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

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Abstract

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 causes safety concerns. There is an urgent need to build structural health monitoring (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.

With the rapid advances in sensing, communication and signal processing technologies, as well as the miniature and low-cost of monitoring devices, SHM systems have been developed and installed on many structures around the world with different levels of success. The development trends over the years are from qualitative visual inspection to quantifiable systematic instrumentation, from human-based and time-based inspection to automatic real-time monitoring, from moderate-scale tethered sensing systems to extremely large-scale wireless sensor networks, from external sensors with relatively large form factors to *in-situ* sensors with multiple sensing modalities, etc. The fundamental idea behind these SHM systems in detecting anomalies in a structure is similar: 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.

Large-scale sensing systems enable the monitoring of the phenomena of interest on a potentially unprecedented scale and with high precision. However, the huge amount of data collected daily is overwhelming, making evaluations difficult and inefficient. The challenge faced has shifted from lack of information to lack of efficient data processing techniques for SHM. In this project, we address this critical issue from three aspects.

Firstly, modeling is an integrated component in model-based SHM, which represents the prior knowledge of the structure under monitoring. Analytical approaches based purely on underlying physical laws can be both infeasible and unnecessary in practice. Statistical approaches are relatively inexpensive computationally and able to describe the system using a relatively small number of parameters. In this project, we propose the physics-based and data-driven modeling. Specifically, dynamic Markov random field models are learned to capture the spatial and temporal correlations of feature states within a structure under both normal and faulty conditions. Due to the solid nature of a structure, feature values tend to be smooth in both space and time. Abrupt changes often occur near the faulty/critical region boundaries. The problems of model selection and parameter estimation are addressed.

The second aspect is to infer the structural health state by coupling sensing data with the prior knowledge represented by the statistical model. Centralized processing by collecting all sensing data at a processing center is infeasible due to the limitation and constraints on bandwidth and energy. Distributed and localized processing is more scalable and robust for the large-scale data processing paradigm. The issues that need to be addressed include what information needs to be extracted and exchanged between neighboring processing nodes, how to take advantage of the prior knowledge of the spatiotemporal information and how to extrapolate the structural health state at any location and any time based on the statistical model.

The third aspect is to conjointly design a cyber-physical system for structural health self-monitoring and mitigation. To add these new capabilities to physical structures, the problems that need to be addressed include determining the optimal number and positions of sensors/actuators, developing efficient sensor sampling and sensor subset selection schemes, developing decentralized control schemes for cost and efficiency reasons. This task is intertwined with modeling in terms of finding the most accurate statistical model representation of the structural spatiotemporal information.

Some results obtained regarding the first two aspects are reported.