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Applying innovative stripes adaptive detection to three-dimensional measurement of color fringe profilometry

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ABSTRACT

This study developed a 3D software and hardware measurement system, and proposes an innovative stripes adaptive detection algorithm. The fringe intensity is regulated automatically according to the reflection coefficient of different analytes, in order to avoid overexposure. For the measurement of the object in discontinuously changing height, a novel intensity difference coding unwrapping phase technology is used, thus overcoming the technological bottleneck of traditional phase unwrapping. In order to increase the measurement efficiency, the stripe pattern is combined with intensity coding pattern by three-channel color information, in order to generate an adaptive compound color stripe pattern. The measurement efficiency is increased by approximately two times compared with traditional gray stripe pattern. In order to increase the measurement accuracy, the uneven brightness is corrected by using brightness gain function. The three-channel intensity nonlinear response is corrected by cubic spline interpolation system response inverse function. The three-channel image is corrected by color cross-talk correction technology. The experiment proved that the system repeatability is 20 μm. The traditional phase-shifting profilometry is improved successfully, overcoming the technical measurement bottleneck of discontinuous change in the analyte height, so as to attain low cost, high measurement accuracy, efficiency and measurement reliability.

1. Introduction

The common methods for industrial three-dimensional (3D) measurement in early stages include stylus and scanning probe microscopy (SPM) [1]. However, the two techniques are of contact measurement, likely to damage the analyte, so it is required to develop non-contact measurement techniques.

At present, the extensively used non-contact measurement techniques include stereo vision [2], laser triangulation [3,4] and fringe projection profilometry (FPP) [5,6]. The stereo vision carries out space conversion depending on the feature points in the analyte, so it is likely to generate reconstruction error, inapplicable to high precision dimensional measurement. In terms of laser triangulation, as the laser light has directionality. The measurement equipment is often required to work with a precision mechanical mobile platform, so that the measurement is slow and the equipment cost is high. The FPP has absolute advantage in the measurement speed for its full-field image analysis. The measurement accuracy is micron scale, so it is applicable to the development of low cost, high measurement speed and high precision measurement system.

The FPP [7,8] is divided into frequency domain and spatial domain analyses for phase analysis. The leading phase method for frequency domain analysis is Fourier transform profilometry (FTP) [7], but the FTP lacks local processing capacity and only uses single image processing. It cannot solve the phase error resulted from object surface reflection effectively. The phase-shifting profilometry (PSP) [8] is the main technique for spatial domain analysis. As it uses multiple images for phase measuring, it has better adaptability to the analyte. For the spatial domain processing, in terms of discontinuous change in the analyte height, the real phase of pixel can be obtained correctly by the code of stripes. But the existing PSP used trial and error method to select the stripe intensity parameter for the difference in the analyte surface reflection coefficient. When the analyte height changes discontinuously, the offset of wrapping phase cannot be obtained, resulting in unwrapping phase error. The measurement efficiency cannot be increased due to the projection of multiple stripe patterns.

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Recent studies have used color fringe to replace traditional gray stripe in order to increase the measurement speed. Zhang et al. [9] used color tri-frequency pattern as measurement pattern, and used special frequency and three-step unwrapping. However, as the above method uses the phase analysis of frequency domain, its measurement accuracy is likely to be influenced as the object surface reflection coefficient damages the phase value of stripes.

Zhang et al. [10] improved the interference of object surface coefficient in [9]. They used 4-step phase shifting as measurement pattern, and used four images for measurement. The measurement required 12 patterns, losing the advantage of color fringe in measurement speed. Su [11] used color-encoded fringe composed of sinusoidal intensity distribution and three-channel periodic sequence coding. Only white object could be measured due to the constraints of color information. The object measurement was limited.

In order to enhance the adaptability to object height change, Zhang and Ma [12,13] corrected the permutation of stripe order, and proposed three order arrangement methods to increase the compile length of periodic sequence However, there was color change after the color information was reflected by the object. The analyte surface must be clear white for correct decoding. Chen et al. [14] used three-step PSP, color coding and three patterns for measurement. As the color information was more likely to be disturbed by the object, only clear white object was used.

Flores Jorge et al. [15] proposed the use of a generalized phase-shifting algorithm with arbitrary phase-shift values. The simulations and experimental results showed that the proposed algorithm could reduce the influence of the color crosstalk. Chufan Jiang et al. [16] and Palousek et al. [17] proposes a method that can measure high-contrast surfaces in real-time without changing camera exposures.

Chen et al. [18] used color gray code to enter sine information into the red channel of each pattern in order to solve the constraints of color object measurement, and entered binary gray code into green and blue channels. Five color patterns were used. The adaptability to the analyte surface color was enhanced, but the measurement efficiency was reduced. Moschetti Giuseppe et al. [19] proposed a method to obtain unambiguous surface height measurements using wavelength scanning interferometry with an improved repeatability. Zhang Chunwei et al. [20] analyzed the reasons for the occurrence of a fringe order error. The experimental results demonstrated that the proposed the multi-frequency fringe projection phase unwrapping algorithm was valid in eliminating the adverse influence of a fringe order error. Chao Jiang et al. [21] proposed method avoided the conventional phase shifting and unwrapping process, as well as the independent calculation of the object height required by existing techniques. Thus, it can be used to measure complex and dynamic objects with depth discontinuities.

According to literatures [9–21] that studied color fringe profilometry, different stripe patterns were used to examine the adaptability to the discontinuous change in the analyte height. There were different measurement constraints due to the pattern coding capability, such as color tri-frequency pattern [9] and color encode pattern [10–14]. The measurement speed was high, but the resistivity to the object surface reflection interference was very low, mostly applicable to only clear white object measurement. However, the color gray code pattern was used to enhance the adaptability to object [18], but the color fringe measurement efficiency was reduced.

The present technological bottleneck is to obtain both of the object surface adaptability and measurement speed, and the constraints of object by the fringe intensity on the phase pattern and the encoding mode of stripe order pattern. Therefore, this study aims to develop a compound color stripe pattern with adaptive ability. The fringe intensity is selected according to the difference in the analyte surface reflection coefficient. The order coding is designed by combining intensity difference coding with color phase shifting compound pattern, so as to reduce the effect of object surface reflection, and to attain high adaptive ability, high measurement accuracy and high measurement speed with minimum patterns.

2. Research methods and related theory

2.1. FPP

The FPP [22] is the 3D measurement method for structured light. The FPP projects sinusoidal structured light on the object surface. The camera obtains the deformed sinusoidal pattern image, and the phase information of pixel is analyzed, as shown in Fig. 1. The phase difference between the pixel and reference plane is calculated and converted by triangular geometrical relationship into the information of object height, expressed as Eq. (1):

$$\overline{BE} = P\left(\frac{\phi_B - \phi_E}{2\pi}\right)\tan(\theta_0) \tag{1}$$

where P is the sinusoid circumference, ϕ_B is the phase value at point B, ϕ_E is the phase value at point E.

2.1.1. PSP

For the design of space pattern, the PSP [7] uses multiple sinusoid images of different initial phases, time-sharing projection to the analyte. Multiple patterns are captured to reduce the effect of the environment on the space pattern, so as to attain high precision measurement, expressed as Eq. (2):

$$I_n(x', y') = a + b\cos\left(\frac{2\pi}{P}x' + \frac{2n\pi}{N}\right) \tag{2}$$

where $I_n(x', y')$ is the space pattern, x' and y' are the image pixel coordinates, a is the stripe background intensity constant, b is the sinusoid amplitude, P is the number of pixels in a sinusoid wavelength, also known as sinusoid period, n is the present step number of the image, N is the total step number of phase shifting.

When the projector projects stripe image, the image captured by the camera is expressed as Eq. (3):

$$I_n' = R\left[a + b\cos\left(\frac{2\pi}{P}x' + \frac{2n\pi}{N} + \phi\right)\right] \tag{3}$$

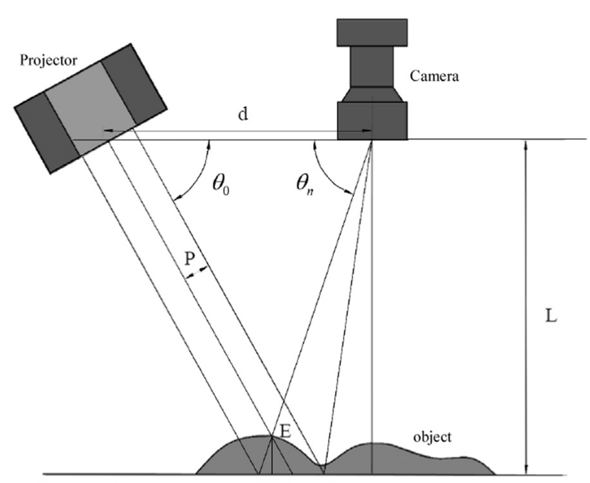

Fig. 1. Geometrical optics chart.