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Free vibration monitoring experiment of a stayed-cable model based on stereovision

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ABSTRACT

To monitor 3D deformations of structural vibration response, a stereovision-based 3D deformation measurement method is presented in this paper. The center extraction and feature matching algorithm of circular target is studied to obtain 3D displacement of structural vibration response. Compared with traditional edge detection algorithms, this method utilizes a Canny-Zernike combination algorithm to attain sub-pixel edge of circular target, and the location accuracy of circular target can achieve 0.02 pixel. A free vibration test of a stayed-cable model is conducted in lab. The out-of-plane and in-plane displacement time histories of three circular targets on the model are gained simultaneously. Experiment results indicate the proposed method has the good agreement with the laser LVDT in in-plane data, the first three order frequencies of stayed-cable model identified by two methods are almost consistent. It is verified that this proposed approach is reliable and useful for monitoring 3D deformations of structural vibration response.

1. Introduction

For decades, testing structural vibration in real-time has become an important research content in civil engineering. The detected dynamic responses include displacement, velocity and acceleration. Because displacement is very intuitive for judging structural performance, research on a fast and accurate deformation measurement method becomes one of the main tasks for structural vibration testing.

Traditional methods used for displacement measurement mainly include dial test indicators, linear variable differential transducers (LVDTs) and laser displacement meters. These sensors except for the laser displacement meter are all contact-type and two-dimensional detection approaches, and need to be installed on structural surface in advance. In addition, preparation work is very complicated [1]. Although the laser displacement meter detects vibration response in non-contact way, it only records the displacement in one direction, and it is expensive. Due to expensive cost on many points measurement, the above-mentioned methods couldn't be used to measure vibration response of structures, such as large-span space structures and high-rise building.

The traditional digital image correlation method can measure the displacements/strains field on planar objects with single camera, however, it is only restricted to the in-plane displacements/strains measurement. Actually, researchers focus more on 3D deformation in vibration testing. The stereovision measurement method with two cameras can provide in-plane and out-of-plane displacement/strain fields on any kind of specimen (planar or not). In addition, this approach has the advantages of high accuracy, non-contact, full-field, 3D, multipoint and real-time measurement. More and more attention has been paid to the binocular stereovision method [2].

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In the last two decades, CCD camera was gradually used to test dynamic response in civil engineering. Olaszek [3] utilized an opto-mechanical system including two lens and a CCD camera to measure the real-time dynamic performance of bridge structures, which was calibrated by a black cross pattern. However, only 1 pixel accuracy for cross edge detection was achieved. Whiteman et al. [4] adopted the two-video camera system to detect the vertical deflections of concrete beam, and 0.25 mm precision was attained by the traditional digital photogrammetry method. Chang and Ji [5] employed the close-range digital photogrammetry technique and computer vision technique to measure 3D structural vibration response of large-scale bridge model in wind tunnel, Zhang Zhengyou calibration algorithm was applied to calibrate two cameras with a planar pattern. Harris corner detection algorithm was employed to extract the skeleton of intersection of target point, which was tracked by DIC method. Three tests in lab indicated the proposed approach combining digital photogrammetry technique and computer vision technique can provide the accurate displacement measurement. Liang et al. [6] presented a new camera calibration algorithm based on Zhang Zhengyou method to measure 3D vibration of large aeroplane model, experimental results showed that the precision of this new algorithm is higher than Zhang's calibration algorithm. Xiao et al. [7] integrated an accurate stereovision system using self-calibration method of cross-shaped target, however, the calibration pattern was very large and wasn't convenient in engineering.

In a word, above-mentioned measurement methods with CCD cameras adopted photogrammetry or videogrammetry technique to detect structural vibration response, and they mainly focused on the methods themselves or calibration algorithm. However, all these methods paid little attention to improve image processing of feature points. To increase measurement precision, this paper proposes a stereovision measurement method combined with image processing of circular target. Based on the stereovision model, the edge detection, center location and feature matching algorithm of circular targets is researched in this paper, and structural vibration response can be attained by tracking 3D position transformation of circular targets with two cameras. To validate the presented approach, a free vibration testing of a stayed-cable model is conducted in the lab.

2. Stereovision-based 3D deformation measurement method

Based on the parallax theory, the stereovision approach can accomplish 3D measurement. In usual case, there exist no requirements for two cameras' positions [8]. As shown in Fig. 1, assuming that the left camera coordinate system $o_l - x_l y_l z_l$ is located on the original point of the world coordinate system and does not rotate, $O_l - X_l Y_l$ is the corresponding image coordinate system of left camera; $o_r - x_r y_r z_r$ is the right camera coordinate system, $O_r - X_r Y_r$ is the corresponding image coordinate system of right camera.

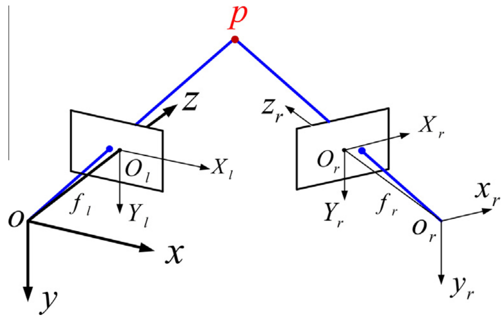

Fig. 1. Mathematical model of stereovision measurement.

Supposing that the matching relationship of the corresponding points on the left and right images has been already known, the 3D coordinates of feature point in the world coordinate system can be obtained according to the geometry constraint of binocular sensors, and the equation is expressed as follows [9]:

$$\begin{cases} x_l = z_l X_l / f_l \\ y_l = z_l Y_l / f_l \\ z_l = \dfrac{f_l (f_r t_x - X_r t_z)}{X_r (r_7 X_l + r_8 Y_l + f_l r_9) - f_r (r_1 X_l + r_2 Y_l + f_l r_3)} \end{cases} \quad (1)$$

where f_l and f_r are the effective focal lengths of the left and right camera, respectively. As can be seen from Eq. (1), if the effective focal length f_l, f_r and the image coordinates $(X_l, Y_l), (X_r, Y_r)$ of feature point in the left and right image coordinate system are all known, the 3D coordinates (x_l, y_l, z_l) of feature point in the left camera coordinate system can be calculated provided that the rotation matrix $R = \begin{bmatrix} r_1 & r_2 & r_3 \\ r_4 & r_5 & r_6 \\ r_7 & r_8 & r_9 \end{bmatrix}$, and translation matrix $T = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$ can be solved, therein the extrinsic parameters $[R \quad T]$ can be acquired by Zhang's calibration algorithm [10] based on 2D planar pattern.

To visually express structural vibration response, this paper sets the *xoy* planar of the world coordinate system $o - xyz$ on structural surface by using 2D planar pattern. Therefore, the structural surface of the initial state, where measured points are located, is regarded as the initiate fixed coordinate. As the world coordinate system doesn't coincide with the left camera coordinate system as above-mentioned, the actual coordinates of measured point can be obtained via coordinate transformation. The transforming procedure is given as follows.

First, as shown in Fig. 2, the single frame image of the planar pattern, which is put on structural surface, is captured by the left camera with the binocular stereovision system. The image coordinate of each intersection in Fig. 2 is extracted through Hough transforming algorithm [11]. z axis coordinate of each intersection on the image of planar pattern is assigned to be zero, x and y axis coordinates are assigned to be the actual coordinate relative to the assumed coordinate origin.

Secondly, the transform matrix $[R \quad T]$ of the left camera coordinate system relative to the established global coordinate $o - xyz$ system is solved. The transform relation