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Three-dimensional digital image correlation with improved efficiency and accuracy

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ABSTRACT

Three-dimensional (3D) digital image correlation (DIC) is a popular image-based non-contact measurement technique. 3D DIC is generally implemented in a stereo vision system. In this study, we present an epipolar geometry-based searching strategy to enhance the efficiency of 3D DIC in searching the corresponding points between the left and right images. Based on the triangulation principle, a novel method is proposed to compute the 3D position which can minimize the reprojection deviation. Moreover, during measuring the in- and out-of-plane displacement of a loaded object, we present a method to build the world coordinate system on the test surface. In the experiment, the proposed 3D DIC method is employed to measure the profile of a mask model and evaluate the loading response of a tensile specimen made from aluminium (Al) 6061-T6. It is shown that the epipolar geometry-based searching strategy can enhance the searching efficiency. The reprojection deviation of the 3D point derived by the proposed method is less than that of the 3D point obtained from the conventional method. The measured Young's modulus of Al 6061-T6 is close to the standard reference value. The proposed method is also utilized to measure the in- and out-of-plane displacements and strains of the loaded specimen.

1. Introduction

Digital image correlation as a non-contact optical technique is becoming increasingly popular for engineering measurement. It is widely used for non-contact shape and displacement measurement and motion tracking [1]. Unlike the conventional gauges and extensometers, DIC is able to make full-filed non-contact measurement of the mechanical properties of materials. Compared with other popular non-contact full-field measurement techniques, such as digital speckle shearing interferometry (DSSI) [2], electronic speckle pattern interference (ESPI) [3], and digital holographic interferometry (DHI) [4], the measurement conditions for DIC are much less stringent. DIC works well under normal environment [5–7]. Refs. [5–7] demonstrate the applications of two-dimensional (2D) DIC. 2D DIC is often employed to measure the in-plane displacement. 3D DIC is able to measure both in- and out-of-plane displacement with higher accuracy. Since 3D DIC was first proposed by Luo et al. [8], it has been studied extensively and has obtained great progresses in the aspects of measurement accuracy, efficiency and robustness [9]. 3D DIC has been successfully applied in various applications, such as the study of mechanical properties of material [10–11], biomedical engineering [12,34], structure monitoring [13–15], vibration measurement [16] and shape measurement [17–18]. Recently, there have also been some attempts to perform 3D DIC in multi-camera systems [18–19]. In this way, it can be applied to a large surface. Additionally, many attempts have also been conducted to implement 3D DIC using a single camera [20–22]. The hardware cost can be reduced and the synchronization problem can be solved well.

3D DIC is generally implemented in the stereo vision system consisting of two cameras. At the beginning of measurement, calibration is required to obtain the intrinsic parameters of the cameras and their pose relationship. Before we compute the 3D position of the point of interest, corresponding points should be located between the images captured by the two cameras. Reliability-guided searching method [23] is robust to search the corresponding points. However, it is not suitable to search the first corresponding point due to no calculated point and it is also not suitable for parallel computing. In fact, there is an epipolar geometry constraint [24] in the stereo vision system and this constraint has not been studied extensively in the 3D DIC methods. In the Ref. [25], the epipolar geometry constraint is used to improve the matching accuracy by correcting the initial corresponding point searched. In this study, we employ the epipolar geometry constraint to enhance the searching efficiency of 3D DIC. After we locate the corresponding points, the 3D position of point of interest can then be computed based on the triangulation principle. The measurement accuracy of the shape and displacement almost depends on the accuracy of the computed 3D position. The reprojection deviation of the measured 3D position is

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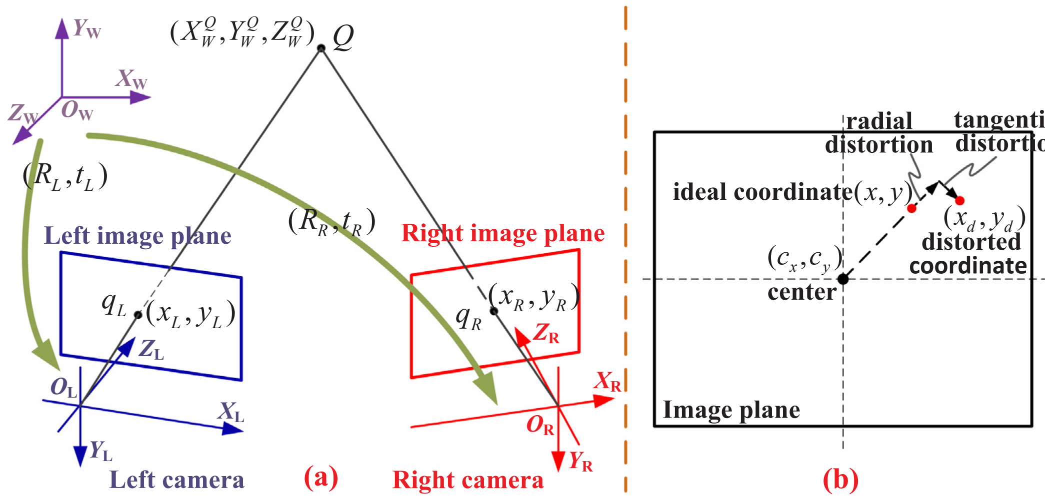

Fig. 1. (color online) (a) Projection principle of a stereo vision system; $O_W-X_W Y_W Z_W$ is the world coordinate system. $O_L-X_L Y_L Z_L$ and $O_R-X_R Y_R Z_R$ are the left and right camera coordinate systems respectively. (R_L, t_L) and (R_R, t_R) denote the pose relationship between the world coordinate system and the left and right camera coordinate systems respectively. (b) The image after lens distortion.

often used to evaluate its accuracy. Generally, lesser reprojection deviation indicates higher measurement accuracy. To our best knowledge, no literature about 3D DIC methods presents the method to compute the 3D position which can minimize the reprojection deviation. In this study, we try to figure out the optimal 3D position with the least reprojection deviation. Usually, the left camera coordinate system is often regarded as the world coordinate system. The computed 3D position in the 3D DIC methods [18,34] is described in the left camera coordinate system. However, when measuring the in- and out-of-plane displacements of a loaded object, the XOY plane ($Z = 0$) of the world coordinate system should be set on the test surface before loading. In this study, we also present a method to build the world coordinate system on the test surface before loading.

2. Projection principle of a stereo vision system

As shown in Fig. 1(a), the position of point Q is (X_W^Q, Y_W^Q, Z_W^Q) in the world coordinate system $O_W-X_W Y_W Z_W$. When it is imaged on the sensor plane based on the pinhole camera model, the depth information will be lost, as expressed by Eq. (1).

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = K\left(R\begin{bmatrix} X_W^Q/Z_W^Q \\ Y_W^Q/Z_W^Q \\ 1 \end{bmatrix} + t\right); \quad K = \begin{bmatrix} f_x & s & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where K is a projection matrix. f_x, f_y, s, c_x, c_y are the intrinsic parameters of the camera. f_x, f_y are the focal lengths in X, Y directions respectively.s is the skew parameter and (c_x, c_y) is the principal point of the image plane. R is a 3×3 rotation matrix that represents the orientation of the world coordinate system in the camera. t is a 3×1 translation vector that represents the position of the world coordinate system in the camera. (x_L, y_L) and (x_R, y_R) are the ideal projection coordinates in the left and right image planes, respectively. In reality, the projection coordinate (x, y) is inevitably affected by the lens distortion, as shown in Fig. 1(b). Assume that (x_d, y_d) are the distorted coordinates. Lens distortion is mainly categorized into radial distortion and tangential distortion. Generally, for the commonly used lens, the tangential distortion is much smaller than the radial distortion [26–27]. In this study, only the radial distortion is considered. Eq. (2) expresses the relationship between (x, y) and (x_d, y_d) .

$$\begin{cases} x = x_d + k_1(x_d-c_x)r^2 + k_2(x_d-c_x)r^4 \\ y = y_d + k_1(y_d-c_y)r^2 + k_2(y_d-c_y)r^4 \end{cases} \tag{2}$$

where $r = \sqrt{(x_d-c_x)^2 + (y_d-c_y)^2}$. k_1 and k_2 are the first- and second-order radial distortion coefficients and they are also the intrinsic parameters.K_L and K_R denote the projection matrices of the left and right cameras respectively, as given by Eq. (3). At first, the left camera coordinate system is normally set as the world coordinate system. In this case, R_L is a unit matrix and t_L is a zero vector. (R_R, t_R) denotes the pose relationship between the left and right camera coordinate systems. Rotation matrix R_R can be determined by the orientation angles (α, β, γ) between the left and right cameras via Eq. (4). t_R is determined by the relative position (t_x, t_y, t_z) between the two cameras: $t_R = [t_x, t_y, t_z]^T$. $(\alpha, \beta, \gamma, t_x, t_y, t_z)$ denotes the extrinsic parameters of the stereo vision system. The intrinsic parameters $(f_x^L, f_y^L, s_L, c_x^L, c_y^L, k_1^L, k_2^L)$, $(f_x^R, f_y^R, s_R, c_x^R, c_y^R, k_1^R, k_2^R)$ of the left and right cameras and extrinsic parameters can be derived by calibration [28].

$$K_L = \begin{bmatrix} f_x^L & s_L & c_x^L \\ 0 & f_y^L & c_y^L \\ 0 & 0 & 1 \end{bmatrix}; \quad K_R = \begin{bmatrix} f_x^R & s_R & c_x^R \\ 0 & f_y^R & c_y^R \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$R_R = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \tag{4}$$

3. Proposed method

The proposed method is described in detail from three aspects. Firstly, an epipolar geometry-based searching strategy is proposed to search the corresponding points between the left and right images. Secondly, in order to improve the accuracy, we propose to compute the 3D position of point of interest by minimizing the reprojection deviation. Thirdly, we present a method to set up the world coordinate system on the test surface.

3.1. Epipolar geometry-based searching strategy

In order to measure the displacement of a point, its 3D position before and after loading has to be computed. In this process, the corresponding points between the left and right images should be located, as shown in Fig. 2(b). Reliability-guided searching method [23] is unable to search the first corresponding point due to no calculated point. It is often difficult to determine the searching area for the first corresponding point. If the searching area is too large, it takes a lot of time to search. On the other hand, if the searching area is too small, the correct