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3D reconstruction of moving object by double sampling based on phase shifting profilometry

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ABSTRACT

When using traditional phase-shift profilometry for 3D measurement, it is necessary to keep the measured object static during the shooting process. When the measured object is moving, errors will occur if the projection and capture of the fringe image is not fast enough. This paper proposes a new method to reconstruct the moving object by double sampling. A trigger control device is applied to the camera and projector, which ensures that after each projection, two consecutive images are captured before the next projection. Then, the phase information is retrieved by analyzing the relationship between the motion and fringe patterns. Finally, the moving object is retrieved successfully. The proposed method increased the frame rate of the moving object reconstruction.

Keywords: phase-shift profilometry, double sampling, increased the frame rate

1. INTRODUCTION

Phase Shifting Profilometry (PSP) is one of the most commonly used three-dimensional measurement techniques, which has the advantages of high precision, strong robustness, and full-field measurement [1-3]. During the PSP reconstruction process, a projector needs to be used to project at least three sinusoidal fringe images with phase shifts onto the surface of the object, and the camera captures the images from another angle. The fringe pattern reflected from the object surface is distorted due to the height of the object, the fringe deformation is analyzed based on the phase information in the sinusoidal fringe pattern, and finally the three-dimensional reconstruction is realized according to the phase information and system parameters. Due to the use of multiple fringe images, the traditional PSP algorithm requires that the object must keep static during the reconstruction process. Once the object moves during fringe projection and capture, errors will be introduced.

In recent years, 3D measurement of moving objects has attracted widespread attention [4]. Lei Lu et al. [5-7] proposed a method for tracking object motion and compensating for motion errors. The motion of the object is tracked by computer vision technology, the rotation and translation vector describing the motion of the object is obtained, and finally the motion error is compensated according to the size of the motion. Ziping Liu et al. [8] proposed a method to reduce motion errors in PSP. Firstly, the motion between the 3D data obtained by adjacent frames is estimated, and then the phase change caused by the motion is obtained, and finally the accurate 3D information of the object is obtained.

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Zhoujie Wu [9] and others solved the unpacking error of moving objects based on high-speed imaging system and shifted Gray code, and realized high-speed measurement of moving objects. Yifan Guo et al. [10] estimate motion from object images starting and ending states. Based on the phase map and the obtained initial displacement data, the displacement inversion is performed for each point, and then the phase jump caused by the motion of the object is compensated. But this method is limited to the uniform motion of the object. Shijie Feng et al. [11-13] used deep learning to obtain high-precision phase from a single fringe pattern. The 3D reconstruction method based on deep learning can realize the 3D measurement of dynamic scenes by a single frame image. However, network training for deep learning is time-consuming and difficult to achieve real-time processing. Therefore, it is also necessary to find a motion error compensation method suitable for real-time phase shift measurement. Yajun Wang et al. [14] proposed a motion error compensation method with additional time sampling. This method collects fringe images twice in each fringe pattern illumination cycle, and uses two sets of fringe images for motion error compensation based on the assumption that the object moves at a uniform speed.

This paper presents a 3D reconstruction method for moving object by double-sampling based on phase-shift profilometry. First, a trigger control device was added to the camera and projector to ensure that the camera took two shots for each fringe image cast by the projector. Then, the object motion and phase changes are analyzed in consecutive three fringe images. Finally, the target is reconstructed according to the phase information and system parameters, so as to realize high-precision three-dimensional measurement for moving object reconstruction.

2. TRADITIONAL PSP

Assuming that N-step phase-shift profilometry is used, the fringe images captured by the camera on the reference plane and the object can be expressed as

$$I_n\left(x,y\right)=\mathrm{a}+b\cos\left(\phi\ \left(x,y\right)+\varphi(x,y)+\frac{2\pi\left(n-1\right)}{N}\right) \tag{1}$$

Where $I_n(x,y)$ is the intensity distribution of the fringe pattern of the object; $n=1,2,\ldots N$ is the serial number of the fringe pattern; a is the ambient light intensity, b is the amplitude modulation of the fringe pattern; $\phi(x,y)$ is the phase distribution of the reference plane, and $\varphi(x,y)$ is the phase change caused by the shape of the object.

The phase distribution on the object can be calculated by Eq. (2):

$$\phi\ \left(x,y\right)+\varphi(x,y)=\arctan\frac{-\sum_{n=1}^{N}I_n^o\left(x,y\right)\sin 2\pi\left(n-1\right)/N}{\sum_{n=1}^{N}I_n^o\left(x,y\right)\cos 2\pi\left(n-1\right)/N} \tag{2}$$

Since the arctangent function $\arctan$ is used, the phase calculated by Eq. (2) is wrapped in $[-\pi,\pi]$. In order to obtain the corresponding relationship between the object fringe pattern and the projected fringe pattern, it is necessary to use the unwrapping algorithm [15-16] to make the repetitive and ambiguous unwrapping operation is performed on the wrapped phase to obtain a continuous monotonous unwrapped phase, and then the three-dimensional reconstruction is

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completed based on the system calibration parameters.

3. 3D RECONSTRUCTION OF DOUBLE SAMPLING MOVING OBJECT BASED ON PSP

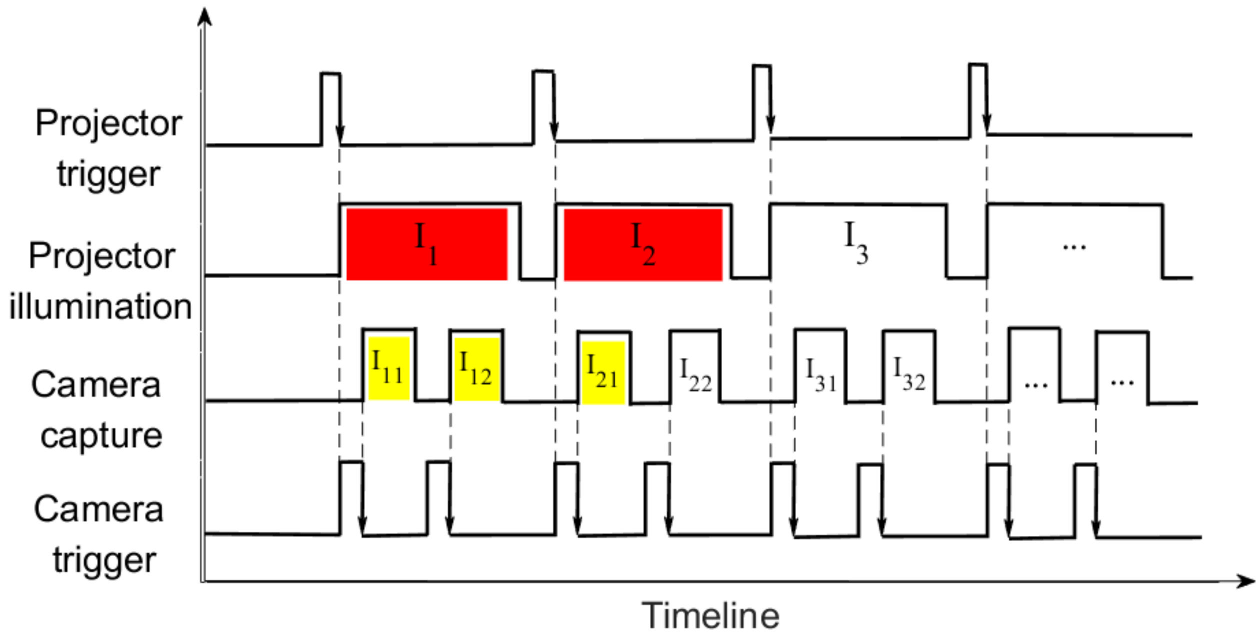

Fig. 1 Trigger sequence between camera and projector

In double-sampling method, two images are captured in one projection as shown in Fig. 1. The projector projects N fringe images at a certain rate, and triggers the camera twice within one projection cycle to complete double-sampling fringe capture, for example, I_{11} and I_{12} are two fringe images taken continuously when projecting fringes I_1. I_{21} and I_{22} are fringe patterns captured when projecting fringe I_2. Among them, there are only phase shifts (such as I_{11} and I_{12}) caused by object motion in the two fringe images taken by the same projected fringe; while the fringe images taken by different projected fringes have phase shift caused by motion, and PSP phase shift. Then, the phase is analyzed between I_{11}, I_{12} and I_{21}.

I_{11}, I_{12} and I_{21} containing motion information and they can be expressed as [17]:

$$\begin{aligned} I_{11}(f_1(x,y),g_1(x,y)) &= a + b\cos(\phi(f_1(x,y),g_1(x,y)) + \varphi(x,y) + \delta_1) \\ I_{12}(f_2(x,y),g_2(x,y)) &= a + b\cos(\phi(f_2(x,y),g_2(x,y)) + \varphi(x,y) + \delta_1) \\ I_{21}(f_3(x,y),g_3(x,y)) &= a + b\cos(\phi(f_3(x,y),g_3(x,y)) + \varphi(x,y) + \delta_2) \end{aligned} \tag{3}$$

where δ_1 and δ_2 represent the phase shift and $\delta_1 = 0$, $\delta_2 = 2\pi / N$; $(f_n(x,y), g_n(x,y))$ is the coordinate

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transformation relationship before and after the motion of the object, which can be obtained from the rotation and translation matrix describing the motion of the object. Rewrite Eq. (3) as

$$\begin{aligned} I_{11}(f_1(x,y),g_1(x,y)) &= A+B\cos(\phi(f_1(x,y),g_1(x,y))+\delta_1)+C\sin(\phi(f_1(x,y),g_1(x,y))+\delta_1) \\ I_{12}(f_2(x,y),g_2(x,y)) &= A+B\cos(\phi(f_2(x,y),g_2(x,y))+\delta_1)+C\sin(\phi(f_2(x,y),g_2(x,y))+\delta_1) \\ I_{21}(f_3(x,y),g_3(x,y)) &= A+B\cos(\phi(f_3(x,y),g_3(x,y))+\delta_2)+C\sin(\phi(f_3(x,y),g_3(x,y))+\delta_2) \end{aligned} \tag{4}$$

where $A=a$, $B=\cos\varphi(x,y)$, $C=-\sin\varphi(x,y)$. The above formula can be expressed in general form as:

$$I_m(x,y)=A+B\cos(\phi(f_n(x,y),g_n(x,y))+\delta_k)+C\sin(\phi(f_n(x,y),g_n(x,y))+\delta_k) \tag{5}$$

where when $m=11$ or 12, $k=1$; when $m=21$, $k=2$. Define the objective equation:

$$\theta(a,b,c)=\sum_{n=1}^{N}(y_n-y)^2=\sum_{n=1}^{N}(I_m-A-B\cos(\phi(h)+\delta_k)-C\sin(\phi(h)+\delta_k)) \tag{6}$$

The value of N in it is 3, and the partial derivatives are calculated for A, B, and C respectively:

$$\begin{cases} \dfrac{\partial\theta}{\partial A}=-2\sum_{n=1}^{N}\left[I_m-A-B\cos(\phi(h)+\delta_k)-C\sin(\phi(h)+\delta_k)\right]=0 \\ \dfrac{\partial\theta}{\partial B}=-2\sum_{n=1}^{N}\left[I_m-A-B\cos(\phi(h)+\delta_k)-C\sin(\phi(h)+\delta_k)\cos(\phi(h)+\delta_k)\right]=0 \\ \dfrac{\partial\theta}{\partial C}=-2\sum_{n=1}^{N}\left[I_m-A-B\cos(\phi(h)+\delta_k)-C\sin(\phi(h)+\delta_k)\sin(\phi(h)+\delta_k)\right]=0 \end{cases} \tag{7}$$

Written in matrix form:

$$D(x,y)X(x,y)=E(x,y) \tag{8}$$

where

$$D(x,y)=\begin{bmatrix} N & \sum_{n=1}^{N}\cos(\phi(h)+\delta_k) & \sum_{n=1}^{N}\sin(\phi(h)+\delta_k) \\ \sum_{n=1}^{N}\cos(\phi(h)+\delta_k) & \sum_{n=1}^{N}\cos^2(\phi(h)+\delta_k) & \frac{1}{2}\sum_{n=1}^{N}\sin 2(\phi(h)+\delta_k) \\ \sum_{n=1}^{N}\sin(\phi(h)+\delta_k) & \frac{1}{2}\sum_{n=1}^{N}\sin 2(\phi(h)+\delta_k) & \sum_{n=1}^{N}\sin^2(\phi(h)+\delta_k) \end{bmatrix} \tag{9}$$

$$X(x,y)=\begin{bmatrix} A & B & C \end{bmatrix}^T \tag{10}$$

$$E(x,y)=\begin{bmatrix} \sum_{n=1}^{N}I_m(h) & \sum_{n=1}^{N}I_m(h)\cos(\phi(h)+\delta_k) & \sum_{n=1}^{N}I_m(h)\sin(\phi(h)+\delta_k) \end{bmatrix} \tag{11}$$

After obtaining $X(x,y)$ using the least squares method, the phase change $\varphi(x,y)$ can be obtained:

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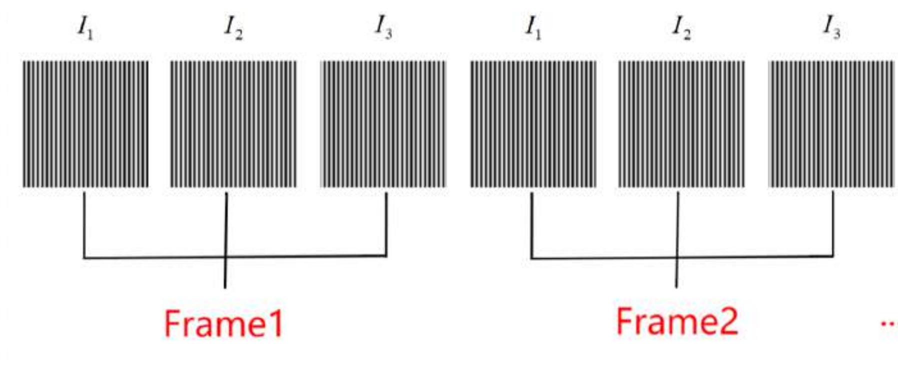
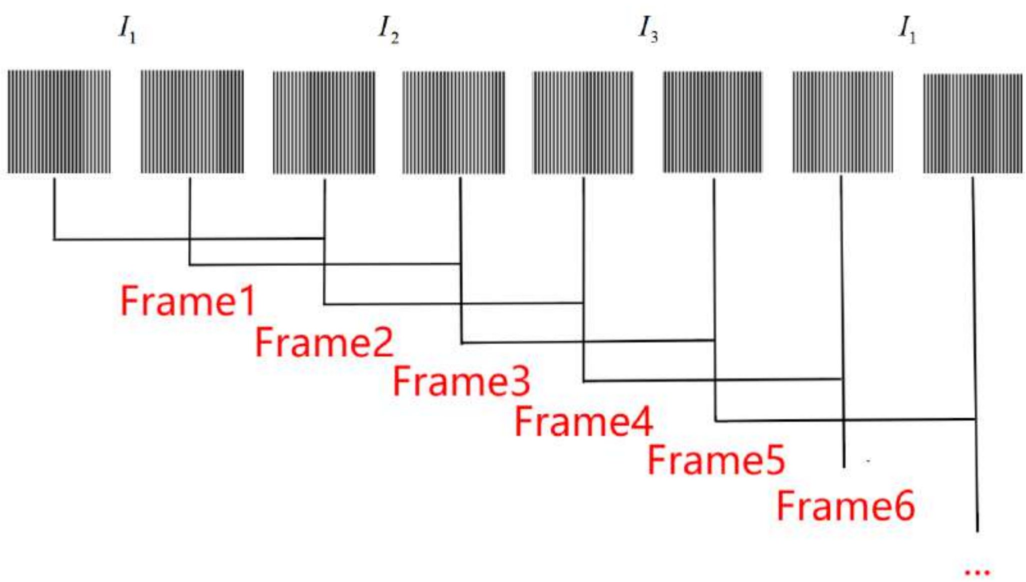
$$\varphi(x,y) = \tan^{-1}[-C/B] \tag{12}$$

The fringe image obtained based on double sampling can increase the frame rate based on the multiplexing method, and the multiplexing timing diagram is shown in the Fig.2.



(a)



(b)

Figure 2. Strategies for fringe pattern projection. (a) Using the traditional PSP to reconstruct the frame rate; (b) The reconstructed frame rate of the method proposed in this paper

4. EXPERIMENT

In this paper, the effectiveness of the algorithm is verified by simulation. The fringe patterns in static and moving states are simulated respectively. The object moves from left to right, and the object moves 10 pixels between each two fringe patterns. In order to facilitate the comparison of the methods, we use the traditional PSP to reconstruct the fringe pattern in the static state, and the results are shown in Fig. 3.

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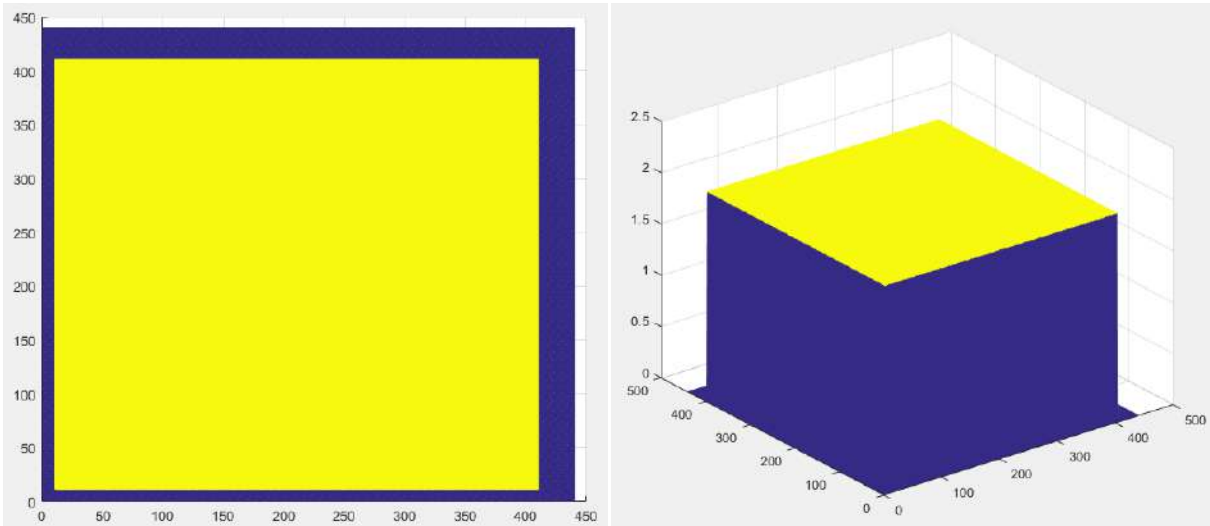

(a) (b)

Fig. 3 Reconstructing stationary objects using traditional PSP. (a) Reconstruction results. (b) Reconstruction results from another perspective.

As shown in Fig. 4, in the fringe pattern in the motion state, it can be seen that the fringe pattern collected by projecting the same fringe pattern only contains the motion of the object, while the fringe patterns between different projected fringe patterns contain both fringe phases shift, but also includes the movement of objects.

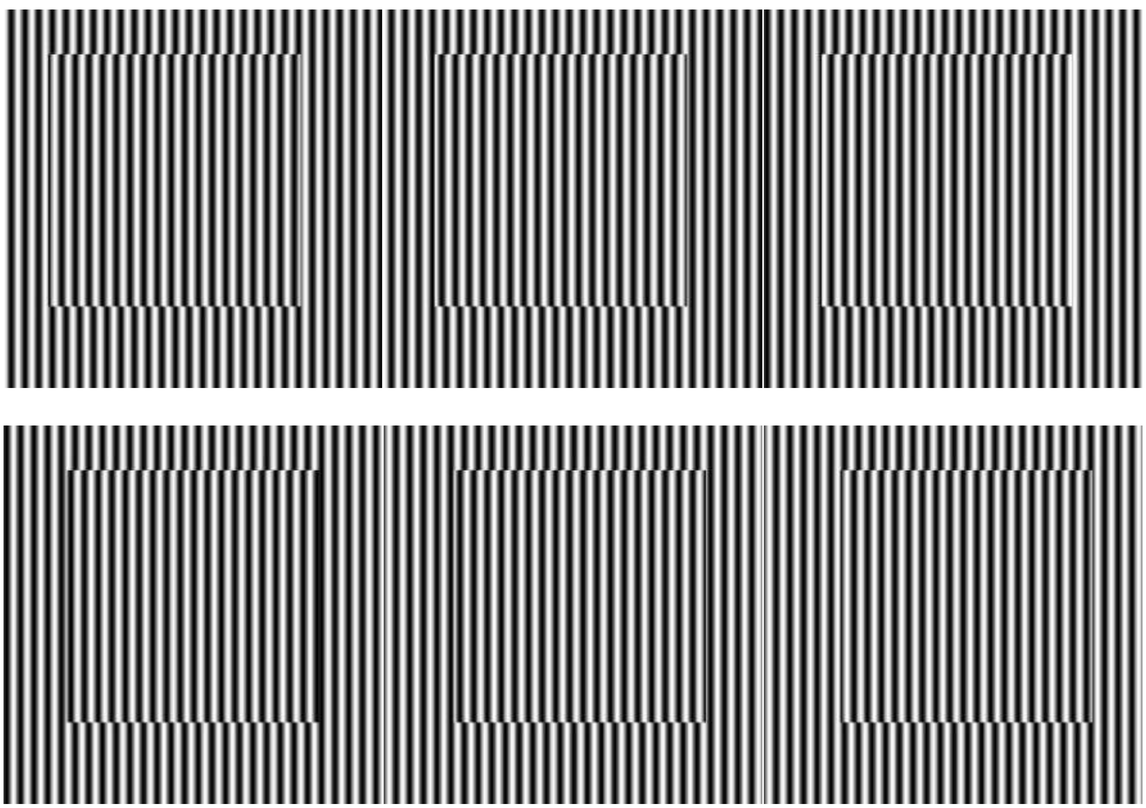

Fig.4 The fringe diagram of the simulated motion state

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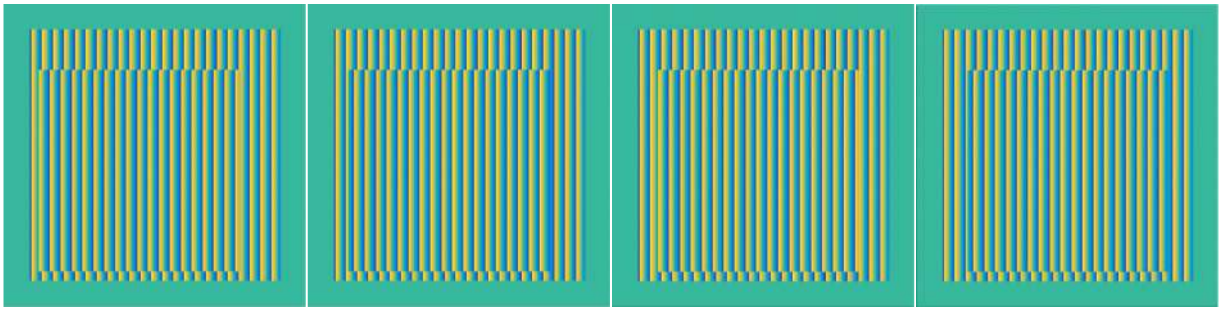
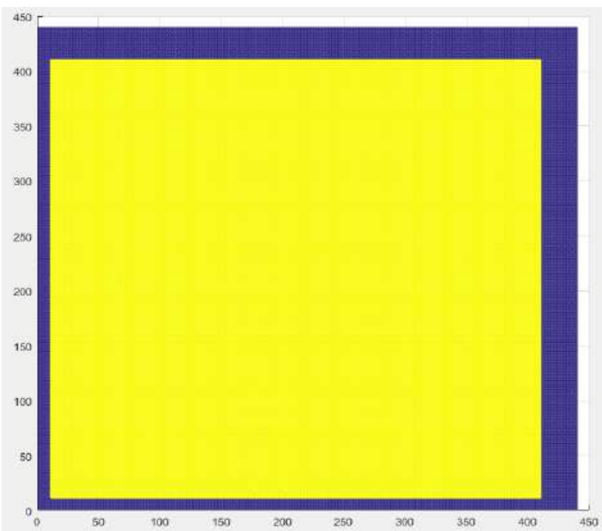
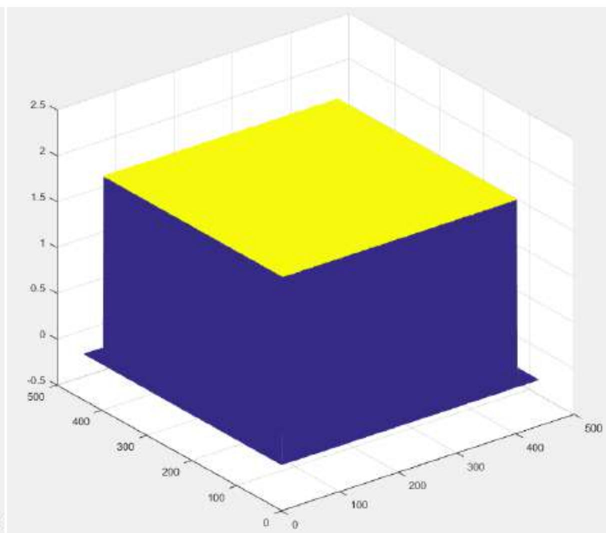
By tracking the motion of the object [18], the rotation matrix and translation vector describing the motion of the object is calculated, and then the phase of the object is calculated using the method in this paper. In order to improve the frame rate of the object, the fringe patterns will be used for multiplexing, and every three images can be calculated to obtain an object phase as shown in Fig. 5(a), and complete the high frame rate 3D reconstruction as shown in Fig. 5(b).



(a)





(b) (c)

Fig.5 Rreconstruction results in motion. (a)Phase maps at different frame; (b)Reconstruction results; (c) Reconstruction results from another angle

In order to compare the reconstruction effect of the algorithm in this paper, the above pictures were also reconstructed using traditional phase-shift profilometry, and the results are shown in Fig. 6. It can be clearly seen that there are large errors in the results.

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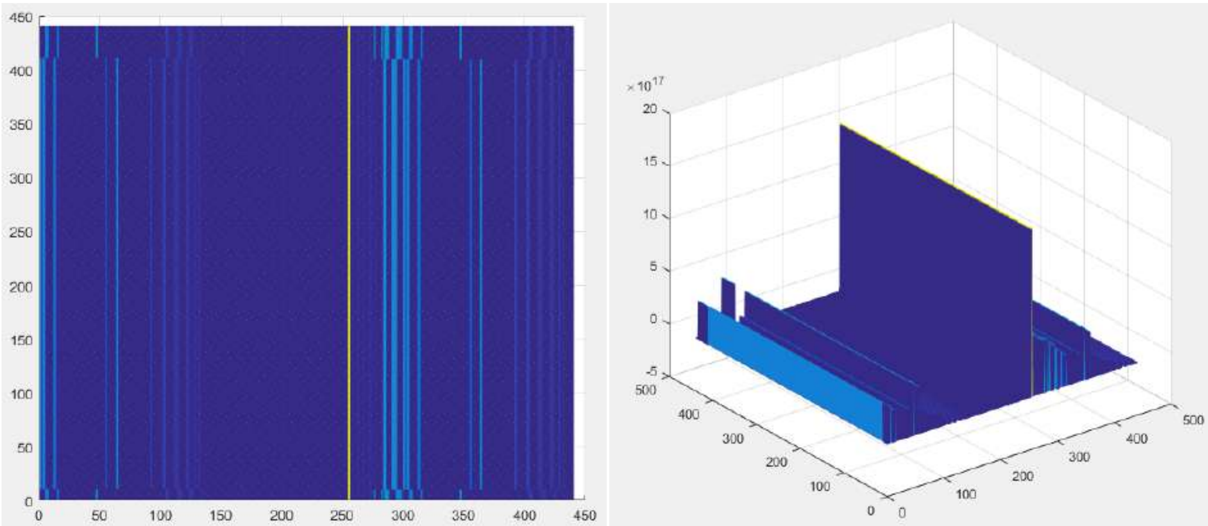

(a) (b)

Fig. 6 Reconstruction of moving objects using traditional PSP. (a) Reconstruction results; (b) Reconstruction results from another angle

5 CONCLUSION

This paper proposes a method to reconstruct the moving object by double-sampling based on PSP. This algorithm can double the shooting frame rate on the basis of the highest frame rate of the projector, and can be at a low cost without losing its advantages. The method only needs to reconstruct the moving object by deriving a new formula and projecting the fringe pattern of the first two steps on the basis of the three-step phase shift. The performance of the algorithm is verified by experiments, and the industrial application value is extremely high.

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