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Normal strain measurement by machine vision

Guannan Li [a], Qingchang Tan [a,*], Qiucheng Sun [b], Yueqian Hou [c]

[a] College of Mechanical Science and Engineering, Jilin University, Changchun, China
[b] College of Basic Science, Changchun University of Technology, Changchun, China
[c] College of Mechanical and Vehicle Engineering, Changchun University, Changchun, China

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ABSTRACT

A machine vision method for measuring normal strain with high precision is presented. In the method, planar projection is modeled in order to enable the measurement without requiring coplanarity of the imaging and measured plane. Some of the model parameters are determined using translational displacements of known value. Along the single direction according to the need of measurement, the correction of distortion is involved in the method to improve the precision. Experiments were designed to validate the accuracy of the proposed method and confirm factors affecting the measurement results.

1. Introduction

Normal strain is an important parameter in studying and evaluating mechanical properties of materials. In industry, the strain is determined by tensile test, which requires deformation of the material measured along the loading direction. Therefore, it is an important research subject to measure the deformation of the material accurately and effectively.

With the development of digital image technology, machine vision was widely used in the deformation measurement [1,2], which made up of much lack of the contact methods. Accuracy is a primary factor to determine whether the machine vision methods can be used for deformation measurement. Although modern imaging techniques have increased the pixel precision [3–6], the model of measuring the deformation still faced some problems, such as replacement of grips of testing machines or change of size and shape of the measured specimens, which caused that the measured plane was not coplanar with the imaging plane. Although the coplanarity could be achieved by adjusting the position and pose of the camera, this adjustment might be inconvenient and time-consuming.

There are essentially two kinds of models in various existing methods of the deformation measurement. One is calibrating the scale factor between the pixel and actual size as a function of pixel coordinates. In 1998, using the function of scale factor, Taylor et al. [7] achieved an accuracy of 1/5600th of the FOV (field of view) in measuring deformation. Paikowsky et al. [8] proposed a second-degree polynomial fit to improve the model, and achieved an accuracy of 1/1266th of the FOV in 2000. Alshibli et al. [9,10] added distortion correction to the model in 2001. By the method, accurate 3D deformations of cylindrical sand specimens at different axial strain levels were reconstructed in tri-axial test aboard the Space Shuttle.

The other model is to employ a parametric perspective imaging model of converting pixel coordinates into object-space position. In 2003, White et al. [11] developed a measuring system based on a 14-parameter transformation which was proposed by Heikkila [12]. Performance of the model is obviously improved in accuracy, precision, and measurement array size with a relatively inexpensive 2-megapixel digital camera only. In 2010, Tang et al. [13] proposed a 3D digital image correlation system for measuring deformation and a stereo camera self-calibration

* Corresponding author. Tel.: +86 431 85094216; fax: +86 431 85094843.
E-mail address: tanqc@jlu.edu.cn (Q. Tan).

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algorithm was used based on photogrammetry to calculate the parameters. An accuracy of 0.4% deviation compared with the extensometer data was obtained. Ke et al. [14] established a stereo-based model with 24 invariant parameters in 2011. Based on the model, a large number of extensive numerical simulations and theoretical analyses were carried out to predict the uncertainty in locations, displacements and strains. Experiments in [15] demonstrated that they were in excellent agreement with actual measurements of surface strains.

In sum, the two models mentioned above bring to deformation measurement both advantages and disadvantages. The first kind of model is simple in calculation, but is valid only if the camera behaves according to the pin-hole model and the object plane is exactly coplanar with the imaging plane. The measurement accuracy will be lower if distortion correction is not employed. On the contrary, the second kind of model improves the precision greatly, but the plethora of parameters increases the complexity of computation, which limits its promotion and application.

The present work proposes a planar projection model to calibrate the measuring scale. The model is established without requiring the coplanarity of imaging and measured plane. Besides the pixel coordinates of the image center and a scale factor, only one parameter is exploited to present the influence of object distance changes on the measurement as the measured plane is not coplanar with imaging plane. In addition, the detected pixel coordinates are corrected along a single direction to increase the measuring accuracy. In this way, a real-time measurement with high-precision for tensile strain will be realized.

The rest of this article is organized as follows: Section 2 outlines the projection model for calibrating the measuring scale, and presents the method of determining the parameters. Section 3 introduces the principle of distortion correction. Section 4 describes the experiments to test measuring accuracy, and the influences of certain factors are analyzed experimentally. Finally, the conclusion is given in Section 5.

2. Imaging model and measurement principle

Since the perspective geometry has been widely applied to model the imaging system of camera [16], a deformation measurement model based on its principle is presented. As shown in Fig. 1, $X_WY_WZ_WO_W$ is the World Coordinate System (WCS) locating on the measured plane I, and xyo is the Pixel Coordinate System (PCS) locating on the imaging plane II. Plane II, III and IV in Fig. 1 are mutually perpendicular to each other. And plane III is parallel to the y-axis.

In practice, the imaging plane could not be placed in a position coplanar with the measured plane. They are related by a relative rotation of φ around y-axis and a relative rotation of θ around x-axis.

As the existence of the rotation angle φ, the object distance s_1 of each point along the mark is different, which affects the imaging position of the mark. However, for the points which have the same x-coordinate, the object distance s_1 will not be influenced by φ. That is to say, if the calibration and measurement are carried out on a fixed plane on which the points have the same x-coordinate (e.g. plane III in Fig. 1), the 3D measurement model could be simplified to a 2D model, as shown in Fig. 2. In practice, the edge points with the same x-coordinate were detected as the pixel positions of marks, and the rotation angle φ certainly could not be involved in the measurement model.

In Fig. 2, a_1b_1 is the distance between the upper and lower marks before deforming, and a_2b_2 is the distance between them after deforming. t_1n_1 and t_2n_2 are the pixel positions of a_1b_1 and a_2b_2, respectively. o_1 is the intersection point of optical axis and measured plane, and o_2 is the image center. Meanwhile, each length is represented by a symbol, as shown in Fig. 2. From the geometric relationships, the perspective projection can be expressed as:

$$\frac{A_1 \cdot \cos\theta}{s_1 + A_1 \cdot \sin\theta} = \frac{T_1}{s_2} \tag{1}$$

$$\frac{A_2 \cdot \cos\theta}{s_1 + A_2 \cdot \sin\theta} = \frac{T_2}{s_2} \tag{2}$$

where s_2 is focal length. Then, A_1 and A_2 are obtained by Eq. (1) and (2):

$$A_1 = \frac{T_1 \cdot s_1}{s_2 \cdot \cos\theta - T_1 \cdot \sin\theta} \tag{3}$$

$$A_2 = \frac{T_2 \cdot s_1}{s_2 \cdot \cos\theta - T_2 \cdot \sin\theta} \tag{4}$$

So actual displacement of the upper mark is:

$$\Delta l_A = A_1 - A_2 = \frac{s_1 \cdot s_2 \cdot \Delta l_T \cdot \cos\theta}{(s_2 \cdot \cos\theta - T_1 \cdot \sin\theta) \cdot (s_2 \cdot \cos\theta - T_2 \cdot \sin\theta)} \tag{5}$$

Dividing numerator and denominator in the right side of Eq. (5) by $s_2^2 \cdot \cos^2\theta$, yields:

$$\Delta\hat{l}_A = \frac{k_1}{(1 - k_2 \cdot T_1) \cdot (1 - k_2 \cdot T_2)} \cdot \Delta l_T \tag{6}$$

where $k_1 = s_1/(s_2 \cdot \cos\theta)$, $k_2 = \tan\theta/s_2$. In the same way, the displacement of lower mark is:

$$\Delta\hat{l}_B = \frac{k_1}{(1 + k_2 \cdot N_1) \cdot (1 + k_2 \cdot N_2)} \cdot \Delta l_N \tag{7}$$

In Eq. (6) and (7), one has $k_2 = 0$ and $k_1 = s_1/s_2$ as $\theta = 0$. Now these two equations become the equivalent viewing model, which indicates that the classical pin-hole model is a particular cause of the proposed model. As the pixel coordinates of the image center (x_0, y_0) has been obtained by the calibration method in Zhang [17], there are only two parameters (k_1, k_2) need to be calibrated here.

In the calibration of (k_1, k_2), the specimen was translated rigidly. Therefore $\Delta l_A = \Delta l_B$, in other word:

$$\frac{k_1 \cdot \Delta l_T}{(1 - k_2 \cdot T_1) \cdot (1 - k_2 \cdot T_2)} = \frac{k_1 \cdot \Delta l_N}{(1 + k_2 \cdot N_1) \cdot (1 + k_2 \cdot N_2)} \tag{8}$$

Two real roots will be obtained by solving the above quadratic equation of k_2. In the actual measurement, it could be inferred that $k_2 = \tan\theta/s_2$ should be a small value