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Rajeev Alur
George J. Pappas (Eds.)

Hybrid Systems: Computation and Control

7th International Workshop, HSCC 2004
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Preface

This volume contains the proceedings of the 7th Workshop on *Hybrid Systems: Computation and Control* (HSCC 2004) held in Philadelphia, USA, from March 25 to 27, 2004. The annual workshop on hybrid systems attracts researchers from academia and industry interested in modeling, analysis, and implementation of dynamic and reactive systems involving both discrete and continuous behaviors. The previous workshops in the HSCC series were held in Berkeley, USA (1998), Nijmegen, The Netherlands (1999), Pittsburgh, USA (2000), Rome, Italy (2001), Palo Alto, USA (2002), and Prague, Czech Republic (2003). This year's HSCC was organized in cooperation with ACM SIGBED (Special Interest Group on Embedded Systems) and was technically co-sponsored by the IEEE Control Systems Society.

The program consisted of 4 invited talks and 43 regular papers selected from 117 regular submissions. The program covered topics such as tools for analysis and verification, control and optimization, modeling, and engineering applications, as in past years, and emerging directions in programming language support and implementation. The program also contained one special session focusing on the interplay between biomolecular networks, systems biology, formal methods, and the control of hybrid systems.

We would like to thank the program committee members and reviewers for an excellent job of evaluating the submissions and participating in the on-line program committee discussions. Special thanks go to Edmund M. Clarke (Carnegie Mellon University, USA), John Doyle (California Institute of Technology, USA), Patrick Lincoln (SRI, USA), and Harvey Rubin (University of Pennsylvania, USA) for their participation as invited speakers. We are also grateful to the Steering Committee for helpful guidance and support. Many other people worked hard to make HSCC 2004 a success. We would like to thank T. John Koo for publicity, Janean Williams for local arrangements, and Valya Sokolsky for putting together the proceedings. We would like to express our gratitude to the US National Science Foundation and the University of Pennsylvania for financial support. Their support helped us to reduce the registration fee for graduate students.

January 2004 — Rajeev Alur and George J. Pappas

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Invited Contribution

Lazy Rectangular Hybrid Automata

Manindra Agrawal[1] and P.S. Thiagarajan[2]

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Abstract. We introduce the class of lazy rectangular hybrid automata. The key feature of this class is that both the observation of the continuous state and the rate changes associated with mode switchings take place with bounded delays. We show that the discrete time dynamics of this class of automata can be effectively analyzed without requiring resetting of the continuous variables during mode changes.

1 Introduction

We introduce here a class of linear rectangular hybrid automata called *lazy hybrid automata* and study its discrete time behavior. A central feature of this class is that the sensors report the current values of the variables and the actuators effect changes in the rates of evolution of the variables with bounded delays. More specifically, the state observed at T_k is a state that held at some time in a bounded interval contained in (T_{k-1}, T_k). Further, if an instantaneous mode change has taken place at T_k, then any necessary change in the rate of a variable will not kick in immediately. Rather, it will do so at some time in a bounded interval contained in (T_k, T_{k+1}). A final restriction is that each variable's allowed range of values is bounded. For convenience, we study the case where there is a single rate vector associated with each control state instead of a bounded rectangular region of vectors as is customary for rectangular hybrid automata [2].

Since both sensors and actuators have delays associated with them, a single symbolic trajectory of the automaton can correspond to uncountably many concrete trajectories; even in a discrete time setting with the initial region being a singleton. Hence computing the discrete time behavior of a lazy hybrid automaton is non-trivial. Our main result is that this can be carried out effectively. It then follows that the discrete time behavior of a network of lazy hybrid automata that communicate by synchronizing on common actions can also be effectively computed.

As is well known, the continuous variables available to an hybrid automaton and the fact that their rates of evolution can change instantaneously during a mode switch endows them with a great deal of expressive power. As a result, in a variety of settings, the control state reachability problem becomes undecidable,

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as reported for instance, in [3]. A sharp characterization of the boundary between decidable and undecidable features of hybrid automata is provided in [8] as well as [2]. These results, as also the positive results reported elsewhere - for example, [5,13,11,10] - make it clear that except under very restrictive settings, one can not expect to get decidability if the continuous variables don't get reset during mode changes; particularly in case their rates change as a result of the mode change. Viewed as a model of digital control systems that interact with physical plants through sensors and actuators, the resetting requirement severely restricts the modeling power of the automaton. Our results show that by introducing bounded delays into the functioning of the sensors and actuators, we can allow the variables to retain their values during mode changes. Admittedly, our positive results are obtained in the restricted setting of rectangular hybrid automata but the wealth of research concerning this setting (for instance, [6,8,5,7]) suggests that this is a natural and well motivated starting point.

We study the discrete time semantics of lazy hybrid automata. From a technical standpoint, our work is a generalization of [7] where the discrete time behavior of rectangular hybrid automata is studied with the requirement that all instantaneous transitions should take place only at integer-valued instances of time. In our terms, [7] further assumes that the sensors and actuators function with zero delays which simplifies their analysis problem. In our setting, things are more complicated due to the non-zero delays associated with the sensing of values and actuating rate changes. Further, we feel that the approach proposed here is of some independent interest from a modeling point of view. It may also lead to the tractable analysis of larger classes of hybrid automata. Finally, our focus on discrete time semantics is relevant -as also argued in [7]- in that, as a model of digital controllers for continuous plants, the discrete time semantics of hybrid automata is more natural and useful than the continuous time semantics.

Our work is, at least conceptually, in line with previous attempts to reduce the expressive power of timed and rectangular automata by taking away their ability to define trajectories with infinite precision [4,9,12]. Typically one demands the set of admitted trajectories to be "fuzzy"; if a trajectory is admitted by the automaton then it should also admit trajectories that are sufficiently close to the trajectory where "closeness" is captured using a natural topology over the trajectories. Surprisingly enough, this idea does not lead to more tractability as detailed in [9] and [12]. The key difference between our work and these previous works is that in lazy hybrid automata, the fuzziness is introduced into the *dynamics*; the observed continuous state based on which a mode change takes place at an instant is different from the actual continuous state that holds at that instant. Similarly, the actual rate at which a variable may be evolving at an instant may be different from the rate demanded by the current mode of the automaton.

In the next section, we formulate the model of lazy hybrid automata. In section 3 we prove our main result, namely, the language of state sequences and action sequences generated by a lazy hybrid automaton are regular. Moreover, finite state automata representing these languages can be effectively computed. In section 4 we discuss the restrictions placed on lazy automata and point out that many of them can be easily relaxed. We also sketch how our main result can be easily extended to networks of automata which communicate by performing common actions together. In the concluding section we summarize and point to some possible future work.

2 Lazy Hybrid Automata

Fix a positive integer n and one function symbol x_i for each i in $\{1, 2, \ldots, n\}$. We will view each x_i as a function $x_i : \mathbb{R}_{\geq 0} \mapsto \mathbb{R}$ with $\mathbb{R}$ being the set of reals and $\mathbb{R}_{\geq 0}$, the set of non-negative reals. We let $\mathbb{Q}$ denote the set of rationals and $\mathcal{I}$ denote the set of closed intervals of the form $[l, r]$ with $l, r \in \mathbb{Q}$ and $l < r$. We view $[l, r]$ as the subset of $\mathbb{R}$ given by $\{z \mid l \leq z \leq r\}$.

A *lazy hybrid automaton* is a structure
$\mathcal{A} = (Q, Act, q_{in}, V_{in}, D, \{\rho_q\}_{q \in Q}, \mathrm{B}, \longrightarrow)$ where:

- Q is a finite set of *control states.*
- Act is a finite set of *actions.*
- $q_{in} \in Q$ is the initial control state.
- $V_{in} \in \mathbb{Q}^n$ is the initial valuation.
- $D = \{g, \delta_g, h, \delta_h\} \subseteq \mathbb{Q}$ is the *set of delay parameters* such that $0 < g < g + \delta_g < h < h + \delta_h < 1$.
- $\rho_q \in \mathbb{Q}^n$ is a rate vector which specifies the rate $\rho_q(i)$ at which each x_i evolves when the system is in the control state q.
- $\mathrm{B} = [B_{min}, B_{max}] \in \mathcal{I}$ is the *allowed range.*
- $\longrightarrow \subseteq Q \times Act \times \mathcal{I}^n \times Q$ is a transition relation such that $q \neq q'$ for every (q, a, I, q') in $\longrightarrow$. Furthermore, if $(q, a, I, q'), (q, a, I', q') \in \longrightarrow$ then $I = I'$.

We shall study the discrete time behavior of our automata. At each time instant T_k, the automaton receives a measurement regarding the current values of the x_i's. However, the value of x_i that is observed at T_k is the value that held at some $t \in [T_{k-1} + h, T_{k-1} + h + \delta_h]$. If at T_k, the automaton is in control state q and observed n-tuple of values $(v_1, v_2, \ldots, v_n)$ is in I with (q, a, I, q') being a transition, then the automaton may perform this transition instantaneously by executing the action a and move to the control state q'. Thus as usual, the x_i's will cease to evolve at the rates ρ_q and instead start evolving at the rates $\rho_{q'}$. However, this change in the rate of evolution will not kick in at T_k but at some time $t \in [T_k + g, T_k + g + \delta_g]$. In this sense, both the sensing of the values of the x_i's and the rate changes associated with mode switching take place in a lazy fashion but with bounded delays.. We expect g to be close to 0, h to be close to 1 and both δ_g and δ_h to be small compared to 1 so that in the idealized setting, the change in rates due to mode switching would kick in immediately $(g = 0 = \delta_g)$ and the value observed at T_k is the value that holds at exactly T_k $(h = 1$ and $\delta_h = 0)$. Indeed, this is the setting considered in [7].

B specifies the range of values within which the automaton's dynamics are valid. The automaton gets stuck if any of the x_i's ever assume a value outside the allowed range $[B_{min}, B_{max}]$. A number of the restrictions that we have imposed