Preface

Hybrid systems arose more than 15 years ago in a bold attempt to yoke together computer science and control theory in the context of, what are now called, cyber-physical systems. Although it is still early to give an unified account of hybrid systems research, certain conceptual similarities, between different results developed by different researchers, have recently come into view. This book aims at highlighting these similarities by providing a systematic exposition of several key verification and control synthesis results.

The guiding concept used in this book is the notion of bisimulation. To understand how it winds through hybrid systems research, a digression into digital control and timed automata is in order. Before hybrid systems, the existing paradigm for computer controlled systems was digital control. Under this paradigm, a computer interfaces with the physical world through an Analog-to-Digital (A/D) converter, transforming measured physical quantities into digital format, and through a Digital-to-Analog (D/A) converter, transforming digital control commands into analog signals. The enabling result of this paradigm states that when the continuous dynamics is described by a controlled linear differential equation, the combination of the continuous dynamics with certain classes of D/A and A/D converters can be represented by a discrete-time linear control system. Consequently, discrete-time linear control systems were widely used as the abstraction of choice for computer controlled physical systems. Although powerful, the digital control paradigm provides no support to study the interaction of software with the physical world. The first models for hybrid systems extended the digital control paradigm by modeling the software as a finite-state machine interfacing with the physical world, described by a controlled differential equation, through A/D and D/A converters. This model for hybrid systems later evolved into hybrid automata but no enabling representation result, such as the one for digital control, was known. The desired representation result had already been partially given by Alur and Dill's work on timed automata. In the 1990 paper [AD90], Alur and Dill showed that timed automata, a special class of hybrid automata, could be represented by a finite-state symbolic model, *i.e.*, a model with finitely many states where each state or symbol represents infinitely many states of the timed automaton. Essential to their results was the observation that the notion of bisimulation was versatile enough to establish a formal equivalence between timed automata and finite-state symbolic models. Bisimulation, originally introduced by Park [Par81] and Milner [Mil89] as a notion of equivalence between software processes, provided the motto for extensions of Alur and Dill's pioneering work to other classes of hybrid systems. Although the initial effort was on representation results for the verification of hybrid systems, later results showed that symbolic models could also be constructed for control design. A further twist in this research stream occurred recently when it was recognized that bisimulation could be generalized to approximate bisimulation with the purpose of further enlarging the class of hybrid systems admitting symbolic models.

The excursion into hybrid systems research, offered in this book, is divided into four parts. The first part presents basic concepts centered around a notion of system that is general enough to describe finite-state machines, differential equations, and hybrid systems. However, a system, by itself, is not very interesting. More interesting are the ways in which systems relate to other systems. Two such relationships are presented in Part II: behavioral inclusion/equivalence and simulation/bisimulation. These relationships are then used to study verification and control synthesis problems for finite-state systems. Only a flavor of the existing results is provided since the focus of the book are the infinite-state (hybrid) systems discussed in Part III and Part IV. By drawing inspiration from timed automata, several classes of hybrid systems with richer continuous dynamics are shown to be related to finite-state symbolic systems in Part III. Once such (bi)simulation relations are established, verification and control synthesis problems can be immediately solved by resorting to the techniques described in Part II for finite-state systems. The same strategy is followed in Part IV by generalizing (bi)simulation relationships to approximate (bi)simulation relationships that can be used for wider classes of hybrid systems.

The choice of results presented in this book is admittedly biased by my view of hybrid systems and my own research interests. Moreover, I confess that the guiding concept of bisimulation warrants a longer route visiting many other important results. The decision not to include such topics was difficult to make, but including them would have required more time than I could give to this project at this stage. In addition to the choice of topics, I faced another challenge: to make the book accessible and interesting to both computer scientists and control theorists. On the one hand, the computer scientist will certainly find Part II to be a very narrow account of formal verification and Part III to treat timed automata very superficially. On the other hand, the control theorist will be intrigued with the notion of system used in this book, yet disappointed with the relegation of nonlinear systems to several cursory sections. Nonetheless, I hope the readers, independently of their technical background, will find the results interesting enough to consult the specialized literature for the missing details.

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