High Resolution Light Field Photography from Split Ray Imaging and Coded Aperture

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Abstract: In this paper, we propose a method for obtaining high resolution 4D light fields by using low resolution camera sensors and controllable coded apertures. Recently, 4D light filed acquisition has been studied extensively in the field of computational photography. Since the 4D light filed consists of much lager information than the ordinary 2D image, we have to use super high resolution camera sensors in order to obtain high resolution 4D light fields. In this paper, we propose a method for obtaining high resolution 4D light fields from low resolution camera sensors. In this method, we combine the standard light field imaging technique with the coded aperture. By using these techniques, we can obtain high resolution 4D light fields from low resolution cameras with small number of image acquisitions. The efficiency of the proposed method is tested by real images.

1 INTRODUCTION

Recently, new imaging techniques, namely computational photography, are widely studied. In the computational photography, we use not only ordinary image processing methods, but also special imaging devices such as coded aperture(Veeraraghavan et al., 2007), moving imaging sensor(Kuthirummal et al., 2011) and so on. In particular, a light field camera(Adelson and Wang, 1992; Georgiev et al., 2007; Liang et al., 2008; Ng et al., 2005; Ng, 2006; Veeraraghavan et al., 2008) is one of the most promising devices in the field of computational photography. The light field camera can record 4-dimensional light field including not only 2D position information but also 2D directional information of light rays. The 4D light filed includes much more information than the ordinary 2D image, and thus, we can achieve much more sophisticated image processing, which cannot be accomplished by using ordinary camera devices. For example, we can generate any images observed by arbitrary focal plane, namely image refocusing, from the 4D light filed(Veeraraghavan et al., 2007).

In order to obtain 4D light fields, many methods have been proposed(Adelson and Wang, 1992; Georgiev et al., 2007; Liang et al., 2008; Ng et al., 2005; Ng, 2006; Veeraraghavan et al., 2008), each of which has different advantage and disadvantage. For example, Ng et al.(Ng et al., 2005) proposed a light field camera using a micro-lens array. In this method, the micro-lens array is set in front of the CCD/CMOS sensor, and then, light rays are separated and projected into different pixels. Veeraraghavan et al.(Veeraraghavan et al., 2007) used light modulation masks, such as cosine mask, for separating light rays. These methods enables us to separate and project different directional light rays into different pixels. We call these methods as *split ray imaging* in this paper.

The split ray imaging is very useful because we can obtain 4D light fields directly by a single shot imaging. Therefore, we can obtain light fields accurately, even if target objects are moving. However, we need a large scale imaging sensor in this method, since 4D light fields include much larger amount of information than ordinary 2D images.

In contrast, Liang et al.(Liang et al., 2008) proposed a light field camera, which enables us to obtain 4D light fields from an ordinary size imaging sensor. In this camera, controllable coded aperture was used. The aperture of this camera is divided into some number of pixels, and we can control the transmittance of these pixels. For obtaining light fields efficiently, the pattern of transmittance of the aperture is changed shot by shot, and different sets of light fields are obtained. Thus, we can obtain high resolution 4D light fields from low resolution imaging sensors. Although it can be achieved by using ordinary size sensors, we have to take a lot of images changing the aperture

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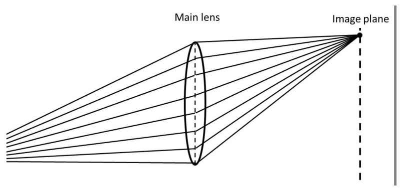


Figure 1: Light rays in an ordinary camera.

pattern for obtaining 4D light fields. Therefore, this method can be applied just to static scenes.

In this paper, we combine the split ray imaging and the coded aperture for obtaining high resolution 4D light filed from low resolution sensor and small number of imaging. Moreover, the proposed light field camera can control the trade off between the resolution of image sensor and the number of imaging. As a result, we can employ the best combination of the resolution of image sensor and the number of imaging.

2 4D LIGHT FIELD

We first explain 4-dimensional light field briefly. Figure1 shows light rays in an ordinary camera, where each pixel on the image plane receives all the light rays, which go through the lens. Since all the rays are mixed up at a single pixel, we cannot separate individual rays just from a single observation at the pixel. In contrast, the light field camera enables us to observe individual light rays, i.e. intensity of individual rays. By using the information acquired by the light field camera, we can achieve a variety of new applications, such as image refocusing, changing viewpoint and so on.

The light ray is represented by not only the position but also the direction. Let us consider a light ray observed at a pixel (x,y) on an image plane as shown in Fig.2. Suppose the direction of the ray is indicated by ϕ and ψ. Then, a single light ray can be considered as a function of a point in the 4D space, which consists of the position, x and y, and the direction, ϕ and ψ. The 4D space is called a light field.

We often represent 4D light field by using a point (x,y) on the image plane Σ and a point (θ,ω) on the other plane Π as shown in Fig.3. In this case, θ and ω corresponds to the direction of the ray. Thus, $L(x,y,\theta,\omega)$ represents a light ray in the light field. For example, a light ray in Fig.3 is represented as $L(1,3,200,150)=0.3$. Note, the plane Π is often defined on a camera lens or on an aperture.

By using the light field, we can generate ordinary 2D images projected onto arbitrary image planes. The intensities at each pixel in the image is computed by summing rays in all the direction. Thus, the ordinary 2D image $I(x,y)$ can be computed from the light field $L(\theta,\omega,x,y)$ as follows:

$$I(x,y) = \iint L(\theta,\omega,x,y)\,d\theta d\omega \tag{1}$$

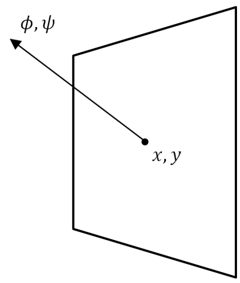


Figure 2: 4D light field.

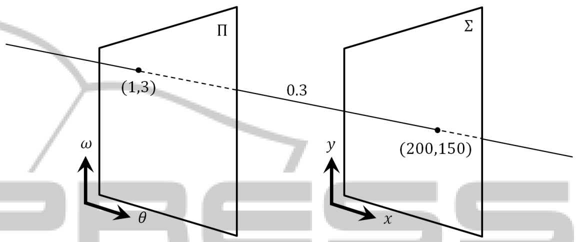


Figure 3: 4D light field represented by 2 different planes.

3 LIGHT FILED ACQUISITION

In recent years, many methods were proposed for obtaining 4D light fields. These methods can be classified into two groups. In this section, we explain these two methods.

3.1 Split Ray Imaging

The most naive method for obtaining 4D light fields is split ray imaging, in which each individual ray is observed by each pixel in the image sensor. This is achieved by using micro lens array, pin-hole array, and so on. In this section, we consider split ray imaging by using the pin-hole array model.

The pin-hole array consists of many pin-holes on a grid. The pin-hole array is set in front of an image sensor, such as CCD and CMOS. The light rays pass through the main lens and the pin-holes successively. After that, they are received by image pixel on the image plane as shown in Fig.4. In this case, resolution of ray position is determined by the number of pin-holes. On the other hand, the resolution of ray direction is determined by the number of pixels in the image sensor. Figure 4 indicates a light filed camera which can record 3×3 directions and 5×5 positions. In this method, the pin-holes must be designed carefully, so that the image sensor behind the pin-holes can capture individual rays properly. Thus, we next consider the design of pin-holes.

At first, we consider the relationship among distance d between pin-hole and image plane, distance v between main lens and pin-hole, size of pixel v, diameter of main lens R and the resolution of light ray direction N_l. These parameters can be figured as Fig.4, and their relationship can be described as follows:

$$R : N_l r = (v - d) : d \tag{2}$$

Therefore, the distance d can be described as follows:

$$d = \frac{N_l r v}{N_l r + R} \tag{3}$$

We next consider an appropriate distance between two adjacent pin-holes. If the distance is not set properly, light rays from different pin-holes are overlapped each other on an image pixel, or we cannot use all image pixels efficiently. Suppose a is an appropriate distance between two adjacent pin-holes. Then, the following relationship holds:

$$a : a' = (v - d) : v \tag{4}$$

where, a' denotes the distance between the center of projected rays through two adjacent pin-holes as shown in Fig. 4. Note that a' is defined as $a' = N_l r$. Therefore, appropriate distance a can be described as follows:

$$a = \frac{N_l r (v - d)}{v} \tag{5}$$

Finally, we can obtain proper pin-hole array $p(x,y)$ as follows:

$$p(x,y) = \sum_{k=-\infty}^{\infty} \sum_{l=-\infty}^{\infty} \delta(x - ka, y - la). \tag{6}$$

By designing pin-holes according to (6), we can obtain 4D light fields properly from 2D images.

In this method, however, we need a very high resolution image sensor in order to obtain 4D light fields with sufficient resolution. This is because we represent 4-dimensional data by using 2-dimensional image plane in this method. For example, if we want to obtain 9×9 directional light rays at 400×400 positions, we need 3600×3600 image pixels. Therefore, we need a large image sensor, which have large number of image pixels, in order to obtain light fields with sufficient resolution.

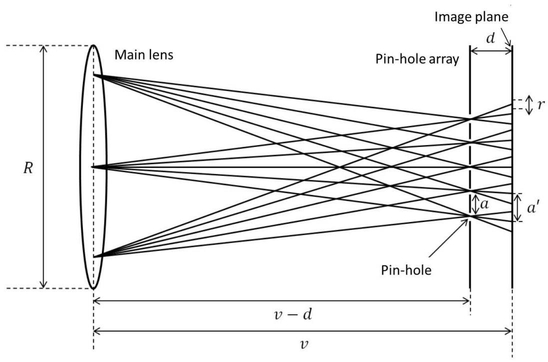


Figure 4: Split ray imaging by a pin-hole array.

3.2 Coded Aperture

We next consider the coded aperture for obtaining 4D light fields. Let us consider a controllable aperture for light field acquisition. The aperture is constructed from many pixels and we can control transmittance of each pixel. A light field camera can be constructed by using this controllable aperture and an ordinary image sensor.

We first consider basic theory of light filed acquisition by using coded aperture. As shown in Fig.3, light rays in the 4D light field can be defined by two planes. The image plane such as CCD and CMOS sensors can be considered as one of these two planes, and the controllable aperture can be considered as the other plane. Let us consider the case where controllable aperture is set onto the main lens. In this case, we can control light rays passing through the main lens by controlling the transmittance of each pixel of aperture. For example, we can obtain $4 \times 3 \times 300 \times 300$ light field, if we use image sensor with 300×300 pixels and controllable aperture with 4×3 pixels.

Suppose a pixel (i, j) on the aperture is open, and the other pixels on the aperture are closed. Let $I_{ij}(x,y)$ be an observed intensity at pixel (x,y) in the image sensor, when the pixel (i, j) is open. Then, the observed intensity $I_{ij}(x,y)$ can be described by the 4D light filed $L(\theta, \omega, x, y)$ as follows:

$$I_{ij}(x,y) = \begin{cases} L(\theta, \omega, x, y) & ,(\theta, \omega) = (i, j) \\ 0 & ,(\theta, \omega) \neq (i, j) \end{cases} \tag{7}$$

Therefore, we can obtain the light field as a set of images under different aperture patterns as follows:

$$L(i, j, x, y) = I_{ij}(x,y) \; (i, j = 1, \cdots, n), \tag{8}$$

where n indicates the number of pixels in the controllable aperture.

However, obtained image intensities become very small, since most of the pixels in the aperture are closed. As a result, the S/N ratio of obtained light field becomes very bad. However, we can avoid the problem by using the coded aperture.

Let us consider a case, where we have k different coded apertures $\mathbf{w}_i (i = 1, \ldots, k)$. Note, $\mathbf{w}_i \in [0,1]^n$. Then, $\mathbf{w}_i$ represents the transmittance of each pixel in the controllable aperture. When we use i-th coded aperture $\mathbf{w}_i$, the light field $L(\theta, \omega, x, y)$ is projected into image $I_i(x,y)$ as follows:

$$I_i(x,y) = \sum_{\theta,\omega} w_i(\theta,\omega) L(\theta,\omega,x,y), \tag{9}$$

where $w_i(\theta,\omega)$ denotes a component of $\mathbf{w}_i$, which corresponds to direction θ and ω.

Let $\mathbf{W}$ be a set of coded apertures as follows;

$$\mathbf{W} = \begin{bmatrix} \mathbf{w}_1 \\ \mathbf{w}_2 \\ \vdots \\ \mathbf{w}_k \end{bmatrix} = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & & w_{2n} \\ \vdots & & \ddots & \vdots \\ w_{k1} & w_{k2} & \cdots & w_{kn} \end{bmatrix} \tag{10}$$

If we make $||\mathbf{w}_i||$ large, the S/N ratio becomes better. Liang et al.(Liang et al., 2008) determined $\mathbf{W}$ by minimizing the following cost function $E(\mathbf{W})$:

$$E(\mathbf{W}) = \mathrm{Trace}((\mathbf{W}^\top \mathbf{W})^{-1}) \tag{11}$$

We next consider reconstruction of 4D light fields from observed images under coded apertures. Equation (9) shows that the observed images are summation of light rays with transmittance of coded aperture. That is, we can describe the relationship between observed images and the intensities of light rays by using the transmittance matrix $\mathbf{W}$ as follows:

$$\begin{bmatrix} I_1(x) \\ I_2(x) \\ \vdots \\ I_k(x) \end{bmatrix} = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & & w_{2n} \\ \vdots & & \ddots & \vdots \\ w_{k1} & w_{k2} & \cdots & w_{kn} \end{bmatrix} \begin{bmatrix} L(1,x) \\ L(2,x) \\ \vdots \\ L(n,x) \end{bmatrix}, \tag{12}$$

where $I_k(x)$ denotes an intensity at position x under k-th coded aperture and $L(\theta, x)$ denotes a light ray at position x with direction θ. We rewrite (12) as follows:

$$\mathbf{I} = \mathbf{W}\mathbf{L} \tag{13}$$

where $\mathbf{I} = [I_1(x), I_2(x), \ldots, I_k(x)]^\top$ and $\mathbf{L} = [L(1,x), L(2,x), \ldots, L(\theta,x)]^\top$. Thus, we can estimate light rays as follows:

$$\hat{\mathbf{L}} = \arg\min_{\mathbf{L}} ||\mathbf{W}\mathbf{L} - \mathbf{I}||_2, \ \mathbf{L} \geq \mathbf{0} \tag{14}$$

where $||\cdot||_2$ indicates L2-norm of vectors. We can obtain complete light field by this estimation.

In this method, we can obtain high resolution light field by using ordinary image sensor. However, we need a lot of images under different coded apertures. This means we need long time to obtain a sufficient light field.

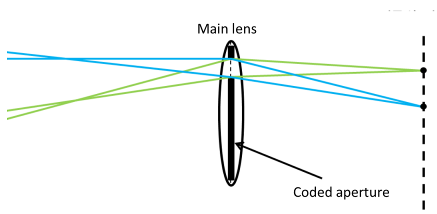


Figure 5: Light field acquisition by using coded apertures.

4 LIGHT FIELD FROM SPLIT RAY IMAGING WITH CODED APERTURE

As described in section 3, there exists two types of method for obtaining light fields. In the former method, super high resolution image sensors are required for obtaining light fields with sufficient resolution, although they are obtained by a single shot. In the second method, we have to iterate image acquisition several times, although light fields can be obtained by using standard resolution cameras. In this section, we propose a new method for obtaining light field efficiently by combining these two existing methods. In our method, we use the pin-hole array (or micro lens array) and the coded aperture simultaneously. As a result, we can reduce the resolution of image sensor and the number of image acquisition required for obtaining light fields with sufficient resolution. We can also control the trade off between the resolution of image sensor and the number of image acquisition according with the situation. This property is practically very important, since we have to obtain sufficient light fields under limited conditions in general.

We first consider the acquisition of 2D light field by using 1D camera in order to simplify the problem. Let us consider the case, where 9 light rays $L(j,i)$ $(j = 1, \cdots, 9)$ go through the coded aperture and pin-holes, and are projected onto 3 pixels in the image sensor as $L'(m,i)$ $(m = 1, \cdots, 3)$, as shown in Fig.6. Because of the geometric relationship shown in Fig.6, $L(1,i)$, $L(2,i)$ and $L(3,i)$ are projected onto $L'(3,i)$. Similarly, $L(4,i)$, $L(5,i)$ and $L(6,i)$ are projected onto $L'(2,i)$, and $L(7,i)$, $L(8,i)$ and $L(9,i)$ are projected onto $L'(1,i)$. We can control the transmittance of aperture in front of the main lens. Let w_{kj} be the transmittance of j-th pixel of k-th aperture pattern $\mathbf{w}_k$. Then, the relationship between the light field $L(j,i)$ $(j = 1, \cdots, 9)$ and the observed intensity $L'_k(m,i)$ $(m = 1, \cdots, 3)$ under k-th aperture pattern can be described as follows:

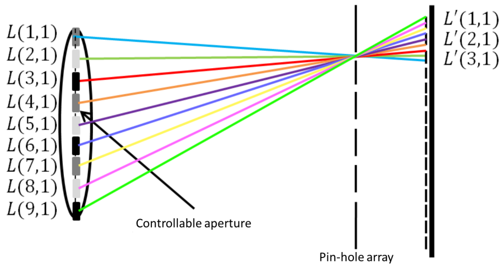


Figure 6: Light field acquisition from split ray imaging and coded aperture.

$$L'_k(1,i) = \sum_{j=7}^{9} w_{kj} L(j,i) \tag{15}$$

$$L'_k(2,i) = \sum_{j=4}^{6} w_{kj} L(j,i) \tag{16}$$

$$L'_k(3,i) = \sum_{j=1}^{3} w_{kj} L(j,i) \tag{17}$$

Since 3 constraints are obtained for light field $L(j,i)$ from each aperture pattern, we can estimate light field $L(j,i)$ from images taken under 3 different aperture patterns. Note, we need 9 different aperture patterns, if we do not combine the pin-hole array. Furthermore, we need 9 image pixels if we do not combine the coded aperture. Thus, the proposed method can decrease the number of image acquisition and the size of image sensor. As a result, the proposed method can solve the problem of coded aperture method and the problem of split ray imaging method.

By using the proposed method, we can obtain high resolution light fields by using a normal image sensor with reasonable number of image acquisition. For example, if we want to obtain a light field with 9×9 directions and 640×480 positions by using the standard lens array method, we need an image sensor with 5760×4320 pixels. Also, if we want to obtain the same light field by using the coded aperture method, we need 81 image acquisitions. However, if we use the proposed method, the same light field can be obtained by using an image sensor with 1920×1440 pixels and 9 image acquisitions as shown in Tab.1. Thus, the proposed method enables us to obtain high resolution light fields from reasonable sensors and reasonable image acquisition.

Table 1: Relationship between the size of image sensor and the number of image acquisitions.

	# of pixels	# of acquisitions
Split ray imaging	5760×4320	1
Coded aperture	640×480	81
Proposed method	1920×1440	9

5 POINT SPREAD FUNCTION OF LIGHT RAYS

5.1 Light Field Representation by PSF

We can obtain high resolution light fields by using the proposed method described in section 4. However, the obtained light fields may not be accurate because of the spread of light in imaging. This problem often occurs when we use micro lens arrays for separating rays. The light rays passed through a micro lens often spread over some pixels in the image sensor. The blur occurs when a distance between the micro-lens and the image plane does not agree with the focal length of the micro lens. The blur of the light rays can be described by a point spread function (PSF).

The PSF can be represented by an image taken under a point light source. Thus, the PSF can be obtained by opening a single pixel on the controllable aperture and taking images.

Let $\mathbf{p}_j$ be a point spread function of j-th pixel in the coded aperture. The observed image $\mathbf{I}$ under a light field $L(j,i)$ can be described as follows:

$$\mathbf{I} = \sum_{j=1}^{n} \mathbf{p}_j L(j,i). \tag{18}$$

This equation can be rewritten as follows:

$$\mathbf{I} = \begin{bmatrix} \mathbf{p}_1 & \cdots & \mathbf{p}_n \end{bmatrix} \begin{bmatrix} L(1,i) \\ \vdots \\ L(n,i) \end{bmatrix}. \tag{19}$$

Note that the number of component of $\mathbf{I}$ and $\mathbf{p}_j$ is smaller than n, since the resolution of observed image is lower than the resolution of light field. Relationship between unblurred light field $[L(1,i),\ldots,L(n,i)]^\top$ and acquired images under different coded aperture can be described as follows:

$$\begin{bmatrix} \mathbf{I}_1 \\ \vdots \\ \mathbf{I}_k \end{bmatrix} = \begin{bmatrix} w_{11}\mathbf{p}_1 & \cdots & w_{1n}\mathbf{p}_n \\ & \vdots & \\ w_{k1}\mathbf{p}_1 & \cdots & w_{kn}\mathbf{p}_n \end{bmatrix} \begin{bmatrix} L(1,i) \\ \vdots \\ L(n,i) \end{bmatrix}, \tag{20}$$

where $\mathbf{I}_k$ denotes k-th acquired image and w_{kj} denotes the transmittance of j-th pixel in k-th aperture pattern, i.e. k-th image acquisition. Then, we can obtain unblurred light field $[L(1,i),\ldots,L(n,i)]^\top$ under different coded apertures as follows:

$$\begin{bmatrix} L(1,i) \\ \vdots \\ L(n,i) \end{bmatrix} = \begin{bmatrix} w_{11}\mathbf{p}_1 & \cdots & w_{1n}\mathbf{p}_n \\ & \vdots & \\ w_{k1}\mathbf{p}_1 & \cdots & w_{kn}\mathbf{p}_n \end{bmatrix}^{+} \begin{bmatrix} \mathbf{I}_1 \\ \vdots \\ \mathbf{I}_k \end{bmatrix}, \tag{21}$$

where $\mathbf{A}^+$ indicates the pseudo inverse of $\mathbf{A}$, and is computed by $\mathbf{A}^+ = (\mathbf{A}^\top \mathbf{A})^{-1}\mathbf{A}^\top$. Therefore, we have to estimate the PSF in order to obtain unblurred light fields from blurred light fields.

5.2 Estimation of PSF

Eq. (19) describes a linear relationship between PSF and light rays. Since it is linear, we can estimate PSF linearly from a set of images taken under known light fields. For this objective, we use a white Lambertian surface as a source of the standard light field. This is because the reflected lights of a white Lambertian surface have constant unit intensity at any points on the surface and toward any directions from the surface.

If we observe a white Lambertian surface by using the proposed light field camera, the relationship between observed image $\mathbf{I}$ and PSF $\mathbf{p}_j$ can be described as follows:

$$\mathbf{I} = \sum_{j=1}^{n} w_j \mathbf{p}_j \tag{22}$$

where, w_j denotes the transmittance of j-th pixel of the aperture. The equation indicates that we can obtain a PSF directory by opening each pixel of the aperture and observing the image. However, the S/N ratio of obtained PSF is bad, because we cannot obtain enough image intensity if most of the aperture is closed. In order to avoid the problem, we use the least means square method.

By obtaining k images of Lambertian surface under different coded apertures, we have a system of linear equations as follows:

$$\begin{bmatrix} \mathbf{I}_1 & \cdots & \mathbf{I}_k \end{bmatrix} = \begin{bmatrix} \mathbf{p}_1 & \cdots & \mathbf{p}_n \end{bmatrix} \begin{bmatrix} \mathbf{w}_1^\top & \cdots & \mathbf{w}_k^\top \end{bmatrix} \tag{23}$$

Thus, a set of PSF $\mathbf{p}_1, \cdots, \mathbf{p}_n$ can be estimated as follows:

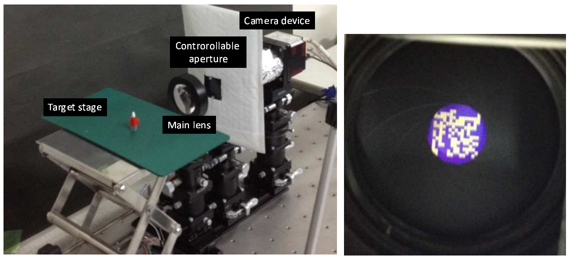
$$\begin{bmatrix} \mathbf{p}_1 & \cdots & \mathbf{p}_n \end{bmatrix}^\top = \begin{bmatrix} \mathbf{w}_1^\top & \cdots & \mathbf{w}_k^\top \end{bmatrix}^{\top+} \begin{bmatrix} \mathbf{I}_1 & \cdots & \mathbf{I}_k \end{bmatrix}^\top . \tag{24}$$

Then, from (21) we can estimate unblurred light field, even if the observed images are blurred. We next consider experimental results by using our proposed method in the following sections.

6 EXPERIMENTAL RESULTS

6.1 Environment

In this section, we show some experimental results from the proposed method. At first, we explain the



(a) (b)

Figure 7: Experimental environment (a) and coded aperture by controllable aperture(b).

experimental devices and environments. In this experiment, a camera and a main lens were set separately as shown in Fig.7(a) in order to adjust camera parameters accurately. The camera used in this experiment is TOSHIBA Teli CSC6M85BMP11, and 1210×730 images are taken by this camera. A micro-lens array is set in front of the CMOS sensor in camera device. The micro-lens array consists of 242×146 micro-lenses and the focal length of each lens is 0.54mm. The focal length of main lens is 72.7mm, and the distance between lenses is 250mm. The target objects are put in front of the main lens. The distance between the stage and the main lens is $110 \sim 130$mm. A controllable aperture is set in front of the camera as shown in Fig. 7(a). It is an LCD with 15×15 pixels. Figure 7(b) shows an example of coded aperture generated by the controllable aperture. Note that we cannot perfectly obstruct a light, even if the aperture is completely closed. Therefore, we subtracted an ambient image obtained by closing all the aperture from input images in order to eliminate ambient intensity.

Figure 8 shows an image taken when all the pixels of aperture are opened. In this figure, some regions around the center of image is magnified. The small circles in the image represent different directional light rays to the same destination (micro-lens). The number of the circles correspond to the number of micro-lens and it is 242×146. The size of circle is 5×5, and thus, the maximum resolution of directional component is 5×5 in this image. The circles are not aligned in grid because of the distortion of micro-lens array, etc. Thus, we aligned the circles in grid by using thin plate spline transformation. The resolution of light field in this image is $242 \times 146 \times 5 \times 5$. In this experiment, we reconstruct a light field with $242 \times 146 \times 15 \times 15$ by using the proposed method.

6.2 PSF Estimation

We first estimate PSF by the method described in section 5.2. The resolution of controllable aperture is 15×15, and then, we needed 225 or more than 225

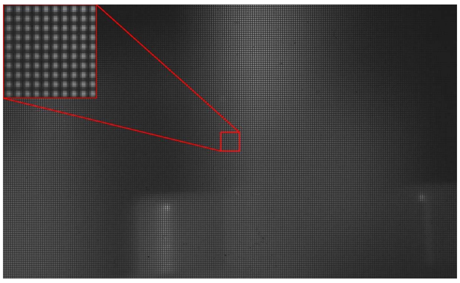
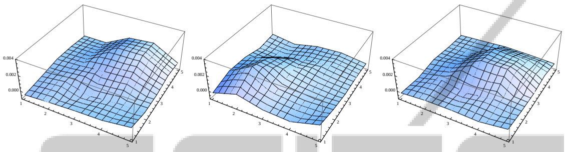


Figure 8: Image taken by opening all the pixels in controllable aperture.



(a) $C(10,15)$ (b) $C(2,3)$ (c) $C(8,8)$

Figure 9: Examples of estimated PSF. (a), (b) and (c) show PSF when aperture (10,15), (2,3) and (8,8) is opened, respectively.

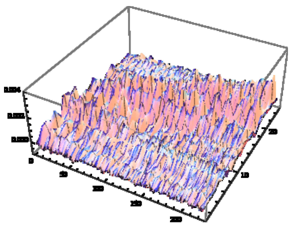


Figure 10: Estimated set of PSF.

images to estimate set of PSF. In order to estimate a set of PSF accurately, we used 675 images for this estimation. We used a Lambertian plane as a calibration object. The estimated PSF of a destination are shown in Fig.9. In these figures, intensities of PSF is represented by color, and each figure shows PSF when aperture (10,15), (2,3) and (8,8) is opened, respectively. Figure 10 shows estimated set of PSF described in Eq.(23). In these results, intensity of light ray was not converged to a pixel nevertheless only one pixel of aperture was opened. The fact indicates that light field recorded by the camera is blurred and we need PSF for accurate light field recording.

6.3 Reconstruction of Light Field

We next show reconstructed high resolution light field by the proposed method. In this experiment, we reconstructed 15×15 directional light rays from 5×5 directional light rays at each position, and thus, 9 or more than 9 images are required for reconstruction.

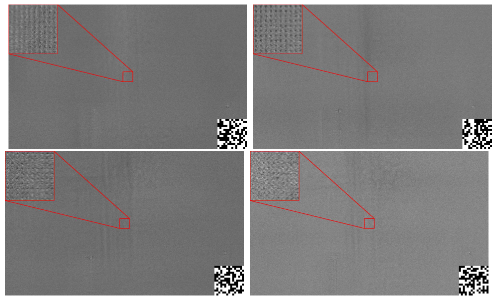
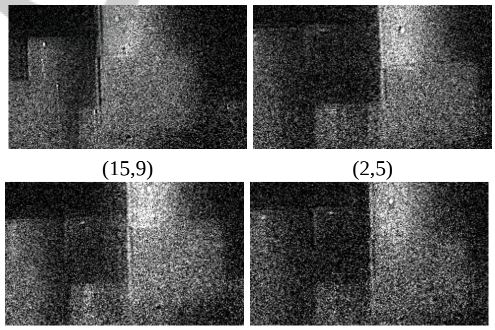


Figure 11: Examples of input images and coded apertures. Coded aperture is shown in right bottom in each image.

Figure 12: Reconstructed high resolution light field.



(15,9) (2,5)

(4,11) (5,7)

Figure 13: Sub-images of light field which have the same directional light rays.

In this experiment, we used 75 images taken under different coded apertures for accurate light field reconstruction. Figure11 shows some examples of input images.

From these images, high resolution light field was reconstructed and the result is shown in Fig.12. Figure13 shows sub-images of light field. In these figures, images were generated from a set of light rays with the same direction.

For comparison, the same light field was reconstructed without considering PSF. The results are shown in Fig.14. In this figure, the reconstructed light field is blurred and is not accurate. It indicates the

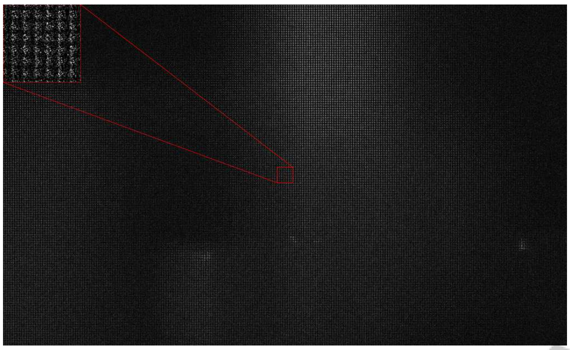
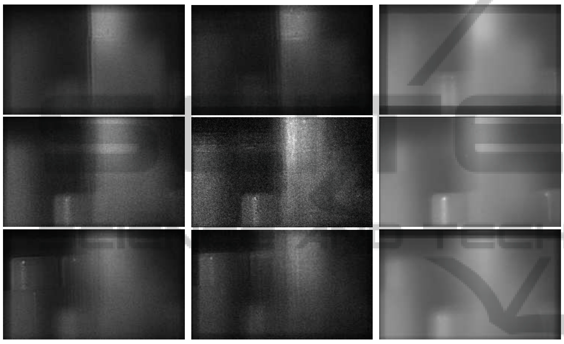


Figure 14: Reconstructed high resolution light field without considering PSF.



(a) proposed method (b) proposed method without PSF (c) input image

Figure 15: Refocused images from a light field obtained by (a) proposed method, (b) proposed method without considering PSF and (c) direct input image. Images in top, middle and bottom rows are focused to the nearest object (left object), middle object (center object) and the farthest object (left object) respectively.

effectiveness of considering PSF in light field reconstruction.

6.4 Image Refocusing by using Light Field

We finally show the results of image refocusing from reconstructed light field. For comparison, we refocused images from (a) result of the proposed method, (b) result without considering PSF and (c) low resolution input image. Figure 15 shows refocused images.

In these results, refocused image in (b) is blurred since the reconstructed light field is also blurred. Result in (c) is also blurred since input light field does not have sufficient resolution. In contrast, result from the proposed method in (a) is accurate. This is because we can use accurate and high resolution light field for refocusing. The result indicates that the advantage of the proposed method.

7 CONCLUSIONS

In this paper, we proposed a method for obtaining high resolution 4D light fields from standard camera with reasonable number of image acquisitions. In particular, we showed that by combining the split ray imaging, such as micro lens array, with the coded aperture, we can reduce the number of image pixels as well as the number of image acquisitions required for obtaining high resolution light fields. Furthermore, we presented a method for calibrating PSF of the proposed light field acquisition method by using the coded aperture.

The proposed method is very practical, since we can control the trade off between the number of image pixels and the number of image acquisitions according to the purpose. Thus, our method can be applied to many applications.

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