Estimating the quality of stripe in structured light 3D measurement*

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Affected by noise, light blocking, color and shape of object, the quality of captured stripes in structured light three dimensional (3D) measurement system is degenerated. As the quality of captured stripes is one of the key factors for measurement accuracy, some large error data is introduced into the measurement results which can only be recognized artificially with prior knowledge of the object to be measured. In this paper, a method is proposed to estimate the quality of stripe image. In the method, two parameters, skewness coefficient of stripe gray distribution and the noise level, are used to estimate the quality of stripe. The simulation results show that the bigger the skewness coefficient is, the bigger the error of stripe locating results is. Meanwhile, the smaller the noise level is, the smaller the error of stripe locating results is. The method has been used to estimate the experimental image, and the same conclusion can be obtained. The method can be used for recognizing large error data automatically by the two parameters.

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Structured light is one of the important three dimensional (3D) measurement methods, which has been widely used[1]. Compared with traditional contact measurement methods, structured light scatteroscopy (SLS) is more efficiency and non-destructive. At present, two typical types of SLS are calculating 3D information by phase and stripe center, respectively. The latter one is less sensitive to noise. There are three common kinds of stripes which are the Gaussian distribution, sinusoidal distribution and rectangular distribution[2]. Since the centers of the former two types are more obvious and have high anti-noise performance, they are widely used in SLS. However, noise and reflection characteristics of object result in the degeneration of the gray level distribution. Furthermore, the degeneration introduces error data into measurement results which decrease measurement accuracy[3].

Some researchers have studied how to enhance the accuracy by improving stripe center locating method or image quality. CARSTEN[4] proposed a method for extracting the center and width of stripe structured light. The profile of the strip line was analyzed using the explicit model of the asymmetric strip line. According to that, an image processing method was put forward for locating stripe center, which not only simplified the calculation of structured light stripe extraction significantly, but also improved the accuracy[5]. DING et al[3] applied Radon transform and gray scale transform enhancement to eliminate noise from the image. Aiming at the error of structured light center extraction, ZHANG et al[6] proposed an adaptive width quadratic weighted centroid method for strip center extraction. It improved the accuracy of center point extraction.

The above methods improve the accuracy of stripe center location. However, for some kinds of degenerated stripes as shown in Fig.1, the accuracy of center locating results is still very low. In addition, image Gaussian noise can also degenerate the accuracy of stripe center. The accuracy of 3D coordinates calculated by the center locations is also low. These 3D points decrease the measurement accuracy of SLS. Some obvious abnormal points can only be removed artificially with prior knowledge of the measured object. Furthermore, there are some low accuracy results not obvious enough and cannot be recognized from 3D coordinates, which also affects measurement seriously.

Since the quality of stripe image determines the accuracy of center locating results, a method is proposed to estimate the quality of stripe image by two parameters, which are the skewness coefficient of stripe and the noise level. In addition, the relationship between the parameters and the accuracy of stripe center locating results is also studied. The simulation results show that the parameters can be used to estimate the accuracy of center locating results.

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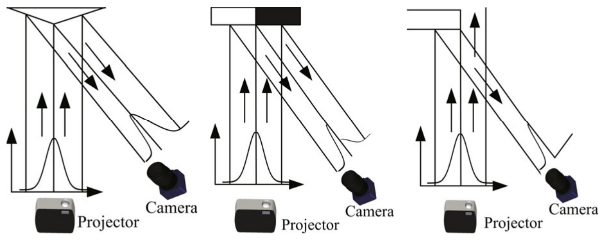
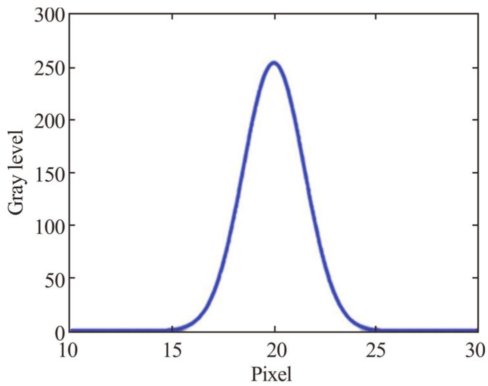


(a) (b) (c)

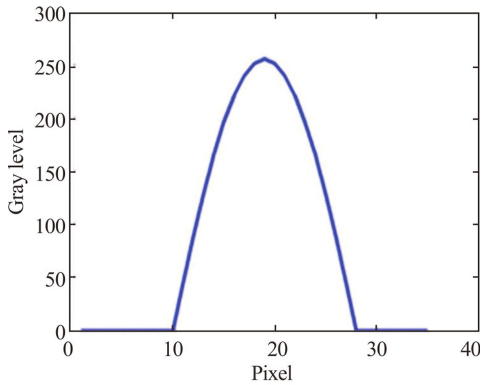
Fig.1 Deformation of stripe gray distribution: (a) Abrupt change of curvature; (b) Abrupt change of reflectivity; (c) Edge of object

Since all methods locate stripe center according to the gray level distribution of stripes[7], the distribution is one of the key factors of the accuracy in structured light measurement[8]. As shown in Fig.2, three typical types of stripe gray distributions are symmetrical[9].

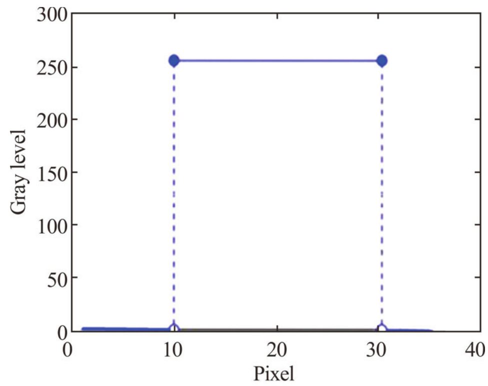
For ideal conditions, the gray distribution of captured stripes remains symmetrical[10]. There are some factors that degenerate the distribution into asymmetric, such as the background light and the reflection or shape of the measured object surface[11]. Typical stripe center locating methods assume that the gray distribution of stripe is symmetrical. Therefore, the asymmetrical distribution of stripes can cause the reduction of measurement accuracy. In addition, if the intensity of captured stripe is low and the noise level is high, the distribution of stripe will also be degenerated. Furthermore, the accuracy of center locating results will be decreased.



(a)



(b)



(c)

Fig.2 Typical gray distributions of stripe: (a) Gaussian gray distribution; (b) Sinusoidal gray distribution; (c) Rectangle gray distribution

However, the error data cannot be recognized objectively without prior knowledge of the target object. Therefore, we propose a method to estimate the quality of stripe image in this paper.

Aiming at asymmetrical distribution and noise degeneration, two parameters are used, which are the stripe skewness coefficient and the noise evaluation coefficient.

Most of stripe extraction methods are based on the gray distribution of stripes. The skewness coefficient will affect the accuracy of stripe extraction. It is proposed according to statistical method in Ref.[9], which establishes the relationship between camera capturing angles and the stripe center locating error. A captured sinusoidal stripe image is processed by the gray gravity method. The center positioning error is defined as the absolute value of the difference between the maximum gray value of the image and the column coordinates. The stripe center positioning error D can be expressed by

$$D=\left|Y_i-Y\right|, \tag{1}$$

where Y represents the column coordinate of the maximum gray value of the captured image, and Y_i is the column coordinate of the maximum gray value. D indicates a monotonic increasing function of the degree of asymmetry of gray distribution. D will be zero in case of symmetrical distribution.

The gray distribution of stripes is symmetrical without interference[12,13]. Due to the effect of occlusion, the features of the object or the angle between object and camera, the gray distribution of the stripe is asymmetric. Therefore, the positioning accuracy of the stripe center is reduced[14]. At present, the effective assessment method is rarely applied into the degeneration of the gray distribution. A statistical method is proposed in this paper to analyze the asymmetry of gray distribution for stripe. In this condition, a weighted method is introduced to calculate gray-scale distribution, which is defined as the skewness coefficient α. α is defined by the third-order central moment. The third-order central moment is divided by the standard deviation to the third power to evaluate the asymmetry degree of stripe gray distribution.

The skewness coefficient is obtained by changing the shooting angle of the camera.

Since the projection image is a sinusoidal stripes image, the captured image is a sinusoidal stripes image as well. Capturing sinusoidal stripes horizontally, the gray distribution is generated. m_3 is the third-order center distance for the gray distribution of stripes in the cross section, which is calculated by

$$m_3 = \frac{1}{N}\sum (X_i - \overline{X})^3, \tag{2}$$

where $\overline{X}$ represents the average gray value of the stripe gray distribution of a single sinusoidal stripe image in the cross section, and X_i refers to the gray value of each pixel in the stripe gray distribution. N denotes the number of pixels in the gray distribution of the stripes. The skewness coefficient based on the third-order central moment is calculated by

$$\alpha = \frac{m_3}{\delta^3}, \tag{3}$$

where δ indicates the square root of the variance of the gray level distribution of the stripe. The increase of skewness coefficient represents the increase of stripe distribution error. α is zero if the stripe shows symmetrical gray distribution.

Typical image evaluation methods are used to evaluate the image by comparing the un-processed image with the after-processed image. The random noise affects stripe images quality. Therefore, the standard of image quality evaluation must include the evaluation of noise level. Based on the characteristics of human visual system (HVS), LI et al[15] replaced the whole image with local variance in blocks. By calculating the difference between the image blocks before and after the low-pass filter, the objective quality evaluation parameters of the original overall image were obtained. This paper adopts the method proposed by LI et al[15].

The image is divided into $m\times n$ block areas recorded as I_b (b=1, 2, ... B), where B is the number of block areas in the image. The variance of each area is recorded as $\sigma(i, j)$. The sum of variances of all areas is calculated using

$$\sigma(b) = \sum\sum_{(i,j)} \sigma(i, j). \tag{4}$$

Threshold T is set as

$$T = \lambda \times \sigma(b)_{\max}, \tag{5}$$

where λ is the sensitive coefficient of HVS, $\lambda\in(0, 1)$, and $\sigma(b)_{\max}$ represents the maximum value of $\sigma(b)$. Let $f_k=\{f_k \mid \sigma(b)>T, k<B\}$, where f_k is the selected block, and k is the number of the selected areas. The number of selected areas is proportional to the size of sensitivity coefficient according to HVS. Then, the selected block area is blurred again. With an image block area f_k exemplified, the process is detailed as follows.

Area f_k is put into filter vertically and horizontally. Then b_v and b_h are obtained. As shown in Eq.(6) and Eq.(7), $\boldsymbol{h}_v$ and $\boldsymbol{h}_h$ are the vertical and horizontal models of the filter, and the expressions are as follows

$$\boldsymbol{h}_v = \frac{1}{9}\times[111111111], \tag{6}$$

$$\boldsymbol{h}_h = (\boldsymbol{h}_v)^T = \boldsymbol{h}_v'. \tag{7}$$

Df_V, Df_H, Db_V and Db_H are the absolute errors in the vertical and horizontal directions, respectively. The differences before and after the block filtering are V_V and V_H, which are calculated as follows

$$V_V = \max(0, Df_V(i, j) - Db_V(i, j)), \tag{8}$$

$$V_H = \max(0, Df_H(i, j) - Db_H(i, j)). \tag{9}$$

Df_V, Df_H, Db_V and Db_H of the area are added to get the regional differences of the whole area, which are sf_V, sf_H, sV_V and sV_H.

The results are normalized as

$$bf_V = \frac{sf_V - sV_V}{sf_V}, \tag{10}$$

$$bf_H = \frac{sf_H - sV_H}{sf_H}. \tag{11}$$

Finally, every block is processed, and the average values of bf_V and bf_H are taken as $\overline{bf_V}$ and $\overline{bf_H}$, respectively. H is treated as the evaluation coefficient

$$H = \max(\overline{bf_V}, \overline{bf_H}), \tag{12}$$

where $H\in[0, 1]$.

In order to obtain the relationship between the accuracy of stripe center locating results and the two parameters, simulations have been carried out on a computer, where Matlab 2009a and 3ds max 2019 are used.

Firstly, the asymmetrical distribution is simulated as follows.

Step 1. As shown in Fig.3, the simulation model was set up in 3ds max, which consists of a target light source (set as a projector), a target camera and a flat board. The optical axes of projector and camera intersect with each other at point Q, which is on the surface of the flat board. A stripe image shown in Fig.4, which contains only a stripe in the center, is generated as the image to be projected.

Step 2. Adjust the shot angle by changing the position of camera. While adjusting, the axis of camera should pass through point Q. As a result, the stripe images with different skewness coefficients can be captured by camera. The skewness coefficient can be obtained according to Eq.(3).

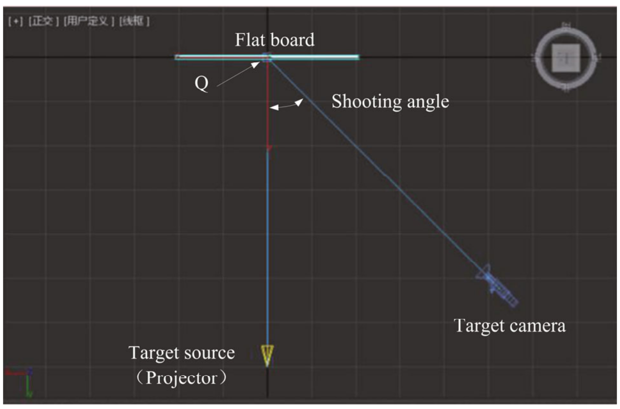


Fig.3 Simulation model in 3ds max

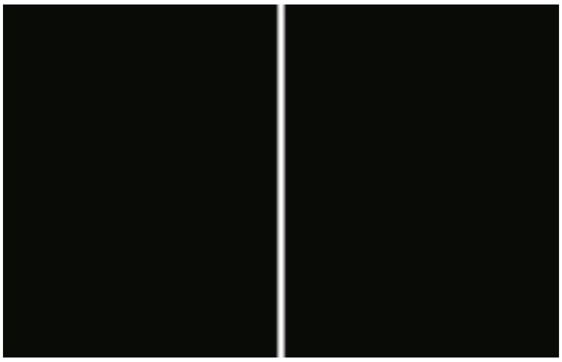


Fig.4 Generated stripe image

Step 3. The centers of captured stripes can be calculated by the center locating method.

Step 4. Since the stripe is in the center of generated image and the two optical axes intersect with each other in point Q, the real center of captured image also lays on the center of captured image.

Step 5. The error of stripe center caused by asymmetrical distribution can be defined as

$$Error = |c' - c|, \tag{13}$$

where c' is the calculated position of stripe center, c is the real position of stripe center.

According to Step 1 to Step 5, 11 groups of data were got by adjusting the position of camera in the simulation model. The relationship is shown in Fig.5, from which we can see that the center locating error increases with the increase of α.

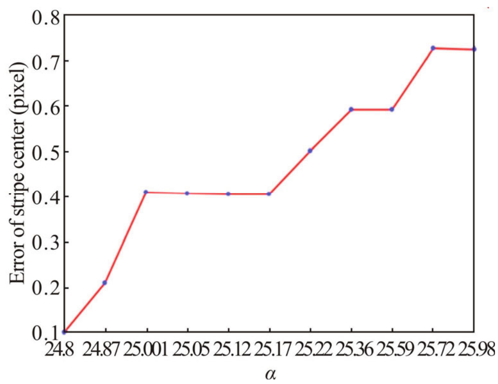


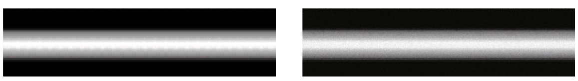
Fig.5 Relationship between stripe center positioning error and *α*

Secondly, the noise estimation is simulated as follows.

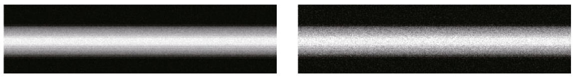
Step 1. A stripe image shown in Fig.6(a), which contains only a stripe in the center, is generated.

Step 2. Adding Gaussian noise with difference variance into Fig.6(a), new images are obtained as Fig.6(b)—(d).

Step 3. Centers of stripes are located by the centroid method, and the error is calculated using Eq.(13).



(a) (b)



(c) (d)

Fig.6 Simulated stripe images: (a) Without noise; (b)—(d) Results of adding noise into (a)

As shown in Tab.1, H increases with the increase of variance. Meanwhile, the center locating error also increases with the increase of variance.

Tab.1 Influence of Gaussian noise on image quality evaluation parameter and the error of center location for Fig.6

	(a)	(b)	(c)	(d)
Variance of noise	0	0.000 5	0.001	0.005
H	0.345 2	0.549 5	0.597 7	0.634 1
Error of stripe center (pixel)	0	0.06	0.09	0.19

Simulation results show that the two parameters can be used to estimate the quality of stripe image.

The experimental system is composed of a camera (Basler acA4600-7gc), a projector (Richon PJX2180), a calibration board and a set of translation stages.

The system was calibrated according to the method in Ref.[16]. As shown in Fig.7, a standard steel ball and a flat board were measured.

(a)

(b)

Fig.7 Objects to be measured: (a) Standard ball; (b) Flat board

The measurement results of ball are shown in Fig.8. Fig.8(a) is 3D point cloud of the ball, and the points with large error (more than 0.7 mm) are labeled in blue color. Fig.8(b) and (c) are the concentration areas of large error data. The intensity of Fig.8(b) is high, but the skewness coefficient of stripe is high because of specular reflection. In Fig.8(c), as the low intensity of stripe and the noise is large, H is high. α of Fig.8(c) is smaller than that of Fig.8(b), because although the intensity of Fig.8(c) is low, the symmetrical level is relatively high. Tab.2 gives H and α corresponding to Fig.8(b) and (c).

Fig.9(a) and (c) show the captured image and 3D points measurement results of flat board. The large error points are on the edge of the board, as the gray distributions of stripes on the edge are degenerated to asymmetric as Fig.9(c). The H and α of Fig.9(b) are 0.642 2 and 1.009 9, respectively.

The same conclusion as simulation results can be obtained. H and α can be used to evaluate the measurement results by estimating the quality of stripe image efficiently.

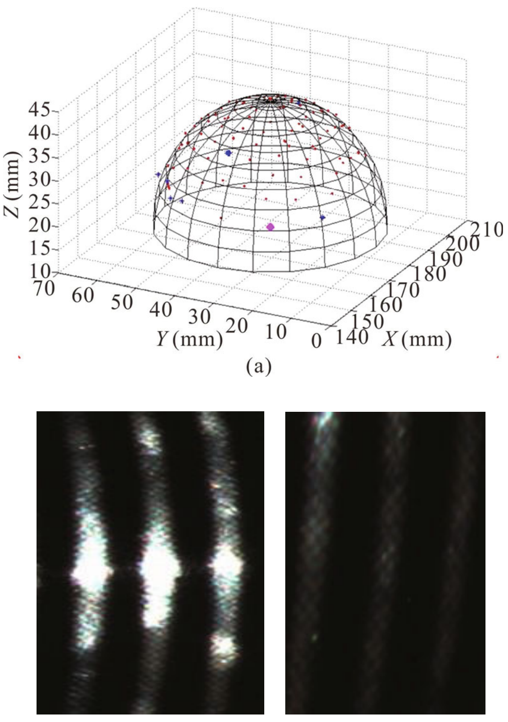


Fig.8 Measurement results of ball: (a) 3D point cloud; (b)—(c) Areas of captured image corresponding to large error points

Tab.2 Evaluation system corresponding to different degradation degrees of stripes

	Image in Fig.8(b)	Image in Fig.8(c)
H	0.447 1	0.614 8
α	1.132 0	0.978 6

In order to estimate measurement results objectively without prior knowledge of the object to be measured, this paper proposed a method to evaluate the stripe image. In the method, two parameters which are skewness coefficient and image noise level are used. According to the calculated results of two parameters, the reliability of 3D measurement results can be estimated. Simulation and experimental results verified the effectiveness and accuracy of the method. The method can be used to recognize large error data without any prior knowledge.

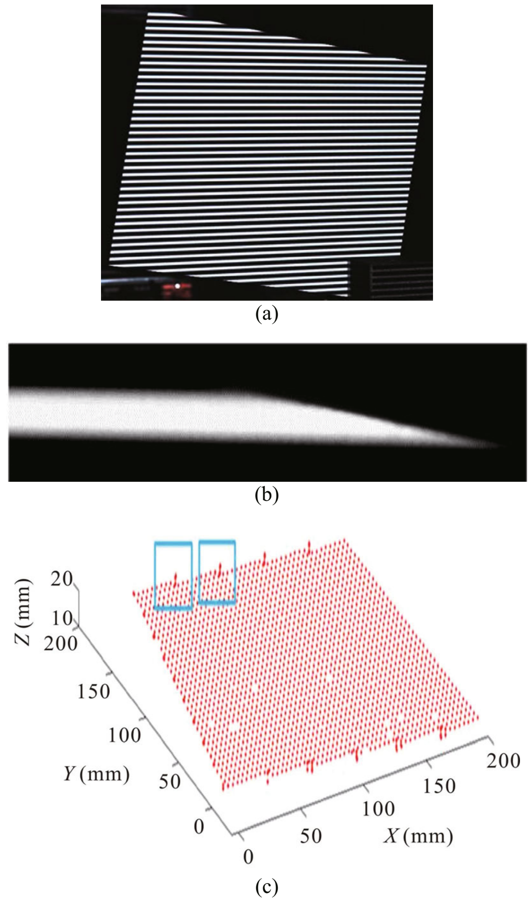


Fig.9 Measurement results of flat board: (a) Cardboard with stripe; (b) Points cloud; (c) Stripe on the edge of the object

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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