CPS: Small: A Unified Distributed Spatiotemporal Signal Processing Framework for Structural Health Monitoring

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PI: Qi Cheng, School of Electrical & Computer Engineering, Oklahoma State University

Abstract

This project is aimed to develop a unified framework that couples spatiotemporal sensing data with physics-based and data-driven models for structural health monitoring (SHM). Complex structural systems have long been playing a vital role in many sectors of our society. However, the integrity and reliability of these systems are constantly threatened due to aging/fatigue, harsh operational and environmental conditions, and improper maintenance, which cause safety concerns. There is an urgent need for SHM systems that can automatically detect, identify, localize, prognose and mitigate anomalies and damages in a structure at an early stage such that catastrophic failures can be avoided.

Conventionally, SHM routines are time-based and are carried out offline. So they cannot provide real-time situational awareness. More recently, online health monitoring systems start to appear thanks to the fast developing technologies in sensing, hardware miniature, embedded computing and communication. Large numbers of sensors can be deployed across a system and form a large-scale, densely-distributed sensor network. They can communicate with each other or the processing center wirelessly. While sensing technologies could be dramatically different for various structures, the fundamental idea in detecting anomalies in a structure is very much alike: sensor measurements or features extracted from these measurements are compared with the predictions from analytical/numerical structural models or human experience. Any deviations indicate that some anomalies may exist in the structure.

Two main categories of approaches:

(1) Traditional model-based methods assume that an accurate physics-based model is available. Drawbacks include:

- Deterministic models cannot handle uncertainties in the system, operating conditions and sensor measurements.
- Complexity is high because numerical procedures such as finite element analysis are used.
- Sometimes simply there is no sufficient domain expertise.

(2) Data-driven approaches are derived directly from routinely monitored system operating data. Large-scale sensing systems enable structural monitoring on a potentially unprecedented scale and with high precision. Commonly used statistical and pattern classification techniques: multivariate analysis, discriminant analysis, support vector machine, neural networks, classification and regression trees/forests, and fuzzy rule-based systems, etc. Drawbacks:

- The model learned is an approximation only of the relation between the explanatory and response variables.
- The fitness of the approximation is limited by the size of training data and assumptions made.
- If the assumptions made are unreasonable, then there is a risk that the conclusions drawn are questionable.
- Data-driven methods are task-specific.

Solution: more sophisticated statistical modeling that can accommodate all available domain knowledge while take advantage of the huge amount of data collected by modern sensing systems. Sensors are usually deployed in a highly dense manner and observations are collected at rapid rates. Therefore, nearby sensors are likely to have similar measurements due to the spatial correlation. Their observations within a short period of time are temporally correlated. This makes the information contained in the spatial configuration and temporal coupling very precious for data processing. In this project, a dynamic Markov random fields (DMRF) based framework is proposed unifying both temporal and spatial information for statistical inference. Unlike FEM based models which provide precise values of all elements given boundary conditions, DMRF models the relations between elements in a structure. The neighborhood system, form of potential functions and parameters can be either manually constructed based on domain knowledge or learned from large training data, or combine both.