Improvement of One-shot Fringe Projection for Shape Measurement

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***Abstract*—**Fringe phase can be detected from one-shot image in shape measurement using color fringe projection. However in practice, it is difficult to analyze the phase precisely because characteristics of spectrum are depend on optical devices and test object. Improvement of measurement accuracy is attempted by correction for detected hue information in this experiment. The hue distribution of the object is modified by using reference hue of a flat surface. The accuracy is improved remarkably even if using general purpose projector and digital camera. Moreover, spatial phase shift method using gray scale fringes is modified to increase measurement accuracy, too. Phase of projecting pattern is shifted perpendicularly to projection direction in advance and analyzed fringes along this direction. Un-uniformity of the measurement sensitivity caused by optical arrangement is corrected by calculations of geometrical relationship. Because the shape measurement is carried out by one-shot image in proposed methods whereas ordinary phase shift method usually needs multiple images, those techniques are applicable to dynamic measurements. An example of dynamic deformation is shown.

***Keywords*—**Fringe Projection; Hue; Shape Measurement; Spatial Phase-shifting; One-shotImage.

***Abbreviations*—**Color-encoded Fringe Projection Profilometry (CFPP); One-step Phase-shift Grating Projection (OPGP).

I. Introduction

SHAPE measurement method by fringe projection is applied to varied objects because of high flexibility of optical arrangement[Editorial, 2010; Zhang, 2010]. Moreover, the method is applicable for dynamic measurement if shape measurement is possible from one-shot image [Zhang, 2012].

Fringe phase can be detected from one-shot color image theoretically (CFPP), [Ma et al., 2012; Dai et al., 2012]. However in practice, it is difficult to detect the phase precisely because of spectrum nonlinearity [Wust & Capson, 1991; Zhang, 2006; Zhang et al., 2010; Ma et al., 2011]. A new practical technique is presented here. Detected hue having nonlinearity is corrected by using reference hue distribution which obtained from flat surface.

The spatial phase shift method is useful to detect fringe phase from one-shot gray scale fringe pattern (OPGP), [Gu et al., 1994]. However measurement error is generated if fringe period is changed owing to the shape of object. A new technique to reduce the error is presented. The phase shift is performed perpendicular to projection direction, though that is analyzed along projection direction generally. Measurement accuracy can be improved by this method, independently setting of fringe projection direction which decides measurement sensitivity.

II. One-Shot Image Analysis of Color Fringe Projection

Two approaches are considered to correct hue of color fringe. One method is adjustment of projecting R, G and B color level by some kind of rule. The method is complicated and needs pre-adjustment. The other is modifying detected hue directly. The later method is attempted in this experiment, because modification of output can be accomplished simpler than that of input.

The correction procedure of detected hue is shown in figure 1 along an example. This result includes not only the hue correction but also modification of un-uniform sensitivity caused by optical arrangement mentioned later. A convex object on flat surface is shown in figure 1(b). The height of that is 14.8mm and the diameter is 89mm. Computer generated R, G, B color fringes are projected by a video projector which spreads commonly (Epson EB-S62). Each color fringe has sinusoidal intensity distribution. The color fringe pattern is captured by a digital camera (Nikon D5000), and converted to 8 bit bitmap R, G, B data with 4288x2848 pixels. The hue H is expressed by the following equation, which is same as the phase shift method of 2π/3 phase steps.

$$H = \tan^{-1}\frac{\sqrt{3}(G-B)}{2R-G-B} \tag{1}$$

where R, G and B are the intensity of each color of corresponding pixel. Figure 1(c) and figure 1(d) show calculated one line hue distribution of the flat surface and the test object, respectively. If R, G, B intensity in the projection and the imaging is ideal the hue distribution of flat surface is linear, though that is non-linear in practice. The correction method in this experiment is shown in figure 1(e). The hue of arbitrary one period of figure 1(c) is selected as the reference phase. The hue of figure 1(d) is compared with the reference phase and corrected to the linear relationship. The corrected phase of the convex is shown in figure 1(f). The unwrapped phase distribution of the corrected phase is shown in figure 1(g), and that of the unprocessed phase in figure 1(h). The non-linear error of the detected phase is improved by the presented method remarkably. Restored 3-D shape of the convex is shown in figure 1(i).

Measurement results of a plane having step are shown in figure 2, to examine the measurement accuracy. The step height is 14mm. The standard deviation of the phase distribution on the plane after correcting the phase and eliminating the influence of geometric arrangement shown in figure 2(b) is 0.063 rad, and that of before correction in figure 2(c) is 0.202 rad. The accuracy is improved by the hue correction remarkably.

Shape measurement of a torso is shown in figure 3. In order to obtain the reference phase, a small flat plate is attached. The error is able to decrease to about one third by the phase correction.

It is thought that residual errors are caused by some minor problems. For example, hue changes slightly depending on the intensity. Especially in low intensity level, it is difficult to keep linearity between computer generated signal level and captured intensity. Therefore, sinusoidal wave generated between 50 and 255 level is used in this experiment. However for example, there are some deviations in the shoulder of torso because of insufficient intensity. Another problem is different optical characteristics between object and reference material. Same material as object ought to use for reference surface if possible.

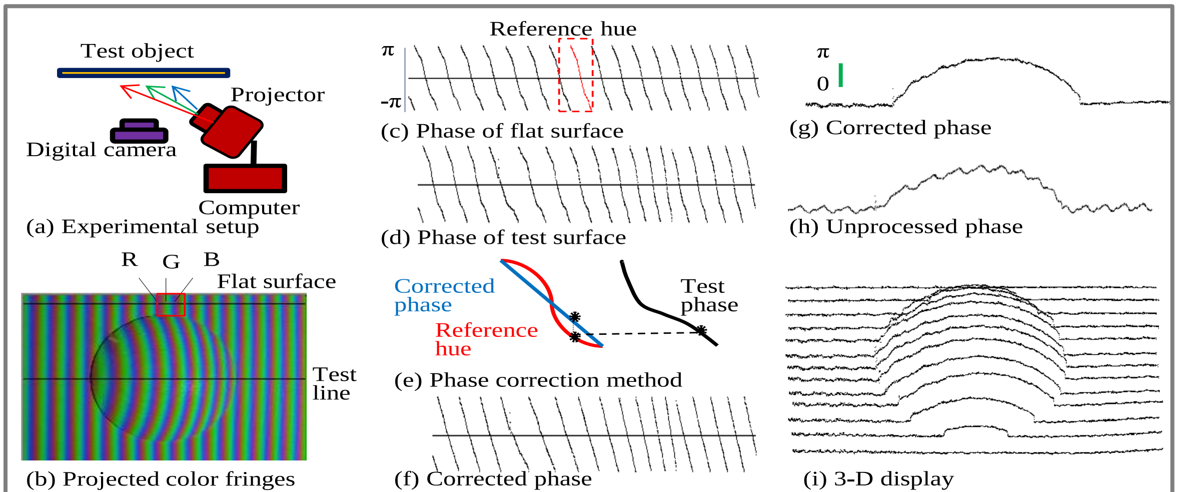


Figure 1: Procedure of Hue Correction

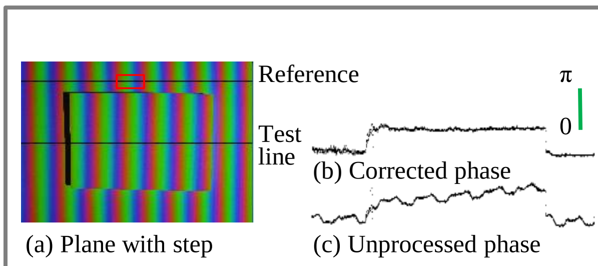


Figure 2: Examination of Measurement Accuracy

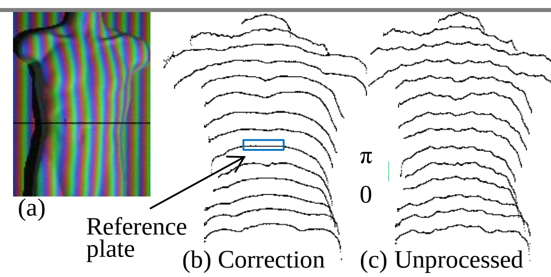


Figure 3: Shape Measurement of Torso

III. One-Shot Image Analysis of Gray Scale Fringe Projection

Spatial phase shift method is useful for one-shot image analysis of gray scale fringe pattern. A new phase detecting method is proposed in which the phase of projected pattern is shifted perpendicularly to projection direction and analyzed fringes along this direction.

The method is shown in Fig.4 schematically. In ordinary procedure shown in figure 4(a), the fringe pattern is projected along x direction and phase of each pixel is analyzed by a period of fringe information along x direction. However in this experiment, as shown in figure 4(b), phase shift pattern for y direction is projected and analyzed along y direction. As for fundamental advantage of this method, phase shift analysis is accomplished without changing setup of x direction. Sinusoidal phase shift pattern instead of discrete phase shift is used in the experiment.

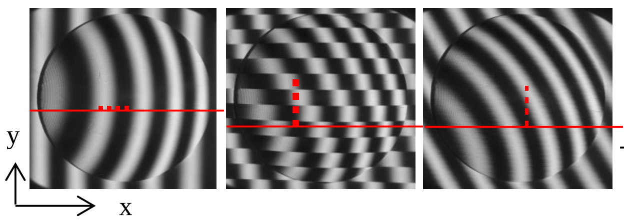
Because the phase is analyzed under the condition that fringe spacing is assumed uniform in the spatial phase shift method, deviation of the spacing caused by shape of test object generates measurement errors. The pitch deviation by slope is shown in figure 5. When fringes are projected along x direction with the incidence angle θ as shown in figure 5(a), the ratio of observed pitch P_0 on the flat surface and pitch $P\alpha$ on the slope with the angle α is expressed by the following equation.

$$\frac{P_\alpha}{P_0} = \cos\alpha \cdot (\cos\alpha - \sin\alpha \cdot \tan(\theta - \alpha)) \tag{2}$$

The projected pattern where phase is shifted along y direction is shown in figure 5(b). The pitch ratio of y direction is expressed by the following equation, here P_{0y}, P_{0x} are standard pitch of y and x direction, respectively.

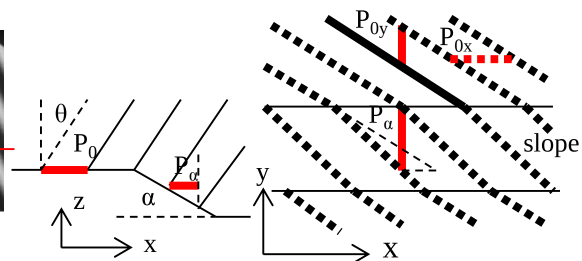
$$\frac{P_\alpha}{P_{0y}} = \frac{1}{1-(P_{0y}/P_{0x})\tan\theta \cdot \tan\alpha} \tag{3}$$

When P_{0y} and P_{0x} are equal the values of Eq.(2) and (3) become almost equivalent, and the value of the Eq.(3) approaches unit in $P_{0y} \ll P_{0x}$. Therefore, the phase detection error is can be reduced by increasing fringe number of y direction independently with x direction conditions.



(a) X projection (b) Y shift (c) Sinusoidal intensity

Figure 4: Spatial Phase-shifting Method

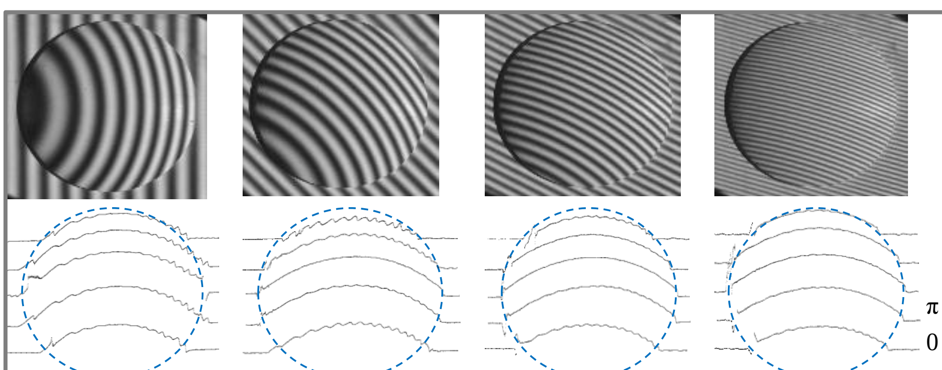


(a) X projection (b) Y shift

Figure 5: Change of Fringe Spacing by Slope

Experimental results of the convex are shown in figure 6, where projected pattern and analysis direction are changed. Fringe pattern is analyzed by the spatial phase shift method using only four pixels data separating by a quarter of fringe spacing each other. No pre-treatment such as averaging is performed. Measurement result by ordinary method is shown in figure 6(a). Periodic phase error appears both sides where strong inclinations are existed. Phase distribution detected by phase shift of y direction is shown in figure 6(b). Phase error appears upper and lower part. The results of reducing pitch of only y direction to half and quarter are shown in figure 6(c) and figure 6(d), respectively. Measurement error is improved by reducing fringe spacing. Though the measurement sensitivity is decided by the fringe spacing and the incident angle, the measurement accuracy is improved by the pitch perpendicular to projection direction independently in this method.

In order to clarify the difference between the measurement accuracy and the sensitivity, especially certainty of 2π ambiguity correction, measurement result of a softball is shown in figure 7. The diameter is 97mm. The phase unwrapping does not completely perform in the circumference parts as shown in figure 7(a). In the pattern quadrupled fringe number of only y direction shown in figure 7(b), the correction is carried out completely for y direction phase shift analysis. This is because phase detection accuracy improved according to the pitch ratio deviation as expressed by Eq.(3). In the pattern quadrupled for both x and y direction shown in figure 7(c), the degree of unwrapping is same as figure 7(a) though the measurement sensitivity quadruple.



(a) X direction shift (b) Y direction shift (c) 1/2 pitch (d) 1/4 pitch

Figure 6: Spatial Phase-shifting Analysis

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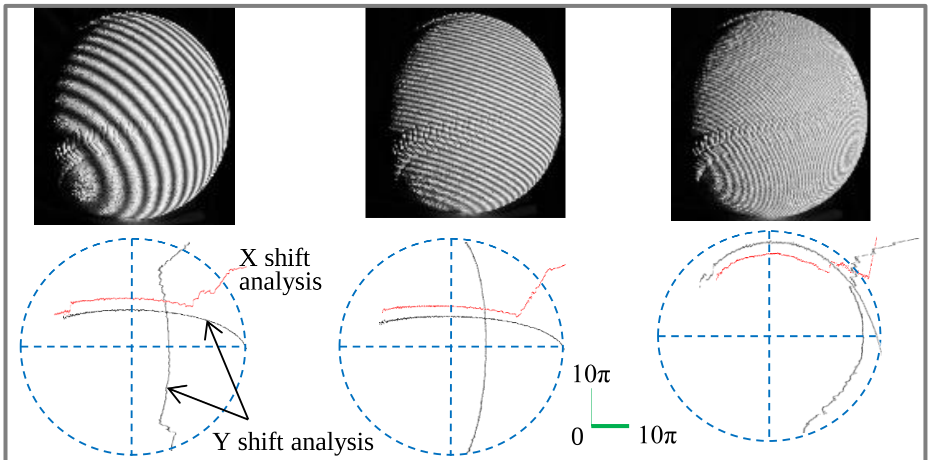


(a) Same pitch of x and y (b) 1/4 pitch for only y (c) 1/4 pitch for x and y

Figure 7: Measurement Accuracy and Sensitivity

IV. Optical Arrangements

Measurement sensitivity of fringe projection is uniform if telecentric optical system is chosen for both projecting and imaging system. However in this experiment, divergent projection system is selected as shown in Fig.8.The fringe pattern is projected with an oblique angle to the test object to obtain higher sensitivity and wide projection area easily. Therefore, the measurement sensitivity differences depend on the position of object. Those influences are eliminated theoretically with three stages.

First stage is correction of un-uniform sensitivity by oblique projection. As the projected fringe spacing on the object surface is not equal as shown in figure 8(a), the phase unwrapping data are non-linear. The correction is accomplished mathematically from the geometric position relation. The lateral relation between x axis in the projected plane and x' axis where fringe spacing is equal is given by

$$X' = X(\cos\theta + \sin\theta \cdot \tan\Delta\theta(X)) \quad (4)$$

$$\tan\Delta\theta(X) = X \cdot \cos\theta / (R_0 - X \cdot \sin\theta) \quad (5)$$

Where $\Delta\theta(x)$ is variable quantities of the incident angle. The correction is accomplished by using those equations.

Second stage is correction of un-uniform depth sensitivity by oblique projection. The measurement sensitivity of depth direction is, as shown in figure 8(b), related to the fringe spacing P'(x) and the incident angle θ'(x) of each position. The normalized sensitivity $S_1(x)$, where the sensitivity factor at the origin is unit, is given by

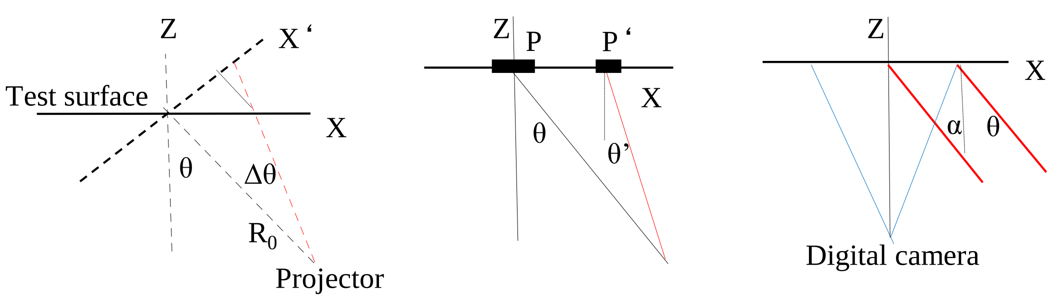
$$S_1(X) = \frac{\tan\theta'(X)/P'(X)}{\tan\theta / P} \quad (6)$$

where P is fringe spacing at the origin. The modification is carried out dividing the former phase distribution by the sensitivity $S_1(x)$. This influence is not large, because two factors tanθ'(x) and 1/P'(x) are act as inverse influence.

Third stage is correction of un-uniform sensitivity by imaging arrangement. As the object is captured by the digital camera with condensed optical arrangement, the measurement sensitivity is depending on each position as shown in Fig.8(c). The normalized sensitivity $S_2(x)$ is given by

$$S_2(X) = \frac{\tan\theta + \tan\alpha(X)}{\tan\theta} \quad (7)$$

where α(x) is imaging angle on the test surface. The final phase distribution is obtained by dividing the former phase by the sensitivity $S_2(x)$.



(a) Ununiform fringe spacing (b) Sensitivity depend on projection (c) Sensitivity depend on imaging system

Figure 8: Un-uniform Sensitivity caused by Optical Arrangement

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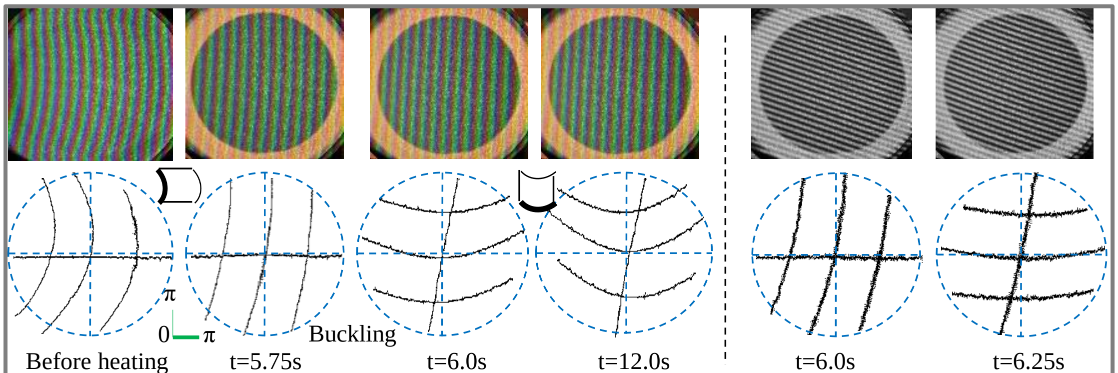
V. DYNAMIC MEASUREMENT

Deformation of bimetal is measured for an example of dynamic measurement as shown in figure 9. Both color and gray scale fringes are analyzed. Circle bimetal plate, which diameter is 90mm and thickness is 0.2mm, is stuck on cloth. Fringe pattern is projected at the incident angle 45° and images are captured every 0.25s. The warp in room temperature is 5.7mm. The plate heated by a halogen lamp from back is buckled after a certain period of heating. Measurement results of color fringes are shown in figure 9(a). Four situations, which are before heating, just before and after buckling, and 10s after heating, are shown. Deformation process can be recognized. Analyzed results of gray scale fringes are shown in figure 9(b). Only the states before and after buckling are shown. As the fringe spacing is set as double of the color fringes, the measurement accuracy is reduced to half. Some deviation of phase distribution is shown, as the fringe pattern is projected on glossy cloth in this experiment. Intensity data of different pixels are applied in the spatial phase shift method.



(a) Color fringe analysis (b) Gray scale fringe analysis

Figure 9: Dynamic Deformation of Bimetal Plate

VI. CONCLUSIONS

Precise phase reanalysis methods of one-shot image for both color and gray scale fringes are proposed, which are applied to shape measurement using fringe projection. For color fringe analysis, nonlinearity of detected hue is corrected by using reference hue distribution of flat surface. The measurement accuracy is improved remarkably. For gray scale fringe analysis using spatial phase shift method, new phase detecting technique is proposed that the phase is analyzed perpendicularly to projection direction. The accuracy is improved by increasing fringe number of analyzing direction. Further, some nonlinearity of measurement sensitivity caused by the geometric optical arrangement is corrected theoretically. Shape measurements of the dynamic phenomena are accomplished by those methods.

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