Measurement 88 (2016) 372–384

Contents lists available at ScienceDirect

Measurement

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

Vision-based structural displacement measurement: System performance evaluation and influence factor analysis

X.W. Ye [a,*], Ting-Hua Yi [b], C.Z. Dong [a], T. Liu [a]

[a] *Department of Civil Engineering, Zhejiang University, Hangzhou 310058, China*
[b] *School of Civil Engineering, Dalian University of Technology, Dalian 116023, China*

ARTICLE INFO

Article history:
Available online 16 January 2016

Keywords:
Structural health monitoring
Vision-based system
Digital image processing
Multi-point pattern matching algorithm
Influence factor analysis

ABSTRACT

In the past decade, the emerging machine vision-based measurement technology has gained great concerns among civil engineers due to its overwhelming merits of non-contact, long-distance, and high-resolution. A critical issue regarding to the measurement performance and accuracy of the vision-based system is how to identify and eliminate the systematic and unsystematic error sources. In this paper, a vision-based structural displacement measurement system integrated with a digital image processing approach is developed. The performance of the developed vision-based system is evaluated by comparing the results simultaneously obtained by the vision-based system and those measured by the magnetostrictive displacement sensor (MDS). A series of experiments are conducted on a shaking table to examine the influence factors which will affect the accuracy and stability of the vision-based system. It is demonstrated that illumination and vapor have a critical effect on the measurement results of the vision-based system.

1. Introduction

In recent years, the machine vision technology has been widely employed in measurement of structural dynamic behaviors and received increasing concerns from the community of structural health monitoring (SHM) [1–7]. With the aid of the digital image processing technique and modern computer and information science, a significant number of vision-based systems have been developed and applied to measure the structural dynamic displacement [8]. Lee and Shinozuka [9] used the digital image processing technique to monitor the real-time displacement of a flexible bridge. Fukuda et al. [10] developed a time synchronization vision-based system for measurement of multi-point structural displacements. Choi et al. [11] introduced a vision-based displacement measurement system and the accuracy of measurement was improved by use of the region of interest (ROI) in the digital image. Santos et al. [12] investigated the calibration problem of vision-based system in displacement monitoring of suspension bridges. Jeon et al. [13] developed a vision-based remote 6-DOF structural displacement monitoring system with high accuracy in real time measurement. Park et al. [14] proposed a 3D displacement measurement model for health monitoring of structures using a motion capture system with multiple cameras.

To achieve the accurate and reliable measurement results by the vision-based system, it is a necessity to carefully examine the error sources and further to make effective measures. Recently, research efforts have been devoted to investigating the factors influencing the performance of the vision-based system, such as subset size [15–17], gray level interpolation [18], and correlation functions or shape functions [19,20]. Yoneyama and Kikuta [21] proposed a method of lens distortion correction in order to improve the measurement accuracy of digital

* Corresponding author. Tel.: +86 571 88208478; fax: +86 571 88208685.
E-mail address: cexwye@zju.edu.cn (X.W. Ye).

http://dx.doi.org/10.1016/j.measurement.2016.01.024
0263-2241/

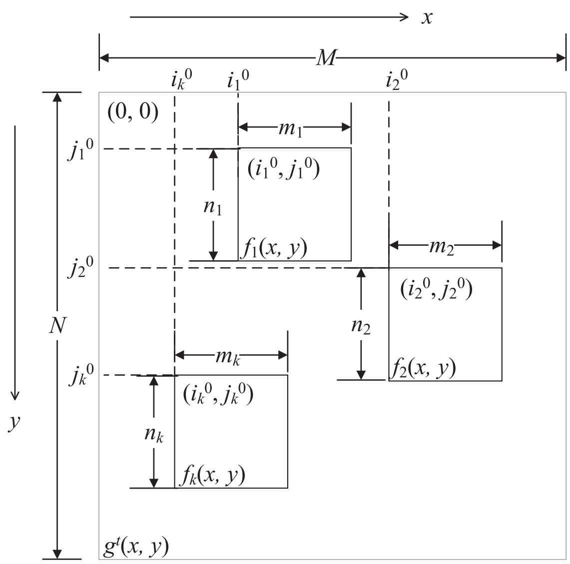

Fig. 1. Correlation between patterns and captured image.

image correlation for two-dimensional displacement measurement. Ma et al. [22] investigated the systematic strain measurement error in digital image correlation caused by self-heating of digital cameras. Fazzini et al. [23] studied the image characteristics on digital image correlation error assessment. Zhou et al. [24] presented a method of adaptive subset offset for systematic error reduction in incremental digital image correlation.

This paper presents a non-contact vision-based structural displacement measurement system which can realize quasi-distributed displacement measurement of structures. A series of experiments are carried out on a shaking table to evaluate the system performance through the comparative study between the results obtained by the developed vision-based system and those simultaneously measured by the magnetostrictive displacement sensor (MDS). The effects of the influencing factors on the measurement accuracy of the developed vision-based system are investigated including the environmental illumination, elevation angle of the digital camera, and vapor surrounding the targets.

Table 1
Test cases for study of illumination effect.

Case	Level of illumination (lux)
1.1	600
1.2	450
1.3	300
1.4	150
1.5	75

2. Vision-based method for multi-point structural displacement measurement

2.1. Multi-point pattern matching algorithm

The vision-based multi-point structural displacement measurement is realized based on multi-point pattern matching algorithm. In the first grayscale image, the patterns are predefined where the measurement targets are incorporated. The action of pattern matching is a process of searching the measurement targets in the subsequent images captured by the digital camera. In this process, the pre-designated patterns with the measurement targets will wander on the subsequent images. The scores representing the matching extent between the patterns and the corresponding regions of the captured images will be calculated on the basis of multi-point pattern matching algorithm. When the scores of the matching tasks reach the maximum values, it indicates that the patterns best correspond with the regions of the captured images and meanwhile the target positions are identified [25].

As illustrated in Fig. 1, the sub-image is extracted to represent the pattern $f_k(x, y)$ with the size of $m_k \times n_k$ in the initial image $g^0(x, y)$ with the size of $M \times N$. Here, k is the number of the patterns. The initial coordinate of the center point of the kth pattern is denoted as (x_k^0, y_k^0). The correlation coefficient $c_k(i, j)$ between the pattern $f_k(x, y)$ and the image $g^t(x, y)$ at the point (i_k, j_k) is given by

$$c_k(i,j) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f_k(x,y) g^t(x+i, y+j) \quad (1)$$

where $i = 0, 1, \ldots, M-1$, $j = 0, 1, \ldots, N-1$, and t is the time on which the image is captured. Assuming that the origin of the image $g^t(x, y)$ is at the top left corner, the correlation computation is the process of moving the pattern $f_k(x, y)$ on

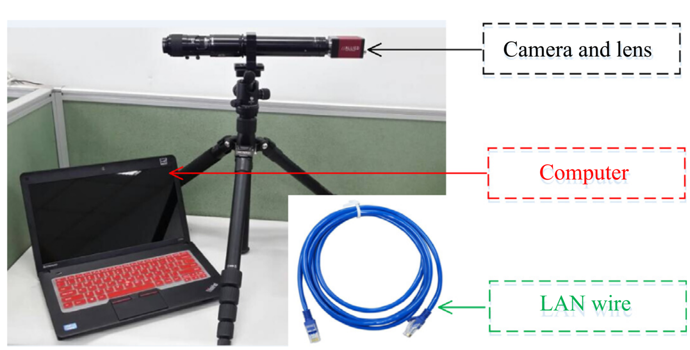

Fig. 2. Vision-based system for multi-point structural displacement measurement.