3D Object Emphasis using Multiple Projectors

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Abstract: In this paper, we propose a method for emphasizing 3D shapes by using patterned light projection from multiple projectors. In this method, we project patterned lights from multiple projectors. Then, the patterned lights are mixed up at the surface of objects. As a result, object regions which are different from preregistered 3D shapes are colored and emphasized visually. In this method, we do not need any computation for image processing, since the image processing is achieved by mixing lights projected from multiple projectors. Furthermore, we do not need to find image correspondences in order to obtain 3D information of objects. In this paper, we propose a method for generating projection patterns for visualizing small difference in 3D shapes such as defects of shape. The efficiency of the proposed method is test by using multiple projectors.

1 INTRODUCTION

3D reconstruction from multiple camera images is one of the most important problem in the field of computer vision, and it has been studied extensively for many years. The existing reconstruction methods can be classified into 2 major methods.

The first one is called passive method (Hartley and Zisserman, 2000; Tomasi and Kanad, 1992; Seitz et al., 2006). In the passive method, multiple cameras are used, and the correspondence of image features, such as points and lines, are extracted and matched in multiple images. Then, the 3D shape of object is reconstructed from the correspondences by triangulation. Although the method can be applied to various scenes, we need some texture on the surface of object for obtaining correspondences.

The second one is called active method (Gokturk et al., 2004). In this method, feature points are projected onto objects from light projection devices, such as projectors. Then, 3D shape of objects is reconstructed from the projected feature points by triangulation. This method sometimes has an advantage over passive method, since it can be applied even if the objects do not have any texture on the surface.

Although these two methods provide us good 3D measurements and are used in various applications in recent years, both of them suffer from an unavoidable fatal problem. That is wrong correspondence problem. Since these methods are based on correspondences between cameras and projectors, if the correspondences are wrong, it is impossible to recover accurate 3D information from these methods. Although many methods have been proposed for reducing wrong correspondences, it is impossible eliminate the wrong correspondence problem completely.

In order to avoid this fatal problem, the coded projection (Sakaue and Sato, 2011) was proposed recently. In this method, 3D shape information is transformed into color information by using the triangulation of multiple projector lights. Since the triangulation is achieved by mixing the multiple lights on objects, the correspondence problem never happens.

Furthermore, Nakamura et. al (Nakamura et al., 2010) proposed a method for emphasizing 3D shape of object by using multiple projectors. They showed that it is possible to visualize the difference in shape just by projecting multiple coded lights on to objects. Although they showed a possibility of visualizing the defects of shape just by projecting coded lights, they also clarified that it is difficult to paint and emphasize 3D space freely. For example, Fig. 1 shows the results from their method. Although we wanted to emphasize 3D space as Fig.1 (a), the result from their method is as shown in Fig.1 (b), and we cannot emphasize the detail of 3D shapes.

In this paper, we propose a method for emphasizing 3D shape accurately just by projecting coded lights from multiple projectors. In particular, we propose a method for visualizing small change in shape as shown in Fig.2. In this method, we focus on not object region but object surface. Since there exists

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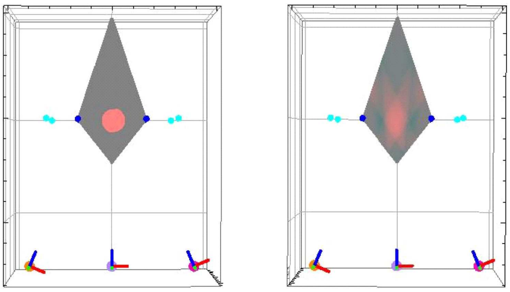


(a) Objective color (b) Projected result

Figure 1: 3D emphasis from (Nakamura et al., 2010): Objective color (a) and projected result (b).

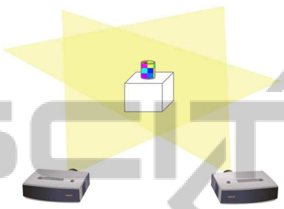
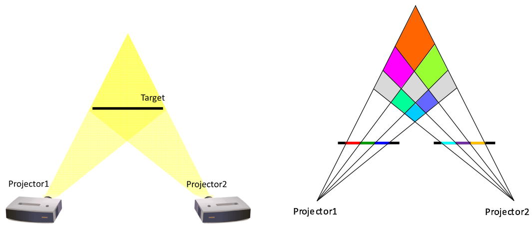
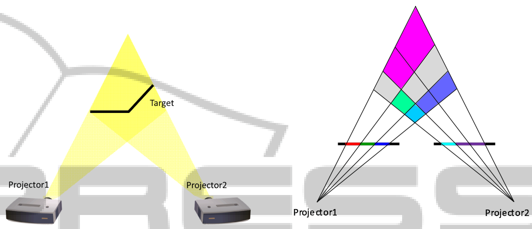


Figure 2: Emphasis of small difference in 3D shape.



(a) Target object (b) Projected result

Figure 3: 3D shape emphasis by multiple projection onto planar surface.



(a) Target object (b) Projected result

Figure 4: 3D shape emphasis for non-planar surface.

one-to-one correspondence between a point on the object surface and a point in the projection image, we can emphasize the detail of 3D shape. The proposed method can be applied to various kinds of applications, such as defect visualization in factory.

2 3D SHAPE EMPHASIS BY COLOR INFORMATION

2.1 3D Shape Emphasis by Multiple Projection

We first explain the basic idea of our 3D shape emphasis. Suppose we have multiple projectors, and these projectors project lights onto the surface of objects in the scene. For simplify the problem, we assume these object surfaces are Lambertian in this paper.

The images projected from these projectors are mixed on the object surface. Therefore, we observe mixed color of projected patterns on the surface. Let $\mathbf{I}^1 = [\mathbf{I}^1_1, \cdots, \mathbf{I}^1_N]$ be a projected pattern from projector 1 and let $\mathbf{I}^2 = [\mathbf{I}^2_1, \cdots, \mathbf{I}^2_N]$ be a projected pattern from projector 2, where i-th components in the projected patterns, $\mathbf{I}^1_i$ and $\mathbf{I}^2_i$, are projected to i-th point on the surface. Under the condition, observed color $\mathbf{I}_i$ at i-th surface point can be described as follows:

$$\mathbf{I}_i = \mathbf{I}^1_i + \mathbf{I}^2_i. \quad (1)$$

Now, if $\mathbf{I}^1_i$ and $\mathbf{I}^2_i$ are complementary colors to each other, we observe white color on the object surface. In this paper, we call a surface, which is colored to white by the combination of projected lights, as basis surface, and its shape is called basis shape. By controlling the projection patterns, we can control the basis shape arbitrarily.

Note that each pixel of these projectors must be corresponding to each other on the basis surface. In order to estimate the correspondences, we use a camera. However, once the correspondences are obtained we do not need any camera afterwards.

In order to simplify the explanation, we consider the case where basis surface is planar as shown in Fig.3 (a). If we project patterned lights from two projectors as shown in Fig.3 (b), then the 3D point on the basis surface is colored to white. For example, the most right pixel of each projector is red and cyan, and these colors are mixed on the basis surface, and thus the basis surface is colored to white. If the object surface is not at the basis surface position, i.e. object shape is changed, combination of projected colors is changed, and mixed colors at the object surface are changed to other colors as shown in Fig.3 (b). The method can also be applied to non-planar surface as shown in Fig.4. Note, the number of pixels of projectors is limited to 3 for simplicity of explanation in Fig. 3 and Fig. 4. Since the actual projectors have large number of pixels, we can design smooth curved surfaces as basis shape.

Unfortunately, the intensity of surface illuminated by projector lights is not determined just by the intensity of projector lights, and it also changes according to the reflectance and orientation of the surface. Thus, we next consider a more realistic light projection model.

Let $\mathbf{R}$ =diag(ρ_r, ρ_g, ρ_b) be a diagonal matrix, whose diagonal components are the reflectance at a surface point $\mathbf{X}_{ij}$, where ρ_r, ρ_g and ρ_b indicate reflectance of each color. Suppose θ_1 and θ_2 are the angles between the surface normal and the light orientation of projector 1 and 2 respectively. Then, the observed color $\mathbf{I}_i$ can be described as follows:

$$\mathbf{I}_i = \mathbf{R}(\frac{1}{L_1^2}\mathbf{I}_i^1 \cos\theta_1 + \frac{1}{L_2^2}\mathbf{I}_i^2 \cos\theta_2), \tag{2}$$

where L_1 and L_2 denote distance from each projector to $\mathbf{X}_{ij}$. Therefore, the complementary color $\mathbf{I}_i^2$ with respect to $\mathbf{I}_i^1$ can be determined as follows:

$$\mathbf{I}_i^2 = \frac{L_2^2}{\cos\theta_2}\left(\mathbf{R}^{-1}\mathbf{W} - \frac{1}{L_1^2}\mathbf{I}_i^1 \cos\theta_1\right), \tag{3}$$

where, $\mathbf{W}$ denotes a white color.

In order to determine a pair of complementary colors as shown in Eq.(3), we need not only pixel correspondences but also normal orientation of object surfaces. Estimation of these parameters can be estimated by ordinary 3D shape measurement methods(Gokturk et al., 2004). Although we need cameras for this estimation, cameras are not necessary after the calibration. Estimation of these parameters is not the main problem of this paper, and thus, we assume that these parameters are known in this paper.

2.2 Epipolar Geometry between Projectors

We next consider the epipolar geometry between projectors. As we have seen, the observed color changes according to the change in corresponding pixels in our method. Seemingly, we have to consider 2-dimensional changes of correspondence, since the image plane is 2D. However, we have only 1-dimensional variation in correspondence, since the epipolar-constraint exists in image planes of two projectors similar to cameras.

The epipolar constraint for 2 projector images can be described by a fundamental matrix $\mathbf{F}$ as follows:

$$\mathbf{m}'^{\top}\mathbf{F}\mathbf{m} = 0, \tag{4}$$

where $\mathbf{m}$ and $\mathbf{m}'$ are a pair of corresponding points in two images. Let us consider the epipolar line $\mathbf{l}' = \mathbf{F}\mathbf{m}$, which corresponds to $\mathbf{m}$. Then, the relationship between $\mathbf{l}'$ and $\mathbf{m}'$ can be described as follows:

$$\mathbf{m}'^{\top}\mathbf{l}' = 0. \tag{5}$$

This equation indicates that a corresponding point of $\mathbf{m}$ exists on the epipolar line $\mathbf{l}'$ regardless of 3D shape. Thus, the correspondence of color changes only on the epipolar line, and we can consider change of colors in each epipolar line. In the following sections, we assume that the fundamental matrix of two projectors is given. Then, we consider desirable patterns on epipolar lines for 3D shape emphasis.

3 PROJECTION PATTERNS FOR 3D OBJECT EMPHASIS

3.1 Random Pattern

We next consider projection patterns for projectors. As shown in Eq.(3), if one of two projection patters is determined, the other projection pattern can be determined automatically as complementary color patterns.

The projection pattern should satisfy the following conditions for efficient 3D emphasis.

1. There exist no identical colors on the epipolar line.
2. The colors of adjacent pixels must be different largely.

If the first condition is satisfied, there exists no white region except basis shape, since a complementary color does not exist on the epipolar line of the other projector except the basis shape. If the second condition is satisfied, the change in color caused by the change in shape becomes large.

There are many sets of colors which satisfies the above two conditions, and one efficient method for finding them is to select a set of colors randomly from the RGB color space. The selected colors are distributed uniformly in RGB space, and both of two conditions are satisfied in most of the case. If the selected set of colors does not satisfy the conditions, just iterate the random selection until the selected set of colors satisfies the conditions.

3.2 Color Pattern Selection in Frequency Space

We next consider color pattern selection more systematically. For this objective, we consider the color pattern in Frequency space, and modify the conditions described in section 3.1 as follows:

1. The wavelength of color pattern is longer than image size.

(a) Projection pattern from high frequency components.

(b) Projection pattern from low frequency components.

Figure 5: Example of projection patterns for 3D shape emphasis. Upper pattern consists of R{2,13}, G{3,11} and B{5,7}. Lower pattern consists of R{11,29}, G{13,23} and B{17,19}.

2. The frequency of color pattern must be as high as possible.

If the first condition is satisfied, there exist no same color on the epipolar line. In addition, since the frequency of color pattern is high as described in the second condition, colors on the epipolar line changes drastically.

Although the first condition and the second condition seem to be conflict to each other, it is possible to satisfy these two conditions simultaneously. This is because the color consists of 3 bands, i.e. R, G and B, and the minimum common multiple of 3 wavelengths of R, G and B is the wavelength of whole color pattern. For example, if the wavelength of red, green and blue components are l, m and n and if they are prime numbers, the wavelength of whole pattern is $l \times m \times n$. Furthermore, wavelength of whole pattern become longer when each color component has several frequencies. Therefore, we can easily obtain sufficiently long wavelength including high frequency components. Figure 5 shows examples of color pattern. In upper pattern, the wavelengths of R, G and B patterns are $\{2,13\}$, $\{3,11\}$ and $\{5,7\}$. In this pattern, the color of each pixel changes drastically, while there are no same color in the pattern. In lower pattern, the wavelengths of R, G and B patterns are $\{11,29\}$, $\{13,23\}$ and $\{17,19\}$. In this pattern, change in color is smoother than that of upper pattern, since the frequency of each component is lower than that of upper ones.

We can control the sensitivity of change in colors easily by considering patterns in frequency space. If we would like to detect small change in shape vividly, we should use high frequency components for generating projection patterns. In contrast, we can ignore small changes in shape and detect only large scale change in shape, if we use low frequency components. As a result, we can use efficient patterns according to the purpose. In the following sections, we show some examples of our 3D shape emphasis.

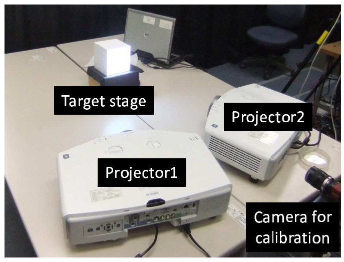


Figure 6: Experimental environment.

(a) Cube

(b) Sculpture

Figure 7: Target objects for 3D shape emphasis.

4 EXPERIMENTAL RESULTS

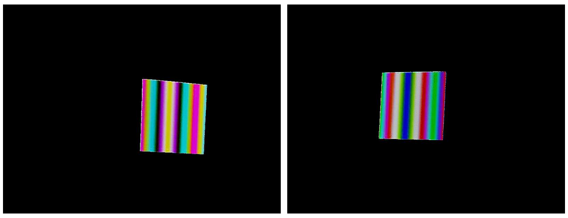
4.1 Environment

In this section, we show some results in 3D shape emphasis. We first explain our experimental environment. In these experiments, two projectors were used and they were set as shown in Fig.6. The projectors are EPSON EB-G5750WU. The image size projected from these projectors is 800×600. The camera in this image was used just for extracting correspondences in images of two projectors. The camera was not used for 3D shape emphasis at all. As target objects, a cube shown in Fig.7 (a) and a sculpture in (b) were used. The targets are made of gypsum and their surface can be considered as Lambertian surface. The targets are set on a target stage in Fig.6 and they were moved 1.5 cm and 3 cm toward front of the target. Basis shape was set as initial position and moved object was colored as changing of shape by the proposed method.

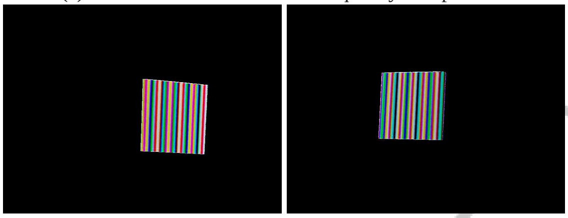
4.2 Shape Emphasis Results

We first show the results of 3D shape emphasis of a cube. In this experiment, two types of color patterns were projected from projectors. Projected patterns are shown in Fig.8. The set of color patterns shown in Fig.8 (a) is derived from low frequency components, while the set of patterns shown in (b) was derived from high frequency components.

These patterns were mixed on the basis surface and the combination of these patterns became white

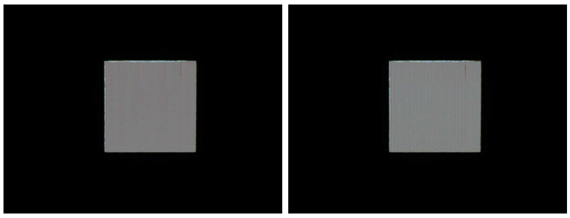


(a) Patterns derived from low frequency components

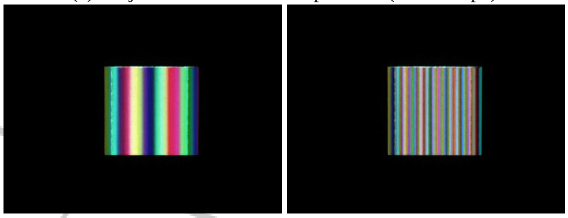


(b) Patterns derived from high frequency components

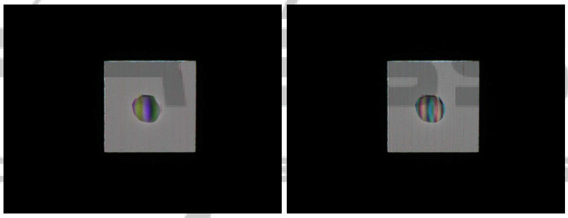
Figure 8: Projection patterns for flat shape emphasis: Wavelength of upper pattern for R,G and B are 61pixel, 36pixel and 34pixel. Wavelength of lower pattern for R,G and B are 47pixel, 21pixel and 17pixel.



(a) Projected result at initial position (basis shape)



(b) moved distance is 1.5cm



(c) with shape error

Figure 9: The result of 3D shape emphasis of cube. The right images are results from pattern (a) which have low frequency, and left images are results from pattern (b) which have high frequency. At the initial point (basis shape), the cube was colored in white. At the other points, the cube was colored in various colors. When the object shape was partially changed, just changed part was colored as shown in (c).

as shown in Fig.9(a). In contrast, if the object was moved in front, the object was colored with various colors as shown in Fig.9(b).Figure9(c) shows results when object shape was changed partially. In this case, only small hemisphere put on a cube was colored by the proposed method as shown in (c). These results indicate that the proposed method can emphasize object shape efficiently just by projecting coded patterns. Furthermore, right images in Figure9 are colored more clearly than left ones. From these results, we find that high frequency patterns provides us better visualization of difference in shape.

We next show the results from a sculpture. The projection patterns for sculpture derived from our method are shown in Fig.10. These patterns were mixed on the sculpture. When the sculpture was situated at the original position, the combination of these patterns became white as shown in Fig.11 (a). Figure11 (b) shows results when object shape was changed partially. In this case, only small hemisphere put on a sculpture was colored by the proposed method as shown in (b). As shown in these figures, the proposed method enables us to visualize change in shape, even if the object shape is complex. Thus, by applying our method, we can visualize defects of products just by projecting coded lights.

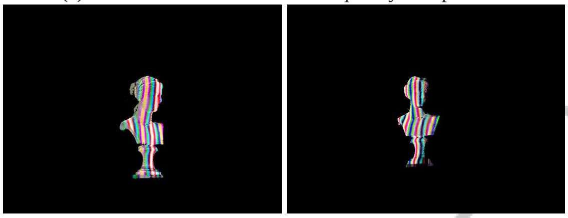
4.3 Analysis

Finally, we analyze the properties of projection patterns by using synthesized environment. In this experiment, two projectors are set as shown in Fig.12. The smooth curve was put at a target area as shown in Fig.13. We projected high frequency and low frequency patterns to the object respectively.

Figure13 (a) shows the results from low frequency patterns, and Figure13 (b) shows the results from hight frequency patterns. As shown in these figures, the high frequency patterns provide us much clear visualization of shape difference. In these figures, the basis shapes are colored in white, since the projected lights are designed so that the basis shape are colored in white. However, some points on the basis shape was colored into non-white colors. This is because the projector images are digitized in general, and projected pixels from two projectors do not overlap completely on the object surface.

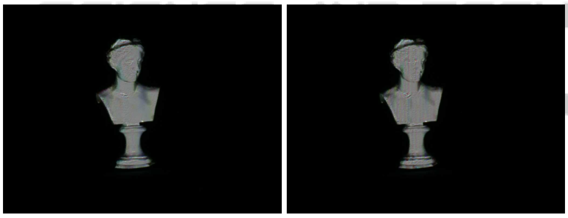
Figure14 shows the cross-section of coloring in the case of low frequency pattens (a) and high frequency pattens (b). This figure indicates how the object surface is colored in the space. It is not easy to see, but a white basis shape exists at around the center of the image, and no other points are colored into white. Since the color changes drastically under high

(a) Patterns derived from low frequency components

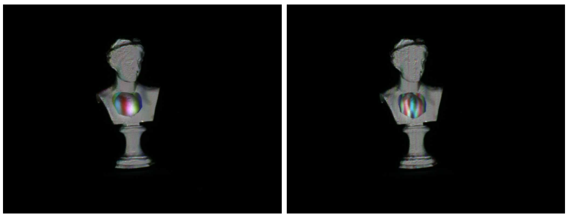


(b) Patterns derived from high frequency components

Figure 10: Projection patterns for sculpture shape emphasis: Wavelength of upper pattern for R, G and B are 61pixel, 36pixel and 34pixel. Wavelength of lower pattern for R,G and B are 47pixel, 21pixel and 17pixel.



(a) Projected result at initial position (basis shape)



(b) with shape error

Figure 11: The result of 3D shape emphasis of sculpture. The right images are results from pattern (a) which have low frequency, and left images are results from pattern (b) which have high frequency. At the initial point (basis shape), the sculpture was colored in white. When the object shape was partially changed, just changed part was colored as shown in (b).

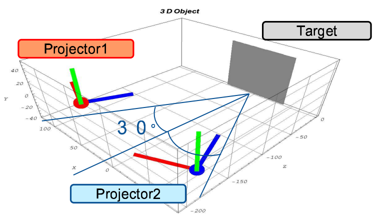
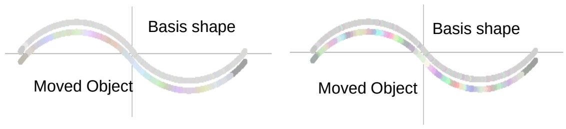
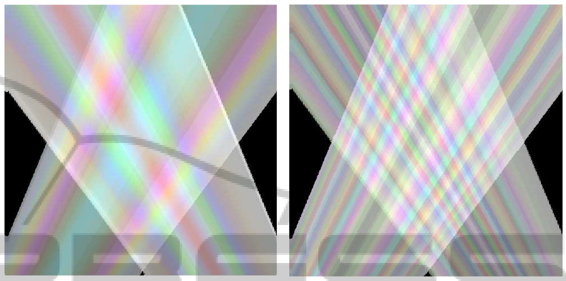


Figure 12: Experimental environment



(a) Result under low frequency patterns (b) Result under high frequency patterns

Figure 13: Basis shape and emphasized shape by low frequency patterns (a) and high frequency pattens (b).



(a) Result under low frequency patterns (b) Result under high frequency patterns

Figure 14: Cross-section of space coloring by low frequency patterns (a) and high frequent pattens (b).

frequency patterns as shown in (b), small change in shape of objects can be visualized in (b), while large change in shape can be visualized efficiently under low frequency patterns as shown in (a). Thus, the proposed method can control the degree of difference in shape extracted by the method by controlling the frequency of projection patterns.

5 CONCLUSIONS

In this paper, we proposed a method for emphasizing 3D shapes just by projecting patterned light from multiple projectors. In our method, the patterned lights are mixed up at the surface of objects, and the mixture of multiple lights provides us image processing. In particular, we proposed a method for extracting and visualizing the difference in shape by projecting coded lights. In this method, we do not need any computation for image processing, since the image processing is achieved by mixing lights projected from multiple projectors. Furthermore, we do not need to find image correspondences in order to obtain 3D information of objects. Thus, the proposed method does not suffer from the wrong correspondence problem. The efficiency of the proposed method was evaluated by emphasizing 3D objects in the real scene. In our future work, we extend our method form emphasizing textured objects and moving objects.

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