Projection Intensity Adjustment Method Based on Multi-threshold for Fringe Projection Technology

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Abstract. Three dimension measurement based on fringe projection technology is widely used in precision manufacturing. However, when measuring objects with reflective surfaces, the measurement accuracy is reduced due to image saturation. This paper presents a projection intensity adjustment method based on multi-threshold. The reflectivity information of fringe pixels and scale factor are used to calculate the multi-threshold. According to the multi-threshold, the optimal projection intensities are obtained, which reduces the image saturation and improves the measurement accuracy. The experimental results show that this method can improve the measurement accuracy effectively.

1. Introduction

Fringe projection technology (FPT) has been widely applied for 3D shape reconstruction in precision manufacturing, reverse engineering, etc. [1-2]. As we all known, the fringe projection system consists of several cameras and several projectors [3]. With the help of phase-shifting algorithm, fringe projection technology can easily achieve high-precision measurement. In recent years, with the progress of digital light processing (DLP) projector, fringe projection technology has been developed rapidly.

However, FPT is more suitable for diffuse reflective surfaces. If the object with high reflective surface was measured by FPT, saturation regions will appear on the fringe images. The phase-shifting algorithm could not calculate the phase values of saturation regions, which reduce the application of FPT[1-3]. To solve the limitations of FPT, many works have been studied. Zhang [4] developed a scanning technique to obtain fringe images under different exposures. Analogously, Waddington [5] obtained many fringe images with different intensities. Zhang [6] obtained several groups of fringe images with optimal light intensity. Combining with the advantages of binocular vision and monocular fringe projection, Yu [2] proposed an adaptive binocular fringe dynamic projection method. Lai [7] provided a Moire Fringe Patterns Sequence algorithm to measure the over-dark and over-bright surfaces. In this paper, we propose a projection intensity adjustment method (PIAM) based on multi-threshold. Firstly, we explain the phase error caused by image saturation. Then, the segmentation threshold of pixel reflectivity is calculated. Several reflectivity thresholds are obtained by introducing scale factor. Thus the optimal projection gray groups can be calculated. Experimental results show that the proposed method is effective.
2. Projection intensity adjustment method based on multi-threshold

For fringe projection technology, assuming $A$ is the average intensity, $B$ is the intensity modulation, $\phi$ is the phase to be solved for, the projection intensity with N-step phase-shifting algorithm can be represented as,

$$I(x, y) = A(x, y) + B(x, y)\cos[\phi(x, y) + \delta_n], \quad \delta_n = \frac{k \cdot 2\pi}{N}, N = 3, 4, 5, \ldots, k = 0, 1, \ldots, N - 1$$

(1)

$$\phi(x, y) = -\arctan\left[\frac{\sum_{i=1}^{N} I_i(x, y) \sin \delta_n}{\sum_{i=1}^{N} I_i(x, y) \cos \delta_n}\right]$$

(2)

In order to calculate easily, the average intensity value is equal to the intensity modulation value, that is, $A=B$. Generally, three-step and four-step phase-shifting algorithm with equal phase-shifting are widely used in FPT [2]. For $N$-step phase-shifting algorithm, let $I_i^c(x, y)$ be the projection intensity, the gray value captured by camera can be written as,

$$\bar{I}_i^c(x, y) = \begin{cases} I_i^c(x, y) & I_i^c(x, y) \leq 255 \\ 255 & I_i^c(x, y) > 255 \end{cases}, \quad i = 1, 2, \ldots, N.$$ 

(3)

Thus, the intensity error and phase error\[8\] caused by image saturation can be calculated as

$$\Delta I_i^c(x, y) = I_i^c(x, y) - \bar{I}_i^c(x, y) = \begin{cases} 0 & I_i^c(x, y) \leq 255 \\ I_i^c(x, y) - 255 & I_i^c(x, y) > 255 \end{cases}$$ 

(4)

$$\Delta \phi(x, y) = \frac{4}{NI(x, y)} \sum_{i=1}^{N} \sin\left[\phi(x, y) - \frac{2\pi}{N}\right] \cdot \Delta I_i^c(x, y).$$

(5)

From the equation (5), if $N$ is large enough, the phase error can be negligible, which will result in low measurement efficiency. Let $I_{opt}$ be the optimal intensity captured by camera. According to the intensity response function[2,6], the corresponding optimal projection intensity is presented as[6]

$$I_{opt}^p = \frac{I_{opt}^b - b}{a}$$

(6)

where $a$ is the pixel reflectivity value, $b$ is the maximum value of ambient light. Let $T$ be the Otsu threshold of pixel reflectivity, and $k = (k_1, k_2)$ is scale factor. Thus, we can get three thresholds, that is, $k_1T, T, k_2T$. The corresponding projection intensities can be expressed as

$$I_{k_1}^p = \frac{I_{opt}^b - b}{k_1T}, I_{k_2}^p = \frac{I_{opt}^b - b}{T}, I_{k_3}^p = \frac{I_{opt}^b - b}{k_2T}$$

(7)

According to equation (1) and (7), groups of projection intensities for 3-step and 4-step phase-shifting can be given respectively as,

$$G_3^p: \begin{cases} I_{3,1}^p = \frac{I_{k_1}^p + I_{k_2}^p}{2} + \frac{I_{k_2}^p}{2}\cos(\phi(u, v) - \frac{2\pi}{3}) \\ I_{3,2}^p = \frac{I_{k_1}^p + I_{k_2}^p}{2} + \frac{I_{k_2}^p}{2}\cos(\phi(u, v)) \\ I_{3,3}^p = \frac{I_{k_1}^p + I_{k_2}^p}{2} + \frac{I_{k_2}^p}{2}\cos(\phi(u, v) + \frac{2\pi}{3}) \end{cases}, \quad i = 1, 2, 3.$$

$$G_4^p: \begin{cases} I_{4,1}^p = \frac{I_{k_1}^p + I_{k_2}^p}{2} + \frac{I_{k_2}^p}{2}\cos(\phi(u, v) - \pi) \\ I_{4,2}^p = \frac{I_{k_1}^p + I_{k_2}^p}{2} + \frac{I_{k_2}^p}{2}\cos(\phi(u, v) + \frac{\pi}{2}) \\ I_{4,3}^p = \frac{I_{k_1}^p + I_{k_2}^p}{2} + \frac{I_{k_2}^p}{2}\cos(\phi(u, v)) \\ I_{4,4}^p = \frac{I_{k_1}^p + I_{k_2}^p}{2} + \frac{I_{k_2}^p}{2}\cos(\phi(u, v) + \frac{3\pi}{2}) \end{cases}, \quad i = 1, 2, 3, 4.$$

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3. Experimental results

We analyze the phase error caused by image saturation for the three-step phase-shifting method and the four-step phase-shifting method, as shown in figure 1 and figure 2. To better illustrate the necessity of saturation modification, fringe images with different saturation degrees are simulated. Phase and phase error are also presented under different saturation degrees. The simulations are carried out with three-step and four-step phase-shifting under different conditions of saturation degree.

Figure 1. Phase simulations under different saturation degrees. (a) intensity distribution with low saturation; (b) absolute phase with (a); (c) phase error with (a); (d) intensity distribution with middle saturation; (e) absolute phase with (d); (f) phase error with (d); (g) intensity distribution with high saturation; (h) absolute phase with (g); (i) phase error with (g).

Figure 2. Phase simulation after modification. (a) intensity distribution after modification; (b) absolute phase after modification; (c) phase error after modification.
From figure 1, the phase error raises with the increase of saturation degree. The maximum phase errors are 0.0411, 0.0859, and 0.1337 rad for figure 1(a), figure 1(d) and figure 1(g) respectively. Phase simulation after modification for figure 1(a) is shown in figure 2. Comparing with figure 1(a), the intensity distribution after modification presents sinusoidal variation, and the absolute phase is a straight line with a phase error about zero. Therefore, the simulation results show the effectiveness of the proposed method.

Several calibration balls with reflective surface are designed in figure 3, and their diameters are needed to be measured. To better verify the performance of PIAM method, compared with Coordinate Measuring Machine (CMM) and FPT method [4-5], the measurement results are shown in table 1.

![Figure 3. Calibration balls: (a) A and B balls; (b) C ball.](image)

Table 1. Measurement results.

| Balls | CMM/mm | FPT [4-5]/mm | PIAM/mm | Mean value/mm | Mean error/mm |
|-------|--------|--------------|---------|---------------|---------------|
| A     | 50.799 | 50.782       | 50.805  | 50.804        | 0.005         |
| B     | 50.797 | 50.784       | 50.803  | 50.802        | 0.005         |
| C     | 25.399 | 25.421       | 25.404  | 25.403        | 0.004         |

Compared with FPT, the mean measurement error values with PIAM for three objects are 0.005 mm, 0.005 mm and 0.004 mm respectively, which shows that PIAM has a higher measurement accuracy. The above experiments demonstrate the effectiveness of the proposed PIAM method. The proposed PIAM method also extends the application range of fringe projection technology.

4. Conclusion

In this paper, we proposed a method to adjust the projection intensity for fringe projection technology. With the aid of intensity response function, we analyzed the segmentation threshold of reflectivity of image pixels. Through multi-threshold, we can obtain several groups of different optimal projection intensities. Thus, the accuracy of fringe projection measurement is improved. Experimental results on three objects show the effectiveness of the proposed method.

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References

[1] Zhang, S. (2018) Absolute phase retrieval methods for digital fringe projection profilometry: a review. Opt. Lasers Eng., 107: 28-37.

[2] Yu C., Ji F., Xue J., Wang Y. (2019) Adaptive binocular fringe dynamic projection method for high dynamic range measurement, Sensors, 19(18), 4023.

[3] Sun, X., Liu, Y., Yu, X., Wu H., Zhang N. (2017) Three-dimensional measurement for specular reflection surface based on reflection component separation and priority region filling theory. Sensors, 17(1), 215.

[4] Zhang, S., Yau, S. T. (2009) High dynamic range scanning technique. Opt. Eng., 48(3), 033604.

[5] Waddington, C.; Kofman, J. (2014) Camera-independent saturation avoidance in measuring high-reflectivity-variation surfaces using pixel-wise composed images from projected patterns of different maximum gray level. Opt. Commun., 333, 32–37.

[6] Zhang, L., Chen, Q., Zuo, C., Feng, S. (2018) High dynamic range 3D shape measurement based on the intensity response function of a camera. Appl. Optics, 57(6), 1378-1386.

[7] Lai, J., Li, J., He, C., Liu, F. (2019). A robust and effective phase-shift fringe projection profilometry method for the extreme intensity. Optik, 179, 810-818.

[8] Sheng, H., Xu, J., Zhang, S. (2017) Dynamic projection theory for fringe projection profilometry. Appl. Optics, 56(30), 8452-8460.