Computer Vision for Structural Dynamics and Health Monitoring

Dongming Feng | Maria Q. Feng

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Computer Vision for Structural Dynamics and Health Monitoring

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Series Preface

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Preface

Over the past few decades, a significant number of studies have been conducted in the area of structural health monitoring (SHM), with the objective of detecting anomalies and quantitatively assessing structural integrity based on measurements using various types of sensors. Although these studies have produced SHM methods, frameworks, and algorithms that have been validated through numerical, laboratory, and field applications, their wide deployment in real-world engineering structures is limited by the prohibitive requirement of installing dense on-structure sensor networks and associated data-acquisition systems. To address these practical limitations, the research and industrial communities have been actively exploring new sensing technologies that can advance the current state-of-the-art in SHM.

Rapid advances in digital cameras and computer vision algorithms have made vision-based sensing a promising next-generation monitoring technology to complement conventional sensors. Significant advantages of the vision-based sensor include its low cost, ease of setup and operation, and flexibility to extract displacements at multiple points on the structure from a single video measurement. In the past 10 years, the authors have been fortunate to lead, participate in, and witness the development of computer vision-based sensing and its application to structural dynamics and SHM. In our activities, however, we have seen a gap between the significant potential offered by this emerging sensing technology and its practical applications. Many undergraduate and graduate students, researchers, and practicing engineers are interested in learning how this sensing technology works and what unique benefits it can offer.

This book is intended to provide a comprehensive introduction to vision-based sensing technology, based primarily on the authors' research. Fundamental knowledge, important issues, and practical techniques critical to the successful development of the vision-based sensor are presented and discussed in detail. A wide range of tests have been carried out in both laboratory and field environments to demonstrate its measurement accuracy and unique merits. The potential of the vision sensor as a fast and cost-effective tool for solving SHM problems is explored. In addition to SHM, novel and practical solutions to other engineering problems are presented, such as estimating cable tension forces using vision-based sensing. Finally, the book outlines the achievements and challenges of current vision-based sensing technologies, as well as open research challenges, to assist both the structural engineering and computer science research communities in setting an agenda for future research.

The goal of this book is to help encourage the application of the emerging vision-based sensing technology not only in scientific research but also in engineering practice, such as assessing the field condition of civil engineering structures and infrastructure systems. Although the book is conceived as an entity, its chapters are mostly self-contained and can serve as tutorials and reference works on their respective topics. The book may also serve as a textbook for graduate students, researchers, and practicing engineers; thus, much emphasis has been placed on making the computer vision algorithms, structural dynamics, and SHM applications easily accessible and understandable. To achieve this goal, we provide MATLAB code for most of the problems discussed in the book. In addition, readers working in structural dynamics and health monitoring will find this book hands-on and useful.

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About the Companion Website

The companion website for this book is at

www.wiley.com/go/feng/structuralhealthmonitoring

The website includes: MATLAB CODES for chapters 2, 4, 6, 7 and appendix_matlab codes.

Scan this QR code to visit the companion website.

1

Introduction

1.1 Structural Health Monitoring: A Quick Review

Structures and civil infrastructure systems, including bridges, buildings, dams, and pipelines, are exposed to various external loads throughout their lifetimes. As they age and deteriorate, effective inspection, monitoring, and maintenance of these systems becomes increasingly important. However, conventional practice based on periodic human visual inspection is time-consuming, labor-intensive, subjective, and prone to human error. Nondestructive testing techniques have shown potential for detecting hidden damages, but the large size of the structural systems presents a significant challenge for conducting such localized tests. Over the past few decades, a significant number of studies have been conducted in the area of structural health monitoring (SHM), aiming at timely, objective detection of damage or anomalies and quantitative assessment of structural integrity and safety based on measurements by various on-structure sensors [1–4]. Most of the SHM techniques are based on structural dynamics, and the basic principle is that any structural damage or degradation would result in changes in structural dynamic responses as well as the corresponding modal characteristics. The SHM process is implemented in four key steps: data acquisition, system identification, condition assessment, and decision-making.

Dynamics-based SHM techniques can be categorized into frequency-domain and time-domain system identification methods. Carden and Fanning [5] presented an extensive literature review of frequency-domain SHM techniques based on changes in measured modal properties such as natural frequencies, mode shapes and their curvatures, modal flexibility and its derivatives, modal strain energy, frequency response functions, etc. Modal properties are obtained using various modal analysis techniques, e.g. the natural excitation technique, frequency

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domain decomposition, stochastic subspace identification, the random decrement technique, blind source separation, and the autoregressive-moving-average model-fitting method. All of these methods have achieved satisfactory performance in numerical and experimental studies. For example, Kim and Stubbs [6] proposed a technique to locate and quantify cracks in beam-type structures based on a single damage indicator by using changes in natural frequencies. Lee et al. [7] presented a neural network–based method for element-level damage detection using mode shape differences between intact and damaged structures. Pandey et al. [8] proposed for the first time that mode shape curvature, which is the second derivative of the mode shape, is a sensitive indicator of damage. Feng et al. [9] developed the first neural network–based system identification framework for updating baseline structural models of two sensor-instrumented highway bridges.

Time-domain SHM techniques, rather than working with modal quantities, directly utilize measured structural response time histories to identify structural parameters. The identification in the time domain is often formulated as an optimization process, wherein the objective function is defined as the discrepancy between the measured and predicted responses. In the majority of existing studies, which are referred to as *input–output methods*, the known or measured excitation forces are a prerequisite for obtaining the predicted structural responses. However, it is highly difficult to measure excitation forces such as vehicle loads on bridges. Recently, there have been attempts to simultaneously identify both structural parameters and input forces from output-only identification formulations. For example, Rahneshin and Chierichetti [10] proposed an iterative algorithm – the extended load confluence algorithm – to predict dynamic structural responses in which limited or no information about the applied loads is available. Xu et al. [11] presented a weighted adaptive iterative least-squares estimation method to identify structural parameters and dynamic input loadings from incomplete measurements. Sun and Betti [12] demonstrated the effectiveness of a hybrid heuristic optimization strategy for simultaneous identification of structural parameters and input loads via three numerical examples. Feng et al. [13] proposed a numerical methodology to simultaneously identify bridge structural parameters and moving vehicle axle load histories from a limited number of acceleration measurements.

On the other hand, various filter-type algorithms for online system identification have been extensively studied in the literature, using either input–output or output-only time-domain data. Examples include the extended Kalman filter, unscented Kalman filter, particle filter, and H_∞ filter. For example, Chen and Feng [14] proposed a recursive Bayesian filtering approach to update structural parameters and their uncertainties in a probabilistic structural model. Soyoz and Feng [15] formulated an extended Kalman filter for instantaneous detection of seismic damage of bridges and validated its efficacy through large-scale seismic