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Realtime 3D profile measurement by using the composite pattern based on the binary stripe pattern

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ABSTRACT

In this paper, a one-shot composite pattern based on three-step binary stripe pattern is developed to meet the demand of real-time 3D shape measurement for complicated objects. Theoretical analysis and numerical simulation prove that the proposed pattern can provide higher accuracy than the composite pattern based on the traditional three-step phase shifting. Furthermore, the significant advantage for the proposed composite pattern is that it can provide the unique location of the stripe boundary, resulting in the elimination of the ambiguity which usually arises for measurement of complicated object with the phase shifting method. The proposed composite pattern has been implemented to measure three different complicated objects. The results demonstrate that it is appropriate for the real-time 3D shape measurement.

1. Introduction

Over the past decade, vision-based 3D profile measurement technology has been increasingly applied in manufacturing industries. The 3D profile of a part, which can be represented by a set of points (a point cloud), is needed in two areas: quality inspection or reverse engineering. Among the existing vision-based 3D measurement approaches, the structured light-based measurement system, including a projector and a camera, is more and more used thanks to its capability of rapid-speed, dense-resolution, high-accuracy, and low-cost measurement performances. The above performance is determined by the pattern encoding strategy. The function of the encoded pattern is to build the accurate and reliable correspondence between the camera and the projector, which is the prerequisite of the 3D shape reconstruction by means of triangulation measurement technique. Therefore, the encoding strategy is of great importance for this technique.

According to the number of the patterns required for the correspondence establishment, existing pattern encoding methods can be categorized into two types: multi-shot and one-shot pattern encoding methods. The one-shot pattern encoding method can be applied to the 3D profile measurement of the moving objects such as the parts on the product line. Therefore, the one-shot pattern encoding strategy is the emphasis in this paper.

To achieve one-shot pattern, a direct-coding approach is a feasible solution, where each pixel has a unique color value in the single pattern, which means a mass of color is required. The captured color in the camera, however, does not only depends on the projected color from the projector, but also is affected by the color property of the scanned object. Therefore, this approach is sensitive to the ambient illumination and the scanned surface property, leading to low reliability. As a result, it is not suitable for quality inspection.

Another solution is to encode the single pattern by using the spatial-neighborhood strategy, in which the primitive is the basic unit of the encoded pattern. The codeword of each primitive is determined by its own value, as well as the values of its neighboring primitives. The first kind of primitive is based on the color, including colored stripe pattern, colored grid pattern, colored slit pattern, colored spot pattern, etc. [1–4]. The major weakness of such a primitive is that the discrimination of the color depends on the colors of ambient illumination and the scanned surface. To improve the measurement reliability, the second kind of primitive is based on the geometry, such as circle, stripe [5], X-point [6], etc. However, the limitation of geometry-based encoding strategy is the scattered resolution of the reconstructed point cloud. The primitives in the single pattern are arranged by the De Bruijn sequence, pseudorandom sequence,

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or M-arrays. It should be pointed out that the De Bruijn sequence and pseudorandom sequence are usually used as the one-dimensional encoding strategy, whereas the M-arrays is for two-dimensional encoding strategy.

At present, the phase-shifting method (PSM) is the most commonly used pattern in 3D profile measurement since it has pixel-level resolution, robustness to the variation of the surface property due to its pixel-independent reconstruction. For this technique, the minimum number of patterns required is three, which does not allow us to directly apply it to real-time measurement [7]. To reduce the number of patterns, a straightforward way is to combine the multiple phase shifting patterns into a single pattern to achieve the real-time measurement [8,9]. The resulting composite pattern, however, still has the common drawback of the PSM, i.e., only the relative phase (the unique location in one sub-patch) can be determined, instead of the absolute phase (the unique location in the entire image). However, the absolute phase is required for 3D profile reconstruction, especially for parts with a complicated shape. As a result, the conventional composite pattern based on phase shifting is not appropriate for the 3D shape measurement of complicated objects.

The Fourier Transform Profilometry (FTP) is another typical example of the one-shot pattern [10]; however, the spectrum aliasing phenomena will intensively reduce the measurement accuracy. Besides, several other pattern encoding methods for one-shot pattern have been reported [11,12].

To the best of our knowledge, a composite pattern with high accuracy and absolute phase is still missing from the literature, motivated by these facts, we develop a one-shot composite pattern based on the binary (black/white) stripe pattern for real-time 3D measurement in this paper. Compared with the traditional composite pattern based on PSM, the proposed composite pattern has two significant advantages: the higher accuracy and the unique location (absolute phase) in the entire image. In the following sections, the conventional composite pattern based on three-step phase shifting is referred to as conventional composite pattern, while the proposed composite pattern based on the three-step binary stripe pattern is abbreviated to proposed composite pattern.

2. Pattern encoding

2.1. Previous research

In our previous study, we proposed a three-step binary stripe pattern which took advantage of both temporal and spatial encoding strategies such that the stripe boundary could be uniquely specified in the entire image [13]. For this technique, the value of the stripe boundary is specified by the intensity variance of the three patterns in time domain, while the codeword of the stripe boundary is determined by its own value and the values of the stripe boundaries in space domain. The developed patterns are the three top binary patterns as shown in Fig. 3. The resolution of the proposed pattern is 768×1024 pixels, where the pitch of each stripe is 6 pixels, thus, there are 128 stripes in total in the entire image.

To precisely locate the stripe boundary, there exist at least two patterns containing two successive stripes with the opposite intensities as illustrated in Fig. 1, where A, B, C, and D are the intensities of the successive pixels n and $n+1$ on the stripe boundary in two patterns. Therefore, the location P of the stripe boundary along the axis-y can be detected with a sub-pixel accuracy by

$$P = n + \frac{A-B}{(A-B)+(C-D)} \tag{1}$$

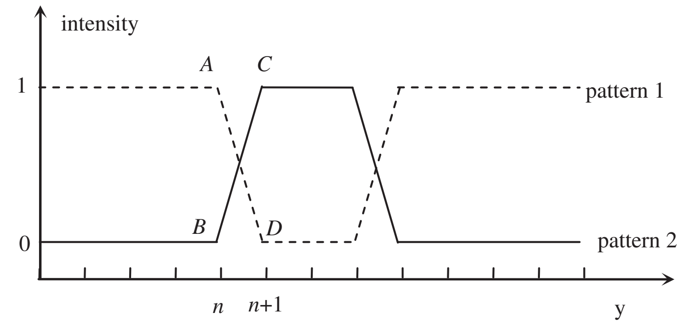

Fig. 1. Stripe boundary location.

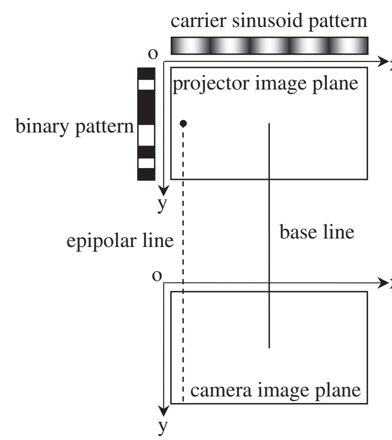

Fig. 2. Epipolar constraint for the composite pattern.

Compared with the PSM, there are two significant advantages for the proposed three-step binary stripe pattern: it can provide the unique location of the stripe boundary in the entire image, leading to the ambiguity elimination of the phase shifting; besides, it has a high accuracy and the sophisticated anti-noise capability. However, the proposed three-step binary stripe pattern still cannot satisfy the requirement of the real-time 3D profile measurement due to the number of the pattern is three. To solve this problem, this paper aims to combine the three binary stripe patterns into a single pattern without loss of accuracy.

2.2. Composite pattern

For the structured light-based measurement system (including a camera and a projector), the projector is considered as an inverse camera. Under the simplest case, assume that the focal lengths of the projector and the camera are equal; the image planes of the projector and the camera are coplanar with both y-axes parallel to the baseline (the line connecting two optical centers). In this case, the epipolar line falls along the vertical scanline of the images as shown in Fig. 2. Thus, for the pixel in the projector, the corresponding pixel must lie on the same vertical scanline of the camera. The three binary patterns are encoded along the baseline, and the three carrier patterns (the sinusoid waveform with different frequencies) are encoded perpendicular to the baseline.

The modulated pattern in each channel is the production of the binary pattern and the carrier pattern; and then the composite pattern I^P in the projector is the sum of the three modulated patterns as shown in Fig. 3. Therefore, we have:

$$I^P = A + B \cdot \sum_{n=1}^{3} I_n^b \cdot \cos(2\pi f_n^p x_p) \tag{2}$$