Fast and accurate 3D reconstruction based on grating projection

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Abstract. The principle model and calibration method of measurement are very important to the measurement system. In the vision measurement system, the auxiliary light source, such as laser, interference light, sine grating and so on, is usually needed in order to achieve high precision measurement results. In the existing 3D measurement methods for the surface topography of complex objects, in order to complete the measurement of absolute phase, it is usually necessary to process at least 6 fringe images, which limits the measurement speed. A method for obtaining the 3D shape of an object by using four sinusoidal fringes is presented. The truncated phase of the sinusoidal fringe is obtained by using the four-step phase shift. When the fringe order is obtained, the time of data processing can be reduced and the measurement speed can be further improved. The reconstruction time is less than two minutes and the maximum absolute error and maximum RMS error are 0.033mm and 0.029mm respectively when the height of the face model is 45mm. The validity and practicability of the method are verified, and it has a wide application prospect in high-speed and real-time 3D measurement of complex topography.

1. Introduction

A projection device projects an auxiliary light source (laser, interference light, etc.) onto the surface of the measured object, and a camera captures an image of the light source field (that is, a fringe image). The image contains the modulation information of the object's height on the light source field. The three-dimensional information of the surface of the object is obtained by processing the fringe image and the related visual algorithm. As a typical active measurement method, the projection grating method projects a grating fringe modulated by periodic function on the surface of the measured object. Due to the change of the surface height of the object, the grating fringes at each point are shifted. From the relationship between the phase offset and the surface height in the optical structure of the measurement system, the three-dimensional coordinates of the object point can be obtained from the phase information. The basic idea is to calculate the initial phase value which contains the three-dimensional information of the surface of the measured object by collecting the fringes with a certain phase shift in multiple frames.

In fringe projection profilometry, the main methods to improve the measurement speed of three-dimensional morphology are to improve the projection speed, reduce the number of projected fringes and shorten the data processing time. Compared with traditional fringe projection profilometry,
Fourier transform profilometry and phase shift method are based on phase calculation. Fourier transform profilometry requires only one frame of image to compute the continuous phase. Gray code plus phase shift [1] is a typical method to measure complex objects. However, in order to assist the phase unwrapping of high-frequency fringes, multiple gray code fringes need to be projected, which limits the measuring speed. Literature [2] proposes a fast three-step phase shift method to achieve high-precision real-time three-dimensional measurement. A color fringe coding method is proposed in literature [3] to speed up the measurement, but the color crosstalk problem will reduce the measurement accuracy. Literature [4] proposes a 2+1 phase shift algorithm to obtain the three-dimensional shape of an object by using a sine stripe of 2 $\pi$ and a single intensity stripe, which can reduce the error caused by the motion of the object. In literature [5], a step-phase-coded fringe plus phase shift method was proposed, where the wrapping phase was obtained by using the four-step phase-shifted fringe, and the fringe order was calculated by using the phase-coded fringe. However, most of these methods require complex computations, such as the inverse tangent function for Fourier transform profilometry and the phase shift method, which is more complex than the four operations based on the intensity ratio. Therefore, in order to improve the speed of data processing, a 3D measurement method based on intensity ratio is proposed. Miyasaka T and Carrihill B [6] proposed a method of the depth of the sensor based on intensity ratio only need 2 pictures, the method measuring speed is good, but has low measurement precision. Based on this, the paper [7] proposes the method of projecting saw-tooth fringe and triangular fringe, which can reduce the impact of image noise on the measurement accuracy. Flores [8] proposed a method to eliminate the triangular wave fringe distortion caused by the gamma effect of the projector. In literature [9], a trapezoidal phase shift method based on strength ratio calculation was proposed, and the energy of this method can reduce effect of small defocus on measurement accuracy. In reference [10], a two-step phase-shift triangular wave fringe method based on the calculated intensity ratio is proposed, and the absolute phase can be obtained only by projecting two frames of fringe. On the basis of their method, literature [11] proposed two sinusoidal fringes and two single-period fringes with linear variations in intensity to obtain the wrapping phase. [12] proposed an ultra-fast absolute phase recovery method, which can measure the surface topography of complex objects, and projected 3 binary defocused fringes and 2 phase-coded fringes, and corrected the fringe order by using the geometric constraints of the measurement system to achieve the accurate phase unwrapping. In order to improve the precision of measurement, this paper presents a 3D method based on five fringe projection. Compared with the traditional 3D measuring method of sinusoidal fringe projection, this method only needs to project 4 sinusoidal fringe respectively and can realize the rapid measurement of complex objects. At the same time, the calculation of fringe intensity modulation and intensity contrast, compared with the calculation of phase, can reduce the time of data processing, further improve the measurement speed, in high-speed, real-time three-dimensional measurement has a wide range of applications. This method uses four sinusoidal fringes with a phase shift of $\pi/2$ to truncate the phase and obtains the order of the fringes to reduce the effect of surface reflectivity by intensity contrast.

2. General approach

The image intensity used in this paper is a standard sine distribution, and its intensity distribution function is:

$$I(x, y) = I'(x, y) + I'(x, y)\cos(\phi(x, y) + \delta)$$

(1)

Where $I'(x, y)$ is the average grayscale of the image. $I'(x, y)$ is gray-scale modulation of image, $\delta$ is image phase shift, $\phi(x, y)$ is relative displacement to be calculated, for $I'(x, y)$, $I'(x, y)$, $\phi(x, y)$ are three unknown quantities. In order to calculate $\phi(x, y)$, at least three images are required. In this paper, we use the standard four-step phase shift algorithm to calculate the phase principal value of the raster image, and the image displacement of the four standard raster images is respectively 0, $\pi/2$, $\pi$, $3\pi/2$. The expressions of the intensity of intensity are as follows:
\[ I_1(x, y) = I(x, y) + I'(x, y)\cos(\phi(x, y)) \]
\[ I_2(x, y) = I(x, y) + I'(x, y)\cos(\phi(x, y) + \pi/2) \]
\[ I_3(x, y) = I(x, y) + I'(x, y)\cos(\phi(x, y) + \pi) \]
\[ I_4(x, y) = I(x, y) + I'(x, y)\cos(\phi(x, y) + 3\pi/2) \]

The phase principal value of raster image can be calculated according to the formula (2 ~ 5):
\[ \phi(x, y) = \arctan\left(\frac{I_2 - I_4}{I_1 - I_3}\right) \]

Then the raster image is projected onto the target object, and the raster image modulated by the target object can be obtained.

![Figure 1. Structural light triangulation diagram.](image)

It is assumed that the four images of the standard map modulated by the target are as follows: \(I_{11}, I_{22}, I_{33}, I_{44}\). The phase values of modulated raster images can be calculated as follows:
\[ \Phi(x, y) = \arctan\left(\frac{I_{22} - I_{44}}{I_{11} - I_{33}}\right) \]

The phase difference between modulation and pre-modulation can then be calculated as follows:
\[ \Delta\Phi = \Phi - \phi \]

Then the height map of the target object is calculated according to the calibration results of the camera and the trigonometric relationship at the time of shooting:
\[ H = -\frac{L \times \Delta\Phi}{D \times 2\pi} \]

In Figure 1, where \( H \) is the height of the target object, \( L \) is the distance from the camera to the reference plane (calibration obtained, unit cm), \( D \) is the distance between the projector's light center and the camera's radio centric connection, the scene is taken as shown above. The image shooting system consists of three coordinate systems, It is the world coordinate system, camera coordinate system and image pixel coordinate system. The perspective projection relationship is:
\[
sp = Z_c \begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} a_x & 0 & u_0 \\ 0 & a_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R \\ T \\ 1 \end{bmatrix} \begin{bmatrix} X_w \\ Y_w \\ Z_w \end{bmatrix} = A[R \ T]P
\] (10)

Of which, \( s \) is Scale factor, \( p \) and \( P \) are homogeneous coordinates of image and space points. \([R \ t]\) is camera external parameter matrix. \( A \) is the camera internal parameter matrix. \( M = [R \ t] \) is a projection matrix.

3. Experimental results

The setup is composed of a Gray point 3.0 camera and DLP 4500 projector. The SL configuration is placed in front of a planar screen, with an arbitrary orientation with respect to the camera and projector.

Get the value of pixel points according to the coordinate position of each point in the output camera coordinate system and the color map, and then get the data sequence of camera coordinate system and the corresponding value of each pixel point involved in the calculation, where it can correspond to the output sequence one by one according to the serial number. After the triangulation operation, three-dimensional points in space can be calculated, and then each three-dimensional point in space can be colored with the color sequence of pixel points. The Figure 2 is the reconstruction result diagram.
use the [3, 5, 6, 8] and the grating projection algorithm to calculate the time of 3D reconstruction. It is obvious that the time used by grating projection algorithm is less than the traditional algorithm.

| No | Grating Projection algorithm | ZHOU Canlin[3] | Zeng Zhuohuan[5] | MIYA SAKA T[6] | FLOR ES J[8] | No | Grating Projection algorithm | ZHOU Canlin[3] | Zeng Zhuohuan[5] | MIYA SAKA T[6] | FLORES J[8] |
|----|-----------------------------|----------------|-----------------|----------------|-------------|----|-----------------------------|----------------|-----------------|----------------|-----------|
| 1  | 108                         | 151            | 197             | 302            | 259         | 16 | 117                         | 153            | 199             | 303            | 258       |
| 2  | 111                         | 149            | 198             | 303            | 257         | 17 | 104                         | 148            | 197             | 301            | 255       |
| 3  | 115                         | 146            | 199             | 300            | 260         | 18 | 109                         | 147            | 198             | 302            | 256       |
| 4  | 107                         | 153            | 200             | 290            | 258         | 19 | 111                         | 144            | 202             | 299            | 255       |
| 5  | 112                         | 155            | 207             | 309            | 261         | 20 | 114                         | 156            | 203             | 297            | 254       |
| 6  | 107                         | 149            | 208             | 310            | 263         | 21 | 103                         | 143            | 206             | 295            | 248       |
| 7  | 116                         | 150            | 192             | 297            | 258         | 22 | 105                         | 157            | 204             | 298            | 249       |
| 8  | 108                         | 147            | 191             | 291            | 256         | 23 | 104                         | 158            | 205             | 299            | 253       |
| 9  | 114                         | 151            | 195             | 293            | 253         | 24 | 109                         | 142            | 199             | 307            | 258       |
| 10 | 106                         | 153            | 196             | 295            | 257         | 25 | 109                         | 139            | 196             | 305            | 257       |
| 11 | 105                         | 156            | 199             | 297            | 248         | 26 | 104                         | 160            | 200             | 304            | 247       |
| 12 | 103                         | 140            | 205             | 289            | 257         | 27 | 111                         | 145            | 198             | 301            | 250       |
| 13 | 108                         | 146            | 210             | 310            | 260         | 28 | 116                         | 150            | 201             | 299            | 266       |
| 14 | 116                         | 148            | 198             | 312            | 258         | 29 | 118                         | 145            | 203             | 298            | 245       |
| 15 | 112                         | 159            | 197             | 311            | 251         | 30 | 104                         | 162            | 205             | 296            | 250       |

Figure 3. Line chart of time according to Table1.

From the above Table 1 and Figure 3, we can clearly get that the Grating Projection algorithm uses the least time in 30 times experiments, which make it clear that it has better speed when compared with[3][5][6] and [8].

From the below Table 2, we can know that the Grating Projection algorithm has the best accuracy in 3D facial reconstruction. The absolute error and RMS error of the grating projection algorithm are 0.033mm and 0.029mm, which has the best measurement result when compared with [3][5][6][8].
Table 2. Method for 3D Facial Reconstruction (mm).

| Reference           | Ground truth height | Measurement height | Absolute error | Root-mean-square error |
|---------------------|---------------------|--------------------|----------------|------------------------|
| ZHOU Canlin[3]      | 45                  | 45.102             | 0.102          | 0.099                  |
| Zeng Zhuohuan[5]    | 45                  | 45.084             | 0.916          | 0.884                  |
| MIYASAKA T[6]       | 45                  | 45.063             | 0.063          | 0.057                  |
| FLORES J L[8]       | 45                  | 45.131             | 0.131          | 0.101                  |
| Grating Projection algorithm | 45                  | 45.033             | 0.033          | 0.029                  |

4. Conclusions
In this paper, a 3D measuring method based on sinusoidal fringe projection is presented. The truncated phase and fringe order of four sinusoidal fringe are obtained, and the accurate phase unwrapping is realized. Compared with the traditional 3D measuring method of sinusoidal fringe projection, this method only needs to project 4 sinusoidal fringe to improve the 3D measuring speed and can measure the 3D shape of complex objects. A new measuring principle and a corresponding system calibration method are established according to the strict constraint conditions in the classical model. Experimental results show that the new model and calibration method simplify the system construction and calibration process, and improve the measurement accuracy of the system. This method has the following characteristics. The rotation matrix and the translation matrix are introduced to describe the position relationship between the camera and the projection device. Due to the introduction of rotation and translation matrix, the spatial structure of the system is described more comprehensively and accurately. In the model, the camera and the projection device can take relative position, which removes the over-strong constraint on the position relationship between the camera and the projection device in the traditional system structure. The phase noise is reduced to a certain extent and the measurement accuracy is improved. This method reduces the number of projected fringes and improves the measurement speed, and has a wide application prospect in the high-speed real-time 3D measurement of complex objects. In the following research work, the gamma effect of the projector and the system non-linearity on the system will be solved.

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References
[1] Zhang yujia and Yilmaz A 2016 Structured Light Based 3D Scanning for Specular Surface by the Combination of Gray Code and Phase Shifting International archives of the photogrammetry XL1-B3 137-142
[2] Huang P and Zhang S 2006 Fast Three-Step Phase-Shifting Algorithm Appl.Opt 45 21 5086-5091
[3] Zhou Canlin Liu Tongchuan and Si Shuchun 2013 An Improved Unwrapping Method Based On Stair Phase Encoding Journal of Optoelectronics.Laser 24 12 2377-2382
[4] Zhang S and Yau S 2007 High Speed Three-Dimensional Shape Measurement System Using a Modified Two-Plus-One Phase-Shifting Algorithm Opt.Eng 46 11 113603-113603-6
[5] Zeng Zhuohuan Li Biao and Fu Yanjun 2016 Stair Phase-Coding Fringe Plus Phase-Shifting Used In 3D Measuring Profilometry Journal of the European Optical Society-Rapid Publications 12 19

[6] Miyasaka T and Araki K 2002 Development of Real-Time 3D Measurement System Using Intensity Ratio Method ISPRS Commission photogrammetric Computer Vision 34 3 181-185

[7] Fang Qiang and Zheng Sunde 1997 Linearly coded profilometry Appl. Opt 36 11 2401-2407

[8] Flores J L, Toreales G and Ferrarari J A 2013 Binary Coded Triangular Fringes For 3-d Surface-Shape Measurement APPL. Opt 52 15 3576 3582

[9] Shan Lina, Yu Xiaoyang and Fu Xiao 2009 3D Measurement Technology Based On Gray Coding Light By Combining Gray Code With Trpezoidal Phase Shift chinese Journal of science instrument 30 6 24-28

[10] Jia Peirong, Kofman J and English C E 2007 Two-Step Triangular-Pattern Phase-Shifting Method For Three-Dimensional Object-Shape Measurement Opt.Eng 46 8 083201-083201-9

[11] Zuo Chao, Chen Qian Gu and Gu Guohua 2012 High-Speed Profilometry For Multiple Objects With Complex Shapes Opt. Express 20 17 19493-19510

[12] Hyun J S and Zhang S 2017 Superfast 3D Absolute Shape Measurement Using Five Binary Patterns Opt.Lasers Eng 90 217-224