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An absolute phase technique for 3D profile measurement using four-step structured light pattern

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ABSTRACT

The aim of this paper is to develop a four-step pattern encoding strategy through the combination of a triangle waveform, a step waveform, and two square waveforms. The proposed pattern encoding strategy makes the range of unique phase distribution up to 10π, which is 5 times as large as 2π of conventional four-step phase shifting encoding approach. Therefore, the proposed encoding strategy enables the structured light-based measurement system to measure complicated objects without ambiguity, which is the common limitation of the phase shifting algorithms. Furthermore, the proposed strategy is a pixel-level method, leading to a high-density 3D reconstruction. The decoding approach is a pixel independent computation, which can eliminate the error propagation and enhance the reliability. The phase errors between the phase shifting and the proposed encoding strategy are compared by the numerical simulation and they are very close. Experiments with different objects are carried out to validate the robustness and accuracy for the proposed encoding strategy. The results show that it is efficient for the 3D reconstruction of complicated objects.

1. Introduction

The 3D profilometry has been intensively applied to the manufacturing industries such as the quality inspection and the reverse engineering, where the 3D shape is usually modeled by a set of points called point cloud. Existing 3D measurement methods can be categorized into two types: contact measurement and non-contact 3D optical measurement. The coordinate measurement machine (CMM) with a touching probe is a typical example of the contact measurement techniques. It captures the surface profile with a high accuracy by probing the measured object through physical touch. This point-by-point scan method, however, has a slow measurement speed. Another potential weakness is that the physical touch may damage delicate objects. Also, the CMM with a touching probe cannot be used for soft objects since they will be deformed by physical touch.

For non-contact optical measurement technique, some light beams with a special wavelength will be emitted onto the measured object, and the 3D profile can be obtained through the analysis of the reflected light. The significant advantage of the non-contact optical measurement over the traditional contact measurement is the fast measurement speed. The non-contact measurement technique can be further classified into two types: time-of-flight (TOF) and triangulation measurement techniques. The TOF is capable of measuring the object at a long distance; therefore, it is suitable for large buildings detection [1]. Compared with TOF, the triangulation method has a high accuracy within a limited measurement range. The extensively used structured light-based 3D profilometry belongs to the triangulation method. This paper will focus on the structured light-based 3D profilometry, where a projector and a camera are the main components. For this method, the projector first shoots encoded patterns to the objects, and the deformed image is recorded by the camera. After that, the correspondence between the camera and the projector can be established via the encoded patterns. Finally, the triangulation method can be used to reconstruct the object's 3D profile. In this process, the pattern encoding strategy plays a critical role to establish the correspondence.

A great number of encoding strategies have been developed over the past decades [2]. Among these methods, the phase-shifting method (PSM) is most widely used for quality inspection in the manufacturing industries thanks to its high accuracy [3]. Another significant advantage is the robustness to the ambient light and illumination, as well as the reflection property of the measured object. Additionally, it can provide the pixel-level resolution reconstruction, which is preferred to represent the details of the measured object well.

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At present, various different PSMs have been proposed for 3D profilometry, including three-step, four-step, and *N*-step algorithms. For this technique, a series of periodical sinusoidal patterns with phase shifting with respect to each other are used to obtain the phase distribution in the camera, which determines the correspondence between the camera and the projector. The minimum number of required patterns is three. Apparently, the more patterns, the higher measurement accuracy because the least-square method can reduce the negative influence of the noise and non-unitary nature of the optical components [4].

However, the solved phase distribution in the camera is restricted in the interval $[-\pi,\pi)$ by using the arctangent function. In this case, the calculated phase in the camera is the periodical value with a measured modulus 2π, which is referred to as the relative phase value in each period. To obtain the unique correspondence between the camera and the projector, the period order has to be determined. In this case, the relative phase is transformed to the absolution phase, which is a unique value in the entire camera image. To solve this limitation, a straightforward solution is to enlarge the wavelength (pitch) of the sinusoidal waveform such that the entire image only involves one period without the detection of period order. However, the measurement accuracy will be significantly decreased since it will be susceptible to the noise [5]. Therefore, some other unwrapping algorithms have been presented to remove the ambiguity of the period order. For example, a line is placed in middle of the pattern along the same phase value, and the value with respect to this predefined mark can be obtained through spatial search in the direction of the phase distribution [6]. The calculated phase is true if the phase difference is less than 2π for any neighboring pixels, which means that this algorithm is only applicable to the smooth surface. However, the sudden change of the surface shape such as steps frequently appears in the industrial part.

A similar coding strategy is called two-step triangular-pattern phase shifting [12], where two triangular waveforms are used to determine the relative phase. Compared with the conventional sinusoidal waveforms, the number of the projected pattern is reduced to 2. However, the captured intensity modulation has to be unique and the ambiguity of the period order still exists.

To overcome the weakness of the PSM, two different strategies are suggested. The first one is to combine the gray code and PSM, in which the gray code is used to obtain the period order in the entire image and then the PSM is employed to specify the fine relative phase [7]. Thus, this technique can remove the 2π ambiguity. The second one is based on the multiple-wavelength PSM [8,9]. In this method, the phase shifting patterns with no less than two different wavelengths are projected onto the measured object in sequence. As a result, two different relative phase values for each pixel in the camera can be obtained such that the unique phase value in the entire image is further determined. However, the common drawback of the above two strategies is the increased number of required patterns, which means that the measurement speed will be sacrificed.

To obtain the period order of the relative phase, a step waveform (stair image) is introduced in [10] with the assumption that any measured point has the approximate surface albedo; thus, the period order can be specified from the captured image. Additionally, a one-shot sawtooth pattern is proposed in [11] to get the reactive phase for the 3D profile measurement, which is also only appropriate for the object with similar surface albedo.

In this paper, an absolute phase technique using four-step structured light pattern is proposed. The proposed patterns consist of a triangle waveform, two square waveform, and a step waveform. The number of proposed patterns is equal to that of the conventional four-step PSM, but the unique phase distribution range is extended to 10π. Compared to the 2π of the four-step PSM, the range is enlarged 5 times, which will remove the ambiguity of the PSM. Therefore, the proposed pattern strategy is suitable for the measurement of complicated objects with abrupt shape change. Moveover, the addressed encoding strategy can also achieve the pixel-level resolution reconstruction; also, the proposed pattern can deal with the object with nonuniform surface albedo. The simulation indicates that the accuracy of our proposed patterns approximates to that of the four-step PSM. Overall, the proposed encoding strategy holds the property of accurate, dense, and rapid 3D profilometry to meet the demand of the industrial requirement.

2. Pattern encoding

The projector is considered as an inverse camera, which transforms the 2D pixel in the projector to the 3D point in the scene. Thus, the correspondence between the projector and the camera satisfies the epipolar constraint. In this case, the pattern encoding is only necessary along one dimension in the entire 2D image.

The basic concept of the proposed pattern encoding strategy is to divide the entire image into small patches through the combination of the step waveforms such that each patch has a unique order, and then in each patch a certain waveform is used to calculate the fine relative phase. To this end, the triangle waveform and sawtooth waveform are the two potential options for the relative phase calculation. However, as a continuous function, the triangle waveform can be accurately implemented by the projector. So the triangle waveform is used in this paper. The task of pattern encoding is decomposed into two steps:

1. Design the relative phase through a proper triangle waveform, whose accuracy is close to that of the four-step PSM.
2. Extend the relative phase in each patch to the unique absolute phase in the entire image through the combination of step waveforms.

2.1. Relative phase design

The relative phase design should have an accuracy close to that of traditional four-step PSM. Thus, we will discuss the anti-noise abilities of the four-step PSM first. For the four-step PSM, the intensity I_i $(i=1,2,3,4)$ can be represented by the following equations:

$$\begin{cases} I_1 = \mathrm{A}+\mathrm{B}\cos(\varphi) \\ I_2 = \mathrm{A}+\mathrm{B}\cos\left(\varphi+\dfrac{\pi}{2}\right) \\ I_3 = \mathrm{A}+\mathrm{B}\cos(\varphi+\pi) \\ I_4 = \mathrm{A}+\mathrm{B}\cos\left(\varphi+\dfrac{3\pi}{2}\right) \end{cases} \tag{1}$$

where *A* and *B* denote the bias brightness and the intensity contrast of the PSM, respectively; the phase shifting value relative to each other is $\pi/2$; φ represents the phase being specified, which can be further determined by the arctangent function as:

$$\varphi = \arctan\left(\frac{I_4-I_2}{I_1-I_3}\right) \tag{2}$$

To simplify the computation, the maximum error is taken into account. Add $a\%$ noise to the I_i $(i=1,2,3,4)$, and then the phase error is analyzed. The maximum phase is calculated as:

$$\varphi_{\max} = \arctan\left[\frac{(1+a\%)I_4-(1-a\%)I_2}{(1-a\%)I_1-(1+a\%)I_3}\right] \tag{3}$$

Thus, the phase error is represented by

$$E_1 = \varphi_{\max}-\varphi = \arctan\left(\frac{B\sin\varphi+A\cdot a\%}{B\cos\varphi-A\cdot a\%}\right)-\varphi \tag{4}$$