Dutch Institute of Systems and Control

Summer School on

Modeling and Control of Hybrid Systems

June 23 - 26, 2003
Veldhoven, The Netherlands

Co-sponsored by the IEEE Control Systems Society

Final Program

DISC Summer School on

Modelling and Control of Hybrid Systems

Veldhoven, The Netherlands, June 23-26, 2003

Invitation

The organizers have the pleasure to invite you to participate in the DISC Summer School on **Modeling and Control of Hybrid Systems**, which is scheduled for June 23-26, 2003. The school will be organized from June 23 to 26, 2003 at the Koningshof, Veldhoven, The Netherlands. The invitation is addressed to research students and staff members of the Dutch Institute of Systems and Control (DISC) and to other researchers and engineers engaged in the computer science or systems and control areas.

Recent technological innovations have caused a considerable interest in the study of dynamical processes of a mixed continuous and discrete nature. Such processes are called hybrid systems and are characterized by the interaction of time-continuous models (governed by differential or difference equations) on the one hand, and logic rules and discrete-event systems (described by, e.g., automata, finite state machines, etc.) on the other hand. In practice, a hybrid system arises, e.g., when continuous physical processes are controlled via embedded software that intrinsically has a finite number of states only (such as on/off control). This school will offer a general overview of the field of hybrid systems ranging from modeling, over analysis and simulation, to verification and control.

Four distinguished speakers will each present a series of approximately three ninety-minutes state-of-the-art survey lectures on various aspects of modeling, analysis, identification, verification, and control of hybrid systems. Several well-known researchers will give advanced topics lectures to complement these surveys.

Scientific purpose

The 2003 DISC Summer School is one in an annual series that was started in 1990 by the predecessor of DISC. Together with the DISC graduate course program, the Summer Schools form part of the educational facilities that DISC offers to PhD students in systems theory, control engineering, and engineering mechanics. The Summer Schools also provide an opportunity for DISC staff members and others to upgrade their knowledge of specific areas of interest.

In recent years, the Summer Schools have concentrated on the relations between systems and control theory and neighboring fields (for instance, in 2001 the topic was "The Impact of Optimization in Control") and on the use of techniques from other fields (for instance, in 2002 the topic was "Modeling and Control of Mechanical Systems"). The 2003 Summer School will highlight the links and interaction between computer science and systems & control theory in the field of hybrid systems modeling and control.

The Conference Center Koningshof offers ample opportunities for participants to discuss with each other and with the speakers, inside as well as outside the lecture rooms. These informal contacts are considered to be a main contribution to the success of the Summer School.

Foreword by the Organizers

"Why a school on hybrid systems?" you may ask. The reason is fairly simple. Hybrid systems arise throughout business and industry in areas such as parallel processing, traffic control, plant process control, telecommunication networks, automotive systems, aircraft and robot design, and path planning. Anywhere were computer-implemented embedded controllers interact with physical, chemical, electrical or mechanical processes, a mixed dynamics occurs, that is well described within a hybrid systems framework. Actually, many consumer products (cars, micro-wave units, washing machines and so on) are controlled by such embedded software, causing the world of hybrid systems to be very wide. These systems abound in our homes, probably more than we realize.

Theoretically hybrid systems arise from the interaction between continuous-variable systems (i.e., describable by a set of difference or differential equations) and discrete-event systems (i.e., asynchronous systems where the state transitions are initiated by discrete events as in automata or finite state machines).
This leads to a formulation with several modes of operation, whereby in each mode the behavior of the system is given by difference or differential equations.
The system switches from one mode to another due to the occurrence of discrete events. As both industry and the academic world realize that mixing different models, techniques and concepts will play an increasingly important role in the future, they are becoming more and more interested in this emerging field.

Many issues are widely open for hybrid systems and it is currently a very active research area. In this Summer School several distinguished speakers will present an overview of the state-of-the-art of methods for modeling, analysis, simulation, control and verification for hybrid systems, from both a systems and control point of view and a computer science point of view. The school will be an enlightening event that brings you to the boundaries of the research field. The informal character of the school and the lively discussions will make it a pleasure to be around! We hope to see you all in June!

Bart De Schutter and Maurice Heemels

Organization

The Summer School organizers are Bart De Schutter (b.deschutter@dcsc.tudelft.nl) and Maurice Heemels (m.heemels@ele.tue.nl), in close cooperation with Alberto Bemporad (bemporad@dii.unisi.it), chair of the IEEE Technical Committee on Hybrid Systems (HYSCOM).

The Summer School is an activity of the Dutch Institute of Systems and Control, DISC, and is co-sponsored by The Netherlands Organisation for Scientific Research NWO (http://www.nwo.nl), and the IEEE Control Control Systems Society (http://www.ieeecss.org).

The organizers can provide further information regarding the program. See also http://lcewww.et.tudelft.nl/~disc_hs. For information regarding the organization of the school contact the DISC Secretariat, Agnes van Regteren, Mechanical Engineering Systems and Control Group, Delft University of Technology, Mekelweg 2, 2628 CD Delft, phone 015-2787884, fax 015-2789387, email secr@disc.tudelft.nl. See also **www.disc.tudelft.nl**

Conference location

The conference will be held in Locht 117, 5504 RM Veldhoven (near Eindhoven), the Netherlands, phone +31 40 253 74 75, fax: +31 40 254 55 15. The participants will be accommodated in comfortable, single rooms. For more information see http://lcewww.et.tudelft.nl/~disc_hs or visit: http://www.nh-hotels.nl/busquedas/detallehotel.jsp?IDHotel=135

Travel information

Veldhoven is situated 15 minutes by car or bus from the Dutch city Eindhoven.
To reach Veldhoven by train you should take the train to Eindhoven Central Station. From there you can take the Hermes bus service (bus 149 or 150) or you can take a train-taxi. The ticket for the train-taxi you can buy at the train-station desk.

For directions to NH Koningshof Hotel by car, see the Summer School website: **http://lcewww.et.tudelft.nl/~disc_hs**

Program

Monday, June 23 (Chair: Arjan van der Schaft)

9.30-10.30	Registration and coffee
10.30-10.45	Opening (by organizers)
10.45-11.45	**Introduction to the field of hybrid systems: origins, examples and applications** Christos Cassandras
12.00-12.45	**Modeling of hybrid systems** Christos Cassandras
13.00-14.00	Lunch Break
14.00-14.45	**Introduction to hybrid systems and applications** George Pappas
15.00-15.45	**Algorithmic verification of hybrid systems** George Pappas
16.00-16.45	**Stability of Switched Systems: part 1** Daniel Liberzon
17.00-17.45	**Stability of Switched Systems: part 2** Daniel Liberzon

Tuesday, June 24, 2003 (Chair: Henk Nijmeijer)

9.00-9.45	**Bisimilar control systems** George Pappas
10.00-10.45	**Finite bisimulations of controllable systems** George Pappas
11.00-11.45	**Hybrid I/O automata: part 1** Frits Vaandrager
12.00-12.45	**Hybrid I/O automata: part 2** Frits Vaandrager
13.00-14.00	Lunch Break
14.00-14.45	**Hybrid models for optimization** Alberto Bemporad
15.00-15.45	**Hybrid systems identification** Alberto Bemporad
16.00-16.45	**Optimal control of hybrid systems: deterministic models and applications** Christos Cassandras
17.00-17.45	**Optimal control of hybrid systems: stochastic models and applications** Christos Cassandras

Wednesday, June 25 (Chair: Jan van Schuppen)

9.00-9.45	**Quantized systems and control: part 1** Daniel Liberzon
10.00-10.45	**Quantized systems and control: part 2** Daniel Liberzon
11.00-11.45	**Discrete-event modeling and diagnosis of quantized systems: part 1** Jan Lunze
12.00-12.45	**Discrete-event modeling and diagnosis of quantized systems: part 2** Jan Lunze
13.00-14.00	Lunch Break
14.00-14.45	**Timed automata and model checking** Kim Larsen
15.00-15.45	**Timed automata and optimal scheduling and control** Kim Larsen
16.00-16.45	**Model predictive control of hybrid systems** Alberto Bemporad
17.00-17.45	**Observability and reachability analysis of hybrid systems** Alberto Bemporad

Thursday, June 26 (Chair: Hans Schumacher)

9.00-9.45	**Mode transition behavior in hybrid dynamic systems** Pieter Mosterman (The Mathworks)
10.00-10.45	**Simulation technologies for hybrid dynamic systems** Pieter Mosterman (The Mathworks)
11.00-11.45	**Switching control of uncertain systems: part 1** Daniel Liberzon
12.00-12.45	**Switching control of uncertain systems: part 2** Daniel Liberzon
13.00-14.00	Lunch Break
14.00-14.45	**Controller Synthesis for temporal logic specifications** George Pappas
15.00-15.45	**Open problems and future directions** Christos Cassandras
16.00-16.15	Closing

Abstracts of lectures

State-of-the-art survey lectures

Alberto Bemporad

Hybrid models for optimization

For hybrid systems described by the interaction of switched affine dynamics, finite state machines, and linear threshold events, we consider a modeling framework oriented to the algorithmic solution of complex analysis and synthesis problems using mathematical programming (such as: linear, mixed-integer, semidefinite programming, and polyhedral computation). We illustrate the class of mixed-logical dynamical (MLD) systems, where the problem of the heterogeneousness of the variables (logic/continuous) is overcome by transforming logical relations into mixed-integer linear inequalities. We also consider the class of piecewise affine (PWA) systems, and highlight constructive equivalence results between PWA, MLD, and other models of hybrid systems. We provide examples of hybrid systems modeled with the modeling language HYSDEL.

Hybrid systems identification

When an exact mathematical description of a hybrid system is not available, a hybrid model must be obtained from experimental data. In particular, the identification of PWA models from data involves the simultaneous estimation of the parameters of the affine submodels and of the partition of the PWA map. We present different algorithms for the identification of hybrid models.

Model Predictive Control of hybrid systems

After reviewing the basic concepts of receding horizon constrained optimal control (also known as model predictive control) of discrete-time linear systems, we show how optimal control problems for MLD/PWA hybrid systems subject to operating and logical constraints can be set up and solved using mixed-integer programming techniques.
We also analyze the asymptotic stability properties of receding horizon strategies based on such optimal control formulations. Then, we describe the basics of multiparametric programming and show its effectiveness for solving in an explicit state-feedback form the finite-time hybrid optimal control problem, and show that the solution is a piecewise affine control law. We provide examples of applications in industrial case studies, in particular in automotive problems where the simplicity of the control law is essential for its implementation.

Observability and reachability analysis

Contrarily to linear systems, observability and reachability properties of switched affine hybrid systems are not global properties, and they cannot be easily deduced from those of the component linear subsystems. However, efficient numerical procedures based on linear programming, mixed-integer linear programming, and polyhedral computation can be employed for determining such properties. For the reachability problem, which is essential for assessing safety, liveness, and robustness properties of a hybrid system, we present a methodology for computing the set of states that a discrete-time affine hybrid system can reach by starting from a given set of initial conditions and under the effect of bounded exogenous inputs to the system (e.g., disturbances). Algorithmic solutions based on mixed-integer optimization and on reachability analysis are also provided for assessing observability properties, a prerequisite for solving the state estimation problem that we address here through moving horizon estimation schemes based on mixed-integer programming. The above techniques are exemplified on application case studies.

Christos Cassandras

Introduction to the field of hybrid systems: origins, examples and applications

The emergence of Hybrid Systems (HS) will be placed in some historical perspective vis-à-vis classical time-driven systems and DES. A number of HS examples will be presented to illustrate different features such as autonomous vs. externally controlled switching and issues related to the number of switches involved in the operation of a HS. Several application domains where the presence of HS is obvious will also be described, among others manufacturing systems, communication networks, and cooperative control of autonomous vehicles. Simple live simulation examples will be used to illustrate problems in HS control.

Modeling of hybrid systems

Modeling frameworks of Hybrid Systems (HS) require the combination of elements from Discrete Event Systems (DES) and classical time-driven systems. These will be reviewed in the first half of the lecture (including untimed and timed automata, Petri nets and max-plus algebra basics). The second half will be devoted to explicit HS modeling.

Optimal control of hybrid systems: deterministic models and applications

Basic deterministic optimal control problems for HS will be formulated with the aim of bringing forth the complexity they involve as one strives to control both continuous and discrete variables. The lecture will then focus on a hierarchical decomposition approach that can lead to explicit solutions of some classes of problems. An application of this approach to the integration of operations with process-level control of manufacturing systems will be presented. An interactive software demonstration will be included.

Optimal control of hybrid systems: stochastic models and applications

The difficulties of applying optimal control methods to stochastic HS will be illustrated to motivate parametric, as opposed to fully dynamic, optimal control methods. We will then focus on a class of HS known as Stochastic 3 Flow Models (SFM) and some gradient-based optimization methods will be discussed for controlling such systems. Applications of this approach to the control of communication networks will be included, such as congestion control and defending against denial-of-service attacks.

Open problems and future directions

As a "grand finale" to the school a number of interesting open problems currently under investigation (cooperative control, network security, sensor networks, etc.) will be outlined. Also ideas collected on the fly during the presentations of the previous three days will be presented. There is a lot of space for questions during this interactive session between speakers and audience.

Daniel Liberzon

Stability of switched systems: part 1 and 2

In this lecture we present basic techniques and main results on stability of systems subject to discrete switching events. We address stability under arbitrary switching as well as under certain specific types of switching. The main tools that we discuss are common Lyapunov functions, multiple Lyapunov functions, commutation relations, and applications of known results on stability of feedback systems.

Quantized systems and control: part 1 and 2

In this lecture we address the problem of stabilizing a system using quantized feedback. We consider and treat this problem in the general context of control with limited information. We explain how a quantized feedback control system can be viewed as a hybrid system, and how techniques discussed in the previous lecture on stability of switched systems can help.

Switching control of uncertain systems

In this lecture we study the problem of controlling a system with large uncertainty. A basic control algorithm that we consider employs a family of candidate controllers, supervised by a high-level switching logic. We discuss ways of designing such switching control algorithms and analyzing the resulting hybrid systems using tools discussed earlier.

George Pappas

Introduction to hybrid systems and applications

Introduction to motivating applications from automotive examples, air traffic control, and genetic regulatory networks. Introduction to modeling of hybrid systems and overview of related research and computational tools. Emphasis on algorithmic approaches to hybrid systems analysis, verification, and control.

Algorithmic verification of hybrid systems

Algorithmic approaches to verifying hybrid systems by extracting discrete abstractions of continuous and hybrid systems. Safety analysis and reachability algorithms. Introduction to language equivalence, simulation and bisimulation relations, and their relationship to temporal logics. Finite bisimulations of continuous systems and presentation of known decidability results for hybrid system verification. Emphasis on discrete abstractions of continuous linear systems.

Bisimilar control systems

Property preserving abstractions of dynamical and control systems. Properties of interest include traditional control theoretic notions such as reachability and stabilizability, but also properties expressible in temporal logics.
Classes of systems include discrete-time and continuous-time linear systems, nonlinear systems, as well as constrained linear systems. Unification of bisimulation notions across discrete, continuous, and hybrid models.

Finite bisimulations of controllable systems

Focus on algorithmic synthesis rather than verification. Given controllable linear system, and desired specification expressed in linear temporal logic, show how to extract a specification dependent, finite-state model from the controllable discrete-time linear system. Property dependent quantization. Language equivalent quotients, and bisimilar quotients of controllable linear systems, with respect to rectangular observations. Minimality results.

Controller synthesis for temporal logic specifications

Synthesis of nonblocking controllers for finite state machines with respect to temporal logic specifications. Refinement of temporal logics to Buchi automata. Further refinement of controllers from the discrete abstraction to the continuous model resulting in closed loop hybrid system which are correct by design.

Advanced topics lectures

Kim Larsen

Timed automata and model checking

Introduction of Timed Automata and their application to modeling and analysis of embedded and real-time control software using the verification tool UPPAAL.
Region construction(s) as the key to decidability results for TA, including model checking and (timed and untimed) bisimilarity.
Algorithms and data structures for analyzing TA, their evolution and impact on performance.

Timed automata and optimal scheduling and control

Modification and application of Timed Automata technology to scheduling (finite and infinite). Priced Timed Automata and optimal scheduling; decidability using priced regions; data structures and algorithms underlying tool implementation.
PTA with controllable and uncontrollable transitions; decidability of optimal control and tool implementation.

Jan Lunze

Discrete-event modeling and diagnosis of quantized systems: part 1 and 2

Quantized systems are continuous variable systems whose inputs and outputs can only be measured through quantizers, which transform the real-valued measurement signals into event sequences. Although the system has internally a continuous behavior, it appears externally as a discrete-event system.
The lecture shows how quantized systems can be represented by automata. It starts with explaining why the discrete-event behavior is nondeterministic and why it does not possess the Markov property. As a consequence, discrete-event models like automata cannot provide a precise description of quantized systems. They have to be a complete model in the sense that they can generate all event sequences that the quantized system is able to generate. The lecture shows how stochastic automata can be found that satisfy this completeness requirement and how such models can be used to diagnose faults that may occur in the quantized system. Finally, the lecture points to industrial applications where this method has been successfully used.

Pieter Mosterman

Mode transition behavior in hybrid dynamic systems

Continuous system dynamics can be described by, possibly large, systems of differential equations. These can be either ordinary differential equations (ODEs) or contain algebraic constraints as well to form differential and algebraic equations (DAEs). Plant modeling benefits especially from the use of implicit equations because it is an intuitive way to describe physical constraints and behaviors (e.g., conservation of mass).
Complex engineered systems often operate in different modes of continuous behavior and when mode changes occur, the continuous dynamics change abruptly, typically because of model abstractions that lead to idealized component behavior. Even small physical components may operate in different modes (e.g., a diode can operate as a short or open circuit), requiring abrupt discrete changes in the system of equations. In an explicit representation, the combination of these local mode switches leads to a combinatorial explosion of the number of global modes.
It is shown how an implicit formulation can be used to formulate these mode switches, thereby circumventing the combinatorial problem. This leads to the use of DAEs for each of the modes that, in case of high index, may cause jumps in generalized state variables. In combination with the inequalities that define mode switching, this leads to rich and complex mode transition behavior. Given such a system operating at multiple scales of time and space, equivalence relations are de-fined over the set of system behaviors. Consequently, the entire domain of operation is partitioned into modes with similar continuous behavior. Discrete transitions move the system from one mode to another. Subtle interactions between the continuous behaviors and discrete transitions require the development of a hybrid modeling and analysis paradigm. An overview of this mode switching behavior and a taxonomy of mode transitions is presented consisting of mythical modes, pinnacles, interior modes, boundary, and sliding behaviors.

Simulation technologies for hybrid dynamic systems

The interest in hybrid dynamic systems is driven by (i) the increasing need for comprehensive analysis of systems where discrete controllers operate on a continuous process, and (ii) efficient handling of otherwise stiff continuous equations. Though individually the numerical simulation of continuous and discrete formalisms is well understood, their interaction causes a number of unique problems that must be addressed to facilitate simulation of mixed continuous/discrete systems.

Complex dynamic system models are composed of declarative submodels specified by noncausal equations. After the complete system of equations is compiled, a sorting procedure assigns computational causality. After sorting, model transformations may be required to reduce the complexity of the simulation problem. Next, consistent initial values of the state variables need to be calculated from user specified values. For example, to start simulation from steady state, all time derivative values can be set to 0. Once the consistent initial values of the system of equations are computed, a numerical solver evolves the system behavior over time. The continuous model part generates discrete events when continuous signal variables cross threshold values. These discrete events may affect continuous behavior evolution by changing active model components and discontinuously changing the continuous state variables. And the entire compilation, sorting, solving and initialization phase may repeat.

An overview is presented of phenomena that emerge in simulation of hybrid systems, reported in previously published literature. They can be classified as (i) event handling, (ii) run-time equation processing, (iii) discontinuous state changes, (iv) event iteration, (v) comparing Dirac pulses, and (vi) chattering. Based on these phenomena, numerical simulation requires specific simulation technologies that are discussed in detail.

Frits Vaandrager

Hybrid I/O automata

This talk presents the *Hybrid Input/Output Automaton (HIOA)* modeling framework, a basic mathematical framework to support description and analysis of hybrid systems, that I developed together with Nancy Lynch (MIT) and Roberto Segala (University of Verona). An important feature of this model is its support for decomposing hybrid system descriptions. In particular, the framework includes a notion of *external behavior* for a hybrid I/O automaton, which captures its discrete and continuous interactions with its environment. The framework also defines what it means for one HIOA to *implement* another, based on an inclusion relationship between their external behavior sets, and defines a notion of *simulation*, which provides a sufficient condition for demonstrating implementation relationships. The framework also includes a *composition* operation for HIOAs, which respects the implementation relation and a notion of *receptiveness*, which implies that an HIOA does not block the passage of time. The framework is intended to support analysis methods from both computer science and control theory. As an example application, I will discuss the specification and analysis of a small LEGO car.

Course material

Copies of the transparencies of the lectures and additional material will be distributed at the beginning of the meeting.

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Publication date June 2003