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Dynamic displacement measurement of large-scale structures based on the Lucas–Kanade template tracking algorithm

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ABSTRACT

The development of optics and computer technologies enables the application of the vision-based technique that uses digital cameras to the displacement measurement of large-scale structures. Compared with traditional contact measurements, vision-based technique allows for remote measurement, has a non-intrusive characteristic, and does not necessitate mass introduction. In this study, a high-speed camera system is developed to complete the displacement measurement in real time. The system consists of a high-speed camera and a notebook computer. The high-speed camera can capture images at a speed of hundreds of frames per second. To process the captured images in computer, the Lucas–Kanade template tracking algorithm in the field of computer vision is introduced. Additionally, a modified inverse compositional algorithm is proposed to reduce the computing time of the original algorithm and improve the efficiency further. The modified algorithm can rapidly accomplish one displacement extraction within 1 ms without having to install any pre-designed target panel onto the structures in advance. The accuracy and the efficiency of the system in the remote measurement of dynamic displacement are demonstrated in the experiments on motion platform and sound barrier on suspension viaduct. Experimental results show that the proposed algorithm can extract accurate displacement signal and accomplish the vibration measurement of large-scale structures.

1. Introduction

Large-scale structures, including bridges and buildings, are exposed to various external loads, such as traffic, earthquakes, and gusts during their lifetime. These external loads may induce structural damage that results in costly repair and loss of human lives. Therefore, a system of monitoring the behavior of large-scale structures is necessary to obtain valuable information for structural safety evaluation. Conventional sensors like accelerometers [1,2] are widely used in the industry to study the behavior of large-scale structures. However, conventional sensors can only obtain vibration acceleration information, which does not provide an intuitionistic exhibition of the actual vibration. Several limitations also restrict the application range of this contact-type measurement. For example, the introduction of sensors may change the behavior of structures. The installation of conventional sensors is sometimes difficult, such as installation on a bridge spanning a wide

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river. In many situations, the measurement results may be interfered with by factors such as remote measurement, high temperature, and magnetic fields. For this reason, interest is growing in the development of non-contact displacement measurement techniques, such as speckle photography [3], global positioning systems (GPS) [4,5], and Laser Doppler vibrometer [6]. However, the high costs of these non-contact systems prevent their wide applications.

Optical devices and cameras offer effective alternatives to non-contact measurement with their advantages of remote measurement and no mass introduction. With these devices, what you see is what you get and movement information can be shown visually. Owing to the wide availability of affordable high-quality digital imaging sensors and high-performance computers, cheaper cameras with high resolution have found growing applications in several areas, including engineering monitoring [7–9], human motion [10,11] and underwater measurement [12]. Recently, vision-based techniques were successfully used for the displacement measurement of large-scale structures with good results [13–18]. Wahbeh et al. [13] realized the measurement of displacements and rotations of the Vincent Thomas Bridge in California by using a highly accurate camera in conjunction with a laser tracking reference. Fukuda et al. [16] proposed a camera-based sensor system that uses a robust object search algorithm to measure the dynamic displacements of large-scale structures. Digital image correlation (DIC) [17,18] is also applied in experimental mechanics for non-contact, full-field deformation measurement.

The traditional camera system for displacement measurement is composed of commercial digital cameras and a notebook computer, both of which are now very affordable. However, commercial digital cameras have low frame rates, for example, 30 frames per second (fps), which limit their range of applications to vibration frequencies of less than 15 Hz [14]. Fortunately, numerous high-speed vision systems that can capture images at 1000 fps or even faster have been developed to overcome these restrictions, and several applications using these systems have been reported in [9,19]. In the present paper, a high-speed camera system composed of a notebook computer connected to a camera head with telescopic lenses is developed for displacement measurement. The camera head uses CCD as an image receiver and captures grayscale images at high speed. The pictures are then streamed into the notebook computer through a USB 3.0 interface. On the notebook computer, the captured video can be processed by a software to realize the tracking of an object and extract motion information.

High-speed cameras have high requirements for motion-tracking algorithms. Conventional image-processing techniques are widely used, but they are complex and cumbersome. They require a series of image-processing steps before relevant information can be extracted for practical purposes. These steps include texture recognition, projection of the captured image, and calculation of the actual displacement using target geometry, in which many parameters need to be adjusted simultaneously to accommodate the specific type of image conditioning. As a result, the computational efficiency and the robustness of the computer algorithms are negatively affected, and expertise is required to adjust the processing parameters for optimal performance. In addition, conventional processing systems previously developed require the installation of a target panel on the measurement point of the structures in advance [13–15]. The target panel with a pre-designed high-contrast black and white pattern contributes to the high-precision tracking of the target movement. However, the installation of the target panel is sometimes rather difficult, such as a bridge spanning a wide river. Although several applications without the targets were developed recently [16,20–22], their measurable locations on the structures are limited by specific characteristics such as cables and gusset plates. In this study, the Lucas–Kanade template tracking algorithm in the field of computer vision is introduced to achieve displacement measurement by using existing features such as edges and texture on the structures instead of an extra target panel. Compared with the paper [20] in which Lucas–Kanade optical flow method was used to obtain the direction of vibration and the canny edge detection algorithm was applied to extract 1D motion displacement, the proposed method got rid of additional image-processing techniques with less adjustable parameters.

Template tracking is a widely studied algorithm in computer vision. It belongs to the direct type of region-based tracking method [23,24] and can date back to Lucas and Kanade [25]. A unifying framework for the Lucas–Kanade algorithm has been reported in [26], and its goal is to minimize the sum of squared error between the template and the image warped back onto the coordinate frame of the template. In particular, the inverse compositional (IC) algorithm [27] is a more efficient version, where the roles of the template and the image are switched, and the Hessian need not be updated at each iteration. Through the direct use of region content of the image, the task of object tracking is accomplished by extracting the template region in the first frame and finding the most matching region in the following frames. In this way, the moving object can be tracked and the motion information can be extracted. Template-tracking algorithms carry both spatial and appearance information, and thus perform well with high levels of robustness and accuracy. They have been widely applied in various applications, including object tracking [28,29], parametric and motion estimation [30,31], and medical image registration [32,33].

Given its excellent characteristics, the Lucas–Kanade IC algorithm is introduced in this study on displacement measurement to solve the problems of conventional image-processing techniques. A rapid and real-time modification for translation transformation based on the original IC algorithm is also proposed. After several optimizations, the computation time of one extraction in the modified algorithm is reduced to less than 1 ms, thereby providing the potential of real-time extraction to the high-speed captured video. Finally, the proposed algorithm is utilized in the high-speed camera system to realize the displacement measurement of actual large-scale structures. And two experiments are carried out under laboratory and realistic conditions for performance verification. The positive results demonstrated the accuracy and efficiency of the camera system in the remote measurement of dynamic displacement.

This paper is organized as follows: Section 2 introduces the components and capability parameters of the high-speed camera system. Section 3 presents the theory of Lucas–Kanade template tracking algorithm. Section 4 describes the