Hybrid Systems and Models of Computation: A Paradigm for Control and its Applications to Power-train Control

Alberto Sangiovanni-Vincentelli
The Edgar L. and Harold H. Buttner Chair of Electrical Engineering and Computer Science
Department of EECS
University of California at Berkeley

Founder and Scientific Director,
PARADES European Economic Interest Group (Cadence Design Systems, Inc., Magneti-Marelli and ST)
Via di San Pantaleo 66, Rome

Abstract:

Hybrid systems have been the subject of intensive study in the past few years by both the control and the computer science communities. Particular emphasis has been placed on a unified representation of hybrid models. Some classical problems such as reachability analysis, stability and safety have been investigated and tools for their solutions, i.e. HyTech, Kronos, Checkmate, developed. However, since the class of hybrid control problems is extremely broad (it contains continuous control problems as well as discrete event control problems as special cases), it is very difficult to devise a general yet effective strategy to solve them. In our opinion, it is important to address significant application domains to develop further understanding of the implications of the hybrid model on control algorithms and to evaluate whether using this formalism can be of substantial help in solving complex, real-life, control problems.

A design (at all levels of the abstraction hierarchy from functional specification to final implementation) is generally represented as a set of components, which can be considered as isolated monolithic blocks, which interact with each other and with an environment that is not part of the design. The model of computation defines the behavior and interaction of these blocks. Compactness of description, fidelity to design styles, ability to simulate, synthesize to an appropriate implementation and optimize its behavior are criteria to follow for the choice of an MOC to describe and manipulate a design. For example, some MOCs are suitable for describing complicated data transfer functions and completely unsuitable for complex control, while others are designed with complex control in mind.

Hybrid systems in the general sense of the term could be considered as formalisms used to describe a complex system as combinations of MOCs where a single one is not powerful or expressive enough. When a hybrid system is simulated, the MOCs used to describe its behavior dictate the way the components of the system interact and execute.

In this talk, we focus on an application domain for hybrid system theory that is of great industrial interest: automotive engine and power train control. The engine control problem is very complex. Air intake and fuel injection can be controlled to yield the desired mix to deliver to the combustion process. The timing of the sparks generated by the spark plugs determines the start of the combustion process that takes place in the cylinders. The torque and the emissions generated by the combustion process depend on the fuel mix (quantity of fuel and its dynamics) and on the spark ignition timing. The torque is then delivered to the power train and the emissions to the exhaust subsystem. The goals for the control strategy are, in general, given in terms of emissions

and torque but it is often the case that sub-goals are given by car manufacturers on all the processes in the chain. Unfortunately, even these goals are quite complex to specify since they depend on the behavior that the driver request the car to have. Based on the data from sensors measuring emissions and car dynamics, embedded controllers compute the control actions to apply. The ever-increasing computational power of micro-controllers has made it possible to extend the performance and the functionality of these embedded controllers to limits that were unthinkable only a few years ago. This opportunity has exposed the need for control algorithms with guaranteed properties that can reduce substantially emissions and gas consumption while maintaining the performance of the car. To do so, we believe that it is important to use more accurate models than the ones proposed so far. An accurate model of a four-stroke gasoline engine has a "natural" hybrid representation because:

- pistons have four modes of operation corresponding to the stroke they are in. Hence, their behavior can be represented with a finite state model;
- power train and air dynamics are continuous-time processes.

In addition, these processes interact tightly. In fact, the timing of the transitions between two phases of the pistons is determined by the continuous motion of the power train, which, in turn, depends on the torque produced by each piston. In engine control literature, the discrete part of the engine behavior is converted into a more familiar and easy-to-handle continuous model where only the average values of the appropriate physical quantities are modeled.

In this talk, we present a general framework for power-train control based on hybrid models and demonstrate that it is possible to find effective control laws with guaranteed properties without resorting to average-value models.

Hybrid models are used in this talk in two ways:

- to describe a reference model that captures the requirements of car manufacturers in a simple yet rigorous formalism;
- to represent engine and power-train behavior.

The hybrid nature of the problem of engine control does not come only from the use of digital control laws, but it is rooted in the plant to be controlled. This characteristic complicates the modeling problem since several components with different mathematical properties are needed to capture the behavior of the engine and of the power train. In fact, our model includes interacting Finite State Machines, Discrete Event Systems and Continuous Time Systems. We believe that the interactions among the different parts of a hybrid model of this type have not always been correctly described and characterized.

For these reasons, we review the concept of models of computation, which is commonly used in the embedded system design literature, and describe a modeling framework called the Tagged Signal Model, proposed recently by Lee and Sangiovanni-Vincentelli, that addresses explicitly time and partial orders among events, and is particularly suited to represent modality of interaction.

Our control algorithms applied to the hybrid model for engine and power-train share the same basic idea: relax the hybrid control problem to a simpler one and, then, modify appropriately the control law determined for the simpler problem to solve the original hybrid problem.

The talk is organized as follows. I first introduce model of computations and the Tagged Signal Model framework. Then, I introduce a hybrid model that captures the car manufacturers' requirements. I describe the hybrid model of the engine and of the power train in detail. Then, I examine three different control problems corresponding to different regions of operation identified in our model and show how hybrid system techniques can be used to develop control strategies with guaranteed properties.