A correction method of color projection fringes in 3D contour measurement*

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In the three-dimensional (3D) contour measurement, the phase shift profilometry (PSP) method is the most widely used one. However, the measurement speed of PSP is very low because of the multiple projections. In order to improve the measurement speed, color grating stripes are used for measurement in this paper. During the measurement, only one color sinusoidal fringe is projected on the measured object. Therefore, the measurement speed is greatly improved. Since there is coupling or interference phenomenon between the adjacent color grating stripes, a color correction method is used to improve the measurement results. A method for correcting nonlinear error of measurement system is proposed in this paper, and the sinusoidal property of acquired image after correction is better than that before correction. Experimental results show that with these correction methods, the measurement errors can be reduced. Therefore, it can support a good foundation for the high-precision 3D reconstruction.

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The measurement method of structured light projection is widely used in three-dimensional (3D) contour measurement[1-3]. The non-contact 3D measurement is widely used in product testing and quality control, virtual reality, heritage preservation, anthropometry and medical engineering. The phase measuring profilometry has high accuracy due to the multiple projections and phase-shift technology, but its measurement speed is low[4]. In order to enhance the speed of 3D contour measurement, the recent studies have focused on the measurement using color images. Compared with the gray phase shift method, the color phase shift method greatly improves the speed of measurement. Da[5] proposed a fringe projection profilometry method based on complementary color-encoded fringe patterns. Han[6] proposed a color structured light technology for 3D shape measurement based on gray code method. Chen[7] proposed a color-coding and phase-shift method for absolute phase measurement. With these methods, the speed of 3D measurement is improved. However, in the actual 3D contour measurement, the adjacent grating strips present coupling or interference phenomenon[8]. It will lead to that the average intensity values of the brightness of the three channels are inconsistent, and the phase can not be accurately extracted. Based on our works[9-11], color grating stripes are used for 3D contour measurement in this paper. The proposed method only needs to project one piece of color sinusoidal fringe in measurement process. For the coupling or interference phenomenon, a color correction is used in this paper to improve the measurement results. In addition, a method is used to correct the nonlinear error. The experimental results show that the proposed method can make the acquired image have a good sinusoidal distribution.

In order to solve 3D coordinate information of the measured object, during the phase-shift grating projection and acquisition, the measured object can not move, and the information of the background light and the surrounding environment should be in an unaltered state. The measurement method used in this paper only needs to project fixed optical information to the object. It projects sine or cosine waveform of three-step phase shift to

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red, green and blue channels, which are three channels of the projection optical system, and the types of waveforms projected to three channels must be the same. Compared with encoding multiple pictures, making the encoded information contained in one picture is more complex. In order to ensure the correctness of phase extraction, the picture should contain much encoding information. In this paper, three channels are used to enrich the encoded information. The red, green and blue channels are projected by red, green and blue phase-shifted sinusoidal fringes. The ideal intensity distributions of three channels are shown in Fig.1. The gratings of red, green and blue channels and the color grating are shown in Fig.2.

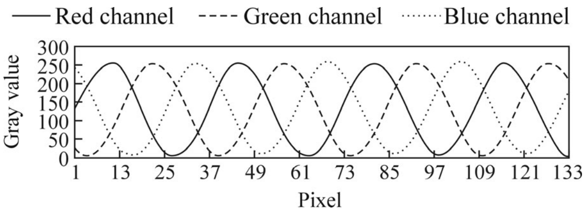
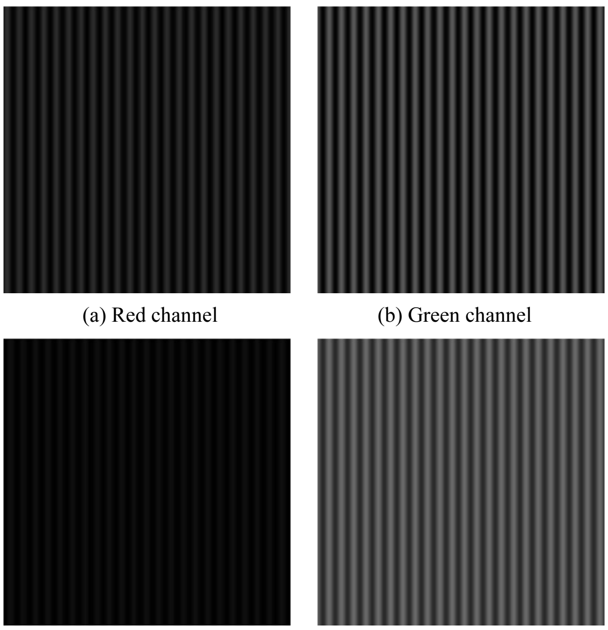


Fig.1 The ideal intensity distributions of red, green and blue channels



(a) Red channel (b) Green channel

(c) Blue channel (d) Color grating

Fig.2 Optical signal waveforms of red, green and blue channels and the color grating

In the actual 3D contour measurement, there is coupling or interference phenomenon between the adjacent grating strips. It will lead to that the color of the acquired images changes compared with that of stripes designed to project. For this phenomenon, a color correction method based on Caspi color response model[12] is used. The relationship between pixel values of the projector and the pixel values collected by the charge coupled device (CCD) is shown as

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a_{RR} & a_{RG} & a_{GG} \\ a_{GB} & a_{GG} & a_{GB} \\ a_{BR} & a_{BG} & a_{BB} \end{bmatrix} \begin{bmatrix} k_R & 0 & 0 \\ 0 & k_G & 0 \\ 0 & 0 & k_B \end{bmatrix} \boldsymbol{P} \left\{ \begin{bmatrix} r \\ g \\ b \end{bmatrix} \right\} + \begin{bmatrix} R_0 \\ G_0 \\ B_0 \end{bmatrix}, \tag{1}$$

which can be expressed as

$$\boldsymbol{M} = \boldsymbol{AKP}(\boldsymbol{I}) + \boldsymbol{M}_0 , \tag{2}$$

where $\boldsymbol{M}$ is the pixel matrix collected by CCD, $\boldsymbol{A}$ is coupling matrix of three channels between projector and color CCD, $\boldsymbol{K}$ is the reflection matrix, $\boldsymbol{P}$ is the correspondence relationship between the setting pixel values of projector and the actual light intensity projected to red, green and blue channels, $\boldsymbol{I}$ is the set pixel matrix of corresponding points on the projector, and $\boldsymbol{M}_0$ is the background pixel matrix influenced by ambient light.

Since $\boldsymbol{A}$ has nothing to do with the positions of the pixels, it can only be measured once in advance, and then the result can be used to correct all the pixels. Because the intensities of ambient light and projected light have a large difference under the condition of indoor illumination, we can ignore the effect of $\boldsymbol{M}_0$. In order to obtain $\boldsymbol{A}$ quickly, we project red, green and blue sinusoidal stripes onto a whiteboard. Since the reflectivity of the whiteboard is 1 approximately, we can get

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a_{RR} & a_{RG} & a_{GG} \\ a_{GB} & a_{GG} & a_{GB} \\ a_{BR} & a_{BG} & a_{BB} \end{bmatrix} \begin{bmatrix} r \\ g \\ b \end{bmatrix} . \tag{3}$$

The values $[r\ g\ b]^T$ of three pieces of sinusoidal stripes for red, green and blue channels are $[0\ 0\ 1]^T$, $[0\ 1\ 0]^T$ and $[1\ 0\ 0]^T$, respectively. After the measured values of $[R\ G\ B]^T$ are determined by the average value, we can calculate the coupling matrix of red, green and blue channels as

$$\boldsymbol{A} = \begin{bmatrix} a_{RR} & a_{RG} & a_{GG} \\ a_{GB} & a_{GG} & a_{GB} \\ a_{BR} & a_{BG} & a_{BB} \end{bmatrix} = \begin{bmatrix} 1.065 & 0.035 & 0.034 \\ 0.035 & 1.135 & -0.164 \\ -0.345 & -0.351 & 1.749 \end{bmatrix} . \tag{4}$$

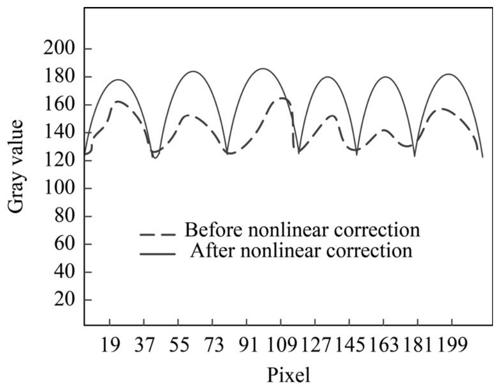
Its inverse matrix $\boldsymbol{A}^{-1}$ is

$$\boldsymbol{A}^{-1} = \begin{bmatrix} 0.933\,2 & -0.035\,4 & -0.021\,5 \\ -0.002\,2 & 0.907\,5 & 0.085\,1 \\ 0.183\,6 & 0.175\,1 & 0.584\,6 \end{bmatrix} . \tag{5}$$

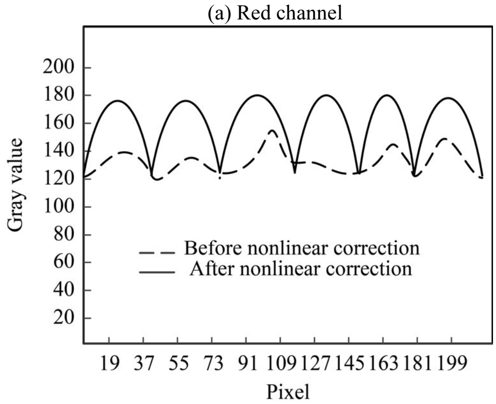
In order to eliminate the effect of the coupling of three channels on color images, we can make each pixel collected from color image to multiply $\boldsymbol{A}^{-1}$ for compensation correction, which can be expressed as

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = \boldsymbol{A}^{-1} \begin{bmatrix} R \\ G \\ B \end{bmatrix} . \tag{6}$$

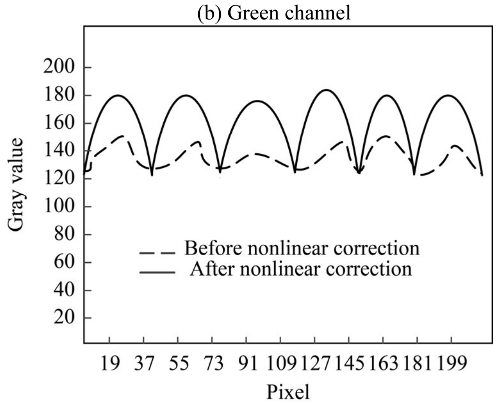
Due to the nonlinear properties of CCD and projector, the measurement system will make the sinusoidal signal become the one without sinusoidal distribution. Therefore, a nonlinear correction method is needed for the signal. We project the signals of red, green and blue channels to the whiteboard, respectively, and acquire an image. Then the quadratic curve fitting between input gray values of signals of red, green and blue channels and output gray values of the acquired image is done. According to the response curve and the obtained intensity, we can get the intensity which will be projected. Then the sinusoidal signal of the acquired image is better after the nonlinear correction. The sinusoidal signals of red, green and blue channels before and after nonlinear correction are shown in Fig.3.



(a) Red channel



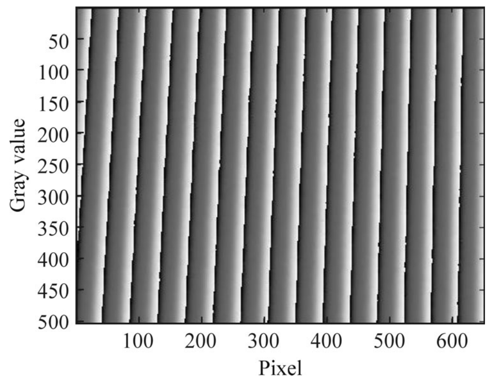
(b) Green channel



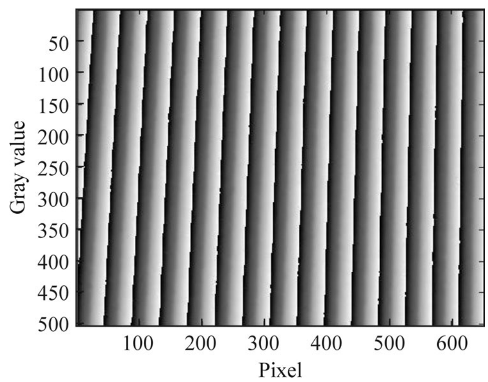
(c) Blue channel

Fig.3 Sinusoidal signals of red, green and blue channels before and after nonlinear correction

To verify the effectiveness of the correction method in this paper, we measure a box and compare the extracted phases before and after correction as shown in Fig.4. Then the extracted phase is unwrapped and the obtained 3D unwrapped phase is shown in Fig.5. We can see the unwrapped phase before correction has significant serrated errors. However, the unwrapped phase after correction is not accompanied by this problem. In the two cases, take a line of unwrapped phase to analyze the error. The comparison between the unwrapped phase before correction and the ideal unwrapped phase is shown in Fig.6. The comparison between the unwrapped phase after correction and the ideal unwrapped phase is shown in Fig.7. The final error comparison is shown in Fig.8.

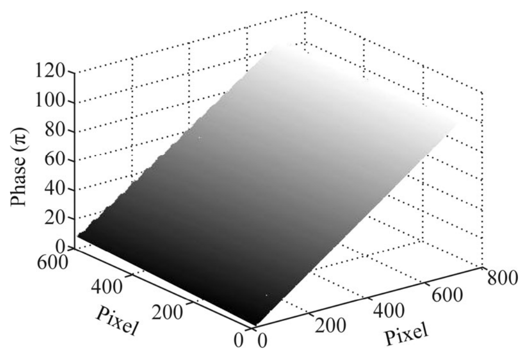


(a) Before correction

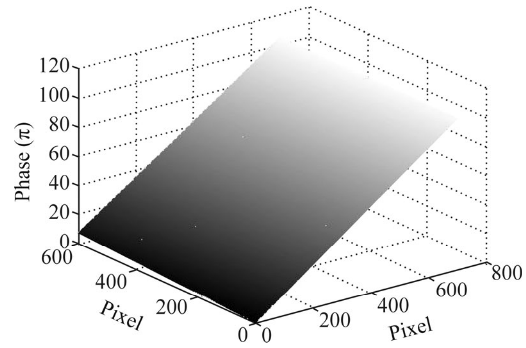


(b) After correction

Fig.4 The extracted phases before and after correction



(a) Before correction



(b) After correction

Fig.5 The 3D unwrapped phases before and after correction

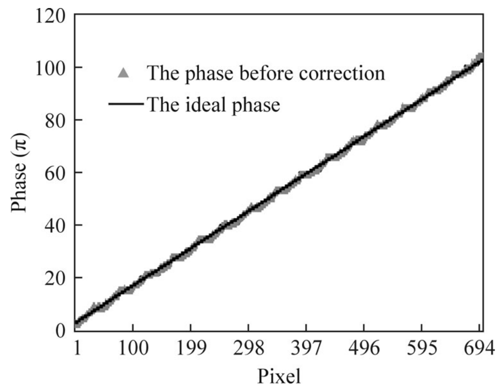


Fig.6 Comparison between the unwrapped phase before correction and the ideal unwrapped phase

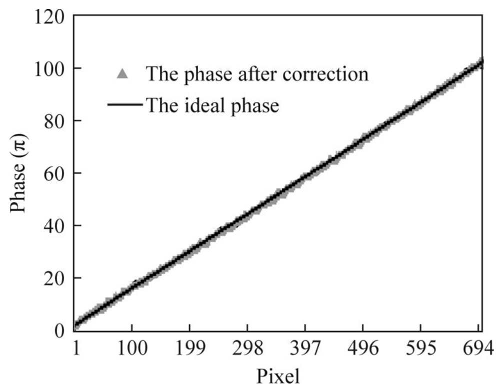


Fig.7 Comparison between the unwrapped phase after correction and the ideal unwrapped phase

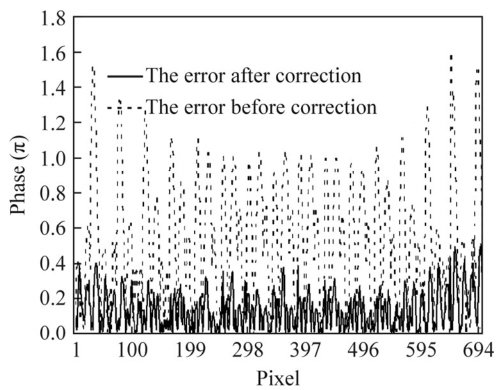


Fig.8 The final error comparison

From above analyses, we can see that the correction method can well reduce the measurement errors and pave the way for high-precision 3D reconstruction.

For low speed of phase shift profilometry measurement, color grating stripes are used to measure objects. With the method, only one piece of color sinusoidal fringe is projected, which greatly enhances the measurement speed. A method for correcting nonlinear error of measurement system is proposed. The experimental results show that the nonlinear correction method can make the sinusoidal properties of the acquired images better. Since in the actual 3D measurement, there is coupling or interference phenomenon between the adjacent grating strips, a method of color correction is used in this paper. With these methods, the measurement errors are reduced. Therefore, it can greatly reduce the errors of 3D reconstruction and improve the precision of 3D reconstruction.

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