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Ray Visualization in Optical System Design: the Role of Ray Coloring

E.D. Biryukov[1], I.G. Ryzhova[2], A.G. Voloboy[3]

Keldysh Institute of Applied Mathematics RAS, Moscow, Russia

[1] ORCID: 0000-0003-4297-6813, birukov@gin.keldysh.ru
[2] ORCID: 0000-0003-1613-3038, ryzhova@gin.keldysh.ru
[3] ORCID: 0000-0003-1252-8294, voloboy@gin.keldysh.ru

Abstract

The design of optical systems is a complex process. Currently, computer simulation is widely used for it. Simulation results can be presented both in quantitative and qualitative form. And of course, one of the main means of qualitative presentation of the results is their scientific visualization which allows to visually evaluate the result without spending significant time and resources on the analysis of the numerical output data. In the paper we present a ray visualization technique with rays colored with artificial colors. We emphasize the role of color in technique. Coloring of the visualized rays or their segments according to the conditions specified by the designer allows you to quickly conduct a qualitative analysis of the optical system under development. The application of this technique significantly speeds up the complex and time-consuming process of the design of the optical systems. Practical examples are given demonstrating the use of colored ray visualization in design of backlight plate of a mobile phone, motorcycle headlight and lens system.

Keywords: optical system design, ray visualization, ray coloring, coloring conditions, optical system efficiency.

1. Introduction

Optical systems are everywhere in the modern world, they are in almost any device. There are several optical systems in a vehicle, in a mobile phones, etc. The design of such systems is a complex process. Currently, computer simulation is widely used for it. Simulation results can be presented both in quantitative and qualitative form. And of course, one of the main means of qualitative presentation of the results is their scientific visualization.

One of the main goals of a qualitative presentation of the results is the ability to quickly visually evaluate the result without spending significant time and resources on the analysis of the numerical output data. The use of color for these purposes cannot be overemphasized. It is precisely the right colors that make it possible to understand at a glance the correctness or fallacy of the design, to see what its deficits and mistakes are, to understand the ways of its further development. Therefore, the correct choice of colors in the scientific visualization of simulation results is extremely important.

The classical Monte Carlo ray tracing [1] is a powerful technique for modeling almost all effects in geometric optics. This method is now one of the most popular ones for lighting simulation of complicated scenes consisting of great number of geometrical objects with different surface and medium properties. A drawback of all stochastic methods is the undesirable noise. There are many techniques of scientific visualization which help to investigate the scene of optical device, in particular investigate the influence of simulation noise. But we focus on one of them: this is a visualization of ray trajectories which are calculated during simulation of complicated optical systems [2, 3]. These rays are displayed directly in the viewport of the lighting simulation program, or in the viewport of the computer-aided design (CAD) system to which the lighting simulation module is attached as a plugin. This way of the presentation of the simulation result allows significantly simplify its interrogation. A designer just sees the cases of incorrect trajectories, understands causes of their appearance and eliminates them. Ray visualization tools are often applied in optical system design [4, 5]. Also this way is useful for software developers, as means of debugging and optimizing algorithms [6, 7].

For display of some particular ray trajectories, display criteria are used. This technique allows displaying only rays satisfying to the specified criteria. For example, one can set hitting some particular object as a criterion, or particular event type occurred with ray (for example, reflection or refraction only, etc.). Building complicated criteria which consist of several conditions combined with logical operators AND, OR, NOT is also possible [7].

In the paper we present a ray visualization technique with rays colored with artificial colors. We emphasize the role of color in technique. Coloring of the visualized rays or their segments according to the conditions specified by the designer allows you to quickly conduct a qualitative analysis of the optical system under development. The application of this technique significantly speeds up the complex and time-consuming process of the design of the optical systems.

A similar approach and analysis of the use of color in industrial design tasks has not been found in the literature known to us.

2. Coloring conditions for ray visualization

In lighting simulation system [8] developed by us in the Keldysh Institute of Applied Mathematics RAS, three coloring modes are currently used for displaying trajectories of rays: natural color mode, artificial color mode with criterion applied to an entire ray (starting from the light source to the moment of ray absorption or collecting by sensors), and artificial color mode with criterion applied to each ray segment. The simplest mode is natural coloring mode. In this mode each ray segment is displayed with the same color as the color which this light has in reality. No additional settings are required in this case. This mode can be useful for analyzing color distortion in an optical system [7].

But if we would like to demonstrate some desirable effect or, contrary, wrong behavior of light then it is possible to color these rays by artificial colors. So a color mode allowed painting of each ray with some color specified by certain criterion should be applied here. In some cases, visualization of rays satisfying only to one criterion is insufficient. Often it is also necessary to show other rays or all traced rays, but the rays satisfying to the criterion should be somehow highlighted to be noticeable. For this case, coloring of rays according to the certain conditions has been developed. In this mode the rays satisfying to some criteria are painted with a color explicitly specified by a program user. User should build a list of criteria with colors corresponding to each criterion. Also he should set the default color which is used for painting rays not satisfying to the defined criteria. In such a way, it becomes possible to simultaneously demonstrate trajectories of rays painted with different colors that satisfy to different criteria.

First of all this mode is convenient because it allows seeing ratio of quantity of rays satisfying to some criterion by quantity of all other rays, or quotas of rays satisfying to different criteria. One more case, when color criteria method is useful, is investigation of rays deviated from expected trajectory in the optical system. At the same time it is possible to compare “expected” trajectory with “incorrect” ones and find particular place (or places) where trajectories have gone in wrong direction. This provides quickly and easily discovering of mistakes or wrong design of the optical systems.

The list of events [9] that can be used as conditions for color criteria are:

- Ray starting at a certain light source;
- Ray hitting on a certain object;
- Ray hitting on any object with certain material applied;

- Ray hitting on some observer (virtual sensor);
- Type of optical event happened with ray (reflection, refraction, absorption) on a scene object; this criterion can be useful, for example, to detect stray reflections on a lens system which cause highlights [10];
- Ray killing, i.e. indefinite state of the ray at the end of its trajectory. This happens usually if the scene is set incorrectly, or if some computational error took place.

The main difference of the color criteria used in our system from the general criteria for ray visualization [11] is the impossibility of creating complex criteria with several conditions combined with logical operators. This implementation was made for the sake of the GUI simplification and ease of use.

Sometimes it is also insufficient to display the entire ray in one color. Most often this happens if the ray satisfies several criteria simultaneously. In this case, it is advisable to paint with the criterion color not the entire ray but only those segments of the ray that directly satisfy the criterion. Besides, this mode can be useful if you need to evaluate the directions of rays after an event has occurred, and compare these directions with the directions of other rays. The segments of other rays may have almost the same directions, and so may be indistinguishable from the segments of interest. Coloring of the segments of interest in a different color allows to highlight them.

In the lighting simulation complex developed by us, the segment is visualized according to color criteria if its starting point satisfies them. For example, if the criterion implies that a ray hits a certain object and some ray is reflected from this object, then the color corresponding to the criterion will be painted on the segment just after reflection, and not on the segment before it. We assume that this is quite natural: an event at the beginning of a segment changes its color ("behavior") after the event has occured.

3. The first example: Cell phone backlight plate

One case where color criteria proved to be useful in the design of an optical system was the design of a light guiding plate for a push-button cell phone. This plate is made of transparent plastic and is used as a light guide to illuminate the buttons. It had perforations and edges of a certain shape located in certain places. All these elements are intended to split the light from two LEDs into several beams and direct them to the phone button areas.

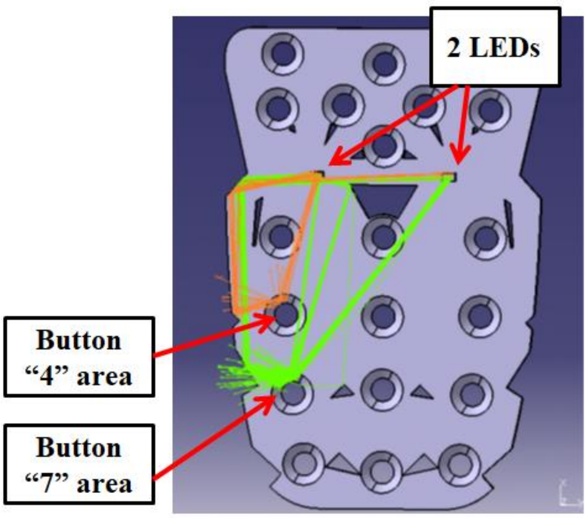

Fig. 1. Visualization of rays hitting the "4" button (orange) and the "7" button (green).

Lighting simulation of this plate found insufficient illumination of the button with the number "4". Although it is located in the second row, closer to the LEDs, it was lit less than the buttons of the third row which are further away from the light sources. This was most noticeable when comparing this button with the adjacent “7” button. This problem first appeared when rendering the built model, but was later confirmed using analysis of propagation of rays by visualizing them with a color criterion. The criteria were as following: the rays hitting the “4” button were painted orange; the rays hitting the ‘7’ button were painted green (Fig. 1). All other rays were hidden using the general ray display criterion. In Fig. 1 one can see that number of rays hitting the “4” button is noticeably less than number of rays hitting the “7” button.

Further analysis has shown that the reason of such behavior is shape and size of the cutouts which are located on the side of the phone keyboard marked by digits 1 and 2 in the Fig. 2. These cutouts should reflect rays which then should hit lower button rows. As it was discovered, after reflection from the upper cutout (number 1) most of rays didn’t reflect from the lower cutout (number 2) and hit the “4” button. But they propagated further and hit the “7” button in different ways. To check this hypothesis, the following criterion had been built: rays hit the lower cutout (number 2) were painted orange, while the rest of rays were painted green. Also the general display criterion was: only rays which hit the upper cutout (number 1) are shown. Result of these criteria application can be seen in Fig. 2.

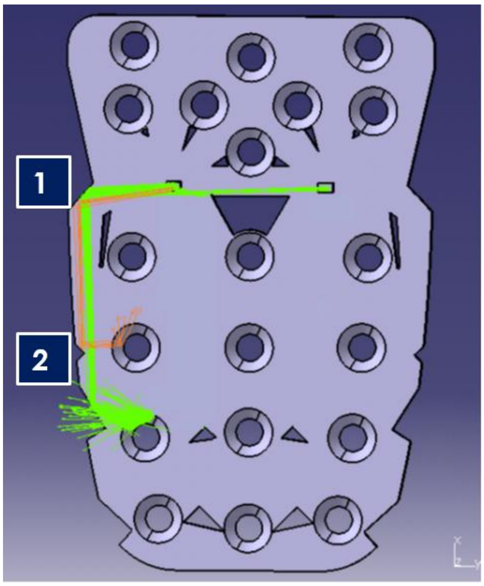

Fig. 2. Upper and lower cutouts of the light-guiding plate.

Enlarging the lower cutout (number 2) with simultaneous reduction of the upper cutout (number 1) corrected the behavior of the light rays. As a result the illumination of all buttons becomes more uniform.

4. The second example: Headlight of a motorcycle

Next example of use of the color criteria is design of the headlight of a motorcycle. Here color criteria help to evaluate many design parameters.

First, the visualization of the colored rays is useful for basic headlight reflector efficiency analysis. For the purpose of this analysis, a virtual measurement device (called an observer) was placed at some distance from the headlight. This observer is an analogue of a real screen which is used to calibrate the headlight beam. After applying the color criterion where rays which hit this observer were painted orange and the rest of rays were painted green, the effectiveness of the headlight reflector can be visually assessed. Result can be seen in Fig. 3.

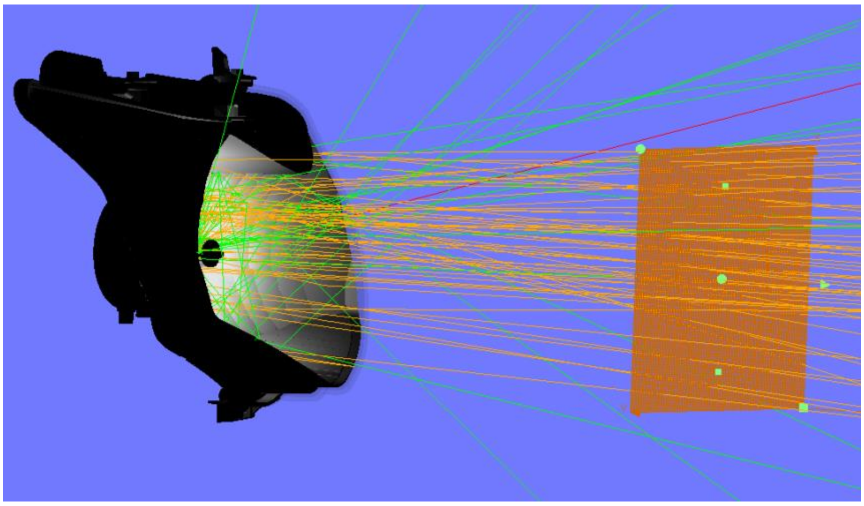
Fig. 3. Evaluation of the headlight efficiency.

By the comparative number of orange and green rays, it is possible to evaluate the overall efficiency of the headlight reflector and by the prevailed directions of the diverged rays, one can understand in which direction the light beam has shifted the most.

It should be noted that there is a red ray in Fig. 3 and this color was not specified by the user. It indicates the “killed” rays, i.e. undesirable rays caused by errors in the object model or in the simulation algorithm.

To clarify the reasons of the appearance of the diverged rays, an additional color criterion was built. This time per-segment coloring mode was selected. The segments after reflection from the headlight reflector were painted purple while all other segments and rays were painted green. Also the general display criterion was set: only rays that did not hit the observer were shown. The result of ray visualization with these criteria is shown in Fig. 4.

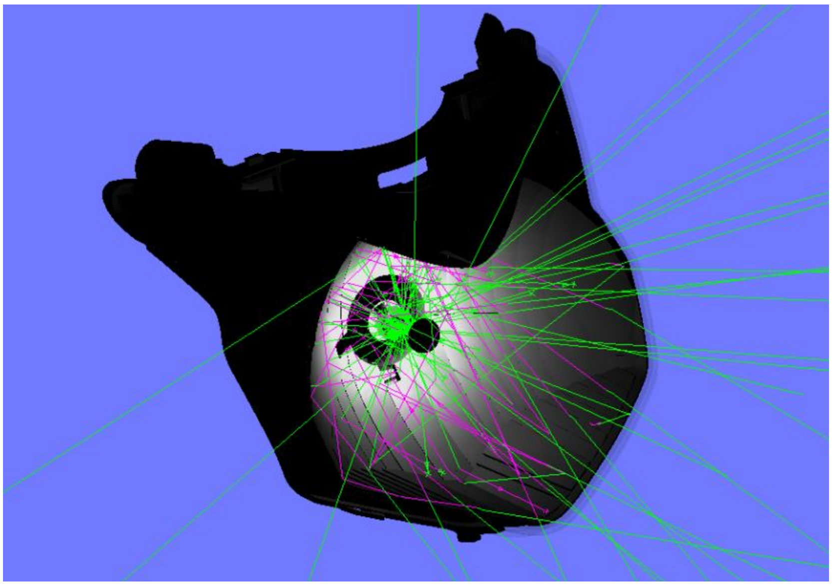
Fig. 4. Reflected segments painted with purple color.

It should be noted that a sufficiently large number of rays hit reflector undergoes secondary reflection of the rays from the reflector sides. This can be seen from the number of purple segments followed one after another: most often they are two or three in one ray. In order to reduce the number of such rays and so increase the efficiency of the reflector, its shape was slightly changed in some places; in particular, the shape and size of its fillets.

One more additional efficiency test for the headlight was the analysis of absorbed rays. The analysis consists of estimation of their number in relation to the number of all rays emitted from the lamp bulb, as well as their allocation and determination of the reasons of their appearance. On Fig. 5 the absorbed rays are highlighted in blue while the rest of rays are colored green.

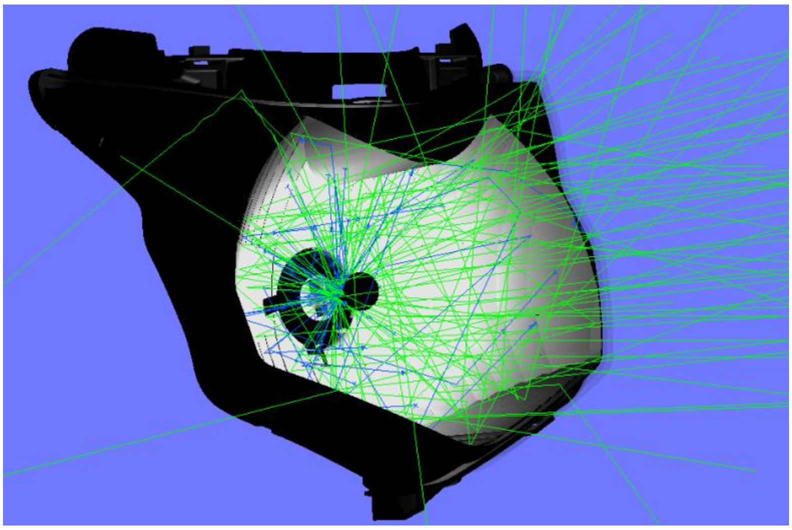

Fig. 5. Visualization of absorbed rays (in blue).

One can see that the total amount of absorbed rays is very small, and they are concentrated mostly near the lamp mount. It is an acceptable situation and no further improvement is required in such a case.

5. The third example: Photo camera lens system

The last considered example of the use of color criteria is analysis of the parameters of the photo camera lens system. As in the previous case, the first test to be carried out is a general check of the lens system efficiency. To do this, the following color criterion was created: rays hit the last lens at the exit from the system were painted orange and the remaining rays were painted green. The test showed that the relative number of rays that did not pass the required path is very small, which indicates the correct design of the lens system as a whole. This can be seen in Fig. 6.

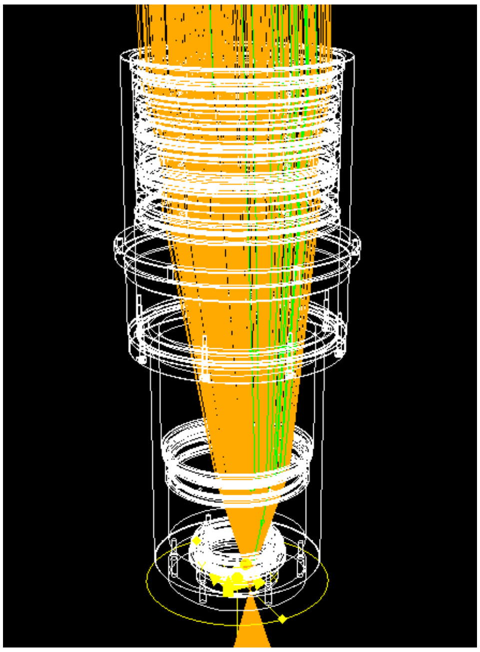

Fig. 6. Efficiency test of the lens system

But additionally it was needed to find the main reasons for the appearance of rays that did not pass the required trajectory till the end. There can be two such reasons: either absorption or secondary reflection of the ray and exit back through the entrance lens. The second case requires special attention because it can lead to the appearance of glare which would significantly degrade the quality of the lens system [12, 13]. To identify such cases the following coloring criterion was constructed: the absorbed rays were painted purple and the secondary reflected rays were painted green. At the same time, a general ray display criterion was established, according to which only rays that did not pass the exit lens were displayed. Thus, all displayed rays except absorbed ones should pass back through the entrance lens. As a result of this test, excessive amount of such rays was found, as seen in Fig. 7.

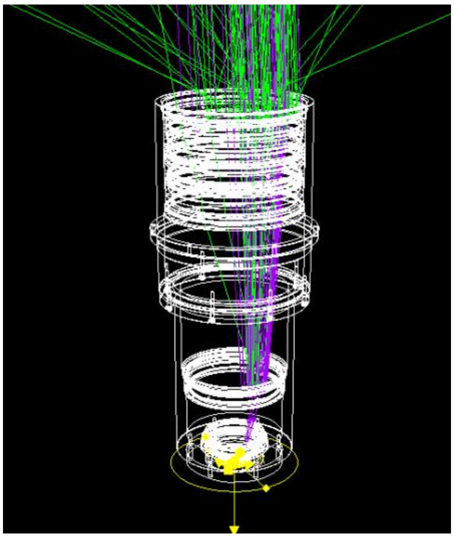

Fig. 7. Rays which haven’t passed through the outlet lens

Since such a phenomenon is highly undesirable, it is necessary to find and eliminate its reason. For this, an additional color criterion was built using per-segment coloring mode. The criterion condition was reflection from any lens. This lens system includes many lenses, so it was easier to set the event type (specular reflection or Fresnel reflection) rather than specific objects as a criterion condition. At the same time, a general display criterion was set to: only rays which have not passed through the exit lens and are not absorbed are shown. The result is shown in Fig. 8.

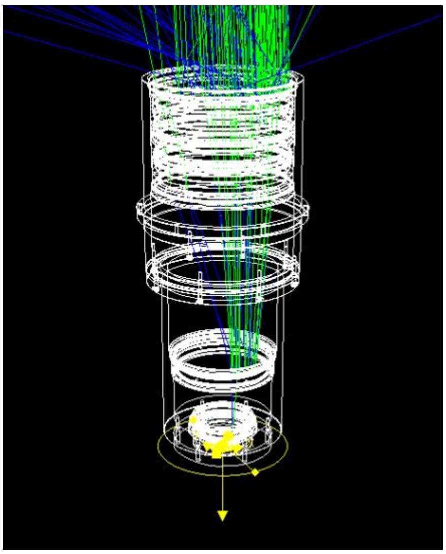

Fig. 8. Not absorbed rays that have not passed through the exit lens

It can be seen here that most of the reflections took place just on the first lens. Therefore, two ways were used to improve the characteristics of the lens system: changing of the material of the entrance lens, as well as increasing the size of the light shield around it.

6. Conclusion

Light ray visualization is a powerful instrument for analyzing optical systems. The ability to display rays using color criteria makes this analysis more efficient. This provides a faster and easier search for errors made in the design of such systems. The efficiency of the proposed method has been tested on the design of many different optical systems, including lens systems, light guides and backlights, lighting devices with reflectors, and so on.

The role of color in the ray visualization technique is significant. Coloring of the visualized rays or their segments according to the conditions specified by the designer allows you to quickly conduct a qualitative analysis of the optical system under development. The use of this technique significantly speeds up the complex and time-consuming process of the design of the optical systems.

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