Engineering Structures 156 (2018) 105–117

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Review article

Computer vision for SHM of civil infrastructure: From dynamic response measurement to damage detection – A review

Dongming Feng*, Maria Q. Feng

Department of Civil Engineering and Engineering Mechanics, Columbia University, New York, USA

ARTICLE INFO

Keywords:
Computer vision
Displacement measurement
Structural health monitoring
Structural dynamics
Damage detection
Natural frequency
Mode shape
Model updating

ABSTRACT

To address the limitations of current sensor systems for field applications, the research community has been actively exploring new technologies that can advance the state-of-the-practice in structural health monitoring (SHM). Thanks to the rapid advances in computer vision, the camera-based noncontact vision sensor has emerged as a promising alternative to conventional contact sensors for structural dynamic response measurement and health monitoring. Significant advantages of the vision sensor include its low cost, ease of setup and operation, and flexibility to extract displacements of any points on the structure from a single video measurement. This review paper is intended to summarize the collective experience that the research community has gained from the recent development and validation of the vision-based sensors for structural dynamic response measurement and SHM. General principles of the vision sensor systems are firstly presented by reviewing different template matching techniques for tracking targets, coordinate conversion methods for determining calibration factors to convert image pixel displacements to physical displacements, measurements by tracking artificial targets vs. natural targets, measurements in real time vs. by post-processing, etc. Then the paper reviews laboratory and filed experimentations carried out to evaluate the performance of the vision sensors, followed by a discussion on measurement error sources and mitigation methods. Finally, applications of the measured displacement data for SHM are reviewed, including examples of structural modal property identification, structural model updating, damage detection, and cable force estimation.

1. Introduction

Structures and infrastructure systems including bridges, buildings, dams, pipelines are complex engineering systems that support a society's economic prosperity and quality of life. As these systems age and deteriorate, their proper inspection, monitoring and maintenance has become increasingly important. The conventional practice based on periodic human visual inspection is inadequate. Nondestructive evaluation (NDE) has shown potential for detecting hidden damage but the structures' large size presents a significant challenge to implement such local inspection methods. Over the past two decades, a significant amount of studies have been conducted in the emerging field of structural health monitoring, aiming at objective and quantitative structural damage detection and integrity assessment based on measurements by sensors, mostly accelerometers [1–11]. For example, Carden and Fanning [7] presented an extensive literature review of the damage detection techniques based on changes in the frequency-domain modal properties, such as natural frequencies, mode shapes and its curvatures, modal flexibility and its derivatives, modal strain energy, and frequency response function. Although these studies have produced SHM methods, frameworks and algorithms validated through numerical, and laboratory and field experimental studies, their wide deployment in realistic engineering structures are limited by the requirement of cumbersome and expensive installation and maintenance of sensors networks and data acquisition (DAQ) systems.

To address these limitations, the research community has been actively exploring new technologies that can advance the current state-of-the-practice in SHM, such as wireless sensors [12–14], fiber optic sensors [15–17], and the interferometric radar system [18]. In recent years, camera and computer vision-based sensors have emerged as a promising tool for non-contact remote measurement of structural responses, in which displacements are extracted by tracking the movement of targets from videos images. Compared to the structural acceleration response (which most of the SHM studies are based on), the displacement response directly reflects the structural overall stiffness, and thus offers a potential for more accurate assessment of structural conditions [2]. Conventional contact-type displacement sensors such as the linear variable differential transducer (LVDT) require a stationary

* Corresponding author.
E-mail address: df2465@columbia.edu (D. Feng).

https://doi.org/10.1016/j.engstruct.2017.11.018
Received 6 May 2017; Received in revised form 4 October 2017; Accepted 8 November 2017

reference point, which is often difficult to find in the field. Thanks to the advances in cameras and computer vision algorithms, the non-contact vision sensor technologies based displacement measurement offers significant advantages over the contact-type and other non-contact-type (e.g., GPS, laser vibrometer) displacement sensors, as summarized below [19–49]:

(1) In contrast to the conventional contact-type sensor (such as an LVDT) that requires time-consuming and costly installation of the sensor on the structure with physical connections to not only a stationary reference point but also DAQ and power supply, the vision sensor does not require physical access to the structures, as the camera can be set up at a remote location. This represents a significant time and cost saving. For bridge monitoring, for example, no traffic control is required.
(2) Compared with the GPS, which still requires installation on the structure (but not the stationary reference point), the vision sensor is far more accurate and less expensive. Depending on the cost, the GPS measurement error is typically in the range of 5 mm–10 mm, more than an order of magnitude larger than that of the vision sensor.
(3) Compared with the non-contact laser vibrometer, which needs to be placed relatively close to the measurement target due to the low laser power for safety concerns, the vision sensor can be placed hundreds of meters away (when using a zoom lens) and still achieve satisfactory measurement accuracy.
(4) In contrast to these conventional sensors, all of which are point-wise sensors, the vision sensor can be termed as a noncontact distributed sensing technique as it can simultaneously tracking multiple points from a long distance. More importantly, one can easily alter the measurement points after the video images are taken.

The research community has applied vision sensor systems on a diverse set of structures to measure their displacements in either controlled laboratory or complex and challenging field environments. In the SHM applications, structural natural frequencies and mode shapes can be conveniently obtained from displacement measurements using one or more cameras. The adoption of vision sensors can significantly reduce test cost and time associated with conventional instrumentations. For example, Poozesh et al. [50] pointed out that testing of a typical 50 m utility-scale wind turbine blade requires approximately 200 gages (costing $35 k–$50 k) and about 3 weeks to set up a conventional strain gauge system. By contrast, a multi-camera noncontact measurement system can significantly reduce the test time and cost. Data analytics for FE model updating, structure damage detection and integrity evaluation can be carried out utilizing the measured displacement time histories and corresponding operational modal analysis results.

In the field of experimental mechanics such as material mechanical testing and structural stress analysis, the digital image correlation (DIC) technique has been commonly used as a practical and effective tool. It can directly provide full-field displacements to sub-pixel accuracy and full-field strains by comparing the digital images of a test object surface acquired before and after deformation. Experimental mechanics applications usually involve specific specimens and the measurements are made in well controlled environments. To achieve reliable and accurate DIC analysis, artificial speckle or texture patterns are often applied on the specimen surface [26]. Pan et al. [51] systematically reviewed and discussed the methodologies of the 2D DIC technique for displacement field measurement and strain field estimation, and provided detailed analyses of the measurement accuracy considering the influences of both experimental conditions and algorithm details. Based on the measured strain fields, various material mechanical parameters including Young's modulus, poisson's ratio, stress intensity factor, residual stress and thermal expansion coefficient can be further identified [51,52]. It is noted that the emphasis of this paper is placed on the vision-based sensor systems for structural dynamic displacement measurement and SHM applications. DIC-based applications for experimental mechanics are not included in this paper.

In summary, this paper aims to provide a review of the collective experience that the research community has gained from the development and application of vision-based displacement sensors, with emphasis on structural dynamics and health monitoring applications. The paper is organized as follows. In Section 2, general principles of vision-based sensor systems are presented by reviewing various template matching techniques, coordinate conversion methods, measurement by tracking artificial targets vs. natural targets, etc. In Section 3, validations of the measurement capacity and accuracy of vision-based sensors are reviewed by providing a description of the current state of experimentation in both laboratory and field environments, followed by the detailed discussion on measurement error sources and error mitigation methods. In Section 4, current studies on using the measured displacement data for structural SHM are reviewed in detail, including examples of modal analysis, model updating, damage detection, and cable force estimation. Finally, Section 5 concludes the paper with a summary and outlook of future directions of vision-based sensors for SHM.

2. Basics and principles of vision-based sensor system

2.1. System basics: hardware and software

The vision-based displacement sensor system typically consists of a video camera (or cameras), a zoom lens (or lenses), and a computer. It may also require lighting lamps for conducting measurements at night [27]. Table 1 shows typical hardware components of a vision sensor system. The camera equipped with the lens is fixed on a tripod and placed at a remote location away from the structure. The camera is connected to the computer, which is installed with an image acquisition and analytics software package. If the software has real-time processing capability, the measured displacement time histories can be displayed on the computer screen in real time and automatically saved to the computer. Otherwise, the images can be saved for post processing. Oftentimes, it is required to take measurements from a remote distance. To guarantee the measurement resolution, optical lens with proper focal length should be selected to zoom in the image to obtain enlarged tracking target/targets.

In literature [54], an easy-to-use user interface, as shown in Fig. 1, is built into a real-time image processing and displacement extraction software package for easy operation by non-technical staff. It summarized that the procedure of the vision-based displacement measurement typically includes:

(1) *Vision sensor setup*. Fix the camera equipped with the lens on a tripod and place it at a remote convenient location away from the structure. The camera is connected to the notebook computer installed with the image-processing software.
(2) *Single- or multiple-target/template registration*. Any natural or artificial texture (summarized in detail in Section 2.7) on the structural surface can be registered as a tracking target, as long as it has pattern with a contrast to surrounding background. For each measurement point, a subset with a proper size should be chosen, which should contain sufficient local texture to allow an accurate pattern matching [49].
(3) *Template matching for displacement extraction*. The template matching algorithm (summarized in detail in Section 2.2), mostly together with subpixel techniques, is employed to track the targets registered in the previous step. The motion of the target is tracked by finding its position in a sequence of video images. It would be highly time-consuming if the target is searched within the whole image of each video frame. To reduce computational time, the searching area could be confined to a predefined region of interest