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Three-dimensional shape measurement with sinusoidal phase-modulating fiber-optic interferometer fringe

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ABSTRACT

A three-dimensional (3-D) shape measurement system using a fiber-optic interferometer fringe projector is presented and demonstrated. The system utilizes sinusoidal phase shifting interferometry to detect the desired phase which is improved by introducing constant scaling factors from linear phase shift interferometry algorithm, and the relationship between the modulation voltage and the phase modulation coefficient is analyzed; the system also utilizes the reflection signal to realize measurement of the disturbance and feed back to the modulated signal. Practical experiments validate the feasibility of this method. The phase accuracy is nearly 37.6 mrad and the measurement error is about 10 nm.

1. Introduction

Recently, measurements using various kinds of interferometer have attracted intensive research interests as a technique for non-destructive and high accuracy three-dimensional (3-D) shape measurement [1–16]. Among these types, sinusoidal phase modulating (SPM) interferometry has been widely studied and used because of its insensitivity to changes in background. Moreover, it has high accuracy, and can easily be performed [5–6]. But one of the drawbacks of these systems is the limit for the external disturbance. For example, random phase errors, which are due to environmental disturbances such as refractive-index variations and vibration, will limit the accuracy of the recovered phase. Several experimental techniques have been developed to eliminate external disturbance [7–16].

The usual interferometer to eliminate the disturbance is Twyman-Green interferometer [11]. But some of the optical devices should be the same size as the object itself, this may enlarge the whole optical system. Also there is a distance between the measuring points with the CCD image sensor and a detecting point with the PD (even if it's very short). Since the optical path is not totally the same, the information obtained from the PD was not a completely representative of the disturbance information of the output signal.

Another way to eliminate the disturbance is direct compensation [12,13]. In this way, the disturbance is obtained by analyzing the output of the image sensor after a series of calculations, and then feeds back to the laser injection current. But the signal of the image sensor is a discrete signal in time, so it must be converted to a continuous signal which is equal to the signal for a specified measuring point. The conversion increases the complexity of the analysis and this is undesirable for manufacturing inspection.

In a previous work [17,18], we either demodulated the sine and cosine value of the disturbance information using PGC method or generated a compensation voltage signal $V_C(t)$ by a DA converter to compensate the external disturbance information, which increases the complexity and time of the system. In this paper, we present a sinusoidal phase-modulating fiber-optic interferometer fringe projector with a feedback control system to eliminate the external disturbances. The system utilizes sinusoidal phase shifting interferometry with some improvements to detect the desired phase. The progress is based on constant scaling factors from linear phase shift interferometry algorithm. Optical fibers provide not only a convenient form of beam delivery, but also a suitable way to implement phase modulation and control. The distal ends of the fibers provide convenient reflections for use in phase measurement. We utilize the change of the modulation voltage of piezoelectric transducer (PZT) to control the phase modulation coefficient z, as the conventional current modulation of the laser affects not only the wavelength but also the intensity of the laser beam, irrespective of modulating wave form [19]. We illustrate the linearity of PZT for phase modulation and demonstrate the effect of the linearity. Since the interference signals are modulated by step-type signals, the reflection signal from the distal ends of

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the fibers detected by a photodetector can be easily used to estimate the disturbance and feed back to the modulating signal. We calculate the external disturbance information and feed back to control the piezoelectric transducer directly. As the signal we obtained by photodetector is a continuous signal, it's much easier to process than the method of obtaining the discrete signal by the output of the image sensor.

We propose the principle of the optical system and the method to obtain a phase map from the sinusoidal phase-modulated interference signal in Section 2, and in Section 3, we describe the method to calculate the phase modulation coefficient z and discuss the relationship between the modulation voltage and the phase angle. The principle of the feedback control for the modulation voltage of PZT is described in Section 4. In Section 5 we construct a fiber-optic interferometer fringe projector to obtain phase modulation coefficient and measure the accuracy of phase stability.

2. Optical setup

The optical setup of the system is shown schematically in Fig. 1. Light from the laser is split into the signal arm (b) and reference arm (c) by a 2 * 2 optical coupler after passing through the optic isolator. The fiber ends of arm (b) and arm (c) are snapped into a fiber clip and compose a Mach–Zehnder interferometer. The reason why we utilize a fiber clip instead of another optical coupler is that the single-mode fiber optics (b) and (c) coil around the piezoelectric transducer (PZT) to generate the modulated signal. These polarization controllers are used to equalize the states of polarization of the emerging beams, thus maximizing the visibility of the projected fringes. The optical paths in both fibers were matched to within 1 mm to reduce the effects of laser frequency noise. The light produces interference fringes at the output and a fraction of this incident light is reflected at the endface of the output fiber and returns from the fiber (d). The light transmitted out of the fiber (d) projects onto the PD (Photodetector). We detect interference fringes with a CMOS image sensor to measure the displacement of the object.

Phase control is vibrated with two fiber optic phase modulators, of which each consists of fiber wrapped tightly around the piezoelectric transducer. The vibration is written as

$$I(t) = I_0 \cos(\omega t + \theta) \quad (1)$$

where I_0 is the amplitude of the current intensity, $\omega = 2\pi f$ is the modulation frequency, θ is the phase difference between CMOS exposure signal and the phase modulated signal. The interference signal which is detected by CMOS sensor is indicated as follows:

$$s(x,y,t) = A + B\cos[z\cos(\omega t + \theta) + \varphi(x,y)] \quad (2)$$

where A and B are the background illumination and the contrast between light and dark fringes; z is phase modulation coefficient, $\varphi(x,y)$ is the interferometer phase to be measured. Defining $\phi = \omega t + \theta$, expanding the harmonic terms of Eq. (2) in terms of its Fourier components yields [20]

$$s(x,y,t) = A + B\cos[\varphi(x,y)]J_0(z) + 2B\cos[\varphi(x,y)] \cdot \sum_{n=1}^{\infty}(-1)^n J_{2n}(z)\cos(2n\phi) - 2B\sin[\varphi(x,y)] \cdot \sum_{n=0}^{\infty}(-1)^n J_{2n+1}(z)\cos(2n+1)\phi \quad (3)$$

where J_n is the Bessel function of the first kind of order n. The time-dependent portion of the intensity signal is therefore a sum of harmonics n of the fundamental phase shift frequency.

Detection of the intensity signal requires collecting photons over a dwell time or integrating bucket, effectively averaging the signal over a portion of the phase shift. We detect the values with the CCD image sensor, and then integrate the mean value of the intensity at the phase shift phase α averaged over the interval β:

$$\bar{s}(\varphi,\alpha) = \int_{\alpha-\beta/2}^{\alpha+\beta/2} s(\varphi,\alpha')d\alpha' \quad (4)$$

where $s(\varphi,\alpha')$ is the instantaneous intensity as given by Eq. (2), and α' is the variable of integration over the dwell time expressed as the phase interval β. The effect of the frame integration is to attenuate the higher frequency harmonics by a factor [21]

$$K(n) = \frac{\sin(n\beta/2)}{n\beta/2} \quad (5)$$

The intensity signal is now

$$\bar{s}(\varphi,\alpha) = F(\varphi) + B\cos\varphi R(\alpha) + B\sin\varphi S(\alpha) \quad (6)$$

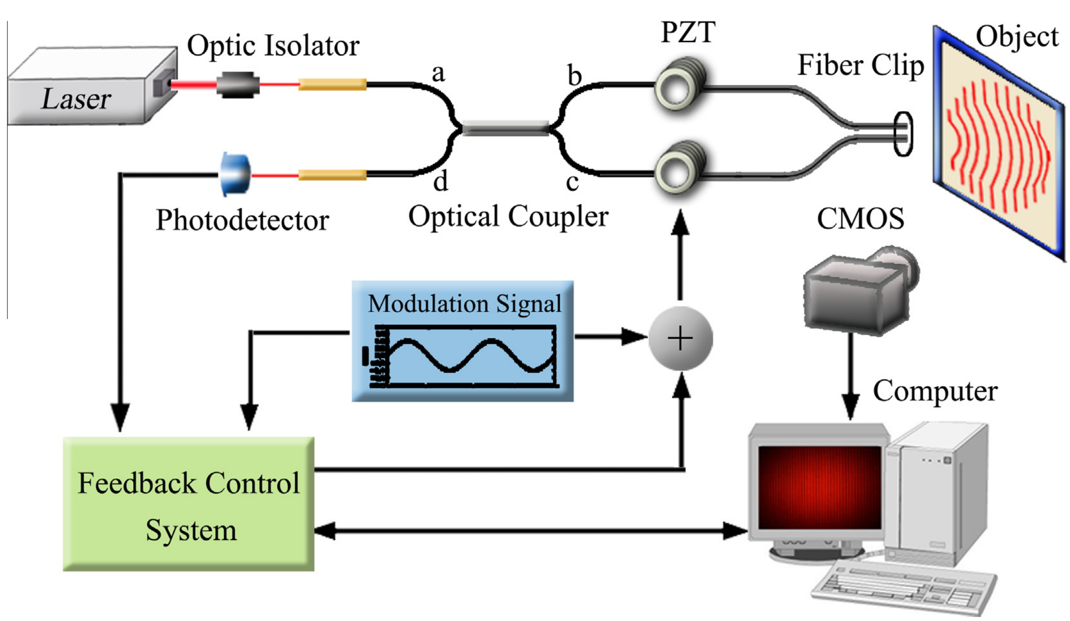

Fig. 1. Sinusoidal phase-modulating fiber-optic interferometer fringe projector with a feedback control system.