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Using light fields to simulate the performance of optical systems

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ABSTRACT

The light field describes the radiance at a given point from a ray coming from a particular direction. Total irradiance comes from all rays passing the point. For a static scene, the light field is unique. Cameras integrate the light field. Each camera pixel sees the integration of the light field over the entrance pupil for ray directions associated with lens aberrations. Images of this scene for any lens can then be simulated if the light field is known at its entrance pupil. Freeware rendering software was used to create a scene's light field and images for real camera lenses with different aberrations are simulated.

Keywords: Light field, Image simulation, Aberrations

1. INTRODUCTION

The light field is a multi-dimensional function that fully characterizes the light properties as a function of position in space. These properties include the energy content, the direction of flow of this energy, the spectral content and the polarization. From a geometrical optics standpoint, the light field defines all the rays passing through a point in space, the amount of energy each ray carries, the "color" of each ray and the orientation of the electric field in a plane transverse to the ray. Knowledge of the light field over a region of space enables the irradiance distribution on a surface to be calculated through integration of the light field. For example, a "red" pixel in the sensor of a digital camera effectively integrates or sums up all of the rays which arrive at the pixel from angles contained within the cone defined by the pixel and the exit pupil of the camera lens. The contribution of each ray is dictated by how much energy is contained in each ray and the transmission profile of the red filter covering the pixel. Levoy and Hanrahan[1] trace the origin of the light field concept back to Gershun[2]. The translators of Gershun's paper in 1939 describe the introduction of the light field as part of a "vigorous attempt to bring the theory of light calculation into conformity with the spirit of physics" to overcome "the absurdly antiquated concepts of traditional photometric theory." The concept of the light field, however, languished through much of the 20th century until practical means of measuring or computing it became available. Adelson and Wang[3] created a plenoptic camera for measuring the light field and Ng *et al.*[4] greatly developed the hardware and reconstruction algorithms associated with plenoptic cameras. Levoy and Hanrahan[1] examined using computational rendering to create light fields. Camera arrays are also used to capture light fields.[5] Here, a rendering software package is used to calculate the light field of a 3D scene across the entrance pupil of a camera. Reverse raytracing is used to determine which rays in this light field contribute to the image formed in the camera. The advantage of this technique is that once the light field is calculated, simulated images through different camera lenses are easily generated.

2. METHODS

To initiate the development of a scene simulator, a representation of the light field is required. For simplicity, the light field will be represented as a 4D function, with two dimensions dedicated to the coordinates (x, y) of a given ray on a plane and two dimensions dedicated to the coordinates (u, v) of the same ray on a separated plane. The trajectory of the ray is then related to the difference between these coordinates and the separation between the planes. The wavelength dependency will be considered over the red, green and blue bands associated with 24-bit color images, but can be extended to more wavelengths as needed. Polarization is also ignored here since most camera systems are agnostic to polarization and most rendering software does not account for polarization. The light field therefore will be represented by $L(x, y; u, v)$ and the first goal of this effort is to calculate this function for a rendered 3D scene.

For rendering, the freely available program Blender v2.79 (www.blender.org) was used. This program enables the user to define arrays of objects and light sources in a 3D space along with their material and spectral properties. The user can also place cameras into the scene and the software uses raytracing techniques to generate photorealistic images of the scene from the camera's perspective. Additional lighting and atmospheric effects are feasible with this program, most of which are beyond the capabilities of the author.

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Fortunately, high quality scenes are readily available. For this modeling, the free model of the Barcelona Pavilion by Hamza Cheggour was used.[6] Figure 1 shows an example image of this scene rendered with Blender. To facilitate capturing light field images from this scene, a Blender add-on from Honauer and Johannsen was used.[7] This add-on enables a camera array to be defined in Blender and upon rendering, images from each of the cameras in the array are automatically generated. For this investigation, a 25×25 array of cameras was used. The separation between each camera is 2 mm, so that the entire array covers a 50 mm x 50 mm square patch. Each camera in the array has a focal length $f_{pin} = 19.44 \text{ mm}$, a full field of view of 84° and is set to F/100 so that it acts as a pinhole camera. Each camera is focused at a distance of 8 m, so the image plane is nominally in the rear focal plane of the system. The dimensions of the images acquired with each camera is 256×256 pixels. The camera array was placed looking along left wall of the pool slightly above the surface of the water. Figure 2 shows several of the 625 rendered images from the camera array. The other images are slightly displaced versions of the initial image. Each image was rendered on a conventional CPU. The total rendering time was approximately 48 hours.

Figure 1. Rendered image of Cheggour's Barcelona Pavilion.

Figure 2. Example images from the camera array. Each image has slightly different parallax in both the horizontal and vertical directions.

To understand how the set of images from the camera array relate to the light field, consider Figure 3. Each camera in the array creates an inverted and reverted pinhole image of the scene. The position of the camera defines the coordinates (x_0, y_0) in the light field. Ray 1 in the figure passes through (x_0, y_0) and intersects the pinhole image at (u_1, v_1) . Consequently, the light field at $L(x_0, y_0; u_1, v_1)$ just corresponds to the *rgb* values in the pinhole image at (u_1, v_1) . Similarly, Ray 2 which has a different trajectory than Ray 1, but passes through the same location in the *xy*-plane has a light field at $L(x_0, y_0; u_2, v_2)$ corresponding to the *rgb* values in the pinhole image at (u_2, v_2) . Figure 3 illustrates some of the issues with sampling the light field. The number of cameras in the camera array determines the spatial sampling of the light field. Here, the spatial sampling is every 2 mm across a 50 mm square patch. The number of pixels in the pinhole image determines the sampling of the trajectory of the rays with each pixel corresponding to $84^\circ/256 \text{ pixels} \approx 20'$. Of course the sampling density in either space can be increased at the cost of increased computation time.

Figure 3. Each array camera creates an upside down and backwards pinhole image of the scene. The coordinates of the pixels in the pinhole image and the focal length of the camera define the trajectory of a ray passing through the location of the camera.

Figure 4 illustrates how the light field can be used to simulate an image with a given camera lens and sensor. The entrance pupil of the simulated camera is placed in the *xy*-plane where the light field has been measured. The test system is reversed raytraced to determine the aberrations associated with the lens. In Figure 4a, rays from a single point on the image plane are traced to the exit pupil. These rays will ultimately map to the entrance pupil and will pick up the aberrations associated with the system. Consequently, the exiting rays will not necessarily converge to the conjugate object point. By the principle of the reversibility of light, the direction of the rays can be reversed so that a set of aberrated rays enters the entrance pupil and as they emerge from the exit pupil, they will perfectly converge to a single point on the image plane. Figure 4b illustrates these reversed rays. Each of these reversed rays will be associated with a pinhole camera from the prior calculations dependent upon where it strikes the entrance pupil. Each of the reversed rays will also have a trajectory that will strike the respective pinhole image. As a result, the contribution to the pixel in the image plane of the test system will just be the sum of the pixel values where the reversed rays strike the pinhole images. This process is repeated for each pixel in the image plane to build the simulated image. The final simulated image needs to be normalized by the number of rays passing through the pupil of the system.

Figure 4. The test system is placed so that the known light field is at the entrance pupil. (a) The test system is reversed raytraced to determine the trajectories of the rays emerging from the system. (b) The direction of these emerging rays is then reversed to determine where they would strike the respective pinhole image. The pixel value in the image plane of the test system is just the sum of all the pixel values of the intersections of the pinhole images.

3. EXAMPLES

To create example scenes, a full description of the wavefront as both a function of the field coordinates and the pupil coordinates is required. Here, the form of the wavefront generalizes the Zernike polynomials to include field dependence similar to the scheme proposed by Gray *et al.*[8] The shape of the wavefront, ignoring the piston term, is given by

$$W(h_x, h_y; \rho, \theta) = -\frac{1}{2}(W_{111}h_y + W_{111y})Z_1^{-1}(\rho, \theta) - \frac{1}{2}(W_{111}h_x + W_{111x})Z_1^1(\rho, \theta) + W_o(h_x, h_y; \rho, \theta), \quad (1)$$

where $Z_1^1(\rho, \theta)$ and $Z_1^{-1}(\rho, \theta)$ are the Zernike x - and y -tilt terms and (h_x, h_y) are the Cartesian representation of the normalized field coordinates. The coefficient $W_{111} = \tan(HFOV)$ is the slope of the ray emerging at full field and $HFOV$ is the half field of view of the system being simulated. The coefficients $W_{111x} = \tan(\theta_x)$ and $W_{111y} = \tan(\theta_y)$ control the global x - and y -tilt so that effectively the camera being simulated can look in different directions relative to the direction the pinhole camera array was looking. The angles θ_x and θ_y are the horizontal and vertical angles between the pinhole camera array look direction and the simulated camera look direction, respectively. The final term of Eq. 1 $W_o(h_x, h_y; \rho, \theta)$ is the wavefront error (i.e. the difference between the reference sphere and aberrated wavefront, under the assumption that the preceding tilt terms have already been removed). In general, this wavefront error will be dependent upon the field coordinates and is just the standard OPD output from lens design code.

Figure 5 helps to illustrate the effect of the tilt coefficients above. A perfect system with a $HFOV = 30^\circ$ is modeled. In Figure 5a, $W_{111x} = W_{111y} = 0^\circ$ and the wavefront is plotted for different field positions. The central wavefront corresponds to $h = \sqrt{h_x^2 + h_y^2} = 0$, or the on-axis case. In this case, the wavefront is a plane wave propagating in the direction that the original pinhole camera array was looking. The other rings in Figure 5a correspond to $h = 0.5$ and $h = 1.0$ for various orientations within the field of view. In these cases, the wavefront remains planar, but the tilt of the wavefront increases linearly with h since the field points are getting progressively more off-axis. In Figure 5b, the simulated camera is rotated $W_{111x} = 10^\circ$ in the horizontal direction and $W_{111y} = 5^\circ$ in the vertical direction with respect to the direction the pinhole camera array was looking. This rotation has the effect of adding a field-independent tilt to each of the wavefronts. This global tilt remains valid as long as the field of view of the rotated simulated system remains within the field of view of the individual pinhole images.

Figure 5. Wavefront for fields of $h = 0$, $h = 0.5$, and $h = 1.0$ for (a) a perfect system looking in the same direction as the pinhole array, and for (b) the same system rotated horizontally 10° and vertically 5° with respect to the pinhole camera array look direction.

The form of Eq. 1 is useful because the trajectories of the rays arriving at the entrance pupil from the scene as shown in Figure 4b are related to the gradient of Eq. 1. Specifically, the unit normal $\hat{n}$ of each ray is given by

$$\hat{n} = (n_x, n_y, n_z) = \left(\frac{1}{A} \frac{\partial W(h_x, h_y; \rho_x, \rho_y)}{\partial \rho_x}, \frac{1}{A} \frac{\partial W(h_x, h_y; \rho_x, \rho_y)}{\partial \rho_y}, -\frac{1}{A} \right), \quad (2)$$

where $\rho_x = \rho \cos \theta$, $\rho_y = \rho \sin \theta$, and $A = \sqrt{(\partial W / \partial \rho_x)^2 + (\partial W / \partial \rho_y)^2 + 1}$.

With the trajectories of the rays calculated, each ray can then be propagated to determine where it strikes its respective pinhole image. Specifically, each ray strikes the pinhole image at

$$(u, v) = \left(f_{pin} \frac{n_x}{n_z}, f_{pin} \frac{n_y}{n_z} \right), \quad (3)$$

where again f_{pin} is the focal length of the pinhole camera lens. For each point in the field, the intersections of the rays entering the pupil of the simulated system with their respective pinhole images are found and the *rgb* values at these points accumulated. Figure 6 shows the simulated images for the two ideal systems with the wavefronts illustrated in Figure 5. In Figure 6a, the simulated camera is looking in the same direction as the pinhole camera array. The original pinhole images each have a $HFOV = 42^\circ$, while the simulated images have $HFOV = 30^\circ$. Consequently, the images in Figure 6 have a tighter field of view than those shown in Figure 2. In Figure 6b, the simulated camera is rotated 10° to the left and 5° up. The field of view is unchanged, but the perspective of the scene is changed. Both image, however, suffer from a loss of the high spatial frequencies found in the original pinhole images. This is likely due to the limited sampling of the light field for this example. Improving this limitation is discussed in more detail in the Discussion.

Figure 6. Simulated images for cases where (a) the simulated camera is pointed in the same direction that the pinhole array was oriented. In (b), the simulated camera is rotated 10° horizontally (left) and 5° vertically (up).

Figure 7. (a) The field-dependent wavefront error and (b) the simulated image for the scene with $10 \mu\text{m}$ of field curvature.

In Figure 7, the effects of wavefront error on the scene are illustrated. As a simple example, the case of pure field curvature, albeit an exaggerated level, is examined. For these simulations, the wavefront error component of Eq. 1 is given by

$$W_o(h_x, h_y; \rho, \theta) = 0.01h^2Z_2^0(\rho, \theta). \quad (4)$$

In Figure 7a, the tilt components from Figure 5b have been removed to better visualize the field curvature. Figure 7b shows the simulated image associated with the field curvature example. As expected, the center of the field is in focus and the focus progressively degrades towards the periphery of the image. Note, that this is just a simple example of the technique and that more complex wavefront errors associated with real lens systems and calculated with lens design software can be used in Eq. 4.

4. DISCUSSION

A technique has been developed to create simulated images of three-dimensional scenes as viewed through different optical systems. The light field for the scene over the region encompassing the simulated camera's entrance pupil is required for the simulations. Calculation of the light field is computationally expensive, but only needs to be performed once to enable modeling of a variety of systems. Here, the light field was calculated over a 50 x 50 mm square patch with a full field of view of 84°. Consequently, any optical system with an entrance pupil diameter smaller than 50 mm and a field of view smaller than 84° can be modeled. Furthermore, if the field of view of the simulated camera is substantially less than the pinhole images, the camera can be rotated to view different portions of the full 84° field. Optical systems meeting these requirements, along with their inherent aberrations, can be modeled with this technique to understand performance limitations and compared to other systems. There are several advantages to this technique. First, the computationally expensive portion of the scene does not need to be recomputed every time a simulation is performed. Effectively, "all" the rays entering the space are pre-computed in the light field and the simulation is just selecting out the relevant rays that are needed for the system under test. This greatly speeds up the calculation times of individual simulations. A second advantage is that the light fields for a series of scenes can be computed, creating a standardized set of test scenes. The performance of new optical systems can be compared to earlier versions or systems from different manufacturers can be compared under identical situations. A third advantage is that the scene is three-dimensional, so differences in perspective with focal length, depth of field with varying aperture, bokeh are all easily handled in the simulations. Note, that this effect is different from traditional simulation techniques that assume shift-invariance and convolve a two-dimensional image with a point spread function and even more sophisticated simulations that superimpose a set of shift-variant point spread functions to simulate two-dimensional scenes. Finally, the wavefront error can be obtained from aberration theory, lens design analysis or through direct measurement of systems through interferometry and wavefront sensing. The technique is general, and applicable to non-axially symmetric systems, so Scheimpflug and freeform systems are easily handled. The main limitation with the current demonstration is the lack of high spatial frequency content contained in the simulated images. This is likely due to limited sampling of the light field, although more investigation is necessary to confirm this suspicion. Future work will examine finding the root cause and resolving this issue, as well as applying the technique to more complicated systems.

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