A Fundamental Study on Coded Aperture Design for 3D Measurement by Genetic Algorithm

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Abstract

This paper proposes a system for active depth measurement using a coded aperture installed on a projector, and a method for aperture pattern design by genetic algorithm. First, a system for depth measurement is designed. The proposed system involves a prototype projector with a coded aperture which is designed for defocus deblur by previous work instead of depth measurement. Then, we propose a method for coded aperture design to optimize the performance for depth measurement. Experimental results showed the proposed method could design an aperture pattern with considering noise by genetic algorithm and simulation for fitness calculation.

1 Introduction

Recent active 3D scanners are widely used for actual 3D model acquisition process. In particular, structured light systems[1, 2] have been intensively researched and commercialized due to their simplicity and accuracy. However, it is neccesary for the systems to retrieve the correspondence between projected patterns and observed patterns for triangulation calculation. Therefore, both a camera and a pattern projector should be in focus on a target. Since depth of field (DOF) of a projector is usually narrower than that of a camera because of a limitation on power of light source, projector's DOF usually limits the range of 3D measurement. Although a light source of a straight beam such as laser extends DOF, it is not easy for laser to make a dense and a complicated 2D pattern, and using a strong laser has safety issue.

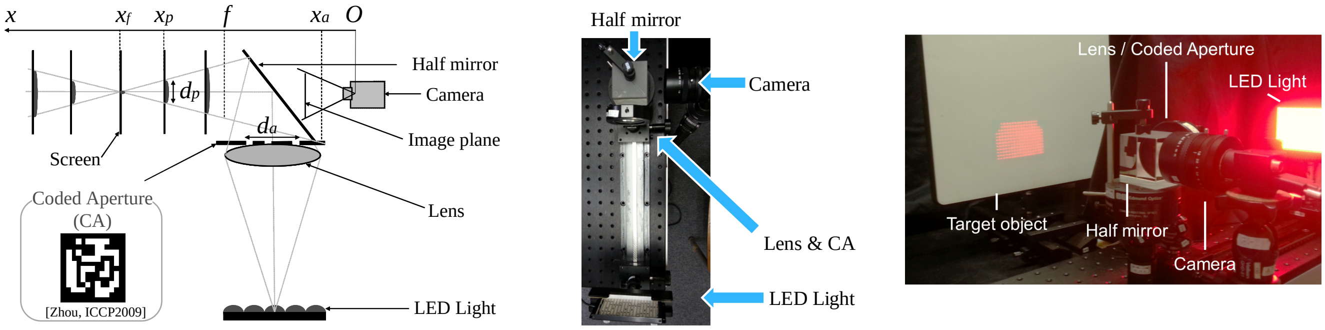
In recent research in the field of Computational Photography a coded aperture (CA) which is a non-circular aperture is widely investigated[3, 4, 5] . It allows many post-processes such as motion deblurring, all-focus image, Depth from Defocus (DfD), and so on. But few attention have been paid on using CA on projector. Grosse et al. proposed a data projection system including programmable CA for expanding projector's physical DOF[6] .

This paper proposes a method for coded aperture design for depth measurement using genetic algorithm (GA)[7] . First, we develop a system consisting of a camera and a prototype projector with a coded aperture which are designed for deblur[8, 9] . And then, we propose a method for designing a coded aperture pattern for the purpose of depth measurement. In particular, the proposed method calculates a fitness value by physical simulation with considering noise. Experimental results show that the proposed system can measure depth with millimeter order, and the proposed aperture design method can generate patterns with considering noise.

2 Related work

2.1 Depth from defocus

General Depth from Defocus (DfD) techniques based on camera's defocus require high-frequency texture on a surface of a target object[10] . DfD based on pattern projector's defocus is also proposed[11] . This method projects a dot grid so that each observed dot's defocus reflects its own depth. As the method only needs rough depth in-



(a) System configuration (b) Implemented system (c) Measurement scene example

Fig. 1 Proposed system

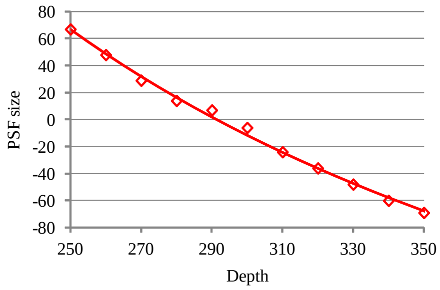


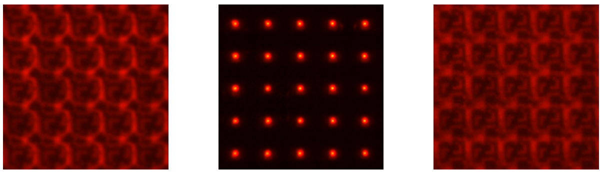
Fig. 2 Calibration result

fomation for image refocusing, projected dot pattern could be sparse and not overlapped with each other. For fine depth measurement, a projected pattern should be dense and might be overlapped with each other when defocusing blur is large. Simple dotted patterns which are blurred and overlapped with each other make it difficult to measure depths.

2.2 Coded aperture

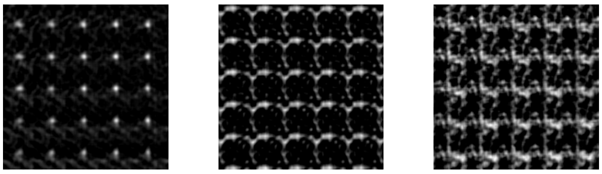
A conventional circular aperture attenuates high frequencies and has zero-crossings in frequecy domain12) . Aperture patterns designed in previous work13) are based on intuitive criteria related to the shape of their power spectrum, but do not explicitly account for the effect of noise and image structure.

Zhou proposed a method for aperture pattern optimization based on the quality of deblurring12) . The obtained aperture produces high quality deblurrings for a wide variety of real-world images.

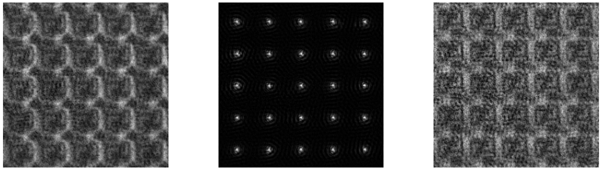


(a) 250mm (b) 300mm (c) 350mm

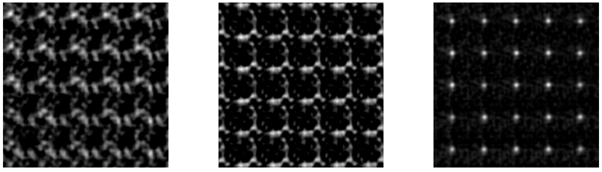
Fig. 3 Images of the captured patterns



(a)250mm/250mm (b)300mm/250mm (c)350mm/250mm



(d)250mm/290mm (e)300mm/290mm (f)350mm/290mm



(g)250mm/300mm (h)300mm/350mm (i)350mm/350mm

Fig. 4 Deconvolved results (actual / estimated distance)

3 Depth measuremen using a coded aperture on a projector

3.1 System configuration

The proposed system consists of a projector and a camera, and the projector consists of a lens, a half mirror, a LED array, and a coded aperture as shown in Fig. 1. To get rid of image distortion by adjusting the optical axes of the projector and the camera, the half mirror is used. The LED array is a prototype of a light source for this method. Although its resolution is not high due to LED arrangement, it is not an actual limitation of the proposed method.

3.2 Calibration

The proposed method expects strongly blurred images whereas general structured light based 3D measurement systems expect sharp enough with little blur. Therefore, a parameter describing a point spread function (PSF) should be calibrated; we use a PSF size as the parameter.

The scaling parameter can be calculated if accurate optical attributes of all of the system components would be clarified. Although it might be possible theoretically, it is quite difficult to conduct such precise calibration with high accuracy. In addition, it is also difficult to make a realistic noise model from system configuration. Therefore, we capture actual blur patterns for several depths to estimate the scaling parameters to create PSFs.

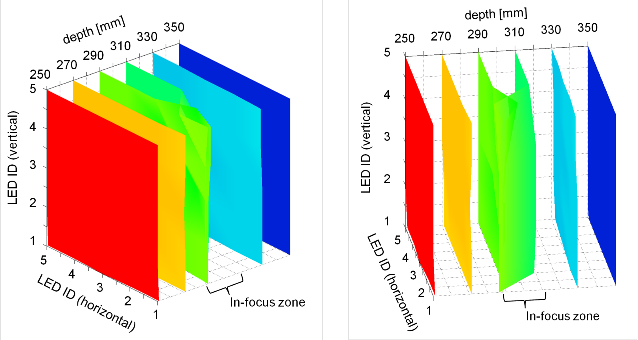
The adjusted scale can be determined by deconvolving with the several scale sizes. Then, the most appropriate scale size is selected according to the similarity of the deconvolved image to a source light pattern. Parameter c can be determined by fitting the obtained appropriate scale size to equation (1):

$$d_p(x_p) = c\left|1 - \frac{x_f}{x_p}\right|, \qquad (1)$$

where c is a constant value calculated by $f\, d_a/(x_f - x_a)$, f denotes the focal length of the lens, x_a denotes the distance between the camera and the lens, x_f denotes the focusing disntance of the projector, x_p denotes the disntance between the camera and the object, and d_a and d_p are sizes of the aperture and the projected pattern, as shown in Fig. 1(a).

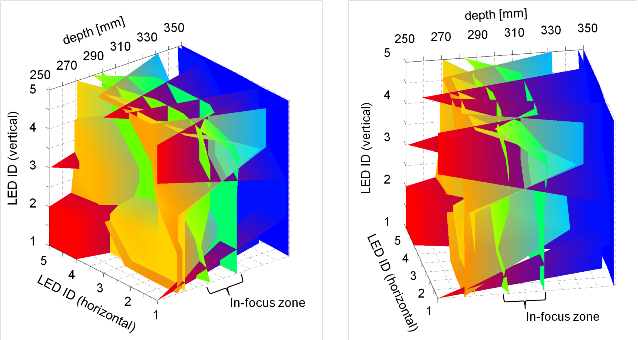
Similarity between a deconvolved image and an original light source pattern is calculated by equation (2) based on kurtosis of histogram:

$$Sim(\boldsymbol{P}) = \sum_{i \in \boldsymbol{P}} \frac{(P_i - \bar{P})^4}{nV^2} - 3, \qquad (2)$$



(a) Diagonal view (b) Side view

Fig. 5 Reconstruction result of a flat board with Zhou's CA.



(a) Diagonal view (b) Side view

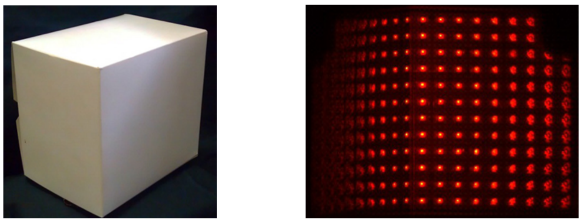
Fig. 6 Reconstruction result of a flat board with a general circular aperture.

where $\boldsymbol{P} = \{P_1, P_2, \ldots, P_i, \ldots\}$ denotes a deconvolved image, P_i denotes the intensity of pixel i, n denotes the number of pixels in $\boldsymbol{P}$, and V denotes a variant of the intensity historgram. The higher $Sim(\boldsymbol{P})$ value is, the more similar to the ideal light source pattern $\boldsymbol{P}$ involves.

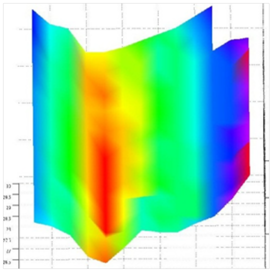
The proposed method uses Wiener filter for deconvolution because it is reported as the best stable4) . Although Richardson-Lucy algorithm14, 15) is known as a good deconvolution algorithm, the algorithm is too much performance to distinguish difference between kernels, consequently depth estimation accuracy cannot be improved.

3.3 Depth measurement

The proposed method estimates a depth from captured images of projected patterns by 1) deconvolving the blurred images with the scale parame-

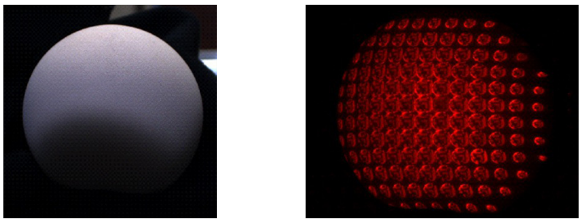


(a) A targt object (b) Projected patterns

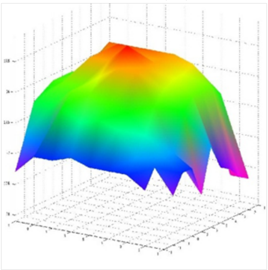


(c) Estimated depth and reconstruction result

Fig. 7 Experiments on arbitrary object (Box).



(a) A targt object (b) Projected patterns



(c) Estimated depth and reconstruction result

Fig. 8 Experiments on arbitrary object (Ball).

ter d_p obtained by the calibration, and 2) choosing the depth in which the deconvolved image is the most similar to the point source image of light. Even if too strong blur makes the patterns overlap each other, the proposed method can divide them by deconvolution with appropriate d_p value and estimate the depth appropriately. A target object shape is reconstructed by iterating the above depth estimation for each pattern.

4 Experiments on depth measurement with a coded aperture

We implemented a system proposed in this paper and conducted experiments to show the effectiveness. The implemented system consists of an achromatic lens with 150mm focal length and 50mm diameter, a CCD camera whose resolution is $1,280 \times 960$, a red LED array of 660nm arranged 18×22 resolution, and a coded aperture proposed by Zhou[12)] whose size is $35 \times 35mm$. The distance between the lens and the light source was 300mm.

First, we calibrated the scaling parameter by capturing one of the projected patterns. The calibration result was shown in Fig. 2. The appropriate scaling parameter could be obtained.

Second, we evaluated the depth estimation performance by using a flat board[†]. Fig. 3 shows the projected patterns where the distance between the board and lens center was set to 250, 290, and 350mm. Fig. 4 shows the deconvolved result images. PSF of correct depth restored the images similar to the light source pattern, whereas PSFs of incorrect depths do not. Figs. 5 and 6 show the reconstruction result of the board at the depth of 250, 270, 290, 310, 330, and 350mm by Zhou's CA and a general circular aperture, respectively. In the case using the general aperture, the farther the board was placed, the more error coudld be seen. This is because it is hard to distinguish the blurred images caused by the general aperture which are observed in front or behind of the focus zone and have the same distance from the focus zone. Zhou's CA, which has an asymmetric pattern, allows to estimate the depth with millimeter order accuracy, except in-focus zone of the projector.

Finally, arbitrary shape reconstruction is conducted[††]. Figs. 7 and 8 show the experimental results of shape reconstruction of a box and a boll, respectively. From Figs. 7(c) and 8(c), rough shapes of the target objects could be seen. Although the center 5×5 patterns of the array allowed appropriate depth estimation, other patterns in outer area

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[†] The only center 5×5 patterns were used in this experiment.

[††] Note that only this experiment was conducted without the half mirror.

caused unstable reconstruction due to lens distortion.

5 Aperture pattern design by GA

A problem for designing a coded aperture pattern is a combinatorial optimization problem whose search space size is $2^{N\times N}$, where a $N \times N$ binary pattern is utilized. In previous work[12) , although N was set to 13, the obtained pattern was essentially 11×11 binary patterns. Therefore we set $N = 11$ and make the 11×11 patterns surrounded by closed cells.

The proposed method uses two-dimensional two-point crossover in which offsprings are generated by exchanging parents' strings in a rectangle region determined by randomly-chosen two points. Bit flip mutation, elite preservation and a simple generation alternation rule, in which parents are always replaced by offsprings, are also used.

Fitness is calculated by simulation as shown in Fig. 9, unlike the previous work[12) . In the simulation, a projected image generation of an aperture pattern, which is a phenotype of an individual to be evaluated, and deconvolution of the image with PSFs of various depths are iterated. And then, fitness is calculated by the following equation:

$$F(x) = \min_{d} \left\{ Sim(\boldsymbol{P}_{d,d}) - \max_{d' \neq d} Sim(\boldsymbol{P}_{d,d'}) \right\}, \tag{3}$$

where $\vec{P}_{d1,d2}$ denotes a deconvolved image of a projected pattern at depth $d1$ with PSF at depth $d2$. Eq. (3) indicates that a fitness value is the worst margin of the appropriateness of depth estimation between correct and incorrect depths.

A drawback of coded apertures is a decline of intensity. To keep the intensity, we define a constraint that opened area size must be more than a half of aperture size.

6 Experiments on aperture pattern design

As a preliminary work to evaluate the effeciveness of the proposed method, we implemented a simulator for evaluation of CA appropriateness, and tried to optimize an aperture pattern for depth measurement. Parameters were configured as shown in Table 1.

```
Step 1: Perform step 2 through 5 with changing
        a simulation distance as 250, 270, 300,
        330, and 350(mm).
Step 2: Make a simulated projection image that
        involves defocus blur by a convolution
        of a point light source wih PSF whose
        size is obtained by the calibration.
Step 3: Add noise to the projection image.
Step 4: Deconvolve the projection image with
        PSF of correct depth, and calculate
        histogram a kurtosis value $K_{cor,d}$ from
        deconvolved image, where $d$ denotes a
        simulation distance.
step 5: Deconvolve the projection image with
        PSFs of incorrect depths, and calculate
        the maximum histogram kurtosis value
        $K_{inc,d}$ from deconvolved images.
step 6: Let the fitness value be the worst mar-
        gin of the appropriateness of depth es-
        timation between correct and incorrect
        dephts.
```

Fig. 9 Pseudo code of depth estimation simulation for fitness calculation

Table 1 Parameter configuration

Population size	100
Generation limit	1,000
Number of elites	3
Crossover method	Two-point in 2D
Crossover rate	$\frac{100-3}{100}$
Mutation method	Bit flip mutation
Mutation rate	0.01
Resolution	11× 11
Noise level	None, $\sigma = 0.00002\%$
Deconvolution	Wiener
Simulation parameter d	250, 270, 300, 330, 350 (mm)
d'	250, 270, 300, 330, 350, $d \pm 5$ (mm)

Fig. 10 shows example aperture patterns by the proposed method in the case without any noise. Several medium-large opened areas can be seen in the outer area, and small opened areas in the center area.

Fig. 11 shows example aperture patterns in the case with Gaussian noise whose average and σ was set to 0 and 0.00002, respectively. Compared to fig. 10, the number of small opened areas increased. This is the same tendency as shown in previous work[12) .

Figs. 12 and 13 show the example fitness transi-

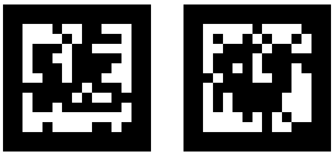

Fig. 10 The obtained aperture patterns in the case without noize.

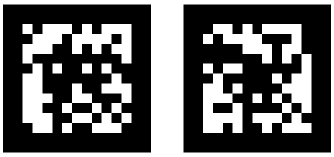

Fig. 11 The obtained aperture patterns in the case with noize ($\sigma = 0.00002$).

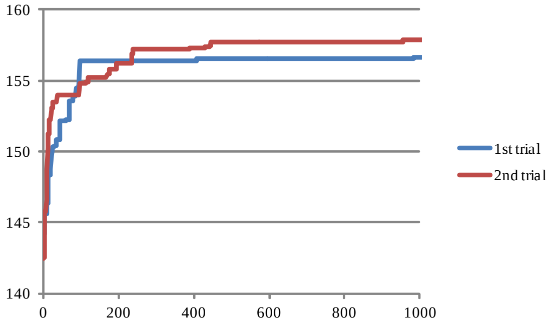

Fig. 12 Fitness transitions in the case without noise.

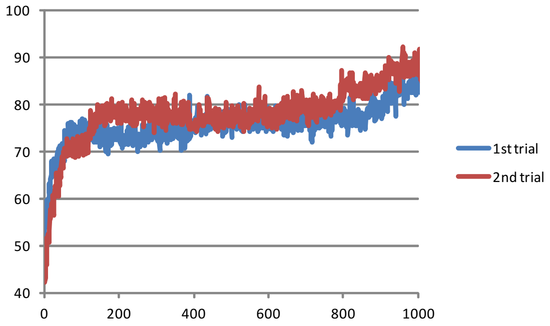

Fig. 13 Fitness transitions in the case with noise ($\sigma = 0.00002$).

tions of the best solutions. In the case with Gaussian noise, the fitness values were not converged after 1,000 generations.

7 Conclusions

This paper proposes a system for active depth measurement using a coded aperture installed on a projector, and a method for aperture pattern design by GA. The proposed system can measure a depth even from strongly defocused images which are overlapped with each other. The proposed CA design method can generate an aperture design by simulation. Experimental results showed that the proposed system with existing CA could measure a depth with millimeter order accuracy against 100(mm) measurement range, and that the proposed method could design an aperture pattern with considering noise.

Depth measurement experiments in real environment with the generated apertures are our future work.

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