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Review

A vision-based system for measuring the displacements of large structures: Simultaneous adaptive calibration and full motion estimation

C. Almeida Santos [a,*], C. Oliveira Costa [b], J. Batista [c]

[a] *Laboratório Nacional de Engenharia Civil, Lisboa, Portugal*
[b] *Laboratório Nacional de Engenharia Civil, Lisboa, Portugal*
[c] *Instituto de Sistemas e Robótica, Faculdade de Ciências e Tecnologia da Universidade de Coimbra, Coimbra, Portugal*

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ABSTRACT

The paper describes a kinematic model-based solution to estimate simultaneously the calibration parameters of the vision system and the full-motion (6-DOF) of large civil engineering structures, namely of long deck suspension bridges, from a sequence of stereo images captured by digital cameras. Using an arbitrary number of images and assuming a smooth structure motion, an Iterated Extended Kalman Filter is used to recursively estimate the projection matrices of the cameras and the structure full-motion (displacement and rotation) over time, helping to meet the structure health monitoring fulfilment.

Results related to the performance evaluation, obtained by numerical simulation and with real experiments, are reported. The real experiments were carried out in indoor and outdoor environment using a reduced structure model to impose controlled motions. In both cases, the results obtained with a minimum setup comprising only two cameras and four non-coplanar tracking points, showed a high accuracy results for on-line camera calibration and structure full motion estimation.

Contents

* Corresponding author. Tel.: +351 218443651; fax: +351 218443041.
E-mail addresses: csantos@lnec.pt (C.A. Santos), ocosta@lnec.pt (C.O. Costa), batista@isr.uc.pt (J. Batista).

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1. Introduction

1.1. Overview

Structural Health Monitoring (SHM) is an emergent powerful diagnostic tool in the identification and prevention of failures in the various components that comprise an infrastructure. In the case of large structures, knowing the motion (displacement and rotation) over time is of utmost importance for their safety assessment. However, the traditional displacement transducers are not suitable due to the dimension and layout of the structure, and also due to the displacements amplitude that can achieve a couple of metres. A common solution is to measure the acceleration and integrate the measured values in time domain. While, in principle, it is possible to recover the time history of the bridge deck displacement, it is well known that this method has several drawbacks [1].

An enhanced solution comprises the use of non-contact measuring systems with dynamic response, accuracy and amplitude range well-suited to the physical phenomenon to measure. Currently, only a few measuring systems meet these requirements, albeit only partially. This reduced set includes the systems based on GPS (*Global Position System*), radar, laser and optical devices [2]. Considering the type of material used in the large structures, usually steel-based, and the large amplitude of the displacements, the vision-based systems are one of the most advantageous solutions, in spite of theirs limitations, as the requirement of a free line of view between the camera and the zone to be monitored [3].

One of the first long range measurement system based on optical devices was developed at Laboratório Nacional de Engenharia Civil (LNEC), in 1969 [4]. The system setup comprised an optical system coupled to a pan&tilt servo-controlled motor system, providing two orientation degrees of freedom to follow the position of a target fixed on the bridge's deck. Despite the good results obtained at that time (0.2 in. accuracy was reported), this measurement system exhibited low dynamic response due to moving parts and required ongoing maintenance. In 1993, Stephen et al. [5] developed one of the first video camera based measurement system, using an off-the-shelf video camera, reducing the maintenance requirements as a result of the elimination of the moving parts of the system. This work was the forerunner of other systems developed in the following years [6–11]. On most structural monitoring vision-based solutions presented in the literature, the vision system calibration methodology is not carried out adequately since, usually, they implement a calibration procedure similar to that applied on the traditional transducers, covering a scale factor estimation [1,4,5] and, in some cases, a couple of additional parameters [6,7]. This occurs because most of them use a very simple camera model, comprising at most three parameters, rather than eight parameters (affine camera) or eleven parameters (perspective camera). In fact the camera model normally used quickly fails when the structure displacement occurs out of a plane parallel to the image plane [2,12]. The camera calibration problem has been addressed more carefully in the recent past as the scientific community realizes its importance and influence in the accuracy measurements [2,3,12]. Recently one has been witnessing a gradual incorporation of more complex camera models, as the cases described in [2,3,11,12]. As reported in [12], although the scale factor approach is widely used it causes poor repeatability and unstable precision of the experiment and, as a result, a global poor flexibility. The results obtained from field experiments allowed to conclude that the uncertainty of the static measurement of the displacement depends on the uncontrolled biased errors which, among others, includes the uncertainty associated to the scale factor and the relative position between the bridge and the camera [13].

In the computer vision there is a large set of works dedicated to the camera calibration for short range (low focal length), rather than for the long range case. The difficulty to calibrate the vision system equipped with large focal lenses is a well-