STRUCTURED LIGHT WITH CODED APERTURE FOR WIDE RANGE 3D MEASUREMENT

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ABSTRACT

In this paper, we propose an active 3D measurement method using structured light system, which can measure wide range of depth. General structured light system requires correspondence between projection patterns and camera observed patterns. Hence, both the projected pattern and the camera image should be in focus on the target. This condition makes a severe limitation on depth range of 3D measurement. Our technique resolves the range limitation by using coded aperture (CA) on projector. It can be understood as a structured light system using Depth from Defocus (DfD) technique, in which defocus of projected light pattern is utilized. By allowing blurry pattern of projection, the measurement range is extended compared to common structured light system. Moreover, CA efficiently improves its accuracy.

Index Terms— Active 3D measurement, Structured light, Coded aperture

1. INTRODUCTION

In typical active 3D measurement system based on structured light, first, correspondence between projected patterns and camera observed patterns is obtained by certain technique. Then, 3D information is recovered from the correspondence by means of triangulation. To retrieve the correspondence accurately, the patterns should be captured clearly by the camera; it sets an implicit but severe condition for the scene. Further, since the depth of field (DOF) of projectors is usually narrower than that of cameras, the DOF of projectors limits the range of 3D measurement. One essential solution for the problem is to use the focus-free light source *i.e.*, laser. However, making a dense and complicated pattern with laser is not easy and strong laser has safety and cost problems.

Depth from Defocus (DfD) technique is known to use defocusing blur to reconstruct the shape. In this paper, we propose a new structured light 3D reconstruction technique using DfD on the projector in which blur effect is actively used rather than avoided. To devise the blur efficiently with structured light, we use coded aperture (CA) on optics. Since the technique actively uses blur effect, the projector's narrow DOF becomes advantageous and the measurement range can be extended compared to normal structured light systems. Main contributions of the paper are as follows.

1. By utilizing blur effects actively, the measurement rage can be extended compared to common methods.
2. Measurement accuracy can be improved by using CA.
3. Overlap in the defocusing pattern is allowed by using deconvolution of CA.
4. Since the baseline between a camera and a projector is not necessary, the system can be compact.

2. RELATED WORK

Active lighting 3D measurement techniques have been intensively researched and commercialized [1, 2]. Among them, structured light system attracts many people. One typical problem for the system is an ambiguity on correspondence and tons of solutions are proposed, *e.g.*, sinusoidal patterns, Gray code patterns or grid patterns[3]. In this way, the past researches of structured light methods are concentrated on resolving the matching between projection patterns and observed patterns. Therefore, there are implicit conditions that both the projection and the observation should be in-focus. One of the techniques to break this restriction is to use a laser [2]. Our proposed method is another approach to solve it by using defocusing patterns with common light sources.

The techniques to measure the depth from defocused images is called DfD [4]. One drawback of DfD is that it needs high-frequency texture on the surface of the object. Moreno-Noguer *et al.* proposed DfD using pattern projector's defocus – not camera's [5]. They projected a grid of dots, so that each observed dot's defocus can reflect its own depth information. Since the goal of the technique was image refocusing, the projection dots can be sparse because they just need rough depth for each segment. Since our purpose is to measure the depth, patterns should be dense and the observed patterns are easily overlapped each other when defocusing blur is large.

Recently, CA techniques are studied in the field of Computational Photography[6, 7, 8]. Thanks to the non-circular aperture in the camera, many special post-processes can be realized, *e.g.*, motion deblurring [6], synthesis of all-focus image [7], DfD [8], etc. In contrast, there are very few studies about CA in projectors. Grosse *et al.* proposed a data projection system including programmable CA[9]. They applied pre-process to the projection data with consideration of CA.As a result, they could extend the DOF of the projector, but the depth estimation was not considered. In this paper, we use CA for extending a depth range of 3D measurement.

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3. SYSTEM CONFIGURATION

3.1. Projector with coded aperture

Our system consists of a lens, LEDs, a CCD camera and a CA as shown in Figure 1. For avoiding lens distortion problems, a half mirror is useful as shown in Figure 2. However, the half mirror brings other problems, *e.g.*, intensity of the light is significantly reduced. In this paper, we take another option, *i.e.*, we installed the lens and the camera as close as possible.

In terms of the light source, one might consider using commonly used video projectors. However, putting an physical aperture in a commercial projector is not easy (sometimes impossible). We use an array of LEDs as the light source for prototype. We can either put a CA in a video projector or use microlens-array if we really need high resolution.

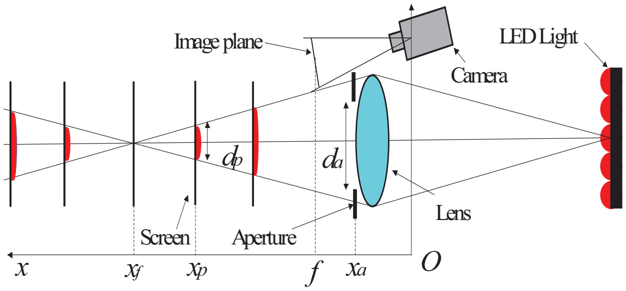


Fig. 1. Diagram of optical system

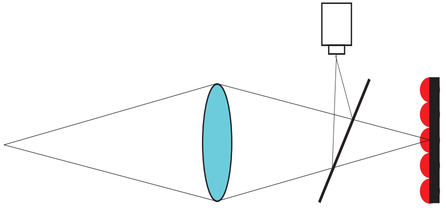


Fig. 2. Designing with a half mirror

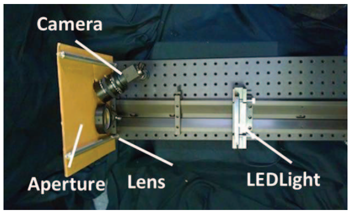


Fig. 3. Actual optical system

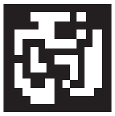


Fig. 4. Coded Aperture

3.2. Aperture shape

In the field of Computational Photography, a variety of CA shapes are proposed depending on their purposes[6, 7, 8]. Since optics of cameras and projectors are almost equivalent, we adopt the same aperture shape of the generic CA camera. In practice, the suitable CA shape for the generic CA camera depends on the camera system's SNR [10]. In this paper, we adopt a CA shape shown in Figure 4, which was the best one (noise ratio $\sigma = 0.001$) in our evaluation of several patterns.

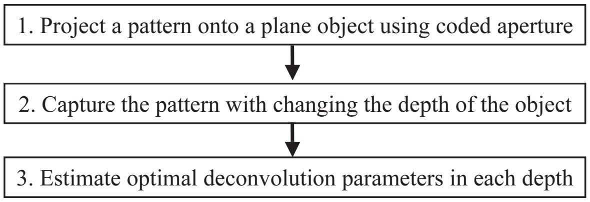


Fig. 5. Calibration algorithm

(a) 250mm (b) 280mm (c) 300mm (d) 330mm (e) 350mm

Fig. 6. Projected patterns on the screen in several depths

4. DEPTH FROM PROJECTOR DEFOCUS

In the proposed technique, the target shape is reconstructed by DfD technique using defocusing blur of the projected pattern, which is come from the projector with CA. The technique mainly consists of two steps. The first is calibration of the blur effects. Then, the second is shape reconstruction which estimates the depth of the observed pattern.The first step is not required unless system setup has changed.

4.1. Calibration of defocus of light source

For DfD technique, the defocusing blur of the system must be calibrated preliminarily. In our case, the defocusing blur by depth is considered dominant. Hence, only two parameters – scale and noise – are calibrated in this paper. These are most important parameters for analyzing blur effect[10].

In theory, the scaling parameter can be calculated if the strict attributes of the system's all optics are known. However, it is a distant idea. At the same time, it is difficult to calculate a realistic noise model from the system attributes. Based on these facts, we capture the actual defocusing blur pattern in several known depths and construct the parametric model from them. Therefore, the applicative parameters for the defocusing blur effects can be obtained.

Figure 5 shows the algorithm of the parameter estimation. For the calibration process, the real projected pattern images of single LED are captured with changing depth of the target board. Since we use LED array in our system, the light sources can be approximated as points. Then, the captured pattern can be considered as convolution of a point spread function (PSF) and CA shape as shown in Figure 6. Therefore, we can directly measure the size of PSF as a scaling parameter.

It is difficult to accurately obtain the noise parameter directly from the captured images. So, we actually apply deconvolution to the captured PSF with changing the noise parameter, and search the best parameter to restore the original CA shape. In terms of deconvolution algorithm, we use Wiener deconvolution technique because it is reported as the best stable[7].

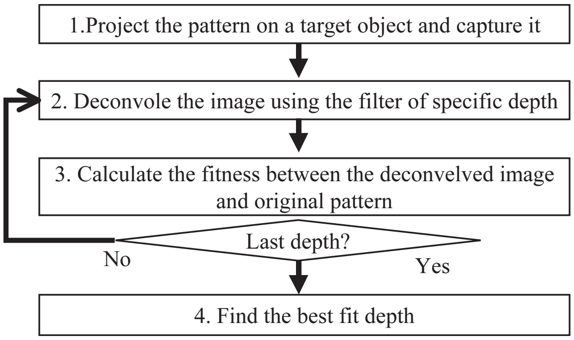


Fig. 7. Reconstruction algorithm

4.2. Depth estimation by deconvolution of pattern

As mentioned above, a pattern is projected onto the object, so that the depth can be estimated from the observed defocus. The key idea of our technique is based on the assumption that the correct filter can make the deconvolved image which is most similar to the original projection pattern. To estimate the best deconvolution filter, we have to evaluate the similarity between the deconvolved image and the projection pattern. The sum of squared distance or correlation is commonly used for the purpose. However, they are not suitable in our case because the actual deconvolution result has some error. In this paper, LED array is used as a light source, which has extremely strong intensities in relatively small area; if a deconvolution filter is correct, the doconvolved image must have a strong single peak. With such assumption, we can evaluate the similarity by using the equation:

$$d = \arg\max_{i} p(D_i(I)), \tag{1}$$

where D_i is a deconvolution filter of depth i and p represents a function to obtain the peak value in the image.

Since we calibrate the parameters at the coarsely sampled depths, parameter estimation for sub-sampling depth is required. A piecewise-linear interpolation is applied for the noise. The scaling parameter is calculated by the following equation using symbols in Figure 1.

$$s = c\left|1 - \frac{x_f}{x_p}\right|, \tag{2}$$

where c is a constant value calculated by $fd_a/(x_f - x_a)$. Figure 7 shows the algorithms described above.

5. EXPERIMENTS

We constructed an experimental system as shown in Figure 8. We used an achromatic lens with 150mm focal length and 50mm diameter. The camera is 1280×960 resolution. The light source was 18×12 LED array, which color was red (660nm). Size of CA was 35mm × 35mm and the distance between the lens and the light source is 300mm. In this system, large distortion appeared at the peripheral region of reflected pattern because we used a single lens. Therefore, we used the center of the pattern where distortion was weak. We calibrate the blur parameters with 10mm depth interval and estimate the depth with 1mm order.

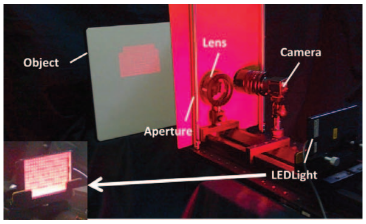


Fig. 8. Equipment and measurement scene.

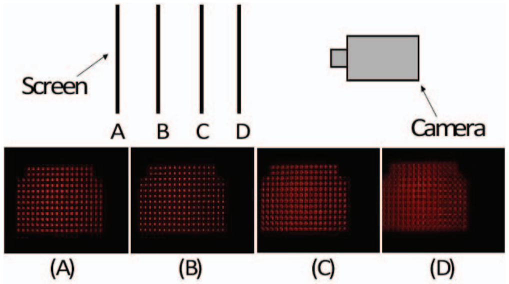


Fig. 9. Plane capture configuration

5.1. Evaluation with plane object

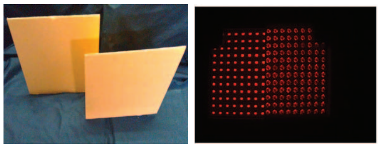
We captured the flat board for evaluation as shown in Figure 9. Table 1 shows the captured patterns (left column) and deconvolved images by each depth filter. We can see the deconvolved images with correct depth filter restored to a sharp pattern. In this way, we can estimate the depth by evaluating the deconvolution results. Figure 10 shows the reconstructed shapes in several depths. As shown in Table 1, the projected patterns in some depths are overlapped. Even in such overlapped cases, the shapes are correctly reconstructed as shown in Figure 10. Figure 11 shows the average and the standard deviation of the error on measured points of the board in each depth. We can clearly see that stronger blur makes the estimation more accurate. .

5.2. Arbitrary shape estimation

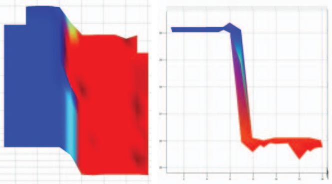
We estimated depths of more general objects. In Figure 12, we measured the two boards. They were placed front-parallel to the system at distance 270mm and 300mm, respectively. Figure 12(b) and (c) show the captured images and the reconstruction results, respectively. We can see that the shapes are restored at the right position.

In Figure 13, we measured a box. The corner of the box was placed at 260mm distance. For testing the curved surface, we measured a ball as shown in Figure 14. The center of the ball was placed at 270mm distance.

In both Figure 12 and 13, we can observe unstable reconstruction at the left and bottom end of the object. We consider this is because the camera was placed at the right side of the projector and a larger distortion appeared at these parts. Such

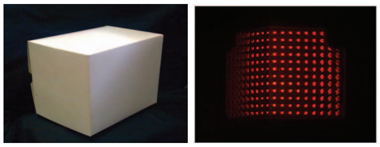


(a)Target object (b)Captured image

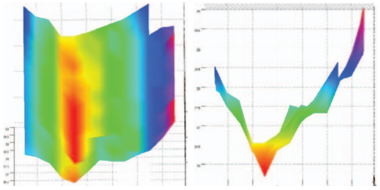


(c) Reconstructed result

Fig. 12. Two parallel planes

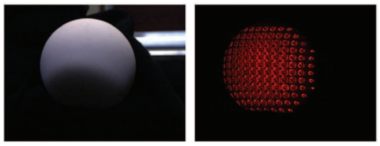


(a)Target object (b)Captured image

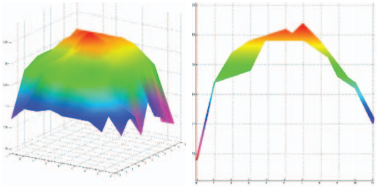


(c) Reconstructed result

Fig. 13. Box



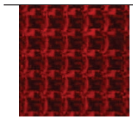
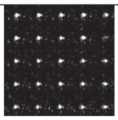
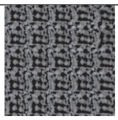
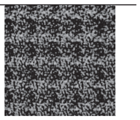
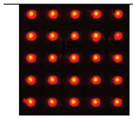
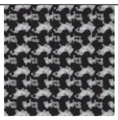
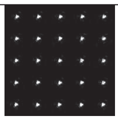
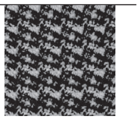
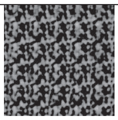
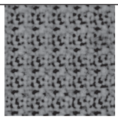
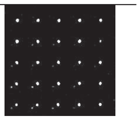
(a)Target object (b)Captured image

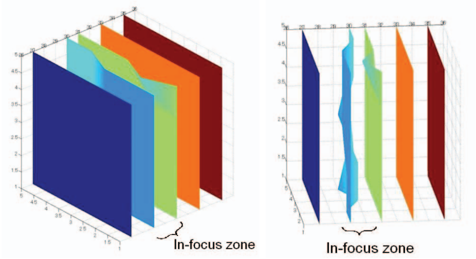


(c) Reconstructed result

Fig. 14. Soft ball (6cm diameter)

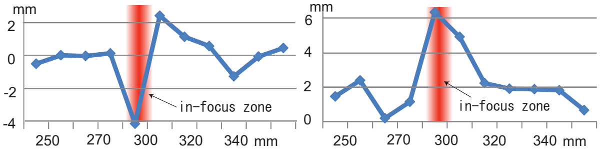
Table 1. Results and restore the screen in each distance

Input \ Filter	depth 25cm	depth 29cm	depth 35cm
 depth 25cm			
 depth 29cm			
 depth 35cm			
	Deconvolution results		



(a) Side view (b) Top view

Fig. 10. Reconstruction result of flat boards.



(a) Average error (b) Standard deviation

Fig. 11. Average and standard deviation of the error of the measured points in each depth. In-focus depth is 290mm.

effects are expected to be resolved by using a half mirror or better optical design. We leave it as our future work.

6. CONCLUSION

In this paper, we propose a structured light based 3D measurement system using CA on projector. Unlike usual structured light systems, we utilize the blur effect to extend the range of depth and improve the accuracy on 3D reconstruction. In the experiment, we verified that our method can recover the shape with high accuracy and stability. Using a half-mirror to avoid distortion is planned as our future work.

7. ACKNOWLEDGMENT

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