RECONSTRUCTION OF POLARIZATION IMAGES FROM A MULTIMOD LIGHT FIELD CAMERA BASED ON THE ALIASING MODEL

Da An, Yan Yuan†, Lijuan Su

Beihang University, Beijing, 100191, China
†E-mail: yuanyan@buaa.edu.cn

ABSTRACT

The multimode light field camera can capture the information of spatial location, spectral and polarization characteristics of target simultaneously. There is aliasing effect of the captured image which will cause that the directly extracted image from a certain filter includes information from other filters. In order to solve this problem, a new reconstruction method for reconstructing polarization images from the captured light field image is proposed along with an aliasing model which describes the pixel response to all the filters. The aliasing model is established by analyzing the imaging principle of the light field system. Then the aliasing coefficient matrix is obtained by calibration experiments. Finally, the images corresponding to the polarization filters are reconstructed. Compared with the conventional directly extracting method, the proposed method can greatly reduce the energy loss, and improve the accuracy of the reconstructed images, which will guarantee the accuracy of polarization information calculation, such as degree of linear polarization and angle of polarization.

Index Terms—Multimode Light Field Camera, Aliasing Model, Polarization Image, Nonlinear Least Square Fitting

1. INTRODUCTION

Polarization detection is an important remote sensing method. It is a powerful supplement to conventional target detection and can provide polarization characteristics of the target. It has been widely used in the resource investigation [1], the atmospheric exploration [2], the ocean monitoring [3], the target monitoring [4] and the biomedicine [5]. The polarization imager is the core of the polarization detection. The polarization imagers based on Stokes vectors should detect several polarization images of the scene [6]. It requires time scanning process or special system design for real time modulation.

In recent years, with the development of light field theory and technology, the light field imaging technology has been modified for real-polarization detection. In 2009, R. Horstmeyer proposed a multimode light field imaging scheme based on a light field camera [7], which can capture the spatial location, intensity, different polarization states and multi spectra of the target simultaneously. It can obtain the target data of different polarization states at a single snap.

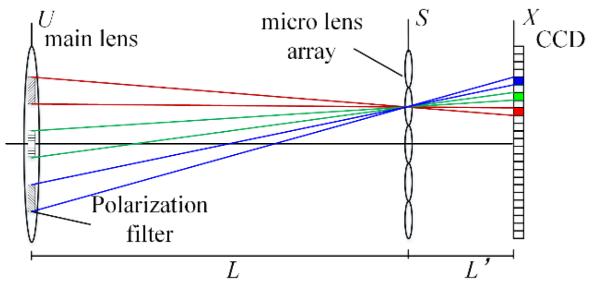
After capturing the data of target, the reconstruction of the polarization image is the basis of information calculation based on Stokes vector, such as degree of linear polarization (DOLP) and angle of polarization (AOP). In the multimode light field imaging system, the polarization filters are imaged by micro-lenses on to the pixels covered by micro-lenses [8]. A polarization image is obtained by extracting the pixels corresponding to the same polarization filter. However, in practice, the polarization information is received by several pixels due to several effects of the system, such as misalignment and diffraction. Furthermore, a pixel receives radiances from multiple filters. Therefore, the gray value of a pixel no longer reflects the radiance through a single polarization filter, the polarization image reconstructed by the directly extracting pixels has large error, which will affect the calculation of DOLP and AOP.

In order to solve this problem, this paper presents a reconstruction methodology based on an aliasing model. The experiment results verify that the proposed method can reconstruct more accurate polarization images than the directly extracting algorithm can. Furthermore, the proposed method can reconstruct polarization image with higher DN values of the scene.

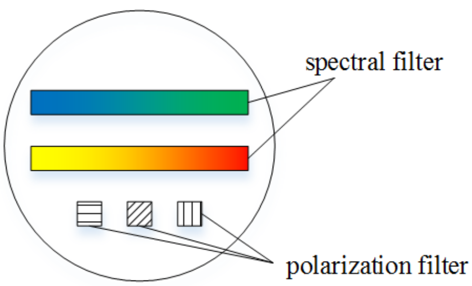
2. POLARIZATION IMAGING BASED ON THE LIGHT FIELD

2.1 Polarization Imaging Theory Based on the Light Field

The multimode light field imaging system can be simplified as a main lens, a spectral and polarization filter-array, a micro-lens array coupled with a CCD array, as illustrated in fig. 1(a). The filters consist of spectral filters and polarization filters, as shown in fig. 1(b). Generally, there are m spectral channels and n polarization channels. The light from the target travels through the filter array in the main lens and is imaged by a micro-lens on the CCD to form a macro pixel. Ideally, a pixel in the macro pixel corresponds to a filter. The light from the target travels through n polarizers, and is recorded by the corresponding pixels. Therefore, different polarization information of the target is obtained at one snapshot. Then, the polarization images of different degrees are reconstructed based on the light field multiplex principles.



(a)

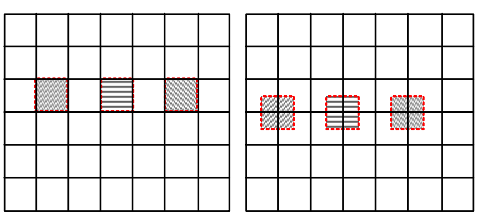


(b)

Fig. 1. The polarization imaging system based on light field: (a) a simple polarization imaging system based on light field, (b) the filters on the main lens.

2.2 Analysis of the Channel Aliasing

Ideally, the aperture image is imaged on one corresponding CCD pixel after traveling through a micro lens, as shown in fig. 1(a). However, there are various factors that can cause information aliasing of imaging system.



(a) (b)

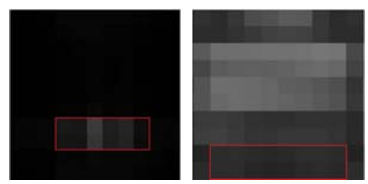
Fig. 2. Polarized aperture imaging on the CCD: (a) an ideal situation, (b) an actual situation.

The first problem is manufacturing error of optical components. For example, the pitch and focal lengths of the micro-lens array are not the same as the designed values.

The second problem is the misalignment of the system. In the designed multimode light field camera, each filter is ideally imaged on a corresponding pixel, as illustrated in fig. 2(a). But in fact, there are assemble errors in the system. For example, there is rotation between the micro-lens array and the CCD array. As a result, a filter is imaged on multiple pixels, as shown in fig. 2(b).

Furthermore, diffraction effect will also cause aliasing. Although the size of the filter is designed carefully to match a single pixel, the light passing through a filter is imaged on more than one pixel due to the diffraction effect of the optics system.

In order to demonstrate the effect, an integrating sphere is used as a light source for experiments. Fig. 3(a) is the image covered by a single micro-lens when there is only polarization filters, while fig.3 (b) corresponds to the spectral filters only. Fig. 3(a) shows that the polarization filters are not exactly imaged on their corresponding pixels respectively as fig.2 (a). Fig. 3(b) verifies the light passing through spectral filters can also be received by pixels corresponding to polarization filters. This also means that the polarization filters not only have aliasing along with each other, but also receive aliasing from the spectral filters.



(a) (b)

Fig. 3. Images of a white light integrating sphere under a micro lens: (a) image with only polarization filters on, (b) image with only spectral filters on.

3. THE METHOD OF POLARIZATION IMAGE RECONSTRUCTION

3.1 Directly Extracting Method

The common processes of extracting pixels corresponding to a certain polarization channel include three steps. Firstly, the pixels which have biggest response of a selected polarization filter is determined by the calibration experiments. Secondly, the gray value of the selected pixel is extracted as the information of the target captured by the micro-lens. Finally, repeat the above processes for all the micro-lenses to reconstruct the whole polarization image of the scene.

3.2 Aliasing Model and the Reconstruction Method

In order to solve the aliasing problem of multimode light field camera and improve the accuracy of reconstructed polarization images, an aliasing model of the imaging system is presented along with the reconstruction algorithm. For a certain pixel, it receives light from spectral and polarization channels. The radiance passing through the m^{th} spectral channel is noted as I_{sm}, and the i^{th} pixel receives $K_{si,m}$ portion of the total radiance. And the radiance passing through the n^{th} polarization channel is noted as I_{pn}, and the i^{th} pixel receives $K_{pi,n}$ portion of the total radiance. As a result, the response of a pixel can be defined as following equation:

$$I_i = K_{si,1} \cdot I_{s1} + \cdots + K_{si,m} \cdot I_{sm} + K_{pi,1} \cdot I_{p1} + \cdots + K_{pi,n} \cdot I_{pn} \quad (1)$$

The aliasing model of an arbitrary micro-lens is given by following equation:

$$\mathbf{I} = \mathbf{K} \cdot \mathbf{I}_{in} = \begin{bmatrix} \mathbf{K}_s & \mathbf{K}_p \end{bmatrix} \cdot \begin{bmatrix} \mathbf{I}_s \\ \mathbf{I}_p \end{bmatrix} \quad (2)$$

where, $\mathbf{I}$ is the response of the pixels covered by the micro-lens. $\mathbf{K}$ is the aliasing coefficient matrix, which consists of spectral coefficients $\mathbf{K}_s$ and polarization coefficients $\mathbf{K}_p$. And $\mathbf{I}_{in}$ is irradiance of the target, which consists of spectral irradiance $\mathbf{I}_s$ and polarization irradiance $\mathbf{I}_p$. Assuming each micro-lens covers t pixels, equation (2) can be rewritten as following expression:

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_t \end{bmatrix} = \begin{bmatrix} K_{s1,1} & \cdots & K_{s1,m} & K_{p1,1} & \cdots & K_{p1,n} \\ K_{s2,1} & \cdots & K_{s2,m} & K_{p2,1} & \cdots & K_{p2,n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ K_{st,1} & \cdots & K_{st,m} & K_{pt,1} & \cdots & K_{pt,n} \end{bmatrix} \cdot \begin{bmatrix} I_{s1} \\ \vdots \\ I_{sm} \\ I_{p1} \\ \vdots \\ I_{pn} \end{bmatrix} \quad (3)$$

In this equation, the coefficients $\mathbf{K}$ should satisfy with following relationship:

$$\begin{aligned} &\sum_{i=1}^{t} K_{si,j} = 1 (j = 1,2,\cdots,m+n), K_{si,j} > 0 \\ &\sum_{i=1}^{t} K_{pi,j} = 1 (j = 1,2,\cdots,m+n), K_{pi,j} > 0 \end{aligned} \quad (4)$$

The spectral coefficients are calibrated by using a monochromatic integration sphere which the output wavelength can be changed. The spectral response of pixels at a given wavelength is normalized by the total response to obtain the coefficients.

The polarization coefficients are also obtained by calibration process. In the calibration process, only the polarization filters allow light passing through. A linear polarizer is placed after the panchromatic integration sphere. During the experiment, the linear polarizer is rotated from 0° to 180°. The imaging system takes images after every 1 degree change. Based on Marius's law, the polarization information is defined as:

$$I_p = I \cdot \cos\theta = \frac{I}{2} \cdot \cos(2\theta) + \frac{I}{2} = A\left[\cos(2\theta + \varphi)\right] + c \quad (5)$$

where, I_p is the polarization irradiance. I is the irradiance of the target. θ is the transmission axis angle. A is the amplitude, φ is the initial phase, and c is the offset.

The polarization coefficients can be calculated by using nonlinear least squares fitting with the transmission axis angle θ as the independent variable. And the cost function is given by following equation:

$$\chi^2 = \min\left\{ \sum_{i=1}^{k} \left[\tilde{\mathbf{I}}(i\Delta\theta) - \mathbf{I}(i\Delta\theta) \right]^2 \right\} \quad (6)$$

where, $\tilde{\mathbf{I}}(m\Delta\theta)$ represents the fitted pixel response. $\mathbf{I}(m\Delta\theta)$ represents the actual pixel response.

After finishing the calibration process, the aliasing matrix of a micro-lens is obtained. Then, the desired information $\mathbf{I}_{in}$ of the target can be calculated by using the least squares algorithm to solve the following equation.

$$\mathbf{I}_{in} = (\mathbf{K}^T\mathbf{K})^{-1}\mathbf{K}^T\mathbf{I} \quad (7)$$

4. EXPERIMENT RESULTS

In this section, the polarization images are reconstructed by directly extracting method and proposed method based on the aliasing model respectively. The light field image of a panchromatic integrating sphere is shown in fig. 4, which is a 900 × 900 pixel area. The directly extracting images are shown in fig. 5, while fig. 6 shows the reconstruction results of the proposed method.

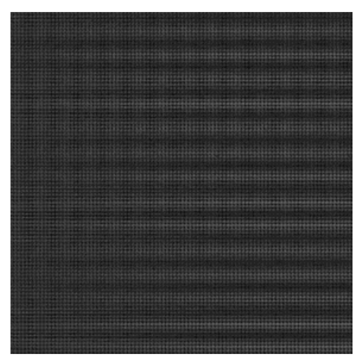
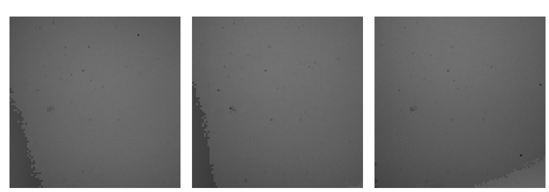


Fig. 4. The selected area of the light field image of white light integrating sphere.



(a) channel 1 (b) channel 2 (c) channel 3

Fig. 5. Directly extracted polarization images of the integrating sphere.

(a) channel 1 (b) channel 2 (c) channel 3

Fig. 6. Polarization images of the integrating sphere extracted by proposed method.

The average value *ave* and standard deviation *std* of each polarization channel of the integration sphere are used to characterize the performance of methods.

$$ave = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N} I_{i,j} \tag{8}$$

$$std = \sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}\left(I_{i,j} - ave\right)^2} \tag{9}$$

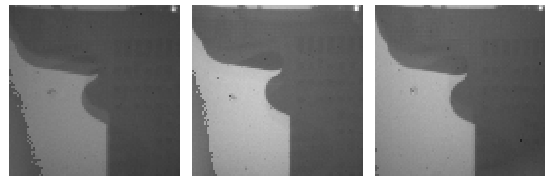
where, M and N are the length and width, $I_{i,j}$ is the grayscale value of pixel (i , j). The results are summarized in Table 1.

Table 1. The gray-value statistic results of the reconstructed polarization images of the integrating sphere light source

		direct method	**proposed method**
channel 1	*ave*	97.7260	193.9770
	std	2.0806	0.4262
channel 2	*ave*	98.3820	192.9595
	std	2.4379	0.3270
channel 3	*ave*	95.3385	191.7176
	std	1.6018	0.4275

As shown in fig. 5 and fig. 6, the polarization images extracted by directly extracting method are darker than those reconstructed by proposed method. The images should have uniform gray values because the target is a uniform area light. However, there are obvious brightness variation in the directly extracted polarization images. The reason is light from a polarization filter is received by several pixels and only one pixel response is extracted. This causes energy loss, which varies as the aliasing effect changes at different micro-lenses. The results showed in table 1 and fig. 6 demonstrate that the proposed method can reduces overall the energy loss and improve the uniformity as the standard deviation is only about 0.2% of the average value of the gray value. The accuracy is greatly improved compared with the directly extracting method.

We also took pictures of two different targets and used the two methods to reconstruct the polarization images of them. The reconstructed results are shown in fig. 7-10. Comparing the results shown in fig. 7-10, the proposed method can eliminate the unwanted boundary and improve the quality of the reconstructed images.



(a) channel 1 (b) channel 2 (c) channel 3

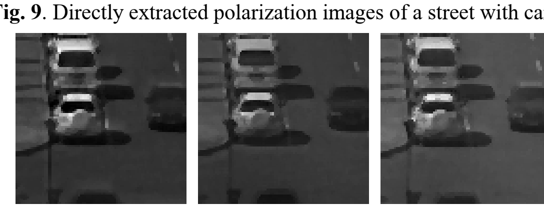
Fig. 7. Directly extracted polarization images of a building.

(a) channel 1 (b) channel 2 (c) channel 3

Fig. 8. Polarization images of a building extracted by proposed method.

(a) channel 1 (b) channel 2 (c) channel 3

Fig. 9. Directly extracted polarization images of a street with cars.



(a) channel 1 (b) channel 2 (c) channel 3

Fig. 10. Polarization images of a street with cars extracted by proposed method.

5. CONCLUSION

In this work, we analyze the reasons causing aliasing of the multimode light field image system. Then the data aliasing model is presented along with the reconstruction method. And we prove the effects caused by aliasing and the feasibility of the proposed method through experiment. The results verify the proposed method based on the aliasing model can extract polarization images more accurately, and the brightness variation can be eliminated. As a result, the proposed method is better than the direct method.

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REFERENCE

[1] Shen H Y, Zhou P C, Feng S R, Polarized Reflection Characteristics of Petroleum Contaminated Soil [J]. Chinese Journal of Soil Science, 2012(4):949-955.

[2] Wang Y J, Hong J, Sun X B, Technique of Polarization Remote Sensing Instrument for Aerosol Measurements and Its Onboard Calibration [J]. Journal of Atmospheric & Envirnomental Optics, 2014, 9(2):131-137.

[3] Luo Y J, Zhu J, Analysis of the advantages of multi - angle polarization remote sensing in oil pollution monitoring [J]. Remote Sensing for Land & Resources, 2011, 2011(3):32-36.

[4] Puttonen E, Suomalainen J, Hakala T, et al. Measurement of Reflectance Properties of Asphalt Surfaces and Their Usability as Reference Targets for Aerial Photos [J]. IEEE Transactions on Geoscience & Remote Sensing, 2009, 47(7):2330-2339.

[5] Miura M, Yamanari M, Iwasaki T, et al. Imaging Polarimetry in Age-Related Macular Degeneration [J]. Investigative Ophthalmology & Visual Science, 2008, 49(6):2661-7.

[6] Tyo J S, Goldstein D L, Chenault D B, et al. Review of passive imaging polarimetry for remote sensing applications [J]. Applied Optics, 2006, 45(22):5453.

[7] Horstmeyer R, Athale R, Euliss G. Modified light field architecture for reconfigurable multimode imaging [J]. Proceedings of SPIE - The International Society for Optical Engineering, 2009, 7468:746804-746804-9.

[8] Zhou Z L, Research on Light Field Imaging Technology [D]. University of Science and Technology of China, 2012.