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Thomas A. Henzinger
Shankar Sastry (Eds.)

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First International Workshop, HSCC'98
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Preface

This volume contains the proceedings of the *First International Workshop on Hybrid Systems: Computation and Control*, HSCC'98, organized April 13–15, 1998, at the University of California, Berkeley. Following several meetings that were initiated by Anil Nerode at Cornell University, this is the first of a newly constituted, regular annual series of workshops on hybrid systems. Papers from the earlier meetings were published in the Springer-Verlag Lecture Notes in Computer Science series, volumes 736, 999, 1066, 1201, and 1273. The steering committee of the new workshop series includes Panos Antsaklis (University of Notre Dame), Nancy Lynch (Massachusetts Institute of Technology), Amir Pnueli (Weizmann Institute, Israel), Alberto Sangiovanni-Vincentelli (University of California, Berkeley), and Jan van Schuppen (CWI, The Netherlands).

The focus of the workshop is on mathematical methods for the rigorous and systematic design and analysis of hybrid systems. A hybrid system consists of digital devices that interact with analog environments. Driven by rapid advances in digital controller technology, hybrid systems are objects of investigation of increasing relevance and importance. The emerging area of hybrid systems research lies at the crossroads of computer science and control theory: computer science contributes expertise on the digital aspects of a hybrid system, and control theory contributes expertise on the analog aspects. Since both research communities speak largely different languages, and employ largely different methods, a major purpose of the workshop is to bring together researchers from both disciplines.

The three-day workshop will feature six invited keynote speakers and 26 contributed talks that were selected from 55 submissions by a technical program committee. The keynote lecturers will be Panos Antsaklis (University of Notre Dame), Stephen Boyd (Stanford University), Edward Lee (University of California, Berkeley), Alberto Sangiovanni-Vincentelli (University of California, Berkeley), Joseph Sifakis (VERIMAG, France), and Murray Wonham (University of Toronto). Additional invited addresses will be given by Linda Bushnell from the Army Research Office and by Helen Gill from the Defense Advanced Research Projects Agency. The workshop will also include demos of software tools for the design, analysis, and simulation of hybrid systems.

The program committee was chaired by the editors and included Rajeev Alur (University of Pennsylvania), Karl Astrom (Lund University, Sweden), Albert Benveniste (INRIA-IRISA, France), Ahmed Bouajjani (VERIMAG, France), Michael Branicky (Case Western Reserve University), Peter Caines (McGill University), Datta Godbole (PATH Berkeley, California), Mark Greenstreet (University of British Columbia), Vineet Gupta (NASA Ames, California), Bruce Krogh (Carnegie Mellon University), Stephane Lafortune (University of Michigan), Kim Larsen (Aalborg University, Denmark), Oded Maler (VERIMAG, France), Stephen Morse (Yale University), Anil Nerode (Cornell University), Peter Ramadge (Princeton University), Roberto Segala (University of Bologna,

Italy), and Howard Wong-Toi (Cadence Berkeley Labs, California). In the selection process, the program committee was aided by the following reviewers: L. Aceto, K. Al-Wahedi, E. Asarin, E. Badouel, G. Barrett, O. Bournez, A. Chutinan, P. Codognet, R. Debouk, A. Deshpande, A. Fehnker, A. Hicks, R. Jagadeesan, M. Kourjanski, Y. Lakhnech, F. Lin, J. Lygeros, H. McClamroch, R. Nikoukhah, G. Pappas, A. Puri, R. Rajamani, H. Schumacher, R. Sengupta, A. Skou, M. Sorine, C. Tomlin, and C. Weise. The steering committee handled all submissions that were co-authored by the program chairs.

We are grateful to all invitees, contributors, and reviewers for making the workshop a success. In addition, we wish to thank Carol Block for administrating the workshop organization, John Lygeros and Serdar Tasiran for organizing the tool demos, Alexa Brudy and Flora Oviedo for organizational support, and the Army Research Office for generous financial support.

January 1998

Thomas A. Henzinger
Shankar Sastry

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Equations on Timed Languages *

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Abstract. We continue investigation of languages, accepted by timed automata of Alur and Dill. In [ACM97] timed regular expressions equivalent to timed automata were introduced. Here we introduce quasilinear equations over timed languages with regular coefficients. We prove that the minimal solution of such an equation is regular and give an algorithm to calculate this solution. This result is used to obtain a new proof of Kleene theorem ([ACM97]) for timed automata. Equations over timed languages can be also considered as an alternative way of specifying these languages.

1 Introduction

Timed automata ([AD94]) form the best investigated class of hybrid systems. It is known which problems about these automata are decidable and which are not, and there are tools for testing emptiness, evaluating reachable states etc. ([DOTY96]). However some theoretical aspects and parallels with ordinary finite automata are still not clear. This paper may be considered as a continuation of ([ACM97]) where timed languages were analyzed from the traditional linguistic viewpoint — and timed regular expression capable to specify exactly the same languages as timed automata were introduced.

We take for a model following classical (forty years old) results about finite automata, regular languages and linear equations (see e.g. [Brz62]).

Any system of linear equations in the form

$$X_i = \alpha_i + \sum_{j=1}^{n} \beta_{ij} X_j \qquad i = 1, \ldots, n, \tag{1}$$

where X_i stand for unknown languages and α_i, β_{ij} — for given regular coefficients, has a regular minimal solution. The regular expression for this solution can be found effectively from the coefficients.

For any finite automaton a system (1) can be easily constructed, each unknown X_i of the system corresponding to a state q_i of the automaton. In the

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minimal solution, the language X_i is exactly the language accepted by the automaton starting from the state q_i.

As a corollary these two classical results imply Kleene theorem ([Kle56]) about regularity of languages accepted by finite automata.

Our aim is to port these results to timed automata and to introduce a class of equations over timed languages capable to specify languages of one-clock timed automata. These equations are similar to classical linear equations (1). However the following example shows that a straightforward timed adaptation of linear equations cannot work.

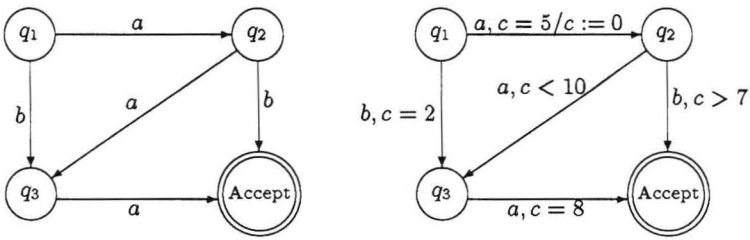

Fig. 1. Two automata

Example 1. The language of the first (untimed) automaton on Figure 1 can be represented by the following equations:

$$\begin{cases} X_1 = aX_2 + bX_3 \\ X_2 = b + aX_3 \\ X_3 = a \end{cases}$$

X_i here stands for the language accepted from the state q_i and each transition from q_i to q_j labeled with a can be represented by a term aX_j in the equation for X_i. Roughly speaking, such a transition corresponds to concatenating its label a to the language.

The case of the second (timed) automaton is more complicated because now there are two kinds of transitions. Some of them reset the clock and in this case they also can be represented by concatenation of the label (with time restriction) to the language. However some transitions do not reset the clock. We cannot write an equation like $X_1 = aX_2 + bX_3$ with a constraint on the sojourn time in state q_1, because after completing action b the automaton enters the state q_3 with a modified clock value.

To deal with this problem we introduce another composition operation on timed languages ($\circ$ operation) which corresponds to non-resetting transitions. We introduce quasilinear equations on timed languages which use both kinds

of concatenation ($\cdot$ and $\circ$) and are strong enough to represent one-clock timed automata.

Our main result is that any system of equations of this class with regular coefficients has a regular minimal solution. We give an algorithm to find out this solution.

The paper is motivated by the theory of timed automata, however the major part of it (sections 3–4) contains an automata-free theory of timed languages, regular timed expressions and quasilinear equations on timed languages. At our opinion, this linguistic approach could be useful for other classes of hybrid systems as well.

The outline of the paper is as follows. In section 2 we recall the definition of timed regular languages from [ACM97]. In section 3 the new operation $\circ$ over languages is formally introduced. This operation is crucial for representing timed automata by equations. We investigate algebraic properties of this operation and show, that $\circ$ can be eliminated in a sense. In section 4 quasilinear equations are introduced and solved. The possibility to solve this kind of equations is the main result of the paper. In section 5 we recall the definition of timed automata and apply our main result to languages of these automata. For any one-clock automaton we construct a quasilinear system, which represents the language of this automaton. This provides an alternative proof of expressive equivalence of timed automata and timed regular expressions from ([ACM97]). In the last section further work is discussed.

2 Timed Regular Languages

We reproduce in a slightly modified form the basic definitions of timed languages and timed regular equations from [ACM97]. Let Σ be a finite *alphabet* and let $\mathbb{R}_+$ denote the set of positive real numbers. A *signal* over Σ is a timed sequence of elements of Σ, i.e. a finite sequence $w = ((a_1, t_1), \ldots, (a_n, t_n))$ with $a_i \in \Sigma$ and $t_i \in \mathbb{R}_+$, such that $0 < t_1 < \ldots < t_n$. We will also write this signal as

$$w = a_1^{r_1} a_2^{r_2} \cdots a_n^{r_n},$$

where $r_1 = t_1$, and $r_{i+1} = t_{i+1} - t_i$, i.e. r_i are relative delays between a_i occurrences. We call t_n the *length* of w and denote it by $|w|$. The empty signal is denoted by ε. Its length equals 0. The set of all signals is denoted by $\mathcal{S}(\Sigma)$. Subsets of $\mathcal{S}(\Sigma)$ are referred to as *(timed) languages*. For every $w_1, w_2 \in \mathcal{S}(\Sigma)$ such that $w_1 = a_1^{r_1} a_2^{r_2} \cdots a_n^{r_n}$ and $w_2 = b_1^{s_1} b_2^{s_2} \cdots b_n^{s_n}$ we define their concatenation as $w = w_1 w_2 = a_1^{r_1} \cdots a_n^{r_n} b_1^{s_1} \cdots b_n^{s_n}$. This notion can be extended naturally to concatenation of languages by letting

$$L_1 L_2 = \{w_1 w_2 : w_1 \in L_1 \wedge w_2 \in L_2\}.$$

An *integer-bounded interval* is either $[l, u]$, $(l, u]$, $[l, u)$, or (l, u) where $l \in \mathbb{N}$ and $u \in \mathbb{N} \cup \{\infty\}$ such that $l \leq u$. We exclude $\infty]$ and use l for $[l, l]$.

Definition 1 (Timed Regular Expressions). The set $\mathcal{E}(\Sigma)$ of timed regular expressions over an alphabet Σ, (expressions, for short) is defined recursively as either a, $\alpha_1 \cdot \alpha_2$, $\alpha_1 + \alpha_2$, α^* or $\langle\alpha\rangle_I$ where $a \in \Sigma$, $\alpha, \alpha_1, \alpha_2 \in \mathcal{E}(\Sigma)$ and I is an integer-bounded interval.

The semantics of timed regular expressions, $[\![\,]\!] : \mathcal{E}(\Sigma) \to \in^{\mathcal{S}(\Sigma)}$, is given by:

$$\begin{array}{ll} [\![a]\!] & = \{a^r : r \in \mathbb{R}_+\} \\ [\![\alpha_1 + \alpha_2]\!] & = [\![\alpha_1]\!] \cup [\![\alpha_2]\!] \\ [\![\alpha_1 \cdot \alpha_2]\!] & = [\![\alpha_1]\!][\![\alpha_2]\!] \\ [\![\alpha^*]\!] & = \bigcup_{i=0}^{\infty}([\![\alpha^i]\!]) \\ [\![\langle\alpha\rangle_I]\!] & = [\![\alpha]\!] \cap \{w : |w| \in I\} \end{array}$$

Some comments should be given here. First, the semantics of a is not a singleton, but a non-countable language. The intuitive meaning of this expression is that some unknown time passes and then event a happens. Operations $+$, $\cdot$ and * are the same as for untimed languages. The only operation which introduces time explicitly is "time restriction" $\langle\rangle_I$ which chooses only those signals in the language, whose lengths belong to the constraining interval I.

Example 2.

$$[\![\langle\langle ab\rangle_{(2;3)}c\rangle_{100}]\!] = \{a^x b^y c^z \,|\, 2 < x + y < 3; x + y + z = 100\}.$$

To simplify notation we write ε for the following regular expression $\langle a^*\rangle_0$, whose semantics is exactly ε.

Expressions introduced here form a proper subclass of those introduced in [ACM97], because here intersection is not allowed in the syntax. This change explains the difference between the formulation of Theorem 15 below from that of the same theorem in [ACM97].

3 Operation $\circ$

Begin with the following *shift operation* over signals, which just delays the beginning by t and preserves relative delays between events.

Definition 2. For a signal $w = a_1^{t_1}a_2^{t_2}\ldots a_n^{t_n}$ let $S^t w = a_1^{t_1+t}a_2^{t_2}\ldots a_n^{t_n}$

We say that a language is *shift-invariant*, if $S^{-t}L = L$ for any $t > 0$, i.e. any signal w belongs (or does not belong) to L simultaneously with $S^t w$. The following condition is sufficient for shift invariance — the regular expression should not begin with something in $\langle\rangle$. Formally speaking

Lemma 3. *If a regular expression has a form $\sum_i \alpha_i\beta_i$ where $\alpha_i \not\ni \varepsilon$ and α_i does not contain $\langle\rangle$, then its language is shift-invariant. We call this type of regular expressions* dull.

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