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On axis fringe projection: A new method for shape measurement

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ABSTRACT

The traditional fringe projection technique requires a non-zero angle between projection and observation directions to have sensitivity in the z direction. In this work, a new method for shape measurement using fringe projection is presented. In our case, the angle between projection and observation directions is zero, but the system presents sensitivity due to divergent projection which changes the fringes frequency in each one of the normal planes to z-axis. The accuracy of the new method proposed here is validated with real measurements obtained with a coordinate measuring machine (CMM) and compared with the standard fringe projection technique. Finally, we discuss the advantages of the new method.

1. Introduction

The use of the fringe projection technique for generating three-dimensional (3D) surface information has become one of the most active research areas in optical metrology during recent years [1–7]. The retrieval of the three-dimensional shape of an object is an issue of great interest for a wide range of applications such as heritage protection and industrial, technical and medical applications [3,4,6]. Standard fringe projection systems use an off axis setup for doing profilometry [1,2], but due to this configuration objects may present shadow areas where no fringe patterns are formed and, as a result, it would be impossible to obtain the elevation measure [8]. Many contributions to resolve the shadows problems have been reported. Hani et al. [8] proposed an image processing method using wavelet analysis for shadows detection. Bringier et al. [9] proposed a photometric stereo method to detect shadow and specularity. Feng et al. [4] proposed a method that predicts the appropriate exposure times based on the histogram distribution. Skydan et al. [10] proposed a method for shadows detection using a camera, two projectors and colored structured light. Hao et al., Harizanova et al. and Sasso et al. [11–13] have proposed methods based on the use of multiple projectors. Flores et al. [6] proposed a panoramic fringe projection method, but to have sensitivity in the system they incorporate a convex axicon. All these techniques are more complex because they use more than one projector, additional devices or need additional image data processing to solve the problem.

Standard fringe projection method uses a setup out of axis and the equation used to recover the shape is

$$z(x,y)=\frac{\varphi(x,y)}{2\pi}\frac{p}{\tan\alpha+\tan\beta} \tag{1}$$

where $\varphi(x,y)$ is the phase of the object, p is the pitch of the fringe pattern, α is the angle between the optical axis and the observer, and β is the angle between the optical axis and the projection direction [1]. It is easy to see that there is an indetermination in the equation when the system is on axis (i.e., $\alpha=0$ and $\beta=0$). However, if we could have an on axis fringe projection system, the problem with the shadows could be significantly reduced. In the following section, we show how to recover the object profile using a projected fringe pattern by using an on axis projection system. A pin-hole camera model is used to obtain the fringe pattern modulation by means of divergent rays. A theoretical model will be shown and it will be supported by experimental results. Discussions and conclusions will be given at the end of this paper.

2. On axis fringe pattern model

Let us consider a 3D orthogonal coordinate system with a camera placed at the origin O and a pinhole camera model, for simplification purposes [14]. The z axis is pointed in the viewing direction of the camera and is referred to as the optical axis. The reference plane S_0 where the fringes are projected on is placed at a distance L_0 from the origin of the coordinate system, as shown in Fig. 1. Without taking into account the background illumination, the equation for the fringe pattern on the reference plane S_0 can be written as follows:

$$I_0(x)=\cos(\omega_0 x) \tag{2}$$

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where $\omega_0 = 2\pi f_0$ and f_0 is the frequency of the fringes pattern projected at the reference plane. Only the light ray coming from a point P positioned at the plane S_0 with coordinates (L_0, p) which passes through the hole at the origin of the camera coordinate system meets the image plane at point P_i [14].

If we move S_0 a distance z from the image plane, perpendicular to the optical axis, the plane would be located at position S_1, and the point P would be shifted to position P' with coordinates (z, p). Now, the light ray passing through the center of the system O towards point P' intersects the plane S_0 in P'' with coordinates $(L_0, p+\Delta p)$ corresponding to point P_i'' at the image plane. The fringe pattern image I_1 can be written as

$$I_1(x) = \cos(\omega_1 x) \tag{3}$$

where $\omega_1 \neq \omega_0$ due to the fact that we are using divergent illumination. Now, we can obtain z by calculating the intersection of the ray $\overline{OP''}$ with the straight line $\overline{P'P}$. That is

$$\begin{cases} \overline{OP''} : x = \frac{p+\Delta p}{L_0} z \\ \overline{PP'} : x = p \end{cases}, \tag{4}$$

and solving for z, from the system equations we obtain

$$z = \frac{pL_0}{p+\Delta p} \tag{5}$$

where all the parameters are known, except Δp. By using Eqs. (2) and (3), Δp can be calculated. In order to do that, Eq. (3) can be rewritten as

$$I_1(x) = \cos(\omega_1 x) = \cos(\omega_0 x + \Delta\varphi(x)), \tag{6}$$

where $\Delta\varphi(x)$ is a shift in the x axis. On the other hand, if we shift the point x a distance Δp we have

$$I_0(x+\Delta p) = \cos(\omega_0 x + \omega_0 \Delta p) = \cos(\omega_0 x + \Delta\varphi(x)), \tag{7}$$

and then, the following equality holds:

$$\omega_0 x + \Delta p = \omega_0 x + \Delta\varphi(x). \tag{8}$$

Solving for Δp we obtain

$$\Delta p = \frac{\Delta\varphi(x)}{2\pi f_0} \tag{9}$$

Finally, substituting Eq. (9) into Eq. (5) we find the equation for z in terms of known parameters

$$z(x) = \frac{pL_0}{p + \frac{\Delta\varphi(x)}{2\pi f_0}} \tag{10}$$

But, as we are interested in the height differences $(h(x))$ measured from the reference plane, we get for a 2D system.

$$h(x) = L_0 - z(x) = L_0 - \frac{pL_0}{p + \frac{\Delta\varphi(x)}{2\pi f_0}} \tag{11}$$

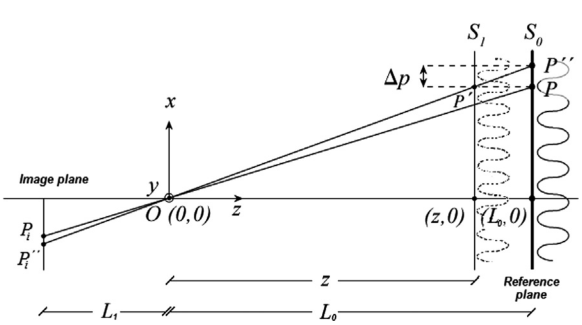

Fig. 1. Geometry of the model as seen from the y axis.

Finally, the system equations for all the rows, $h(x, y)$, can be expressed as

$$h(x,y) = L_0 - z(x,y) = L_0 - \frac{xL_0}{x + \frac{\Delta\varphi(x,y)}{2\pi f_0}} \tag{12}$$

Eq. (12) allows to recover the 3D object profile for all x, y, except for points in the vertical line $x=0$, because when $x=0$, $\Delta\varphi(x,y)=0$ and there is an indetermination in the equation right second term.

The latter can be clarified with the help of Fig. 2a that shows the reference plane perpendicular to the optical axis in 3D with a fringe pattern projected on it. If we place a new plane at distance $h(x, y)$ in front of the reference plane, we could see that the fringes that are in both sides of this plane would move laterally but the one that is in the optical axis would not. This effect is shown in Fig. 2b. This corresponds only to the fringe that is at the optical axis, and therefore, $\Delta\varphi(x,y)=0$ when $x=0$ and we cannot recover $h(x, y)$ at the optical axis. However, this can be solved by interpolating $h(x, y)$ for $x=0$ once we have

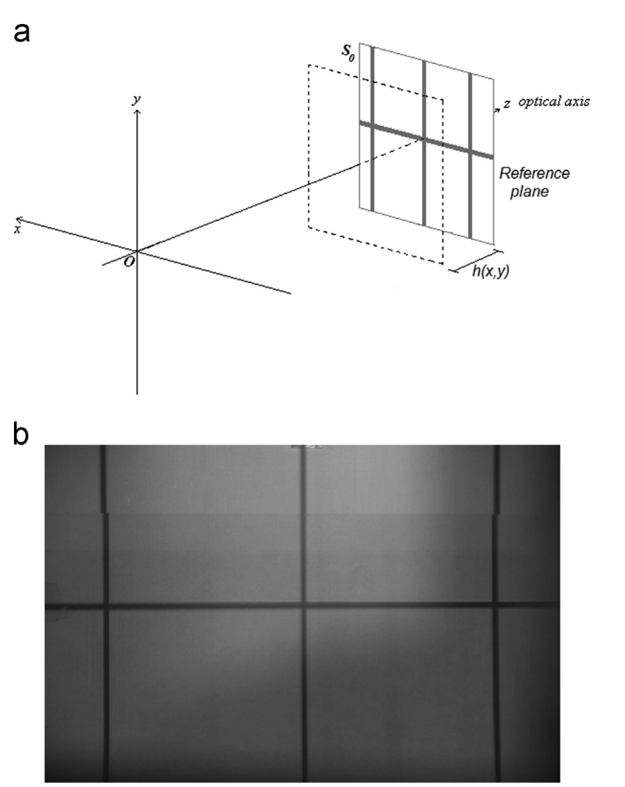

Fig. 2. (a) Diagram of the reference plane aligned with the optical axis in 3D, and (b) image captured with the camera showing the fringe shift when an additional plane of smaller height is placed in front of the reference plane.

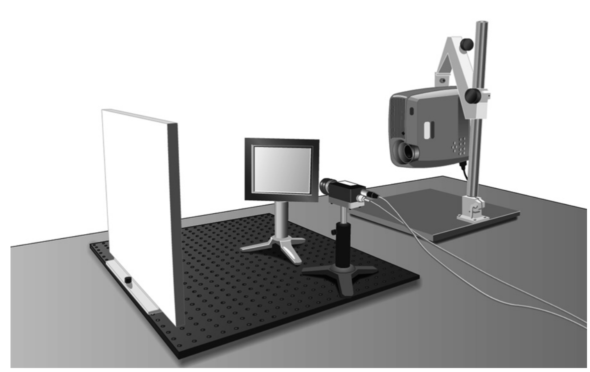

Fig. 3. Experimental setup.