Accurate Detection and Visualization of 3D Shape Deformation by using Multiple Projectors

Masayasu Yoshigi, Fumihiko Sakaue and Jun Sato
Nagoya Institute of Technology, Gokiso, Showa, Nagoya, Japan

Keywords: Shape Deformation Detection, Projector-projector Systems, Object Deformation Visualization, Super-resolution.

Abstract: In this paper, we propose a method for detecting the deformation of object shape by using multiple projectors. In this method, a set of specially coded patterns are projected onto a target object from multiple projectors. Then, if the target object is not deformed, the object is illuminated by plain white color, and if the object is deformed, it is illuminated by radical colors. Thus, we can visualize and detect the deformation of object just by projecting lights from multiple projectors. The proposed method uses the disparities of multiple projectors, and thus, we do not any complicated method for detecting object shape deformation. In addition, we utilize image super-resolution technique for object deformation visualization, so that we can visualize extremely small deformation easily.

1 INTRODUCTION

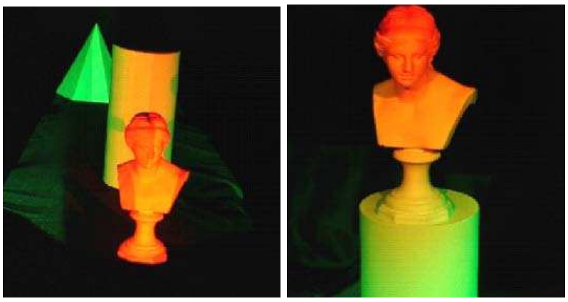
Object shape measurement is very important in many fields such as industry, 3D event detection and so on. In particular, 3D shape reconstruction is the most important challenge in the field of computer vision. In ordinary cases, stereo camera systems composed of multiple cameras are used for 3D object measurement. In this method, several images are taken by multiple cameras, and 3D shape are estimated from the set of images (Hartley and Zisserman, 2000). By using this reconstructed 3D information, many kinds of applications such as event detection are done.

For this purpose, the projector-camera (active camera) systems are also used for 3D shape measurement in recent years. For example, the Microsoft Kinect is used for various kinds of applications. In these method, a specific pattern is projected from the projector to the scene, and is observed by a camera. Then, we can reconstruct 3D shape from the relationship between projected patterns and observed images. In many cases, 3D reconstruction from projector-camera systems is more stable and accurate than that from ordinary multiple camera systems, since the projector-camera systems can project corresponding points explicitly and extraction of corresponding points is much easier and denser than the ordinary stereo camera systems.

In recent years, a projector-projector system was also proposed for visualizing 3D information of objects (Sakaue and Sato, 2011). In this method, multiple patterns projected from multiple projectors are combined physically on the surface of object, and the combined lights on the object surface represent the 3D information of the object. This method uses the disparity of multiple projector images efficiently for visualizing the 3D information just by projecting coded lights from projectors. For example, it can visualize 3D information such as the distance from the projector to the object and the height of object by using color as shown in Fig.1. This method does not require 3D measurements from sensing systems, and thus it does not need any sensing devices such as cameras and sensing costs of computer. The projector-projector system also enables us to avoid system delays caused by sensing and computation, since it does not need any sensing and computation for obtaining 3D information and visualizing it. This is a very big advantage for industrial applications, and hence several methods have been proposed based on this framework(R. Nakamura, 2010; S. Takada, 2014; K. Suzuki, 2013). In addition, we can obtain 3D information easily just taking the scene by using the camera devices and just simple image processing such as color detection.

However, unfortunately these methods cannot visualize detail structure of the scene because of the limit of projector resolution. Thus, we in this pa-

Yoshigi M., Sakaue F. and Sato J..
Accurate Detection and Visualization of 3D Shape Deformation by using Multiple Projectors.
DOI: 10.5220/0005455405770582
In *Proceedings of the 10th International Conference on Computer Vision Theory and Applications* (MMS-ER3D-2015), pages 577-582
ISBN: 978-989-758-090-1



(a) Distance visualization (b) Height visualization

Figure 1: Distance visualization by projector-projector system. In figure(a), objects are colored by red, yellow and green when objects are arranged near, middle and far from projectors, respectively. In figure(b), height from floor is visualized by green, yellow and red.

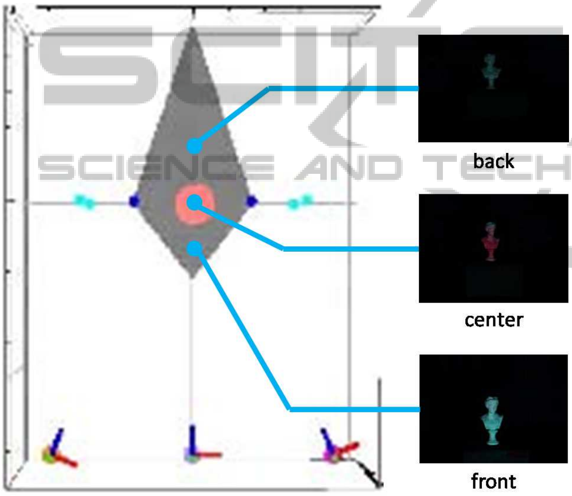


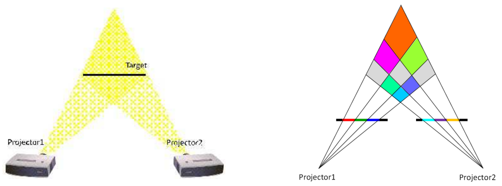
Figure 2: 3D structure visualization by using projection from multiple projectors.

per propose a new projector-projector coordination method, which enables us to visualize very tiny deformation of object shape just by projecting images from multiple projectors. For this objective, we use more than 3 projectors, and realize super-resolution visualization of object deformation.

2 OBJECT EMPHASIS BY USING MULTIPLE PROJECTORS

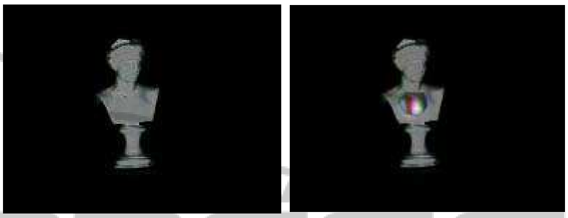
2.1 Object Shape Emphasis

We first introduce the detail of object shape emphasis using multiple projectors. Nakamura et al.(R. Nakamura, 2010) proposed 3D structure visualization using multiple projectors. By using their method, we



(a) Target surface (b) Projection result

Figure 3: Visualization of surface deformation from 2 projectors.



(a) without deformation (b) with deformation

Figure 4: Visualization of surface deformation from 2 projectors.

can visualize arbitrary 3D structure just by projecting specific images from multiple projectors. We summarize their method in this section.

Let us consider the case where we visualize the 3D space as shown in Fig.2. In this case, an object situated at the center of the region is colored by red, and an object situated at the other regions is colored by white. In this case, the object position is visualized by colors, and thus we can catch the 3D position of the object intuitively. Figure 2 shows the result of visualized position by their method. As shown in Fig. 2, the object is colored by red when it exists at the center region, and it is colored by white when it exists at the other region.

2.2 Object Deformation Visualization

The 3D structure visualization described in the previous section can be extended to visualization of arbitrary 3D structures if we can use infinite number of projectors. However, we can use limited number of projectors in reality, and thus, we cannot visualize arbitrary 3D structure. This is because projected images from projectors are 2-dimensional images, while the object has 3-dimensional structure in general.

In order to avoid this problem, Takada et al.(S. Takada, 2014) proposed a method for emphasizing 3D surface just by using 2 projectors. In their method, they focused not on 3D structure but on 3D surface. In this case, we only need to consider projected pattern on a 2-dimensional curved surface, and thus we can emphasize object surface by using only 2 projectors. Figure 3 shows the basic principle of this

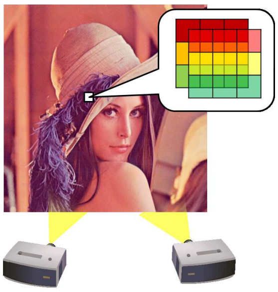


Figure 5: Image super-resolution by superimposed images.

method. The object shown in Fig. 3 (a) is illuminated by a set of projectors. Then, 2 images projected from 2 projectors are combined on the object surface. The projected images has complementary colors, e.g. red and cyan, at a pair of corresponding pixels. Then, the combined color at the object surface becomes white when the target object is at the calibrated position. If the object surface is deformed or moved from the calibrated position, the pair of corresponding pixels of 2 projectors changes, and thus the observed color also changes as shown in Fig.3 (b). Thus, we can visualize the changes in object shape by using the changes in projected colors on the object surface.

The method can visualize object deformation just by projecting specific patterns from multiple projectors. However, the accuracy of visualization strongly depends on the resolution of projected images. Therefore, we need high resolution projectors if we want to visualize small deformation of object shape. However, the resolution of projectors is determined by display devices such as DLP and LCD, and thus their resolution is physically limited.

3 SUPER-RESOLUTION OF PROJECTED IMAGES

In order to improve the resolution of projected images, image super-resolution using multiple projectors were invented in recent years (Venkata and Chang, 2007). In this method, multiple images are projected from multiple projectors to the same area of the screen simultaneously as shown in Fig.5. The projected images have sub-pixel shift as shown in this figure. Thus, we can represent higher resolution images by controlling the sub-pixel information efficiently.

Let us consider image projection for image super-resolution. The image projection from each projector is described by a linear equation as follows:

$$\mathbf{y} = \mathbf{A}_i\mathbf{x}_i \qquad (1)$$

where $\mathbf{y}$ indicates a vector which consists of the components of an $M' \times N'$ high resolution image, $\mathbf{x}_i$ indicates a vector which consists of the components of an $M \times N$ low resolution image projected from i-th projector and $\mathbf{A}_i$ indicates a projection matrix from the i-th projector. The j-th column of $\mathbf{A}_i$ represents the PSF (Point Spread Function) of j-th pixel of the i-th projector. Thus, the projected image $\mathbf{y}$ consists of a weighted sum of the PSF.

From Eq.(1), the evaluation function for image super resolution can be described as follows:

$$E = ||\mathbf{y} - \sum_i \mathbf{A}_i\mathbf{x}_i||^2 \qquad (\mathbf{0} \le \mathbf{x}_i \le \mathbf{I}_{max}) \qquad (2)$$

where I_{max} is the maximum intensity which can be projected from the projector. By estimating $\mathbf{x}_i$ which minimize E in Eq.(2) and projecting them from the multiple projectors, we can generate a super-resolution image from superimposed images.

By using the above method, we can utilize higher resolution projectors virtually, even if we use only low resolution projectors. Furthermore, the projection surface is not limited to a planar surface. If we compute the PSF matrix $\mathbf{A}_i$ on a curved surface, the super-resolution images can be generated even on the curved surface. This means the image super-resolution can be achieved in the visualization of object surface deformation, and we can visualize the change in shape more precisely, even if we use low resolution projectors.

4 SUPER-RESOLUTION OF SHAPE DEFORMATION VISUALIZATION

4.1 Visualization of Shape Deformation with Image Super-resolution

Let us consider a method for achieving accurate visualization of object surface deformation by using a set of low resolution projectors. The simplest way to achieve high resolution visualization of surface deformation is to compose 2 sets of virtual high resolution projectors, each of which is composed of a set of low resolution projectors. However, this is not the most efficient way to improve the accuracy of surface deformation visualization, since we can only utilize sub-pixel information of each virtual projector. If we use sub-pixel information generated by all projectors, we may be able to visualize object surface deformation more accurately. Thus, instead of considering the relationship among a set of projectors in a single virtual projector, we consider the relationship among all projectors used for visualizing object surface deformation, and derive the most efficient projection patterns of these projectors for improving the accuracy of surface deformation visualization.

4.2 Efficient Super-resolution Visualization

In order to realize accurate surface deformation visualization, we define an evaluation function of projection patterns.

In the surface deformation visualization, we generate projection patterns, so that the object is colored by white if there is no deformation, and is colored by the other colors if there exist surface deformations. Thus, for evaluating the whiteness of object surface with original shape, we define the following evaluation function:

$$E_s = ||\mathbf{w} - \sum_i \mathbf{A}_i \mathbf{x}_i||^2 \qquad (\mathbf{0} \leq \mathbf{x}_i \leq \mathbf{I}_{max}) \tag{3}$$

where $\mathbf{w}$ is a super-resolution white color pattern on the object surface. By minimizing E_s, we can observe white color on the original object surface. Note that the white color on the object surface is not necessarily composed of the projection of white color, and it can be composed of the projection of various colors from multiple projectors. Also, basis white color on the original object shape can be changed to arbitrary colors if we want. For example, we can add shading information to the basis white color such that the surface is illuminated by a single light source, which is useful for visualizing 3D information of original surface shape. If we use truly white color in Eq.(3), shading information of object surface disappears.

We next consider the evaluation function for visualizing the deformation of object surface. For accurate surface deformation visualization, the object surface color should be changed drastically when object shape is changed. The change in color can be represented by the derivative of the observed color, and then the derivative should be as large as possible for efficient deformation visualization. Since the derivative of the observed color depends on the color of projected images, the derivative of projected images should be as large as possible for efficient surface deformation visualization. Thus, we define the second evaluation function as follows:

$$\begin{aligned} E_d &= ||\sum_i \mathbf{D}_x \mathbf{x}_i||^2 + ||\sum_i \mathbf{D}_y \mathbf{x}_i||^2 \\ & \quad (0 \leq \mathbf{x}_i \leq \mathbf{I}_{max}) \end{aligned} \tag{4}$$

where $\mathbf{D}_x$ and $\mathbf{D}_y$ indicate the derivative operators in horizontal and vertical directions. By maximizing E_d, the image derivatives become large. Note that, corresponding points among projector images are on epipolar lines defined by arbitrary two projectors, and the change in corresponding points caused by the deformation of object shape occurs on the epipolar lines. Therefore, the derivatives along the epipolar lines are important for visualizing the shape deformation. For example, if the epipolar lines are parallel to the horizontal axis, we only need to consider horizontal derivatives. Thus, the horizontal and vertical derivatives in Eq.(4) can be replaced by directional derivatives along with the epipolar lines.

Since we want to derive projection images so that they minimize E_s and maximize E_d, we define the evaluation function for visualizing object shape deformation as follows:

$$E_c = wE_s - (1-w)E_d \tag{5}$$

where w is a weight. By minimizing E_c, we can obtain optimized projection images of multiple projectors for visualizing object surface deformation.

5 EXPERIMENTS

5.1 Environment

We evaluated the proposed method by using multiple projectors. We used 3 projectors as shown in Fig.6. The resolution of these projected images are 50×50. The projector images are projected onto a target object shown in Fig.7. The object was situated in front of the projectors. The PSF in projection matrices $\mathbf{A}_i$ were measured at each pixel on this object. Figure 8 shows examples of the measured PSF. In this experiment, color images were used, and thus, PSF for red, green and blue were measured respectively. In these figures, the bottom left region shows resized PSF. Note, the resolution of a camera image is much higher than the resolution of projector images. Thus, the measured PSF is spread over some pixels in these images. By using the PSF, the projection images for visualizing object surface deformation were computed. The computed images for each projector are shown in Fig.9. For comparison, projection images for not only 3 projectors, but also 2 projectors were computed. These images were projected onto the target object simultaneously from multiple projectors.

5.2 Results

Figure10 shows illuminated results when the target object was situated at the original position. As shown in this figure, although the target object was slightly

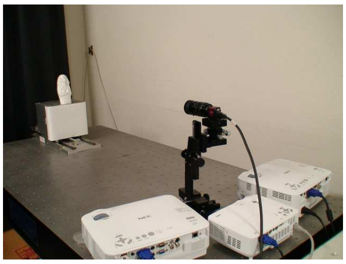
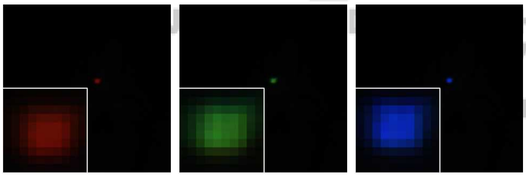
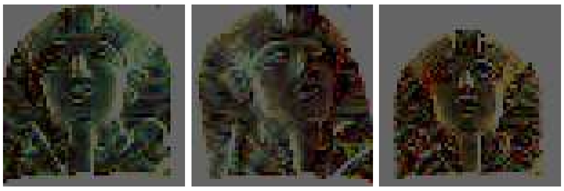


Figure 6: Experimental Environment.

Figure 7: Target object.



(a) PSF (Red) (b) PSF (Green) (c) PSF (Blue)
Figure 8: Examples of measured PSF.



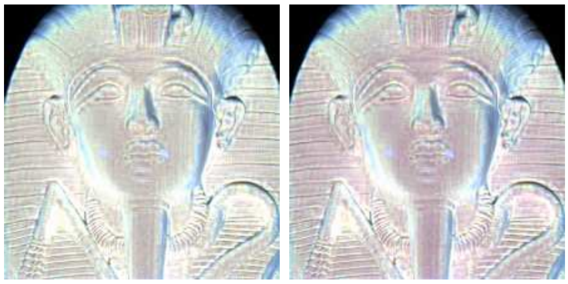
(a) Projected images for 3 projectors.

(b) Projected images for 2 projectors.

Figure 9: Images projected by 3 projectors and 2 projectors.

colored, the object was observed as it is illuminated by an ordinary single white light source. In particular, the result projected by 3 projectors is more close to white and better, since the projected images can approach to ideal result by using larger number of projectors.

We next translated the object with 3 mm. This object translation indicates whole shape deformation of



(a) by 3 projectors (b) by 2 projectors

Figure 10: Observed results when the object was situated at the original position.

(a) by 3 projectors (b) by 2 projectors

Figure 11: Observed results when the object was moved from the original position.

the target object. The observation result is shown in Fig.11. As shown in this figure, the appearance of the target object was drastically changed, and the object was colored by various colors. These results show that the proposed method can visualize the change in object surface accurately. In addition, we can detect object shape deformation by using simple image processing method such as color detection.

From the comparison of results of 2 projectors and 3 projectors in Fig.11 (a) and (b), we find that larger change in appearance occurs in 3 projectors than in 2 projectors. The result indicates that we can visualize the deformation of object shape more efficiently and accurately by using larger number of projectors.

5.3 Evaluations

We next evaluate the accuracy of the proposed method. In this experiment, target object was moved step by step, and the change of appearance was evaluated at each distance. An object shown in Fig 7 was used as a target object. For comparison, the target object was illuminated by 2 different projector systems, that is 2 projector system and the proposed 3 projector system.

Figure 12 shows the changes in appearance in the 2 projector system and the 3 projector system respectively. In this figure, the horizontal axis shows the magnitude of object motion and the vertical axis shows the RMS difference of intensity from that at the original position. As shown in this figure, when we use the 3 projector system, the change in appearance is larger than that of the 2 projector system. From these results, we find that the proposed method can visualize object surface deformation more efficiently and accurately.

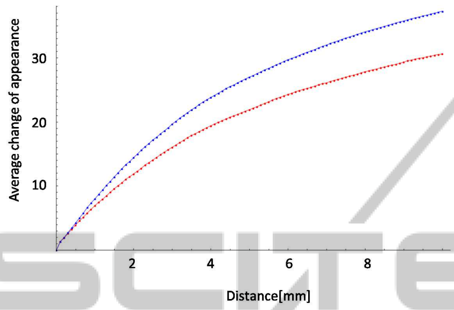


Figure 12: Relationship between object motion and change in appearance.

6 CONCLUSIONS

In this paper, we proposed a method for visualizing/detecting the deformation of object surface by using the disparity in multiple projector images, in which the deformation of object surface is visualized by color information. In order to visualize the small shape deformation accurately, we utilized the image super-resolution technique. By using the proposed method, we can use the sub-pixel information of projected images efficiently, and can visualize extremely small object deformation accurately. The experimental results show that our method can visualize small shape deformation more accurately than the existing method. The proposed method does not require computers nor cameras for visualizing the deformation of object surface once the projector system was calibrated. Thus, the proposed method is very useful for many industrial applications such as defect inspection in factory automation and 3D event detection.

REFERENCES

Hartley, R. and Zisserman, A. (2000). *Multiple View Geometry in Computer Vision*. Cambridge University Press.

K. Suzuki, F. Sakaue, J. S. (2013). 3d invariants from coded projection without explicit correspondences. In *Proc. International Conference on Computer Vision and Applications(VISAPP2013)*, pages 286–293.

R. Nakamura, F. Sakaue, J. S. (2010). Emphasinzing 3d structure visually using projection from multiple projectors. In *Proc. Asian Conference on Computer Vision*, pages 619–632.

S. Takada, F. Sakaue, J. S. (2014). 3d object emphasis using multiple projectors. In *International Conference on Computer Vision Theory and Applications(VISAPP2014)*.

Sakaue, F. and Sato, J. (2011). Surface depth computation and representation from multiple coded projector light. In *Proc. International Workshop on Projector-Camera Systems(PROCAMS2011)*, pages 75–80.

Venkata, N. and Chang, N. (2007). Realizing super-resolution with superimposed projections. In *Proc. International Workshop on Projector-Camera systems(Procams)*, pages 1–8.