A complementary binary code based phase unwrapping method*

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Phase unwrapping is used to establish the mapping relationship between camera and projector, which is one of the key technologies in fringe projection profilometry (FPP) based three-dimensional (3D) measurement. Although complementary Gray code assisted phase unwrapping technology can get a good result on the periodic boundary, it needs more coded images to obtain a high frequency fringe. Aiming at this problem, a complementary binary code assisted phase unwrapping method is proposed in this paper. According to the periodic consistency between the wrapping phase and binary codes, the coded patterns are generated. Then the connected domain strategy is performed to calculate the fringe orders using the positive and negative image binaryzation. To avoid the mistake near the periodic boundary, complementary binary code inspired by the complementary Gray code is proposed. The fringe order correction is also discussed for different situations in the first measured period. Only two binary images are needed in the proposed method, and the fringe frequency is not limited. Both the simulation and experiment have verified the feasibility of proposed method.

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Fringe projection profilometry (FPP) is widely used in fields of manufacturing, automobile, and medicine benefit from the advantages of non-contact, high accuracy, quick speed. The technologies of FPP include system calibration, camera calibration, nonlinear correction, phase unwrapping, and so on[1-6]. Among them, phase unwrapping technology is used to establish the matching relationship between camera and projector, which is critical to the three-dimensional (3D) reconstruction accuracy[7,8]. Phase unwrapping methods can be divided into spatial phase unwrapping method and temporal phase unwrapping method. The former is related to the surrounding critical points[9], and generally cannot process the complex surfaces. The later calculates the fringe order by pixel-wise, which avoids the accumulative error efficiently[10].

Temporal phase unwrapping methods mainly include multi-frequency heterodyne method[11], phase coding method[12] and Gray code method[13]. Multi-frequency heterodyne uses low-frequency fringe to assist the phase unwrapping of high-frequency fringe pattern, which needs more 8 bits patterns. Phase coding used the step phase to code the fringe order, which is robust. While the position matching between step phase and wrapping phase period is important. Gray code uses a series of binary images to confirm the fringe order by pixel-wise, and complementary Gray code can solve the problem of mismatch between wrapped phase period and fringe order, which is quick and robust. WU et al[14] adds a complementary Gray code to calculate the complementary fringe order, which can avoid the error caused by the period jump. The number of Gray code patterns depends on the period of wrapped phase. For example, if there are 64 periods in the wrapped phase, it needs six Gray codes images. The more wrapped periods are generated, the more Gray code patterns are needed. ZHENG et al[15] proposed a method based on ternary Gray code, which combined a new binary pattern with Gray code to reduce the number of projected patterns. XU et al[16] expounded a new ternary Gray code method, which used two-dimensional modulation to replace the one-dimensional modulation. It can ensure that the intermediate gray region is more uniform under different defocusing levels. HE et al[17] employed a quaternary gray-code phase unwrapping method using only two defocused binary patterns. Besides, continuity/geometry constraints are integrated with this phase unwrapping method to further reduce the number of required patterns. CAI et al[18] reported a periodic phase unwrapping method, which only needed two grayscale coding modes. Because of the hybrid coding strategy, the number of patterns was reduced, but it takes more time to get the fringe order. In order to improve the coding efficiency, WU et al[19] developed a time-overlapping coding method to reduce the coding

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patterns. WANG et al[20] used a robust stripe-wise decoding scheme to extract the N-bit codeword, and the fringe orders are determined.

A phase unwrapping method based on complementary binary codes is proposed in this paper. Although only the relative unwrapping phase is gotten, the isolated objects also can be reconstructed as long as the proposed unwrapping phase method is used in the system calibration. Compared to the traditional Gray-code methods, only two binary patterns are needed to assist the phase unwrapping. The complementary fringe order map is used to avoid mistake caused by the period mismatch between fringe order and wrapped phase. Both the simulation and experiments will verify the feasibility of the proposed method.

Fig.1 is the schematic diagram of the FPP based 3D measurement, mainly including projectors, cameras and computers. The encoded patterns project onto the measured surface through the digital light projector (DLP), and are captured by the camera. The phase calculation algorithm is performed to obtain the phase information, and the depth information of measured surface is gotten according to the system calibration.

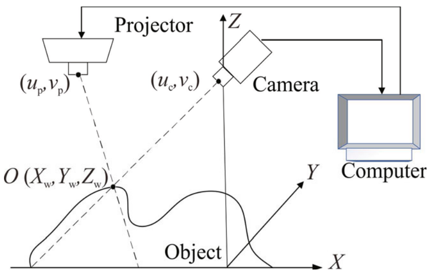


Fig.1 3D measurement system

The inverse camera method is used to reconstruct the objects. The world coordinates of O can be calculated as

$$\boldsymbol{Z}_c\begin{bmatrix}u_c\\v_c\\1\end{bmatrix}=\boldsymbol{H}_c\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix},\boldsymbol{Z}_p\begin{bmatrix}u_p\\v_p\\1\end{bmatrix}=\boldsymbol{H}_p\begin{bmatrix}X_w\\Y_w\\Z_w\\1\end{bmatrix}, \quad (1)$$

where (X_w, Y_w, Z_w) is the world coordinate of point O. $\boldsymbol{H}_c$ and $\boldsymbol{H}_p$ are the homography matrixes of camera and projector systems, respectively, which can be gotten by camera calibration. $\boldsymbol{Z}_c$ and $\boldsymbol{Z}_p$ denote the scaling coefficients of camera and projector. According to the unwrapping phase consistency, the pixel coordinate (u_p, v_p) in the projector can be expressed as

$$u_p=\frac{\Phi_v(u_c,v_c)P_v}{2\pi},v_p=\frac{\Phi_h(u_c,v_c)P_h}{2\pi}, \quad (2)$$

where $\Phi_v(u_c, v_c)$ and $\Phi_p(u_c, v_c)$ represent the unwrapping phase at the horizontal and vertical directions. P_v and P_h are the numbers of pixels in the vertical and horizontal directions per period. After the system calibration, the relationship between (X_w, Y_w, Z_w) and absolute phase is established. Therefore, the absolute phase calculation is a key step to reconstruct the 3D information.

Fig.2 shows the flow chart of proposed phase unwrapping algorithm. By capturing the images with sinusoidal fringes, the wrapped phase is calculated using least square method. With the same period as sinusoidal fringes, two fringe order coding patterns have a half-period mismatch to get the complementary fringe order maps. The robustness of fringe order calculation at period boundary is improved. The specific phase unwrapping algorithm flow is as follows.

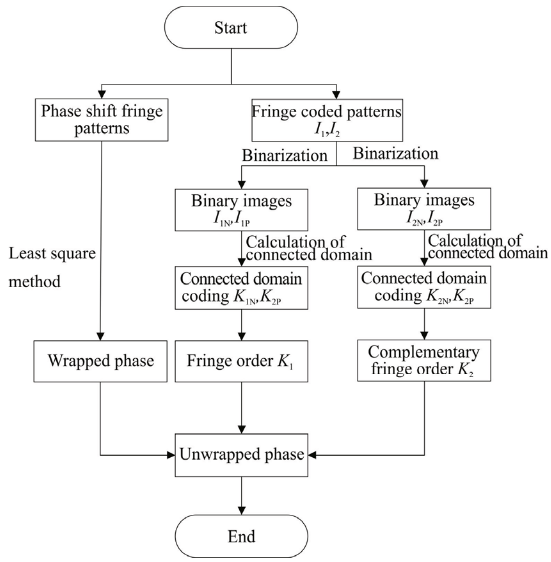


Fig.2 Complementary binary phase unwrapping flow chart

The expression of the fringe grating image projected on the surface of the object by N-step phase-shifting method is

$$I(x,y)=A(x,y)+B(x,y)\cos[\varphi(x,y)-2\pi n/N], \quad (3)$$

where $A(x, y)$ is the background light intensity, $B(x, y)$ is the modulation light intensity, (x, y) is the image coordinate of each pixel in the fringe image, $\varphi(x, y)$ is the wrapped phase, and N is the number of phase-shifting steps. The parameters $A(x, y)$ and $B(x, y)$ can be used to the intensity normalization when the binaryzation operations are performed to the coded images. According to the equation set from Eq.(2), the calculation formula of $A(x, y)$ and $B(x, y)$ are as follows

$$\begin{cases}A(x,y)=\sum_{i=0}^{N-1}I_i(x,y)/N\\B(x,y)=\frac{2}{N}\sqrt{[(\sum_{n=0}^{N-1}I_n(x,y)\cos(2\pi n/N))^2+(\sum_{n=0}^{N-1}I_n(x,y)\sin(2\pi n/N))^2]}\end{cases}. \quad (4)$$

The wrapping phase is calculated based on least square method as

$$\varphi(x,y)=\tan^{-1}\left[\frac{\sum_{n=0}^{N-1} I_n(x,y)\sin(2n\pi/N)}{\sum_{n=0}^{N-1} I_n(x,y)\cos(2n\pi/N)}\right]. \tag{5}$$

According to Eq.(5), the phases are limited at [−π, π], which is difficult to match the pixel position. To avoid the ambiguity, the process of phase unwrapping is necessary. Two binary patterns are used to code the fringe orders:

$$\begin{cases} I_8(x,y)=A(x,y)+B(x,y)\text{sign}[\sin(x*f)] \\ I_9(x,y)=\sim I_8(x,y) \end{cases}, \tag{6}$$

where f is the projected fringe frequency which is the same with sinusoidal fringes, and sign is the symbol confirmation of the input array. Symbol ~ denotes negative logic operator. Especially, the subscripts 8 and 9 used here denote the 8th and 9th patterns to be projected, and the 7-step phase shifting is used to avoid the influence of non-linearly errors.

The camera captures the coded patterns with gray model, and binarization is needed to ensure the fringe orders. Firstly, intensity normalization is performed to reduce the influence of reflection difference as

$$I_n(x,y)=\frac{I(x,y)-A(x,y)}{B(x,y)}, \tag{7}$$

where $A(x, y)$ and $B(x, y)$ are calculated by Eq.(3). Each coded pattern can obtain two binary patterns with opposite black and white stripes I_{8P}, I_{8N} and I_{9P}, I_{9N}. The expression for binarization using I_{8P} as an example is

$$I_{8P}(x,y)=\begin{cases} 1, & I_8(x,y)>T \\ 0, & I_8(x,y)\le T \end{cases}, \tag{8}$$

where T is the threshold of binarization, which is generally set as 0.5.

Secondly, noise filter is operated, as shown in Fig.3.

The 3×3 convolution kernel with all one is put on the binary with noise, and area of central pixel is calculated. The area threshold A_{th} is used to confirm the binary of central pixel $P(x, y)$, as presented in Eq.(9). After the operation above, the noise in the black region is efficiently suppressed, and the logical NOT operation is performed to reduce the noise in the white region.

$$P(x,y)=\begin{cases} 0 & area\le A_{th} \\ 1 & area> A_{th} \end{cases}. \tag{9}$$

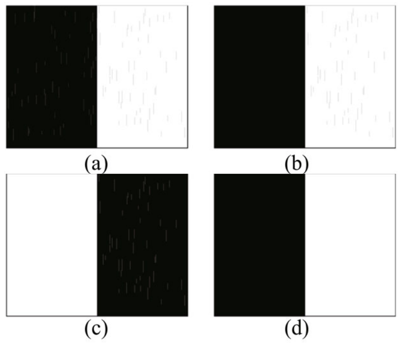


Fig.3 Noise filter: (a) Binary image with noise; (b) Noise suppressed pattern in black region; (c) A logical NOT is applied to (b); (d) Noise suppressed pattern

According to the binary image gotten above, the connected region operation is performed to determine the fringe order using the function of *bwlabel* in MATLAB. Taking I_{8P} as an example, the expression of the connected regions is

$$k_{8P}(x,y)=bwlabel(I_{8P}(x,y))=\begin{cases} li, \text{ if } I_{8P}(x,y)=1 \\ 0, \text{ otherwise} \end{cases}, \tag{10}$$

where k_{8P} is the code value corresponding to I_{8P} obtained after finding the connected region. Each white connected area is assigned a unique label*li* (*li*=1, 2, 3….).

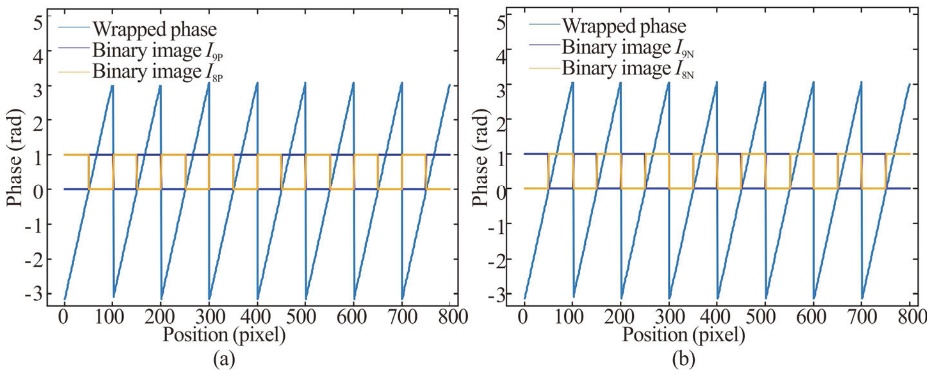
Fig.4 shows the flow of fringe order calculation according to the binary coding image and complementary binary coding image atone row respectively. It can be seen that there is a dislocation of 1/2 period between the two fringe orders.

The fringe order calculation above has supposed that the first period is whole, which may be different with the experiment situation. As shown in Fig.5(a), when the first period is less than half a period, the black or white region of coding image will not appear in the first period, which will result in calculation error of fringe order.

Therefore, the fringe order should be corrected as

$$\begin{cases} k_{8P}=k_{8P}+1, \text{and } k_{8P}(k_{8P}=1)=0, \text{if } \varphi(1,1)\ge 0 \\ k_{9P}=k_{9P}+1, \text{and } k_{9P}(k_{9P}=1)=0, \text{if } \varphi(1,1)<0 \end{cases}. \tag{11}$$

The unwrapping phase can be calculated as



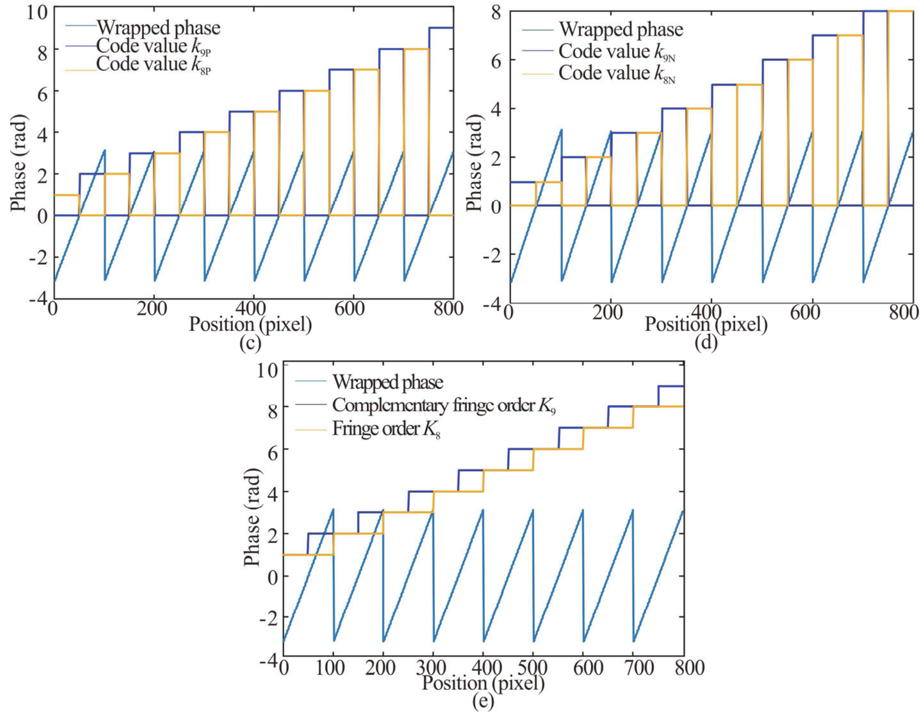


Fig.4 Flow of coded fringe order and complementary fringe order calculation: (a) Relationship between wrapped phase, binary images I_{8P} and I_{9P}; (b) Relationship between wrapped phase, binary images I_{8N} and I_{9N}; (c) Code values corresponding to I_{8P} and I_{9P}; (d) Code values corresponding to I_{8N} and I_{9N}; (e) Relationship between wrapped phase, fringe order K_8 (K_8=k_{8P}+k_{8N}) and complementary fringe order K_9 (K_9=k_{9P}+k_{9N})

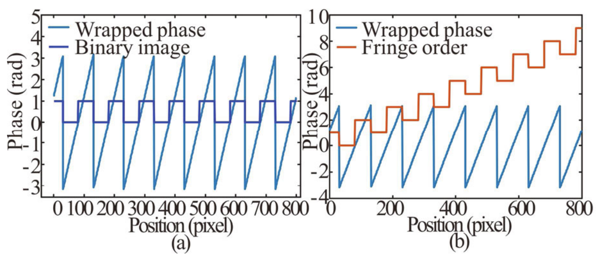


Fig.5 Fringe order correction: (a) The first period is less than half a period; (b) Error in fringe order calculation

$$\begin{cases} K_8 = k_{8P} + k_{8N} \\ K_9 = k_{9P} + k_{9N} \end{cases}, \tag{12}$$

$$\Phi(x, y) = \begin{cases} \varphi(x, y) + (s_2 + K_9)2\pi, & \varphi(x, y) > \pi/2 \\ \varphi(x, y) + 2K_8\pi, & -\pi/2 \le \varphi(x, y) \le \pi/2 \\ \varphi(x, y) + (s_1 + K_9)2\pi, & \varphi(x, y) < -\pi/2 \end{cases},$$

$$\begin{cases} s_1 = 1, s_2 = 1, & \text{if } \varphi(1, 1) \ge 0 \\ s_1 = 0, s_2 = -1, & \text{otherwise} \end{cases}. \tag{13}$$

Fig.6 shows the simulation analysis using peaks function, including coded image, fringe order map, unwrapping phase and calculation error. It can verify the feasibility of the proposed method.

The experimental platform mainly includes a Da Heng Industrial camera with a resolution of 1 600×1 200 pixels (MV-EM120M) and a Texas Instruments industrial projector with a resolution of 1 280×800 pixels (DLP4500). To reduce the influence of nonlinear projection, 7-step phase-shifting was performed to get the wrapped phase. The inverse camera model was used to reconstruct the 3D information, and the complementary Gray coded method was chosen as the comparison method.

The feature points on the calibration plate are reconstructed after the system calibration, and the distances of adjacent feature points are calculated to verify the feasibility of the proposed method. The theoretic distance is 10 mm. The results are shown in Fig.7 and Tab.1. It could be seen that the distribution of measured distances calculated by two methods is comparatively close, while the proposed method is faster than the complementary Gray code method. It implies that the proposed method is feasible and superior. In order to fatherly verify the feasibility of the proposed method, the standard sphere was chosen as the measured object.

The parameters of standard sphere are shown in Tab.2. As shown in Fig.8, the fringe orders are corrected using the proposed method, and reconstruction result is presented in Fig.9. The calculation results of standard sphere diameter are shown in Tab.3. The proposed method can get the comparative accuracy with complementary Gray code method.

Furthermore, the 3D reconstruction of the plaster head with more complex surface was carried out. As shown in Fig.10, the plaster head can be reconstructed efficiently, and the texture mapping is correct, which verifies the feasibility and superiority of the proposed method.

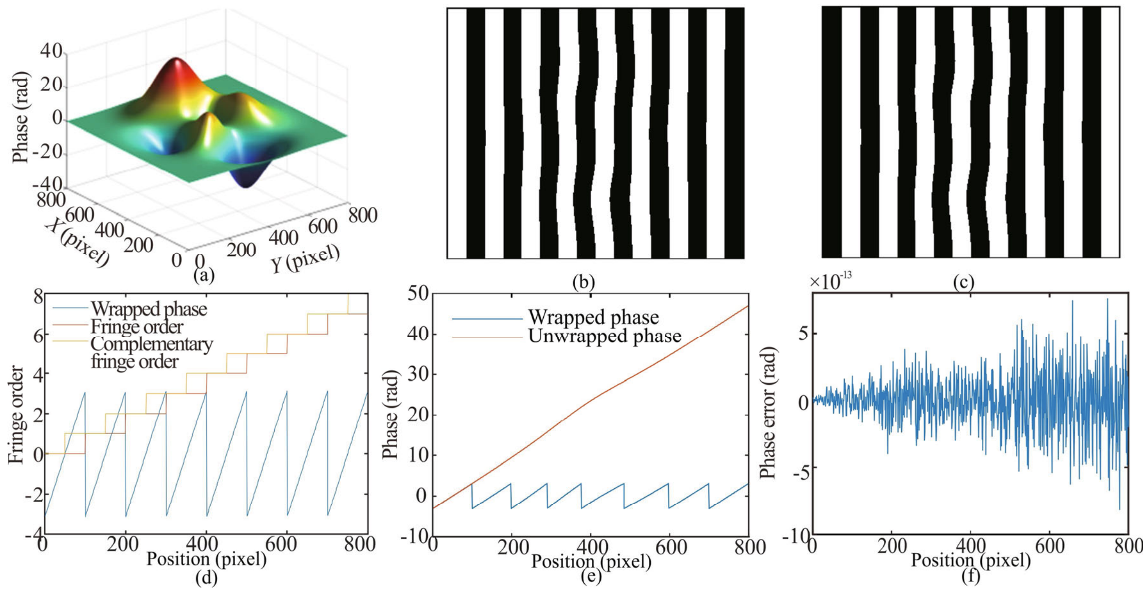


Fig.6 Simulation analysis: (a) Peaks function with 800 pixel×800 pixel; (b) Binary coded image and (c) complementary binary coded image modulated by the object; (d) Fringe order calculation; (e) Phase unwrapping; (f) Calculation error

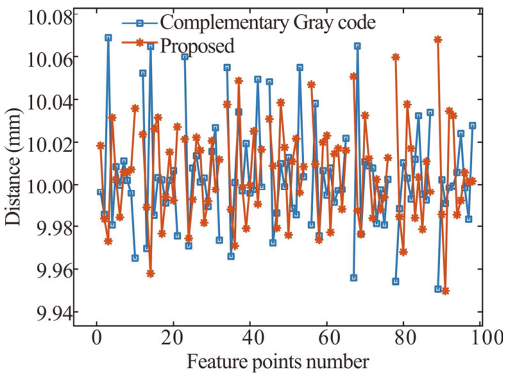


Fig.7 Distances of feature points calculated by different methods

Tab.1 Results comparison

	Mean distance (mm)	Time (s)
Complementary Gray code	10.011 7	3.26
Proposed method	10.014 1	1.02

A complementary binary codes based phase unwrapping method is proposed in this paper. The connected regions labels are used to confirm the fringe orders, which is convenient. Noise filter is also discussed in detail. The complementary fringe orders can efficiently avoid the phase unwrapping errors at the boundary of fringe period. The feasibly and superiority of the proposed method are verified by theory, simulation and experiment. In the experiment, the performance of the proposed method is comparative with the complementary Gray code method, while fewer patterns and time cost are needed in the proposed method, which is attractive.

Tab.2 Parameters of the standard sphere

	Content
Diameter	38.084 5 mm
Type	DS-MCB-D38.1GZ
Company	Nanchang Ding Sheng Automatic Technology Corporation

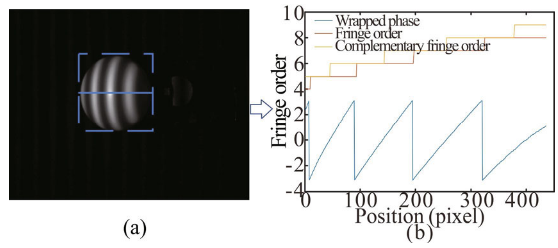


Fig.8 Standard sphere measurement: (a) Coding image; (b) Fringe order image

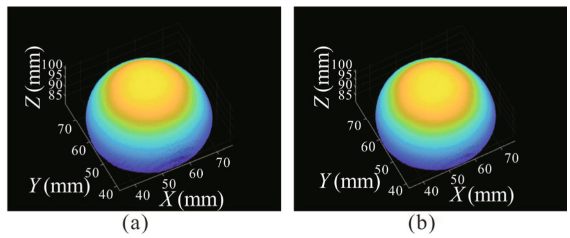


Fig.9 Standard sphere reconstruction: (a) Complementary Gray code method; (b) Proposed method

Tab.3 Experimental results on the standard sphere

	Measured diameter (mm)	Difference of diameter (mm)
Complementary Gray code method	38.144 6	0.058 1
Proposed method	38.137 2	0.052 7

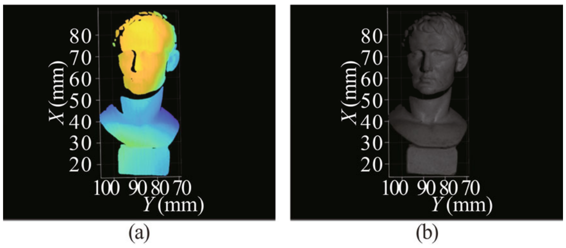


Fig.10 3D reconstruction results of human head: (a) Point cloud; (b) Texture mapping

In our method, only the relative unwrapping phase is calculated, so the whole coded images are needed to get the fringe order. It is not cost-effective although a little time is added. So the absolute unwrapping phase calculation combining geometric constrain will be performed in our future work.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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