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Descriptions, Measurements and Visualizations of Light Distributions in 3D Spaces

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ABSTRACT

The aim of our studies is to understand the physical structure and human perception of natural light fields. The light field depends on the primary illumination, the scattering properties of the environment and the scene geometry. We present our newly developed methods to describe, measure and visualize visually complete descriptions of the light field, the 5-dimensional "plenoptic function". The structures of natural light fields were found to be rather smooth and built up of just a few possible topologies. We show that our visualizations by means of light tubes represent the well-known "flow of light" lighting design concept in a surprisingly intuitive way.

Keywords

Light field, appearance, plenoptic function, visualization, flow of light, scale of light, light-zones.

INTRODUCTION

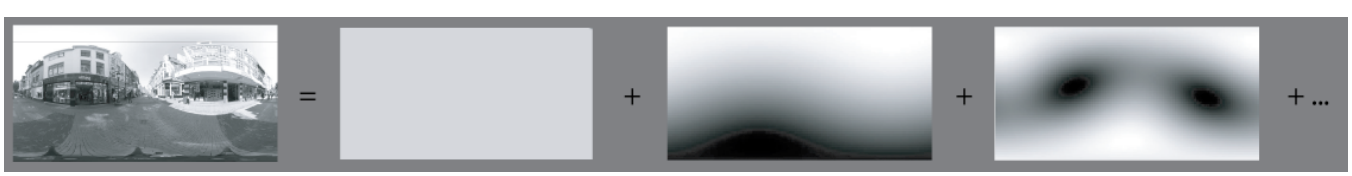
Lighting influences our perceptions of our surroundings, including the "visual light field" [6]. We investigate which aspects of the appearance of scenes underlie these perceptions and how the appearance changes with lighting variations. In this paper we focus on the physical description, measurement and visualization of the light field in three-dimensional (3D) spaces in order to scientifically assess the spatial and form-giving characteristics of light, and we analyze the structure of natural light fields.

On a most basic level one might draw relations between lighting and how well people can see details around them. Such maximization of luminance contrast of visual detail forms the basis of many lighting recommendations and standards. However, lighting may vary in many more ways and influences the appearance of scenes and our perceptions in a very complicated manner [2]. The directional properties of the illumination strongly affect the appearance of an object. For instance, in fully diffuse illumination even a specular object looks rather matte. Diffuse illumination can have directional properties – illumination from an overcast sky is directed vertically downwards. However, the properties of diffuse and highly directional (collimated) illumination are very different. In collimated illumination the shading is dominated by cast and body shadows, whereas in diffuse illumination the shading gradients are much more gradual.

Examples of light properties which artists (light designers, architects, photographers, painters, etcetera) know to be important aspects of scene appearance are the diffuseness, density variations, flow of light, and 3D modeling properties of the light. Such light properties depend in a complicated way on the primary illumination, the scattering properties of the environment and the scene geometry and typically cannot be represented by just a simple number. Moreover, they vary from point to point in 3D scenes. Therefore we first need a visually complete description of the luminous environment, or "the plenoptic function" [1]. If we constrain ourselves (for simplicity) to static scenes and if we ignore color, we can describe the plenoptic function, or the (white) light distribution in 3D space, by the 5D "light field" [4] (the radiance as a function of the 3D position and 2D direction). The light fields of natural scenes are often highly complicated functions. The angular variations can be almost arbitrary, ranging from smooth (such as under an overcast sky) to very spiky (such as on a sunny day on the beach or under forestry). In contradistinction, the surface irradiance is typically fairly smooth, because surface elements of a convex object are illuminated from half spaces.

In this paper we will address our newly developed methods to describe, measure and visualize light fields in 3D spaces. In the discussion we will draw a relation between our visualizations and well-known concepts from lighting design and architecture, namely "the flow of light" [2], "the scale of light"[3], and "light-zones" [8].

Figure 1 A panoramic image (a local light field measurement) and its first three spherical harmonic components (see text for explanation).



FORMAL DESCRIPTIONS OF THE LIGHT FIELD

The light field is a complicated 5D function of position and direction. At any point in space the light field is a function of direction, a spherical function (a 360° × 180° panoramic view), which may well be described by a superposition of components of different angular frequencies. At first sight it might seem important to include all those frequencies in light field studies. However, most objects around us are quite matte and low-pass or "diffuse" the illumination. Thus, only the low frequencies of the light field influence their appearance. This suggests that a decomposition of the light field in components of different frequencies might be useful. For a spherical function such as the light field this comes down to spherical harmonics, usually known as a multipole development in physical context.

Mathematically, it was shown that a second order spherical harmonics description, which is a superposition of just three qualitatively different, low angular frequency components, is sufficient to describe the appearance of perfectly matte convex objects [15]. These three components are physically equivalent to:

- the flux density (a number representing the monopole contribution or average radiance from all directions in the point under consideration),
- the light vector (a number and direction representing the dipole contribution or magnitude and direction of the net maximum transport of light in the point), and
- the squash tensor [12] (two numbers and a direction representing the quadrupole contribution or magnitudes and orientation of a set of orthogonal light and dark two-fold lobes).

The flux density describes a constant illumination from all directions, which is usually known as "ambient illumination" in computer graphics, or Ganzfeld illumination in psychology. Light fields in which this monopole component dominates are rare in nature. An example is an overcast sky over a snow cover ("polar white-out"). The combination of a monopole and a dipole term yields what is known as the "point source at infinity with ambient term" in computer graphics. A natural light field that approximates a dipole dominated field is the overcast sky or hemipsherically diffuse source. Quadrupole dominated light fields occur in the case of ring sources or two point sources at opposite sides of the region of interest – therefore we called it the "squash tensor".

In figure 1 we show a local light field measurement (a panoramic image) and its first three spherical harmonic components; the first component represents the flux density, (it is clearly a constant); the second component represents the light vector (here it is clearly oriented vertically); the third component represents the squash tensor (the two light and two dark lobes are clearly visible).

In figure 2 we show spherical maps of the panoramic image, of the sum of the first three components (mathematically: the second order spherical harmonic approximation), and of matte spheres rendered in those high-resolution and approximated low-pass local light fields. The spheres indeed look the same. Thus, only 9 numbers are sufficient to describe the appearance of a matte convex object.

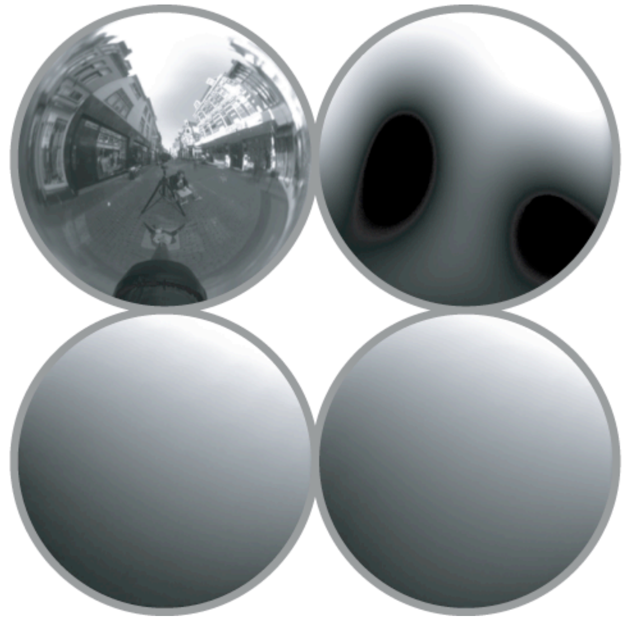


Figure 2 A panoramic image (a local light field measurement; upper left image) mapped on a sphere, which may be thought of as photographed on a specular sphere. The upper right image shows the superposition of the first three spherical harmonic components, which were shown separately in figure 1. The second row shows renderings of matte spheres in the high-resolution local light field and its low-pass approximation. It is clear that the superposition of flux density, light vector and squash tensor is sufficient to describe the appearance of such a matte convex object.

MEASUREMENTS OF THE LIGHT FIELD

The enormous luminance range that is common in natural scenes forms a second challenge in light field studies. This so-called very high dynamic range (HDR) cannot be covered by photographical methods, even if the dynamic range is extended by techniques such as photographical composition from multiple exposures. This range can however be covered by HDR sensors consisting of a photo-diode and a logarithmic amplifier. The combination of the low-pass approach and HDR sensor finally resulted in the design for our light field measurement system, the "Plenopter", see figure 3. This custom-made apparatus allows for local light field measurements in the order of a second. The Plenopter contains 12 sensors in a regular configuration. A single, local measurement results in 12 numbers, which allow for the estimation of the local low order approximation (9 numbers) which was described in the previous section.

Then, from a set of such local measurements on a suitable matrix of points in a 3D space we can reconstruct the global structure of the light field in that 3D space [10] (by interpolation). This reconstruction thus gives the flux density, light vector and squash tensor at each point within the 3D space. These data can be used to make computer graphics renderings of matte convex objects, e.g. spheres, at arbitrary points in this space (see figure 4 bottom row, for a maybe somewhat more interesting shape). It is known from artistic practice, e.g. in lighting design and architecture [2, 9] that such renderings give a good impression of the visual quality of light in a scene and therefore this method may be very useful in applications.

Figure 3 The plenopter: 12 high dynamic range sensors in a regular dodecahedron configuration. Local measurements result in 12 numbers from which we can estimate the second order spherical harmonic approximation. Sets of local measurements over an array of positions in 3D space allow for reconstructions of the light field in that space by interpolation.

We used our methods to measure 24 different light fields in an empty office room (daylight was screened off) in the Light Lab at Philips Research. We made reconstructions of each of these light fields, which consist of 9 numbers, or the three components depicted in figure 1, at each point of the finite 3D space that we covered with our measurements. Since these basic data of which each of the 24 reconstructed light fields exist are rather abstract and bulky we need intuitive visualizations in order to get some insight into the global structure of the light fields.

VISUALIZATIONS OF LIGHT FIELDS

We visualized the light fields through it's “light tubes” [4], see figure 4, which represent the *net* flow of light (not the rays of light - light tubes can be curved and light rays cannot). The tubes directions are locally tangential to the light vector (the direction of maximum net energy transfer) and their widths are locally inversely related to the magnitude of those vectors (the larger the light transport, the smaller the tube). The tubes usually start at light sources, where they are quite narrow, and end on light absorbing surfaces, where they tend to be quite wide.

In figure 4 we show three light fields with quite typical structures. The upper image shows a case for primary illumination existing of three quite diffuse lamps on the ceiling in a row close to one of the long walls of the empty office room. The tubes diverge out from the sources towards the floor and opposite wall. In the second case the tubes diverge from a diffuse lamp in the middle of the ceiling towards the walls and floor. In the third case the tubes diverge from four quite narrow beams towards the walls and the floor, where they curve upwards due to interreflections from the floor. We rendered white, matte bunnies at three points along one of these curved tubes. The right bunny was rendered closest to the primary illumination in the right front corner of the room. It is clearly visible from its appearance that the light comes from above and slightly towards the right. The shading and shadowing contrasts over the bunny are quite strong, though a small effect of secondary illumination is visible at the bunnies’ breast. In the middle case the bunny is clearly illuminated from both primary and secondary illumination. The shading and shadowing contrasts are quite weak. The left bunny is primarily illuminated from below due to interreflections.

In natural scenes the light fields are due to complicated combined effects of primary illumination, scattering and screening by the objects in the scene, and scene geometry. However, the global structures of natural light fields show perhaps surprisingly smooth behavior and can be modeled in a very simple way [10]. Moreover, for 2D light field descriptions we showed which generic topological configurations are possible. These configurations could be described by a small range of singular points [12].

CONCLUSION AND DISCUSSION

Our methods allow low order, HDR measurements of a light field in a finite 3D space. The low order representations exist of the flux density, light vector and squash tensor. We visualized our measurements by means of reconstructions of light tubes, which represent the net transport of flux in the space. These visualizations give intuitive pictures of the light fields, allowing insightful inferences about the light quality in that space. For instance, it could be a scientific tool in the quantitative assessment of “light-zones” [8], or the areas where light from roughly different directions “meet” [9].

In lighting design the concept of the “flow of light” [2] describes the potential of lighting to produce distinct shading patterns. The associated metrics of the flow of light are the vector/scalar ratio of the illuminance, the illuminance vector direction and the flow of light ratio.

Note that our methods deal with the radiance, not the illuminance. Nonetheless, the illuminance vector/scalar ratio and illuminance vector direction correspond to the light vector magnitude and direction up to some normalization factor. Thus, our tubes visualizations directly represent the flow of light.

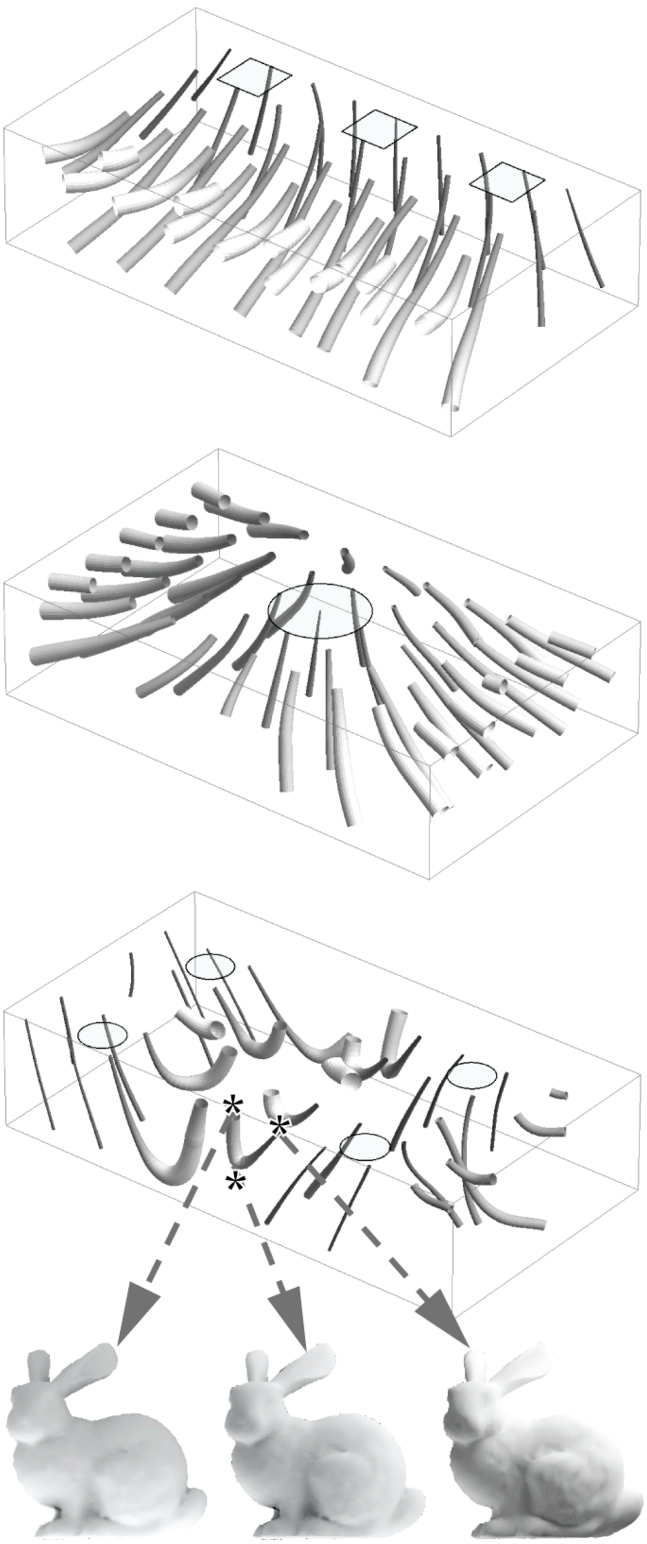


Figure 4 Light fields visualizations by means of light tubes. The local tubes' directions are tangential to the light vectors and the local widths are inversely related to the vectors' magnitudes. The box represents the room and the squares and circles on the ceiling represent the primary light sources, which were quite diffuse in the upper two cases and quite narrow beams in the bottom case.

Cuttle [2] proposed to examine the flow of light using a small matte white sphere to reveal the shading pattern. Madsen and Donn [9] did experiments with a "light-flow-meter" consisting of a grid of matte white spheres that was placed vertically in scenes. They used this method for the visual assessment of the spatial and form-giving character of (day-)light, that is, simultaneous judgments of the flow of light and Frandsen's "scale of light" [3]. The "scale of light" is a measure of the diffuseness of the illumination, ranging from fully collimated to hemispherically diffuse. In psychophysical studies on light field and material perception we found that for smooth matte spheres human observers confuse illumination diffuseness with illumination direction [14] and that they confuse illumination with material properties [13], due to basic image ambiguities. In figure 5 we illustrate the diffuseness-direction ambiguity. The figure shows matte white spheres rendered under illumination which was more or less diffuse (from left to right) coming from the right to almost frontal directions (from top to bottom). Note the similarities of images along the above left to below right diagonals. This diffuseness-direction ambiguity causes interactions of visual judgments of the "scale of light" and the "flow of light". This problem was implicitly noted by Madsen and Donn [9]. The "scale of light" estimates might improve if they would be done for views of matte spheres perpendicular to their average illumination directions or light vectors, since Frandsen's illustrations [3] were made under this condition.

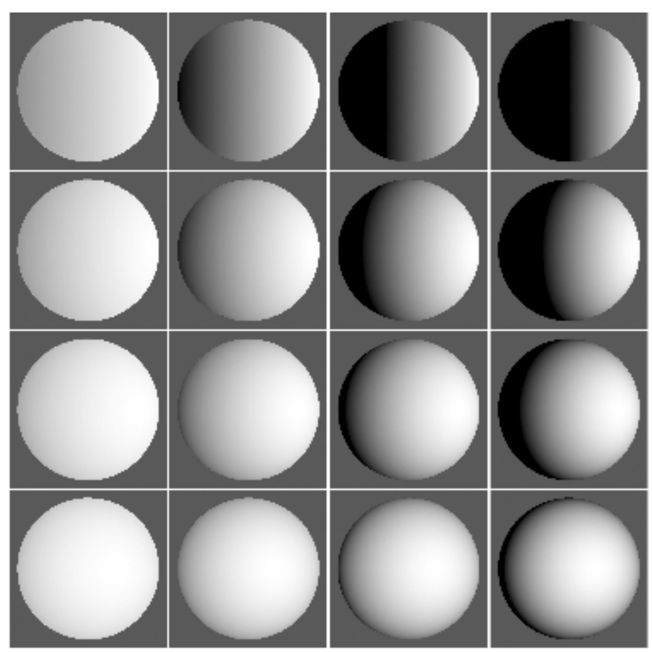


Figure 5 Rendered Lambertian spheres for which the illumination diffuseness and direction were varied systemati- cally: from left to right the diffuseness varies from halfway between fully diffuse and hemispherically diffuse to fully collimated, and from the top to the bottom the direction varies from 90 to 22.5 degrees in steps of 22.5 degrees. Notice that variations along the diagonals from above left to below right result in illuminance patterns which are more similar than along other directions (confusing judgments of the diffuseness and direction).

In figure 6 we demonstrate effects of type of illumination on the appearance of a rough white sphere. The golf-ball shows harsh body shadows and strong texture gradients for collimated illumination (left photograph), medium strong texture gradient for hemispherically diffuse illumination (middle image) and hardly any contrast for totally diffuse, Ganzfeld illumination (right image). The roughness texture provides cues about the illumination, which are additional to the shading and which human observers use to resolve confounds in material and illumination judgments [13]. Therefore, we propose to examine the flow of light with a rough sphere instead of a smooth one. The development of simple intuitive probes for the examination of lighting qualities stays an interesting challenge for future research.

Figure 6 Photographs of a golf-ball in different light fields. The effects on the appearance are huge. The images show, from left to right, harsh effects in collimated illumination, medium in hemispherically diffuse illumination, and very weak in totally diffuse (Ganzfeld) illumination.

Currently we are investigating relations between light field descriptions and visually relevant, known and new measures of lighting.

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