Coded Aperture for Projector and Camera for Robust 3D measurement

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Abstract

General active 3D measurement system using structured light is based on triangulation, which requires correspondence between projection pattern and camera observed pattern. Since both the projected pattern and the camera image should be in focus on the target, the condition makes a severe limitation on depth range of 3D measurement. In this paper, we propose a technique using coded aperture (CA) for projector and camera system to relax the limitation. In our method, Depth from Defocus (DfD) technique is used to resolve the defocus of projected pattern. By allowing blurry pattern of projection, measurement range is extended compared to common structured light methods. Further, overlapped blur pattern can also be resolved with our technique.

1 Introduction

Active 3D measurement systems based on structured light, first, retrieve correspondences between projected patterns and observed patterns, and then, 3D information is recovered by triangulation. To retrieve the correspondence accurately, the patterns should be captured clearly by the camera. Thus, both the camera and the pattern projector should be in focus on the target; we need a severe condition for the setting of them. Since depth of field (DOF) of projector is usually narrower than that of camera because of a limitation on power of light source, the DOF of projector usually limits the range of 3D measurement. One essential solution for the problem is to use special light source which emits straight beam without blur such as laser. However, making a dense and complicated 2D pattern with laser is not easy and using strong laser has safety issue also.

In this paper, we propose a new structured light based 3D reconstruction technique in which strong blur effects are allowed. To devise the blur efficiently with structured light, we use coded aperture on the light source and camera with DfD technique. Since the technique actively uses blur effect, projector's narrow DOF could be advantageous and the measurement accuracy can be improved under blurry condition. Main contributions of the paper are as follows.

1. Measurement accuracy on blurry pattern can be improved by using CA in projector and camera.
2. Based on deconvolution technique, overlapped pattern can be used for reconstruction.
3. Projector and camera w/wo CA is evaluated.

2 Related work

Currently, active 3D measurement devices are widely available [5, 6]. They are usually based on triangulation using structured light because it has practical advantages in the accuracy and cost effectiveness. To conduct triangulation, accurate and dense correspondences are required [1] and all of these methods assume that the optics of both the pattern projector and the camera are well focused on the target surface. This makes actual measurement range severely limited. One of the solution for the problem is to use a focus-free pattern projection (*i.e.*, laser beam [6]). Our proposed method is taking another approach using defocused pattern with common light source.

The techniques of DfD is well known for camera system [8], but not for projector system. Moreno-Noguer *et al.* [7] proposed DfD using pattern projector's defocus – not camera's defocus. They used a grid of dots, so that each observed dot's defocus can reflect its own depth information. Since goal of the paper [7] was not 3D measurement, but for image refocusing, the projection dot were sparse. Instead, since our purpose is to measure the depth, dense pattern is required. In such case, patterns are inevitably overlapped each other when blur becomes large, and thus, solution is required.

Recently, CA theory and techniques are researched in the field of Computational Photography[9, 4]. In the technique, the non-circular aperture is used, many special post-processes can be realized, *e.g.*, motion deblurring [10], all-focus image [9], DfD [4], etc. In contrast, there are few researches about CA in projector. Grosse *et al.* proposed a data projection system including programmable CA[3]. They made use of CA theory for expanding projector's physical DOF, but not for 3D measurement.

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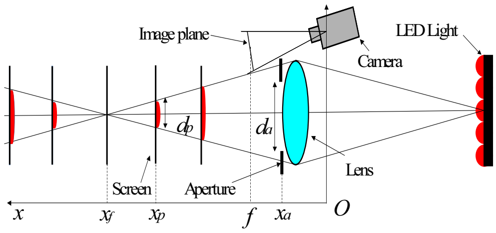


Figure 1. Optical system

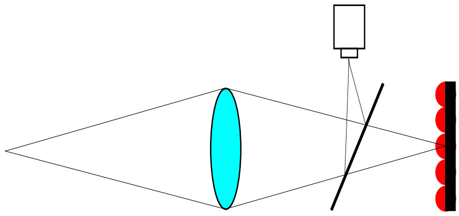


Figure 2. Designing with a half mirror

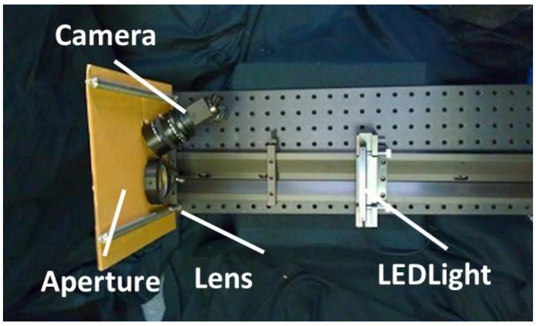


Figure 3. Actual optical system

3 System configuration

The proposed system consists of lens, LED, CCD and CA as shown in Fig.1. Since the proposed technique is based on DfD, it is ideal if the system is designed with a half mirror as shown in Fig2 to capture images without distortion. However, since construction of actual system with a half mirror is not easy and light intensity is severely decreased *i.e.*half or less, we take another option. In our technique, we installed a projector's lens and a camera as close as possible; such configuration is allowed because baseline is not required with our system.

In terms of light source, we use an array of LEDs for prototype. Because each LED is independently arranged, resolution is low, however, it is just for evaluation purpose and it is not an actual limitation of the system. We can either put a CA in a video projector, micro-array-lens or diffractive optical element (DOE), if we need high resolution.

In terms of design of CA, we used a pattern generated by genetic algorithms for DfD [11]. Since the shape of pattern differs according to system noise, we actually tested several patterns to find best parameter for the system. With our system, we used $\sigma = 0.001$ and actual pattern is shown in Fig.4 (a).

4 Depth from defocus of projected pattern

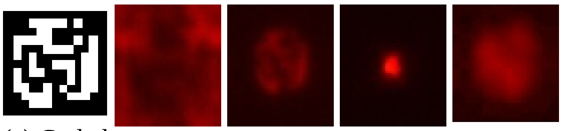
With the proposed technique, shape is reconstructed by DfD using defocus blur of reflected light pattern which is projected from a projector with CA. The technique mainly consists of two steps: the first is a calibration step which carries out estimation of parameter of blur effects for each depth and the second is a shape reconstruction step which estimates the depth of the reflected pattern on the object. Note that the former calibration process is only required once for the system. In addition, it is assumed that the intrinsic parameter of a camera is calibrated by known algorithm *e.g.*, openCV [2].

4.1 Calibration of defocus of light source

For usual structured light based 3D measurement system, it is assumed that the reflected pattern is sharp enough with little blur. On the other hand, since strong blur is expected with our technique, the parameters which represent defocus effects should be calibrated *i.e.*, the parameters to describe point spread function (PSF). Although the shape of the PSF varies dependent on both depth (scaling) and noise, main factor is a scaling. By using the extrinsic camera and projector parameters, scaling can be calculated and PSF for specific depth can be created from shape of CA. However, in our case, PSF is a convolution of two CAs of projector and camera, and thus, it is difficult to make accurate PSF for specific depth using only the extrinsic parameters. Based on the above facts, instead of creating the PSF with the extrinsic parameters, we capture actual blur pattern for several depths to estimate the scaling parameters to create PSFs. With the approach, although a calibration process becomes complicated, more accurate blur effect can be obtained. Further, extrinsic calibration of camera and projector is not required.

For actual calibration, first, the blur pattern using CA is projected on a flat board and several images are captured by changing the depth of the board. Since we use LEDs as light source which can be approximated as point light source, the projected pattern can be considered as a PSF itself (Fig.4).

To estimate the scaling parameters for PSF from captured images, we actually apply deconvolution to the captured images, changing the scaling parameter of PSF to search the best scaling parameter where deconvolved image is most similar to the original one. Since it is



(a) Coded Aperture (b) depth 250mm (c) depth 280mm (d) depth 300mm (e) depth 330mm

Figure 4. Projected and captured CA. Note that all the captured patterns are blurry because CA is set in both projector and camera.

a 2D search and there are two scaling parameters for camera and projector, we conduct full-search to retrieve solution. In terms of deconvolution algorithm, we use Wiener filter deconvolution technique [9].

4.2 Depth estimation by deconvolution

In the proposed method, a pattern is projected onto the target object so that the depth can be estimated from the observed defocus. Fig.5 shows the algorithm. Since we measure the defocusing parameters (scaling parameters of camera and projector in our method) by sampled known depths, we conduct deconvolution using all the PSFs for all depth. Then, we consider the filter in which the deconvolution result is most close to the original projection pattern represents the correct depth.

If defocus is strong or dot density is high, the defocused dots will overlap. However, by using the correct filter, the overlap of the pattern can be canceled by the deconvolution, and thus, we can get the depth of individual dots without interference of the overlap. This is one of the strength of our method.

For the estimation of the best deconvolution filter, simple solution is to calculate the similarity between projection pattern and deconvolution result. For similarity measurement, sum of squared distance (SSD) can be used. However, actual deconvolution result usually has error and similarity calculation with SSD becomes sometimes unstable. Therefore, we also try another method to find the best filter. Since we use LED for light source, which has extremely strong intensity in small area, doconvolved image should have a single strong peak when the best filter is applied. Based on it, we use the following equation to decide the depth.

$$d = \arg\max_i p(D_i(I)) \tag{1}$$

where p represents a function to calculate peak value in image and D_i represents deconvolution with filter of depth i. If light source can be considered to be a point light source, we take this method.

Since, we have the calibrated filters at the coarsely sampled depths, we have to estimate the sub-sampling parameters to acquire the fine depth values. In the paper, we linearly interpolate PSF.

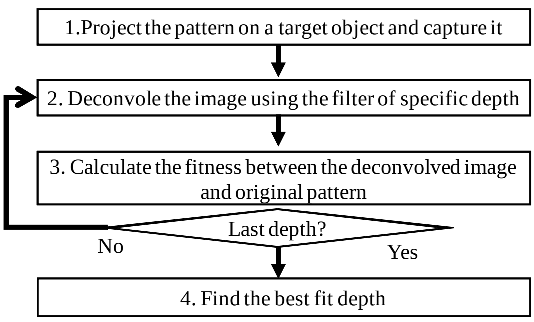


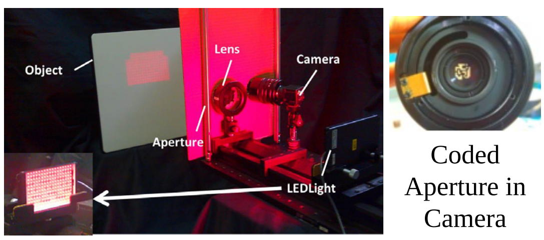
Figure 5. Reconstruction algorithm

5 Experiments

We constructed an actual system and conducted experiments to show the effectiveness of the method. The actual system is shown in Fig6. We used an achromatic lens with 150mm focal length and 50mm diameter. CCD camera is resolution 1280×960 and red LED array of 660nm arranged 18×12 resolution was used. Size of CA was 35mm × 35mm and a distance between the lens and the light source was 300mm. In the system, since we only used a single lens, large distortion appeared at the peripheral region of reflected pattern. Therefore, we only used a center of the pattern where strong distortion was not observed. Such distortion can be eliminated by certain optical design and it is our important future work. We calibrated PSF with 10mm intervals and estimate the depth with 1mm order.

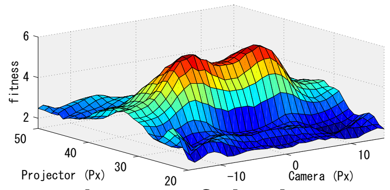
5.1 Calibration of defocus

We calibrated PSF, and estimated scaling parameter with changing depth. We projected blur pattern using CA on a flat board and captured with 10mm interval changing the depth in the 250 to 350 mm range. A part of results is shown in Fig.4. Fig.**??** show the example of 2D search and the estimated scaling parameters from these images are shown in Fig.7. We can find that smooth curves are acquired by our calibration technique.

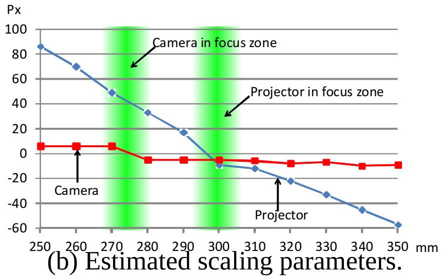


Coded Aperture in Camera

Figure 6. Equipment and measurement scene.

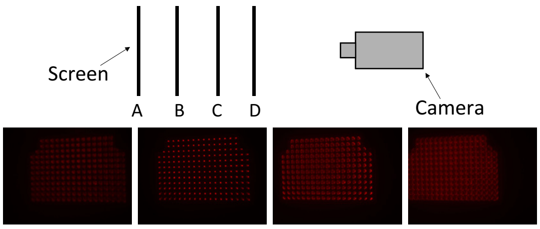


(a) 2D search space to find scaling parameters.



(b) Estimated scaling parameters.

Figure 7. Calibration results of PSF.



(a) (b) (c) (d)

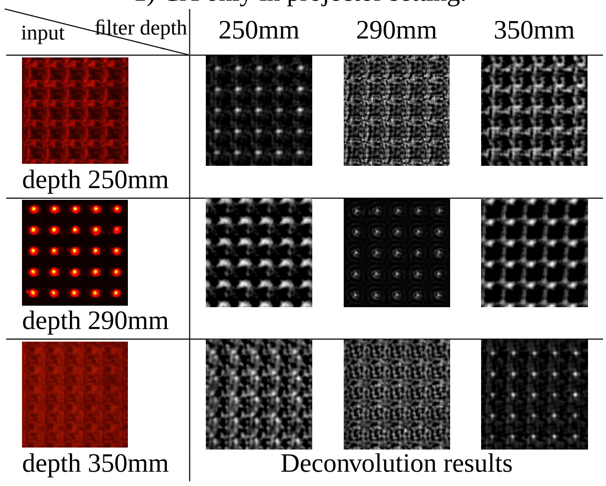
Figure 8. Flat board capturing configuration and captured images.

5.2 Plane estimation for evaluation

Fig.8 shows the relationship between the device and the board. The light irradiated from LED array is reflected on the board and reflected patterns are observed on the target object. Then, the patterns are captured by the camera and shapes are reconstructed. We conducted experiments with three different settings, such as 1) CA only in projector, 2) CA only in camera and 3) CA in both projector and camera. Table 1 shows the captured patterns (left column) and deconvolved images by calibrated parameter with each depth filter of setting 1) and 3). We can confirm that deconvolved images with correct depth filter restored a sharp pattern. Using those restored images, we can estimate the depth. Results are shown in Fig.9. From the figure, we can confirm that the shapes are correctly restored with our technique. Note that, even with largely blurred images which make a large overlapping area between the patterns (e.g., depth 25 or 35), shapes are correctly reconstructed; with such blurry patterns, shapes cannot be restored by conventional structured light method.

Table 1. Restored images using PSFs of each distance.

1) CA only in projector setting.



3) CA in both projector and camera setting.

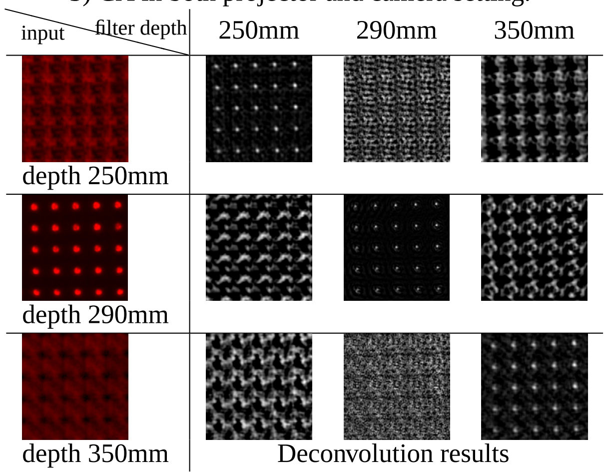
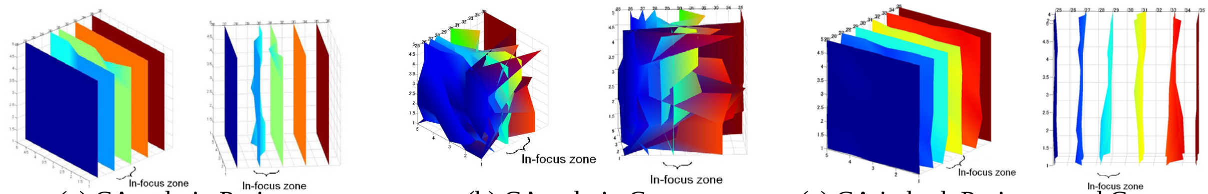


Fig.10 shows the average and standard deviation of the depth. From the figures, we can see that the result of setting 1) is the best with average error. However, the standard deviation of 1) increases when the depth is in focus; this is because without blur, ambiguity increases with DfD and setting 3) is better than 1) near in-focus zone. We consider that a camera blur helps to decrease the ambiguity in a complementary manner.

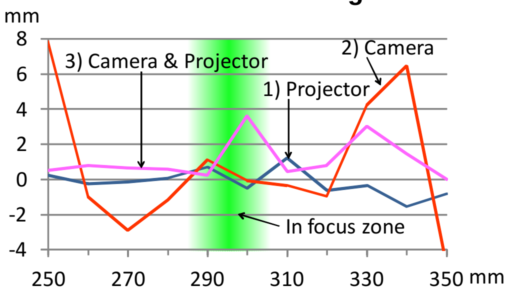
5.3 Arbitrary shape estimation

Next, we estimated a depth of more general objects. We measured the white statue as shown in Fig.11(a). Center of the statue is placed at 270mm apart from the lens. Fig.11(b) shows the reflected pattern and (c) and (d) show the reconstruction results. We can see that although blur patterns are overlapped each other, the shape is robustly restored with our technique. At the same time, we can observe unstable reconstruction at

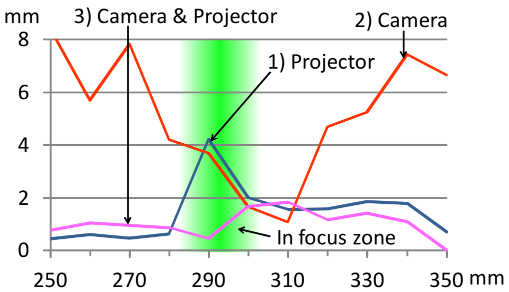


(a) CA only in Projector (b) CA only in Camera (c) CA in both Projector and Camera

Figure 9. Restoration of flat board results



(a) Average error



(b) Standard deviation

Figure 10. Statistical results. In-focus depth of projector is 290mm and 180mm for camera.

some parts of the object. We consider this is because the camera was placed a bit distant from the lens of projector and patterns are distorted especially at slanted parts. Such effects are expected to be resolved by using a half-mirror and it is our future work.

6 Conclusion

In this paper, we propose a structured light based 3D measurement system using CA. By using our system, blur effects are efficiently resolved with DfD on both camera and projector. In the experiment, we verified that the shape can be recovered with high accuracy by our method and showed that the curved surfaces are successfully reconstructed. In the future, using a half-mirror to avoid distortions is considered.

7 Acknowledgment

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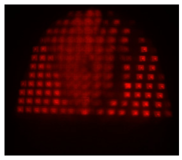
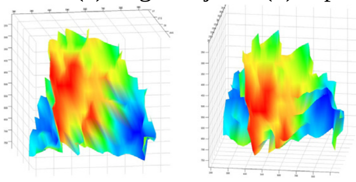
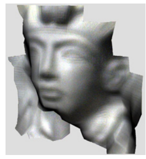


(a)Target object (b)Captured image



(c)Reconstructed result with pseudo-color



(d)Shape with texture

Figure 11. Reconstruction result. Although small errors exist, shapes are robustly reconstructed under overlapped patterns.