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Simulation of light-field camera imaging based on ray splitting Monte Carlo method

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ABSTRACT

As microlens technology matures, studies of structural design and reconstruction algorithm optimization for light-field cameras are increasing. However, few of these studies address numerical physical simulation of the camera, and it is difficult to track lighting technology for forward simulations because of its low efficiency. In this paper, we develop a Monte Carlo method (MCM) based on ray splitting and build a physical model of a light-field camera with a microlens array to simulate its imaging and refocusing processes. The model enables simulation of different imaging modalities, and will be useful for camera structural design and error analysis system construction.

1. Introduction

In 2005, Ng et al. [1] proposed the concept and technology of light-field imaging based on the surface radiation mechanism. Light-field imaging is characterized by its ability to focus fast-moving images accurately under low light conditions. The internal structure of a light-field imaging camera is unlike that of an ordinary camera. An ordinary camera captures light via its main lens and then focuses the light on the film or photoreceptor that lies behind the lens. The light converges from all incident directions to form each pixel of the photograph and ultimately form an image. In contrast, there is a microlens array, which is composed of a large number of microlens, between the main lens and the photoreceptor of a light-field camera. Each microlens receives the light from the main lens and then transfers the light to the photoreceptor. However, it is not the light (energy) that comes from various directions to be converged by the main lens that is received by photosensitive component; instead, the photoreceptor receives the light (intensity) that originates from a single direction and that is transferred by each microlens. By this method, the true information of the light field can be captured [2]. In recent years, many researchers have commenced research into the technology and applications of light-field imaging, which is based on the mechanism of surface radiation [3–5].

Turola et al. [6] used 4D light-field glasses to simulate the effects of the image's background scattered light and eye movement on retinal imaging. Wetzstein et al. [7] found that although the photographic sensors for these cameras had undergone rapid development over the past few years, there is an irreversible loss of the image signal during the transformation process between the target signal and the light-field signal. Yang et al. [8] designed a real-time distributed light-field camera that could obtain a clear photograph of a dynamic target and used a distributed rendering algorithm to solve problems with the inherent data bandwidth of the dynamic light field. The algorithm not only reduces the total data bandwidth, but also reduces the number of cameras in the system without increasing the net bandwidth. Atanassov et al. [9] noted that the spatially discrete value of the image restoration depth of field is associated with the value of the image depth of field section. Different values of the depth of field section in turn provided different values of the depth of field resolution. Zhou et al. [10] combined the principle of the light-field with image processing technology that had been developed for light-field camera calculations, and obtained better image resolution than an ordinary camera. Georgiev et al. [11] analyzed focusing in a plenoptic camera's optical phase space, and proposed basic, mixed and depth of field-dependent rendering algorithms, which provided a basis for high resolution image capture. Lumsdaine et al. [12] performed a Fourier analysis of the internal imaging principle of a camera that used light-field imaging technology, and developed an extended Fourier slice rendering algorithm, which could efficiently increase the digital zoom image resolution. By

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Nomenclature

L	geometric path length
MCM	Monte Carlo Method
R	radius
L_t	transmission length of radiative transfer
n	refractive index
R_θ,R_φ	uniformly distributed random number of zenith angle θ and circumferential angle φ

Greek symbols

θ_t	refraction angle of incident ray
ρ	reflective index
θ_i	incident angle of incident ray
φ	circumferential angle of solid angle

measuring mixed high-resolution images and low-resolution wavefronts, Lu et al. [13] proposed an iterative algorithm for high-resolution imaging that could increase the axial and transverse image resolutions.

In terms of research categories, current research into light-field cameras mainly focuses on the efficiency of the reconstruction algorithms, and image resolution and precision, with further research into the optical instruments based on transfer functions and Fourier transforms, but relatively few studies involve numerical simulation of the camera's physical imaging processes. However, proper structural design of these cameras, including aspects such as installation error analysis and calibration, using a reasonable physical model for simulation can reduce device costs and increase efficiency [14]. It is therefore necessary to establish a physical simulation model based on light-field camera imaging light transmission.

Two methods are commonly used for numerical analysis of light transmission [15]: one is based on ray tracing, while the other is based on the discrete transfer equation. The discrete transfer equation, which discretely computes spaces or angles, is difficult to use for simulation of irregularly-shaped structures, and it is therefore difficult to use to simulate the camera imaging process. The Monte Carlo method (MCM), the zone method, ray tracing and nodal analysis are commonly used in these simulations. The MCM, which is also a simulation method [16–18], was first applied to radiative transfer problems by Howell et al. [19]. The main idea is that the radiative transfer process is divided into independent sub-processes, such as emission, reflection, transmission or absorption, and scattering, and is then transformed into random problems (modeling using the probabilistic model of each sub-process [20]). The MCM has been applied to various radiative transfer problem-solving methods, including transient radiation, polarization emission, and gradient refractive index radiative transfer, and has a very wide range of applications.

Therefore, to solve the problems of physical simulation of light-field cameras [21], this paper uses the MCM with a light-splitting technique to simulate the light-field camera imaging process. Using our MC code, we achieve simulation of the physical process (light illuminating the target object, followed by light scattering by the object, and subsequent camera imaging) and by analysis of simulations performed under various conditions, we obtain the optimal parameters. The imaging capabilities of different cameras are also discussed and the results are used to establish a foundation for design and system error mode analysis of light-field cameras.

2. Models

2.1. MCM

Use of the MCM to simulate radiation transfer is usually based on the physical model of geometrical optics, and does not involve wave optics. While there are some MCM models that involved interference, diffraction and other wave optics phenomena, they simply instructed the random probability model of those phenomena with the existing physical equation, and did not simulate the wave optics mechanism. Using the MCM based on geometrical optics [22], this paper decomposed the transfer of photons (light beams, rays, radiation, and energy beams) into several processes as described in the following, and constructed the corresponding random model:

(1) surface (interface): emission, absorption, reflection, projection, and refraction;
(2) medium or medium with particles (dispersion): emission, decay (including absorption and scattering of medium or particle).

The process compares the magnitude of the homogeneous random number R_θ in the [0, 1] range, and the equations that describe the physical processes determine whether or not the physical process occurs. In another way, R_θ is used to calculate the condition of the physical process. Taking the equation for the surface emission energy direction as an example, the relationship between the zenith angle θ and its homogeneous random number R_θ can be described by Eq. (1):

$$\theta = \frac{\arccos(1 - 2R_\theta)}{2} \tag{1}$$

For the light-field camera, the probability model for reflection and refraction when the light threads through a medium interface is very important. The following will introduce that model briefly and another probability model can be found in the literature [20].

Refraction and reflection will occur when the light threads through an interface between media with different refractive indices, and the proportion of refraction and reflection will change with the angle of incidence. When the unpolarized light is injected at the smooth interface, the reflective index can be determined using [23]:

$$\rho(\theta_i) = \frac{1}{2}\left[\frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)}\right]^2 + \frac{1}{2}\left[\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}\right]^2 = \frac{1}{2}\left[\frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)}\right]^2\left[1 + \left(\frac{\cos(\theta_i + \theta_t)}{\cos(\theta_i - \theta_t)}\right)^2\right] \tag{2}$$

When the light is injected in the vertical direction, θ_i and θ_t are both 0, and thus the reflective index can be determined using:

$$\rho = \left(\frac{n_t - n_i}{n_t + n_i}\right)^2 = \left[\frac{(n_t/n_i) - 1}{(n_t/n_i) + 1}\right]^2 \tag{3}$$

If the interface is rough, then either diffuse reflection or diffuse transmission will occur. When the light is transferred from the optically thinner medium to the optically denser medium, its diffuse reflectivity can be described by