Preface

In 1995, the Deutsche Forschungsgemeinschaft (DFG), the largest public research funding organization in Germany, decided to launch a priority program (Schwerpunktprogramm in German) called KONDISK– *Dynamics and Control of Systems with Mixed Continuous and Discrete Dynamics*. Such a priority program is usually sponsored for six years and supports about twenty scientists at a time, in engineering and computer science mostly young researchers working for a doctoral degree. There is a yearly competition across all disciplines of arts and sciences for the funding of such programs, and the group of proposers was the happy winner of a slot in that year. The program started in 1996 after an open call for proposals; the successful projects were presented and re-evaluated periodically, and new projects could be submitted simultaneously. During the course of the focused research program, 25 different projects were funded in 19 participating university institutes, some of the projects were collaborative efforts of two groups with different backgrounds, mostly one from engineering and one from computer science.

There were two main motivations for establishing KONDISK. The first was the fact that technical systems nowadays are composed of physical components with (mostly) continuous dynamics and computerized control systems where the reaction to discrete events plays a major role, implemented in *Programmable Logic Controllers* (PLCs), *Distributed Control Systems* (DCSs) or real-time computer systems. These two elements interact closely, and the resulting behavior can be surprisingly complex even for very simple systems, as demonstrated for the filling of three or more tanks by a switched server (Chase et al., 1993, Engell et al., 1997). Such complex behavior can neither be analyzed nor synthesized by methods that are based on either purely continuous or purely discrete systems theory. Despite the lack of theoretical tools or even powerful simulation environments for systems with mixed continuous and discrete dynamics, such systems have been engineered successfully on a trial-and-error basis, applying a combination of “divide and conquer” and “separation of concerns”. The price that has to be paid, however, is extensive testing, frequent iterations in the design process, and the lack of guarantees for safety and performance properties.

The second important factor in the creation of the priority program KONDISKwas the growing awareness of the need for a more comprehensive approach to hybrid systems both in the computer science and the control engineering communities, and the fact that important foundations had been laid in both camps – and sometimes across their borders as well. It was one of the key ideas in the call for proposals that the interaction of scientists from computer science and control engineering should be stimulated, and this resulted in several interdisciplinary projects. These projects not only led to interesting and novel results but generally created a deeper understanding of the complementary theories and issues on both sides. Some of these cooperative projects can be recognized from the list of authors of the contributions in this volume.

A good German tradition in Engineering Science is that the results of academic research should somehow be applied to reality, if not in industry then at least in laboratory experiments. Thus several practical examples of systems with mixed continuous-discrete dynamics were studied in the projects of KONDISK, e.g.

- a conveyor belt, p. 26,
- an annealing furnace, p. 29,
- a wire stretching plant, p. 43,
- a membranous filtration process, p. 63,
- a batch evaporator, pp. 99, 212,
- a combined heating and material handling process, pp. 116, 201, 291, 302.
- a two-tank-system, pp. 167, 187, 297,
- a distillation column, p. 260,
- a titration plant, p. 280,
- a diesel engine, p. 288
- a multi-arm transportation task, p. 324,
- an underactuated two degree-of-freedom robot arm, p. 327,
- a chemical reactor, p. 349,
- an aircraft elevator system, p. 369,
- a three-tank-system, p. 409,
- and a multi-fingered robotic hand, p. 437.

Benchmark problems were formulated, most prominently the batch evaporator control problem, which provided the focus for a special issue of the European Journal of Control (Kowalewski et al., 2001b), and the combined heating and material handling process (Nixdorf and Lunze, 2000b).

This volume summarizes the results of KONDISK. Its structure follows the general scheme of most books on controller design: it is divided into the chapters Modeling, Simulation, Analysis, Controller Synthesis, and finally Applications. Of course, several contributions cover more than one of these topics, but an effort was made to arrange the papers according to their main focus.

Modeling

In continuous system theory, there is one single underlying modeling framework that provides a compact and powerful description of physical dynamic systems and serves as a starting point of most pieces of theoretical work: systems of differential and algebraic equations. In mixed continuous-discrete systems, the diversity of the available descriptions of reactive discrete event systems and the various choices to restrict the dynamic behavior of the continuous part for the sake of decidability and efficiency of the analysis result in a large number of possible combinations of discrete and continuous formalisms, each one with its own advantages and often tailored to specific application domains. This leaves the choice of the modeling framework open for discussion. Rather than trying to find out which paradigm might possibly be applicable to all potential problems, it pays off to analyze which one is particularly suited for the problem at hand. Following this line of thinking, the chapter on modeling presents several different proposals for the modeling of mixed dynamic systems.

The chapter starts with a somewhat provocative statement by Lunze that challenges hybrid systems theory by putting forward that only those systems are truly hybrid that contain jumps of the continuous state whereas other forms of discontinuities can be dealt with in either the discrete or the continuous domain. In the second article by Drath et al, discrete-event Petri Nets are enhanced with continuous components such as firing speeds for the transitions or continuous attributes of the tokens. A hierarchy is introduced by an object-oriented encapsulation of subnets. The contribution by Bender et al. presents a hybrid extension to the *real time object-oriented methodology* (ROOM) for the model based development of hybrid systems, and discusses its application in two tools for simulation and test case generation.

The fourth article by Münnemann et al. defines encapsulations and templates for function blocks in a manner similar to ROOM. That way, standardized components, such as generic control units, can be reused. Their behavior is formally specified by condition/event systems. Many problems in hybrid systems can be dealt with efficiently on the basis of a simpler, sometimes even purely discrete model. This model must match the behavior of the original model in the sense of an over-approximation, or abstraction. The article by Lunze and Raisch examines the properties of discrete abstractions of continuous systems, and discusses the implications of the resulting non-deterministism of the discrete-event models.

Simulation

Compared to the models used for analysis and controller synthesis, much more complex models can be handled efficiently in simulation. Currently, simulation is the only available tool that can cope with nonlinear dynamics interacting with complex discrete event dynamic systems. The description of a large hybrid system must be represented in a manner that combines (re-)usability with efficient simulation. On the algorithmic level, there is ongoing research how to integrate structural changes and discrete event handling with the established methods for solving differential equations or DAE-systems.

Remehle et al. introduce a software environment for the integration of complex hierarchical discrete-event models in MODELICA, a powerful object-oriented language for continuous systems. Graphical editors and translators for the discrete parts of the overall system support various formalisms, modularity and hierarchy. The overall model can be solved efficiently using the preprocessing and event-handling capabilities of MODELICA-based simulators.

The paper by Pawletta et al. presents a hierarchical modeling approach that supports time-varying structures of coupled systems. A combination of modular and monolithic simulation techniques avoids the overhead that is otherwise necessary for the coordination of the subsystems in strictly modular simulators. In the contribution by Nordwig, the software engineering concepts of restricted genericity and structural dynamics are applied to the modeling of hybrid systems. Based on the object-oriented specification language ZimOO, the graphical tool zooed is presented.

Analysis and Verification

The survey paper by Kowalewski gives an introduction to the formal analysis of hybrid systems. It highlights different directions from which hybrid models and their analysis are approached in computer science and engineering. Fundamental problems arising from the combination of discrete and continuous dynamics are discussed, and the following articles in this chapter are related to the different basic approaches.

The contribution by Nenninger et al. presents the so-called net-state-model, a combination of a continuous (ODE) system and a Petri Net, and discusses the reachability analysis for a class of hybrid systems. A control design scheme for hybrid systems with piecewise affine dynamics is introduced that is based on left eigenvector assignment. The analysis of fluid stochastic Petri Nets is discussed in the paper by Wolter et al. An improved numerical solution algorithm based on discretization is proposed for nets with two continuous dimensions. An example illustrates how performance metrics can be obtained from such models.

Simon et al. describe a method to deal with time critical problems in the field of automatic control of manufacturing systems. They determine values of the parameters of timestamp Petri Nets which prevent the net from getting blocked because of timing conditions by solving a linear optimization problem. Finally, the use of formal methods in the analysis and control of hybrids systems is reviewed in the paper by Huuck et al. They introduce some formal concepts and models, and present a compositional approach to the verification of hybrid automata based on the assumption/commitment paradigm.

Controller Synthesis

Analysis and verification are ex post activities which require that a controller has been designed beforehand. In analogy to synthesis procedures for continuous controllers, which have been the ultimate goal of control theory for decades, the obvious alternative is to come up with synthesis procedures for hybrid systems so that the desired properties are satisfied by design and no verification step is necessary. Moor and Raisch use the abstraction of a continuous system with discrete external signals, as presented in the chapter on modeling by Lunze and Raisch, to synthesize a discrete controller. They show that the temporal evolution of the quantization cells can be conveniently over-approximated if the dynamics of the system is monotone.

In the case of a fault in a system, it may be necessary to change not only the parameters but also the structure of the controller. The paper by Lunze and Steffen presents a method where the faulty system is modeled by a timed stochastic automaton. First, a discrete controller takes the system to an equilibrium state by choosing new actuators, sensors or set-points. Then a linear controller is designed to stabilize the system around the new equilibrium.

Wegele et al. present an iterative scheme for the optimal control design for hybrid systems. Each iteration of the overall optimization consists of an automatic controller design and then testing the controlled system for the violation of given constraints. A violation results in an additional penalty term in the cost function associated with the controller. The optimization algorithm can modify the controller parameters as well as choose a different design method. A procedure to detect and prevent undesired transitions of a discrete control of a continuous system is proposed by Müller et al. The system is modeled by Place/Transition nets that are fully deterministic. Undesired transitions are detected in the condensation of the evolution graph and excluded by modifications of the Petri Net and the firing conditions.

Two papers are concerned with the optimization of hybrid systems. Buss et al. present an approach for the computation of optimal trajectories of nonlinear hybrid systems. The continuous subproblem, including resets and switchings at fixed points in time, is solved by direct collocation. For the remaining problem of determining the times when discrete transitions occur, two alternative methods are proposed: finding suboptimal solutions on a grid and solving a mixed integer program. The method is applied to examples from robotics and a scalable hybrid travelling salesman problem. The paper by Stursberg et al. describes a linear mixed-integer discrete-time approximation of a hybrid system for the calculation of optimal continuous and discrete inputs for a linear cost function. In contrast to other approaches, a disjunctive formulation is used in the transformation to a mixed-integer linear program, and the combinatorial explosion is reduced by using a moving horizon and variable time steps.

Applications

The first paper by Decknatel et al. deals with the performance analysis of moving and fixed-block train protection systems. An extension of Colored Petri Nets is used where the tokens contain the current value of an attribute and parameters describing the continuous behavior of that value. Performance analysis is carried out using the tool Design/CPN. In the contribution by Mosterman et al., a complex object-oriented model of aircraft dynamics, hydraulic actuators, and continuous controllers is combined with a complex redundancy management system and the overall system is simulated. The general approach is the one described by Remehle et al. in the chapter on modeling with extensions to handle structural changes in DAE systems.

Manz and Göhner present an online monitoring method based on a combination of qualitative and dynamic models. An online state space reduction and an online analysis for failure detection and hazard predicton are carried out, based on the qualitative model. The approach is applied to a three-tank-system. Models of traffic flow of varying detail are combined in the paper by Czogalla et al. in order to obtain a model that provides sufficient accuracy as well as acceptable computational performance. The approach decomposes the overall model and uses more abstract submodels where certain effects of the refined model can be neglected.

The final contribution by Schlegl et al. presents a hybrid controller for a robotic hand. It involves a hybrid planning scheme for grasping and re-grasping, impedance control algorithms based on sensor information, and a formal compensation method for discrete contact state errors. The resulting performance is illustrated by dynamical simulations and experiments.

Summarizing the whole impact created by the research of this priority program, a substantial progress concerning different aspects can be observed. One indication is the apparent and increasing international visibility of the research on this topic in Germany, quantified by the number of publications presented on national and international conferences, e.g. EKA, WODES, ADPM, ECC, etc., and journals. The volume's extensive bibliography witnesses the broad publishing activities. In addition, having reached their academic merits relying on this work, the young researchers equipped with comprehensive knowledge of and theoretical experience in handling complex facts have been employed in strategic positions within leading industrial companies, mainly of the automotive branch. Moreover, some researchers decided to start up an entrepreneurship by founding a company of their own.

Regarding the scientific and first practical results – in comparison with evolution in biology – some of the early approaches to tackle the methodological challenges of continuous-discrete systems have been observed to survive the selection by efficiency and effort. Hence, the long-term evidence of this priority program on hybrid systems research will only become apparent after several years, maybe a decade. It may, however, be assumed that the promising research has theoretically opened the inherent potential of the advanced approaches to solve more complex applications on the one hand, and to exhaust the given boundaries of existing systems on the other.

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