Essential parameter calibration for the 3D scanner with only single camera and projector*

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A calibration method for the five essential parameters is proposed. Using the calibration results, the three dimensional (3D) reconstruction can be performed directly. The five essential parameters include the distance between the camera and the projector, the distance between the reference plane and the camera, the fundamental frequency of the fringe pattern, the scale factor from the image coordinates to the world coordinate system in X axis direction and that in Y axis direction. The proposed calibration method is implemented and tested in our 3D reconstruction system. The mean calibration error is found to be 0.0215 mm over a volume of 400 mm (H)×300 mm (V)×500 mm (D). The proposed calibration method is accurate and useful for the 3D reconstruction system.

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The accuracy of the single camera three-dimensional (3D) scan system depends on the calibration precisions of the camera and the projector. There are two typical geometric calibration models proposed by Mao[1] and Takeda[2]. The calibration methods based on geometric model of Takeda include neural networks based method[3], bundle adjustment based method[4], absolute phase based method[5], etc. The above three calibration methods need complicated procedures, and the calibration procedures vary with the available system parameters. Besides, Zappa[6] proposed a calibration method based on the geometric model proposed by Mao[1]. Soon afterwards, they provided an innovative calibration technique[7] which removes the hardware for the accurate positioning of the calibration planes. The shortcomings of Zappa's method are that the camera must be previously calibrated.

In this paper, the calibration method for the five essential parameters for 3D reconstruction is proposed, which are as follows: the distance between the camera and the projector, the distance between the reference plane and the camera, the fundamental frequency of the fringe pattern, the scale factor from the image coordinates to the world coordinate system in X axis direction and that in Y axis direction. Using the five parameters, the 3D coordinate can be calculated directly.

Camera calibration has been widely used in 3D reconstruction. A camera is often described by a pinhole model with intrinsic parameters including focal length, principle point, pixel skew factor and pixel size, and extrinsic parameters including rotation and translation from a world coordinate system to a camera coordinate system. Among the existing camera calibration methods, Zhang's[8] calibration method with a patterned planar target is well known in the community of computer vision, and its validity and accuracy have been widely discussed and demonstrated[9-11]. Although our previous calibration research[12] has high precision, the target is expensive and difficult to be produced. In this research, we choose the calibration method proposed by Zhang[8]. The schematic diagram of the 3D calibration system is shown in Fig.1. A planar target with pattern of 99 circles is selected as the calibration target. The circles on the calibration target are coded in sequence from 0 to 98. The five big circles in the center are used to confirm the direction.

The projector in the 3D system can be regarded as the inverse of a camera, because it projects images instead of capturing them. The calibration of the projector is the same as the calibration of the camera.

Different from the calibration method proposed by Zhang in Ref.[13], the calibrations of the camera and the projector are performed simultaneously.

In order to establish the correspondence between the

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projector pixels and the calibration target, the phase shifting method is used. Six sinusoidal phase-shifted fringe patterns are generated in a computer, and projected to the calibration target sequentially by a projector. Suppose $I^{'}(x,y)$ is the average intensity, $I^{''}(x,y)$ is the intensity modulation, f_0 is the fundamental frequency of the fringe pattern, and the intensities of the six sinusoidal fringe patterns can be got from Ref.[8].

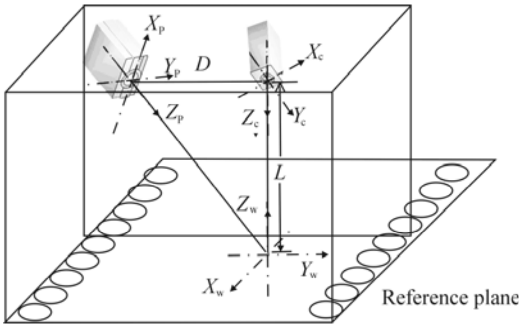

Fig.1 Schematic diagram of 3D calibration system

The phase at each pixel $\phi(x,y)$, which is between 0 and 2π, can be calculated based on the phase-shifting algorithm as follows,

$$\phi(x,y)=\tan^{-1}\left[\frac{\sum_{i=1}^{6}I_i(x,y)\times\cos(\frac{2\pi\times5}{6})}{\sum_{i=1}^{6}I_i(x,y)\times\sin(\frac{2\pi\times5}{6})}\right]. \quad (1)$$

If horizontal fringe patterns are used, points with the same phase are in a horizontal line. If vertical fringe patterns are used, points with the same phase are in a vertical line. If both horizontal and vertical fringe patterns are used, the pixel at the intersection of these two lines is the corresponding pixel on the projector chip. In order to get the global absolute phase of each point, the Gray code phase shift profilometry (GCPSP) is used.

GCPSP method combining the Gray code method with the phase shift profilometry method is based on the projection of n black and white fringe patterns at subsequent instants of n=10. The first 7 patterns of the sequence, denoted by GC_0, GC_1,⋯, GC_6, are formed in such a way that their projection corresponds to the formation of a Gray code of 7 bits. Rows R_0, R_1, R_2 and R_3 of the table can be interpreted as the binary representation of patterns GC_0, GC_1, GC_2 and GC_3 along the X direction, provided that black fringes are assigned to the logic value 0, and white fringes are assigned to the logic value 1. Columns C_0, C_1, ⋯ , C_{15} are the code words.

The actual phase is calculated by

$$\varPhi(x,y)=\phi(x,y)=2\pi m(x,y), \quad (2)$$

where $\varPhi(x,y)$ is the global absolute phase, $\phi(x,y)$ is the wrapped local phase, and $m(x,y)$ is integer calculated from the Gray code.

The calibration target without fringe patterns is first captured by the camera, and the center of the circles in the image is (x_{ci},y_{ci}), $(i=0,\cdots,98)$. Each absolute phase of the center point should be calculated using phase unwrapping method. The phases of center point (x_{ci},y_{ci}) in horizontal and vertical directions are $\varPhi_{\mathrm{H}}(x_{ci},y_{ci})$ and $\varPhi_{\mathrm{V}}(x_{ci},y_{ci})$. Suppose the resolution of the projector is $L_{\mathrm{R}}\times L_{\mathrm{C}}$, and then the coordinate of the center point in the projector chip (x_{pi},y_{pi}) can be computed from the horizontal and vertical phases, which is shown as:

$$x_{pi}=\frac{\varPhi_{\mathrm{V}}(x_{ci},y_{ci})\times L_{\mathrm{R}}}{2\pi N_{\mathrm{v}}}, \quad (3)$$

$$y_{pi}=\frac{\varPhi_{\mathrm{H}}(x_{ci},y_{ci})\times L_{\mathrm{C}}}{2\pi N_{\mathrm{h}}}, \quad (4)$$

where N_{v} is the number of the Gray codes in vertical direction, and N_{h} is the number of the Gray codes in horizontal direction. In our experiments, the resolution of the projector is 1024×768, and then $N_{\mathrm{v}}=N_{\mathrm{h}}=64$.

In Zhang's calibration method[8], the calibration target is placed at 3 different positions. In each position, the circle center should be extracted. The relationship between the camera coordinate and the world coordinate is as follows:

$$\begin{bmatrix}x_c\\y_c\\z_c\end{bmatrix}=\boldsymbol{R}_c\begin{bmatrix}x_w\\y_w\\z_w\end{bmatrix}+\boldsymbol{T}_c. \quad (5)$$

The relationship between the projector coordinate and the world coordinate is as follows:

$$\begin{bmatrix}x_p\\y_p\\z_p\end{bmatrix}=\boldsymbol{R}_p\begin{bmatrix}x_w\\y_w\\z_w\end{bmatrix}+\boldsymbol{T}_p. \quad (6)$$

Because the camera and the projector are calibrated simultaneously, they use the same world coordinate. The centers of the camera coordinate and the projector coordinate are $\begin{bmatrix}x_c\\y_c\\z_c\end{bmatrix}=\begin{bmatrix}0\\0\\0\end{bmatrix}$ and $\begin{bmatrix}x_p\\y_p\\z_p\end{bmatrix}=\begin{bmatrix}0\\0\\0\end{bmatrix}$, respectively. If the centers of the camera coordinate and the projector coordinate can be converted to the world coordinate, the distance D can be expressed as the distance of two points in one coordinate. Eqs.(5) and (6) can be transformed to

$$\begin{bmatrix}x_w\\y_w\\z_w\end{bmatrix}=\boldsymbol{R}_c^{-1}(\begin{bmatrix}x_c\\y_c\\z_c\end{bmatrix}-\boldsymbol{T}_c), \quad (7)$$

$$\begin{bmatrix}x_w\\y_w\\z_w\end{bmatrix}=\boldsymbol{R}_p^{-1}(\begin{bmatrix}x_p\\y_p\\z_p\end{bmatrix}-\boldsymbol{T}_p). \quad (8)$$

In order to distinguish the camera and the projector coordinates, $\begin{bmatrix} x_{wc} \\ y_{wc} \\ z_{wc} \end{bmatrix}$ and $\begin{bmatrix} x_{wp} \\ y_{wp} \\ z_{wp} \end{bmatrix}$ are used to express the camera and the projector centers in the world coordinate.

Because $\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ and $\begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$, then

$$\begin{bmatrix} x_{wc} \\ y_{wc} \\ z_{wc} \end{bmatrix} = -\boldsymbol{R}_c^{-1}\boldsymbol{T}_c \quad , \quad \begin{bmatrix} x_{wp} \\ y_{wp} \\ z_{wp} \end{bmatrix} = -\boldsymbol{R}_p^{-1}\boldsymbol{T}_p . \tag{9}$$

Then the distance D between the camera and the projector can be expressed as follows:

$$D = \sqrt{(x_{wc} - x_{wp})^2 + (y_{wc} - y_{wp})^2 + (z_{wc} - z_{wp})^2} . \tag{10}$$

In order to calibrate the distance from the camera to the reference plane accurately, the calibration target and the reference plane should be placed at the same position. Otherwise, the reference plane should be calibrated using other methods. In our experiment, the reference plane is just the last position of the calibration target. The relationship between the camera coordinate and the reference plane coordinate is shown in Fig.2.

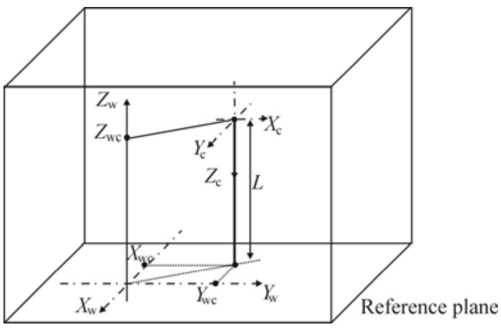

Fig.2 Relationship between the camera coordinate and the reference plane coordinate

In the center of the camera coordinate, $\begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$, and then $\begin{bmatrix} x_{wc} \\ y_{wc} \\ z_{wc} \end{bmatrix} = -\boldsymbol{R}_c^{-1}\boldsymbol{T}_c$. From Fig.2, the distance L from the camera to the reference plane is equal to z_{wc}, and thus the distance L can be calculated by $L = z_{wc}$.

In the 3D measurement, although the frequency of the sinusoidal fringe in the projector coordinate is known, the frequency of the fringe in the world coordinate should be calibrated. The calibration of the fundamental frequency is based on the unwrapped phase of the circle centers.

There are 99 circles on the calibration target, and the left column and the right column are shown in Fig.3. All the circles on the calibration target are coded in sequence.

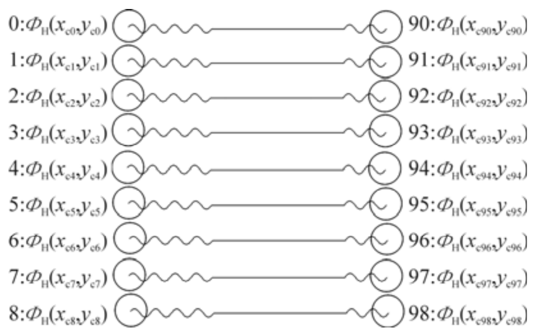

Fig.3 Left and right columns on the calibration target

The unwrapped phases of the number 0 circle and the number 90 circle are $\varPhi_H(x_{c0}, y_{c0})$ and $\varPhi_H(x_{c90}, y_{c90})$. If there are N periods between the number 0 circle and the number 90 circle, N can be calculated as follows:

$$N = \frac{\varPhi_H(x_{c90}, y_{c90}) - \varPhi_H(x_{c0}, y_{c0})}{2\pi} . \tag{11}$$

The distance between the number 0 and the number 90 circles is $D_{big\text{-}H}$, and then the period P in the world coordinate can be calculated by

$$P = \frac{D_{big\text{-}H}}{N} = \frac{2\pi \times D_{big\text{-}H}}{\varPhi_H(x_{c90}, y_{c90}) - \varPhi_H(x_{c0}, y_{c0})} . \tag{12}$$

Because the frequency is the reciprocal of the period, the frequency in the world coordinate can be calibrated by

$$f_0 = \frac{1}{P} = \frac{\varPhi_H(x_{c90}, y_{c90}) - \varPhi_H(x_{c0}, y_{c0})}{2\pi \times D_{big\text{-}H}} . \tag{13}$$

In order to avoid the influence of the unwrapped phase error in each circle center, the average frequency based on all the left and right circles is better than that only using 0 and 90 circles. The average frequency can be calibrated by

$$f_0 = \frac{\sum_{i=0}^{8} \frac{\varPhi_H(x_{c(i+90)}, y_{c(i+90)}) - \varPhi_H(x_{ci}, y_{ci})}{9}}{2\pi \times D_{big\text{-}H}} . \tag{14}$$

In order to get the real X coordinate of the object, the scale factor from the image coordinate to the world coordinate should be calibrated. The calibration of the scale factor is also based on the left and right circles on the calibration target. In order to avoid the circle center extraction error, the scale factor R_x is also averaged based on all the left and right circles, which is shown as follows

$$R_x = \sum_{i=0}^{8} \frac{D_{big\text{-}H}}{9 \times |x_{ci} - x_{c(i+90)}|} . \tag{15}$$

Similar to the calibration of the scale factor in X direction, the scale factor R_y in Y direction is based on the top and the bottom circles on the calibration target. The numbers of the top circles are 0, 9, 18, 27, 36, 45, 54, 63, 72, 81 and 90, which can be expressed by $y_{c(i\times 9)}\big|_{i=0-10}$. The numbers of the bottom circles are 8, 17, 26, 35, 44, 53, 62, 71, 80 and 98, which can be expressed by $y_{c((i+1)\times 9-1)}\big|_{i=0-10}$. If the distance between the top and the bottom circles is $D_{\text{big-V}}$, the scale factor R_y in Y direction can be calibrated by

$$R_y=\sum_{i=0}^{10}\frac{D_{\text{big-V}}}{11\times\left|y_{c(i\times 9)}-y_{c((i+1)\times 9-1)}\right|}\ . \tag{16}$$

A real-time absolute 3D shape measurement system is set up. A digital light processing (DLP) projector is placed in the center, and the resolution is 800×600. The CCD camera is a digital camera with an image resolution of 1280×1024.

All circle centers in the camera coordinate and the projector coordinate can be captured. Some of the calibration data, whose numbers are from 1 to 5 and 91 to 95, are shown in Tab.1.

Tab.1 Calibration data from the calibration target

No.	x_c	y_c	x_p	y_p	x_w	y_w	z_w
1	213.075	175.161	124.904	208.752	-180	-132	0
2	213.130	256.390	125.563	229.244	-180	-99	0
3	213.112	337.775	126.213	249.535	-180	-66	0
4	213.213	418.948	126.875	269.591	-180	-33	0
5	213.391	499.968	127.541	289.439	-180	0	0
91	1067.830	190.186	287.070	205.503	180	-132	0
92	1067.140	267.652	286.839	226.106	180	-99	0
93	1066.870	345.217	286.386	246.754	180	-66	0
94	1066.180	422.534	286.143	266.907	180	-33	0
95	1065.911	499.822	285.686	286.834	180	0	0

Using the calibration method proposed in this paper, the five essential parameters can be calibrated, which are shown in Tab.2.

Tab.2 Calibration results of the five essential parameters using the method proposed in this paper

Parameter	Calibration result (mm)
D	300.2999
L	1251.2065
f_0	0.4157
R_x	0.0694
R_y	0.0689

Based on the previous works in our researches[14-19], the depth of the object according to the reference plane can be calculated by $\dfrac{\Phi(x,y)\times L}{\Phi(x,y)-2\pi f_0 D}$.

In order to test the precision of the proposed calibration method, the calibration target placed at 10 different positions is measured over a volume of 400 mm (H)×300 mm (V)×500 mm (D). Using the 3D reconstruction method, the 3D data of the circle centers can be calculated, which are shown in Fig.4. Suppose the standard distance between the two adjacent circles is D_{H} in horizontal direction, and D_{V} in vertical direction. The precision evaluation can be performed by

$$\varepsilon=\frac{\sum_{i=1}^{90}\frac{\left|xd_i-D_{\text{H}}\right|}{90}+\sum_{j=1}^{88}\frac{\left|xd_j-D_{\text{V}}\right|}{88}}{2}\ , \tag{17}$$

where ε is the measurement error deviated from the standard value, xd_i is the measured value between two adjacent circles in horizontal direction, xd_j is in vertical direction, D_{H} is the standard value in horizontal direction, and D_{V} is in the vertical direction.

In the 10 calibration targets, the measurement errors are listed in Tab.3, where the mean error ME and the standard deviation SD are calculated by:

$$ME=\frac{\sum_{i=1}^{n}\varepsilon_i}{n}\ , \tag{18}$$

$$SD=\sqrt{\frac{\sum_{i=1}^{n}(\varepsilon_i-ME)^2}{n}}\ . \tag{19}$$

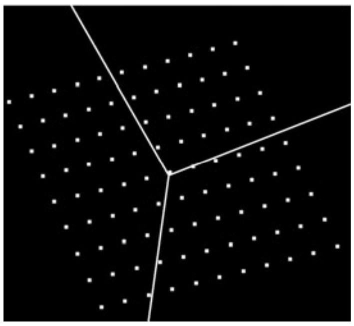

Fig.4 3D data of the circle centers

Tab.3 Measurement errors in ten calibration targets

No.	Measurement error (mm)	Mean error (mm)	Standard deviation (mm)
1	0.0213	0.0215	0.00129
2	0.0240		
3	0.0218		
4	0.0198		
5	0.0235		
6	0.0201		
7	0.0213		
8	0.0208		
9	0.0220		
10	0.0207		

A calibration method for the five essential parameters used in the 3D reconstruction is proposed in this paper. Using the calibration results, the 3D reconstruction can be performed directly. The proposed calibration method is implemented and tested in our 3D reconstruction system. The mean calibration error is found to be 0.0215 mm over a volume of 400 mm (H)×300 mm (V)×500 mm (D). The proposed calibration method is accurate and useful for the 3D reconstruction system.

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