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Invalid-point removal based on epipolar constraint in the structured-light method

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A B S T R A C T

In structured-light measurement, there unavoidably exist many invalid points caused by shadows, image noise and ambient light. According to the property of the epipolar constraint, because the retrieved phase of the invalid point is inaccurate, the corresponding projector image coordinate (PIC) will not satisfy the epipolar constraint. Based on this fact, a new invalid-point removal method based on the epipolar constraint is proposed in this paper. First, the fundamental matrix of the measurement system is calculated, which will be used for calculating the epipolar line. Then, according to the retrieved phase map of the captured fringes, the PICs of each pixel are retrieved. Subsequently, the epipolar line in the projector image plane of each pixel is obtained using the fundamental matrix. The distance between the corresponding PIC and the epipolar line of a pixel is defined as the invalidation criterion, which quantifies the satisfaction degree of the epipolar constraint. Finally, all pixels with a distance larger than a certain threshold are removed as invalid points. Experiments verified that the method is easy to implement and demonstrates better performance than state-of-the-art measurement systems.

1. Introduction

Recently, three-dimensional (3D) measurement based on structured-light methods have been widely applied in industry inspection, inverse engineering and cultural heritage, etc. [1]. The measurement system consists of a projector and a camera. During measurement, fringe patterns with phase-shift are projected on the tested object by the projector. After being distorted by the surface of the tested object, the fringes are captured by the camera. By analyzing the distortion of the captured fringes, the 3D point cloud of the object is obtained [2]. Due to shadows, image noise and ambient light, there are many invalid points in the point cloud, which will significantly influence the post-processing of the point cloud [3]. Consequently, the invalid-point removal method has been the focus of a great deal of research in the last decade.

According to the invalidation criterion used, invalid-point removal methods can be classified into three types of methods. By assuming the phase is continuous and monotonous, the first method uses the continuity and monotonicity of the phase as the invalidation criterion. Points that do not satisfy the criterion are regarded as invalid points and then removed [3–5]. However, limited by the above assumption, these methods cannot be used for objects with a discontinuous surface. The second type of method, which is based on temporal phase unwrapping, adopts the quality of phase unwrapping as the criterion for invalid-point removal [6,7]. For example, Chen et al. [6] employed the least-square fitting of the unwrapped phase with different fringe frequencies, and the root mean square error (RMSE) of the fitting was used as the invalidation criterion. Then, pixels with a large RMSE were identified as invalid points. In contrast to the first type of method, this method has a wider application because no prior assumptions are made. Nevertheless, since these methods are sensitive to noise, sufficient fringe frequencies are needed for reliable results, which indicates more patterns are needed, and the measurement efficiency will be low. According to the relation between the modulation and the signal-to-noise ratio (SNR) of the fringe, the third type of method uses the modulation as the invalidation criterion [3,8–10]. Pixels with low modulation are treated as invalid points and are removed by threshold modulation. Because the third kind of method requires no additional fringe frequencies and is easy to implement, they are the most promising among the three types of methods. How to select a proper threshold is a crucial but very challenging task in the third type of method [10]. Even though many thresholding methods are represented, a proper threshold is still difficult to select for some objects with a complex surface. For instance, when the reflectivity varies spatially across the tested surface, the modulation will also vary spatially, leaving some low-modulation regions and some high-modulation regions on the surface. For regions with low modulation close to the background, there is no proper threshold to separate these regions from the background. Moreover, when there is significant interreflection on the surface, even though the regions influenced by interreflection have

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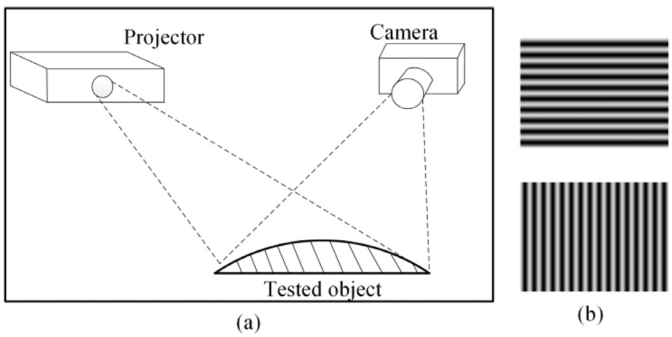

Fig. 1. (a) The sketch of the measurement system; (b) patterns with horizontal and vertical fringes.

high modulation, there are still many invalid points that cannot be detected and removed by the third type of method.

In this paper, a novel invalidation criterion is introduced based on the epipolar constraint, and an invalid-point removal method based on this criterion is presented. Since the criterion directly relates to the 3D reconstruction accuracy of the tested object and is independent of the object surface reflection characteristic, the method can be widely used in complex scenarios containing background, shadows, noise and interreflection. Early works used epipolar constraint in the structured light method, and there have been abundant achievements recently, e.g., phase unwrapping or finding correspondence between the captured point and the projected point [11–13]. However, little research has been done on the invalid-point removal with epipolar constraint.

The paper is arranged as follows. Section 2 gives the principle of the proposed method. The experimental results are given in Section 3. Section 4 is the conclusion.

2. Methods

2.1. Principle of the structured-light method

A typical measurement system consists of a projector and a camera, shown in Fig. 1(a). In the measurement, patterns with horizontal and vertical fringes (see Fig. 1(b)) are projected onto the surface of the tested object, and captured by the camera successively. The captured fringe pattern can be expressed as

$$I_i(x,y) = A(x,y) + B(x,y)\cos[\varphi(x,y) + i\delta]. \tag{1}$$

where (x,y) is the camera image coordinate (CIC). $A(x,y)$, $B(x,y)$, and $\varphi(x,y)$ are the average intensity, modulation and phase of the captured fringe pattern respectively. $\delta = 2\pi/N$ is the phase-shift, and i ($i=1,2,\ldots,N$) refers to the i-th phase-shift. N is the phase-shift number.

The wrapped phase and modulation can be calculated using the phase-shifting algorithm [14] as

$$\varphi^{w}(x,y) = -\arctan\frac{\sum_{i=1}^{N} I_i \sin(\delta i)}{\sum_{i=1}^{N} I_i \cos(\delta i)} \tag{2}$$

$$B(x,y) = \frac{2}{N}\sqrt{\left[\sum_{i=1}^{N} I_i \sin(\delta i)\right]^2 + \left[\sum_{i=1}^{N} I_i \cos(\delta i)\right]^2}. \tag{3}$$

Then, the obtained phase is unwrapped as [15]

$$\varphi_k^{uw}(x,y) = \varphi_k^{w}(x,y) + \mathrm{INT}\left(\frac{\varphi_{k-1}^{uw}\frac{f_k}{f_{k-1}} - \varphi_k^{w}}{2\pi}\right)2\pi. \tag{4}$$

where $k = 1,2,3\ldots,M$ refers to the k-th fringe pattern, and M is the number of the patterns. $\varphi_k^{w}(x,y)$ and $\varphi_k^{uw}(x,y)$ are the k-th wrapped and unwrapped phases respectively, and $f_M > \ldots f_k > f_{k\text{-}1\ldots} > f_1 = 1$ is the number of fringes in the pattern. INT is the round function.

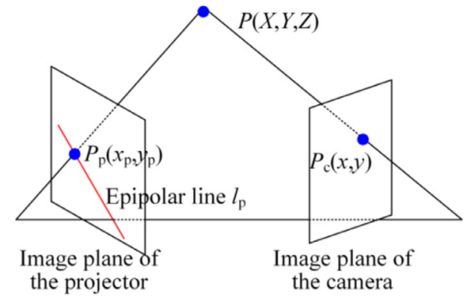

Fig. 2. Sketch of image planes of the projector and camera.

According to Eq. (4), unwrapped phase $\varphi_H(x,y)$ and $\varphi_V(x,y)$ of the horizontal and vertical fringe patterns is obtained respectively. Subsequently, the corresponding projector image coordinate (PIC) of a pixel, where we refer a "pixel" to the pixel in the camera image plane (CIP) in the paper, is retrieved as

$$\begin{cases} x_p = \frac{\varphi_V(x,y)}{2\pi} f_V \\ y_p = \frac{\varphi_H(x,y)}{2\pi} f_H \end{cases}, \tag{5}$$

where f_V and f_H are fringe numbers of the patterns with the highest frequency vertical and horizontal fringes respectively.

A pair of corresponding image coordinates of a point $P(X,Y,Z)$ of the object are obtained, namely, $P_c(x,y)$ and $P_p(x_p,y_p)$; see Fig. 2. According to the mathematical model of the system, the 3D coordinates (X,Y,Z) of the point are obtained by solving the following equations [2].

$$\begin{cases} (x,y)^T = M_c(X,Y,X) \\ (x_p,y_p)^T = M_p(X,Y,X) \end{cases}, \tag{6}$$

where M_c and M_p are the parameter matrices of the camera and projector respectively.

2.2. Epiploar constraint

Assume there is no lens distortion, and the camera and projector are modeled by the pin-hole model. Given a pixel in the CIP, e.g., $P_c(x,y)$ in Fig. 2, its corresponding epipolar line l_p in the projector image plane (PIP) is expressed [16] as

$$l_p = F\begin{pmatrix} x \\ y \\ 1 \end{pmatrix}, \tag{7}$$

where F is a 3×3 matrix, which is known as the fundamental matrix. It represents the mapping from a pixel in the CIP to its epipolar line in the PIP.

According to the epipolar constraint, the corresponding PIC $P_p(x_p,y_p)$ and epipolar line l_p of the pixel $P_c(x,y)$ must satisfy the collineation constraint,

$$(x_p, y_p, 1)l_p = 0, \tag{8}$$

or

$$(x_p, y_p, 1)F\begin{pmatrix} x \\ y \\ 1 \end{pmatrix} = 0. \tag{9}$$

2.3. Invalid point removal based on epipolar constraint

According to the analysis in Section 2.2, given a pair of corresponding image coordinates, e.g., $P_c(x,y)$ and $P_p(x_p,y_p)$ in Fig. 2, they must satisfy the epipolar constraint or satisfy Eq. (9). However, for invalid