Dynamic 3-D surface profilometry using a novel color pattern encoded with a multiple triangular model

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Abstract

In this article, a novel active structured fringe method for dynamic 3-D surface profilometry is presented with a color-encoded fringe pattern having multiple phase-shifted triangular modulation. Rapid 3-D surface profilometry is extremely important to automatic optical inspection (AOI) in modern high-tech industries. Three-step phase shifting can be simultaneously performed by encoding and analyzing red, green and blue color components of the projected color fringe patterns. Significant advantage can be obtained in eliminating arctangent calculation and one-shot imaging for obtaining dynamic full-field 3-D surface profile reconstruction. The experimental tests have been conducted to verify the capability of the method in achieving high-speed 3-D measurement with a maximum measurement error less than 2.8% of the overall detection range.

Keywords: Automatic optical inspection (AOI), 3-D surface profilometry, simultaneous phase-shifting, structured fringe

1. Introduction

The article presents a novel active structured fringe method for dynamic 3-D surface profilometry. Active structured-light projection employing triangulation principle is one of the most powerful 3-D profilometry techniques. This method has been widely applied to diverse industrial areas such as inspection of semiconductor chips, automobiles, food and pharmaceutical industries. The most common 3-D algorithm includes the following three kinds: Fourier Transform Profilometry (FTP), color-encoded structured light and phase shifting respectively. FTP is one of the important methods of 3-D profilometry, in which Takeda first proposed the idea [1]. Some improvements such as using Fourier Transform speckle to increase measurable step heights [2], modifying Fourier Transform to obtain better measurement performance [3], extending 1-D to 2-D Fourier Transform for reduced measurement time [4], or encoding patterns for generation of tilting-fringe projection [5, 6]. For color encoded structured light methods, Huang first employed a series of discontinuity number to form a spatially encoded structured-light pattern and proposed a general matrix to minimize the measured time [7]. However, this method has measurement limitation on its spatial resolution. To improve the drawback, Hall-Holt proposed a time-sequence color code to increase the resolution [8]. The other method is phase shifting method which may possibly satisfy measurement accuracy [9, 10, 11]. However, heavy computation of the arctangent operation required for phase retrieving may make the measurement difficult to be employed for any on-line inspection or machine vision. To resolve this, a considerable amount of research work has been carried to breakthrough such a bottleneck. Some recent research [12] [13] attempted to employ specially-defined structured patterns to obtain the phase map without phase unwrapping. The major drawback of the above method lies on traditional phase shifting procedure, which is too time-consuming and error prone. To improve this, simultaneous phase–shifting principle [14, 15] using multiple color structured pattern
projection were proposed to capture various phase-shifted fringe patterns within single CCD exposure time.

Therefore, the proposed method developed an innovative color encoded fringe pattern for simultaneous 3-D measurement. The triangular patterns were discussed in [12] which requires many images for calculating phase map of object surface. In proposed method, three-step phase shifting can be simultaneously performed by encoding and analyzing red, green and blue color components of the projected color patterns. Significant advantage can be obtained in eliminating arctangent calculation and one-shot imaging for obtaining full-field 3-D surface profiles. The developed system consists of a digital micro-mirror device (DMD) having a 1024 × 768 pixel resolution for generating color encoded fringe patterns, a three-chip color CCD with a high speed of up to 60 fps or higher, a personal computer for controlling the projector and acquiring the images through a suitable frame grabber and a set of optical lenses for obtaining the desired optical characteristics of the projected triangular pattern. The experimental results have been conducted to prove that the method is capable of achieving high-speed 3-D measurement with a maximum measurement error less than 2.8% of the overall detection range.

2. Simultaneous phase-shifting method using color structured patterns

![Diagram](image)

Fig. 1. (a) Schematic diagram of the developed 3-D vision system and (b) Flow chart of the proposed method.

The optical configuration and measurement principle of the developed method are shown in Fig. 1 (a) and (b), respectively. Digital fringe projection using optical triangulation principle is employed to detect optical path difference (OPD) using a simultaneous three-step phase shifting algorithm. The proposed method generates the color fringe pattern by combining three-color phase-shifted patterns into a single one, in which the period of the projecting fringe can be controlled flexibly according to the surface characteristics underlying measurement. When the pattern is projected on to the object surface, the color deformed fringe image captured by using a triple-color CCD camera is further separated to three individual images of red, green and blue, which are phase shifted 120 degrees between each other. Following this, the intensity ratio is calculated by evaluating the three color components detected from each deformed color fringe. To obtain the intensity ramp, a
strategy by adding a step value on each phase discontinuous point is developed. The intensity ramp being obtained can be regarded as the phase difference in the traditional phase-shifting method. Unwrapping process is then applied to obtain the continuous phase map of the object’s surface. Employing the triangulation principle, the relationship between the phase difference and the height information of object’s surface can be further determined.

The image intensities of red, green and blue of the deformed color fringe pattern being acquired from the object’s surface can be described by Eq. (1), (2) and (3), respectively.

\[
I_r(x, y) = \begin{cases} 
I_{\text{min}} + I_m \left( \frac{2}{3} + \frac{2x}{T} \right), & x \in [0, T/6) \\
I_{\text{min}} + I_m \left( \frac{4}{3} - \frac{2x}{T} \right), & x \in [T/6, 2T/3) \\
I_{\text{min}} + I_m \left( \frac{2x}{T} \right), & x \in [2T/3, T) 
\end{cases}
\]

(1)

\[
I_b(x, y) = \begin{cases} 
I_{\text{min}} + I_m \left( \frac{2x}{T} \right), & x \in [0, T/2) \\
I_{\text{min}} + I_m \left( 2 - \frac{2x}{T} \right), & x \in [T/2, T) 
\end{cases}
\]

(2)

\[
I_g(x, y) = \begin{cases} 
I_{\text{min}} + I_m \left( \frac{2}{3} - \frac{2x}{T} \right), & x \in [0, T/3) \\
I_{\text{min}} + I_m \left( \frac{2x}{T} - \frac{2}{3} \right), & x \in [T/3, 5T/6) \\
I_{\text{min}} + I_m \left( \frac{8}{3} - \frac{2x}{T} \right), & x \in [5T/6, T) 
\end{cases}
\]

(3)

Where \(I_r(x, y)\), \(I_g(x, y)\) and \(I_b(x, y)\) are the light intensities of red, green and blue components at point \((x, y)\), respectively; \(I_{\text{min}}\) and \(I_{\text{max}}\) are the minimum and maximum intensities of the projecting pattern, respectively; and \(I_m = I_{\text{max}} - I_{\text{min}}\) is the intensity range of the projected color pattern.

The intensity ratio is defined as the sum of the difference between \(I_{\text{high}}\) and \(I_{\text{medium}}\) and the difference between \(I_{\text{low}}\) and \(I_{\text{min}}\), where \(I_{\text{high}}\), \(I_{\text{medium}}\) and \(I_{\text{low}}\) are the high, medium and low values of the image set \{(\(I_r\), \(I_g\), \(I_b\))\}, respectively. The intensity ratio is further divided by \(I_m\) for normalization and it can be described as follows [12]:

\[
I_{\text{ratio}}(x, y) = \frac{I_{\text{high}} - I_{\text{medium}} + I_{\text{low}} - I_{\text{min}}}{I_m}
\]

(4)

To obtain the phase map of the object’s surface instead of using arctangent function required by the traditional phase-shifting method, the proposed method defines the phase value by defining the above intensity ratio, \(I_{\text{ratio}}(x, y)\). The intensity ramp, \(I_{\text{ramp}}(x, y)\), can be further evaluated and obtained as the phase value by determining the red component of the deformed fringe pattern, which is correlated to the other two color components. The intensity ramp can be described by:
\[ I_{\text{ramp}}(x, y) = 2 \times \text{round} \left( \frac{R-1}{2} \right) + (-1)^{R-1} I_{\text{ratio}}(x, y); \quad R = 1, 2, \ldots, 6 \quad (5) \]

Where \( R = \left( \left( x \mod T \right) \text{div} \left( T/6 \right) \right) + 1 \) is the region number. The values of \( I_{\text{ratio}}(x, y) \) and \( I_{\text{ramp}}(x, y) \) are shown in Fig. 2 for a color fringe pattern with a spatial period of \( T \). In every period of the color pattern, there exist six color regions having a width of \( T/6 \) in \( x \)-direction, the horizontal direction of projecting pattern.

The intensity ramp can be considered as the wrapped phase for further phase unwrapping. Because of its linear relationship with the spatial axis, the wrapped phase can be determined more accurately and efficiently than any other previous method.

3. **Optical system setup**

The hardware setup of the developed system is shown in Fig. 3. It consists of a digital micro-mirror device (DMD) having a \( 1024 \times 768 \) pixel resolution for generating color encoded fringe patterns, a three-chip color Sony DXC-390 CCD with a high speed of up to 60 fps, a personal computer of Dual Core Intel Pentium D, 3400 MHz with RAM memory of 2 GB SDRAM for controlling the projector and acquiring the images through a suitable frame grabber for obtaining the desired characteristics of the color pattern.
Fig. 3. Optical system setup of the developed methodology.

4. Experimental results and analysis

In the experiment, a standard step height of $5.0 \pm 0.001$ mm (A zero-grade precision gauge block) was employed to evaluate the accuracy of the depth measurement according to the Geometrical Product Specifications (GPS) of ISO 5436-1. The encoded structured color fringe with a spatial pitch of 15.0 mm was projected on to the measured surface and its single deformed fringe image was rapidly acquired by the CCD camera (shown in Fig. 4(a)). From a general least-squares step-height evaluation method, it is confirmed that the step height can be calculated with an accuracy of 2.8% deviation of the overall measuring depth range by a general 30-time repeatability evaluation. The acquisition time of approximate 3.5 ms and a 3-D map detection rate of 60 frames per second (fps) or higher is achievable for real-time 3-D vision. The intensity ramp, phase map and 3-D profile of the detected step-height surface are shown in Fig. 4 (b), (c) and (d), respectively.

The other experimental results of a computer mouse is given to demonstrate that the method is suitable for high-speed measurement of 3-D object having free-form surface. The deformed fringe patterns and the reconstructed 3-D profiles are shown in Fig. 5 (a) and (b), respectively.
Analyzing the above measurement results reveals that the developed 3-D machine vision method is capable of providing 3-D surface detection with a high accuracy and efficiency. The developed method is excellent in possessing an extremely short image-capturing time, thus achieving good resistance to potential vibration disturbance induced from various environmental sources.

5. Conclusion

In the research, simultaneous phase-shifting technique using an innovative color fringe pattern with a multiple triangular modulation was successfully developed for dynamic 3-D machine vision, especially for in-field automatic optical inspection (AOI). By employing the encoded color triangular fringe pattern for phase retrieving, the proposed method can reduce significant calculation time in comparison with the sinusoidal pattern required by traditional phase-shifting methods. Using the developed method, the image acquisition speed can reach to 60 fps or higher while high accuracy of 3-D surface profilometry can be achieved for a maximum detection error to be less 2.8% of the overall depth detection range. The experimental results show the developed 3-D vision system is capable of capturing 3-D object’s surface map accurately and effectively. The work provides a feasible possibility in providing 3-D image vision for inspection robots and pattern recognition.
References