Optics & Laser Technology 79 (2016) 115–123

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Digital multi-step phase-shifting profilometry for three-dimensional ballscrew surface imaging

Cheng-Yang Liu*, Tzu-Ping Yen

Department of Mechanical and Electro-Mechanical Engineering, Tamkang University, New Taipei City, Taiwan

ARTICLE INFO

Article history:
Received 15 September 2015
Received in revised form
3 November 2015
Accepted 1 December 2015
Available online 10 December 2015

Keywords:
Phase-shifting
Fringe projection
Ballscrew

ABSTRACT

A digital multi-step phase-shifting profilometry for three-dimensional (3-D) ballscrew surface imaging is presented. The 3-D digital imaging system is capable of capturing fringe pattern images. The straight fringe patterns generated by software in the computer are projected onto the ballscrew surface by the DLP projector. The distorted fringe patterns are captured by the CCD camera at different detecting directions for reconstruction algorithms. The seven-step phase-shifting algorithm and quality guided path unwrapping algorithm are used to calculate absolute phase at each pixel position. The 3-D calibration method is used to obtain the relationship between the absolute phase map and ballscrew shape. The angular dependence of 3-D shape imaging for ballscrews is analyzed and characterized. The experimental results may provide a novel, fast, and high accuracy imaging system to inspect the surface features of the ballscrew without length limitation for automated optical inspection industry.

1. Introduction

Ballscrew is a high-efficiency mechanical actuator with the ball making a rolling motion between the nut and the screw. By using ballscrew, the rotational motion can be translated to the linear motion with little friction, low noise, and high carrying capacity. Therefore, ballscrew is widely used in the field of manufacturing and machine industries that require high acceleration, stiffness, and positioning accuracy. The positioning stability and accuracy of the ballscrew are directly affected by machining errors such as thread pitch error, ball track cross-section error, and ball track surface roughness. In order to ensure the required accuracy and reliability, the thread profile inspection of ballscrew is a significant study. The measurement of thread profile has been developed more than 20 years [1]. The several physical principles which involve mechanical and optical methods are used frequently. In traditional mechanical methods, the thread gauge or probe are usually used to estimate the thread profile. However, mechanical contact methods are less efficient and time consuming. For fast inspection of thread profile, the optical methods provide better accuracy. Laser interferometry has been applied to measure cross-sectional profiles of complicated shapes such as V-shaped grooves, gear tooth flanks, and thread gauge [2–5]. They presented a sinusoidally vibrating interference pattern as an exact spatial scale to detect the phase distribution. The measurement errors of laser interferometry are less than 4 μm in width and 0.2° in the angle for the groove shape. Recently, non-contact optical systems for measuring ballscrew profile have been proposed. A ballscrew contact angle measurement system is developed by using the photoelastic effect and digital image processing techniques [6]. The contact angle of ballscrew can be determined by using a photoelastic disk. Furthermore, a laser-based measuring system is proposed for the ballscrew and is used to decrease error by man-made factors [7,8]. The proposed systems combine a laser diode and a position sensitive detector and are simple installation for profile measurement. However, the measuring error in the image acquisition system is usually introduced as an effect of the adjustment of focal length and distortion of lens. The performance of the laser measuring system depends on the rotary error of the mechanism and the centric error between the laser beam and the lens. These laser-based measuring systems take long measuring time and only can measure the cross-section profile of ballscrew. Therefore, a fast, convenient, and high accuracy measuring system is required to inspect the surface features of the ballscrew without length limitation.

A series of optical information acquisition techniques for three-dimensional (3-D) shape measurement using phase-shifting fringe projection method have been developed [9–19]. Such optical system typically uses a projector to project fringe patterns onto target surfaces, a camera to acquire the distorted fringe patterns, and a computer to calculate the phase unwrapping and reconstruct the

* Correspondence to: No. 151, Ying-chuan Road, Tamsui District, New Taipei City, Taiwan.
E-mail address: cyliu@mail.tku.edu.tw (C.-Y. Liu).

http://dx.doi.org/10.1016/j.optlastec.2015.12.001
0030-3992/

3-D surface geometry. The processing steps for 3-D geometric reconstruction include digital fringe projection, wrapped phase estimation, phase unwrapping and 3-D geometric transformation. The multi-step phase-shifting algorithm is widely used in optical shape measurement because of its high resolution and speed. In phase-shifting algorithm, the phase difference between a target wavefront and a reference is altered and the resulting irradiance distribution is collected at each step. The wrapped target phase can be obtained according to the generalized multi-step phase-shifting algorithm. Many phase-shifting algorithms are performed well with sinusoidal periodic waveforms. The multiple phase-shifting techniques have been proposed to mitigate the phase error of non-sinusoidal fringe. An unwrapped phase is obtained from a phase-unwrapping method. Finally, a 3-D surface geometry can be reconstructed from the unwrapped phase and the geometric phase-height relationship. The theoretical and experimental results have proved that the distorted fringe patterns give us a wealth of information to illustrate 3-D surface of many targets. Many researchers have demonstrated that the fast shape measurement system can acquire and display high-quality 3-D reconstructed images of multiple targets with complex shapes [20–28]. The distorted fringe patterns on target surfaces are very sensitive to the profile of that target. A valid point detection framework has been proposed for fringe projection profilometry which includes k-means clustering, unwrapping error correction, and noisy point detection. Monotonicity, a root mean square error, and second order derivatives are used to suppress the noise influence. The phase-shifting fringe projection techniques can be used to gauge the complicated surfaces of ballscrew.

The phase-shifting fringe projection technique have been widely investigated in recent year with the development of charge-coupled device (CCD) camera and digital light processing (DLP) projector. In this paper, we present a digital imaging system to assess 3-D ballscrew surface based on the multiple-step phase-shifting technique. The straight fringe patterns generated by software are projected onto the ballscrew surface by the DLP projector. The distorted fringe patterns are captured by the CCD camera at different detecting directions for reconstruction algorithms. The seven-step phase-shifting algorithm and quality guided path unwrapping algorithm are used to calculate absolute phase at each pixel position. We have established a 3-D calibration method for the relationship between the absolute phase map and 3-D ballscrew surface. The principle of 3-D digital imaging system based on absolute phase measurement is introduced in Section 2. The experimental data on capturing 3-D ballscrew surface are demonstrated in Section 3. Finally, Section 4 gives the conclusions and future works.

2. Principle of 3-D digital imaging system

In order to achieve high stiffness and repeatable positioning, the ballscrews are required zero axial backlash and minimal elastic deformation. Therefore, after the fabrication process the measurement of 3-D ballscrew surface is very important. Seven-step phase-shifting fringe projection technique is used to obtain 3-D shape of ballscrew. Fig. 1 depicts the experimental apparatus of digital phase-shifting imaging system. The imaging system consists of a DLP projector (Acer K132+), a 1620 × 1236 pixels CCD camera (JAI AT-200CL), a motorized rotation stage (Sigma Koki KST-160YAW) and an industrial computer. The fringe patterns are created by computer program and projected onto a measured ballscrew surface by the DLP projector. The fringe pattern has a resolution of 1280 × 720 pixels. The camera assembly is mounted on a motorized rotating arm that detecting angle θ could be varied precisely. The fringe patterns are deformed with respect to the ballscrew surfaces. The deformed fringe patterns are captured by the CCD camera and saved into computer for post-processing.

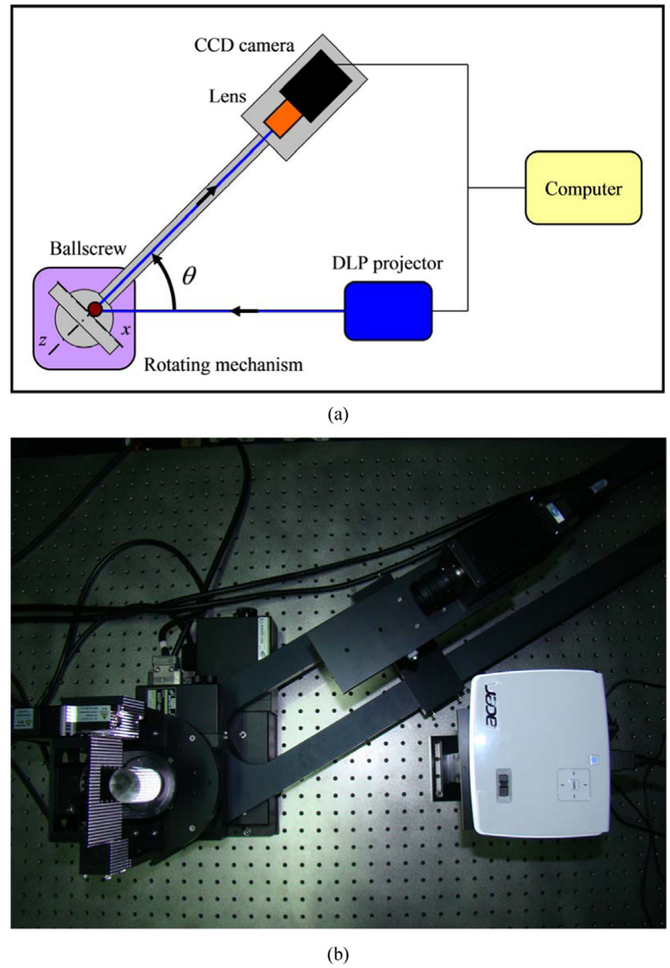

Fig. 1. Digital phase-shifting imaging system: (a) schematic diagram and (b) photograph.

Fig. 2 depicts the flowchart of 3-D ballscrew surface imaging acquisition and processing. The mathematical model and calculation process of fringe patterns are briefly described here. Four-step phase-shifting algorithm has been widely used to calculate phase information for many industrial applications [20–25]. The intensity distribution of a fringe pattern can be expressed in the general form:

$$I_k(i, j) = I_B(i, j) + I_A(i, j)\cos[\phi(i, j) + \alpha], \quad k = 1, 2, 3 \ldots \tag{1}$$

where i and j are the pixel indices along vertical and horizontal directions in the images, $I_k(i, j)$ is the intensity of the kth pattern at (i, j) pixel position, $I_B(i, j)$ and $I_A(i, j)$ are the intensity of the illumination and the fringe modulation, $\phi(i, j)$ is the phase corresponding to the shape information of object, α is the phase-shift of the patterns. The classical phase-shifting algorithms can therefore be used to determine the phase $\phi(i, j)$. In order to increase accuracy, the well-known four-step phase-shifting algorithm can be transformed into a seven-step phase-shifting algorithm which can be expressed as: