Corneal surface reconstruction by using heterodyne moiré method

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ABSTRACT

In this paper, we propose a simple method for reconstructing the corneal surface profile by using the Talbot effect, projection moiré method, and heterodyne interferometry. A linear grating is obliquely illuminated by an expanding collimated light, and a self-image of this grating can be generated and projected on the corneal surface. The deformed grating fringes are imaged on the second grating to form the moiré fringes. If the first grating is moved with a constant velocity along the grating plane, a series of sampling points of the sinusoidal wave which behave like the heterodyne interferometric signal can be recorded by a CMOS camera. The phase distribution of the corneal surface then can be obtained with the IEEE 1241 least-square sine fitting algorithm and 2D phase unwrapping. Finally, the corneal surface profile can be reconstructed by substituting the phase distribution into special derived equation. This method provides the advantages of a simple optical setup, ease of operation, high stability, and high resolution.

Keywords: Corneal surface profile, projection moiré, Talbot effect, heterodyne interferometry.

1. INTRODUCTION

The refractive power of the cornea is over two-thirds of the total refractive power of the human eye. A slight variation of the corneal surface can significantly affect the normal human vision. Therefore, the accurate construction of corneal surface profile provides important and essential information in vision diagnosis process. Presently, various methods have been proposed for this purpose, such as the placido-disc topography[1,2], the slit scanning method[3,4] and the Scheimplug imaging method[5,6]. In this study, we propose a simple method for reconstructing the corneal surface profile. It is based on the Talbot effect, projection moiré method, and heterodyne interferometry. A linear grating is obliquely illuminated by an expanding collimated light, and a self-image of this grating can be generated and projected on the corneal surface. The deformed grating fringes are imaged on the second grating to form the moiré fringes. If the first grating is moved with a constant velocity along the grating plane, a series of sampling points of the sinusoidal wave can be recorded by a CMOS camera. The phase distribution of the corneal surface then can be obtained with the IEEE 1241 least-square sine fitting algorithm and 2D phase unwrapping. Finally, the corneal surface profile can be reconstructed by substituting the phase distribution into special derived equation. This method has the benefits of projection moiré method, Talbot effect, and heterodyne interferometery, including simple optical setup, ease operation, high stability and high resolution.

2. PRINCIPLE

Fig. 1 shows the optical configuration. For convenience, z-axis is set to be the observation axis of the CMOS camera, and the y-axis is set perpendicular to the paper plane. A laser light with a wavelength λ passes through a beam expander to form an expanded and collimated light, and impinges on a linear grating G_1 at an incident angle α with respect to the normal of the grating plane. The self-images of grating G_1 can be generated at the Talbot distances Z_T and can be expressed as[7]

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$$Z_T = \frac{mp^2}{\lambda}\cos^3(\alpha), \qquad m = 1, 2, 3... \tag{1}$$

where p is the pitch of grating G_1. Arranging the tested sample on the first Talbot distance (m = 1) of grating G_1, the grating fringes are self-imaged on the sample and deformed by the height distribution. Then, the deformed fringes are imaged with the magnification 1× on the grating G_2 of a pitch p to form the moiré fringes and captured by the CMOS camera C via a camera lens L_3. The moiré fringes can be extracted by filtering the high-order harmonics, and can be expressed as[8]

$$I(x,y) = I_0(x,y) + \gamma(x,y)\cos[\theta(x,y)+\eta], \tag{2}$$

where $\gamma(x, y)$ is the visibility of the signal, η is the relative phase induced by the relative displacement between two gratings, and $\theta(x, y)$ denotes the phase of the height distribution on the sample and can be expressed as

$$\theta(x,y) = \frac{2\pi}{p} H(x,y)\tan\alpha. \tag{3}$$

In Eq. (3), H(x, y) is the height distribution on the sample. Eq. (3) can be rewritten as

$$H(x,y) = \frac{p}{2\pi\tan\alpha}\theta(x,y). \tag{4}$$

According to above equation, it is obvious that the $\theta(x, y)$ is a function of H(x, y). Hence, the height distribution of the sample H(x, y) can be estimated by an accurately measurement of the phase $\theta(x, y)$.

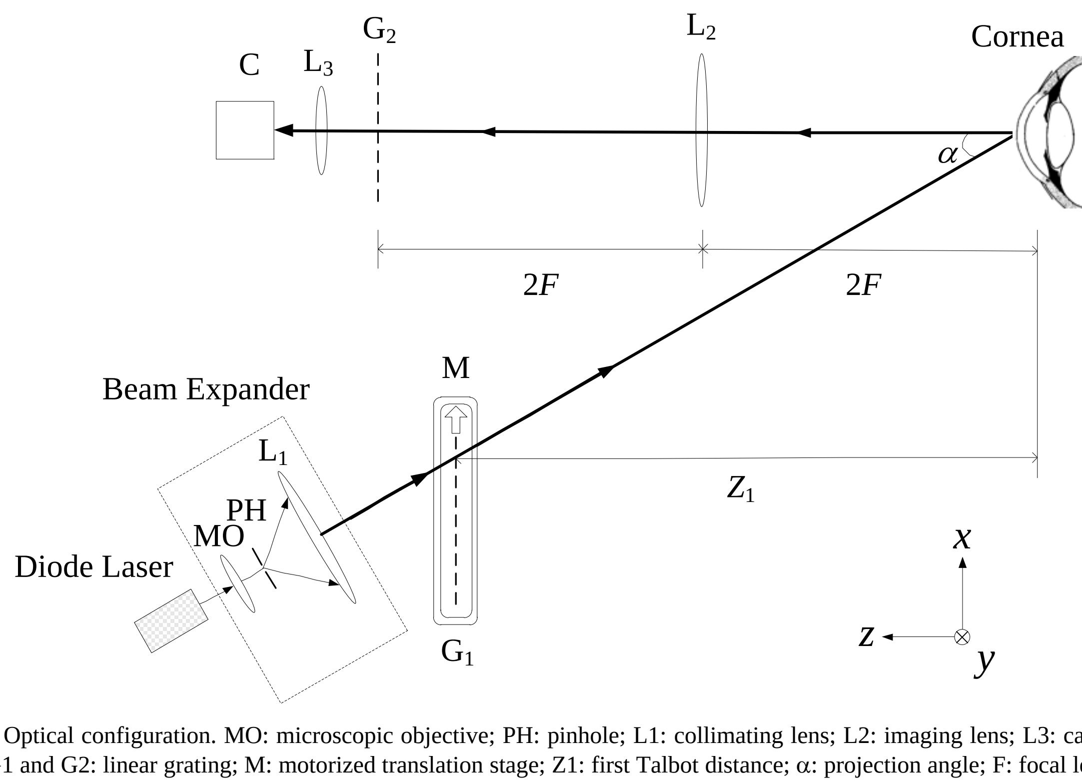


Fig. 1. Optical configuration. MO: microscopic objective; PH: pinhole; L1: collimating lens; L2: imaging lens; L3: camera lens; G1 and G2: linear grating; M: motorized translation stage; Z1: first Talbot distance; α: projection angle; F: focal length of imaging lens; C: CMOS camera.

In addition, when a motorized translation stage M moves the grating G_1 along the grating plane at a constant velocity v, the time-varying phase can be induced and expressed as

$$\eta = \frac{2\pi v t}{p} = 2\pi f_h t, \tag{5}$$

where f_h is the heterodyne frequency resulted from the time-varying phase. Each pixel of the CMOS camera records a series of sampling points of the sinusoidal waves. These sinusoidal waves behave like heterodyne interferometric signals. Hence, the light intensity at the CMOS camera C can be expressed as

$$I(x, y) = I_0(x, y) + \gamma(x, y)\cos[2\pi f_h t + \theta(x, y)], \tag{6}$$

To obtain $\theta(x, y)$, Eq. (9) can be rewritten as

$$I(x, y) = A\cos(2\pi f_h t) + B\sin(2\pi f_h t) + C, \tag{7}$$

where A, B, and C are real numbers, and the relationship between A, B, and $\theta(x, y)$ can be shown as

$$\theta(x, y) = \tan^{-1}\left(\frac{-B}{A}\right). \tag{8}$$

The terms A and B can be estimated by the least-squares sine wave fitting algorithm. Substituting A and B into equation (8) yields the corresponding phase $\theta(x, y)$ of the pixel. The phase distribution of the sample can be obtained by applying this procedure to the each pixel and using 2D phase unwrapping. The sample surface profile can then be reconstructed by Eq. (4).

3. EXPERIMENTAL RESULTS AND DISCISSION

To prove the feasibility of the proposed method, we measure the corneal surface of a pig eyeball, as shown in Fig. 2. The experiment setup includes: a diode laser with a wavelength of 473 nm, two linear gratings with a pitch of 0.2822 mm, a imaging lens with a focal length of 200 mm, a motorized translation stage (Sigma Koki/SGSP(MS)26 -100) with a resolution 0.05 μm to produce a heterodyne frequency f_h = 2 Hz (v = 0.5644 mm/s), and a CMOS camera (Basler /A504k) with a 8-bit gray level and the 1280×1024 image resolution. For convenience, the projection angle is set to be 30°, the frame rate of the camera f_s=30 fps, the exposure time Δt = 0.033 sec, and total recording time ΔT = 1 sec to record the interferometric signals at different time points. To improve the visibility of the projected grating fringes, we stain the fluorescein on the corneal surface. The experimental results have been shown in Fig. 3–Fig. 4. Fig. 3(a) and Fig. 3(b) show the moiré fringes recorded by the camera at 0 sec and 7/15 sec, respectively. Fig. 4 shows corneal surface profile estimated by the least-squares sine fitting algorithm and 2D phase unwrapping.

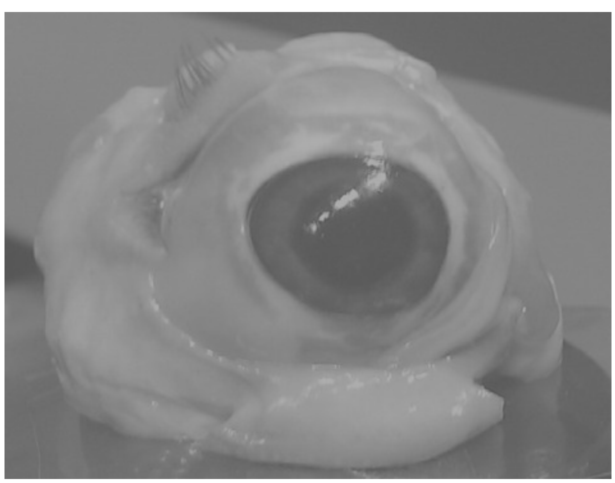
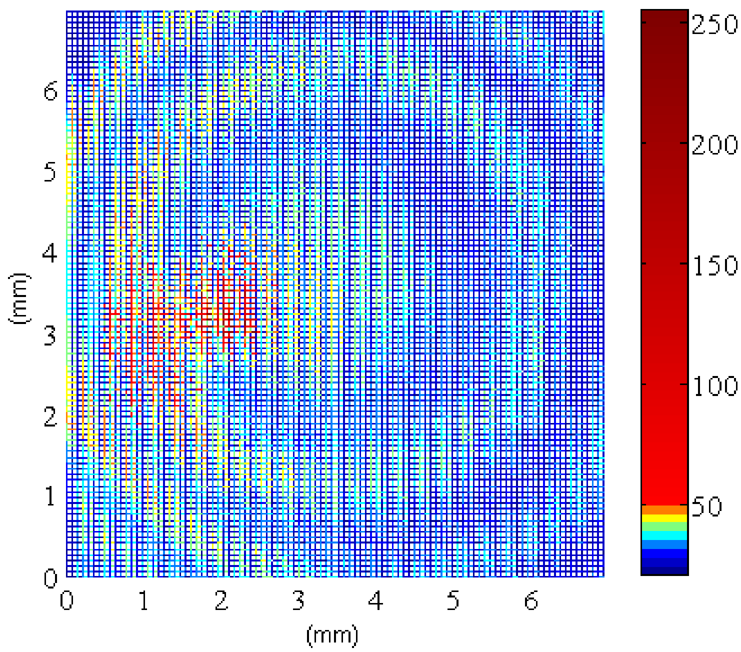
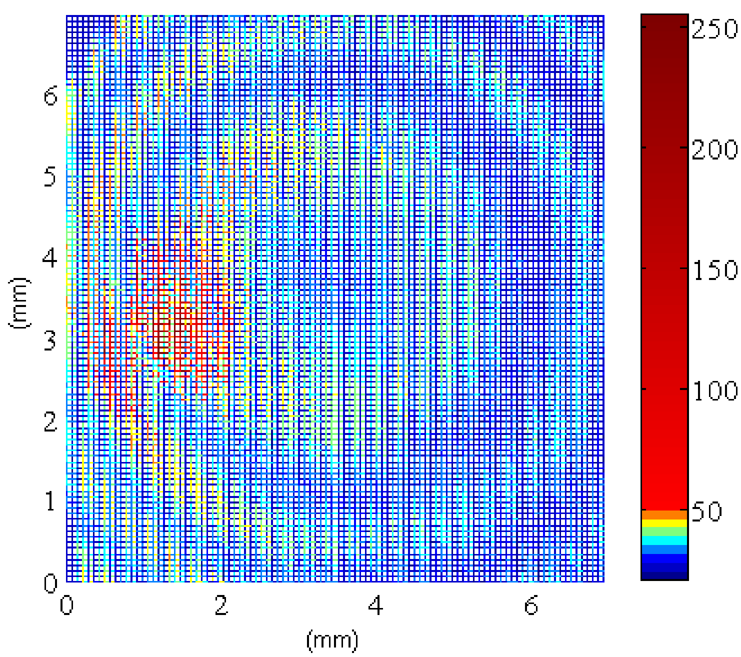


Fig. 2. The test sample of the pig eyeball



(a)



(b)

Fig. 3. Moiré fringes recordes by CMOS camera. (a) and (b) show the Moiré fringes at 0 s and 7/15 s.

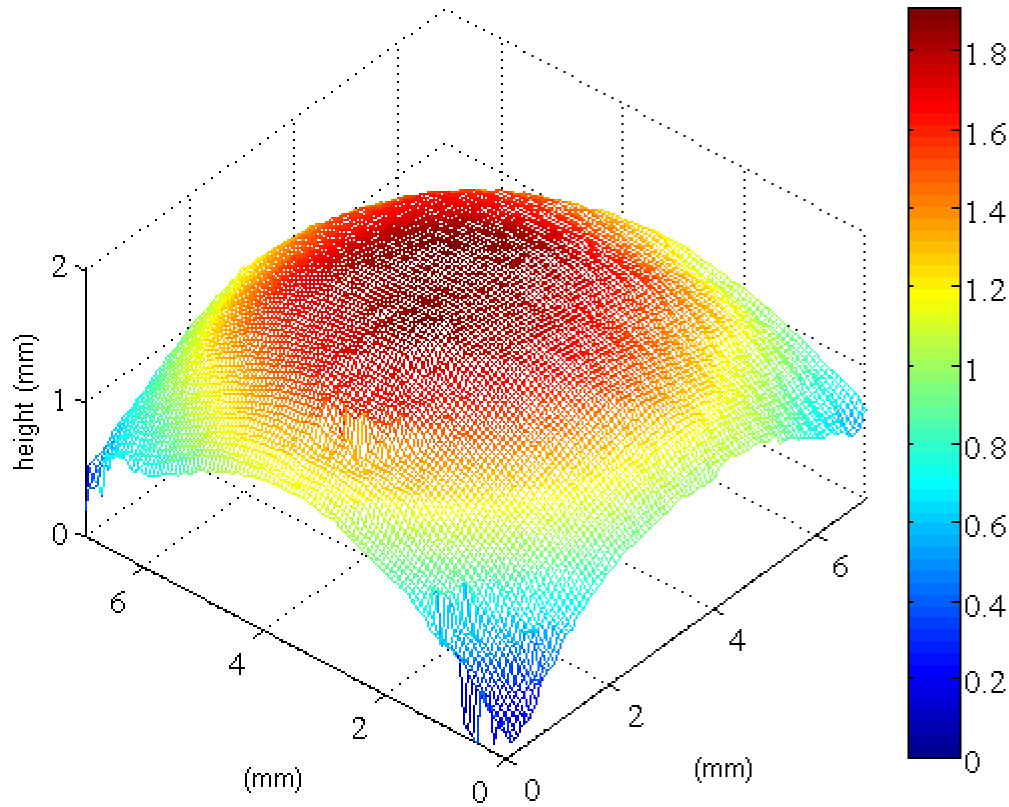


Fig. 4. Reconstructed surface profile of the pig cornea.

According to Eq. (4), the measurement height error ΔH can be expressed as:

$$\Delta H = \left|\frac{\partial H}{\partial p}\Delta p\right| + \left|\frac{\partial H}{\partial \alpha}\Delta \alpha\right| + \left|\frac{\partial H}{\partial \theta}\Delta \theta\right|. \tag{9}$$

where Δp is the grating pitch error, $\Delta\alpha$ is the projection angle error , and $\Delta\theta$ is the phase error. The grating pitch error Δp is caused by the grating fabrication. The gratings in experiment are fabricated by chromium plating on the glass substrates with the mask laser writer. So, the grating pitch error Δp is approximately 0.1 μm. The projection angle error $\Delta\alpha$ is introduced by the axis alignment error and the resolution of the rotary stage for alignment. Considering that the axis alignment error in experiment is 0.05° and the resolution of the rotary stage is 10 arcmin, the projection angle error $\Delta\alpha$ can be estimated about 0.22°. The phase error $\Delta\theta$ is introduced by the sampling error[9]. Considering that the visibility of the moiré fringes is 0.3, and according to the heterodyne interferometry, the phase error $\Delta\theta$ can be estimated about 0.32°. Substituting the experimental condition, Δp, $\Delta\alpha$, and $\Delta\theta$, into Eq. (9), the measurement height error ΔH is about 2.6 μm. This error analysis appears the proposed technique has high accuracy and high resolution. Therefore, the resultant corneal surface profile can provide the ophthalmologists more detailed information to make a better diagnosis.

4. CONCLUSION

This study proposes a simple method to reconstruct the corneal surface profile by using the Talbot effect, projection moiré method, and heterodyne interferometry. To show the validity of the proposed method, a corneal surface of the pig eyeball was measured in the experiment. The measurement resolution is approximately 2.6 μm. The proposed system approach has the benefits of projection moiré method, Talbot effect, and heterodyne interferometery, including simple optical setup, ease of operation, high stability, and high resolution.

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