Abstract

A Bayesian Decision-Theoretic Framework for Real-Time Monitoring and Diagnosis of Complex Systems: Theory and Application

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This work presents a theoretical framework for real time monitoring and diagnosis of complex systems. This framework addresses issues associated with supervisory control of complex systems: sensor validation, multi-sensor data fusion, and fault detection. This work subsequently applies and demonstrates the resulting algorithms and methods in the context of extant practical systems, namely gas turbine power plants and automated vehicles in an intelligent vehicle highway system (IVHS).

This work develops a single unified framework, which is the synthesis of techniques used in artificial intelligence and in ‘modern control theory’, with probability theory as the common thread between them. By combining these two approaches into a broad and integrated framework, we provide a new perspective, that not only draws from, but also builds on previous work. We use networks and graphs to represent the various states of the system, the relationships between them, and the uncertainty associated with them. We derive rigorous calculi for inference in these graphical structures. We illustrate how many previously developed algorithms, such as the Kalman filter, interacting multiple model, as well as new algorithms can be derived by using this graphical representation and the rules for inference developed here.

In order to build our framework, we extend Gaussian probabilistic networks to the case where a node could be used to represent multiple variables, thus creating vector Gaussian probabilistic networks. We derive rigorous rules for inference in these vector probabilistic networks. These rules have been developed using, two different approaches, first the method of message propagation and second, the method of topology transformation. These two approaches lead to the development of algorithms, that can be implemented either in a centralized or a decentralized architecture. We model the process of on-line learning of temporal transition probabilities in these networks as an optimization problem and derive a recursive method for it. We also illustrate how additional uncertainty in the system can be modeled by the addition of discrete nodes.

Using our framework, we have built on previous work to develop a better algorithm for sensor fusion. This algorithm can learn the relative performance of the various sensors over time and leads to better fused estimates in the presence of clutter and non-Gaussian noise. We have extensively investigated the performance of various Bayesian algorithms for a number of conditions through Monte Carlo simulations.

Using these concepts, we develop a comprehensive methodology for sensor validation, fusion, and sensor fault detection for complex systems. The methodology consists of four steps. (1) Redundancy Creation generates multiple values. (2) State Prediction uses temporal information. (3) Sensor Data Validation and Fusion determines integrity of the information, and combines various estimates. (4) Fault detection evaluates the performance of the sensors. We illustrate this methodology by applying it to data obtained from a gas turbine power plant.

Using our unified framework we also develop a probabilistic methodology for sensor validation and fusion to be used in automated vehicles in an IVHS. We investigate the efficacy of the various algorithms developed in this dissertation by simulating platooning operations and by applying it to real data. Our methodology leads to improved ride quality, better tracking, and increases the safety of the IVHS system.

The concepts and the unified framework developed here are generally applicable to most dynamic sensor-based systems, that have uncertainty associated with them. In this dissertation, we provide the reader with a new perspective in addressing issues related with: sensor validation, multi-sensor data fusion, and fault detection.