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Reconstruction of refocusing and all-in-focus images based on forward simulation model of plenoptic camera

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ABSTRACT

In this paper, we establish a forward simulation model of plenoptic camera which is implemented by inserting a micro-lens array in a conventional camera. The simulation model is used to emulate how the space objects at different depths are imaged by the main lens then remapped by the micro-lens and finally captured on the 2D sensor. We can easily modify the parameters of the simulation model such as the focal lengths and diameters of the main lens and micro-lens and the number of micro-lens. Employing the spatial integration, the refocused images and all-in-focus images are rendered based on the plenoptic images produced by the model. The forward simulation model can be used to determine the trade-offs between different configurations and to test any new researches related to plenoptic camera without the need of prototype.

1. Introduction

Based on the micro-lens arrays, a technique called integral photography was first proposed by Ives and Lippmann [1,2] over 100 years ago and greatly refined by Ives [3,4] in 1930s. This technique reemerged with the introduction of the plenoptic camera and regained much attention in recent years. In fact, the concept of light fields and plenoptic function was initially introduced by Adelson and Bergen [5] in 1991 and improved by Levoy and Harahan [6] and Gortler [7]. With the developments in the theories for analyzing and processing light fields, many designs and prototypes have been proposed [8–12].

In the basic micro-lens based design proposed by Adelson and Wang, a microlens array is placed in front of the sensor by one focal length of the microlens [8]. In 2005, Ng et al. improved the design and built a handheld plenoptic camera which is called plenoptic camera 1.0 [9]. One noticeable limitation of the plenoptic camera is that the resolution is limited to the number of microlens which is much lower than the sensor's. Georgiev and Lumsdaine modified the plenoptic camera by increasing the microlens-sensor separation and the prototype is called the focused plenoptic camera or plenoptic camera 2.0 which can capture higher spatial resolution radiance data [10]. Besides, there are still other two important radiance-capturing plenoptic camera prototypes, the heterodyne light field camera and the camera arrays [11,12]. However, our research focus on the plenoptic camera based on the micro-lens and detailed analysis will be presented in the following sections.

Compared with the traditional camera, plenoptic camera is considered as a cascade of a main lens system followed by a microlens system. Plenoptic camera can capture the 4D light field including 2D spatial information and 2D directional information in a single snapshot. Rays from the space objects focused by the main lens are separated by the micro-lens and finally captured on the sensor. Capturing images with plenoptic cameras makes greater processing capabilities possible and solves many of the problems faced by the conventional photography. Rendering refocused images, all-in-focus images, 3D scene reconstruction, HDR and super-resolution are just a few of the emerging techniques [13–15].

This paper examines the simulation of image formation process in plenoptic cameras through a forward simulation model and associated the depth map and image rendering algorithm. In detail, it presents:

1. The basic models of the plenoptic cameras.
2. A complete development of the forward simulation model of the plenoptic camera, including detailed description of the plenoptic image formation process.
3. A development of rendering algorithms that provides refocusing images, depth map and all-in-focus images. In addition,

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artifacts are talked about as well.

4. The presentation of computer simulation for the proposed forward simulation model including the rendering algorithm based on the plenoptic images capture by the simulation model.

2. Simulation model

2.1. Plenoptic camera

Fig. 1a illustrates the setup of plenoptic camera 1.0 which is based on a microlens array positioned at the image plane of the main lens, with a photo-sensor placed one focal length behind the microlens array. The main lens images the object in the scene onto the micro-lens array plane which maps the rays onto the photo-sensor below the corresponding microlens. The micro-lens samples the 2D position information, while the sensor records the direction information in the exit pupil from which the rays came. However, the limited resolution which is related to the number of micro-lens has been a significant drawback to the conventional plenoptic camera.

Besides the plenoptic camera 1.0, another alternative optical setup has been developed by Georgiev, plenoptic camera 2.0, as demonstrated in Fig. 1b. The relative position of the microlens array is the main difference in the prototype between the plenoptic camera 1.0 and 2.0. The microlens array is now focused on the image plane of the main lens instead of infinity. The result is that this setup can be considered as a relay imaging system and the micro-lens projects a portion of the image formed by the main lens onto the sensor. Compared with plenoptic camera 1.0, plenoptic camera 2.0 can produce images of much higher resolution, but at the cost of decreasing the angular resolution.

In this paper, we focused on the plenoptic camera 2.0 and established a forward simulation model in the remainder of the paper.

2.2. Forward simulation model

“Forward” denotes that the rays are traced from the object in the scene, through the main camera lens, then through the micro-lens array, and finally mapped into the photo-sensor [16].

For simplicity, only 1D of plenoptic camera is described in the following simulation model. As Fig. 2 shows, D and d represent the diameters of the main lens and microlens, respectively. L and b represent the distances from the main lens to microlens array and from microlens array to the photo-sensor, respectively. To maximize the use of sensor resolution, sub-images formed by the adjacent micro-lenses should be compactly adjacent to each other. With reference to Fig. 2, the following equation could be derived simply by the similarity triangles [9]:

$$\frac{d}{D} = \frac{b}{L+b} \approx \frac{b}{L} \tag{1}$$

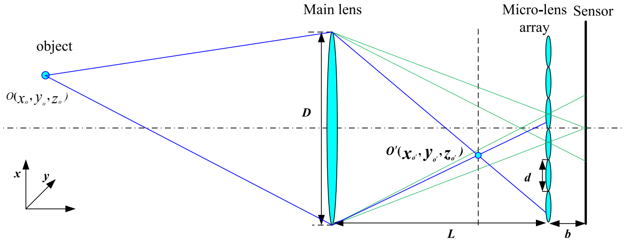

Fig. 2. Schematic of light field calculation and *F*-matching.

Based on paraxial optics and Lambertian scene assumption, supposing an object point $O(x_o, y_o, z_o)$ in the scene, we calculate its image point $O^{'}(x_{o'}, y_{o'}, z_{o'})$ by the lens equation. The radiance intensity of each ray from the object point is defined by its corresponding pixel value. Assuming the focal length of the main lens is F, the well-known lens equation is obtained.

$$\frac{1}{z_o} + \frac{1}{z_{o'}} = \frac{1}{F} \tag{2}$$

Once we know the coordinate of the object, the position of the image point formed by the main lens could be calculated. However, as Fig.3 depicts, the rays passing through O' cover an area on the microlens array. The coverage position and area could be deduced by simple geometrical equations.

$$\frac{s}{D} = \frac{L - z_{o'}}{z_{o'}} \tag{3}$$

where s represent the area covered by the light on the micro-lens array.

Assuming the coordinate of the point where the ray coming from the object point intersects with microlens array plane is $u(x, y)$, its maximum and minimum coordinates are represented as $u(x_{max}, y_{max})$ and $u(x_{min}, y_{min})$, respectively. As Fig. 3 describes, once the coordinate of $O^{'}$ is calculated, $u(x_{min}, y_{min})$ can be deduced based on the geometry relation. Making reference to the above description and Eq. (3), the maximum and minimum coordinates could be obtained easily.

$$x_{max} = \frac{L}{z_{o'}} x_{o'} \tag{4}$$

$$x_{min} = x_{max} - s \tag{5}$$

Similarly, y_{max} and y_{min} could be obtained. Furthermore, the values scope of x_u and y_u are defined as following, $x_u \in [\frac{Lx_{o'}}{z'_o} - \frac{L - z'_o}{z'_o}D, \frac{Lx_{o'}}{z'_o}]$, $y_u \in [\frac{Ly_{o'}}{z'_o} - \frac{L - z'_o}{z'_o}D, \frac{Ly_{o'}}{z'_o}]$. The next step is to remap the image point onto the sensor through the micro-lens covered by the ray from the object point. Finally, we obtain the light field image on the sensor [17].

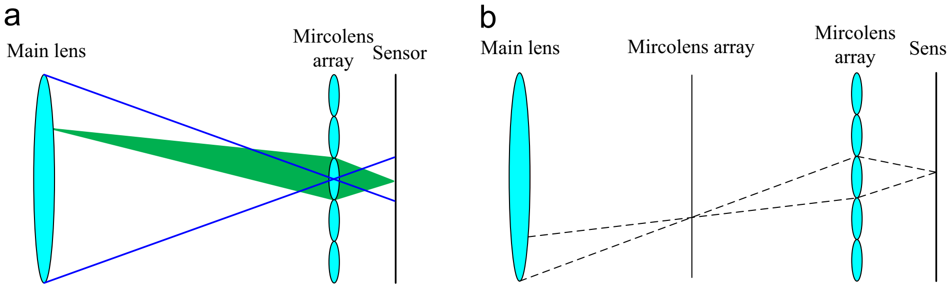

Fig. 1. (a) Plenoptic camera 1.0 projects the objects of the scene onto the microlens array. (b) In plenoptic camera 2.0, the object is imaged in front of the micro-lens array.