An Innovative Three-dimensional Profilometer for Surface Profile Measurement Using Digital Fringe Projection and Phase Shifting

Liang-Chia Chen[1], Shien-Han Tsai[1] and Kuang-Chao Fan[2]

[1] Institute of Automation Technology, National Taipei University of Technology, 1, Sec. 3, Chun-Shiao East Rd., Taipei, 106, Taiwan, R.O.C., E-mail: lcchen@ntut.edu.tw

[2] School of Mechanical Engineering, National Taiwan University, No.1, Sec. 4, Roosevelt Road, Taipei, Taiwan 106, R.O.C., E-mail: fan@ccms.ntu.edu.tw

Abstract. This article presents the development of a three-dimensional surface profilometer using digital fringe projection technology and phase-shifting principle. Accurate and high-speed three-dimensional profile measurement plays a key role in determining the success of process automation and productivity. By integrating a digital micromirror device (DMD) with the developed system, the exclusive advantages in projecting flexible and accurate structured-light patterns onto the object surface to be measured can be easily obtained. Furthermore, the developed system consists of a specially designed micro-projecting optical unit for generating flexibly optimal structured-light to accommodate requirements in terms of measurement range and resolution. Its wide-angle image detection design also improves measurement resolution for detecting deformed fringe patterns. This resolves the problem in capturing effective deformed fringe patterns for phase shifting, especially when a coaxial optical layout of a stereomicroscope is employed. Experimental results verified that the maximal measured error was within a reasonable range of the measured depth. Thus, the developed system and methodology can provide a useful and effective method for 3-D full-field surface measurement ranging from μm up to cm scale.

Introduction

Accurate three-dimensional optical contour measurement is greatly important to product design innovation and manufacturing automation. Current point-type measurement, either contact or non-contact, cannot always satisfy demanding market requirements, such as rapid design evaluation or guaranteed product quality. Fast and accurate three-dimensional measurement techniques with full-field measurement capability are thus highly demanded for sharpening product competitiveness. In particular, design and manufacturing of micro-electromechanical system (MEMS) devices require such a measuring solution for micro-scale and even submicro-scale dimensional inspection. This article thus focuses on the development of an innovative DMD-based 3-D contour measurement system to meet the above needs.

The projected fringe measurement technique is a kind of triangulation for out-of-plane and topology measurement. It refers to the use of different methods for creating a light pattern to be projected onto the surface of the object. Various light-path principles and photo sensors are used to detect the characteristic data of the object surface, and the technique can be roughly classified into active type and passive type depending on the manner of light source projection. The active type method projects the specially designed structured-light patterns onto the object's surface. The patterns can be light-dot-array, periodical sine waves or light beams. Variations in the curvature on depth of the object surface contour may lead to the deformation of the structured fringe projected onto the surface of the object. Therefore, subsequent to capturing the images of the deformed patterns, the object's three-dimensional contour data can be analyzed using the

acquired information. Methods of analysis used include the triangulation measurement method and the phase shift interference method.

This research aims to develop a three-dimensional surface profilometer using digital micromirror device (DMD) projection and phase-shifting principle. Integrating the DMD with the developed optical lens unit, the proposed system possesses the following measurement capabilities.

(1) Flexible (single, multiple or arbitrary period) projection of structured-light patterns onto the object surface to suit various inspection requirements, such as diverse sizes, colors and surface conditions of the object to be measured.

(2) Fast and accurate (high-contrast, high-resolution and high-brightness) projection of micro-scale structured-light patterns onto the object surface.

(3) Accurate acquisition of micro-scale surface contour of objects using the developed micro-projecting optical system.

Review Of Current 3-D Surface Measurement Technology Using Digital Fringe Projection Technique

In recent years, how to capture three-dimensional contour size of the object at high speed using optical non-contact techniques has been widely discussed. Comprehensive reviews of these techniques were provided by Tiziani [1], Chen [2] and Zhang [3]. Among various methods, the fringe projection technique is more commonly employed due to its easy setup and less intensive 3-D calculation. The fringe can be generated by projecting parallel light through optical grating slides with various projecting patterns, such as sinusoidal-like modulation. The traditional phase shifting method which involves moving a grating or a reference mirror physically has two problems, namely inefficiency due to mechanical movement, and unavoidable phase shifting errors incurred during the phase shifting process. Therefore, a computer-controlled LCD (liquid crystal display) or DMD was further proposed to generate flexible structured-light patterns with highly precise phase shifting.

The computer LCD projection method was first proposed to generate simultaneously arbitrary fringe patterns of a plurality of sets of different colors [4]. This method achieves better precision in generating structured-light fringes and more uniform projection, superior to the ordinary fixed projection light grating fringes. However, the LCD projection method is not the best and the size of LCD may be too big to be integrated for other applications that demand miniature instrument volume. This drawback may be overcome by replacing LCD with DMD chips. Thus, Zhang [5] and Chang [6] proposed the use of DMD for fringe generation. Their proposed system integrated digital projection moiré (DPM) and stereo zoom microscope for micro-scale surface measurement. Although their system can obtain successfully micro-scale gratings and micro-resolution surface measurement, the deformed fringe image may not be effectively acquired by the CCD due to the limitations of the existing coaxial optical layout of the stereomicroscope. This shortcoming may reduce the view depth of measurement and impede potential application. To overcome the above restriction and increase the flexibility of the light projection, this article develops a 3-D micro-scale surface profilometer system with a different optical layout.

SYSTEM DESIGN

Taking the above needs into consideration, we develop a three-dimensional DMD-based surface measurement system. This system integrates a light projection unit (DMD chip embedded), a developed optical lens unit and phase shifting technique for micro-level three-dimensional contour measurement. The schematic diagram of the system is depicted in Figure 1 and its hardware setup is illustrated in Figure 2. The optical lens unit is composed of the optical lens set of the projection module, a stereomicroscope and an image capture device. The digital light projector (DLP) can generate computer-controlled structured-light

patterns and project them onto the object's surface to be measured through the optical lens unit. The image-sensing element is then utilized to capture the deformed structured fringe image. The developed system consists of the following four subsystems.
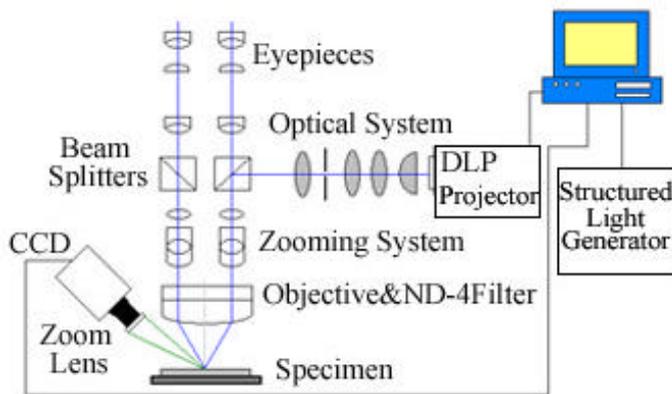

Figure 1   The schematic diagram of the developed DMD-based 3-D surface profilometer

Figure 2   Hardware setup of the developed micro-level measurement system

(1) Main control unit: this unit is connected to the optical projection unit and the image capture unit. It is used to adjust and control the structured-light pattern output of the optical projection unit and process the image information obtained by the image capture unit.

(2) Optical projection unit: this unit is designed for generation of parallel-like structured-light patterns with sinusoidal intensity. It is mainly composed of a DLP operated with DMD chip and the set of optical lens. A couple of collimating lens and the spatial-filter optical set are used to generate the desired image output. The structured-light pattern is first generated by a personal computer and passes through the set of optical lens, in which a parallel-like structured-light pattern can be produced and guided into the side port of the stereomicroscope. The rectangular size of the light pattern can be flexibly adjusted between 6.4x4.8 mm^2 and 2.8x2.1 mm^2. This fits the projected pattern perfectly into the various window sizes of the zoom lens when the zoom range varies between 1 and 6.3. This arrangement is important in obtaining the full resolution of the projecting DMD chip (a 1024x768 pixel resolution) for its best measurement accuracy.

(3) Micro-scale grating generator: a Nikon stereoscopic zoom microscope (SMZ 1000 or other similar model) is used to zoom the projected light pattern into micro-resolution light grating. Incorporating the optical unit with a zoom lens (1- 6.3 magnification range) and a 2X objective, the size of the projected rectangular pattern can be adjusted between 0.5x0.38 mm^2 and 11x8.25 mm^2. A projected light grating with a size down to 10 micrometers (shown in Figure 6(a)) can be generated when a structured-light with a period of 12 pixels is projected. For a cm-scale object measurement, a larger light pattern (2 - 50 cm^2) can be easily generated when the microscope is removed from the system.

(4) Image capture unit: this unit is mainly composed of the set of optical zoom lens and the image sensing element (a CCD). The set of optical lens captures the deformed structured fringe image from the object to be measured and sends them to the image sensing element, which can output the image information to the main control unit. It is important to note that the angle between the incident light and the image capturing axis was set to be larger than 45° for effective detection of deformed fringes.

Principle And Characteristics Of Digital Micromirror Device (DMD)

The DMD is an array of fast digital micromirrors, monolithically integrated onto and controlled by a memory chip [7, 8]. The digital light processing systems present bright and high contrast images using DMD.

The fast switching time of the mirrors enables the use of a pulse width modulation technique for the production of gray scale. Digital light is accurate because the light pulse durations are determined by the precise division of time. In addition, each digital light switch of the DMD is an aluminum micromirror, $16 \ \mu m^2$, which can reflect light in either direction, depending on the state of an underlying memory cell. The mirror rotation is limited by mechanical stops up to ± 10 degrees.

Fundamentals Of the Phase Shifting Technique

As shown in Figure 3 (depicted in the next page), a DMD chip is used as a light modulator to produce arbitrary structured-light patterns to be projected onto the object's surface. The structured-light patterns can be controlled and manipulated precisely by the computer. As sketched in Figure 5, Point O represents the center of the optical lens used for the CCD sensor [4]. If *Po* represents a 3-D point located on the object's surface and *Po¢*refers to the projected point on the X-Z plane, the depth (*Zo*) of *Po* can be represented as Equation (1):

$$Z_o = \frac{a}{\tan \boldsymbol{a} - \tan \boldsymbol{e}}$$ (1)

where $\boldsymbol{e} = \tan^{-1} \frac{x}{z}$

$(x, y, z) =$ image coordinate on the image coordinate $\boldsymbol{a} = (n + \boldsymbol{d}_n)\boldsymbol{a}_p$

$\boldsymbol{a}_p =$ angular pitch between projected fringes

$n =$ order of the projected fringe in which P_o locates

$\boldsymbol{d}_n =$ fractional order of the projected fringe in which P_o locates.

In Equation (1), $\boldsymbol{d}_n$ can be derived from the phase of P_o. According to the principle of general phase shifting, when the phase shifting sequence is set as p/2, p, 3p/2 and 2p; and the optical image strength on P_o can be recorded as I_1, I_2, I_3 and I_4, respectively $\boldsymbol{d}_n$ can be obtained from Equation (2).

$$\boldsymbol{d}_n = \frac{1}{2\boldsymbol{p}} \tan^{-1} \frac{I_3 - I_1}{I_4 - I_2}$$ (2)

Calibration And Error Compensation Of the Optical Lens System

The purpose of lens calibration is to identify the mathematical model for the accurate coordinate transformation between the lens system and the object's coordinates. In the calibration, the CCD's geometric and optical characteristics must be considered in order to compensate for distortions generated from the non-square aspect ratio, misalignment of the optical axis, lens distortion and some inaccurate image scanning parameters. The rigid body transformation from the CCD's coordinate system to the object system also needs to be determined. Tsai's camera calibration method [9], using a single view of non-coplanar points, has been employed to achieve the objectives outlined above. The errors encountered by the distortions were effectively measured and calibrated by the established camera model to be kept within an acceptable range (5%) of the overall measuring depth.

3-D Measurement Examples And Results

Some phase-shifting measurement experiments were performed to evaluate the performance of the developed 3-D profile measurement system. The developed system was first calibrated for its grayscale curve compensation and optical lens distortion and camera lens parameters to obtain a satisfactory accuracy of projected light patterns and detected image. The phase-shifting module was then used to generate phase-shifting patterns for projection and 3-D data calculation. The three-dimensional information was derived through image processing (low- and band-pass filtering) and phase wrapping and unwrapping processes.

The resolution of the DMD chip deployed in the developed system is 1024x768 pixels and the projected area of fringe patterns can be adjusted between 1736x1302 mm^2 and 0.5x0.38 mm^2 by manipulating the optical lens module. This allows a wide inspection range to suit different measurement requirements. Meanwhile, the system is capable of generating different colors of projected fridge patterns to suit different surface conditions of object for obtaining the optimum contrast. In addition, it is practically feasible that the speed of projecting fringe can be increased up to 30-100 Hz when the DMD color wheel with RGB (Red, Green and Blue) grayscale projection is synchronized with the CCD image acquisition.

In the experiment, two overlapping gauge blocks with an accurate step size of 0.500 mm were deployed to calibrate the system. As illustrated in Fig. 4, the 3-D map obtained by the developed system was employed to determine the system measurement accuracy. The results indicate that the measured errors are within 3% of the measured step size. In addition, a 3-D object with a sculptured human face was measured (shown in Figure 5(a)) to demonstrate the system's capability in macro-scale measurement. The size of the measured area was 60mm x 452 mm. Figures 5(b)-(d) show the 2-D phase-shifted image (b) and the phase wrapped image (c). The phase unwrapped image and its 3-D reconstructed profile are shown in Figure 5 (d) and (e), respectively. The accuracy of the measurement was evaluated by a coordinate measurement machine equipped with a touch-triggered probe (1μm accuracy) and the maximal measured error was found within 5% of the measured depth range. Another example (shown in Figure 6) with measurement of a BGA (ball gray array) sphere ball of a 750 μm diameter was performed to verify the system's capability of micro-scale grating projection (10μm interval) and surface contour measurement. Figure 6 (e) indicates that a sphere 2-D profile with a depth range of 200 μm was obtained.
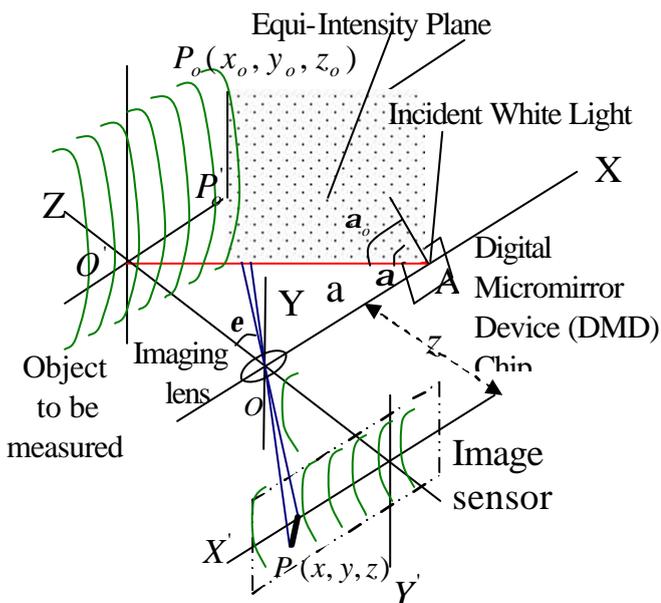

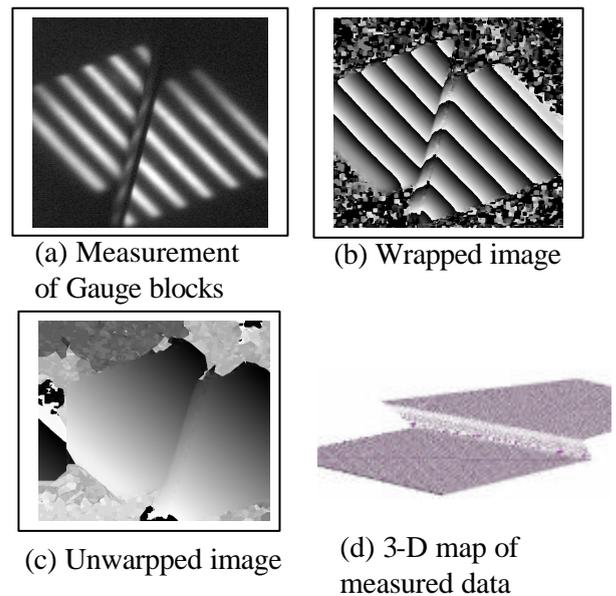Figure 3 Illustration of the 3-D DMD-based measurement system setup

(a) Measurement of Gauge blocks

(b) Wrapped image

(c) Unwarpped image

(d) 3-D map of measured data

Figure 4   Example of measurement of gauge blocks

(a)

(b)

(c)

(d)

(e)
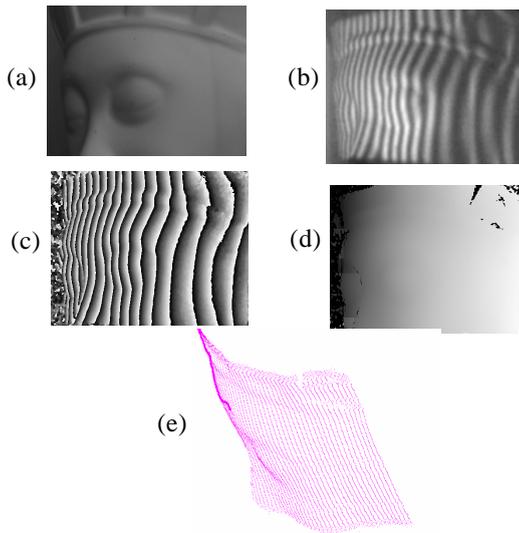
Figure 5   A sculptured human face (shown in (a)) with a rectangular size of 60x45mm^2 was measured as an example for macro-scale measurement. Figures (b) and (c) show the 2-D image of one of four phase-shifted fringe patterns (b) and the phase wrapped image (c). The phase unwrapped image and its 3-D reconstructed profile are shown in (d) and (e), respectively.
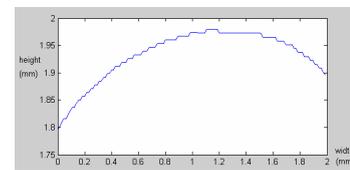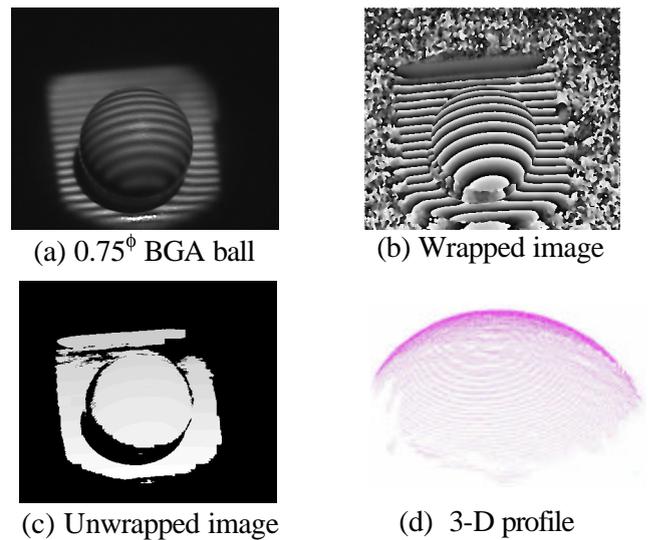

(a) 0.75$^\phi$ BGA ball

(b) Wrapped image

(c) Unwrapped image

(d) 3-D profile

(e) 2D section profile

Figure 6   A BGA sphere ball with a diameter 0.75mm was measured as an example for micro-scale measurement.

Conclusions

The proposed system has been successfully developed and some surface measurements were made to verify the system performance. The computer-controlled digital projection unit was used to generate four-step phase-shifting sinusoidal fringe patterns and the deformed fringe images were detected using a calibrated CCD. The three-dimensional surface contour was derived through image processing (signal processing, phase wrapping and unwrapping) and 3-D calculation. It was verified that the maximal measured error was within 5% of the measured depth range for 3-D macro and micro-scale surface contour measurement. Experimental results show that the developed system and methodology is effective in obtaining 3-D full-field surface measurement.

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