits_{4\pi} BSDF(\vec{p},\vec{v},\vec{v}',c)L(\vec{p},\vec{v}',c)(\vec{n}\cdot\vec{v}')d\omega \end{pmatrix} \quad (1)$$

where:

$L_0(\vec{p},\vec{v},c)$ – the luminance of the object emission at the point of observation,

$\tau(\vec{p},\vec{v},c)$ – the transmittance (transparency) of the medium between the observer and the observation point,

$\frac{1}{\pi}\int\limits_{4\pi} BSDF(\vec{p},\vec{v},\vec{v}',c)L(\vec{p},\vec{v}',c)(\vec{n}\cdot\vec{v}')d\omega$ – the luminance formed by primary and secondary illumination of the observed object.

where:

$BSDF(\vec{p},\vec{v},\vec{v}',c)$ – the luminance factor of the surface (or Bidirectional Scattering Distribution Function (BSDF)) from the source $\vec{v}'$ in direction $\vec{v}$ to observer,

$L(\vec{p},\vec{v}',c)$ – the luminance of the ambient light in a solid angle $d\omega$ in the direction $\vec{v}'$ to the observation point $\vec{p}$.

$\vec{n}$ – the normal to the surface at the point of observation.

The rendering equation (1) is an equation with infinite recursion. If the contribution of the secondary radiation to the total value of the apparent luminance is significant, then the bidirectional stochastic ray tracing based on the "Russian roulette" method using photon maps for calculating the caustic and secondary luminance allows performing physically correct infinite integration in the most efficient manner [10].

Stochastic ray tracing method can be based on the stochastic forward and backward ray tracings. Each component of the ray tracing can be used for the image synthesizing. The main problem of the separate methods is a significant reduction of the simulation efficiency when the scene contains scattering elements. In the latter case the most effective soltion is one of the variations of stochastic bidirectional ray tracing with photon maps method. This method allows us to collect illuminance from scatterings elements of the optical system. On the other hand, if the scene do not contain scattering elements the efficiency of the methods (vs. bidirectional stochastic ray tracing) significantly increases. As a result, to increase the efficiency of synthesizing an image formed by the optical systems without scattering elements the authors had extended the general approach of bidirectional stochastic ray tracing with photon maps. The extension allowed merging of an image components formed with stochastic forward or backward ray tracing only.

Note that for realistic visualization and correct evaluation of image quality in HUD, we implemented the model of the eye as a lens camera.

To calculate the local illuminance value we can use well know dependence between the luminance of the small pupil area and illuminance from this light area:

$$dE(\vec{p},c) = L(\vec{p}_i,\vec{v}_i,c)(\vec{n}\cdot\vec{v}_i)d\omega_i \qquad (2)$$

where $L(\vec{p}_i,\vec{v}_i,c)$ – the luminance of the pupil area in the point $\vec{p}_i$ and direction to the pupil area $\vec{v}_i$,

$d\omega_i$ – the solid angle from the image point $\vec{p}$ to the pupil area in the point $\vec{p}_i$,

$\vec{n}$ – the direction of the exit pupil normal.

The eye luminance can be recalculated from the illuminance (2) using the following equation.

$$L(\sigma,c) = \frac{E(\vec{p},c)}{\cos(\sigma)\cdot\Omega} \qquad (3)$$

where σ – the field of view angle.

Figure 5 illustrates the method of the local luminance calculation. The total illuminance is obtained by integrating all local illuminance values computed for a given image point.

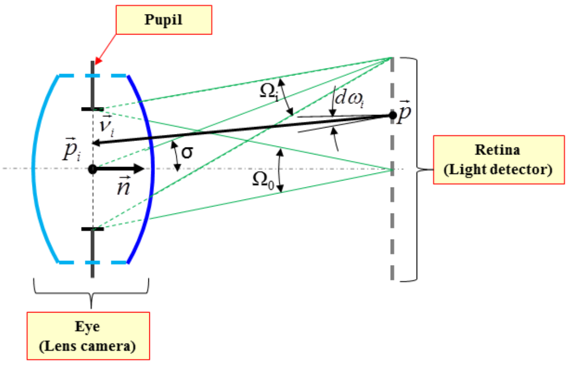

Fig. 5. Local illuminance calculation from the lens exit pupil area.

4. Investigation of the results for a scheme with a diffuse screen

Figure 6 shows the simulation results of an augmented reality photorealistic image (with closed channel of the real environment luminance). The main effect under simulation is the rear projection effect that forms a bright spot on top of an image with graphical and digital information. In this case, the most appropriate method is stochastic bidirectional ray tracing with photon maps. Since there was only one diffuse surface with dozens of specular surfaces on the path between light source and observation plane, all the illumination was reduced to caustic illumination and common methods based on important sampling solutions gave no advantage. Also methods of sole forward or backward ray tracing have not succeeded, that means that no distinct image was synthesized at the equivalent time. The latter is due to low effectiveness of collimation and projection lenses of this device. The most efficient solution was simple bidirectional ray tracing with photon maps.

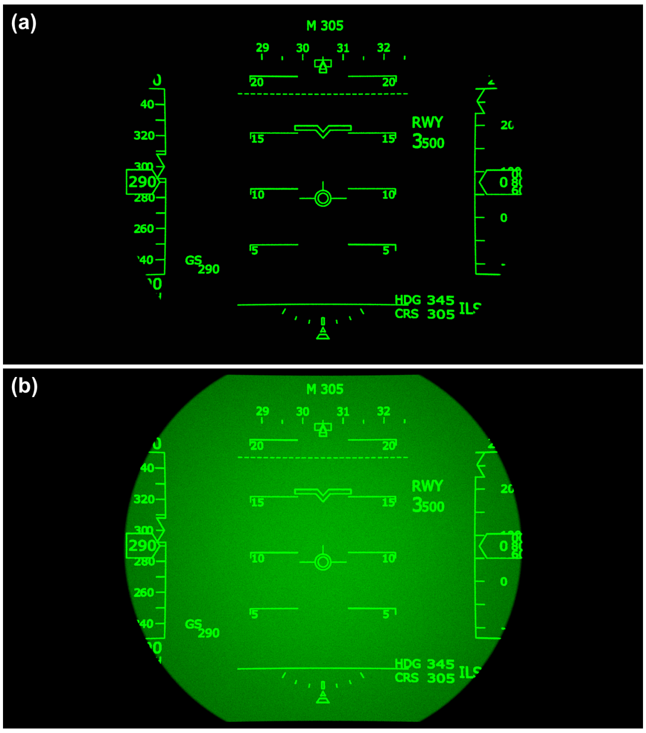

Fig. 6. The HUD image simulation result for case (a) LCD with absolute contrast and (b) LCD with real contrast.

Figure 7 shows the result of an image synthesis in HUD with an open channel to monitor the real environment.

Fig. 7. An example of AR image synthesis for the environment with a high level of luminance.

The HDRI of a spherical panorama was used as a model of the real environment. In this case, the HUD luminance is 1600 cd/m^2. The maximum and minimum luminance of HDRI is 21013 cd/m2 and 292 cd/m^2, respectively. The eye is adapted to the average luminance, which level, in this case, is 2140 cd/m^2.

It is clearly seen that in the case of a very bright object in the field of view, the level of LED luminance is not enough for a good visualization of useful information in the HUD.

The next figure (Fig.8) shows a case with a much less level of the real environment luminance.

Fig. 8. An example of AR image synthesis for the environment with a low level of luminance.

In this case, the HUD luminance is equal to 10000 cd/m^2 and it is the maximum level of luminance in the entire image. The minimum luminance of HDRI is 34 cd/m^2. The eye is adapted to the average luminance, which level, in this case, is 234 cd/m^2.

From the example, it is seen that with a low level of the real environment luminance, all the additional useful information in the HUD is completely distinguishable. However, in this case, a disadvantage in the form of an undesirable bright spot in the field of view is clearly visible, which worsens the conditions for observing the real environment.

By reducing the LED luminance, one can achieve the optimal ratio between luminances of useful graphic information and an unwanted spot caused by the direct visibility of the light source through the non-absolutely black background of the LCD. Figure 9 shows the simulation result of augmented reality image with the optimal level of luminance in the AR channel of HUD.

Fig. 9. Example of AR image synthesis for optimal selection of the LED brightness level.

In this example, the HUD luminance value is 1600 cd/m^2 and it is the maximum level of luminance in the entire image. The minimum brightness of HDRI has not changed and is 34 cd/m2. The eye is adapted to the average luminance, which value, in this case, has decreased to the level of 142 cd/m2.

5. The investigation results for a scheme without diffuse screen

The HUD scheme without a diffuse screen is the most promising, both in terms of dimensions and in terms of energy saving. However, simulation of such a scheme using the method of bidirectional stochastic ray tracing is practically impossible because, in this case, there are no sources of secondary and caustic radiation. In this case, the integral in the rendering equation (1) goes to zero and only the luminance of the direct vision L_0 remains. This circumstance, in turn, leads to a fatal decrease in the effectiveness of the method of bidirectional ray tracing using photon maps, since we see the source directly, and this source has a very small area of the order of 0.04 mm2. In other words, we switch to the ordinary backward ray tracing, which reads the brightness of the primary light source.

Figure 10 shows the HUD images obtained in result of simulation of the scheme without a diffuse screen for the LCD matrix with ideal and real contrast respectively.

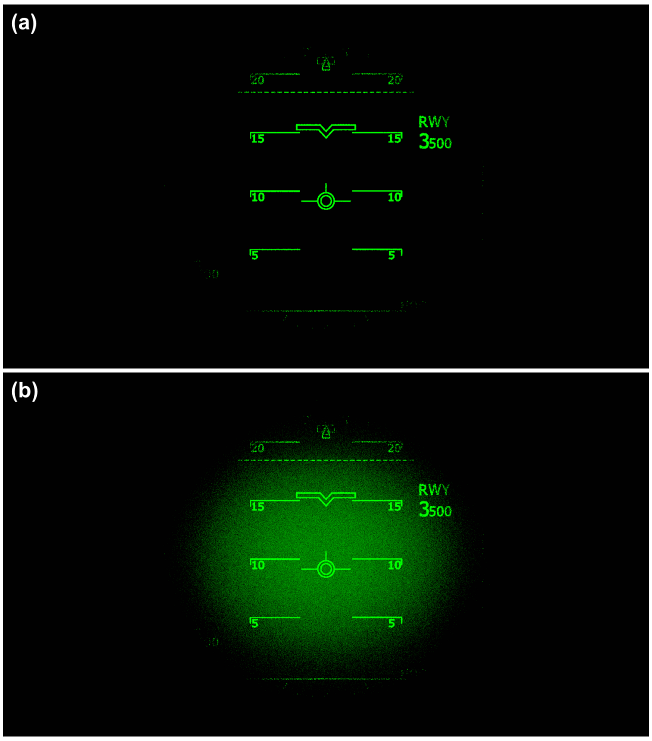

Fig. 10. The HUD image simulation result for case (a) LCD with absolute contrast and (b) LCD with real contrast.

The fact that only part of the LCD is in the field of view is explained by the fact that in this case we used a simplified version of the collimating lens (singlet) with a limited field of view. This circumstance does not hinder our research because the essence of the research is to find the most effective method of stochastic ray tracing for particular types of HUD, and not to design the optical system of the lens with a large field of view.

In fist case modeling was performed by the pure Path Tracing method. It collected luminance from LEDs that illuminate the screen. It should be noted that the calculation of the HUD images shown in Fig. 10, takes two days. At the same time, the noise level is quite high, that noticeably reduces the image quality. This is because of the fact that the size of the LED is small and, accordingly, the effectiveness of the backward ray tracing method is low.

Since in this case the method of backward ray tracing turned out to be ineffective, we used the method of forward stochastic ray tracing. The idea of the method is that the light source emits rays with a density proportional to the angular intensity distribution, and the rays, propagated through the optical system, are accumulated on the radiation receiver, which is specified as the model of the eye. We implemented a method of forward stochastic ray tracing and carried out a similar simulation of an image formation in the HUD. The result of this simulation is shown in Fig. 11.

High image quality, obtained by the method of direct stochastic ray tracing, allowed visualization of image defects caused by the peculiarities of illumination optics design. The calculation time required to achieve the same quality is 2 to 3 orders of magnitude lower than in the case of backward ray tracing.

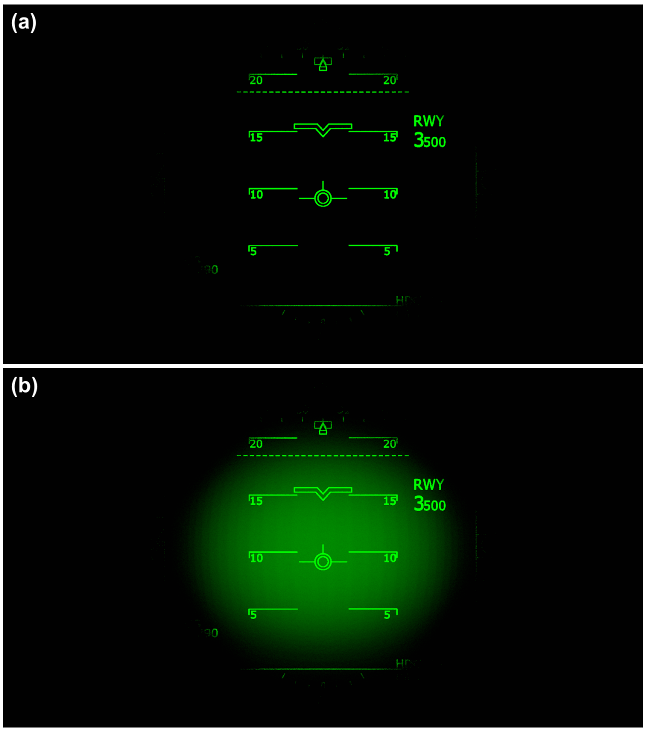

Fig. 11. Example of AR image synthesis with use of forward ray tracing.

To form the full image in real environments, we implemented a hybrid ray tracing method. In this method, the full image is synthesized from images obtained both by the method of forward ray tracing and by the method of bidirectional ray tracing using photon maps. The results of such a hybrid simulation are shown in Fig. 12. At the moment, the automatic generation of image obtained by the hybrid method is not possible and merging is performed manually by summing two synthesized images in real luminance.

Fig. 12. Example of AR image synthesis with use of hybrid ray tracing.

In this case, the luminance of HUD in the central part of the field of view is 10000 cd/m2. The maximum and minimum luminance of HDRI is 21013 cd/m2 and 292 cd/m2, respectively. The eye is adapted to the average luminance, which level, in this case, is 2940 cd/m2.

6. Conclusion

As a result of the current research, we found out that the method of forward stochastic ray tracing can be successfully used for virtual prototyping of augmented reality systems.

We extended the model of bidirectional stochastic ray tracing by separate forward ray tracing procedure which efficiency simulates image formed by HUD systems without diffuse components.

We are planning to improve the method of hybrid ray tracing by possibility of automatic selection of the type of ray tracing used to form various image components.

7. Acknowledgements

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8. References

[1] Eric P. Lafortune, Yves D. Willems. Bi-directional path tracing // Proceedings of Third International Conference on Computational Graphics and Visualization Techniques (Compugraphics '93), p.145-153, Alvor, Portugal, December 1993.

[2] Hachisuka Toshiya, Jensen Henrik Wann. Stochastic progressive photon mapping // ACM Trans. Graph. 2009. dec. Vol. 28, no. 5. P. 141:1 141:8. URL: http://doi.acm.org/10.1145/1618452.1618487.

[3] Iliyan Georgiev, Jaroslav Křivánek, Tomaś Davidovič, Philipp Slusallek, Light Transport Simulation with Vertex Connection and Merging // ACM TOG 31(6), SIGGRAPH Asia 2012.

[4] J. T. Kajiya. The rendering equation // Computer Graphics (SIGGRAPH '86 Proceedings), 1986, vol. 20, p.143-150.

[5] James Melzer "Head Mounted Displays", Mac Graw Hill (1997) (ISBN 978-1456563493).

[6] Jensen Henrik Wann, Christensen Per. High quality rendering using ray tracing and photon mapping // ACM SIGGRAPH 2007 courses. SIGGRAPH '07. New York, NY, USA: ACM, 2007. URL: http://doi.acm.org/10.1145/1281500.1281593.

[7] M.Pharr, G.Humphreys Physically Based Rendering. From theory to implementation // Morgan Kaufmann, 2004.

[8] Ozan Cakmakci and Jannick Rolland, "Head-Worn Displays: A Review", Journal of Display Technology, Vol. 2, No. 3, September 2006

[9] Toshiya Hachisuka, Jacopo Pantaleoni, and Henrik Wann Jensen. 2012. A path space extension for robust light transport simulation. ACM Trans. Graph. 31, 6, Article 191 (November 2012), 10 pages

[10] Veach Eric. Robust monte carlo methods for light transport simulation: Ph. D. thesis. Stanford, CA, USA: Stanford University, 1998. AAI9837162.

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