Dr. Igor Mezić,
Department of Mechanical Engineering
University of California, Santa Barbara, CA 93106.
Email: mezic@engineering.ucsb.edu
Tel: 805 893-7603

Complexity Management in Control Design for Automotive Systems

Number of embedded, software intensive, control systems in a modern vehicle, providing safety, comfort and optimal driving conditions, is growing, and thus the number of scenarios where these systems have overlapping and possibly conflicting actions is growing as well. Design of such systems is difficult due to system complexity (the rapidly growing number of software components and their interconnectedness) and often conflicting performance constraints. In addition, the systems involved are a combination of cyber and physical, adding the complexity of mixed representation (state machine vs. continuous time) and encompassing a vast range of time scales, from microsecond scales involved in communication and processing to much slower (on the scale of seconds) occurring in the physical realm. Thus, there is a necessity for developing techniques that reduce the complexity of the resulting design and/or retrofit processes that give designer a reduced but accurate representation of the range of control system behaviors and interconnectedness of their actions.

The Control Design Challenge Modern automotive control systems have nonsmooth (switching) components, information technologies elements, large number of degrees of freedom, and often exhibit nonlinear behavior. Simulation tools such as MATLAB, Simulink or Modelica are enabled to model such features, but do so by performing a *monolithic simulation of a trajectory* of a set of equations whose number of degrees of freedom can be large. Due to this, and design timescales, often only a small number of single-parameter vector simulations are typically performed, leaving the issues of uncertainty, sensitivity and optimality of control gains unexplored. We have developed a set of techniques, incorporated into a software package GoSUM (www.aimdyn.com), that provide some insight into behavior of hybrid control systems under uncertain conditions, examine their sensitivity and provide optimization routines for control system design. There are three main components to GoSUM approach:

1. Fast sampling of parameter space based on a new Quasi-Monte Carlo technique that adapts easily to nonlinear constraint shape and arbitrary (including correlated) sampling densities.
2. Machine learning-based meta-representation of the control system based on Support Vector Machine technology.

3. ANOVA-type decompositions that provide insight into global sensitivities of the output to system parameters and control gains.

Under 1) the shear number of physical parameters and control design parameters involved in the design of an embedded control system often renders such systems amenable to formal verification only in reduced representation. However, there are components that can be verified probabilistically and whose verification can be done within specified probabilities. For such components, one could attempt to deploy recent probabilistic model checking techniques that avoid the difficulties associated with formal verification methods, specifically the curse of dimensionality associated with the dimensional (exponential) explosion in the number of states to check. However, the time-complexity (convergence to prescribed probability of failure) of order $\mathcal{O}(1/\sqrt{N})$ associated with such methods can be prohibitive. In our methodology we develop a Quasi-Monte Carlo set of techniques that enable reduction of that complexity as good as $\mathcal{O}(1/N)$.

Under 2), modern data representation techniques such as Support Vector Machines enable an analytical representation of system behavior that in turn enables fast system analyses such as sensitivity and uncertainty analysis. The set of techniques we are developing admits mixed (discrete, continuous, even categorical) format data.

Under 3), ANOVA-type decompositions provide a rigorous set of techniques for global sensitivity and uncertainty analysis that utilizes the analytical representation techniques developed in 2). First, second or higher order influences of parameters to variations in outputs can be studied, and provide the designer with sometimes substantially reduces set of parameters to worry about. In many examples that we have studied, even though several 10's or even 100's of parameters are present in the formal description, the techniques we developed uncovered only several that have critical contribution to output behavior. Optimization of such performance is now enabled since the number of parameters to optimize has been reduced. in addition, the understanding gained by uncovering importance of particular input parameters to outputs enables better physical understanding of the resulting optimal vector.

This combination of techniques is utilized to reduce design complexity and provide probabilistic verification of the underlying system performance. It is also important to represent the results in a visually appealing form for the designer. In figure 1 the heat map representation of the effect of input parameter variation to outputs of the system is presented in the form of a heat map. Three different parameter distribution types (uniform, gaussian and boundary) are shown. As seen, the type of parameter distribution does not affect its effect the variance of the output much in this case.

In summary, a new set of techniques is emerging, capable of providing design strength tools for mixed-type systems of systems that are prevalent in modern automotive applications. These tools draw equally from dynamical systems and sensitivity analysis as from probability theory and sampling methods. Providing a coherent visual representation of results that such tools enable alleviates their transition into engineering design practice.

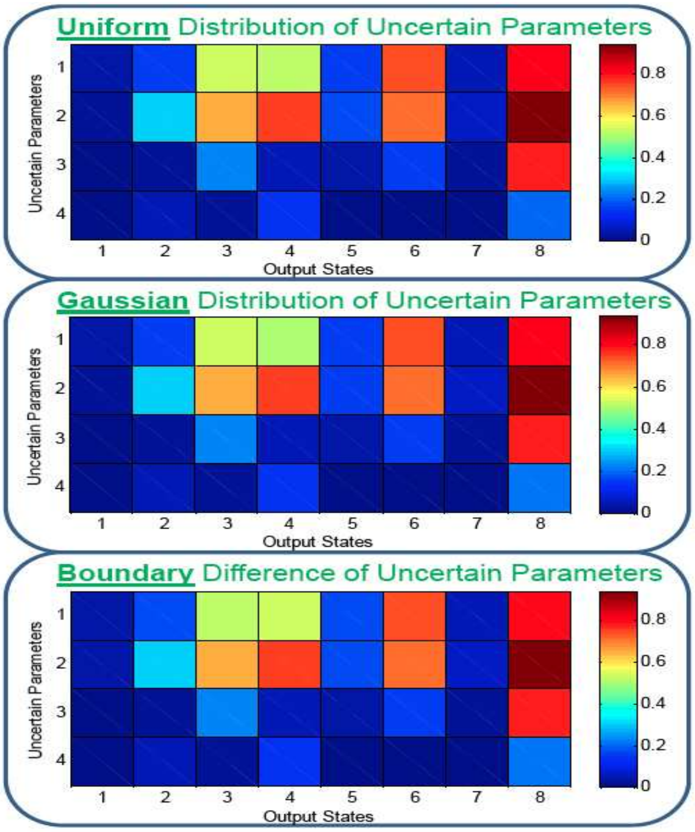

Figure 1: Top: Heat map showing high sensitivity (red) and low sensitivity (blue) pairs of parameters and outputs of an automotive system

Biography of the Author Igor Mezić works in the fields of dynamical systems and control theory and their applications. He holds a Ph.D. in Applied Mechanics from the California Institute of Technology. Dr. Mezić was a postdoctoral researcher at the Mathematics Institute, University of Warwick, UK in 1994-95. From 1995 to 1999 he was a member of Mechanical Engineering Department at the University of California, Santa Barbara where he is currently a Professor. In 2000-2001 he has worked as an Associate Professor at Harvard University in the Division of Engineering and Applied Sciences. He won the Alfred P. Sloan Fellowship, NSF CAREER Award from NSF, the George S. Axelby Outstanding Paper Award from IEEE and the United Technologies Corporation Vice President's Award. He is an Editor of Physica D: Nonlinear Phenomena and an Associate Editor of the Journal of Applied Mechanics and SIAM Journal on Control and Optimization.

Organization/affiliation: Department of Mechanical Engineering, University of California, Santa Barbara and Aimdyn, Inc.
Phone number: 805 893-7603.
E-mail: mezic@engineering.ucsb.edu; mezici@aimdyn.com