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Local error and its identification for microlens array in plenoptic camera

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ABSTRACT

A microlens array (MLA) is a key optical element in light-field imaging, but surface errors caused by manufacturing defects can result in the loss and deviation of light-field information transmission. To address this issue, we establish a local error model for an MLA arranged in a matrix form, and develop a method for identifying error microlenses based on image quality evaluation indexes. The local imaging characteristics and degradation mechanism of three basic errors are analyzed through simulation. The local errors on different microlenses cause different degradations of the corresponding sub-images, and the trend of change in light-field image quality is related to the error type, error value, and error direction. The simulation results also verify the accuracy and effectiveness of the proposed method and models.

1. Introduction

A plenoptic camera can capture and display the 4D light-field distribution of a target scene with a single exposure; that is, it obtains the 2D spatial information and 2D directional information of the light radiation in the space [1]. Compared to a conventional camera, it provides additional directional information that can be implemented in various applications via an appropriate algorithm, such as digital refocusing, depth estimation, 3D scene reconstruction, target recognition, and real-time monitoring [2–8]. A typical example of a plenoptic camera system is plenoptic camera 1.0, which is designed by Ng et al. [9]. In this imaging system, a microlens array (MLA) is located at the imaging plane of the main lens, and a coupled image sensor is placed at one focal length behind the MLA. The MLA divides the main lens pupil into several sub-apertures, and each microlens records the rays from multiple directions at the same position through different sub-apertures. In this manner, a complete set of light-field data is acquired. As an important optical element for 4D light-field analysis in plenoptic camera systems, the MLA determines the imaging quality and the reconstruction results of the applications, and it is required to have a high accuracy and maintain strict registration with other components.

However, because of manufacturing technology limitations and assembling deviations, the MLA parameters may vary, leading to surface shape errors [10–12] and coupling misregistration [13–15]. This also decreases the spatial resolution and focusing accuracy of the plenoptic camera, affecting the light-field information transmission. Therefore, it is necessary to identify and calibrate the MLA errors in plenoptic cameras. Dansereau et al. [16] presented a 15-parameter camera model that decoded the image pixels into their corresponding spatial rays, and proposed a projected-ray objective function and calibration scheme. They used these elements to calibrate and correct a commercial plenoptic camera without prior knowledge of its physical parameters. Su et al. [17] proposed a calibration method for the orientations of the MLA to determine the relationship between the microlens and sub-image centers. In addition, proper error functions and optimization algorithms were presented and applied for calibrating the distance and tilt between the MLA and sensor. The authors believed that the estimated results were affected by the pitch error of microlenses in practice. Bok et al. [18] demonstrated a method for calibrating the intrinsic and extrinsic parameters of the MLA by line features directly extracted from raw images. The geometrically calibrated sub-aperture images had only minor projection errors and a low level of noise, which was attributed to microlens errors and model limitations. Li et al. [19] established an error evaluation standard and corresponding correction models for possible MLA assembly errors in plenoptic cameras.

At present, it can be seen from the above studies that parameter calibration and error correction for the MLA are generally performed in an integral way; that is, the MLA errors are rectified as a whole. This type of method can recognize the MLA assembly error and, to a certain extent, solve the ray projection error caused by misregistration. However, in the case of manufacturing errors, the MLA surface shape error exhibits several local differences owing to various manufacturing methods, processing materials, and the complicated structure of the array. For example, Liu et al. [20] built a machining error analysis model of the MLA in ultra-precision turning. The simulation and experimen-

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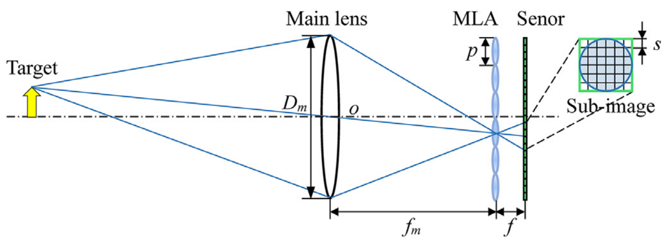

Fig. 1. Physical model of the plenoptic camera.

tal results showed that the integral distribution of the MLA form error was axisymmetric; the microlenses in the center column and row had the smallest form error, whereas the microlenses in the diagonal direction had the largest error. The error of each microlens is random and asymmetric. Mukaida et al. [21] machined MLAs on single-crystal silicon by slow tool servo diamond turning. The form error and surface morphology of the processed MLA were related to the cutting direction (microlens position), and the error forms and values at different angular positions were not identical. Therefore, the integral calibration method cannot adequately identify and correct the image quality degradation and light-field information confusion caused by manufacturing errors, such as changes in image brightness, resolution, and spot position, as well as refocus image blurring, aliasing, and distortion [22].

In this study, we develop a local manufacturing error model for the MLA by utilizing a ray-tracing-based simulation imaging system [23], and we analyze the local imaging characteristics under various error conditions. In addition, an effective method is proposed to identify the MLA errors in a plenoptic camera. Microlens center calibration and the corresponding sub-image division are performed, following which the microlens units with error are screened by the sub-image quality evaluation results. This study can serve as a reference for further correction of MLA local errors in plenoptic cameras.

2. Model and method

2.1. Plenoptic camera model

In this study, we construct a simulation model for Plenoptic Camera 1.0 based on the Monte Carlo method [23]. Fig. 1 illustrates the structural layout of the camera model. An MLA is placed at the imaging plane of the main lens, and an image sensor is positioned at one back focal length of the MLA. The optical axis of the main lens sequentially passes through the centers of the two. Rays from the target scene are focused by the main lens, diverge through the microlenses, and are projected on the image sensor, which forms a series of sub-images. The positions of the sub-images correspond to the 2D spatial light-field information, and the positions of the pixels covered by sub-images correspond to the 2D directional light-field information. The main parameters of the main lens, MLA, and image sensor in the simulation model are listed in Table 1.

2.2. MLA geometry model

In order to increase the light area and reduce optical information loss, a square-aperture MLA is adopted, as shown in Fig. 2. The fill factor (the ratio of effective light area to total area) is 100%. The entire MLA consists of $N_W \times N_H$ microlenses arranged in a tight matrix form. The length and pitch of the microlenses are both p. The two sides of the microlenses are spherical surfaces with radius r, the lens thickness is t, and the focal length is f. Table 1 lists the related parameters.

We establish the MLA global coordinate system, o–xyz, in which the MLA center is taken as the origin o, the y and z axes are parallel to the square grids of the microlenses, and the x axis coincides with the optical axis of the main lens and is perpendicular to the MLA plane. Fig. 3 shows a schematic of the coordinate system in the o–yz plane. Each unit of

Table 1
Main parameters of plenoptic camera model.

Parameters		Value
Main lens	Lens diameter D_m	42 mm
	Thickness at the vertex T_m	14.5 mm
	Radius of curvature R_m	106 mm
	Focal length f_m	105 mm
	Refractive index n_m ($\lambda = 632.8$ nm)	1.5168
MLA	Number of microlenses $N_W \times N_H$	102 × 102
	Pitch(side length) p	100 μm
	Radius of curvature r	469 μm
	Thickness at the vertex t	10 μm
	Focal length f	420 μm
	Refractive index n ($\lambda = 632.8$ nm)	1.56
CCD senor	Pixel size s	5.0 μm
	Number of pixels $W \times H$	2048 × 2048

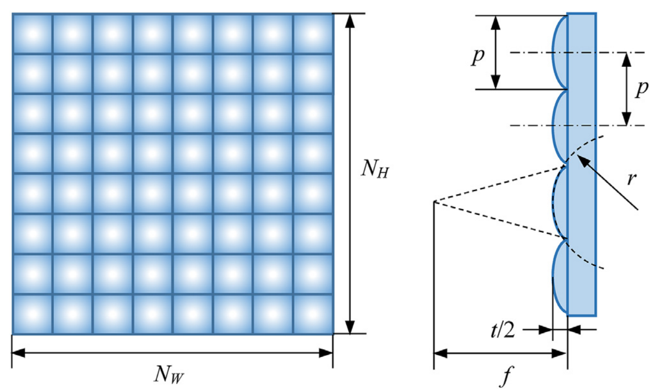

Fig. 2. Structure and parameters of the MLA.

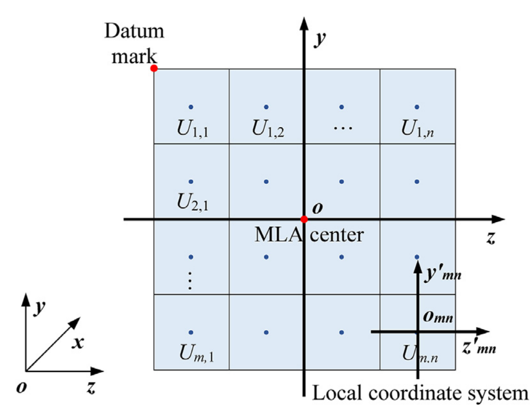

Fig. 3. Coordinate system of the geometric model of the MLA.

the MLA is denoted as $U_{m,n}$, indicating that the unit is positioned in the mth row and nth column of the MLA, where $m = 1, 2, \cdots, N_H$ and $n = 1, 2, \cdots, N_W$. For example, the microlens in the upper-left corner is in the first row and the first column, and it is denoted as $U_{1,1}$. Setting the upper-left corner of the MLA as the datum mark, the central coordinates of the microlens $U_{m,n}$ are given by

$$\begin{cases} y_{mn} = y_0 - (m - \frac{1}{2})p \\ z_{mn} = z_0 + (n - \frac{1}{2})p \end{cases} \quad (1)$$

where y_0 and z_0 are the coordinates of the datum mark, which can be calculated from $y_0 = \frac{1}{2} N_H p$ and $z_0 = -\frac{1}{2} N_W p$, respectively; p is the microlens pitch; and N_H and N_W are the number of microlens rows and columns, respectively.

For an accurate and independent description of each microlens profile in the MLA, we define the microlens local coordinate system, o_{mn}-