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Hybrid ray tracing method for photorealistic image synthesis in head-up displays

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ABSTRACT

The paper describes the use of stochastic ray tracing methods for synthesizing of photorealistic images, formed by optical systems of augmented reality devices, that combines image synthesized by the optoelectronic device with the surrounding environment. As the result of the research, new methods are proposed that make it possible to increase the efficiency and preserve the physical correctness of stochastic ray tracing methods in the task of the photorealistic images synthesis formed by optical systems. The authors show that in such cases the methods of direct stochastic ray tracing are more effective for visual modeling of the augmented reality picture on an example of the head-up display (HUD) optical system. The proposed approaches allow to combine direct, inverse and bi-directional stochastic ray tracing methods in one calculation. The work is illustrated by examples of the synthesized images observed in HUD optical systems.

Keywords: stochastic ray tracing, optical system, photorealistic image, light scattering, HUD, virtual prototyping, augmented reality.

1 INTRODUCTION

Recently the task of physically correct modeling and photorealistic visualization of optically complex scenes has become more important for the modeling and design of complex optical devices operating in real environments. Of particular relevance is the physically correct modeling and virtual prototyping of the augmented and mixed reality systems, where photorealistic visualization of the real environment model is combined with the synthesized image projected by the optical system into the eye of the observer. In a number of optical system design software packages, for example, in ZEMAX, it is possible to construct a flat object image, like Bitmap Image Analysis, but this visualization does not reflect all the effects that arise in the optical system (light scattering on the elements of the optical system and the structural elements, diffusion on LCD matrices, diffuse screens, etc.) and does not take into account the three-dimensionality of the observed scene, which does not allow modeling of such an effect as variable defocusing within the visible field of view. On the other hand, a number of computer graphics systems allow modeling of three-dimensional scenes images obtained using a polynomial model of lens. In the simplest cases, such systems that are presented in published works[1,2,3] are very effective from the point of view of the ray tracing speed through the optical system but do not take into account the light scattering on the elements of the optical system, lens housing, frames and the lens ends. In this case, the optical system participates in the ray tracing not as a geometry, but as a "black box" that guides the rays falling into it in accordance with a given conversion function that connects the coordinates on the pupil with the coordinates in the focal plane. The disadvantages of such models include a significant decrease in the efficiency of image synthesis for high-aperture and wide-angle optical systems when the position and size of the pupil vary greatly in the field of view.

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As noted above, the distinctive feature of the augmented and mixed reality systems modelling is in combining the images of the real scene observed through the so-called combiner and the synthesized image projected by the optical system[4,5]. A schematic diagram of the Augmented Reality system illustrating the HUD is shown in Figure 1.

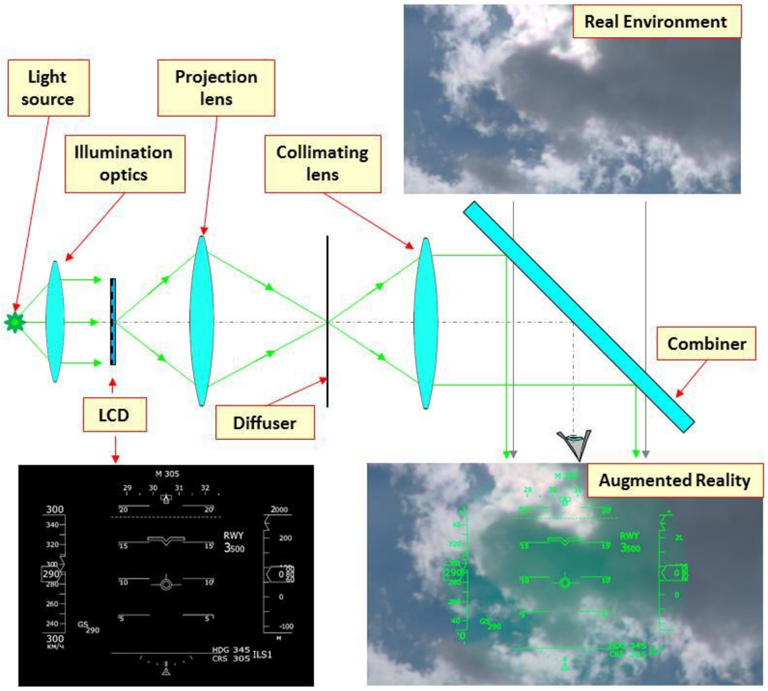

Figure 1. Principal scheme of HUD with LCD image source.

In this example, the LCD matrix, with a dynamic slide with a synthesized image is illuminated and projected onto a diffuse screen, located at the focus of the collimation system projecting the image of the slide through the combiner to the observer's eye. At the same time, the observer sees the surrounding space through the same combiner. In this case, the eye model as a point observer (pinhole camera) may turn out to be inaccurate because of the possible uneven illumination of the pupil and the effects associated with aberrational vignetting. So, for a physically correct simulation, it should be replaced by an eye model with characteristics such as pupil size, field of view and focal length. Therefore, to solve the problem of rendering using the "real" eye model, it is necessary to add two dimensions of integration of the visible brightness, namely, on the exit pupil of the eye. This task is analogous to the task of calculating the distribution of illumination on the image receiver and for its solution, forward, backward and bidirectional stochastic ray tracing methods using photonic maps can be used. As a rule, the method of ray tracing is selected depending on the physical effect that is expected in the imaging model, for example, the "ideal" image of the scene, the scattering of light on elements of the optical system or elements of its construction, glare, etc., and also depending on the ratio of aperture of the observer and light sources.

There are a large number of methods that allows synthesizing a physically correct image of 3D scene. Starting with Kajiya[6] with a solution of rendering equitation with backward ray tracing method a huge number of approaches were invented to numerically solve that equitation. Veach[7] described the base principles of the photorealistic image synthesis methods. They include stochastic bidirectional ray tracing methods[8,9], photon maps based methods[10,11], Vertex Connection and Merging method[12]. However, we should take in account that these methods are designed to synthesize an image of scene which does not contain complex optical system of dozens of specular faces between scene and observer. The use of bidirectional ray tracing methods has made it possible to significantly improve the efficiency of image synthesis and take optical and geometric parameters of the optical system elements (lenses and mirrors) into account during the image synthesis. It should be also taken into account, the optical and geometric parameters of the mechanical design of this lens influences on the image synthesis result.

However, not in all cases, the method based on the bidirectional stochastic ray tracing approach are the most effective. In particular, a significant efficiency decrease can occur when virtually prototyping the augmented reality systems with this method. Therefore, in the scope of the current research an investigation of the stochastic ray tracing methods was performed to find out which of them allows obtaining maximum efficiency when synthesizing the physically correct images formed by the HUD optical system.

2 OPTICAL SYSTEM MODEL

Synthesis of photorealistic images of optically complex scenes formed by optical systems is solved using ray tracing methods that can be either forward or backward, stochastic or deterministic. The methods of forward ray tracing solve the problem of transferring light energy from light sources to the observer, and the methods of backward ray tracing allow integrating the apparent luminance of image points within the visible aperture. In this case, the luminance in each direction inside the visible aperture is calculated using the rendering equation[6]. For static scenes, the luminance of the color component of the object c at the point of the surface $\overrightarrow{p}$, with the local normal $\vec{n}$ and in the direction $\vec{v}$, can be written as following:

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

where $L_0(\vec{p},\vec{v},c)$ is the own object luminance in an observation point,

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

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

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

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. Equation (1) allows us to calculate only the luminance in the direction of observation. 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:

$$dE(\vec{p},\vec{v},c)=L(\vec{p},\vec{v},c)(\vec{n}\cdot\vec{v})d\omega \tag{2}$$

where $\vec{n}$ is the normal to the exit pupil surface.

The total illumination that forms the image is the integral of luminance in all possible directions. From the point of view of the calculations efficiency, arises the fundamental question: what solid angle should be used to integrate the brightness, performed by the ray tracing method. Partial solutions of this problem have been previously presented by Livshits et al[13].

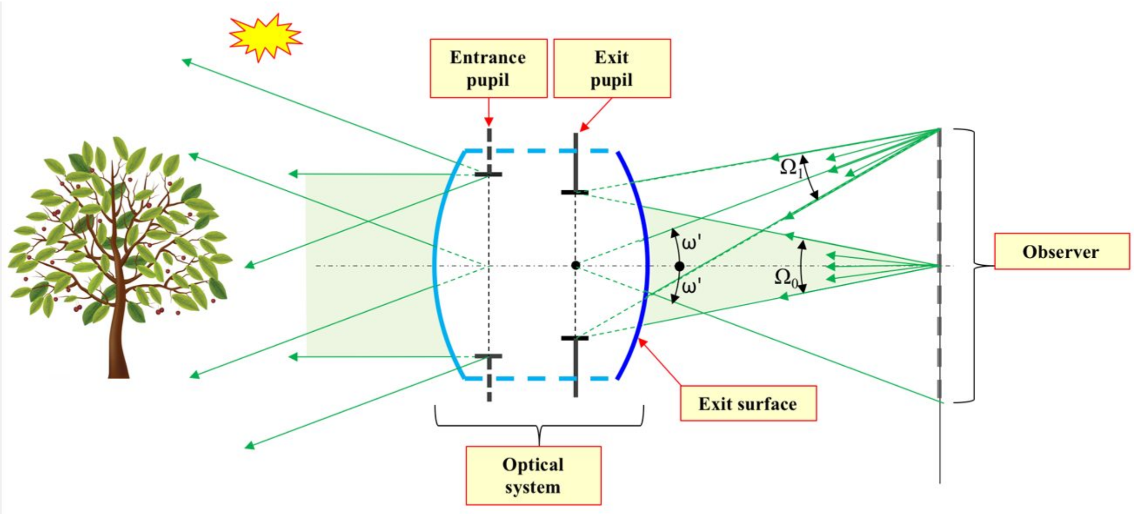

Figure 2. Calculation of the image illuminance distribution by the backward ray tracing method.

Figure 2 shows two possible integration options - integration over the exit pupil of the optical system and integration over the possible viewing area through the optical system. In the first case, we synthesize the "ideal" image formed by the optical system, and in the second case we synthesize a "real" image containing a mixture of "ideal" and background images caused by the effects of light scattering in the optical system. It should be noted that the "ideal" image includes all the aberration effects that arise in the optical system forming the image. To calculate the "ideal" component of the image, the luminance integration is carried out over the exit pupil of the optical system, i.e. over the area that limits the light flux coming to the image point. In the simplest case, for example, a single lens, the exit pupil is defined by the lens boundary, however in complex optical systems its angular size can differ greatly from the angular size of the last element of the optical system. In wide-angle optical systems, the angular size of the exit pupil can be orders of magnitude smaller than the angular dimension of the last lens element and collecting the illumination of the image within this element can slow the image synthesis process by an order of magnitude. If the modeling requires taking into account the effects of light scattering on the elements of the optical system, then integration of the luminance must be performed on its output surface. Naturally, when collecting luminance from the entire output surface of the optical system, an "ideal" image component will be formed, but due to the high noise component its quality might be unacceptable. This effect is observed mainly in stochastic methods of ray tracing. The optimal solution for this task is sequential synthesis and addition of two images formed for the area of the exit pupil and the region outside of the exit pupil, respectively. To implement this process, within the framework of one calculation, a stratification method was used that divides the integration region into the pupil and non-pupil parts. In the case of uniform emission of rays onto the surface of the exit pupil and the output surface of the optical system, the integrated illuminance of the image point is the sum:

$$E(\vec{p},c)=\frac{1}{N}\left(\frac{A_P\sum_{j=1}^{N}L\left(\vec{p},\vec{v_j},c\right)\left(\vec{n}\cdot\vec{v_j}\right)^4}{Z_P^2}+w\frac{(A_L-\mathrm{A}'_P)\sum_{i=1}^{M}L(\vec{p},\vec{v_i},c)(\vec{n}\cdot\vec{v_i})^4}{Z_L^2}\right) \qquad (3)$$

where w is the a user-defined weigh factor equal to the ratio of the number of rays N emitted to the exit pupil area (which area size is A_P and is located at a distance Z_P from the image plane) to the number of rays M emitted into the output surface area (which area size is A_L minus the exit pupil area size projected to the output surface A'_P and is located at a distance Z_L from the image plane).

It should be noted that the backward ray tracing method is not always quite effective when modeling an optical system. In some cases, a more efficient solution will be the use of the forward ray tracing method. In this case, the optical system focuses rays emitted by the light source in the image plane. Figure 3 illustrates this calculation method.

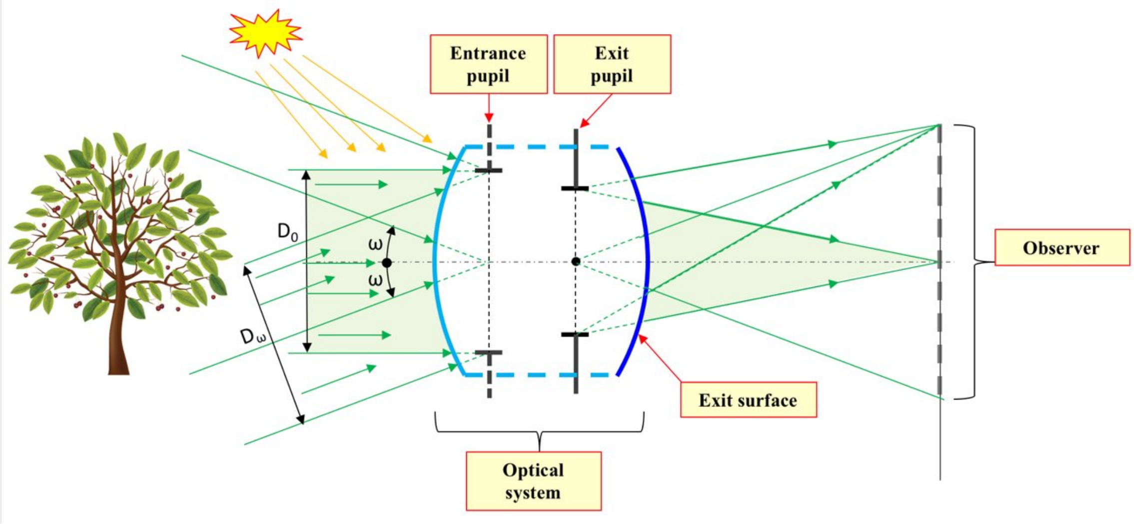

Figure 3. Calculation of the image illuminance distribution by the forward ray tracing method.

Unlike the method of backward ray tracing, the accumulation of rays forming the image illuminance can be made, first, within the entrance pupil and the field of view of the optical system and, secondly, within its first surface and in the 360° field of view. In the first case, the "ideal" image component is formed, and in the second case the background component is formed which is caused by the light scattering in the optical system. As a rule, the radiant sources (primary or secondary) are located at a considerable distance from the first surface or the entrance pupil of the optical system and the probability of their light emission in needed direction is extremely small (from 10^{-4}), therefore stochastic methods of direct ray tracing are extremely disadvantageous. Even effective multi-threaded ray tracing methods cannot help here. To increase the efficiency of stochastic ray tracing methods, it was suggested to use the technique of stratified sampling of rays falling on objects and are in direct line of sight of the optical system. To model the components of the "ideal" image, an additional condition to use of this sampling method is that light source is in the field of view of the optical system. For direct stochastic ray tracing, this sample is randomly split into two independent samples. At first, it is a standard multiple importance sampling, used in the stochastic ray tracing methods that excludes light scattering in the direction to the optical system, and, secondly, it is sampling in the direction of the optical system. Since sampling in the direction of the optical system is narrow and focused, it can be assumed that the probability density of radiation in this solid angle is constant and proportional to the value of the radiant intensity (scattering) in the direction toward the center of entrance pupil of the optical system. By analogy with (3), a weighting factor w is set that will determine the probability of scattering to the area of the optical system or its entrance pupil if the scattering source is in the field of view and the "ideal" image component is modeled. At the same time, in the method of forward stochastic ray tracing, the energy transferred by the beam is modified. For rays that do not go in the direction of the optical system, the energy is scaled by $1/(1-w)$, and for rays oriented to the optical system, by $I_P \cdot \Omega_P/(w \cdot I_S)$, where I_P is the radiant intensity (scattering) in the direction to the surface of the optical system, Ω_P is the solid angle to the optical system, I_S is the integral radiant (scattering) intensity. Such a solution makes it possible to effectively use the method of stochastic ray tracing during the synthesis of the image formed by the optical system.

The forward and backward ray tracing methods show quite high computational efficiency when there are no sources of scattering inside the optical system. If the optical system contains diffuse elements or we need to simulate the effects of light scattering on its elements, then these methods may show themselves ineffective. To maintain efficiency, it is necessary to use methods of bi-directional stochastic ray tracing with photon maps. These methods allow to form photon maps on the optical system surfaces and then read their luminance in the direction of the observer.

The developed methods were implemented and used for modeling and virtual prototyping of the head-up display system (HUD).

3 HUD OPTICAL SYSTEM MODELS

Within the framework of current research, a study was made of the effect of the background created as a result of the rear projection of the LCD matrix of the HUD optical system on the quality of the image being formed under various environmental conditions. Two approaches to the image forming in augmented reality of HUD optical system were investigated:

- In the first case, a classical projection system with an intermediate diffuse screen was used. The augmented reality image formed on the LCD matrix is projected onto a screen visible by an observer through a combiner with a collimation lens (see Figure 4).

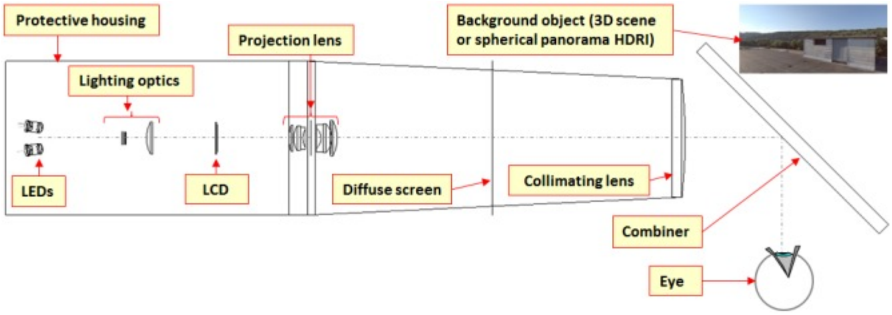

Figure 4. Scheme of HUD device with intermediate diffuse screen.

- In the second case, the intermediate diffuse screen was excluded from the HUD optical system and the observation of augmented reality image projected directly from the LCD matrix was investigated (see Figure 5).

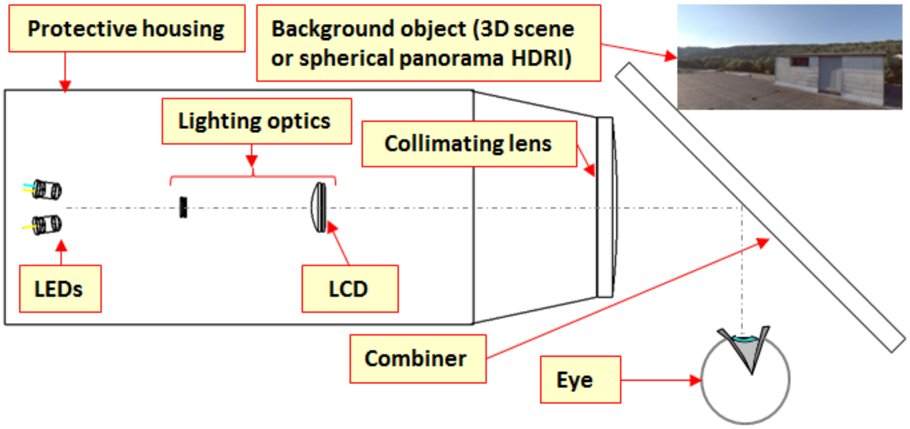

Figure 5. Scheme of HUD device with direct image formation.

Light sources are LEDs with a very small emitting area. The emitting surface size is 0.2mm X 0.2mm. The lighting optics provides uniform illumination of the entire LCD surface. LCD matrix forms a slide with text or graphic information (see Figure 6).

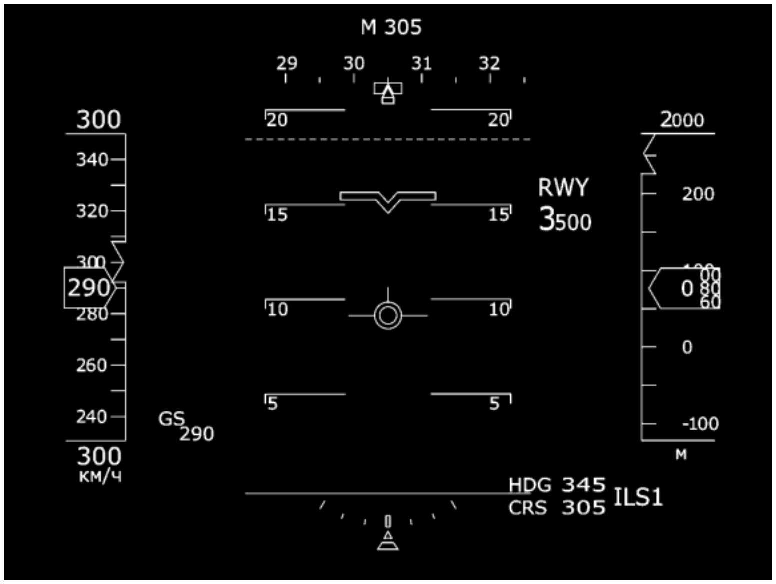

Figure 6. An image example formed on LCD screen used in virtual prototyping of HUD devices.

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.

In the first type of the HUD device optical system, the actual slide image enlarged by the projection lens is formed on the diffuser, which is the source of secondary radiation, and in its turn is projected by the collimator system and the combiner into the observer's eye. The main drawback of this solution is the reduction in the brightness of the augmented reality image due to light scattering on the diffuse screen.

The second type uses similar lighting optics, but it does not have an intermediate projection system and a diffuse screen. The collimator system and the combiner project the image formed on the LCD matrix directly into the observer's eye. Compared with the first solution, this approach allows to reduce the size of the HUD optical system and to reduce the energy loss caused by the diffusion of light on the diffuse screen. The drawbacks of this solution include a significant diffraction scattering and a physical structure of the LCD, that can be seen in a collimator with a large magnification.

A common drawback of both solutions is the background illumination of the image caused by the non-absolute contrast of the LCD matrix. In this paper, an investigation of the possibility of physically correct modeling of visual effects arising in the HUD augmented reality systems and the effectiveness of various stochastic ray tracing methods for solving photorealistic visualization problems was made.

4 SIMULATION RESULTS ANALYSIS

In the scope of research, virtual prototypes for both HUD system designs were implemented. A visual quality was evaluated along with ergonomics to the device user.

4.1 HUD optical system with an intermediate diffuse screen

The main simulated effect in the HUD optical system with an intermediate diffuse screen is the rear projection effect, which results in a bright spot on top of the image projected from the LCD matrix. Since the optical system contains scattering objects, the forward and backward stochastic ray tracing methods are not effective. This is due to the low efficiency of the collimating and projection optical components of the HUD optical system, as well as the wide diffusion angle of the intermediate diffuse screen. If we treat the computational efficiency as the ratio of the number of rays successfully detected by the receiver (in the case of forward ray tracing) or the light source (in the case of backward ray tracing) to the total number of emitted rays, then the efficiency of the methods of forward and backward ray tracing would be a fraction of a percent. Therefore, the most optimal method is bidirectional stochastic ray tracing with the integration of secondary and caustic luminance components on the diffuse screen. If we exclude external illumination from consideration, the main contribution to lighting is created by caustic illumination scattered on a diffuse screen. In this model we used the method of bidirectional stochastic ray tracing, based on creating maps of direct, caustic and diffuse visibility. These maps were formed in the process of backward stochastic ray tracing, and the component of caustic and diffuse illumination was formed in the process of direct stochastic ray tracing when direct beams hit the area of these maps.

Figure 7 shows the simulation results of an augmented reality photorealistic image. The channel of the real environment luminance was closed, that allowed to visualize a rear projection effect with higher contrast.

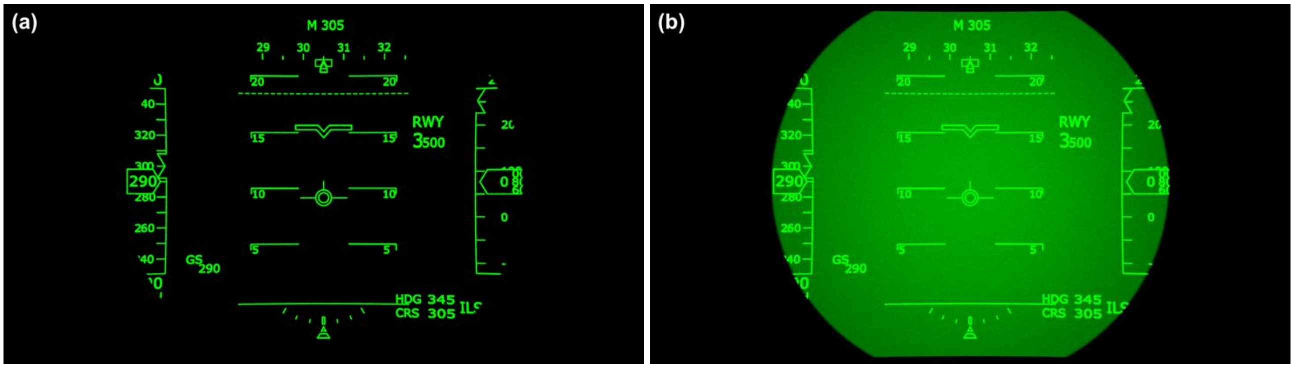

Figure 7. The HUD with an intermediate diffuse screen image simulation result for case of (a) LCD with absolute contrast and (b) LCD with real contrast.

As modeling was also aimed at investigation of the visibility of the useful augmented reality information within the real environment and influence of the bright light spot caused by the rear projection effect on the visibility of the environment. From a practical point of view, this was to determine the power parameters of HUD light sources (LEDs), so that this spot would have the minimum possible contrast (or would not be visible at all) against the real objects, and the useful information formed on the LCD matrix would be clearly visible (have maximum contrast).

To simulate the conditions of real observation, two types of scenes were used:

- spherical panoramas with a high dynamic range, given in luminance values;
- 3D scenes in which the level and luminance differences could be synthesized in accordance with conditions close to real.

In both cases the same bidirectional stochastic ray tracing method was used. In the case of the spherical panorama model this method is reduces to simple backward stochastic ray tracing.

Figure 8 shows the result of an image synthesis in HUD with an open channel to monitor the real environment.

Figure 8. The HUD image simulation result within the real environment in the case of high environment luminance and low HUD light source 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 adopts 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 (Figure 9) shows image simulation in the case of the much smaller level of the real environment luminance with keeping HUD light source luminance the same.

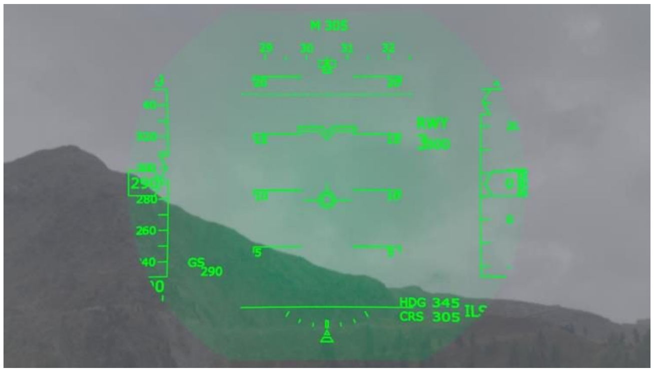

Figure 9. The HUD image simulation result within the real environment in the case of low environment luminance and high HUD light source luminance.

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

As we can see from this simulation when level of the real environment luminance is low all the additional useful information in the HUD is completely distinguishable. However, it is clearly seen disadvantage here is a visible bright spot in the field of view caused by a rear projection effect. It seriously 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 undesired bright spot caused by the direct visibility of the light source through the non-absolutely black background of the LCD. Figure 10 shows the simulation result for augmented reality image with the found optimal level of LED luminance in the AR channel of HUD.

Figure 10. The HUD image simulation result within the real environment in the case of low environment luminance and optimal HUD light source luminance.

In this example, the HUD luminance value is set to optimal value of 1600 cd/m^2 and it is the maximum level of luminance in the entire image. The minimum brightness of HDRI is 34 cd/m2. The eye is adapted to the average luminance, which value has decreased to 142 cd/m2.

4.2 HUD optical system without an intermediate diffuse screen

The HUD scheme without an intermediate diffuse screen looks much more promising due to the smaller size and greater energy efficiency. However, it is almost impossible to use the bidirectional stochastic ray tracing method to model such type of optical system, because there are no sources of secondary and caustic luminance in the HUD optical system. In this case, the indirect luminance component in the rendering equation (1) drops to zero, and the final luminance is formed only by the direct visibility luminance component L_0. This leads to the fact that to model the component of the augmented reality image formed on the LCD matrix, it is necessary to use the forward or backward stochastic ray tracing methods. It should be noted that both these methods of stochastic ray tracing in separate are also quite ineffective. The problem of the backward ray tracing method is in the small size of the light source which is about 0.16 mm^2, while an eye sees area of dozens of mm^2. In its turn in forward ray tracing methods the main problem is the small area of the eye entrance pupil in relation to the area of the collimator system exit pupil, i.e. light sources illuminate the area much greater than the size of the eye entrance pupil. In scope of this research a comparison was made between the efficiency of forward and backward stochastic ray tracing methods in constructing an image of the augmented reality of the HUD optical system.

Next figure (Figure 11) shows the simulation result of constructing a photorealistic image for a HUD system without an intermediate diffuse screen and for LCD matrices with absolute and real contrasts.

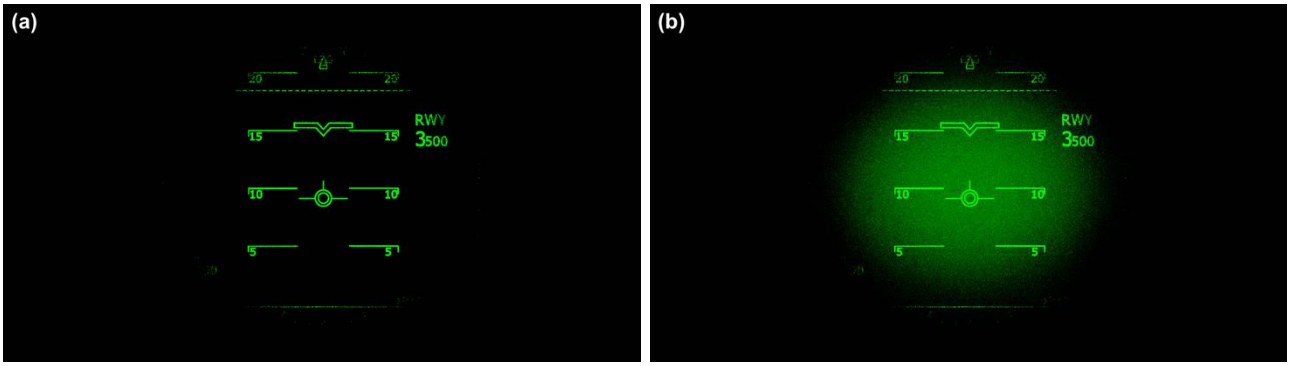

Figure 11. The HUD without an intermediate diffuse screen image simulation result with backward stochastic ray tracing method for case of (a) LCD with absolute contrast and (b) LCD with real contrast.

The simulation was executed with use of the backward stochastic ray tracing method. The rays were traced from the eye retina through the eye pupil, through the optical system, were modulated by the LCD matrix and if after that they hit the emitting surface of the LED, its luminance was read and recorded on the retina of the eye. The small size of the LEDs and the presence of raster scatterers in the illuminating channel of the HUD reduces the probability of the rays reaching the light sources, which can explain the quite low quality of the resulting image. As result it took full 2 days of calculations to get the images shown in the figure 11.

As the method of backward stochastic ray tracing shows very low efficiency in this optical system, the method of forward stochastic ray tracing was used. This method corresponds to the model of natural perception of the image and can be used in the case when the observer has a nonzero aperture (the eye pupil in this case). In this method, the rays are emitted by light sources with a probability density proportional to the distribution of the spatial and angular intensity of the radiation. Propagating through the optical system, the rays are modulated by the LCD matrix and hit on the entrance pupil of the observer's eye, where they are accumulated as the illuminance on its retina. Using expression (2), this accumulated illuminance can be recalculated in form of the visible luminance of the LCD matrix image. The result of image formation simulation with this method applied to the same HUD optical system is presented at the figure 12.

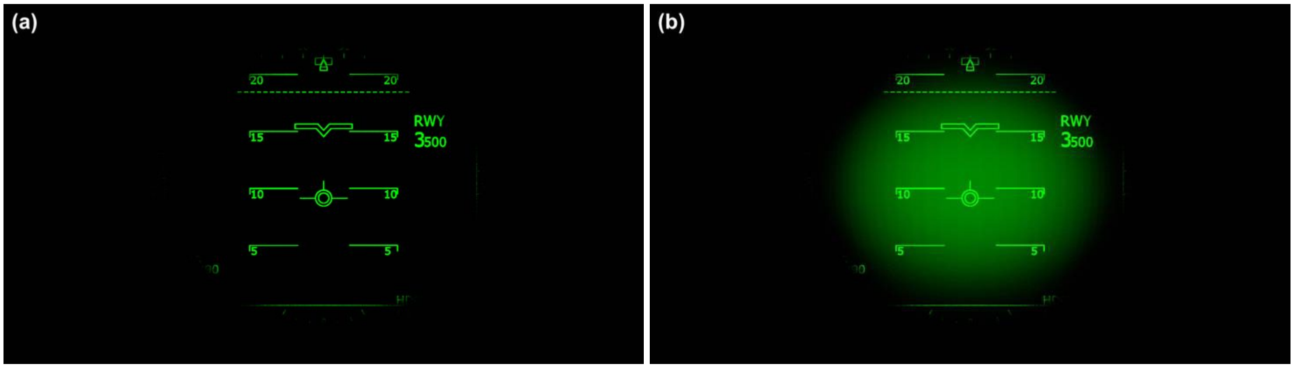

Figure 12. The HUD without an intermediate diffuse screen image simulation result with forward stochastic ray tracing method for case of (a) LCD with absolute contrast and (b) LCD with real contrast.

The use of the forward stochastic ray tracing method resulted in the significant synthesized image quality improvement and allowed to visualize the image defects caused by the lighting optics design features and the LCD matrix cellular structure. It also should be mentioned that the calculation time required to synthesize this image was only about 4 hours. So, in this case the forward stochastic ray tracing method is by 2-3 orders of magnitude more effective than the backward stochastic ray tracing.

To synthesize a full image of the augmented reality system of HUD in a real environment, two methods of stochastic ray tracing were combined. In current approach, to construct the full image, images from two channels were summed: the first one was calculated by the forward stochastic ray tracing method, and the second one by the bidirectional stochastic ray tracing method with photon maps. The full image synthesized with this approach is shown in the next figure (Figure 13).

Figure 13. The HUD without an intermediate diffuse screen image simulation result with merged forward and bidirectional stochastic ray tracing methods within the real environment.

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

5 CONCLUSION

As the result of the current research it was found that synthesizing photorealistic images formed by optical systems can be performed by the forward stochastic ray tracing method in the most effective way in comparison with the methods of backward and bi-directional stochastic ray tracings.

In the framework of the research, it was shown that computer graphics methods based on stochastic ray tracing methods can be successfully applied in analysis and virtual prototyping of various types of augmented reality optical systems, including systems that do not contain scattering components.

In the following research the authors plan to automate the process of selecting the optimal ray tracing methods and automatically merge the results of the simulation into one final image in the case of several ray tracing methods used simultaneously.

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REFERENCES

[1] Hanika, J. and Dachsbacher, C., "Efficient Monte Carlo Rendering with Realistic Lenses," Proc. EUROGRAPHICS 2014, Volume 33 (2014), Number 2.

[2] Wu, J., Zheng, C., Hu, X. and Xu, F., "Rendering realistic spectral bokeh due to lens stops and aberrations," Vis Comput DOI 10.1007/s00371-012-0673-4.

[3] Joo, H., Kwon, S., Lee, S., Eisemann, E. and Lee, S., "Efficient Ray Tracing Through Aspheric Lenses and Imperfect Bokeh Synthesis," Proc. Eurographics Symposium on Rendering 2016, Volume 35, Number 4 (2016).

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

[5] Zhdanov, D.D., Potemin, I.S., Kishalov, A.A., Zhdanov, A.D. and Bogdanov, N.N., "Stochastic ray tracing methods in problems of photorealistic image synthesis for augmented reality systems," Proc. 27th International Conference on Computer Graphics and Vision, Perm, PSU, 24-28 September 2017, 42-46 (2017).

[6] Kajiya, J. T., "The rendering equation," Proc. SIGGRAPH '86, Computer Graphics, vol. 20, 143-150 (1986).

[7] Veach E. “Robust monte carlo methods for light transport simulation," Ph. D. thesis. Stanford, CA, USA: Stanford University, AAI9837162 (1998).

[8] Lafortune, E.P. and Willems, Y.D., "Bi-directional path tracing," Proc. Third International Conference on Computational Graphics and Visualization Techniques (Compugraphics '93), Alvor, Portugal, December 1993, 145-153 (1993).

[9] Pharr, M. and Humphreys G., "Physically Based Rendering. From theory to implementation," Morgan Kaufmann (2004).

[10] Toshiya, H. and Wann, J. H., "Stochastic progressive photon mapping," ACM Trans. Graph., Vol. 28, no. 5. P. 141:1 141:8 (2009).

[11] Wann, J.H. and Per. C., "High quality rendering using ray tracing and photon mapping," Proc. ACM SIGGRAPH 2007 courses. SIGGRAPH '07. New York, NY, USA: ACM (2007).

[12] Georgiev, I., Křivánek, J., Davidovič, T. and Slusallek, P., "Light Transport Simulation with Vertex Connection and Merging," ACM Trans. Graph Vol. 31, no. 6, SIGGRAPH Asia (2012).

[13] Livshits, I., Letunovskaya, M., Potemin, I., Okishev S. and Zhdanov, D., "Aberration vignetting phenomena and its visualization in wide angular objectives," Proc. SPIE 10021, 2 November 2016, Optical Design and Testing VII, 100210A (2016).