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# A viewing direction control camera without mechanical motion based on computational imaging

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## Abstract

*To capture an image of object at long distance, viewing direction of the camera must be controlled when long-focal length is used. Therefore, there is method of control viewing direction at high-speed using galvanometer scanner. In this method, vibration of the mirror influences captured image due to mechanical motion. To get image of an object without mechanical motion, a camera should get an image of entire field of view. Then, object image can be got by clipping it from the image of entire field of view. In this method, camera must get also information other than the object at once to capture an entire image with wide range. Therefore, the object image is low-resolution because a number of image sensor's pixel which contributes the object is few. Thus, we propose a camera which has controllability of viewing direction and can capture high-resolution image without mechanical motion based on computational imaging. By using this camera, it is possible to control at high-speed. Moreover the camera has no influence of vibration. We did a simulation and confirmed that the proposed camera which has controllability of viewing direction got high-resolution image of an object without mechanical motion.*

## 1. INTRODUCTION

To capture an image of object at long distance, a telephoto camera which has long focal-length lens is used. The telephoto camera which has controllability of viewing direction is used in a variety of situations. The camera is used to capture image of fast moving object such as tracking of fast flying object. Moreover, the camera is used when distance between the camera and object changes depending on time such as traffic condition recognition. For these situation, fast viewing direction control is necessary.

One of ways of viewing direction control is by moving camera itself using servomotor (pan-tilt zoom camera). By this method, it is difficult to control viewing direction at high speed due to weight of long focal-length lens. Therefore, there is method of view direction control at high-speed using galvanometer scanner by Okumura et al. and Hachisu et al. [1] [2]. In this method, it is possible to control viewing direction by controlling angle of galvanometer scanner which is located on optical axis of the camera. However, vibration of the mirror influences captured image.

For tracking of object as shown in Figure 1(a) without mechanical motion, a camera should capture image of wide field of view as shown in Figure 1(b). Then, object image can be obtained by clipping it as shown in Figure 1(c). In this method, camera must get also information other than the object at once to capture an entire image with wide range. Therefore, the object image is low-resolution because a number of image sensor's pixel which contributes the object is few.

In Recent years, there is camera based on computational imaging as representative light field camera [3] [4] [5]. Light field camera gets many rays of light as light fields and captures image based on image processing.

We propose a camera which has controllability of viewing direction and can capture high-resolution image without mechanical motion based on computational imaging. By using proposed camera, it is possible to control at high-speed because of no mechanical motion. Moreover, the camera has no influence of vibration.

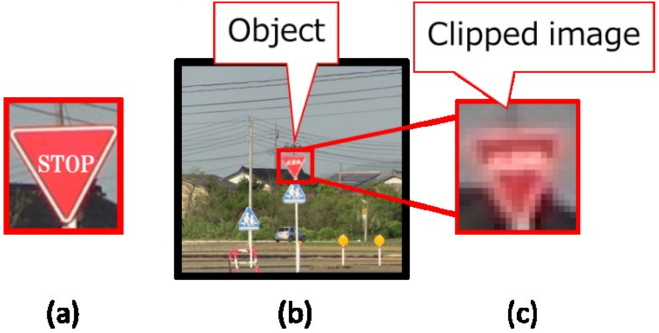

***Figure 1.*** *(a)Original signal of object (b) Image of wide field of view camera (c) Low-resolution image of object by clipping it from the image (b)*

## 2. STRUCTURE OF OPTICAL SYSTEM

We have proposed the structure of optical system as shown in Figure 2. By using lens array, a number of image sensor's pixel which contributes object can be increased. Next, a pair of convex lenses and aperture which is made of liquid crystal limit direction of ray into the image sensor to control viewing direction. We call a pair of convex lenses and aperture "range of angle of ray direction limiter optics". Moreover, high-resolution image can be reconstructed by using super-resolution processing.

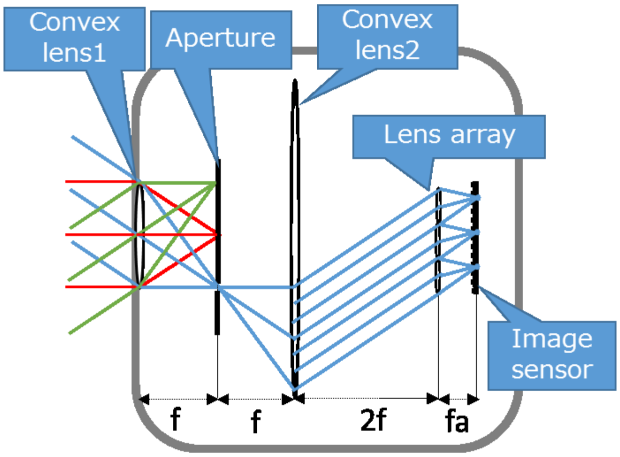

***Figure 2.*** *Structure of optical system (f is focal length of convex lens 1 and 2, fa is focal length of lens array)*

### Principle of proposed camera

"Range of angle of ray direction limiter optics" is put before the lens array. By controlling position and size of aperture, range of angle direction is decided. Therefore, rays enter to the image sensor under limited range of angle direction. These rays form multiple images on the image sensor by lens array as shown in figure 3 (b) and (c).

Figure 3 (b) shows optical images formed by the lens array when position of the aperture is controlled to capture object 1 in center of figure 3 (a). By changing position of aperture, the camera gets optical images of object2 in different direction as shown in figure 3(c). In this way, view direction control is realized by controlling position of the aperture. The purpose of proposed camera is to capture object at long distance. Therefore, we assumed that incident rays are parallel. All optical images by elemental lens of the lens array are same because they are formed parallel rays. In this situation, small multiple optical images are captured by most of image sensor. Therefore, a number of image sensor's pixel which contributes object can be increased in proposed method. However, multiple optical images are low-resolution image because they are small.

Copies of multiple low-resolution images of the target object are captured when image sensor outputs image. Therefore, it is necessary to reconstruct high-resolution image from low-resolution images. Therefore, we adopt super resolution reconstruction. It is a method to reconstruct high-resolution image from multiple low-resolution images which are sampled at different sampling positon. In proposed method, we set ratio of lens pitch and pixel pitch is non-integer, each copy of optical image is digitized at different sampling position as shown in Figure 4 (b). Figure 4 (c) $img_1$, $img_2$ and $img_3$ are optical images by lens array $l_1$, $l_2$ and $l_3$ respectively. These optical images are sampled at different sampling position when the camera captures target object as shown in Figure 4 (a).

Next, we explain method of super resolution reconstruction. The camera needs super resolution processing assuming image contains noise such as shot noise and thermal noise. Therefore, we adopt Tikhonov regularization [6].

Vector of pixel value of image sensor $\mathbb{Y}$ expresses as

$$\mathbb{Y} = \mathbb{A}\mathbb{X} \tag{1}$$

where $\mathbb{X}$ is vector of object information and $\mathbb{A}$ is degradation matrix. $\mathbb{Y}$ is vector of information of multiple low-resolution images when the camera captures image of object. By Tikhonov regularization, estimation image of object $\tilde{\mathbb{X}}$ expresses as

$$\tilde{\mathbb{X}} = (\mathbb{A}^T\mathbb{A} + \zeta\mathbb{I})^{-1}\mathbb{A}^T\mathbb{Y} \tag{2}$$

where $\zeta$ is constant to reduce noise. It is necessary to use large $\zeta$ when large noise occurs in image sensor. $\mathbb{A}$ has to be made according to control viewing direction in advance.

The camera obtains high resolution image by this principle. The viewing direction is controlled without mechanical motion by the aperture made of liquid crystal.

### Comparison with light field camera

Light field camera captures information about light field for applications such as refocusing and measurement of distance to object. For refocusing, the camera captured multiple optical images which have different parallax by elemental lens of lens array.

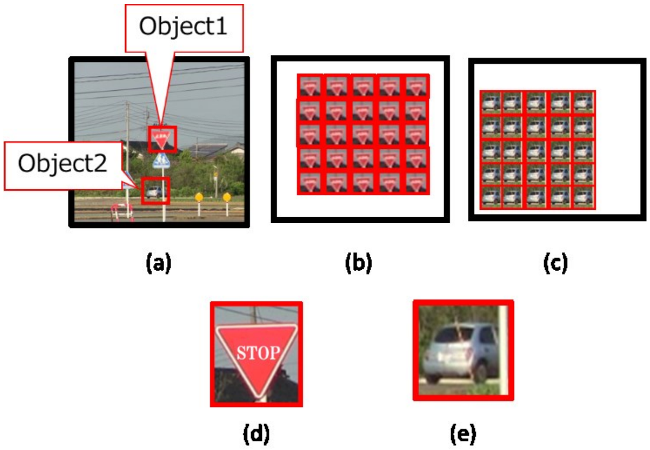

***Figure 3.*** *(a) Objects at long distance (b) Optical images of Object1 on image sensor by lens array (c) Optical images of Object2 on image sensor by lens array (d) Reconstructed result of Object1 (e) Reconstructed result of Object 2*

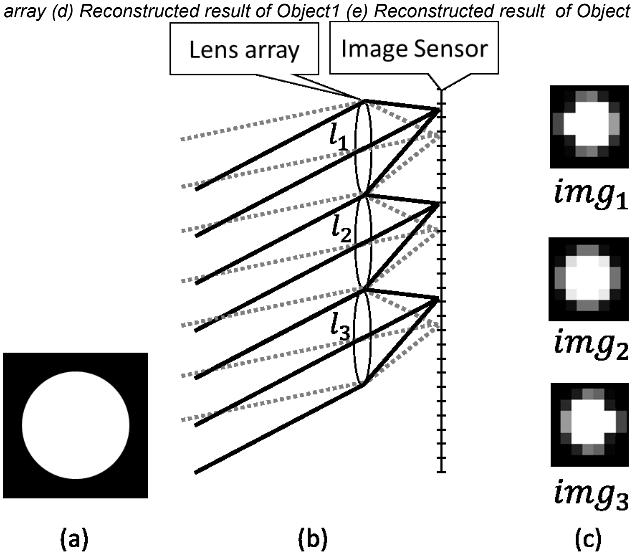

***Figure 4.*** *(a) Image of target object (b) Optical image on image sensor when pitch of lens array and pitch of image sensor are non-integral multiple (c) Results of output image which are sampled at different sampling position by image sensor*

There are two differences between light field camera and proposed camera. One of the differences is presence or absence of parallax of optical images formed by the lens array. A purpose of light field camera is to obtain parallax or depth information. In contrast, proposed camera obtains non-parallax images to capture image of object at long distance.

The other of the differences is FOV (Field Of View) of each lens of lens array. The FOV in proposed camera is narrower than light field camera because the purpose of proposed camera is to capture high-resolution image of object at long distance.

## 3. SIMULATION

We did ray tracing simulation and super resolution processing to confirm principle. First, emitted rays from object entered the proposed optical system, and optical image on image sensor were formed in ray tracing simulation. Second, the camera got output image by image sensor. Third, we assumed Gaussian noise as noise of pixel value. Finally, object image were reconstructed by super resolution processing from output image by image sensor.

We set specification of proposed camera as shown in Table 1. In this simulation, target image were put at maximum angle of viewing direction as shown in Figure 5. We designed optical system using a pair of plano-convex lens and plano-convex lens array to meet the specification of camera. Specification of the lens is shown in Table 2, and structure figure of the optical system is shown in Figure 6. Moreover, specification of image sensor is shown in Table 3. From these specifications, a number of elemental images on image sensor is calculated as 22*18 = 396.

**Table 1: Specification of proposed camera**

| | |
|---|---|
| Maximum angles of viewing direction Φ(X and Y direction)[deg] | 9.076 |
| Field of view θ(X and Y direction)[deg] | 0.924 |
| Resolution[PIX] | 200*200 |

**Table 2: Specification of lens**

| | Plano-convex lens 1 | Plano-Convex lens 2 | Plano-convex lens array |
|---|---|---|---|
| Focal length[mm] | 85.72 | 85.72 | 18.6 |
| Back focal length[mm] | 70.4 | 83.2 | 17.8 |
| Curvature radius[mm] | 81.76 | 81.76 | 8.6 |
| Size[mm] | Ø10 | Ø50 | 10*10 |
| Thickness[mm] | 30 | 5.0 | 1.2 |
| Pitch[mm] | | | 0.3 |
| Material (refractive index) | TAFD45(1.95375) | | Silica(1.4585) |

**Table 3: Specification of image sensor**

| | |
|---|---|
| Size[mm] | 6.9*5.5 |
| Pixel size[mm] | 0.0212*0.0212 |
| Resolution[PIX] | 320*256 |

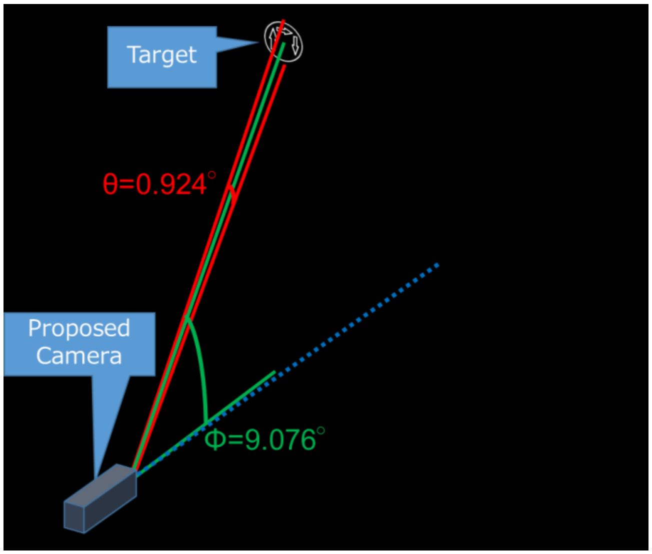

***Figure 5.*** *Location of target image*

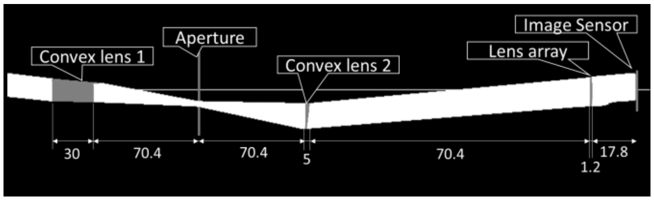

***Figure 6.*** *Design result of structure of optical system*

Figure 7 shows image of target object. Output image of image sensor under noiseless is shown in Figure 8. Images which have Gaussian noise when standard deviations $\sigma = 0.5, 0.05, 0.005$ are shown in Figure 9, Figure 10 and Figure 11 respectively.

From these image and coefficient matrix, we reconstructed target image by using super resolution processing. Figure 12 shows a reconstructed result from figure 8 (Output image of image sensor under noiseless). Figure 13 shows a result of reconstruction from figure 9, figure 10 and figure 11(Noise images). We choose a value of $\zeta$ to become close appearance of target.

As shown in figure 12 (a), half of the image can't be reconstructed correctly, because elemental images blur by aberration of lens. Elemental images are resemble each other by blur. Therefore, one of the reason why image can't be reconstructed correctly is calculation error because difference of pixel value becomes small. As shown in figure 12 (b), image of object can be reconstructed correctly when $\zeta$=1. One of reasons of correct image that there are no calculation error. From this result, we confirmed that viewing direction of camera can be controlled without mechanical motion under noiseless.

As shown in figure 13, quality of reconstructed images is influenced by value of σ. In particular, figure 13 (a) can't be restored correctly. Therefore, it is important to reduce noise as possible in proposed camera.

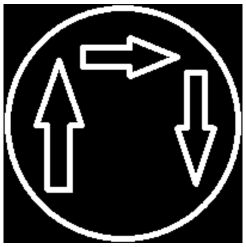

***Figure 7.*** *Image of target object*

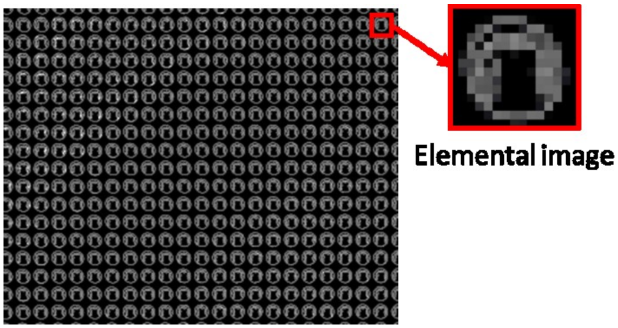

***Figure 8.*** *Output image of image sensor under noiseless*

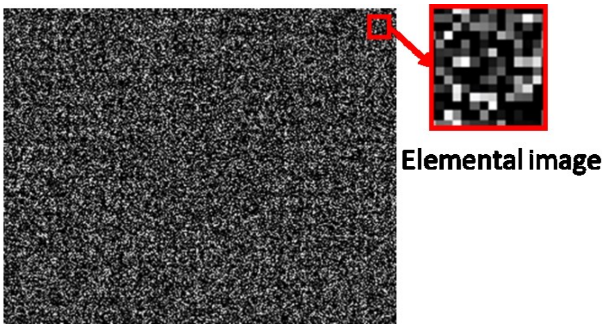

**Figure 9.** *$\sigma=0.5$, noise image of image sensor*

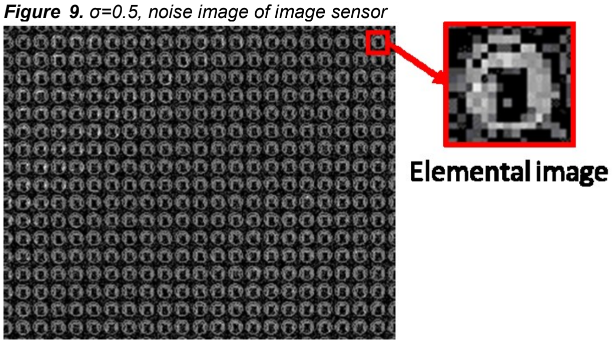

**Figure 10.** *$\sigma=0.05$, noise image of image sensor*

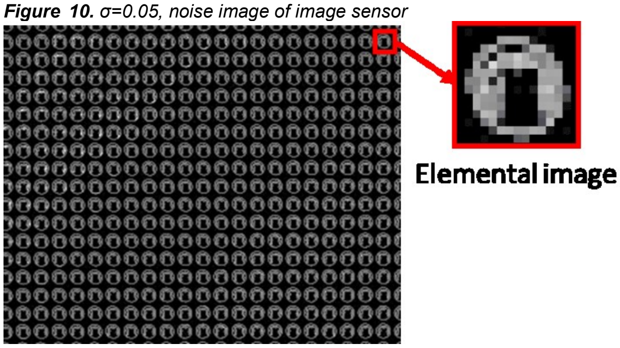

**Figure 11.** *$\sigma=0.005$, noise image of image sensor*

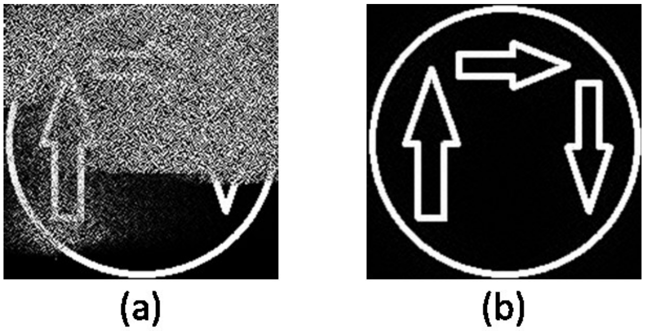

**Figure 12.** *(a) $\zeta=0$, reconstructed result of image from figure 8 (b) $\zeta=1$, reconstructed result of image from figure 8*

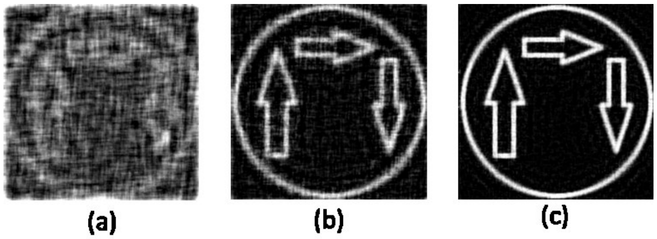

**Figure 13.** *(a) $\sigma=0.5$, $\zeta=10000$, reconstructed result of image from figure 9 (b) $\sigma=0.05$, $\zeta=1000$, reconstructed result of image from figure 10 (c) $\sigma=0.005$, $\zeta=100$, reconstructed result of image from figure 11*

## 4. CONCLUSION

We propose a camera which has controllability of viewing direction and can capture high-resolution image without mechanical motion. Moreover, we did a simulation to confirm that viewing direction of camera can be controlled without mechanical motion. From simulation results under noiseless, we confirmed principle of proposed camera. From simulation results of noise image, it is important to reduce noise as possible in proposed camera.

The future work includes experiment by actual equipment.

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