2010 Fourth Pacific-Rim Symposium on Image and Video Technology

One-shot entire shape acquisition method using multiple projectors and cameras

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***Abstract*—In this paper, we propose an active scanning system using multiple projectors and cameras to acquire a dense entire shape of the object with a single scan (*a.k.a.* one-shot scan). One of the potential application of the system is to capture a moving object with high frame-rate. Since the pattern used for oneshot scan is usually complicated and those patterns interfere each other if they are projected on the same object, it is difficult to use multiple sets of them for entire shape acquisition. In addition, at the end of the closed loop, errors on each scan are accumulated, resulting in large gaps between shapes. To solve the problem, we propose a oneshot shape reconstruction method using a projector projecting a static pattern of parallel lines with one or two colors. Since each projector projects just parallel lines with a small number of colors, those patterns are easily decomposed and detected even if those patterns are projected multiple times on the same object. We also propose a kind of multi-view reconstruction algorithm for the proposed projector-camera system. In the experiment, we actually built a system which consists of six projectors and six cameras and dense shapes of entire objects were successfully reconstructed.**

***Keywords*-projector-camera system; entire shape aquisition; 3D measurement; structured light; active sensing; 3D scanner; dynamic scene capturing;**

I. INTRODUCTION

Dense entire shape acquisition with a single-shot capturing is strongly required from many areas. For example, for capturing a dancing person who wears soft clothes or a moment of explosion of the object, entire shape acquisition method with one-shot scanning is desirable. So far, for the purpose of capturing such an entire shape of a moving object, *shape from silhouette* [11] technique is widely used. In addition, for static object, multi-view stereo (MVS) technique is intensively researched and the results are greatly improved recent years. However, it is difficult to recover concavity and small bumps with silhouette based techniques and it is still difficult to retrieve a dense and precise shape with MVS if texture is uniform and a number of image is small.

On the other hand, active 3D scanning methods are used for practical purposes, because of its accuracy and fidelity. Especially, a structured light system that consists of a projector and a camera is widely developed and commercialized because it can capture a wide range of view with a short period of time. However, there remain several essential problems to use multiple sets of them, surrounding a target object to capture an entire shape of the object. For example, a temporal-encoding-based projector-camera system, which is most popular now, requires a set of images in which the object is captured with different patterns, and thus, it is basically difficult to achieve entire shape acquisition with a short time. On the other hand, a system based on a spatial-encoding technique is also proposed; that requires just a single input with static pattern for reconstruction, however, the pattern used for the system is usually complicated and the patterns interfere each other if those are projected on the same object. Therefore, it is difficult to use multiple sets of them to capture an entire shape of the object. Further, since errors on each scan are accumulated at the end of the loop, large gaps between shapes usually occur.

If a spatial-encoding-based projector-camera system using just a small number of colors with parallel line pattern is realized, aforementioned line detection problem can be resolved. Recently, the methods that can reconstruct the shape from a single image using a static grid pattern with only a single or two colors are proposed [8], [13], [16]. However, since the projected pattern consists of vertical and horizontal dense parallel lines, it is still difficult to decompose them when the patterns are projected from multiple projectors onto the same object, because they interfere each other. Furthermore, since the methods use density of line intervals to retrieve the unique solution, it is impossible to make both vertical and horizontal lines to be dense; this results in not only sparse reconstruction, but also failure in reconstruction of small objects.

In this paper, we propose a shape reconstruction method using intersections of two sets of parallel lines projected by two projectors, respectively. With the method, since interference of patterns is greatly reduced, freedom on installation of multiple projectors is significantly improved and

978-0-7695-4285-0/10 $26.00 © 2010 IEEE
DOI 10.1109/PSIVT.2010.25

entire shape acquisition can be possible. Another advantage of the proposed method is that the unique solution can be retrieved only from intersection points, and thus, both the vertical and horizontal lines can be dense as possible, resulting in realization of reconstruction of small objects. We also propose a multi-view reconstruction algorithm in which shape reconstruction based on grid patterns [13] is utilized. We also construct the actual system, which consists of multiple projectors and cameras to show several experiments with evaluations.

The main contributions of the paper are as follows: (1) one-shot dense entire shape reconstruction by using multiple projectors and cameras is proposed, (2) linear solution for shape from grid pattern is presented, (3) a reconstruction algorithm for multi-view projector-camera system, and (4) an actual system which can capture an entire shape of an object is constructed.

II. RELATED WORK

Entire shape acquisition system has been researched for a long time from several purposes, *e.g.* CAD, motion capture, etc., and many techniques based on multi-view stereo (MVS) has been proposed [5], [6], [15]. However, if texture information is not enough and a number of input image is small, density and accuracy of reconstruction become sparse and unstable. In addition, since applying MVS to dynamic scene is not realistic because of its high computational costs, silhouette based techniques are usually used for capturing dynamic objects because of its efficiency on calculation and robustness [9], [2]. However, the technique still has several critical issues, such as sparse and inaccurate reconstruction especially for textureless and concavity part.

So far, for practical 3D acquisition purposes, an active system has been widely used and a projector camera based system is intensively researched because of its efficiency and simple installation [18], [1]. In terms of projector camera based 3D reconstruction techniques, the techniques can be categorized into two types, such as temporal and spatial-encoding technique. Although temporal-encoding technique can achieve dense and accurate reconstruction, the technique requires a set of images in which the object is captured with different projected patterns; thus, it is basically difficult to use multiple sets of them at one time.

Douglas *et al.* proposed a temporal-encoding-based entire shape acquisition system by using a special set-up of multiple mirrors [10], however, it is also difficult to extend the technique for general purposes.

On the other hand, techniques using only spatial encoding of a pattern which allow scanning with only a single-frame image have been proposed [7], [17]. However, they typically use complex pattern with many colors for decoding and may be easily affected and leads to ambiguities on textured object or near depth boundaries. In addition, if those patterns are projected on the same object for an entire shape acquisition, they interfere each other and it is almost impossible to decompose them.

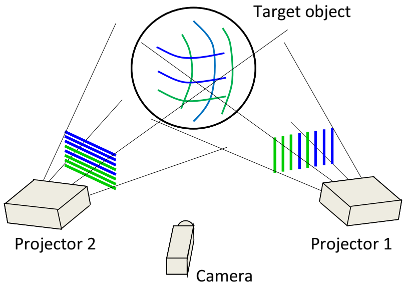


Figure 1. The minimum setup of the proposed approach consist of two projectors and a camera. The two projectors project vertical and horizontal line patterns, respectively, and the camera observes the intersection points of the lines.

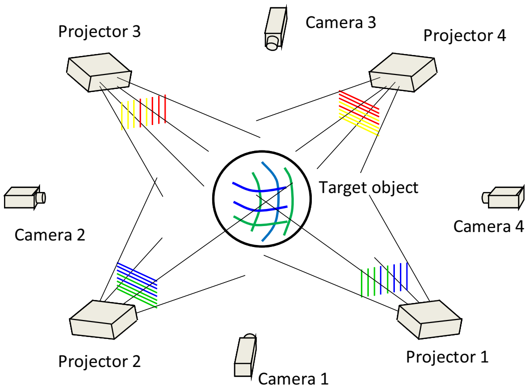


Figure 2. An example setup to reconstruct the whole shape consist of four projectors and four cameras. The patterns are constructed by using different colors to discriminate the vertical or horizontal patterns each other.

Recently, solutions for the complex pattern of spatial-encoding method by using a simple grid pattern which embeds information in relation of connection of parallel lines have been published [8], [13], [16]. However, since the system still projects dense vertical and horizontal grid patterns, it is still difficult to decompose them after projected on the same object. If the pattern is just one directional parallel lines with one or two colors for each projector, the problems can be drastically reduced; we propose such a technique in the paper.

In terms of MVS for projector and camera system, several papers have been published, especially for temporal coding based system [3]. However, applying conventional MVS to the grid pattern based systems is not easy, because point correspondences are not explicitly given; therefore some solution is required.

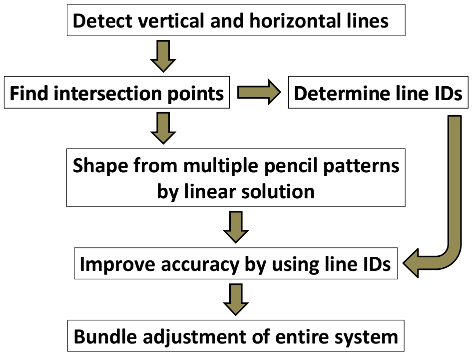


Figure 3. Overview of the proposed algorithm.

III. DENSE ENTIRE SHAPE ACQUISITION SYSTEM

A. System configuration

In the proposed 3D measurement system, a camera observes line patterns projected from multiple projectors. The projected pattern is fixed and does not change, so synchronization is not required. The minimum setup consists of two projectors and a camera as shown in Fig. 1. The camera and the projector are assumed to be calibrated (*i.e.* , the intrinsic parameters of the devices and their relative positions and orientations are known). The two projectors project vertical and horizontal lines patterns, respectively, and the system reconstructs the shape of a target object by observing the intersection points of the lines. Although the proposed method can reconstruct shape from monochrome line patterns, we use color patterns to improve accuracy and robustness. In this paper, a periodic pattern of two colors is used based on the de Bruijn sequence.

When we reconstruct the entire shape of an object, multiple projectors and cameras are used as shown in Fig. 2. The projectors and cameras are placed so that each camera can observe the intersection points of line patterns. To discriminate patterns projected from different projectors, color information is used. In this paper, we experimented with six projectors and six cameras.

B. Algorithm overview

The overview of the proposed algorithm is shown in Fig. 3. First, vertical and horizontal patterns projected from two projectors are detected separately, and the intersection points on an object made by the line patterns are found. Consequently, the lines form grid graphs in an image are obtained from the graph.

Since the line projected from a projector becomes a plane in the 3D space, a linear constraint of the plane parameter is obtained from the fact that an intersection point exists on two planes and the line of sight of the camera. By obtaining multiple constraints using the intersection points, a set of linear simultaneous equations of plane parameters can be constructed.

Additionally, to improve accuracy and computational efficiency, local ID (*i.e.* , ID that is not globally unique) of each line is obtained by using color information (Sec. III-C). The local IDs are used for detection of wrong connection between detected curves, and for matching in the following steps.

In reality, reconstruction sometimes becomes unstable because of the effect of noise or a limited number of intersection points at a small area. Therefore, we propose a multi-view reconstruction technique which is specialized for the single line based one-shot scanning method. With the method, reconstruction error of a unit system which consists of two projectors and a camera can be efficiently reduced.

C. Color pattern and line detection

The proposed method uses color code based on de Bruijn sequence [7], [14], [19] to determine each line ID. A q-ary de Bruijn sequence of order n is a sequence of length q^n consisting of an alphabet of size q in which every possible subsequence of length n is present exactly once. If a projected pattern is encoded by two or more symbols distinguished in a camera image, the correspondence between an element in the projected pattern and the observed pattern is uniquely determined by matching subsequences of length n in a de Bruijn pattern.

Instead of using large q and n as [7], [19], we used periodic patterns generated with small q and n as [13]. In this paper, we used the number of colors $q = 2$ and the length of codes $n = 3$. Namely, each cycle of the pattern consists of eight lines, and the line IDs are from 0 to 7.

The position of intersection points of vertical and horizontal lines are computed in sub-pixel accuracy. Also, in the case that two intersection points that belong to different lines are wrongly connected in the image, the wrong connection can be cut by using the color pattern [13].

D. Calibration of a system with multiple projectors and cameras

The proposed method obtains shapes by using multiple projectors and cameras. Therefore, the devices should be calibrated simultaneously. This paper calibrates a system based on bundle adjustment to estimate all parameters of multiple projectors and cameras simultaneously. Since the correspondences of camera-camera, camera-projector, and projector-projector are required for bundle adjustment, they are obtained as follows.

First, the corresponding points between a camera and a projector are given by projecting structured-light patterns from a projector (we use time-multiplexed patterns based on Gray code in our method). Next, if the patterns of a projector are observed by two cameras, the correspondence between the points of the two cameras that correspond to the same coordinate of the projector is given. Additionally, if a camera observes the patterns from two projectors, the coordinates of the two projectors that correspond to the same point in the camera image is set as the corresponding points.

The intrinsic and extrinsic parameters of cameras and projectors are estimated by using implementation provided by Lourakis *et al.* [12].

IV. THEORY AND ALGORITHM

A. Shape from multiple pencil pattern

First, we describe our reconstruction method for a minimum configuration of two projectors and a single camera. All the patterns of parallel lines projected from a projector form a set of planes that share a single line. These planes are elements of a pencil of planes. A plane from a pencil of planes can be parametrized by a single parameter. By using this representation, simple linear constraints can be obtained from the detected intersections of lines projected from two projectors.

Kawasaki *et al.* [8] used a single projector that projects both vertical and horizontal lines(*e.g.* , a grid pattern). In this configuration, axes of the two pencils of planes(vertical and horizontal) intersect at the optical center of the projector. This enables elimination of all the constant terms of the linear equations obtained from the grid points. Thus, the linear equations have 1-DOF indeterminacies. They determined a unique solution by using a modulated grid pattern in which the intervals between lines are varied randomly.

In this paper, we propose a shape acquisition method with multiple projectors and multiple cameras. In the method, each of the projectors projects vertical or horizontal parallel lines. The axes of the pencil of planes are configured to be skew. The linear equations constructed from this configuration have constant terms and generally have a unique solution.

In our method, a pattern plane p is represented by an equation

$$p_1x + p_2y + p_3z + 1 = \mathbf{p}^\top \mathbf{x} + 1 = 0, \tag{1}$$

where a 3D vector $\mathbf{p} = (p_1, p_2, p_3)^\top$ is a parameter vector of the plane. Let an axis of vertical planes be l_v. Then, all the vertical pattern include l_v, and l_v include optical center of the projector. Then, the set of planes that includes l_v can be parametrized by a single parameter μ as the following equation [13], [4]:

$$\mathbf{v} = \mathbf{v_0} + \mu \mathbf{v_{inf}}, \tag{2}$$

where $\mathbf{v_0}$ and $\mathbf{v_{inf}}$ are constant vectors that can be determined from the position of line l_v. Similarly, the set of horizontal planes is parametrized by a parameter ρ as follows.

$$\mathbf{h} = \mathbf{h_0} + \rho \mathbf{h_{inf}}. \tag{3}$$

Suppose that an intersection between vertical pattern v and horizontal pattern h is detected at (s, t) in the coordinates of a normalized camera. Let $\mathbf{v}$ and $\mathbf{h}$ be represented by $\mathbf{v}^\top \mathbf{x} + 1 = 0$ and $\mathbf{h}^\top \mathbf{x} + 1 = 0$, respectively. Then, from the formulation of [13], [4],

$$\mathbf{u}^\top (\mathbf{v} - \mathbf{h}) = 0. \tag{4}$$

By using equations (3) and (2), we obtain

$$\begin{aligned} & \mathbf{u}^\top (\mathbf{v_0} + \mu \mathbf{v}_{\mathrm{inf}} - \mathbf{h_0} - \rho \mathbf{h}_{\mathrm{inf}}) \\ = \;& (\mathbf{u}^\top \mathbf{v}_{\mathrm{inf}})\mu - (\mathbf{u}^\top \mathbf{h}_{\mathrm{inf}})\rho + \mathbf{u}^\top (\mathbf{v_0} - \mathbf{h_0}) = 0. \end{aligned} \tag{5}$$

Since equation (5) can be obtained for each intersection point, a system of simultaneous linear equation can be obtained from the detected image. Let μ_i be the parameter μ in equation (2) of the plane formed by the i-th detected vertical pattern. Similarly, let ρ_j be the parameter ρ (equation (3)) of the j-th detected horizontal pattern. Suppose that K intersections are detected. We also define maps α and β from indices of intersections to indices of detected patterns, such that the k-th intersection point ($\mathbf{u}_k = (s_k, t_k, -1)$) is an intersection between the $\alpha(k)$-th detected vertical pattern and the $\beta(k)$-th detected horizontal pattern. Then, we obtain

$$\begin{aligned} A_k \equiv \mathbf{u}_k^\top \mathbf{v}_{\mathrm{inf}},\; B_k \equiv \mathbf{u}_k^\top \mathbf{h}_{\mathrm{inf}}, C_k \equiv \mathbf{u}_k^\top (\mathbf{v_0} - \mathbf{h_0}), \\ A_k \; \mu_{\alpha(k)} - B_k \; \rho_{\beta(k)} = -C_k, \end{aligned} \tag{6}$$

for $k = 1, \cdots, K$.

By solving the simultaneous equations obtained from equations (6) , the planes formed by the detected patterns can be solved. Actually, the equation becomes $\mathbf{Mx} = \mathbf{c}$, where $\mathbf{x}$ is a vector that consists of μ_i and ρ_j. If sufficient number of intersections are given, the constraints are larger than the number of variables, and the solution is computed by $\mathbf{x} = (\mathbf{M}^\top \mathbf{M})^{-1} \mathbf{M}^\top \mathbf{c}$. The computation of $(\mathbf{M}^\top \mathbf{M})^{-1}$ is done by LU decomposition.

By applying triangulation to these planes, 3D shape reconstruction of the detected patterns can be achieved.

B. Multi-view reconstruction with error correction

Theoretically, the proposed method can obtain a unique solution only from linear equations by using a system with two projectors and a camera. However, the linear solution sometimes becomes unstable when the minimum eigenvalue of matrix $(\mathbf{M}^\top \mathbf{M})^{-1}$ becomes nearly zero (*i.e.* , nearly degenerate condition). Suppose that an extreme condition that the intersections $\mathbf{u}_i = (u_i, v_i, -1)$ are all the same. Then, it can easily confirmed that the system of equations (6) has a 1-DOF indeterminacy (Note that such error is a similar indeterminacy mentioned in [8], [13], [16]). Although this is an extreme case, the situation can be nearly degenerate if the angle of view of the camera is small, or if the region of the connected grid has only a small area; and such conditions sometimes happen for actual system. In this situation, the solution becomes sensitive to errors in calibration and line detection step.

In this paper, we propose the method to reduce the error of 1-DOF by using the constraint between multiple cameras.

When a 3D curve reconstructed from a line by a pair of Camera 1 and a Projector 1 is reprojected to Camera 2 of a system, the projection of the curve overlaps the detected line of Camera 2 if there is no occlusion and the 3D reconstruction is correct. Additionally, to further stabilize the solution and to reduce the computational complexity, we use periodic IDs of de Brujin sequence obtained in the line detection step. Therefore, overview of the method is as follows.

First, we define 1-parameter representation of the solution as the following. Let the linear equation be $\mathbf{M}\mathbf{x} = \mathbf{c}$ and the solution be $\mathbf{x}_0$. Due to the error in $\mathbf{M}$ and $\mathbf{c}$, $\mathbf{x}_0$ has some error. Since the distribution of the error can be explained by 1-DOF indeterminacy, let the correct solution $\bar{\mathbf{x}}$ be $\bar{\mathbf{x}} = \mathbf{x}_0 + s\mathbf{e}$, where s is a parameter and $\mathbf{e}$ is the direction vector of the space of the error. Then, $\mathbf{e}$ can be computed as the vector that minimizes $||\mathbf{M}\mathbf{e}||$, which is the eigenvector corresponding to the minimum eigenvalue of of $\mathbf{M}^\top \mathbf{M}$. By searching the parameter s by using a criterion different from the linear equation, the proposed method improves the solution. The actual algorithm becomes as follows:

- Step 1 Iterate the following steps (from 1.1 to 1.3) by changing s such that the $\mathbf{x}(s) = \mathbf{x}_0 + s\mathbf{e}$ sweeps the possible positions of the pattern planes.
- Step 1.1 From the candidate solution $\mathbf{x}(s) = \mathbf{x}_0 + s\mathbf{e}$, decide the correspondences between the detected curves and the line patterns on the projector, by finding the nearest line pattern that has the same de Bruijn ID to the solution of a detected curve.
- Step 1.2 Re-project the 3D curve computed from the correspondences to the adjacent camera 2.
- Step 1.3 Compare the reprojected curves with the curves detected in Camera 2 by calculating a cost function that represents distances between those curves. The cost function is basically the sum of distances from all the points from the reprojected curves to the detected curves. The distances are computed only if the de Bruijn IDs of the curves are the same.
- Step 2 Select s of the minimum cost function. Output the correspondences between the detected curves and the line patterns computed for this s.

C. Detecting lines from multiple projectors

The method for line detection is based on [13]. While the number of line directions in the paper was only two such as vertical and horizontal directions, however, in our case, since the entire shape is projected by multiple projectors, the patterns of more than three directions are observed in a captured image. Therefore, it is necessary to discriminate those patterns projected from different projectors. In addition, the method in [13] detects nearly vertical lines to discriminate from horizontal lines; however, if more than three patterns are projected, the relative angle between different patterns is smaller than 90 degrees. It causes misclassification of lines.

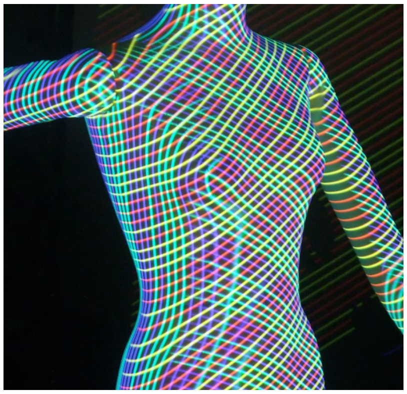


Figure 4. Line patterns projected from three projectors.

We hence propose two methods to discriminate lines. First, we used different colors for the vertical (or horizontal) patterns that can be observed simultaneously from a camera. In this paper, two color pairs are used: the ones are blue and cyan, and the others are red and yellow. By changing the colors for the color code, detecting lines of different projectors can be suppressed.

The second approach is rotating the image to be processed. For example, in Fig. 4, the patterns are projected from three projectors, one vertical pattern and two tilted patterns. If the vertical pattern is to be detected, the one of the tilted pattern can be detected because the color is still the same. Therefore, we slightly rotate the image in counter clockwise to satisfy both detecting the vertical pattern and suppressing to detect the tilted pattern. Before the post processing including color decoding and 3D reconstruction, the positions of detected lines are rotated back to the original positions.

V. EXPERIMENTS

A. Entire shape acquisition using synthetic data

To confirm the effectiveness of the proposed method, synthetic data is used for reconstruction. We use the Stanford bunny as the target. We virtually set six cameras and six projectors surrounding the target object and render the captured images by using POV-Ray. Synthesized images are shown in Fig. 5 (a). We apply the curve decomposition and detection method to the images and detection results are shown in 5 (b). From those detection results, we can observe that lines near occluding boundaries were compressed and failed to detect, whereas most curves are successfully detected.

By using the intersection of detected curves of adjacent two projectors, simultaneous equations are constructed and shapes are reconstructed by solving the equations with the proposed multi-view reconstruction technique as shown in Fig. 5 (c)-(g). From the figures, we can see that the most of the part are successfully recovered, whereas, several parts

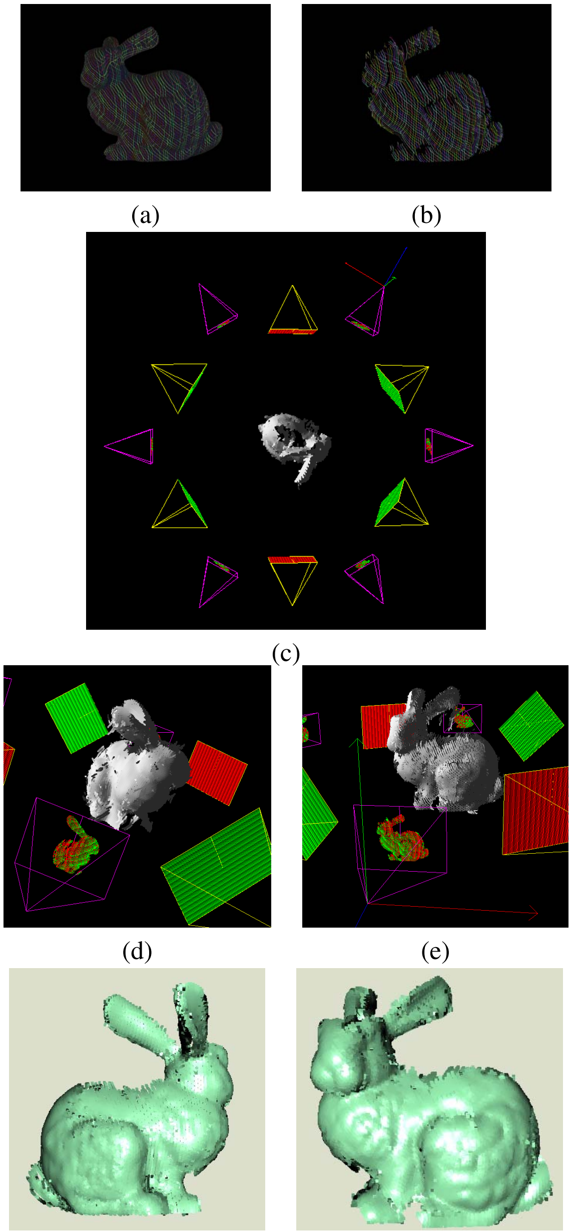

(a) (b) (c) (d) (e) (f) (g)

Figure 5. Reconstruction results: (a) synthesized image by POV-Ray (b) detected curves with de Bruijn ID (c)-(e) recovered shape with camera and projector position, and (f)(g) shaded results.

that are small area or parts near occluding boundaries are failed to recover the true shape.

B. Evaluation by using the real system

Next, we constructed an experimental system to evaluate multi-view reconstruction method for projector and camera system described in Sec. IV-B using two cameras (Sony SX-910s) and two LCD video projectors of SXGA resolution as shown in Fig. 6(a). Using the system, we measured a cube-shaped object with two methods. In method A, 3D reconstruction is done by using only linear equations (6) using two projectors and a single camera. In method B, 3D reconstruction is further improved using the second camera, using the multi-view reconstruction algorithm. As the ground truth, we also measured the target object using gray-code, in which the correspondences are correct (*i.e.* , the 3D reconstruction is correct up to calibration errors).

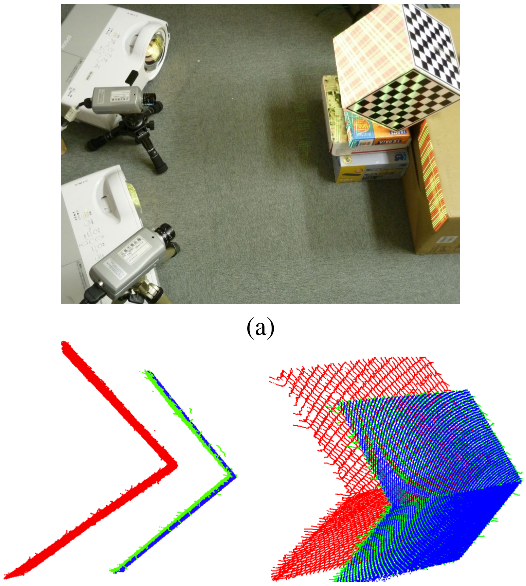

(a) (b) (c)

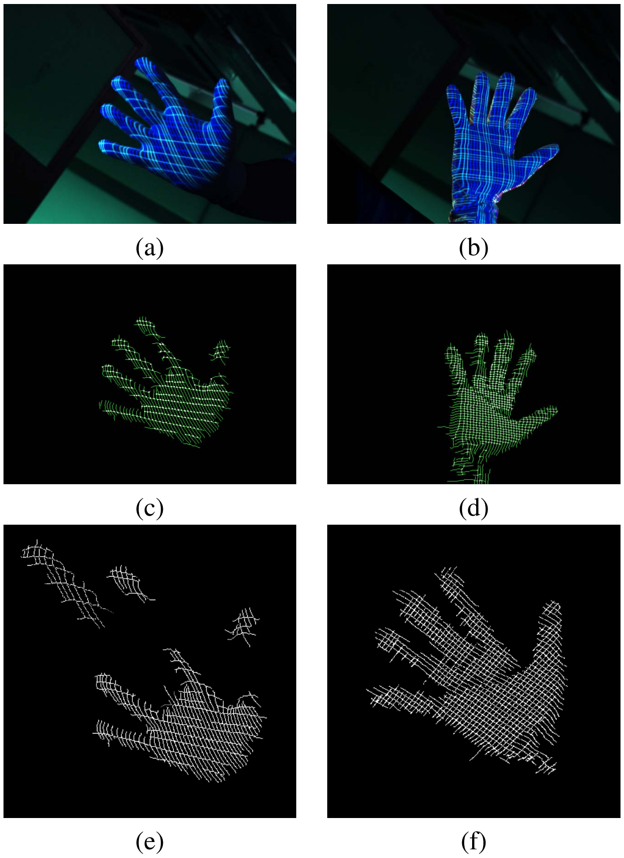
Figure 6. Evaluation of multi-view reconstruction: (a) The experimental system composed of two cameras and two projectors. (b)-(c) The reconstruction results. Red, green and blue points are the results of method A, method B and gray-code (ground truth up to calibration errors).

3D reconstruction results are shown in Fig. 6(b)-(c). To evaluate the reconstruction results of method A and B, two faces of the cube-shaped object are extracted and fit to 3D planes, and the angles between the fit planes (they should be the right angle) and the RMSEs from the fit planes were measured, which are shown in Tab. I. Since the true scale was not known, RMSEs were normalized such that average distances between the points and the camera became 1.0.

As shown in Fig. 6(b)-(c), the results of method A (red) include errors from the ground truth (blue), whereas the results of method B (green) almost coincide with the ground truth (the bias from the ground truth is caused by curve detection algorithm). From Tab. I, the result of the method B is much more precise than method A about the angle between the faces. About the RMSEs from the fit planes, the result of method A is smaller than method B. This is because, in method A, the distances between the horizontal and vertical patterns at the intersection points are minimized at the expense of the correctness of the global shape.

Table I
EVALUATION OF ACCURACY IMPROVEMENT BY USING MULTI-VIEW RECONSTRUCTION FOR GOS.

Evaluation values	Method A	Method B
Angle between 2 faces(deg.)	97.7	90.1
RMSE of points from fit planes	0.00094	0.00181



(a) (b)

(c) (d)

(e) (f)

Figure 7. A hand is reconstructed by [13] (left) and the proposed method (right). The top row is the input images, the middle row is the grid graph by line detection, and the bottom row is the reconstructed shape.

C. Comparison with the previous method

We compare the proposed method with one-shot scanning method with one projector [13]. The proposed method can use more dense pattern than that in [13] because the 1D search for shape reconstruction is not necessary in the proposed method. The advantage is that reconstruction of small object like thin fingers is easier for the proposed method than for [13]. Fig. 7 shows the result of reconstructing a hand by the both methods. The top row is the input images, the middle row is the grid graph by line detection, and the bottom row is the reconstructed shape. The result of the proposed method (right column) succeeded to reconstruct all fingers, while the result by [13] (left column) failed some fingers due to insufficient density of the grid graph.

D. Entire shape acquisition using the real system

Finally, we constructed an experimental system to capture an entire shape with six cameras and six projectors as shown in Fig. 8 (a). The cameras are Point Grey Research Flea2 (SXGA resolution), and the projectors are LCD video projectors of SXGA resolution.

One of the captured images is shown in Fig. 8 (b). We apply the curve decomposition and detection method to the images, and the detection results are shown in Fig. 8 (c) and (d).

By using the intersection of detected curves of adjacent two projectors, shapes are reconstructed by solving the equations with MVS technique as shown in Fig. 8 (e)-(j). From the figures, we can see that the large areas are successfully recovered, whereas, several parts that are not observed by cameras nor projected by the projector were not reconstructed. Other parts that failed to be recovered were small areas disconnected from larger parts. This is because the system of equations with small areas with small number of lines tends to become “nearly degenerate” equations. Reducing these reconstruction failure is our future research.

VI. CONCLUSION

In this paper, active oneshot scanning system using multiple projectors and cameras for capturing an entire shape of a object was presented. One critical problem to use multiple projector at the same time is that multiple patterns projected on the same object interfere each other and it is difficult to decompose them. To solve the problem, we proposed a new method with which each projector projects just a set of parallel lines with two colors. Reconstruction is achieved by solving linear equation derived from intersection points between lines. We also implemented multiview reconstruction technique for the poposed projector-camera system to improve accuracy. In our experiment, we constructed a system that consists of six projectors and six cameras and captured moving object successfully. In the future, to scan an entire shape of a object with dynamic motion is important. For a future work, we are developping a system that uses infrared projectors that does not interfear with visible appearance of the scenes. Using infrared light patterns, we plan to capture dynamic scenes and visible textures simultaneously.

ACKNOWLEDGMENT

This work was supported in part by Strategic Information and Communications R&D Promotion Programme(SCOPE) No.101710002 and Grant-in-Aid for Scientific Research No.072103013, No.19700098 and 21700183 in Japan.

REFERENCES

[1] J. Batlle, E. Mouaddib, and J. Salvi. Recent progress in coded structured light as a technique to solve the correspondence problem: a survey. Pattern Recognition, 31(7):963–982, 1998.

[2] J.-S. Franco and E. Boyer. Fusion of multi-view silhouette cues using a space occupancy grid. In ICCV, volume 2, pages 1747–1753, Los Alamitos, CA, USA, 2005. IEEE Computer Society.

[3] R. Furukawa and H. Kawasaki. Uncalibrated multiple image stereo system with arbitrarily movable camera and projector for wide range scanning. In IEEE Conf. 3DIM, pages 302–309, 2005.

[4] R. Furukawa, H. Kawasaki, R. Sagawa, and Y. Yagi. Shape from grid pattern based on coplanarity constraints for one-shot scanning. IPSJ Transaction on Computer Vision and Applications, 1:139–157, 2009.

[5] Y. Furukawa and J. Ponce. Accurate, dense, and robust multi-view stereopsis. In CVPR, 2007.

[6] Y. Furukawa and J. Ponce. Dense 3d motion capture from synchronized video streams. In CVPR, 2008.

[7] C. Je, S. W. Lee, and R.-H. Park. High-contrast color-stripe pattern for rapid structured-light range imaging. In ECCV, volume 1, pages 95–107, 2004.

[8] H. Kawasaki, R. Furukawa, , R. Sagawa, and Y. Yagi. Dynamic scene shape reconstruction using a single structured light pattern. In CVPR, pages 1–8, June 23-28 2008.

[9] K. N. Kutulakos and S. M. Seitz. A theory of shape by space carving. International Journal of Computer Vision, 38:307–314, 2000.

[10] D. Lanman, D. Crispell, and G. Taubin. Surround structured lighting for full object scanning. In The 6th IEEE Conf. 3DIM. IEEE, 2007.

[11] A. Laurentini. How far 3d shapes can be understood from 2d silhouettes. IEEE Trans. on PAMI, 17(2):188–195, 1995.

[12] M. A. Lourakis and A. Argyros. SBA: A Software Package for Generic Sparse Bundle Adjustment. ACM Trans. Math. Software, 36(1):1–30, 2009.

[13] R. Sagawa, Y. Ota, Y. Yagi, R. Furukawa, N. Asada, and H. Kawasaki. Dense 3d reconstruction method using a single pattern for fast moving object. In ICCV, pages 1779–1786, 2009.

[14] J. Salvi, J. Batlle, and E. M. Mouaddib. A robust-coded pattern projection for dynamic 3D scene measurement. Pattern Recognition, 19(11):1055–1065, 1998.

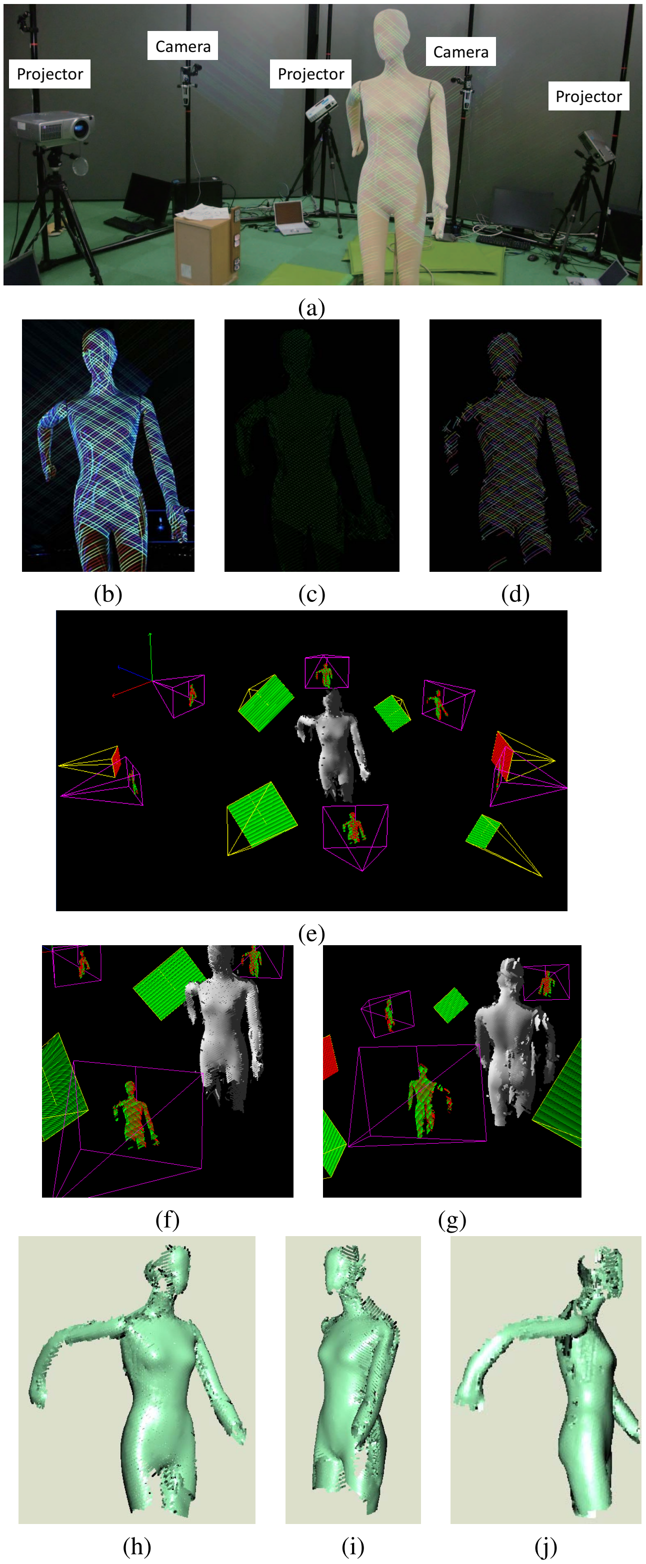
[15] S. M. Seitz, B. Curless, J. Diebel, D. Scharstein, and R. Szeliski. A comparison and evaluation of multi-view stereo reconstruction algorithms. In CVPR, volume 1, pages 519–528, 2006.

[16] A. O. Ulusoy, F. Calakli, and G. Taubin. One-shot scanning using de bruijn spaced grids. In The 7th IEEE Conf. 3DIM, 2009.

[17] P. Vuylsteke and A. Oosterlinck. Range image acquisition with a single binary-encoded light pattern. IEEE Trans. Pattern Anal. Mach. Intell., 12(2):148–164, 1990.

[18] M. Young, E. Beeson, J. Davis, S. Rusinkiewicz, and R. Ramamoorthi. Viewpoint-coded structured light. In IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR), June 2007.

[19] L. Zhang, B. Curless, and S. Seitz. Rapid shape acquisition using color structured light and multi-pass dynamic programming. In Proc. First International Symposium 3D Data Processing Visualization and Transmission, pages 24–36, 2002.



(a)

(b) (c) (d)

(e)

(f) (g)

(h) (i) (j)

Figure 8. Experiments using real system: (a) A configuration of six projectors and six cameras (this figure shows a part of the system, three projectors and two cameras), (b) captured image of one camera, (c) detected lines, (d) de Bruijn ID, (e)-(g) recovered shape with camera and projector position, and (h)-(j) shaded results.