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A shooting direction control camera based on computational imaging without mechanical motion

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Abstract

To take an image of object at long distance, a camera which has long-focus lens is used. However, if the focal length is long, the field of shooting becomes narrowed. Therefore, the shooting direction of the camera must be controlled. Recently, pan/tilt camera, whose direction is driven mechanically, has been used for surveillance. However, it is difficult to control quickly for long-focus camera because of weight of lens. We proposed a camera which has controllability of shooting direction without mechanical motion and high-resolution image of distant object based on computational imaging. The proposed camera is composed of ray-direction limiting optics and lens array. The direction of incident rays are limited and determined by the position of the aperture in the ray-direction limiting optics, it is possible to control the shooting direction without mechanical motion. By using a lens array, a number of small optical images are formed on most area of the image sensor and digitized. Each digitized image is low-resolution because of small size. To reconstruct high-resolution image from low-resolution images, we adopted reconstruction-based super resolution technique. We did simulation under realistic conditions and confirmed the principle of the proposed camera.

Introduction

In recent years, there are a lot of cameras with various uses in town. For example, there is a car-mounted camera. In automatic driving vehicles and driving support systems, road information such as traffic jam and accidents must be obtained as soon as possible for getting to know about road conditions in advance. Therefore, it is necessary to take a picture of a distant object. A camera with a long focus lens, a telephoto camera is used for taking a picture of a distant object. A telephoto cameras can take a picture clearly objects at distance, but the shooting range is narrowed. In order to take a picture the range as wide as possible, it is necessary to control the shooting direction of the camera. In addition, when taking a picture of an object moving at high speed such as a car, or when a car-mounted camera in a moving automobile take a picture of a stationary object such as a signage or a guideboard, it is necessary to control the shooting direction of the camera at high speed.

One of ways of shooting direction control is to move camera itself using servomotors. This is called pan-tilt zoom camera. In this method, it is difficult to control the shooting direction at high speed because the telephoto lens is large and heavy. Therefore, high speed shooting direction control method was proposed using galvanometer scanners by Hachisu et al. and Okumura et al. [1] [2]. In this method, it is possible to control viewing direction by controlling angle of the galvanometer scanners which is located on optical axis of the camera. However, there are problems that it is difficult to downsize and be lighter by mechanical motion. Moreover, the vibration of the mirror influences the captured image.

For controlling the shooting direction without mechanical motion, a method of cutting out an object after taking a picture of a wide range around the object is conceivable. In this method, as shown in Figure 1, there is a problem that the image of the object becomes lower in resolution than the image captured in the wide range before cutting out.

Therefore, we proposed a camera based on computational photography that can control the shooting direction without mechanical motion [3]. By using proposed camera, it is possible to control at high speed because of no mechanical motion. Moreover, the proposed camera can be downsize and lighter.

Previously, we did a basic simulation and confirmed the basic principle of the proposed camera. Therefore, we did a realistic simulation and confirmed the principle of the proposed camera under more realistic conditions.

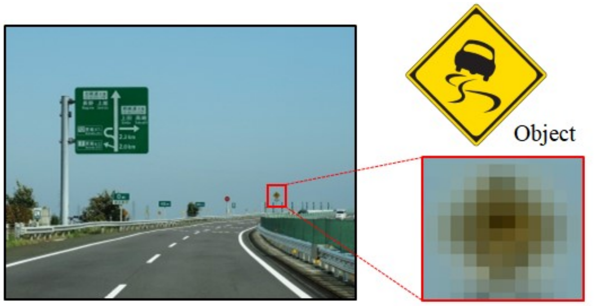


Image of captured in a wide range   Image of the cut out object

Figure 1. Resolution by cutting method

Proposed optical system

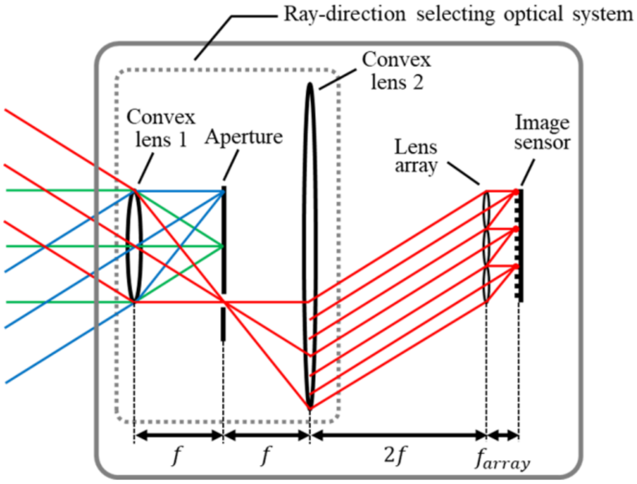
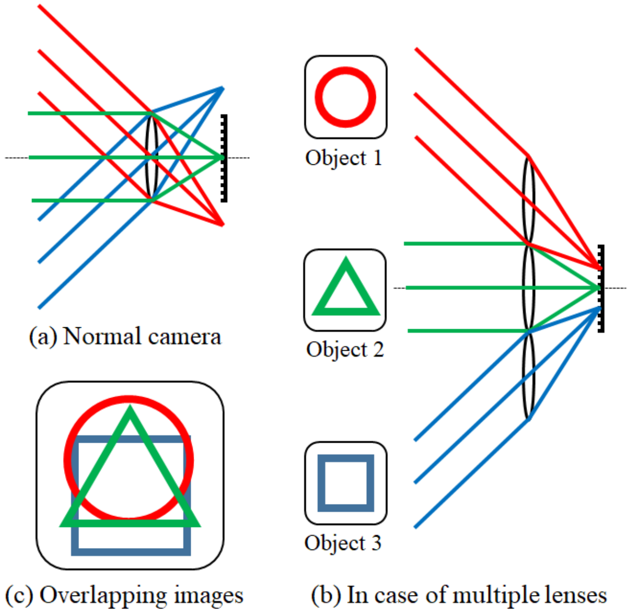


Figure 2. Structure of the proposed camera

The entire structure of the proposed optical system is shown in Figure 2. This optical system consists of a ray-direction selecting optical system, a lens array, and an image sensor [3]. The ray-direction selecting optical system consists of two convex lenses and an aperture. In the ray direction selection optical system, the distance between the aperture and the convex lens is the focal length of the convex lens. The distance between the convex lens 2 and the lens array is two times the focal length of the convex lens and the distance between the lens array and the image sensor is the focal length of the lens array. The proposed camera is supposed to take a picture of an object at infinity.

Principle of the proposed optical system

In the case of a normal camera, there is one convex lens as shown in Figure 3 (a). At this time, only when the shooting direction is close to the optical axis, an image of an object is formed on the image sensor. However, when the shooting direction is away from the optical axis, image of the object is not formed on the image sensor. Hence, if multiple of convex lenses are arranged as shown in Figure 3 (b), objects are formed on the image sensor even when the shooting direction is away from the optical axis. However, as shown in Figure 3 (c), the objects formed overlap each other on the image sensor. Hence, incident rays are selected by the shooting direction selecting optical system, and only the selected rays are entered. Therefore, it is possible to widen the shooting range by arranging multiple of lenses.



(a) Normal camera (c) Overlapping images (b) In case of multiple lenses

Figure 3. Relationship between shooting direction and number of lenses

The entire camera is increased in size by arranging the multiple of the convex lenses used in normal cameras, and this is not realistic. Therefore, in the proposed optical system, the shooting range is widened by using a lens array which multiple of small lenses are arranged. In addition, only rays from the shooting direction is selected, and other incident rays are blocked the aperture in the ray-direction selecting optical system. As a result, it is possible to only enter the shooting direction ray.

From the above, it is possible to control the shooting direction by controlling the position of the aperture. It is possible to control the shooting direction without mechanical motion by the aperture made of liquid crystal.

The desired shooting direction ray is entered on the convex lens 1 of the ray-direction selecting optical system and focused at the position of the aperture. It is necessary to adjust the size of the aperture so that the focused rays can enter the lens array.

Multiple small images of the object are formed on the image sensor by using a lens array which multiple of small lenses are arranged. They are low resolution because these multiple images are small. Therefore, we use reconstruction type super resolution technology. This is a technique for generating one high resolution image by using multiple of low resolution images which are sampled at different positions. The multiple of identical images are formed as multiple of images with different sampling positions as shown in Figure4 by setting the pitch of each lenses of the lens array and the pixel pitch of the image sensor to a non-integral multiple. It is possible to obtain one high resolution object image by applying the reconstruction type super resolution technique to multiple of images with different sampling positions.

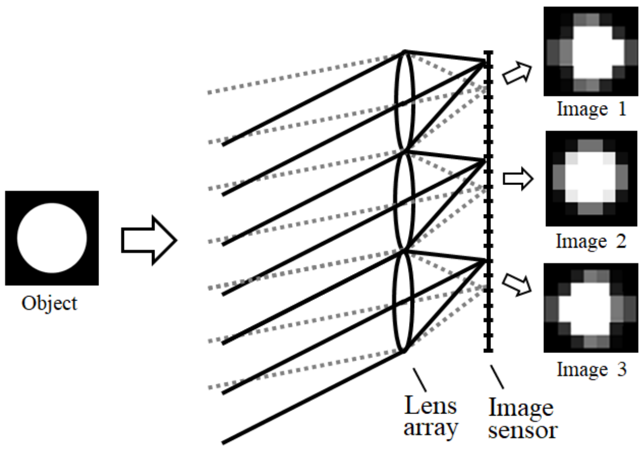


Figure 4. Multiple images with different sampling positions

Definition of viewing angle and control range

In the proposed optical system, the angle of view is narrow in order to take a picture of objects at distance. When the sizes of the lens array and the image sensor are equal, the angle of view θ of each lens of the lens array as

$$\theta = 2 \cdot \tan^{-1}(d/2f)\ [°] \tag{1}$$

where f is the focal length of the lens array, and d is the pitch of each lens of the lens array. A range which the images do not overlap each other on the image sensor is the angle of view.

The control range of the shooting direction is determined from the number of lenses of the lens array. The control range is the range that the images of the object are formed on the entire of the image sensor. When the sizes of the lens array and the image sensor are equal, it is possible to take a picture only in the case of the object is close to the optical axis. On the other hand, if the size of the lens array is larger than the size of the image sensor, it is possible to take a picture even when the object is away from the optical axis. Therefore, it is possible to widen the control range of the shooting direction by increasing the number of each lens of the lens array. The control range of the shooting direction (control angle φ) as

$$\varphi = 2 \cdot \tan^{-1}(d \cdot n - l/2f) \; [°] \quad (2)$$

where f is the focal length, d is the pitch of each lens of the lens array, n is the number of lenses of the lens array, and l is the size of the image sensor.

Method for creating high resolution image

A vector $\boldsymbol{y}$ of the captured image on which multiple small images of the object are formed as

$$\boldsymbol{y} = A\boldsymbol{x} \quad (3)$$

where, $\boldsymbol{x}$ is a vector of the high resolution image of the object, and A is a coefficient matrix showing how much specific pixels of the object affects pixels on the image sensor. Tikhonov regularization is used because the image includes noises such as shot noise and thermal noise. Therefore, the estimated vector $\tilde{\boldsymbol{x}}$ of the vector $\boldsymbol{x}$ as

$$\tilde{\boldsymbol{x}} = (A^T A + \zeta I)^{-1} A^T \boldsymbol{y} \quad (4)$$

where, I is the identity matrix, and ζ is a constant that reduces the influence of noise. It is necessary to increase this constant when a large noise occurs in the image sensor.

The coefficient matrix varies depending on the shooting direction. However, the coefficient matrix does not change depending on the shooting object. Therefore, it is possible to measure the coefficient matrix in advance in each shooting direction.

Design

The previously designed optical system is shown in Figure 5. The specifications of the convex lens in this optical system are shown in Table 1. In this optical system, the convex lenses of special materials and shapes are used, and this is not realistic.

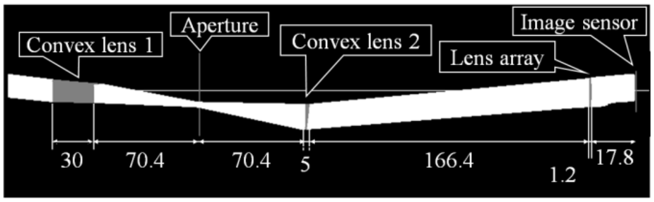


Figure 5. Structure of previously designed optical system [3]

Table 1 Specification of previously designed lenses

	Convex lens 1	Convex lens 2
Shape	Plano-convex	Plano-convex
Focal length [mm]	85.72	85.72
Back focal length [mm]	70.4	83.2
Curvature radius [mm]	81.76	81.76
Size [mm]	ϕ 10	ϕ 50
Thickness [mm]	30	5.0
Material (refractive index)	TAFD45 (1.954)	TAFD45 (1.954)

The imaging performance is deteriorated by the aberrations of the real lens, and it adversely affects the captured image. Therefore, it is necessary to suppress aberrations as much as possible. However, the characteristics of aberrations was not be considered in the previously proposed design of the optical system.

In order to improve the above two points, we optimized the lens and newly designed the proposed optical system.

Optimization of lenses

Since the two convex lenses of the ray direction selection optical system have aberration and give great influence, these two lenses was optimized.

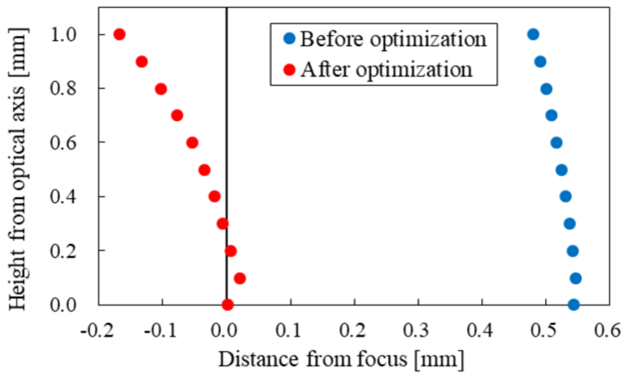
CODE V, an optical design evaluation software, was used for the lenses optimization. For the optimization, the evaluation function of the lateral aberration was used. The specification of the lens when the value of this evaluation function becomes the smallest is adopted.

The specifications of the optimized convex lenses are shown in Table 2. The material of the lens is BK 7 which is generally used. We confirmed how much the aberration was reduced by comparing some parameter before and after the optimization. A graph of the relationship between the position of the incident rays and the aberration is shown in Figure 6. The spherical aberration in the vertical direction is shown in Figure 6 (a). The spherical aberration is an aberration caused by the spherical shape of the lens. After the optimization, the spherical aberration was reduced to about one third. The astigmatism is shown in Figure 6 (b). The Astigmatism is an aberration caused by the fact that the focal point in the horizontal direction and the vertical direction of a lens are different. After the optimization, almost no aberration was seen in both the horizontal direction and the vertical direction. The distortion aberration is shown in Figure 6 (c). After optimization, almost no aberration was observed.

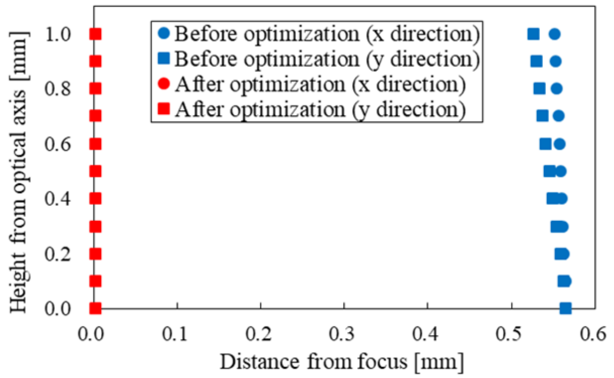
We designed an optical system with reduced influence of the aberration by incorporating the optimized convex lenses. The structure of the designed optical system is shown in Figure 7.

Table 2 Specifications of the optimized convex lens

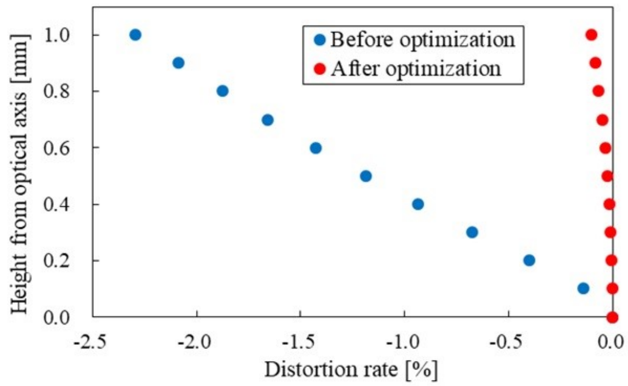
	Convex lens 1	Convex lens 2
Shape	Convex meniscus	Convex meniscus
Focal length [mm]	79.0	79.0
Back focal length [mm]	78.5	72.5
Curvature radius [mm]	26.18 70.00	37.11 349.27
Size [mm]	ϕ 12.7	ϕ 30.0
Thickness [mm]	2.5	11.4
Material (refractive index)	BK7 (1.519)	BK7 (1.519)



(a) Longitudinal spherical aberration



(b) Astigmatic field curve



(c) Distortion aberration

Figure 6. Comparison of aberrations before and after the optimization of convex lens

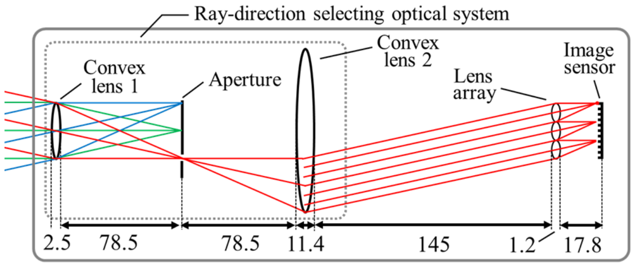


Figure 7. Structure of the designed optical system

Simulation

We confirmed the principle of the proposed camera by more realistic simulation. This simulation was done using the newly designed optical system. In order to create a coefficient matrix, ray tracing was performed. An image on the image sensor was generated using the created coefficient matrix. In the image on the image sensor, multiple small images of the objects with different sampling positions are formed. A high resolution image of the object was generated by applying the super resolution technique to multiple of low resolution images formed on the image sensor.

Improvement of simulation method

In order to run a more realistic simulation, we improved the incident rays on the lens array and the incident rays from the object.

In the previous basic simulation, one ray had been entered each lens of the lens array. In reality, rays are continuously entered the optical system, but in this method incident rays are discrete. This is not realistic. Therefore, multiple incident rays were entered on each lens of the lens array. We improved the simulation to make it more realistic using this method.

In the previous basic simulation, one ray had been output per pixel in the image of the object. This method is not realistic because it creates a coefficient matrix that considers only the influence of rays in a direction on one pixel. As shown in Figure 8, sixteen rays are outputted from one pixel by dividing one pixel into sixteen. By using this method, the simulation was improved so that a coefficient matrix can be created in consideration of the influence of multi-directional rays. The coefficient matrix in one pixel of the object uses the average of the values of coefficient matrices obtained from sixteen rays each.

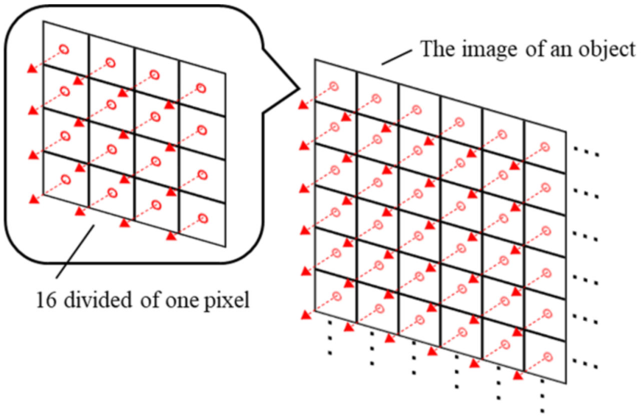


Figure 8. Rays output from the input image of the object

Specifications and conditions

The lens array specifications is shown in Table 3. The specifications of the image sensor is shown in Table 4. The angle of view and the maximum control angle are obtained using the above specifications and formulas (1) and (2). The specifications of the proposed camera is shown in Table 5.

The image of the object to be photographed is shown in Figure 9. The resolution of the image of the object is 50 pixels × 50 pixel.

The entire structure of the simulation is shown in Figure 10. The object to be photographed was placed 100 meters away from the proposed camera and placed in the maximum control range.

Table 3 Specification of the lens array

Shape	Plano-convex
Focal length [mm]	18.6
Back focal length [mm]	17.8
Curvature radius [mm]	8.6
Size [mm]	1.5 × 1.5
Thickness [mm]	1.2
Pitch [mm]	0.3
Number of the lenses	5 × 5 (25 lenses)
Material (refractive index)	BK7 (1.519)

Table 4 Specification of the image sensor

Size [mm]	0.9 × 0.9
Resolution [pixel]	64 × 64
Pixel size [mm]	0.0141 × 0.0141

Table 5 Specification of the proposed camera

Angle of view [degree]	0.924
maximum control angle [degree]	1.848
Resolution of image [pixel]	50 × 50

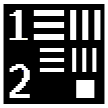


Figure 9. The image of the object

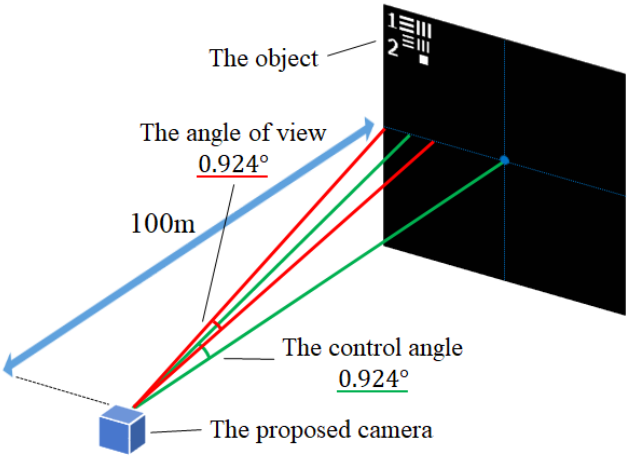


Figure 10. The entire structure of the simulation

Result

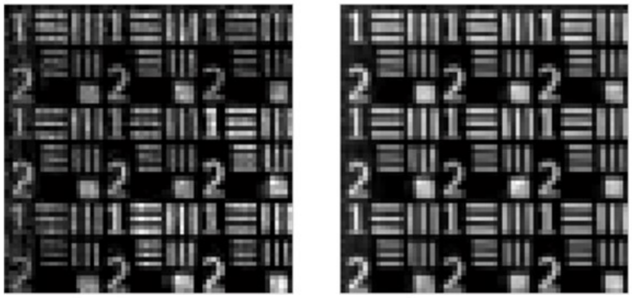
The magnify images on the image sensor before and after improvement are shown in Figure 11 (a). When comparing the images on the image sensor before and after the improvement of the incident rays, the image near the left side and the upper side became dark before the improvement, the image near the lower right became bright before the improvement. A difference in the brightness of the image was observed in the image before the improvement. After the improvement, the brightness of the image was uniform, and the improvement of the difference in the brightness of the image was confirmed. In reality, incident rays are continuous, and the brightness of all the images of the object is uniform. Therefore, the improved image is more realistic.

The image of the lower right part on the image sensor before and after improvement are shown in Figure 11 (b). When comparing images of the lower right part on the image sensor before and after improvement of the incident rays, variations were observed in pixel values of adjacent pixels before improvement. After the improvement, we confirmed that the variation of the pixel value of the adjacent pixels became small. In reality, incident rays are continuous, and changes in pixel values of adjacent pixels are very small. Therefore, the improved image is more realistic.

From the above, we confirmed that this simulation is a more realistic simulation.

We confirmed the principle of the proposed optical system in more realistic simulation. The image on the image sensor generated using the coefficient matrix obtained by ray tracing is shown in Figure 12 (a). We confirmed that multiple image of the low resolution are formed. The high-resolution image of the object generated by applying the super resolution technique using the coefficient matrix and the image on the image sensor is shown in Figure 12 (b). We confirmed that the high resolution image of the object was correctly generated.

Therefore, the principle of the proposed camera was confirmed under more realistic conditions.



Before improvement After improvement

(a) The image on the image sensor (magnification image)

Before improvement After improvement

(b) A part of the image on the image sensor

Figure 11. The images on the image sensor before and after improvement of the incident rays

(a) Multiple small images of the object (b) High resolution image of the object

Figure 12. The result images in the more realistic simulation

Conclusion

In order to perform realistic simulation, we optimized the convex lens considering aberration, and designed the optical system with reduced aberration. The simulation using this optical system became a more realistic simulation by improving the method. As a result, the principle of the camera proposed under more realistic conditions was confirmed.

The future work includes reducing the processing time of simulation and verifying the principle using actual equipment.

Acknowledgment

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Author Biography

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