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Experimental validation of cost-effective vision-based structural health monitoring

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ABSTRACT

Monitoring structural displacement responses can provide quantitative information for both structural safety evaluations and maintenance purposes. To overcome the limitations of conventional displacement sensors, advanced noncontact vision-based systems offer a promising alternative. This study validates the potentials of the vision displacement sensor for cost-effective structural health monitoring. The results of laboratory experiments on simply-supported beam structures demonstrate the high accuracy of the vision sensor for dense full-field displacement measurements. The identified natural frequencies and mode shapes from measurements by using one camera match well with those from an array of accelerometers. Moreover, the smoother mode shapes make possible the noncontact damage detection based on the conventional mode shape curvature index. This study also discusses the issues concerning the practical applications of the vision displacement sensors, such as the scaling factor determination, measurement with small camera tilt angles, tradeoffs between the measurement resolution and measurement points or field of view, etc. Furthermore, the remote, real-time and multi-point measurement capacities of the vision sensor are confirmed through field tests of Manhattan Bridge during train passing.

1. Introduction

Over the past few decades, considerable efforts have been made towards vibration-based structural health monitoring (SHM) techniques. Most of the existing SHM systems are equipped with accelerometers and/or strain sensors [1–6]. Such practice is highly expensive to operate, mainly due to cumbersome, time-consuming, and expensive installation of sensors and their data acquisition systems. One other main bottleneck lies in that the spatial resolution of the obtained mode shapes depend on the total number of deployed sensors, which may result in less accurate damage localization. Therefore, in order to recover the hidden structural information, complicated techniques have been explored and studied for structural modal analysis, system identification and damage detection [7]. Noteworthy, for small-scale structures, e.g., mechanical structures and scaled models of large structures, mass of attached sensors may change the system dynamic behaviors, causing inaccurate identification results.

Although the displacement response is considered a more important structural index since it's directly related to the structure stiffness, sensors currently available for measuring structural displacements have limitations in practical applications. As an emerging noncontact method, the vision-based displacement sensor systems offer a promising alternative. Compared to other frequently used contact-type (e.g., LVDT) and noncontact-type (e.g., GPS, laser vibrometer and radar interferometry system) displacement sensors, significant advantages of the vision sensor include its low cost, ease of operation, and flexibility to extract

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structural displacements at multiple points from a single measurement [8–34].

Vision-based displacement sensor systems are primarily enabled by the template matching/registration techniques, including pattern matching [32], edge detection, digital image correlation (DIC) [13], Hough transforms [16], the RANSAC algorithm [10], the optical flow-based method [30], the upsampled cross correlation (UCC) and orientation code matching (OCM)[35], etc. For example, on the basis of UCC and OCM, the authors developed two sets of vision displacement sensors [35]. The study [35] examined the robustness of the vision sensor against ill environmental conditions. It's found that the OCM scheme is more robust, since UCC utilize the image intensity values for template matching which relies on the image quality, while OCM employs the gradient information in the form of orientation codes which is inherently invariant to variations in image intensity and thus more robust when irregularities are present. Recently, efforts have also been made to investigate the feasibilities of displacement measurements utilizing the advanced onboard sensing capabilities of the smartphone technologies, such as embedded high-resolution/speed video features, powerful processors and memories, and open-source computer vision libraries, etc. For example, Min et al. [36] developed a smartphone software application for real-time displacement measurement and shaking table tests were conducted to study its accuracy.

However, most of the existing vision-based sensors have one or more of the following limitations in practical applications: (1) The adopted template matching techniques gives displacement with integer-pixel resolution since the minimal unit in a video image is one pixel. Although in many applications the pixel-level accuracy is adequate, it is often far from the required accuracy in case of small structural vibrations. (2) Most existing vision sensor systems can only be used for post-processing the recorded video files, and thus cannot perform real-time displacement measurement, which limits its application for continuous online monitoring. (3) It's well-known that the accuracy of the template matching techniques is largely dependent on the image quality, which is often difficult to guarantee in outdoor field environmental conditions such as illumination variation, partial target occlusion, partial shading, and background disturbance, etc.

It's known that the in-plane displacement measurement accuracy of an object using a single-camera based vision system is sensitive to out-of-plane motion. Sutton et al. [37] found that the in-plane measurement error due to out-of-plane translation is proportional to $\Delta Z/Z$, where ΔZ is the out-of-plane translation displacement and Z the distance from the object to the camera. Thus in actual applications for remote sensing, satisfactory measurement accuracy could be achieved for cases of small ΔZ and much larger Z. In fact, a stereovision system with a pair of cameras can be used to minimize the out-of-plane motion effect. One other major challenge concerning the vision-based sensor is how to accurately determine the scaling/calibration factor, which converts the image coordinates in the unit of pixels into physical coordinates. In general, it can be estimated based on the intrinsic parameters of the camera as well as the extrinsic parameters between the camera and the object structure. However, the prerequisite is the perpendicularity of the camera's optical axis to the object surface, thus to ensure all points on the object surface have equal depth of fields. Such a requirement would impose some difficulties in the practical implementations because small magnitude of camera misalignment angle can be unnoticed during the experiment setup especially when the object distance from the camera is relatively large. Moreover, in outdoor field tests, it is sometimes unavoidable to tilt the camera optical axis by a small angle in order to track the measured object surface. The effects of the optical axis tilt angle and lens focal length has been theoretically studied by the authors based on the 1D in-plane translation [31]. It can be seen that the error increases as the tilt angle increases and the error is inversely related to the focal length. These finds are yet to be experimentally validated.

Additionally, as an emerging technique, most of the existing vision sensor studies are focusing on the sensor performance evaluation, without discussing the use of the measured displacement data. Only a few attempts have been made towards applying the vision-based sensors for structural safety assessment. For example, Dworakowski et al. [38] obtained the deflection curve of small-scale laboratory beams by means of DIC. Then two deflection shape-based algorithms are evaluated for damage detections of the beams. Song et al. [16] presented a proof-of-concept application of virtual vision sensor for damage localization in laboratory steel cantilever beams. Kim et al. [14] proposed a vision-based monitoring system using DIC to evaluate the cable tensile forces of a cable-stayed bridge. Wang et al. [39,40] demonstrated that the region-based Zernike moment descriptor (ZMD) is a robust image processing technique for mode-shape recognition and finite element model updating of simple plate structures. Furthermore, Wang et al. [41] carried out vibration measurement on the 3D surface of a car bonnet by a 3D DIC system. Shape features of the bonnet are extracted from a series of full-field transient responses under random excitation. Using developed vision sensors, Feng and Feng [35], Yoon et al. [42] and Oh et al. [43] respectively conducted laboratory vibration experiments on frame structures. Modal parameters are identified and compared with those from conventional accelerometer-based method, which show good agreements. Moreover, the identified modal parameters are used to successfully update the inter-story stiffness of the frame structure [35].

Despite the aforementioned advances, study of vision-based sensor applications is still at an early stage. As an effort to explore the potentials of the vision sensor for low-cost SHM, this study aims to experimentally demonstrate the usefulness of the displacement data for structural modal analysis and damage detection through laboratory experiment of simply-supported beam structures. An easy and practical calibration method is presented for cases of non-perpendicular camera optical lens axis. Furthermore, field tests of the Manhattan Bridge were conducted to confirm the remote, real-time and multi-point measurement capacities of the vision sensor.

2. Description of computer vision-based displacement sensor

The proposed vision sensor system simply consists of a video camera, a zoom lens and a notebook laptop. In the implementation, an initial area in the first image of a sequence of video frames captured is defined as a template. The template can be located in the successive images using the template matching techniques. Thus the displacement in pixels is obtained, which can be further