Parameter-Invariant Monitor Design for Cyber Physical Systems
CPS week tutorial: April 11th, 9:00 am - 12:30 pm

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With recent advances in low-power low-cost communication, sensing, and actuation technologies, Cyber Physical Systems (CPS) have revolutionized automated medical diagnostics and care, building energy management, and smart grids. With this revolution, dawns a new era of CPS monitoring where fusing measurements from multiple devices provides unprecedented early detection of critical events. However, some applications (e.g. medical diagnostics) explicit models and/or rich training data relating available measurements to events are unavailable or impractical. Under these troublesome scenarios, this tutorial presents a parameter-invariant approach to monitor design which has successful in developing monitors for medical conditions, building control failures, and network disturbances. Owing its mathematical origin to the robust radar signal processing literature, the parameter-invariant approach to is presented as consisting of three components: (1) foundations of parameter-invariant design, (2) modeling CPS for parameter-invariance, and (3) applied parameter-invariant monitoring. To illustrate each component, the tutorial makes extensive use of case study monitors related to medical alarms (e.g. hypoxia, hypovolemia, and hypoglycemia), building energy management, and power grids.

The foundations of parameter-invariant design consists of a design philosophy aimed at providing a monitor robust to nuisance artifacts/parameters in the data. This ultimately requires the co-design of physical models and test statistics such that maximal invariance is achieved with respect to the nuisances. In this component, we first motivate the robust monitoring problem using real-world monitoring applications, and then present the mathematical foundations for parameter-invariant design, making extensive use of simple illustrative examples.

While there are many approaches to CPS modeling, the parameter-invariant design utilizes a lumped-parameter linear time-invariant model of the physical dynamics coupled with a sequential hypothesis testing approach. The lumped-parameter model is constructed to capture the general trends associated with the monitoring event, while the sequential parameter invariant testing eliminates three common transformations namely: translation, scale, and rotation. This component concludes by providing a general hypothesis testing form for which a parameter-invariant test is optimal.

The final tutorial component applies the parameter invariant modeling approach for CPS to various case studies in medicine and energy. Consistent with the model development, all concepts related to parameter-invariant testing are demonstrated (and evaluated) through the case studies. Extensions of the general testing form provided in the previous tutorial component are considered and insight into advanced techniques for establishing invariance in CPS applications will be discussed.

Novice participants with an undergraduate-level understanding of linear algebra will be introduced to a new and powerful monitor design technique for CPS. Those familiar with signal processing will enjoy the elegance and rigor of the parameter-invariant monitor design and gain invaluable insight into application dependent modeling for medicine, buildings, and power grids. Complementary, those with practical experience will gain insight into how high-fidelity models can be reduced to useful models for the purposes of CPS monitoring. Upon completion of this tutorial, all participants will be able to apply the general form of the parameter-invariant monitor to the application of their choice.

James Weimer is currently a Postdoctoral Researcher in the Department of Information and Computer Science at the University of Pennsylvania and holds a Ph.D. in Electrical and Computer Engineering from Carnegie Mellon University. His research interests focus on the design, analysis, and implementation of cyber-physical systems with application to medical devices and monitors, automotive systems, building energy management, and smart grids.

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