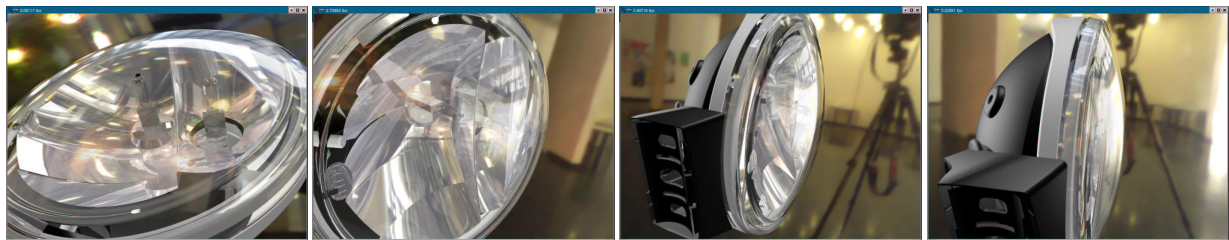


Interactive Headlight Simulation – A Case Study of Interactive Distributed Ray Tracing –

Carsten Benthin, Tim Dahmen, Ingo Wald, Philipp Slusallek

Computer Graphics Group
Saarland University
{benthin,dahmen,wald,slusallek}@graphics.cs.uni-sb.de



Abstract

Today's rasterization graphics hardware provides impressive speed and features making it the standard tool for interactively visualising virtual prototypes early in the industrial design process. However, due to inherent limitations of the rasterization approach many optical effects can only be approximated. For many products, in particular in the car industry, the resulting visual quality and realism is inadequate as the basis for critical design decisions. Thus the original goal of using virtual prototyping — significantly reducing the number of costly physical mockups — often cannot be achieved.

Interactive ray tracing on a small cluster of PCs is emerging as an alternative visualization technique achieving the required accuracy, quality, and realism. In a case study this paper demonstrates the advantages of using interactive ray tracing for a typical design situation in the car industry: visualizing the prototype of headlights. Due to the highly reflective and refractive nature of headlights, proper quality could only be achieved using a fast interactive ray tracing system.

1. Introduction

Interactive visualization of virtual prototypes is becoming an essential tool in the industrial design process. Virtual prototypes are increasingly used as the basis for critical and early design decisions in order to shorten the design process and evaluate more design alternatives. If decisions can be based on accurate data from visualizing the virtual prototypes, costly and time-consuming physical mockups can be avoided.

In this paper we concentrate on the design of car headlights. Headlights are often called the “eyes” of a car and are particularly important for the overall visual impression of the car. Thus, significant efforts are spent on their appro-

priate appearance. The design is constrained by the required lighting properties, but also by the shape and placement dictated by the design of the car body and other factors.

Currently, for each new model of a car several iterations of building and evaluating physical prototypes are performed. Each iteration takes several weeks to months and is fairly expensive due to custom-made tools required to form the front glass and the reflector. Virtual prototyping should be able to reduce the number of physical prototypes, and reduce cost and time in the design process.

However, there are many constraints that must be met in order for a visualization technique to be used in the daily design process.

1.1. Realism

Designers and managers must be able to rely on the data provided by the visualization of a prototype. They can not the loss of realism and accuracy caused by coarse limitations in current graphics hardware. With current graphics technology the accuracy, quality, and realism of virtual prototypes are inadequate as the basis for important design decisions. Hardware heavily relies on approximations for rendering important visual effects. For example, it is impossible to accurately simulate the reflection and refraction of light in curved surfaces with rasterization hardware. Ray tracing, however, is able to simulate these effects but due to its high computational cost is still used only as an offline visualization technique.

1.2. Interactivity

Interactivity is another key factor for the effective visualization of prototypes. Certain optical effects may only appear during interaction with the prototype. This is particularly relevant for optical effects, such as highlights and reflection patterns in especially designed reflectors. Such highlights appear only from very specific positions or lighting conditions. Designers must be able to interactively explore such situations in order to find optimal solutions.

1.3. Geometric Complexity and Automatic Processing

The original car models used by design systems are often of high geometric complexity. This results from the fact that these systems usually work with free-form geometry like NURBS, and use tessellation to convert them to triangles, often yielding hundreds of thousands of triangles. Furthermore, modeling tools also use libraries of existing parts, which can be arbitrarily geometrically complex themselves, even though they form only a minor part of the whole model.

The geometric complexity of the whole model is usually too high for current graphics hardware, and has to be reduced to tractable levels. This process is usually only semi-automatic, and requires significant time and manual effort. It would be highly desirable to have a system that can handle the geometric complexity of the original model.

2. Previous Work

There is currently no solution to visualize car headlights with a high-enough quality to be used in the design process. State-of-the-art is to render an animation using an animation/rendering package based on ray tracing (e.g. Maya/Alias Wavefront¹). Specifying and rendering the animation alone may take several days and is often performed over the weekend. Even then, the results are not adequate for critical decisions, as they do not allow interactive exploration.

Rasterization based systems do not allow accurate simulation of reflections off curved surfaces, nor can they handle multiple reflections and self-reflection.

Ray Tracing would allow for an accurate simulation of the optical effects in headlights, but has been too slow for interactive use. Recently, systems for interactive ray tracing have been developed: Using a large shared memory super-computer, Muss et. al^{3,4} have demonstrated that a traditional ray tracer can interactively render several hundred thousands of CSG primitives that would correspond to several million polygons after tessellation.

Similarly, at the University of Utah Parker et. al⁶ have built an interactive ray tracing system that is also based on a large shared-memory computer. Beside standard ray tracing their system is being used to visualize volumetric data sets and to render high-quality iso-surfaces^{7,5}.

Recently, Wald et. al^{13,11} showed that distributed ray tracing using a cluster of commodity PCs is also able to interactively visualize highly complex models with up to 12.5 million polygons. Wald et al. also demonstrated that their ray tracing engine can be used to build an interactive global illumination system¹². We build on this distributed ray tracing engine for this case study.

3. Headlight Visualization - A Case Study

In order to provide exact results for the visualization of car headlights, we use a distributed ray tracing system running on commodity PC hardware. In order to be usable in practice, our visualization system has to meet several requirements.

First, our system has to meet the quality standard set by the car industry. Even though no actual physical comparisons have been performed yet, the rendering quality achieved by our system should at least match the quality of the current off-line visualization tools. In general, the system has to be 'sufficiently accurate' to help the designers in their design decisions. Therefore, we have been provided with several reference images (see Figure 5).

Second, the system has to deliver interactive performance. It should allow the user to move to and inspect any desired location with interactive feedback (i.e. more than one frame/sec) at video resolution.

Third, the geometry handling should be fully automatic. In our example, the headlight model consists of roughly 800,000 triangles in total. This would already be challenging for many systems based on triangle rasterization. Due to the logarithmic cost in scene complexity it is a rather moderate scene complexity for ray tracing. Therefore, we can directly load the original model without the need for geometric simplification and approximations.

Finally, the price of a system has proven to be only a minor issue if a system can solve a problem that would not be

solvable at all otherwise. Our system uses a cluster of commodity PCs, which in total costs less than \$30.000 for 16 nodes.

4. Implementation

In the following, we will give a brief overview of how our system is implemented and which techniques are used to provide realistic visualization.

4.1. Software Environment

In order to achieve interactive ray tracing performance, we use the OpenRT rendering engine ¹⁰, which provides a simple interface to a fast distributed ray tracing system. An OpenRT-based VRML viewer parses all geometry data and transfers it to the ray tracing core. Communication between VRML application and library is done exclusively via the OpenRT API. The simulation code itself is implemented as a surface shader attached to specific geometry.

As mentioned before the OpenRT ray tracing core supports distributed rendering on a cluster of commodity PCs. It uses a client/server-based architecture where the server hosts the application, and a cluster of client PCs is used for rendering. All OpenRT commands, including scene data is broadcast to all rendering clients. In order to exploit the compute power of all clients the server uses dynamic load balancing ⁸ and schedules work based on image tiles. After an image tile has been rendered by a client, the corresponding color information is sent back to the server.

Due to the ray-tracing-based rendering core a spatial index structure has to be built before rendering. Building this data structure and transferring all required data takes only a couple of seconds. In order to achieve better image quality without loss in performance OpenRT supports progressive anti-aliasing: if no user interaction occurs subsequent frames will be accumulated using different pixel sampling patterns per frame.

4.2. Glass Simulation

As the reflective and refractive nature of the glass body forms the actual core problem of the application, most work has been spent on the glass simulation. However, even with a very fast ray tracing system, some compromises had to be made to achieve interactive performance. However, the same limitations also hold for the currently used off-line visualization tools.

Currently, our system does not handle wavelength-specific effects, and uses only a single index of refraction for all color components. As such, prism-effects will not be simulated. Similarly, we currently ignore polarization effects.

For the actual reflection and refraction calculations, our glass shader is in principle not much different from other

glass shaders used in many ray tracers. For each incoming ray, a reflection and a refraction ray are generated, recursively traced through the environment, and weighed with their respective physical contribution based on the respective Fresnel term.

However, some important differences do exist: In order to avoid infinite recursion for rays being 'trapped' in a glass body, most ray tracers usually specify a maximum reflection depth of usually 4 to 8. For a simulation of such a complex glass body as used in our system, this would not be sufficient: A typical ray has to enter and leave the front glass, perhaps pass through two layers of glass surface on the front and two on the back of the light bulb before hitting the reflector, and has to take the same way out, not even considering multiple reflections inside the object. The maximum recursion level used to compute the different pixels can be seen in Figure 1.

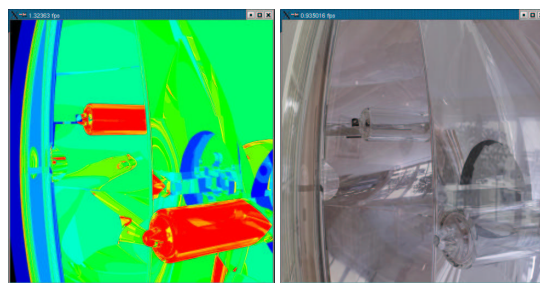


Figure 1: The left image illustrates the recursion depth required for computing each pixel (accuracy 95%). Each color corresponds to a different depth: black(0), blue(≤ 5), magenta(≤ 10), green(≤ 15), yellow(≤ 20), red(> 25). The right image shows the original image for comparisons.

On the other hand, tracing rays up to a recursion level of 20 and more creates a huge performance problem: As glass is usually both reflective and refractive, tracing both rays at each recursion level would lead to an exponential explosion of rays traced per pixel (approximately one million for a single pixel with reflection depth 20). Sub-sampling the whole shading tree with Monte Carlo techniques such as Russian Roulette sampling at each recursion level is an option, but would require considerable effort to remove the Monte Carlo noise that would be extremely disturbing in an interactive setting.

To overcome this problem, we currently track the contribution of each path to the actual pixel. Purely local decision – e.g. by comparing each local weight to a minimum threshold- is not sufficient, as the accumulation of weights can lead to a ray becoming unimportant even though every local weight is above the threshold. However, this requires that the different shaders in the system have to communicate on which values have to be tracked and updated at each reflection point.

By not tracing paths that would not lead to a significant pixel contribution, the rays traced per pixel can be reduced to a tolerable level. We define this contribution threshold as 'accuracy'. An accuracy of 99% means that a ray will be terminated if its pixel contribution is below 1%. Tests have shown that using an accuracy of more than 95% produces no visual improvement. Figure 2 presents the number of rays shot per pixel using an accuracy of 95%.

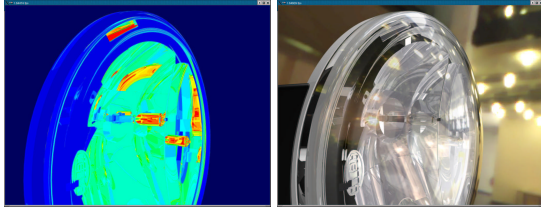


Figure 2: The left image shows the number of rays used to compute each pixel (accuracy 95%). Each color represents a different number: black(< 1 rays per pixel), blue(≤ 10), magenta(≤ 20), green(≤ 30), yellow(≤ 40), red(> 50). The right image shows the original image for comparisons.

4.3. High-Dynamic-Range Environment Map

Due to the highly reflective nature of the headlight, almost all illumination comes from the environment. In order to simulate these effects, we took the common approach of using an environment map. Real environments usually cover a high dynamic range of radiance values. As such, using high-dynamic-range environment maps is very important, as they increase the fidelity of the images. As our rendering engine uses full floating point accuracy for all lighting and shading computations, this was easily integrated into our visualization system. See Figure 3 for the impact of high-dynamic range effects. In principle, supporting high-dynamic range environments allows to put the virtual headlight prototype into any kind of measured environment.



Figure 3: Enhanced visual quality using a High Dynamic Range Environment Map: Low dynamic range rgb environment map on the left, and a high dynamic range environment map on the right.

4.4. Tone Mapping

Using high-dynamic-range environment maps also requires tone mapping¹⁴ before displaying the image. We currently use the tone mapping method proposed by Schlick⁹. As our system is purely software-based, implementing tone mapping is straight forward. However, some caution has to be taken due to parallelization: as a client sends only discretized 8-bit RGB values back to the server, tone mapping has to be applied on the clients. This is problematic because the tone mapping algorithms usually need information about the whole image. We solve this problem by adapting the tone mapping parameters for the next frame based on the results for the current frame. The improvements due to using high-dynamic-range environment maps and tone mapping can be seen in Figure 3.

5. Results

All tests were performed on a cluster of 16 dual-AthlonMP 1800+ PCs, leading to a maximum of 32 CPUs. Using this configuration we are able to achieve frame rates of up to 10 frames per second at video resolution (of 640x480). Figure 4 shows the nearly linear scalability offered by the OpenRT ray tracing core depending on the number of clients.

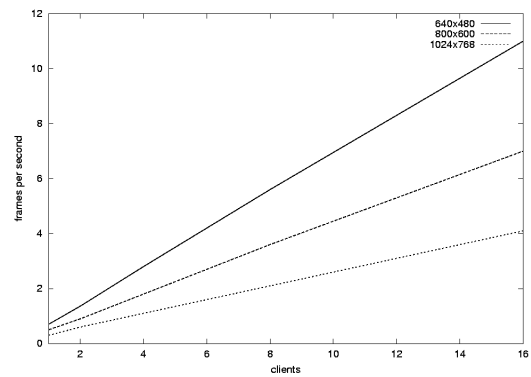


Figure 4: Frame rate of our system at various image resolutions, and with different numbers of clients: Almost linear scalability is achieved even up to 16 clients (32 CPUs).

Due to the limitations of the underlying network architecture (bandwidth, latency), our system currently cannot handle efficiently the broadcast of the whole geometry per frame. However, the location of certain (static) parts can be interactively changed. As such, the light bulb can be moved out of the lamp, the glass cover can be taken off, etc. Other missing effects as discussed in Section 4.2 can be added easily.

As described before, we have been provided with reference images created with the previously used off-line visualization tools. Comparing our images to these reference images demonstrate that our system offers at least the same



Figure 5: Rendering quality achieved by our visualization system: The left image illustrates the reference quality produced by an off-line ray tracer, and the right image shows the quality achieved by our system. For comparison, the middle image is a photo of the physical model.

quality – but at interactive speeds. Comparing to actual photographs of a physical model of the headlight show that we are able to achieve a very realistic visualization, as can be seen in Figure 5.

6. Conclusions and Future Work

This paper demonstrates that interactive ray tracing is becoming an important alternative to current interactive visualization techniques. For some applications, like the headlight simulation discussed here, it is the only viable solution. As the trend towards more realism and geometrically more complex models continues, it seems that ray tracing will become increasingly important for future applications.

Of particular importance in this context is the flexibility of extending the basic ray tracing algorithms with custom programmed shaders. With ray tracing, shading is separated from visibility computations and is not constrained by the strict pipeline model of rasterization hardware. Therefore, different shaders are independent of each other and are much simpler to write.

Implementation of the headlight simulation required relatively little effort, as most of the actual work is performed by the underlying rendering engine. Therefore, modifications to the system can also be applied by non-expert users through editing the shaders.

Highly complex lighting simulations, as the one presented here, still require considerable compute power in the form of a small PC cluster. Even though Moore's law will help over time, it seems necessary to add some form of hardware support. Both CPU and GPU designers are currently investigating such hardware support for ray tracing.

Our system depends mainly on dynamically loaded shaders, and does not interfere with the underlying interactive distributed ray tracing engine. Therefore, we can exploit the full performance of the OpenRT rendering engine, and can efficiently scale to many CPUs. Using a cluster of 16 Dual-AthlonMP 1800+ PCs, we are able to achieve frame

rates up to 10 frames per second for the complete reflection simulation at a resolutions of 640x480 pixels.

Due to the OpenRT's ability to handle complex scenes, we are able to directly handle the high geometric complexity of 800.000 triangles without the need for geometric simplifications and approximations. As such, our system is fully automatic, and can greatly reduce the turn-around times in the industrial design process.

In future, we are considering to make our system available to the industry by integrating it into commercial applications. Furthermore, our system can easily be adapted to solve similar problems in the industry, e.g. simulating reflections in car windshields, or in instruments of aircraft cockpits. Finally, it would be desirable to integrate the system with a full lighting simulation in order to be able to also visualize the lighting effects of the headlight.

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