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A method for dynamic 3D shape measurements based on multiple-shot FTP and motion compensation

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Abstract

2019 SPIE. Fringe projection profilometry (FPP) has attracted considerable interests for addressing the challenge of measuring three-dimension (3D) shapes of moving objects. Compared with phase shift profilometry (PSP) which requires the capture of multiple fringe patterns and is thus only suitable for static objects, Fourier transform profilometry (FTP) is less sensitive to motion-induced errors. However, FTP is prone to the influence of background lights and variations of the surface reflectivity, which may result in less accurate measurements. There are studies aimed to reduce the measurement errors with FTP using more sophisticated processing of the fringe patterns. However, existing works focus on schemes based on single images and the correlation of the dynamic 3D shapes is largely unexplored. In this work, we present a new method that refines FTP-based dynamic shape measurements. Assuming 3D rigid movements of the targets, we propose to utilize knowledge of the motion parameters and combine the multiple height maps obtained from several FTP measurements after compensating the motion effect. Approaches for automatically combining the height information are studied. It is observed that the measurement accuracy can be improved using the proposed method and the influence due to ambient lights and reflectivity variations can be suppressed. Computer simulations are performed to verify the effectiveness of the proposed method. The proposed method can also be integrated into other FPP systems to improve the performance for dynamic object measurements.

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A Method for Dynamic 3D Shape Measurements Based on Multiple-Shot FTP and Motion Compensation

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ABSTRACT

Fringe projection profilometry (FPP) has attracted considerable interests for addressing the challenge of measuring three-dimension (3D) shapes of moving objects. Compared with phase shift profilometry (PSP) which requires the capture of multiple fringe patterns and is thus only suitable for static objects, Fourier transform profilometry (FTP) is less sensitive to motion-induced errors. However, FTP is prone to the influence of background lights and variations of the surface reflectivity, which may result in less accurate measurements. There are studies aimed to reduce the measurement errors with FTP using more sophisticated processing of the fringe patterns. However, existing works focus on schemes based on single images and the correlation of the dynamic 3D shapes is largely unexplored. In this work, we present a new method that refines FTP-based dynamic shape measurements. Assuming 3D rigid movements of the targets, we propose to utilize knowledge of the motion parameters and combine the multiple height maps obtained from several FTP measurements after compensating the motion effect. Approaches for automatically combining the height information are studied. It is observed that the measurement accuracy can be improved using the proposed method and the influence due to ambient lights and reflectivity variations can be suppressed. Computer simulations are performed to verify the effectiveness of the proposed method. The proposed method can also be integrated into other FPP systems to improve the performance for dynamic object measurements.

Keywords: Fourier transform profilometry; dynamic object measurements; motion compensation

1. INTRODUCTION

3D shape measurement for object surface shape reconstruction has potential applications in many areas, such as security, manufacturing, entertainment, and so on. Fringe projection profilometry (FPP) is a representative non-contact technique for 3D shape measurements [1]. Phase shift profilometry (PSP) is one of the most widely studied FPP techniques. With PSP, three or more fringe patterns are projected. The patterns deformed by the object are captured by a camera and then analyzed to retrieve the 3D shape information. In general, PSP is robust to noise. However, the conventional PSP assumes static objects and the motion of the objects can significantly degrade the performance due to the loss of the correspondence of the points. Liu *et al.* [2] propose an error compensation algorithm by estimating the motion parameters of the object from successively captured 3D frames and then use the projector's pinhole model to compensate the motion error. Lu *et al.* [3] propose a modified PSP approach targeting dynamic objects, which estimates the motion parameters (i.e., the rotation matrix and translation vector) using feature points. After that, the correspondence between the pixels in the different fringe patterns are utilized to retrieve the shape of the moving object. These methods generally require higher computational complexity and the existing techniques can only handle certain special cases such as 2D movements.

Fourier transform profilometry (FTP) can reconstruct the object shape based on a single fringe projection, and is thus less sensitive to the motion-induced errors in dynamic shape measurements. However, it is more sensitive to background light and the inherent noise in the system as compared with PSP [4], [5]. Meanwhile, FTP may perform poorly when the object

has fast variation or discontinuity in its height [1, 6]. It is thus of interests to improve the FTP. Numerous approaches have been studied [7, 8]. For example, the π -shift FTP method [9] uses two line-scan cameras and phase-shifted subpatterns to improve the measurement of objects moving at a constant speed. With this method, each point is measured twice during movement and shape reconstruction is improved by removing the influence of background light. Sophisticated carrier removal techniques also improve the measurement accuracy [10, 11]. In [12], two-dimensional Hanning windowing is applied to two-dimension FTP to achieve better separation of the height information from noise, which is particularly helpful for discontinuous surfaces. A similar approach based on windowed Fourier transform and Gaussian filtering is studied in [13]. There are also studies that improve the phase unwrapping performance for dynamic shape measurements [14]. Most of the above modified FTP schemes are single-shot methods and their performance is still limited.

In this paper, we propose to modify the traditional single-shot FTP scheme. In order to suppress the influence of noise for dynamic object measurements, we propose to fuse the measurement results from multiple fringe patterns, utilizing the motion parameters and the correspondence between the points in different measurements. Examples for two-dimensional and three-dimensional movements are demonstrated, which shows that the proposed method can effectively improve the measurement accuracy.

2. SYSTEM MODEL

The FTP system consists of a projector that projects the fringe patterns and a camera capturing the patterns deformed by the object, as illustrated in Fig. 1. The distance between the lens of the projector and that of the camera is d_o and the distance between the lens of the camera and the reference plane is L_o . The optical axis P1-P2 of the projector lens crosses the optical axis I1-I2 of the camera lens at point O on the reference plane. A light from point P2 to point A is reflected by the object, producing the deformed fringe pattern. From the image captured by the camera, the phase difference caused by the object as compared to the reference pattern is used for retrieving the height h of the object.

Figure 1. FPP system model

The fringe pattern deformed by the object can be written as [8]:

$$g(x, y) = r(x, y) \sum_{n=-\infty}^{\infty} A_n \exp \left(i(2\pi n f_0 x + n\phi(x, y)) \right), \quad (1)$$

and the reference fringe pattern is given by

$$g_0(x, y) = r_0(x, y) \sum_{n=-\infty}^{\infty} A_n \exp \left(i(2\pi n f_0 x + n\phi_0(x, y)) \right), \quad (2)$$

where $r(x, y)$ is the (nonuniform) reflectivity of the object surface and $r_0(x, y)$ is the reflectivity on the reference plane, A_n is a Fourier series coefficient and f_0 is the fundamental frequency of the projected fringe pattern. The differences $\Delta\phi(x, y) = \phi(x, y) - \phi_0(x, y)$ between the phases $\phi(x, y)$ and $\phi_0(x, y)$ carry the height information of the object relative to the reference plane.

With FTP, the fringe patterns are bandpass-filtered in the frequency domain, producing the filtered fringe patterns

$$\hat{g}(x, y) = A_1 r(x, y) \exp \left(i(2\pi f_0 x + \phi(x, y)) \right), \quad (3)$$

and

$$\hat{g}_0(x, y) = A_1 r_0(x, y) \exp \left(i(2\pi f_0 x + \phi_0(x, y)) \right). \quad (4)$$

From (3) and (4), the phase difference distribution [2] can be obtained as

$$\Delta\phi(x, y) = \text{Im}\{\log[\hat{g}(x, y) \times \hat{g}_0^*(x, y)]\} \quad (5)$$

where $*$ denotes conjugate. Note that $\{\Delta\phi(x, y)\}$ are limited to the range $[-\pi, \pi]$ with 2π discontinuities and phase unwrapping is used to obtain the absolute phase distribution $\Delta\Phi(x, y)$ [15]. Finally, the height distribution is found as

$$h(x, y) = \frac{L_0 \Delta\Phi(x, y)}{\Delta\Phi(x, y) - 2\pi f_0 d}. \quad (6)$$

3. MOTION COMPENSATION FOR MOVING OBJECT MEASUREMENTS

Because FTP requires only one captured image, the 3D shape information of the object can be retrieved regardless of the motion. However, it is sensitive to noise which cannot be fully mitigated by filtering [7]. Meanwhile, multiple measurements may be conducted for the same moving object and thus they can potentially be integrated to improve accuracy. In this work, we propose a scheme to combine the height maps retrieved from the multiple images captured, such that the influence from noise can be alleviated. In this paper, we assume rigid movements and that knowledge of the motion parameters is available, e.g., acquired using mark-based techniques [16].

We first consider 2D movements where the position of each single point in the x-y plane can change but the height remains unchanged. Assume that K images are acquired at K time instants, $k = 1, 2, \dots, K$, each generating a height map after applying FTP. Consider a point P on the object surface. Let (x_k^P, y_k^P) be its coordinate on the x-y plane at time instant k . The 2D movement, relative to the time instant $k = 1$, can be described by

$$\begin{bmatrix} x_1^P \\ y_1^P \end{bmatrix} = \mathbf{R}_k \begin{bmatrix} x_k^P \\ y_k^P \end{bmatrix} + \mathbf{t}_k, \quad \begin{bmatrix} x_k^P \\ y_k^P \end{bmatrix} = \bar{\mathbf{R}}_k \begin{bmatrix} x_1^P \\ y_1^P \end{bmatrix} + \bar{\mathbf{t}}_k, \quad (7)$$

where $\mathbf{R}_k, \bar{\mathbf{R}}_k, \mathbf{t}_k, \bar{\mathbf{t}}_k$ are referred to as rotation matrices and translation vectors

$$\mathbf{R}_k = \begin{bmatrix} r_k^{11} & r_k^{12} \\ r_k^{21} & r_k^{22} \end{bmatrix}, \quad \mathbf{t}_k = \begin{bmatrix} t_k^1 \\ t_k^2 \end{bmatrix}, \quad \bar{\mathbf{R}}_k = \begin{bmatrix} \bar{r}_k^{11} & \bar{r}_k^{12} \\ \bar{r}_k^{21} & \bar{r}_k^{22} \end{bmatrix}, \quad \bar{\mathbf{t}}_k = \begin{bmatrix} \bar{t}_k^1 \\ \bar{t}_k^2 \end{bmatrix}, \quad (8)$$

$$\bar{\mathbf{R}}_k = \mathbf{R}_k^{-1}, \quad \bar{\mathbf{t}}_k = -\mathbf{R}_k^{-1} \mathbf{t}_k. \quad (9)$$

With 2D movements in the reference plane, the true height of the point P does not change during the movements, i.e.,

$$h_1(x_1^P, y_1^P) = h_2(x_2^P, y_2^P) = h_3(x_3^P, y_3^P) = \dots = h_K(x_K^P, y_K^P) \quad (10)$$

where $h_k(x, y)$ denotes the height profile of the object at the k th time instant. With the proposed method, we first retrieve rough height maps $\tilde{h}_k(x, y)$ by applying the standard FTP method to each image captured at the different time instants $k = 1, 2, \dots, K$. We next combine these height maps after compensating the motion effect to improve accuracy. This is based on the observation in (10). Note that due to the variations of the signal-to-noise-ratio (SNR), reflectivity, and orientation of the object with respect to the fringe patterns, the measured heights for the same point at different time instants have different accuracies. In order to effectively improve the overall accuracy, an appropriate way to combine the multiple height maps is required. Let the combining weights be $\{w_k\}$. The estimate of the height of the point P is computed as

$$\hat{h}_1(x_1^P, y_1^P) = \sum_{k=1}^K w_k * \tilde{h}_k(x_k^P, y_k^P), \quad (11)$$

where we have used the coordinates at time instant $k = 1$ to present the results. The optimal choice of $\{w_k\}$ is an open issue. In the present work, we consider a heuristic approach similar to the maximum ratio combining (MRC) [17] that chooses $\{w_k\}$ according to estimates of the SNR in the images $d(x, y)$ captured by the camera, which can be modelled as:

$$d(x, y) = a + b \cos(\varphi(x, y)) + n(x, y) \quad (12)$$

where the reflectivity effect is ignored, a and b are the background intensity and intensity modulation, $\varphi(x, y)$ is the phase, and $n(x, y)$ is the noise. Let T be the period of the fringe and Q the number of fringes. Assume zero-mean noises with variance σ^2 , which are independent of the fringe signals. We can verify

$$\frac{1}{QT} \sum_x d^2(x, y) \approx a^2 + \frac{b^2}{2} + \sigma^2. \quad (13)$$

Note also that the parameters (a, b) are known parameters. Therefore, we can obtain an estimate of the SNR of the captured image as

$$\Gamma \triangleq \frac{\frac{1}{QT} \sum_x (a + b \cos(\varphi(x, y)))^2}{\frac{1}{QT} \sum_x n^2(x, y)} \approx \frac{a^2 + \frac{b^2}{2}}{\frac{1}{QT} \sum_x d^2(x, y) - (a^2 + \frac{b^2}{2})}. \quad (14)$$

Using (14), we can estimate the SNR for the K images as $\{\Gamma_k\}$. Similarly to [16], we then set the combining weights in (11) as

$$w_k = \frac{\sqrt{\Gamma_k}}{\sum_{n=1}^K \sqrt{\Gamma_k}}. \quad (15)$$

The above treatments can be extended to the general three-dimensional movement. Similarly, the movement of a point P on the object surface is moved to a new point (x_k^P, y_k^P) following the relationship below

$$\begin{bmatrix} x_1^P \\ y_1^P \\ h_1^P \end{bmatrix} = \mathbf{R}_k \begin{bmatrix} x_k^P \\ y_k^P \\ h_k^P \end{bmatrix} + \mathbf{t}_k, \quad \begin{bmatrix} x_k^P \\ y_k^P \\ h_k^P \end{bmatrix} = \bar{\mathbf{R}}_k \begin{bmatrix} x_1^P \\ y_1^P \\ h_1^P \end{bmatrix} + \bar{\mathbf{t}}_k, \quad (16)$$

where the rotation matrices and translation vectors are

$$\mathbf{R}_k = \begin{bmatrix} r_k^{11} & r_k^{12} & r_k^{13} \\ r_k^{21} & r_k^{22} & r_k^{23} \\ r_k^{31} & r_k^{32} & r_k^{33} \end{bmatrix}, \quad \mathbf{t}_k = \begin{bmatrix} t_k^1 \\ t_k^2 \\ t_k^3 \end{bmatrix}, \quad \bar{\mathbf{R}}_k = \begin{bmatrix} \bar{r}_k^{11} & \bar{r}_k^{12} & \bar{r}_k^{13} \\ \bar{r}_k^{21} & \bar{r}_k^{22} & \bar{r}_k^{23} \\ \bar{r}_k^{31} & \bar{r}_k^{32} & \bar{r}_k^{33} \end{bmatrix}, \quad \bar{\mathbf{t}}_k = \begin{bmatrix} \bar{t}_k^1 \\ \bar{t}_k^2 \\ \bar{t}_k^3 \end{bmatrix}, \quad (17)$$

From the motion models we have

$$h_1^P(x_1^P, y_1^P) \triangleq f_k(x_k^P, y_k^P, h_k^P) = r_k^{31} * x_k^P + r_k^{32} * y_k^P + r_k^{33} * h_k^P(x_k^P, y_k^P) + t_k^3, \quad (18)$$

$$x_1^P = r_k^{11} * x_k^P + r_k^{12} * y_k^P + r_k^{13} * h_k^P(x_k^P, y_k^P) + t_k^1, \quad (19)$$

$$y_1^P = r_k^{21} * x_k^P + r_k^{22} * y_k^P + r_k^{23} * h_k^P(x_k^P, y_k^P) + t_k^2. \quad (20)$$

Let $\tilde{h}_k(\tilde{x}_k^P, \tilde{y}_k^P)$ be the height map estimated at the k th time instant. We can have a similar scheme to combine the height maps

$$\hat{h}_1(x_1^P, y_1^P) = \sum_{k=1}^K w_i * f_k(\tilde{x}_k^P, \tilde{y}_k^P, \tilde{h}_k^P). \quad (21)$$

4. SIMULATION

Consider an FTP system with $l_0 = 4000\text{mm}$ and $d_0 = 600\text{mm}$. The fringe spatial frequency is set to have 20 pixels in a period. A hemi-ellipsoidal object is placed on reference plane.

Fig.2. Reconstruction results by traditional FTP for a 2D movement object: (a) Retrieved height map with SNR=30dB at time instant $k = 1$; (b) Retrieved height map with SNR=25dB at time instant $k = 2$; (c) Retrieved height map with SNR=20dB at time instant $k = 3$;

Fig.3. Reconstruction result by proposed method for 2D movement object

In the 2D movement example, we assume three consecutive measurements are made with rotation and translation parameters given by

$$\bar{\mathbf{R}}_2 = \begin{bmatrix} 0.9986 & 0.0523 \\ -0.0523 & 0.9986 \end{bmatrix}, \bar{\mathbf{t}}_2 = \begin{bmatrix} 1.2 \\ 3 \end{bmatrix}, \quad \bar{\mathbf{R}}_3 = \begin{bmatrix} 0.9986 & -0.0523 \\ -0.0523 & 0.9986 \end{bmatrix}, \bar{\mathbf{t}}_3 = \begin{bmatrix} 3 \\ 2 \end{bmatrix}. \quad (22)$$

The reconstruction results are shown in Fig. 2 for three time instants with different SNRs. The object height estimates have mean square errors (MSEs) 0.008, 0.0139 and 0.0374, respectively. After combining the results as in (11), the MSE is reduced effectively to 0.0053 in Fig.3, which shows significant improvements in the measurement accuracy.

Fig.4. Reconstruction results by traditional FTP for a 3D movement object: (a) Retrieved height map with SNR=27dB at time instant $k = 1$; (b) Retrieved height map with SNR=25dB at time instant $k = 2$; (c) Retrieved height map with SNR=23dB at time instant $k = 3$;

Fig.5. Reconstruction result by proposed method for 3D movement object

We also consider a 3D movement example with the following parameters

$$\bar{\mathbf{R}}_2 = \begin{bmatrix} 0.9999 & -0.0056 & -0.0083 \\ 0.0056 & 0.9999 & 0.0083 \\ 0.0083 & -0.0084 & 0.9999 \end{bmatrix}, \quad \bar{\mathbf{t}}_2 = \begin{bmatrix} 4 \\ -2 \\ 1 \end{bmatrix}, \quad (23)$$

$$\bar{\mathbf{R}}_3 = \begin{bmatrix} 1 & -0.0028 & 0.0056 \\ 0.0027 & 1 & -0.0056 \\ 0.0056 & 0.0055 & 1 \end{bmatrix}, \quad \bar{\mathbf{t}}_3 = \begin{bmatrix} -2 \\ 2 \\ 1 \end{bmatrix}. \quad (24)$$

The SNR of 27 dB, 25dB and 23dB are assumed for the three time instants and the resulting MSEs are respectively observed as 0.0224, 0.0333 and 0.0309 in Fig.4. After combining the results with the motion effect compensated, the final MSE in Fig.5 is reduced to 0.0101.

5. CONCLUSION

In this paper, a new method is proposed to improve the surface measurement accuracy for objects in motion. The measurement errors with FTP due to noises are suppressed by fusing the results measured at different time instants using weighted average after compensating the motion effects. Both 2D and 3D movements are considered. The performance of the proposed method is verified by simulations. The proposed method is based on conventional FTP, and thus its performance is still sensitive to the slope of the object. The computational complexity is slightly higher than single-shot FTP. Our future work includes experimental study of the proposed method and its implementation with practical motion parameter estimation.

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