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An Introduction to Hybrid Dynamical Systems

With 28 Figures

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Preface

The term "hybrid system" has many meanings, one of which is: a dynamical system whose evolution depends on a coupling between variables that take values in a continuum and variables that take values in a finite or countable set. For a typical example of a hybrid system in this sense, consider a temperature control system consisting of a heater and a thermostat. Variables that would in all likelihood be included in a model of such a system are the room temperature and the operating mode of the heater (on or `off`). It is natural to model the first variable as real-valued and the second as Boolean. Obviously, for the temperature control system to be effective there needs to be a coupling between the continuous and discrete variables, so that for instance the operating mode will be switched to on if the room temperature decreases below a certain value.

Actually most of the dynamical systems that we have around us may reasonably be described in hybrid terms: cars, computers, airplanes, washing machines—there is no lack of examples. Nevertheless, most of the literature on dynamic modeling is concerned with systems that are either completely continuous or completely discrete. There are good reasons for choosing a description in either the continuous or the discrete domain. Indeed, it is a platitude that it is not necessary or even advisable to include all aspects of a given physical system into a model that is intended to answer certain types of questions. The engineering solution to a hybrid system problem therefore has often been to look for a formulation that is primarily continuous or discrete, and to deal with aspects from the other domain, if necessary, in an *ad hoc* manner. As a consequence, the field of hybrid system modeling has been dominated by patches and workarounds.

Indications are, however, that the interaction between discrete and continuous systems in today's technological problems has become so important that more systematic ways of dealing with hybrid systems are called for. For a dramatic example, consider the loss of the Ariane 5 launcher that went into self-destruction mode 37 seconds after liftoff on June 4, 1996. Investigators have put the blame for the costly failure on a software error. Nevertheless, the program that went astray was the same as the one that had worked perfectly in Ariane 4; in fact, it was copied from Ariane 4 to Ariane 5 for exactly that reason. What had changed was the continuous dynamical system around the software, embodied in the physical structure of the new launcher which had been sized up considerably compared to its predecessor. Within the new physical environment, the trusted code quickly led into a catastrophe.

Although the increasing role of the computer in the control of physical processes may be cited as one of the reasons for the increased interest in hybrid systems, there are also other sources of inspiration. In fact a number of recent developments all revolve in some way around the combination of continuous and discrete aspects. The following is a sample of these developments, which are connected in ways that are still largely unexplored:

- computer science: verification of correctness of programs interacting with continuous environments (embedded systems);
- control theory: hierarchical control, interaction of data streams and physical processes, stabilization of nonlinear systems by switching control;
- dynamical systems: discontinuous systems show new types of bifurcations and provide relatively tractable examples of chaos;
- mathematical programming: optimization and equilibrium problems with inequality constraints can fruitfully be placed within a regime-switching dynamic framework;
- simulation languages: element libraries contain both continuous and discrete elements, so that the numerical simulation routines behind the languages must take both aspects into account.

It is a major challenge to advance and systematize the knowledge about hybrid systems that comes from such a large variety of fields, which nevertheless from a historical point of view have many concepts in common.

Even though the overall area of hybrid systems has not yet crystallized, we believe that it is meaningful at this time to take stock of a number of related developments in an introductory text, and to describe these from a more unified point of view. We have not tried to be encyclopaedic, and in any case we consider the present text as an intermediate product. Our own background is clearly reflected in the choice of the developments covered, and without doubt the reader will recognize a definite emphasis on aspects that are of interest from the point of view of continuous dynamics and mathematical systems theory. The title that we have chosen is intended to reflect this choice. We trust that others who are more qualified to do so will write books on hybrid systems emphasizing different aspects.

This text is an expanded and revised version of course notes that we have written for the course in Hybrid Systems that we taught in the spring of 1998 as part of the national graduate course program of the Dutch Institute of Systems and Control. We would like to thank the board of DISC for giving us the opportunity to present this course, and we are grateful to the course participants for their comments. In some parts of the book we have relied heavily on work that we have done jointly with Kanat Çamlıbel, Gerardo Escobar, Maurice Heemels, Jun-Ichi Imura, Yvonne Lootsma, Romeo Ortega, and Siep Weiland; it is a pleasure to acknowledge their contributions. The second author would in particular like to thank Gjerrit Meinsma for his patient guidance on the intricacies of LaTeX. Finally, for their comments on preliminary versions of this text and helpful remarks, we would like to thank René Boel, Peter Breedveld, Ed Brinksma, Bernard Brogliato, Domine Leenaerts, John Lygeros, Oded Maler, Sven-Erik Mattson, Gjerrit Meinsma, Manuel Monteiro Marques, Andrew Paice, Shankar Sastry, David Stewart, and Jan Willems. Of course, all remaining faults and fallacies are entirely our own.

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