

# CODED APERTURE STEREO

## *For Extension of Depth of Field and Refocusing*

Yuichi Takeda<sup>1</sup>, Shnisaku Hiura<sup>2</sup> and Kosuke Sato<sup>1</sup>

<sup>1</sup>Graduate School of Engineering Science, Osaka University, 1-3 Machikaneyama-cho, Toyonaka, 560-8531 Osaka, Japan

<sup>2</sup>Graduate School of Information Sciences, Hiroshima City University, Ozuka-Higashi, Asa-Minami-Ku, 731-3194 Hiroshima, Japan

**Keywords:** Computational Photography, Coded Aperture, Stereo Depth Estimation, Deblur, Depth of Field, Refocusing.

**Abstract:** Image acquisition techniques using coded apertures have been intensively investigated to improve the performance of image deblurring and depth estimation. Generally, estimation of the scene depth is a key issue in the recovery of optical blur because the size of the blur kernel varies according to the depth. However, since it is hard to estimate the depth of a scene with a single image, most successful methods use several images with different optical parameters captured by a specially developed camera with expensive internal optics. On the other hand, a stereo camera configuration is widely used to obtain the depth map of a scene. Therefore, in this paper, we propose a method for deblurring and depth estimation using a stereo camera with coded apertures. Our system configuration offers several advantages. First, coded apertures make not only deconvolution but also stereo matching very robust, because the loss of high spatial frequency domain information in the blurred image is well suppressed. Second, the size of the blur kernel is linear with the disparity of the stereo images, making calibration of the system very easy. The proof of this linearity is given in this paper together with several experimental results showing the advantages of our method.

## 1 INTRODUCTION

Optical blur (defocusing) and motion blur are typical errors in photographs taken in dark environments. If the aperture of the lens is stopped down to extend the depth of field, moving objects are likely to be blurred with a slow shutter speed to keep the exposure value constant. In other words, insufficient light from the scene causes a trade-off between depth of field and exposure time, and thus it is difficult to take a clear sharp picture of a moving object in a dark scene using a hand-held camera. Consequently, post processing of captured images including deblurring and denoising, have been intensively studied in prior years. In this paper, we propose a method that extends the depth of field computationally using a stereo camera with coded apertures.

Typically, the performance of deblurring depends on the knowledge about the point spread function (PSF). If the shape of the PSF is not known, it should be estimated during deconvolution. This technique, called blind deconvolution, is generally an ill-posed problem when dealing with only a single image, and some kind of priors about the scene must be introduced

(Levin et al., 2007). However, if the prior is not suitable for the scene, simultaneous estimation of the PSF and latent image will fail. Therefore, multiple images with different optical parameters such as focus distance or aperture shape are commonly used to make the problem solvable (Hiura and Matsuyama, 1998; Zhou et al., 2009). In this paper, we explore the use of disparity introduced by a stereo camera pair to determine the size of the PSF. Contrary to sequential capture with different optical settings, stereo cameras can deal with moving scenes. To determine the size of the PSF, we need to calibrate the relationship between disparity and focus. In this paper, we present a proof showing that the diameter of the blur kernel is directly proportional to the relative disparity from the focus distance.

The other important factor in the preciseness of deblurring is the characteristics of the PSF. If a normal circular aperture is used, information in the high spatial frequency domain is almost lost (Veeraraghavan et al., 2007). Therefore, we introduce coded apertures to two lenses of the stereo camera to retain the information of the scene as far as possible. The special aperture also makes the stereo matching robust,

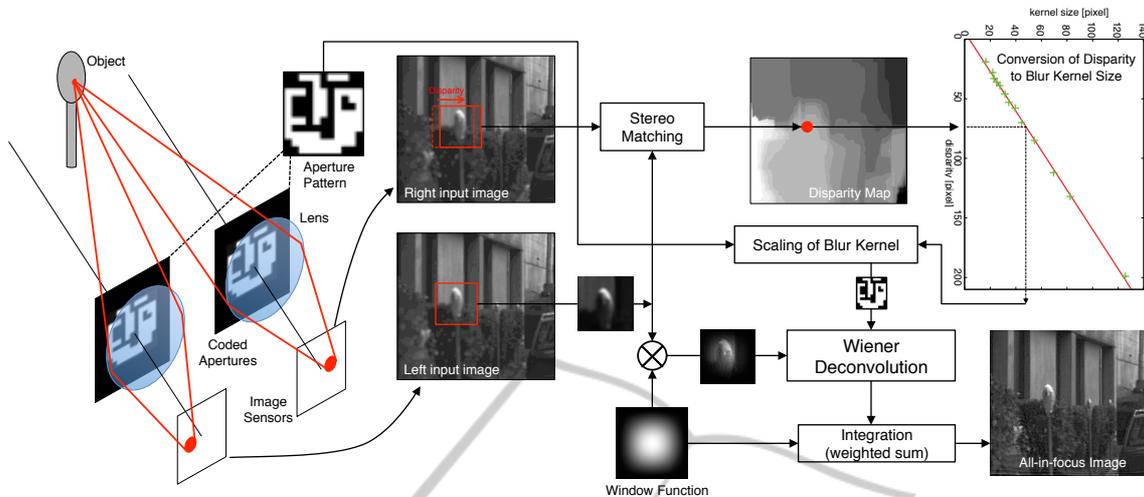


Figure 1: Process flow of proposed method.

and the clear scene is stably recovered using the precisely determined PSF.

Related work is briefly summarized in Section 2. An overview of the proposed system and the algorithms is presented in Section 3, together with a proof of the linear relationship between blur size and disparity. Experiments are discussed in Section 4, while Section 5 concludes the paper.

designed coded apertures. Desirable aperture shapes have been explored by Zhou et al. (Zhou and Nayar, 2009) and Levin et al. (Levin, 2010).

## 2 RELATED WORK

Optical blur (defocus) appearing in images captured with conventional cameras is modeled as the convolution of the sharp original scene and a blur kernel (i.e., the PSF). Thus, the latent image can be reconstructed by applying an inverse filter or deconvolution techniques to the captured image. Several methods including Richardson-Lucy deconvolution (Richardson, 1972) and MAP estimation (Lam and Goodman, 2000) have been proposed; however, the performance of the reconstruction depends greatly on the correctness of the blur kernel. In particular, a circular blur kernel in a conventional aperture contains many zero crossings in the spatial frequency, while reconstruction at a frequency of low gain is unstable with much noise influence. Therefore, the idea of designing an aperture shape with the desirable spatial frequency characteristics was proposed. Hiura et al. introduced a coded aperture to improve the preciseness of depth estimation using the defocus phenomenon (Hiura and Matsuyama, 1998). Similarly, Levin et al. (Levin et al., 2007) and Veeraraghavan et al. (Veeraraghavan et al., 2007) tried to remove the defocus effect from a single image taken by a camera with independently

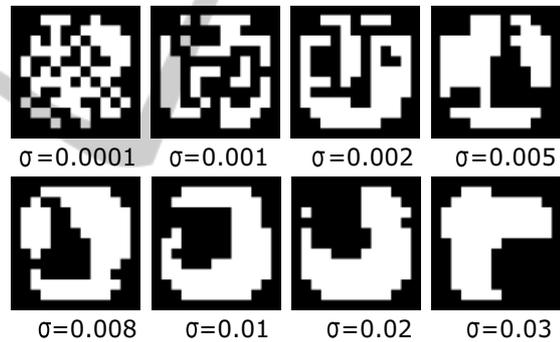


Figure 2: Shapes of Zhou's codes for various noise levels,  $\sigma$  (Zhou and Nayar, 2009).

Since the size of the blur kernel varies with the distance between the camera and object, it is necessary to estimate the depth of the captured scene accurately. Depth estimation through the optical defocus effect is called Depth from Defocus, and a number of studies on this aspect have been carried out (Schechner and Kiryati, 2000). In general, it is not easy to estimate the depth of a scene using a single image, because simultaneous estimation of the blur kernel and latent image is under constrained. Therefore, Levin et al. (Levin et al., 2007) assumed a Gaussian prior to the edge power histogram to make the problem well-conditioned. However, this method is not always robust, and the authors mentioned that human assistance was sometimes necessary.

Several studies estimating depth from multiple images captured by different optical parameters have

been conducted to make Depth from Defocus robust. Nayar et al. (Nayar et al., 1995) proposed a method that captures two images with different focus distances from the same viewpoint by inserting a prism between a lens and image sensor. Similarly, Hiura et al. (Hiura and Matsuyama, 1998) used a multi-focus camera that captures three images with different focus distances, and introduced a coded aperture to simultaneously estimate the depth map and a blur-free image of the scene using an inverse filter.

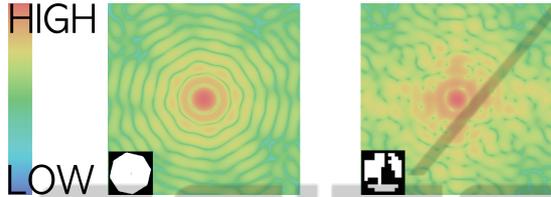


Figure 3: Log of the power spectrum of the aperture shape: (left) the conventional iris diaphragm; (right) Zhoufs code as used in this paper.

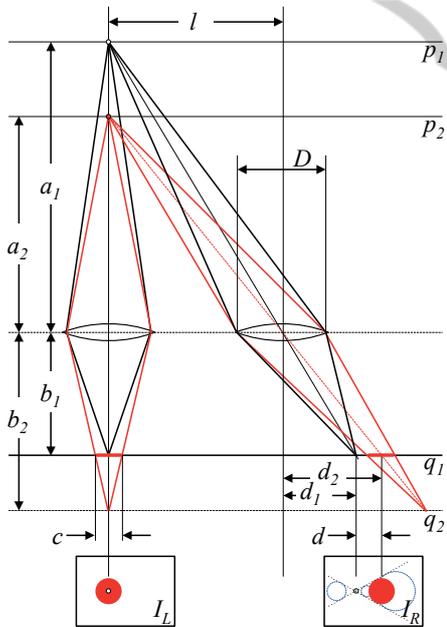


Figure 4: Relation between disparity and blur size.

Similarly, other optical factors can be incorporated to make the deblurring problem solvable. In the research by Zhou et al. (Zhou et al., 2009), two different aperture shapes were used to estimate the depth map and latent image. The authors also proposed optimal aperture shapes for their system, where the centroid of the opening is offset from the center of the aperture. This means that the difference in aperture shapes occasionally has the effect of disparity, which

is commonly used in stereo cameras. However, accuracy of the depth estimation of Depth from Defocus is lower than that of stereo depth estimation as pointed out by Schechner et al. (Schechner and Kiryati, 2000) because the disparity caused by the change in aperture shape is limited to within the lens diameter. Additionally, their system cannot deal with moving scenes because images with different aperture shapes are captured sequentially.

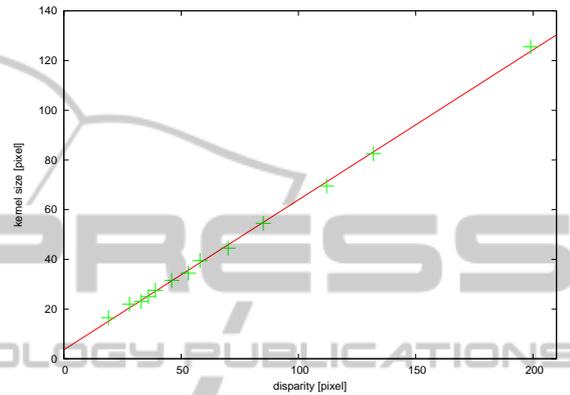


Figure 5: Relation between disparity and blur kernel size. Blur kernel size is linear with disparity. The red line denotes the calibrated parameters.

To summarize, there are two methods for capturing multiple images from a single lens with varying optical parameters. In the first, an optical device such as a prism or mirror is placed between the lens and image sensor (Green et al., 2007), while in the other, images are captured sequentially with changing parameters (Liang et al., 2008). The former method is expensive and complicated with specially made optics, while the latter is not applicable to moving scenes. Additionally, using a single lens limits the preciseness of the depth estimation to a short baseline length within the lens aperture. Therefore, we propose a robust depth estimation and deblurring method using images captured by a stereo camera with coded apertures. Stereo depth estimation is widely used since it is not necessary to use special optical devices in the camera. Furthermore, a stereo camera makes it possible to control the baseline length, which is independent of the blur size of the lens, thus leading to robust depth estimation. Coded apertures make not only deconvolution but also stereo matching very robust, because the loss of high spatial frequency domain information in blurred image is adequately suppressed. Calibration of the system is very easy because the size of the blur kernel is linear with the disparity of stereo images.

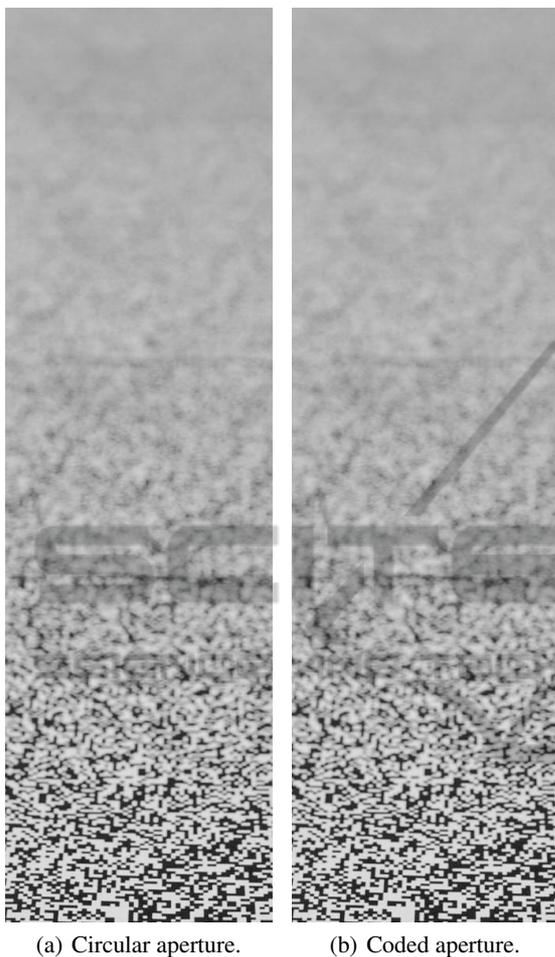


Figure 6: Captured images for the first experiment. Focus was set at the nearest point (lower part of figures).

### 3 CODED APERTURE STEREO

An overview of our system and proposed method is illustrated in Figure 1. Input images are captured by a stereo camera with coded apertures. The shape of the aperture is the same, and therefore, the effect of the defocus is common to both input images.

First, stereo matching is calculated for the two captured images, providing a depth map of the scene. Any stereo matching algorithm for normal stereo cameras without coded apertures can be used, because the input images defocused by common coded apertures are still identical at any distance.

Next, the input image is deblurred by applying Wiener deconvolution. Since the size of the blur kernel (diameter of circle of confusion) depends on the distance to the object, disparity of the stereo matching is used to calculate the size of the blur kernel. Since

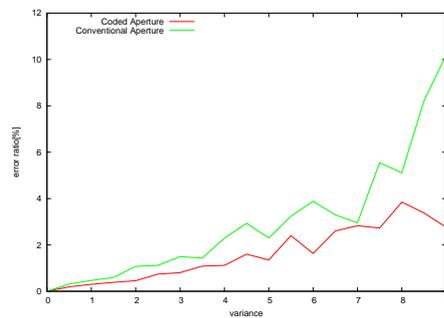


Figure 7: Experiment 1: comparison of error ratio in stereo matching.



Figure 8: Experiment 2: disparity map with coded aperture, where a high intensity denotes a large disparity.

the scene consists of various distances, the input image is clipped to many overlapping small regions using a window function. The final result of the whole deblurred image is created by integrating all clipped regions using a weighted average of the window function.

In this section, we first discuss the improvement in depth estimation using a coded aperture. Then, we show that the disparity of stereo matching is linear with the size of the blur kernel.

#### 3.1 Effect of a Coded Aperture on Stereo Matching

Since the scene to be measured by the stereo camera has various depths, input images are inevitably affected by the optical blur phenomenon caused by lenses focused at a fixed depth. In general, such blurring effect degrades the accuracy of stereo depth measurement, so the aperture of the lens is usually stopped down as much as possible to extend the depth

of field. However, as described before, this decreases the amount of light passing through the lens, and the longer exposure time introduces motion blur. Therefore, we propose coded aperture stereo, that is, stereo depth measurement using images captured with a coded aperture inserted in the lenses.

Since a coded aperture changes the shape of the blur kernel, it is able to control the effect of optical blur to the desirable characteristics. From the viewpoint of a spatial frequency domain, the high frequency component of the scene texture should be kept to make the stereo matching robust. This is the reason that we use pan-focus settings for the stereo cameras. For example, the blur kernel of an extremely small aperture can be assumed to be a delta function, which is considered to be one of the broadband signals. However, the transmission ratio inside the lens aperture is less than 1, so the exposure value decreases if we use small apertures. Therefore, we use a specially designed aperture to keep the high spatial frequency component with a sufficient amount of light using a coded aperture.

Several aperture shapes have been proposed in various studies on coded apertures (Levin et al., 2007; Veeraraghavan et al., 2007). In particular, Zhou et al. (Zhou and Nayar, 2009) tried to find an optimal aperture shape for the given signal-to-noise ratio of the sensor. Henceforth, this code is referred to as Zhou's code. A genetic algorithm was used to find Zhou code that is optimal for Wiener deconvolution under the condition of a  $1/f$  distribution of the spatial frequency for the scene as a prior. The final result varies according to the noise level  $\sigma$  of the sensors as shown in Figure 2.

Figure 3 shows the spatial frequency response of the convolution using both circular and Zhou code aperture shapes. A conventional aperture has periodical low values even at low spatial frequency (near the center of the image), whereas even the high frequency components are well kept with Zhou's code. These characteristics are expected to enhance the robustness of the stereo matching like pan-focus settings as verified later through an experiment.

### 3.2 Disparity of Stereo Matching and Circle of Confusion

In traditional studies on extending the depth of field using a coded aperture (Hiura and Matsuyama, 1998; Levin et al., 2007; Veeraraghavan et al., 2007; Zhou et al., 2009; Levin, 2010), determining the size of the blur kernel corresponds directly to the depth estimation. In other words, the depth of a scene is estimated through the recovery of the original images using a

deblurring technique. In our research, however, the blur kernel must be independently estimated from the disparity computed by the stereo matching. Therefore, it is necessary to determine the relation between disparity and blur size. In this subsection, we show that the disparity in stereo measurement corresponds linearly with the size of the circle of confusion.

Figure 4 depicts a stereo camera with optical axes parallel with each other, and the two cameras having lenses with the same diameter,  $D$ . Here, the optical images of planes  $p_1$  and  $p_2$  are at planes  $q_1$  and  $q_2$  behind the lens, respectively. Without loss of generality, we can assume that the object is on the optical axis of the left camera. The distances between the lens and the four planes denoted by  $a_1$ ,  $a_2$ ,  $b_1$ , and  $b_2$  in Figure 4 have the following relationships with the raw lenses:

$$\frac{1}{a_1} + \frac{1}{b_1} = \frac{1}{a_2} + \frac{1}{b_2} = \frac{1}{f} \quad (1)$$

where  $f$  is the common focal length of the lenses.

Then, we assume that two image sensors are placed on plane  $q_1$ , and an object on plane  $p_2$  is out of focus while the one on  $p_1$  is in focus. Since the two lenses have the same aperture shape, images of the point on plane  $p_2$  are observed as the same figures on images  $I_L$  and  $I_R$ . In Figure 4, these are depicted as red circles. Images of the points on planes  $p_1$  and  $p_2$  have disparities  $d_1$  and  $d_2$ , respectively. Using these parameters, we can calculate the relative disparity,  $d$ , from the focus distance as

$$d = d_2 - d_1 = \left( \frac{1}{a_2} - \frac{1}{a_1} \right) b_1 l \quad (2)$$

where  $l$  is the length of the baseline of the stereo camera.

Next, the diameter of the circle of confusion  $c$  for the point on plane  $p_2$  can be expressed as

$$c = \frac{b_2 - b_1}{b_2} D \quad (3)$$

using the distance between  $q_1$  and  $q_2$ . Thus, using Eqs. (2) and (3), we can calculate the ratio between the size of the blur kernel and the disparities as

$$\frac{d}{c} = \frac{b_1 b_2}{b_2 - b_1} \left( \frac{1}{a_2} - \frac{1}{a_1} \right) \frac{l}{D}. \quad (4)$$

However, we can replace the terms in parentheses as follows

$$\frac{1}{a_2} - \frac{1}{a_1} = \frac{1}{b_1} - \frac{1}{b_2} = \frac{b_2 - b_1}{b_1 b_2} \quad (5)$$

to obtain the final equation,

$$\frac{d}{c} = \frac{b_1 b_2}{b_2 - b_1} \frac{b_2 - b_1}{b_1 b_2} \frac{l}{D} = \frac{l}{D} \quad (6)$$

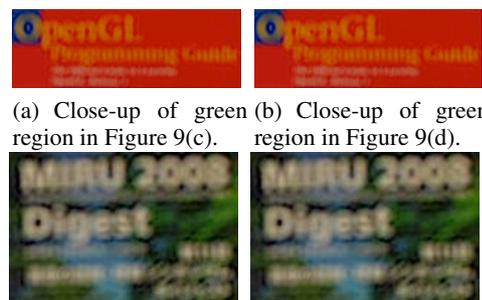


Figure 9: Experiment 2: Deblurring of scene with depth variation.

where the ratio between the diameter of the blur circle is directly proportional to the relative disparity from the focus distance, and the constant of proportion is the ratio between the diameter of the lens and the length of the baseline.

More intuitively, as shown in the right image  $I_R$  in Figure 4, the circle of confusion simultaneously scales and shifts along with the distance, and the envelope of the circle of confusion forms two lines crossing at the focal point.

This conclusion makes it very simple to convert the disparity between two images to the size of the blur kernel. If the two optical parameters, the size of the aperture, and the baseline length are precisely known, we can directly convert the disparity to the blur size. If not, we can simply use two point light sources at different distances in the scene, and we can measure the size of the blur kernel and dispar-



(a) Close-up of green region in Figure 9(c). (b) Close-up of green region in Figure 9(d).

(c) Close-up of red region in Figure 9(c). (d) Close-up of red region in Figure 9(d).

Figure 10: Close-ups of deblurred images (Figures 9(c) and 9(d)).

ity from the captured images to obtain the coefficient. If a more precise estimate is needed, we can use the simple least squares method.

Figure 5 illustrates an example of the relationship between disparity and blur size. With point light sources placed at varying distances, we measure the size of the blur kernel and disparity. In the figure, green crosses indicate measured points, while the red line is a fitting line calculated using the least squares method. Since the focus distance of the lens was set to infinity, the size of the blur kernel size was estimated to be zero when the disparity was also zero.

### 3.3 Extension of Depth of Field

With captured image  $y$  and known blur kernel  $f$ , a latent, blur-free image  $x$  can be estimated by Wiener deconvolution. Using a Fourier transform, we can calculate  $Y(\omega)$  as the frequency domain representation of  $y$  and  $F(\omega)$  as the frequency domain representation of  $f$ . Then, the Fourier transform of latent image  $x$  can be calculated by

$$X(\omega) = \frac{F^*(\omega)Y(\omega)}{|F(\omega)|^2 + \sigma} \quad (7)$$

where  $F^*(\omega)$  is the complex conjugate of  $F(\omega)$  and  $\sigma$  is a constant to avoid emphasis of noise where the blur kernel has low power components or division by zero. This term should be determined by the noise level of the input images, and also used to select the appropriate Zhou code (Zhou and Nayar, 2009). The original scene  $x$  can be calculated by an inverse Fourier transform of  $X(\omega)$ .

Since Wiener deconvolution is a processing in the frequency domain, blur kernel  $f$  should be uniform within the processed image. However, as the depth of the scene is not uniform, the captured image must be clipped out from the captured image using a window function, and the Wiener deconvolution applied to each region. In the experiment, we used a Hamming window as the window function, and the image was clipped to 64 pixels square, shifting 8 pixels.

## 4 EXPERIMENTS

In this section, the results of three experiments are given. First, robustness of stereo matching by Zhou's code is investigated by evaluating the matching error with images to which white noise has been intentionally added. Second, an image of the depth of field extension is shown by removing blur from the captured image using the process shown in Figure 1. And finally, we present the refocusing result, computed from an all-in-focus image and depth map, to be artificially focused on a distance different from the captured image, and otherwise blurred.

The camera and lens used in the experiments were a Nikon D200 and SIGMA EX 30mm f/1.4 EX DC, respectively. The image format was 8 bit JPEG. Instead of using two cameras, a camera was placed on a sliding stage, and images were captured by moving the camera laterally. The distance of the translation (length of the baseline) in the experiments was 14 mm. The aperture code used in the experiments was one of Zhou's codes for noise,  $\sigma = 0.005$ , in Figure 2, inserted at the rear of the lens. To avoid vignetting, the f-number of the original lens aperture was set to f/1.4. For comparison with normal aperture shapes, the code mask was removed from the lens, and the f-number of the original lens was set to f/5.0 to keep the exposure value and shutter speed equal. As a result, the area of the coded aperture was equal to that of the circular aperture.

### 4.1 Experiment 1: Robustness of Stereo Matching

We conducted an experiment to evaluate the robustness of the stereo matching with Zhou's code. While we used actual captured images, we intentionally added white noise to the images.

A random black-and-white pattern with a 1-mm grid size was printed on a sheet of paper and placed on a table. Cameras were placed at oblique angles, with the distance from the camera to the object varying along the vertical axis of the image. The depth range was around 50 cm to 100 cm from the bottom to the top of the image, and the focus distance was adjusted at the nearest distance of the object. Captured images with circular and coded apertures are shown in Figures 6(a) and 6(b), respectively.

From these images, we can see that the exposure values of the normal and coded apertures are almost the same, but compared with the image by the circular aperture, the image with the coded aperture preserves some texture information well, even in the heavily defocused regions.

To evaluate robustness of stereo matching, zero-mean white noise was added to both captured images. The variance of the noise ranged from 0 to 9.0 with a 0.5 step, and the error ratio of stereo matching was calculated.

Figure 7 shows the error ratio of stereo matching, where the error ratio is defined as the number of pixels whose disparity differs from that in the noiseless image. The average error ratio is 3.22% and 1.72% for the circular and coded apertures, respectively. As the variance increases, so too does the error ratio. However, the error ratio of the coded aperture is always lower than that of the circular aperture.



Figure 11: Experiment 3: Refocusing.

This shows that broadband code such as Zhou's code makes stereo matching robust.

## 4.2 Experiment 2: Robustness of Deblurring

We conducted a depth of field extension experiment using a real scene.

For the scene shown in Figure 9, images were captured with circular and coded apertures, and we conducted stereo matching and deblurring using our system. In this experiment, the focus distance of the lens was set to a point further than the furthest distance in the scene to show the deblurring effect clearly. The disparity map using the coded aperture is shown in Figure 8.

Figures 9(a) and 9(b) show one of the captured images with circular and coded apertures, respectively, while Figures 9(c) and 9(d) give the corresponding results after deblurring. Figure 10 shows close-ups of the rectangles in Figures 9(c) and 9(d). It is clear that sharpness is greatly improved in images with the coded aperture, while the result with the circular aperture has slightly improved sharpness and does not

show much effect of deblurring.

## 4.3 Experiment 3: Refocusing

As an application of our method, we show an example of a refocused image computed from an all-in-focus image and a disparity map. The same setup as in experiment 2 was used, with the focus set to the furthest part in the scene to clearly show the effect of refocusing. For the input image shown in Figure 11(a), we can see the effect of blurring on a book placed on the right side. In Figure 11(b), an all-in-focus image is shown. Optical blur of the objects on the table and the PRML book has been removed and the image sharpened. The refocused image created by blurring the all-in-focus image with the circular aperture kernel and disparity map is shown in Figure 11(c). Contrary to the input image, close objects are seen sharply, while other distant objects are blurred in the refocused image.

## 5 CONCLUSIONS

In this paper, we presented a depth of field extension method for defocused images, which removes blur in the captured image using coded aperture stereo and Wiener deconvolution. We proved that disparity of stereo matching is proportional to the size of the blur kernel, and this theory makes PSF estimation from disparity easy. We also showed that stereo matching with a coded aperture makes stereo matching robust. We showed through experiments that our system can remove defocus blur from captured images accurately by estimating the PSF from disparity and deblurring. As an application, we presented a refocused image computed from an all-in-focus image and a disparity map.

In the experiments, instead of using a stereo camera, we set a camera on a sliding stage and captured the static scene. Nevertheless, using two cameras, it is possible to use our method to capture a dynamic scene.

In this paper, the same aperture pattern and focus distance were used in the cameras. Our future work aims to integrate Depth from Defocus and stereo, and extend the theory to the case with different apertures and focal settings.

## ACKNOWLEDGEMENTS

This work was partially supported by Grant-in-Aid for Scientific Research (B:21300067) and Grant-in-Aid for Scientific Research on Innovative Areas (22135003).

## REFERENCES

- Green, P., Sun, W., Matusik, W., and Durand, F. (2007). Multi-aperture photography. In *ACM SIGGRAPH 2007 papers*, SIGGRAPH '07, New York, NY, USA. ACM.
- Hiura, S. and Matsuyama, T. (1998). Depth measurement by the multi-focus camera. In *Computer Vision and Pattern Recognition, 1998. Proceedings. 1998 IEEE Computer Society Conference on*, pages 953–959.
- Lam, E. Y. and Goodman, J. W. (2000). Iterative statistical approach to blind image deconvolution. *J. Opt. Soc. Am. A*, 17(7):1177–1184.
- Levin, A. (2010). Analyzing depth from coded aperture sets. In *Proceedings of the 11th European conference on Computer vision: Part I, ECCV'10*, pages 214–227, Berlin, Heidelberg. Springer-Verlag.
- Levin, A., Fergus, R., Durand, F., and Freeman, W. T. (2007). Image and depth from a conventional camera with a coded aperture. In *ACM SIGGRAPH 2007 papers*, SIGGRAPH '07, New York, NY, USA. ACM.
- Liang, C.-K., Lin, T.-H., Wong, B.-Y., Liu, C., and Chen, H. H. (2008). Programmable aperture photography: multiplexed light field acquisition. In *ACM SIGGRAPH 2008 papers*, SIGGRAPH '08, pages 55:1–55:10, New York, NY, USA. ACM.
- Nayar, S., Watanabe, M., and Noguchi, M. (1995). Real-time focus range sensor. In *Computer Vision, 1995. Proceedings., Fifth International Conference on*, pages 995–1001.
- Richardson, W. H. (1972). Bayesian-based iterative method of image restoration. *J. Opt. Soc. Am.*, 62(1):55–59.
- Schechner, Y. Y. and Kiryati, N. (2000). Depth from defocus vs. stereo: How different really are they? *Int. J. Comput. Vision*, 39:141–162.
- Veeraraghavan, A., Raskar, R., Agrawal, A., Mohan, A., and Tumblin, J. (2007). Dappled photography: mask enhanced cameras for heterodyned light fields and coded aperture refocusing. *ACM Trans. Graph.*, 26.
- Zhou, C., Lin, S., and Nayar, S. (2009). Coded aperture pairs for depth from defocus. In *Computer Vision, 2009 IEEE 12th International Conference on*, pages 325–332.
- Zhou, C. and Nayar, S. (2009). What are good apertures for defocus deblurring? In *Computational Photography (ICCP), 2009 IEEE International Conference on*, pages 1–8.