Guest Editorial
Hybrid Control Systems: An Introductory Discussion to the Special Issue

Abstract— **This introductory paper provides an overview of hybrid systems and gives a brief introduction to the major approaches in hybrid systems research with several book references. A brief guide for the papers in this special issue, which present several approaches to modeling, analysis, and synthesis of hybrid systems, is also given.**

I. The Hybrid Nature of Hybrid Systems

HYBRID means, in general, heterogeneous in nature or composition. The term hybrid systems is understood to mean systems with behavior defined by entities or processes of distinct characteristics. The hybrid systems of interest here are dynamic systems where the behavior of interest is determined by interacting continuous and discrete dynamics. These systems typically contain variables or signals that take values from a continuous set (e.g., the set of real numbers) and also variables that take values from a discrete, typically finite set (e.g., the set of symbols $\{a, b, c\}$). These continuous or discrete-valued variables or signals depend on independent variables such as time, which may also be continuous or discrete; some of the variables may also be discrete-event driven in an asynchronous manner.

There are many examples of hybrid systems. In the control area, a very well-known instance of a hybrid system is when a continuous-time linear time-invariant plant described by linear differential equations (which involve continuous-valued variables that depend on continuous time) is controlled by a discrete-time linear time-invariant plant described by linear difference equations (which involve continuous-valued variables that depend on discrete time). These types of systems are typically studied in courses under the name of sampled-data systems or digital control systems; digital control systems may of course include more general types of systems such as time-varying and nonlinear plants and controllers. If one also considers quantization of the continuous-valued variables or signals, then the hybrid systems contain not only continuous-valued variables that are driven by continuous and discrete times, but also discrete-valued signals as well. Note that recent studies of digital control systems in the hybrid systems literature typically involve nonlinear plants and controllers. Another familiar example of a hybrid control system is a switching system where the dynamic behavior of interest can be adequately described by a finite (small) number of dynamical models, that are typically sets of differential or difference equations, together with a set of rules for switching among these models. These switching rules are described by logic expressions or a discrete-event system with a finite automaton or a Petri net representation. Another existing area that has been brought recently under the hybrid systems framework is the study of properties (e.g., stability) of dynamical systems described by differential equations with discontinuities present.

A familiar simple example of a practical hybrid control system is the heating and cooling system of a typical home. The furnace and air conditioner, along with the heat flow characteristics of the home, form a continuous-time system which is to be controlled. The thermostat is a simple asynchronous discrete-event driven system which basically handles the symbols {too hot, too cold} and {normal}. The temperature of the room is translated into these representations in the thermostat and the thermostat's response is translated back to electrical currents which control the furnace, air conditioner, blower, etc.

There are several reasons for using hybrid models to represent the dynamic behavior of interest. Reducing complexity was and still is an important reason for dealing with hybrid systems. This is accomplished in hybrid systems by incorporating models of dynamic processes at different levels of abstraction; for example, the thermostat in the above example sees a very simple, but adequate for the task in hand, model of the complex heat flow dynamics. For another example, in order to avoid dealing directly with a set of nonlinear equations one may choose to work with sets of simpler equations (e.g., linear) and switch among these simpler models. This is a rather common approach in modeling physical phenomena. In control, switching among simpler dynamical systems has been used successfully in practice for many decades. Recent efforts in hybrid systems research along these lines typically concentrate on the analysis of the dynamic behaviors and aim to design controllers with guaranteed stability and performance. The advent of digital machines has made hybrid systems very common indeed. Whenever a digital device interacts with the continuous world, the behavior involves hybrid phenomena that need to be analyzed and understood. Whenever the behavior of a computer program depends on values of continuous variables within that program (e.g., continuous-time clocks), one needs hybrid system methodologies to guarantee correctness of the program and the safe operation of the hybrid system; in fact, the verification of such digital computer programs has been one of the main goals of several serious research efforts in hybrid systems literature.

It is perhaps interesting to point out that when we learn how to deal effectively with systems that contain interacting groups of entities or processes of distinct characteristics, we

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will probably stop calling them “hybrid systems,” because at that stage the distinct character of the system’s parts will be of no importance or significance anymore and there will be no need any longer for the hybrid nature to be stressed in a name. That is, success will bring the loss of identity! This is of course only a conjecture.

II. Hybrid Control Systems

Hybrid control systems typically arise from the interaction of discrete planning algorithms and continuous processes, and, as such, they provide the basic framework and methodology for the analysis and synthesis of autonomous and intelligent systems. Hybrid control systems contain two distinct types of components, subsystems with continuous dynamics and subsystems with discrete-event dynamics, that interact with each other. Such systems are important in a variety of contexts; frequently such systems arise from computer-aided control of continuous processes in manufacturing, communication networks, autopilot design, computer synchronization, traffic control, and industrial process control, for example. Another important way in which hybrid systems arise is from the hierarchical organization of complex control systems. In these systems, a hierarchical organization helps manage complexity, and higher levels in the hierarchy require less detailed models (discrete abstractions) of the functioning of the lower levels, necessitating the interaction of discrete and continuous components. Examples of such systems include flexible manufacturing and chemical process control systems, interconnected power systems, intelligent vehicle highway systems, air traffic management systems, and computer communication networks. The study of hybrid control systems is essential in designing sequential supervisory controllers for continuous systems, and it is central in designing intelligent control systems with a high degree of autonomy. The investigation of hybrid systems is creating a new and fascinating discipline bridging control engineering, mathematics, and computer science.

The areas of science and engineering that can be brought to bear on the issue of hybrid control are numerous. These include engineering disciplines such as linear, nonlinear, and optimal control, stochastic processes, and stochastic approximation; mathematical disciplines such as functional analysis, variational calculus, dynamical systems, partial differential equations, Lie algebras, differential geometry; operations research disciplines such as linear and integer and nonsmooth mathematical programming; computer science disciplines such as distributed and agent-based systems, automata theory, and program validation and verification; and branches of mathematical logic and applied logic such as temporal logic and logic programming. Control systems that contain both continuous and discrete dynamics have been studied of course off and on for the past 40 years; related results are the results on bang–bang control and on sliding mode control among others. Recently there has been significant research activity in the area of hybrid systems and control. This activity follows closely and has been motivated in part by the development of research results in the control of discrete-event systems that occurred in the 1980’s and of adaptive control in the 1970’s and 1980’s, and of the renewed interest in optimal control formulations in sampled-data systems and digital control. At the same time there has been growing interest in hybrid systems among computer scientists and logicians with emphasis on verification of design. The safe operation of the hybrid system, expressed in terms of formal specifications that must be verified, is of primary interest. Note that efficient verification methodologies are essential for complex hybrid systems to be useful in applications. An illustrative simple example is the verification of the safe operation of a hybrid system that consists of a train approaching a rail crossing and a set of gates that control the flow of vehicles across the rails.

III. Approaches to Hybrid Systems

A look at literature clearly shows that there are many approaches to modeling, analysis, and synthesis of hybrid systems. They can be characterized and described along several dimensions. In broad terms, approaches differ with respect to the emphasis on or the complexity of the continuous and discrete dynamics and on whether they emphasize analysis and synthesis results or analysis only or simulation only. On one end of the spectrum there are approaches to hybrid systems that represent extensions of system theoretic ideas for systems (with continuous-valued variables and continuous time) that are described by ordinary differential equations to include discrete time and variables that exhibit jumps or extend results to switching systems. Typically these approaches are able to deal with complex continuous dynamics and emphasize stability results. On the other end of the spectrum there are approaches to hybrid systems that are embedded in computer science models and methods that represent extensions of verification methodologies from discrete systems to hybrid systems. Typically these approaches are able to deal with complex discrete dynamics described by finite automata and emphasize analysis results (verification) and simulation methodologies. There are additional methodologies spanning the rest of the spectrum that combine concepts from continuous control systems described by linear and nonlinear differential/difference equations, and from supervisory control of discrete-event systems that are described by finite automata and Petri nets to derive, with varying success, analysis and synthesis results. Several approaches to modeling, analysis, and synthesis of hybrid systems are represented in this special issue.

There are analogies between certain current approaches to hybrid control and digital control systems methodologies. Specifically, in digital control one could carry the control design in the continuous-time domain then approximate or emulate the controller by a discrete controller and implement it using an interface consisting of a sampler and a hold device (A/D and D/A, respectively). Alternatively, one could obtain first a discrete model of the plant taken together with the interface and then carry the controller design in the discrete domain. In hybrid systems, in a manner analogous to the latter case, one may obtain a discrete-event model of the plant together with the interface using automata or Petri nets; the controller is then designed using DES supervisor methodologies. Approaches analogous to the former also exist. Optimization methodologies are also used in hybrid control synthesis that include convex optimization and game theoretic approaches.

It is self-evident that a special issue in a journal such as the IEEE TRANSACTIONS ON AUTOMATIC CONTROL can only include a rather small number of papers describing unpublished original work that was completed in time for the special issue. So it only represents a view of the field from a window in time. It should be noted that approaches that address issues of interest to systems and control are particularly emphasized in this special issue. We made every effort to include a variety of approaches; however, the coverage is by no means complete.

Further information on hybrid systems may be found in references [1]–[7] below. Some of the early references in hybrid systems that have helped define and have shaped the main approaches in the current research of hybrid systems can be found in there; many of these are of course references of the papers included in this special issue.

IV. SPECIAL ISSUE PAPERS

In this special issue the papers are arranged from papers that extend conventional system theoretic results and emphasize differential/difference equation approaches, to papers that incorporate automata models and verification ideas from computer science. Therefore, the papers by Ye *et al.* and Johansson and Rantzer represent the former approach and the papers by Henzinger *et al.* and Deshpande *et al.* the latter. There are also a number of papers in this special issue that emphasize applications, because (please allow me to paraphrase a quote attributed to Leonardo da Vinci by substituting "applications" for "mechanics" in the original quote) "Applications represent the paradise of the mathematical sciences, because by means of applications one comes to the fruits of mathematics." A brief but rather detailed description of the contents of each paper is included in the "Scanning the Issue" section of this issue. The descriptions are arranged in the sequence in which the papers appear.

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Panos J. Antsaklis (S'74–M'76–SM'86–F'91) received the undergraduate degree from the National Technical University of Athens (NTUA), Greece, and the M.S. and Ph.D. degrees in electrical engineering from Brown University, Providence, RI.

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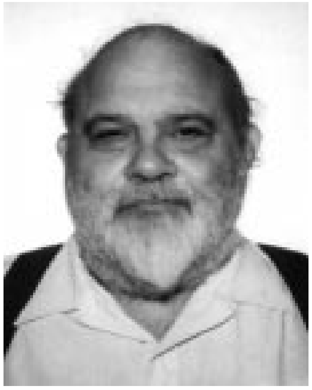
Dr. Antsaklis has been keynote and plenary speaker in a number of conferences, and he is a Distinguished Lecturer of the IEEE Control Systems Society (CSS). He serves on the editorial boards of several journals, and he has been Guest Editor of special issues on Neural Networks (*IEEE Control Systems Magazine*, 1990 and 1992), on Intelligence and Learning (*IEEE Control Systems Magazine*, 1995), and on Hybrid Systems (*Journal of Discrete Event Dynamic Systems*, 1998). He has served as program chair and general chair of major systems and control conferences, and he was the 1997 President of the IEEE CSS. In 1998 he serves as the CSS Past-President.



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