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Dynamic testing of a laboratory model via vision-based sensing

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ABSTRACT

In the class of not-contact sensors, the techniques of vision-based displacement estimation enable one to gather dense global measurements of static deformation as well as of dynamic response. They are becoming more and more available thanks to the ongoing technology developments. In this work, a vision system, which takes advantage of fast-developing digital image processing and computer vision technologies and provides high sample rate, is implemented to monitor the 2D plane vibrations of a reduced scale frame mounted on a shaking table as available in a laboratory. The physical meanings of the camera parameters, the trade-off between the system resolution and the field-of-view, and the upper limitation of marker density are discussed. The scale factor approach, which is widely used to convert the image coordinates measured by a vision system in the unit of pixels into space coordinates, causes a poor repeatability of the experiment, an unstable experiment precision, and therefore a global poor flexibility. To overcome these problems, two calibrations approaches are introduced: registration and direct linear transformation. Based on the constructed vision-based displacement measurement system, several experiments are carried out to monitor the motion of a scale-reduced model on which dense markers are glued. The experiment results show that the proposed system can capture and successfully measure the motion of the laboratory model within the required frequency band.

1. Introduction

In view of reconstructing the stress and strain fields inside the medium, non-contact displacement sensors are preferred since they can directly monitor the displacement of existing structures without posing any special constraints to the structure [1,2]. When a scale-reduced model is studied, conventional sensors cannot be mounted, sometimes, because the introduction of such sensor masses could affect the behavior of the models. For full-scale applications, non-contact sensors do not undergo the same force or deformation patterns as the structure does, and thus their durability is increased. For these reasons, there is a growing interest in developing non-contact displacement sensors. Recent investigations suggest the application of laser based system [3,4] or radar-based systems [5,6]. Applications of vision-based systems [7–9] are also reported in the literature.

A vision-based displacement system was described by Olaszek and was used to measure the vibration response of a railway viaduct in Huta Zawadzka [10]. However, the camera in this application is tailor-made. Recent progresses in vision-based techniques and systems have made the vision-based devices more available and affordable. University of Southern California scientists constructed a vision system and applied it to monitor the displacement of Vincent Thomas Bridge [11]. They also applied 3D scene reconstruction for evaluating the defect evolution in structures [12] and to detect the concrete crack [13]. Lee and Shinozuka [7] utilized a commercial digital video camera with a sample rate at 30 Hz to monitor the displacement of a Steel-Box Girder Bridge. In the work of Uhl et al. [14], a vision-based measuring apparatus was used to monitor the in-plane deformation of a steel frame and three-dimensional vibration of a steel frame. Jurjo et al. [8,15] utilized a vision system to study the uni-dimensional and two-dimensional non-linear dynamic behavior of a clamped-free slender metallic column subject to its own weight. Wieger and Caicedo [16] proposed an elaborate system which utilizes two lasers located in each measuring point on the structure and directed to a displacement recording station (DRS). A camera located inside the DRS is used to record the location of the laser markers. Displacements and rotations of measuring points are obtained according to the change in positions and orientations of the lasers with respect to the camera reference frame. In this way, the synchronization between the measurements is not necessary given that only one camera is used for several measurements and the changing lighting conditions has minimal effects on the methodology. Additionally, the size of the structure is not a limiting factor in the displacement calculations. Another elaborate system is proposed by Jeon: it is “a paired structured light system” and consists of two cameras, three laser lights driven by servos and

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two screens. This system can measure the relative 6-DOF displacements between two sides, i.e. the relative translational and rotational displacements [17]. However, except the systems constructed by Jurjo et al. [8,15], the other aforementioned systems provide sample frequencies varied from 0.1 to 30 Hz, which could be insufficient for dynamic experiments in some cases. Moreover, in order to construct such systems, one should have deep knowledge in image processing, high-level language programming (such as Visual C++), computer vision and even servo controlling. This refrains from a diffusion of vision-based measurement approach.

This paper introduces a vision-based system for monitoring the 2-dimensional displacement of a laboratory structure on which markers are simply glued. The image sequences recorded by the camera are processed by a commercial software to obtain the image coordinates of the markers. The real coordinates of the markers are reconstructed by algorithms programming in Matlab. Thus, one can quickly construct his own vision-based displacement measurement system and perform experiments. Specially, the camera used in this system can provide sample rate up to 60 Hz. The following of this paper is organized as follows: in Section 2, the camera parameters and the connections between those parameters and the practical scene are illustrated. In Section 3, the image processing procedure for obtaining the image coordinates of the markers is presented. In Section 4, approaches to reconstruct the space coordinates from image coordinates are demonstrated. The displacement in real coordinates can be obtained intuitively by multiplying the one in image coordinates by a scale factor. Since the accuracy of this approach is greatly influenced by the camera orientation due to the projective distortion, and this affects the repeatability of the experiment, two reconstructive approaches are introduced to solve this problem: registration and direct linear transformation (DLT). Finally, a vision-based displacement sensing system is constructed and laboratory experiments are carried out to verify its applicability.

2. The vision-based monitoring device

While selecting the vision device, one faces a sequence of parameters: image resolution, lens focal length, image sensor size (i.e. Charge Couple Device (CCD) sensor size), and sample rate. One merit of vision-based displacement measurement is that several markers can be fixed on the structure and their displacement can be monitored simultaneously by the camera. Therefore, the upper limitation of marker density is another issue which must be considered. The connections between those parameters and the scene are explained below.

Given the ratio of the measurement distance and the focal length, the image sensor size and the corresponding image resolution of a camera are related to the field-of-view and the expected measurement resolution. As proposed, for example, in [18], the field-of-view of a camera (named $H \times V$) can be approximately evaluated as the product of the CCD sensor dimension (named $h \times v$) by the ratio between the work distance, W, and the focal length, f, as illustrated in Eq. (1). The measurement resolution can also be estimated through the dimension of each pixel element in the CCD sensor according to this equation. Therefore, the larger of the CCD sensor size, the larger field-of-view can be captured when keep other factors invariant.

$$f/W = h/H = v/V \tag{1}$$

The lens focal length determines its angle of view: wide angle lenses have short focal length, while telephoto lenses have longer corresponding focal length. According to Nyquist theorem, in order for anti-aliasing, the sample rate must be at least twice of the highest frequency component of the measured signal.

A vision-based system allows one to place dense markers on the monitored structure. The motion of each marker is tracked by finding its position in all images. It will be highly time-consuming if the marker is searched inside the whole image. An alternative way is to assign an Area of Interest (AOI) for each marker to be searched in a new image according to its current position and adopted motion prediction model. The new AOI of a marker (T1) must be able to cover its potential position at next frame. If there is another marker (T2) coming into the AOI of T1, misjudgment is introduced: this limits the density of the markers.

3. The image processing procedure

In the following shaking table experiments, several markers (LED lights) are glued on the monitored structured. Since only the motions of markers are cared, a short exposure is adopted to make the background as dark as possible and therefore to increase the contrast between the markers and the background. After the image sequences has been digitalized and stored into the memory, image processing is carried out by a commercial software, such as the Image Pro Plus 6.0 or the Image Gear. The image processing procedure is summarized in Fig. 1. Before focusing on the markers, the captured image is preprocessed in order to well identify the markers and reduce the noise, i.e. by contrast enhancement and/or filter. In this case, the contrast enhancement, which utilizes various intensity transformation techniques (such as Gamma transformation or contrast stretching [19]), is used to further increase the intensity contrast between the bright markers and the dark background. The calibration approaches, such as the scale factor approach or the registration approach, are also set in this step. Then the Area of Interest (AOI) is selected in order to focus the successive image processing on the markers. A threshold is defined in order to segment the markers from the background. Otsu's method is efficient in deciding the intensity threshold when the image histogram consists of two different narrow peaks which are separated by a deep valley [19]. However, it cannot be directly used in this case: the image histogram is dominated by a large peak since the markers are relatively small compared to the background in area and that would cause a high concentration of bright pixels. Therefore, an edge image is first obtained, based on which a mask image can be generated. This mask image is used to remove the large histogram peak before applying the Otsu's method to decide the threshold [19]. Then some geometry features are adopted to represent the potential markers by a numerical method. The markers are, hence, recognized by applying some constraints introduced on the basis of these geometry features or statistics features. In this case, the area can be used to represent the potential markers and a reasonable region is used to filter the false markers out. The aforementioned procedure is applied to all images to track the motion of the markers and the results are recorded as the image coordinates of the markers. These data are then exported to be further processed by a user-developed Matlab m-file.

4. Reconstruction of the space coordinates of the markers

The motions of the markers, as acquired from the image processing procedure, are in image coordinates, i.e. pixels, and should be converted into motions in space coordinates, i.e. cm or m. Heuristically, the scale factor approach, which supposes that the object is equally scaled down into the image, can fulfill this conversion. Indeed, this approach is universally employed in several applications [20,21]. But this supposition is based on an approximation that the depth-of-fields of all points in the object plane are equal, which introduces errors into the reconstruction results. Moreover, this supposition quickly becomes false when the optical