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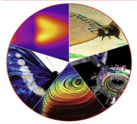

Full length article

Intrinsic feature revelation of phase-to-height mapping in phase measuring profilometry

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ABSTRACT

In traditional phase measuring profilometry (PMP) setup, the connecting line between the exit pupil center of projector and entrance pupil center of CCD camera must parallel to the reference plane and the optical axes of projector and CCD camera must intersect at the same point on the reference plane. At this condition, the coefficients of phase-to-height mapping are constants because they are proved to be only dependent on the structural parameters. But lots of experimental results show that some of coefficients are not constants. Further analyzing this phenomenon, it is found that the above two restricted conditions can hardly to be guaranteed due to the invisible of the exit pupil, the entrance pupil and the optical axes. The more popular situation is that the above connecting line may not parallel to the reference plane and the above optical axes do not intersect on the reference plane. So a new universal mapping algorithm is derived at this situation. It reveals some of coefficients of the mapping really remain constants which are dependent on only the structural parameters, while some of coefficients are really not constants which are dependent on not only the structural parameters but also the phase distribution of the reference plane. It also reveals that the traditional mapping algorithm is just a special case of the derived mapping algorithm. Furthermore, it reveals that the accuracy of PMP can be improved distinctly by calibrating the phase of the reference plane. Experimental results have shown the feasibility and validity of the derived phase-to-height mapping algorithm.

1. Introduction

Optical three-dimensional (3D) measurement with the advantages of high precision measurement, non-contact, non-destructive measurement, has been extensively used in medicine [1], reverse engineering [2], quality control [3], the mapping of topography[4] and so on [5]. Due to the advantages of point to point calculation and the whole field analysis, phase measuring profilometry (PMP) [6] is more popular in the industry. Traditional PMP system requires not only that the connecting line between the exit pupil of the projector and the entrance pupil of the CCD camera must parallel to the reference plane, but also that the two optical axes of projector and camera intersect at the same point on the reference plane [7–9]. When measuring the three-dimensional shape of the object, the phase of measured object can be obtained by the PMP system. In order to get the height of the object, phase-to-height mapping algorithm should be established [10,11]. The undetermined coefficients of the phase-to-height mapping algorithm can be obtained by structural parameters, such as the distance between reference plane and the exit pupil of the projector, the distance between the exit pupil of the projector and entrance pupil of the CCD camera and the angle between projector optical axis and CCD camera optical axis, etc [12–15]. But these structural parameters are hard to be accurately measured directly. So the undetermined coefficients of phase-to-height mapping algorithm can be calibrated by sufficient planes with known height and the corresponding phase distribution of the object [16–18]. Indeed, the above restrictions might be hard to be guaranteed in measurement. Therefore, many scholars are committed to changing the structure of measuring system and the corresponding phase-to-height mapping algorithms [19–21] had been developed sequentially. Zhou et al. [19] proposed that a direct phase-to-height mapping algorithm for PMP was presented. It had also shown that the mapping algorithm is the same in the two non-coplanar optical axes system as in the two coplanar optical axes system. Xiao et al. [20] discussed the connecting line above did not have to be parallel to the reference plane and the optical axis

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Abbreviations: SP1, structural parameters 1; SP2, structural parameters 2; Tra, traditional; Prop, proposed.

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of camera did not have to be orthogonal to the reference plane. But the two optical axes have to intersect at the same point on the reference plane. And it needs to consider CCD imaging and imaging space coordinate conversion. Mao et al. [21] discussed the connecting line between the exit pupil of the projector and entrance pupil of the CCD camera did not have to parallel to the reference plane and the two optical axes did not have to intersect at the same point on the reference plane. It was discussed and used in Fourier-transform profilometry (FTP) [22].

In this article, a more popular setup of PMP is discussed. Without considering that the connecting line between the exit pupil center of the projector and entrance pupil center of the CCD camera must parallel to the reference plane and that the optical axis of the projector and the optical axis of the CCD camera must intersect at the same point on the reference plane, the corresponding phase-to-height mapping algorithm in PMP is derived. It is found that some of the coefficients of the mapping algorithm are dependent on not only the structural parameters but also the phase distribution of the reference plane. It is also found that the traditional phase-to-height mapping algorithm is just a special case of the proposed phase-to-height mapping algorithm.

2. The principle of PMP

While a phase-shifting sinusoidal pattern is projected onto the measured object by projector, the intensity of the deformed pattern [6,7] captured by CCD camera is:

$$I(x,y) = R(x,y)[A(x,y) + B(x,y)\cos(\phi(x,y) + \delta)] \tag{1}$$

where $R(x, y)$ denotes heterogeneous reflectance of the object's surface, $A(x, y)$ is background intensity, $B(x, y)$ reflects the fringe contrast, $\phi(x, y)$ is phase modulated by the object's height, δ is the shifting phase. For N ($N \geq 3$) steps phase-shifting method, N frames of phase-shifting sinusoidal patterns are projected on the measured object one by one, the corresponding deformed patterns can be captured as:

$$I_n(x,y) = R(x,y)[A(x,y) + B(x,y)\cos(\phi(x,y) + 2n\pi/N)] \quad (n = 1, 2 \ldots N), \tag{2}$$

So the phase $\phi(x, y)$ can be retrieved [6]as:

$$\phi(x,y) = \arctan\left[\sum_1^N I_n(x,y)\sin(2n\pi/N) \Big/ \sum_1^N I_n(x,y)\cos(2n\pi/N)\right] \tag{3}$$

Due to its arctan operation, $\phi(x, y)$ is wrapped in $[-\pi, \pi]$. It is discontinuous. In order to get the unwrapped phase $\varphi(x, y)$, phase unwrapping [23–26] is needed. In order to get the height of measured object, the phase-to-height mapping algorithm should be established.

3. Traditional phase-to-height mapping algorithm

Fig. 1 shows the traditional setup of PMP system. The point P and E are the light centers of the projector and the CCD camera respectively. PO is optical axis of the projector. EO is the optical axis of the CCD camera and is orthogonal to the reference plane. PO and EO cross at the point O on reference plane. The connection line PE is parallel to reference plane. Where d is the distance of PE, and L is the distance between CCD camera and reference plane, and l is the distance between projector and point O on reference plane, and θ is the angle between projector optical axis and CCD camera optical axis, they are all the structural parameters of the system.

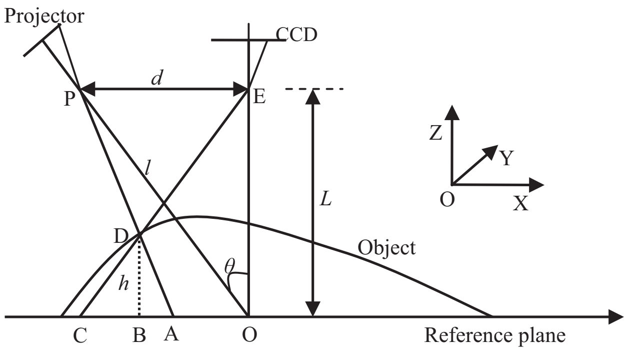

Fig. 1. Traditional setup of PMP.

In Fig. 1, D is the arbitrary point on the tested object, h denotes the distance between D and reference plane. In ΔPDE and ΔADC,

$$1/h = 1/L + (d/L)(1/\overline{AC}) \tag{4}$$

$$\text{where } L = l\cos\theta,\ \overline{AC} = (\varphi_C - \varphi_D)\,p/2\pi = \varphi_{CD}\,p/2\pi, \tag{5}$$

in Eq. (5), p denotes the patterns period of reference plane under divergent illumination, $1/p = \cos\theta(1 - 2x\sin\theta/l)1/kp_0$ [27], where p_0 is the period of sinusoidal patterns, and k is the magnification of the projecting system.

$$\text{Let} \begin{cases} a_1 = 1/l\cos\theta \\ b_1 = 2\pi\tan\theta/p \end{cases}, \tag{6}$$

Eq. (4) can be expressed as:

$$1/h = a_1 + b_1/\varphi_{CD}, \tag{7}$$

where a_1 and b_1 are called the coefficients of phase-to-height mapping. Li Wansong et al [18] proposed to consider aberrations of the imaging system in measurement. Eq. (7) is amended as:

$$1/h = a_1 + b_1/\varphi_{CD} + c_1/\varphi_{CD}^2, \tag{8}$$

c_1 is the coefficient for aberrations. With the detector arrays [19], the Eq. (8) is rewritten as:

$$1/h(x,y) = a_1(x,y) + b_1(x,y)/\varphi_{CD}(x,y) + c_1(x,y)/\varphi_{CD}^2(x,y) \tag{9}$$

At present, the Eq. (9) is still widely used [28–30]. From Eq. (6), it is found that the coefficients $a_1(x, y)$ and $b_1(x, y)$ are only related to the structural parameters of system in theory and they should be constant. Therefore, they can be generated by calibration. Considering the difference of sensitivity about CCD pixel and random error, $a_1(x, y)$ and $b_1(x, y)$ are not constant, which should be presented the characteristic distribution of a horizontal plane with a certain fluctuating thickness. However, from a large number of experimental results, it is found that $b_1(x, y)$ does not show the characteristics of the above analysis. It is an oblique plane with a certain fluctuating thickness. Fig. 2 shows the characteristic distribution of $b_1(x, y)$ in three different structural parameters. From Fig. 2, the distributions of $b_1(x, y)$ are all oblique planes with different thickness and different angles.

Analyzing the above phenomenon, we know the exit pupil, the entrance pupil and optical axis are not visible, it is difficult for us to ensure that the connecting line PE parallels to the reference plane, and it is difficult for us to ensure that the above two optical axes just intersect at the same point O. The more popular setup with the above two restrictions relaxed is shown as in Fig. 3.