Automatic Digital Fringe Projection for Advanced Micro-Scale Connector Manufacturing System

Ching-Hua Lu, Cheng-Yang Liu

Department of Biomedical Engineering, National Yang-Ming University, Taipei City, Taiwan

cyliu66@ym.edu.tw

Abstract. The digital fringe projection microscope has been investigated and used to estimate three-dimensional shape of micro-scale connector for advanced manufacturing system. This measurement system consists of digital projector, optical lenses, stereo microscope, and digital camera. In the software, the imaging program based on including black and white structure light, seven-step phase-shifting calculation, and path-independent phase unwrapping is well developed. The imaging results indicate that the three-dimensional shape of micro-scale connector is acquired by using this measurement system. The optical resolution of this measurement system is 3 μm and the measurement speed is 0.6 s. This measurement system has excellent performance including easy operation, fast measurement speed and high resolution. This measurement system can be applied to real-time three-dimensional shape detection in product processing of micro-scale connector.

1. Introduction

In recent years, three-dimensional (3-D) optical shape measurement has become a popular research subject [1-10]. As a significant contactless shape measurement technology, phase-shifting projected fringe profilometry is widely used in profile inspection, reverse engineering, and advanced manufacturing system [11-20]. Compared to other 3-D measurement methods, such as laser scanning, phase-shifting fringe projection has the advantage of real-time acquiring dense point clouds. 3-D surface calculation is typically based on triangulation known from photogrammetry. Finding homologous points from captured images by phase information is a critical work for fringe projection system. Current method for establishing is one camera and one projector. In order to simplify match corresponding points, epipolar geometry is introduced into fringe projection calculation. This method can be utilized to calibrate the extrinsic parameters and further calculate the points of 3-D surface. A potential advantage of fringe projection calculation is that the desired 3-D coordinates can be easily received by defining the resolution of phase raster. The phase correlation is used to calculate complex shape by combining fringe projection and photogrammetry. If all phase maps from camera are well captured, phase correlation can perform very well in finding homologous surface. However, in real applications, phase maps may inevitably represent abrupt and discontinuous because of the complexity of object surface and the directions of camera. To solve the problem of finding homologous surface from the complex phase maps, we propose the optical lenses based on a stereo microscope. By converting fringe projection from optical lenses and stereo-microscope, homologous surface of micro-scale connector can be easily and exactly calculated by phase values.
2. Principle of the system
For three-dimensional (3-D) measurement, a structured light is used by encoding seven fringe patterns and capturing the deformed patterns using a digital camera. Figure 1 shows the automatic digital fringe projection for advanced manufacturing system. The components of this system include a projector, a stereo-microscope, a set of optical lenses, a digital camera with 1920×1080 resolution and an industrial computer. A set of optical lenses includes a plano-convex lens, a biconcave lens, and a biconvex lens. The ray tracing calculation is used to obtain the position relationship of a set of optical lenses. The fast pattern switching is reached by the projection mechanism of the digital light processing. Seven fringe patterns are projected sequentially which permits to capture seven deformed patterns separately.

![Figure 1. Automatic digital fringe projection for advanced manufacturing system: (a) schematic diagram and (b) picture.](image)

Because the maximum numbers of fringe patterns are needed for calculations, the seven-step phase-shifting calculation is better for high-resolution measurement. A fringe pattern for different intensity distributions is defined by \( I_N \). The intensity distribution of the \( N \)th pattern is \( I_N' \). The average intensity of the background description is \( I' \). The distributed amplitude of the pattern intensity is \( I'' \). The phase shift between each fringe pattern is \( \pi/2 \). The equations of seven fringe patterns are described as:

\[
I_1 = I' + I'' \cos[\phi - \frac{3\pi}{2}]
\]

\[
I_2 = I' + I'' \cos[\phi - \pi]
\]

\[
I_3 = I' + I'' \cos[\phi - \frac{\pi}{2}]
\]

\[
I_4 = I' + I'' \cos[\phi]
\]

\[
I_5 = I' + I'' \cos[\phi + \frac{\pi}{2}]
\]

\[
I_6 = I' + I'' \cos[\phi + \pi]
\]

\[
I_7 = I' + I'' \cos[\phi + \frac{3\pi}{2}]
\]

The intensity of light source and fringe patterns is supposed in the same value. The phase in these fringe patterns can be retrieved by the equation (2).

\[
\phi = \tan^{-1}\left[\frac{3I_4 + I_7 - I_1 - 3I_5}{4I_4 - 2I_2 - 2I_6}\right]
\]
The phase value is a range of \(-\pi\) to \(+\pi\) in Eqs. (2) and (4). The continuous phase information is obtained by phase unwrapping calculation. We use quality guided path algorithm for unwrapping calculation. The quality guided path calculation is suitable for unwrapping from complex surfaces.

3. Results and discussion

A structured light is used by encoding seven fringe patterns for high-speed surface measurement. Figure 2 shows the seven-step fringe patterns projected on a micro-scale connector. Seven phase-shifted fringe patterns are used to reconstruct 3-D profile through phase wrapping, phase unwrapping and phase to dimension conversion processes. The wrapped phase map is obtained by applying seven-step phase-shifting algorithm.

![Figure 2. Seven-step fringe patterns projected on the surface of micro-scale connector. The insert in the bottom right is the picture of micro-scale connector.](image)

Figure 3 shows the calculated wrapped phase map and unwrapped phase map by seven-step phase-shifting algorithm for micro-scale connector. This phase map indicates that the shape change strongly contributes to the wrapped phase information. Since the phase information in Fig. 3(a) is a periodic function of \(2\pi\), the unwrapped phase map is obtained by phase unwrapping calculation. Figure 3(b) illustrates the unwrapped phase map by quality guided path calculation for micro-scale connector. The absolute phase map is a continuous value in which the highest value shows a white point and the
lowest value shows a black point. The absolute phase map is converted into real 3-D shape by using the calibrated coefficients. The distorted fringe patterns are used to reconstruct 3-D shape through phase wrapping, phase unwrapping and phase to real size conversion. Using the proposed digital fringe projection system, micro-scale connector is captured and processed to obtain the 3-D representation. Figure 4 shows the 3-D representation of the captured micro-scale connector. The experimental results clearly show that the 3-D imaging system based on fringe projection technique correctly obtains the 3D surface of micro-scale connector. The seven-step phase-shifting calculation obviously mended the smoothness of the connector surface. The nonlinear phase errors in the 3-D representation are balanced by quality guided path unwrapping. The measurement capabilities of complexity and high-resolution for our digital fringe projection system are well proven.

![Figure 4](image)

**Figure 4.** 3-D representation of micro-scale connector.

4. Conclusion
In this research, a high-speed digital fringe projection microscope is proposed to measure 3-D surface of micro-scale connector. The optical source used in this microscope is structured light with fringe patterns. A projector is used as optical source to project structured light onto the connector surface. The distorted fringe patterns are imaged by the digital camera. The seven-step phase-shifting and quality guided path unwrapping calculations are used to compute the phase values. The digital camera is controlled by using an industrial computer. A complete 3-D surface of micro-scale connector is obtained by our digital microscope. The phase acquisition, shape reconstruction and exhibition have performed simultaneously at a speed of 0.6 s. The experimental results may provide a high-resolution and real-time 3-D shape detection for micro-scale connector in advanced manufacturing system.

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