Spectral Optics Simulation for Rapid Image Systems Prototyping: Ray-tracing, Diffraction and Chromatic Aberration

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Abstract: We describe a software tool that models multicomponent spherical lenses, and calculates the spectral irradiance and depth maps for three-dimensional scenes. Combined with image systems simulations, this tool allows for the rapidly prototyping of imaging systems.

1. Introduction

Simulation can be a valuable tool for designing and evaluating imaging systems [1]. The value of image systems simulation is greatly increased to the extent that we can use naturalistic inputs and realistic optics to calculate the spectral irradiance image at the sensor. Here, we describe a software tool (in Matlab) that models critical properties of the image formation optics for the case of multicomponent spherical lenses. Combining the tool with image systems simulations software makes it possible to rapidly prototype imaging devices, including cameras and microscopes. We integrated this tool with computer-graphics software (PBRT). Used in this way, the system calculates the sensor spectral irradiance, depth maps, and light fields for naturalistic three-dimensional multispectral scenes.

The optics tool can be used to characterize lenses comprising a series of spherical surfaces, each with its own wavelength-dependent index of refraction. The tool accounts for the aperture, which is important to characterize depth of field effects and approximates the effects of diffraction. Finally, the tool is computationally efficient and can be integrated with image systems simulation software so that the designer can interactively adjust parameters and visualize the consequences.

2. Theory

We modeled four categories of optics: pinholes, diffraction-limited thin lenses, thin and thick spherical lenses, and multiple spherical lenses. In all cases we assume a circular aperture. The basic correspondence between points in the scene and the sensor surface is established by ray-tracing [2]. Traditionally this method traces the path of light rays ignoring diffraction. To incorporate diffraction, we introduce uncertainty into the ray angle using a function that depends on the position of the ray with respect to the aperture [3]. The calculation is performed separately for different wavelengths to account for chromatic aberrations. The effect of the optics is summarized by a collection of point spread functions (PSFs) that depend on the field position, wavelength, and depth of each point in the scene.

2.1 Ray-tracing

Diffraction-limited thin lenses are modeled using the thin-lens equation for an isoplanatic region. Given the focal length and point source distance, the thin lens equation specifies the focal distance. Thin and thick spherical lenses are modeled using Snell's Law. At each intersection of a ray and spherical surface, the original ray direction, normal vector direction, and index of refraction of the interacting media determine the direction of refraction according to Snell's Law [4]. Calculations for multiple lenses are the concatenation of the calculation through multiple surfaces.

2.2 Chromatic aberration

Chromatic aberration arises mainly due to wavelength-dependent variations in the index of refraction. These variations are the source of longitudinal chromatic aberration; transverse chromatic aberrations arise because of the position of the aperture with respect to the center of the lens. The tool includes several examples of index of refraction for different materials.

2.3 Diffraction

We use the technique described by Freniere et al. [3] to simulate diffraction when using ray-tracing through a circular aperture. A line, $L1$, is drawn from the ray to the closest aperture point, and the distance is recorded. The distance to the aperture along a line perpendicular to $L1$ is also recorded. The ray angle, measured in the aperture plane, is randomized according to an independent bivariate Gaussian distribution; the two standard deviations are inversely related to the two distances from the aperture. This model captures the wavelength-dependent point spread caused by diffraction, but it does not capture features such as the Airy rings.

3. Implementation

The implementation performs a forward-calculation of the PSF, chromatic aberration, and diffraction. The Matlab code that produces the figures in this paper can be found at https://github.com/ydnality/Scene3D/tree/rayTrace.

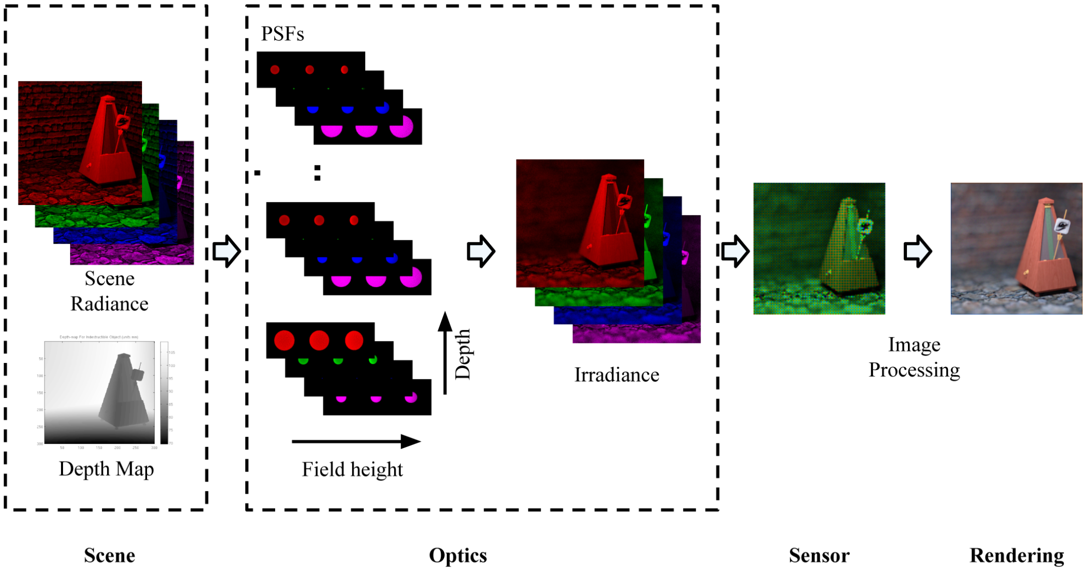

Figure 1: Full image system simulation pipeline.

3.1 PSF calculations: Depth, field height, and wavelength

The PSF calculations proceed from the scene to the sensor. Monochromatic light rays originate at point sources in the scene, and these rays are uniformly spaced at sample positions on the front lens element. The rays are traced through the optics until they arrive at the sensor surface. The number of rays per unit area at each point on the sensor surface is recorded and stored as the PSF. We calculate and store PSFs for points spanning a range of field heights, depths, and wavelengths. Because the PSFs vary relatively slowly with respect to these variables, we can calculate the PSFs at a modest sampling resolution and use PSF interpolation to calculate PSFs at intermediate parameter values.

When there are only a small number of scene sample points, and their locations are known, calculating from the scene through the optics to the sensor (forward-calculation) is more efficient than the usual computer graphics calculation that sends rays from the sensor to the scene (backward-calculation). Hence, we use the forward-calculation for the rapid prototyping of the optics, and we use the backward-calculation for final scene rendering.

3.2 Integration with image systems simulation

A number of metrics can be used to evaluate the collection of PSFs and thus the optics, but it is also useful to visualize the impact the optics have on typical natural images. We integrated this optics prototyping tool with image systems simulation software to help the designer evaluate the effect of design decisions on natural image renderings (**Figure 1**).

Multispectral scene radiance and depth information can be obtained from a variety of sources, including empirical measurements [5] and computer graphics simulations. For each wavelength and each point, the scene radiance is blurred using the interpolated PSF. The result of this calculation is the estimated sensor spectral irradiance. Image systems simulation software combines the irradiance data with a model of the image sensor to produce an estimate of the sensor voltage response. The sensor voltages are passed through an image processing pipeline to produce the final rendered image.

3.3 Final Rendering

The Matlab tool is efficient for rapid prototyping, but applying point-wise blurring introduces artifacts at large depth boundaries. These artifacts arise because point-wise blurring does not account for partial occlusion of the light from the distant surface. For a more accurate, artifact-free image, we modified a ray-tracing tool (PBRT). In this computer graphics tool, rays start at the sensor and are traced from the sensor through the lens to the scene (backwards-calculation). This calculation is efficient when modeling a scene that comprises many points and depths. The ray-tracing package accurately accounts for partial occlusions and avoids the depth edge artifacts.

4. Results

The HURB ray-tracing method produces the expected line spread width as well as the wavelength-dependence (**Figure 2**), although it does not produce the multiple lobes present in the Airy disk. The wavelength-dependent multi-element spherical lens model successfully produces plausible images displaying longitudinal chromatic aberration (**Figure 3**). The reverse-calculation produces plausible defocus blur using various apertures and sensor noise settings (**Figure 4**).

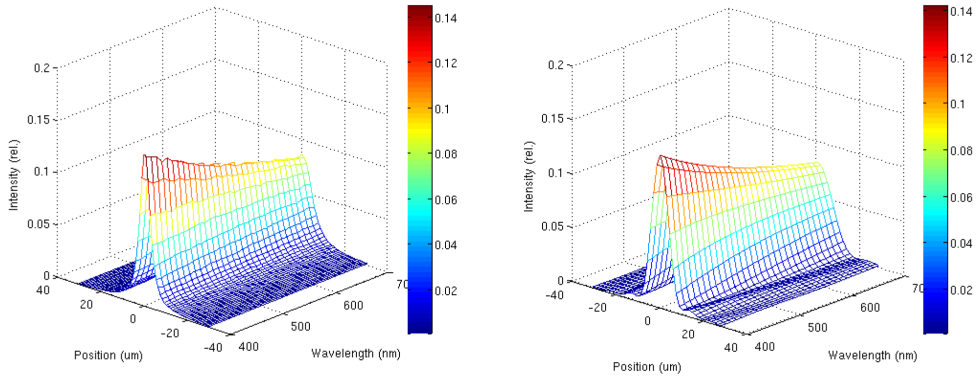

Figure 2: Line spread functions using the HURB ray-tracing method for diffraction simulation (left) compared with the theoretical line spread of a circular aperture (right). The height of the meshes represent the relative irradiance as a function of spatial position and wavelength.

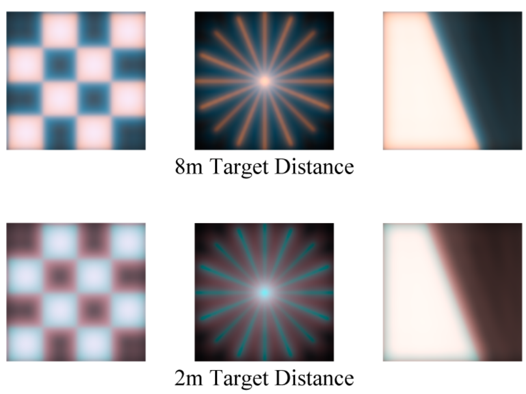

Figure 3: Longitudinal chromatic aberration illustrated for a 50mm 2-element lens with an 8m focal distance. The optical irradiance images are generated for 3 simulated targets placed at a distance of 8 m (top) and 2 m (bottom).

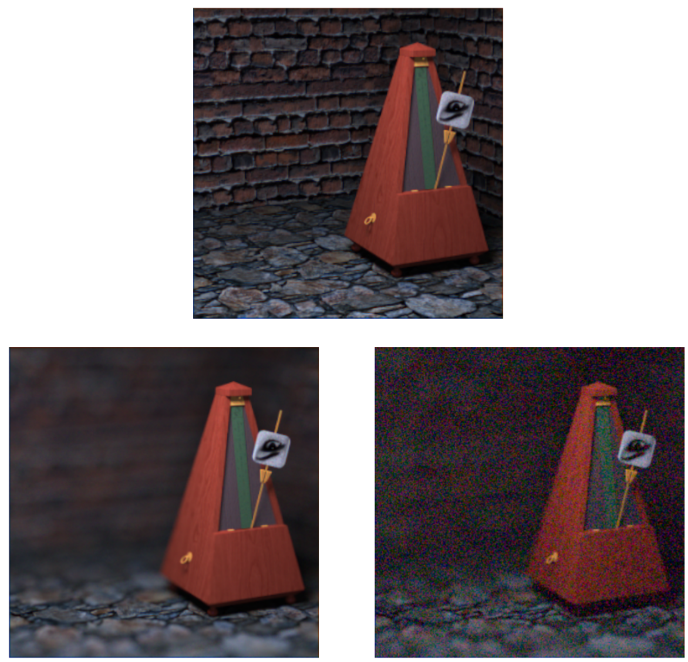

Figure 4: Final rendering examples for a 50 mm, 2-element lens. Images were produced with a pinhole aperture and no read noise (top); f/5 and no read noise (left); f/5 and .05V read noise (right).

5. Conclusion

We combined spectral optics simulation, computer graphics and image systems simulation into a tool for rapidly prototyping optics design. The tool begins with three-dimensional spectral scenes and simulates the optics to produce the sensor irradiance. The multispectral ray-tracing infrastructure produces physically accurate diffraction and chromatic aberration artifacts. The ability to create these scenes and fully simulate the imaging pipeline greatly increases the range of input images that we can use to rapidly prototype and evaluate computational imaging systems.

6. References

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