



Automatic Verification

2022-10-26

On the Synthesis of Discrete Controllers for Timed Systems [2]

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An Extended Abstract

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Introduction

This paper presents algorithms for the automatic synthesis of the real time controllers by finding a winning strategy for certain games defined by the timed automata of Alur and Dill.

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└ Introduction
└ Abstract

This paper presents algorithms for the automatic synthesis of the real time controllers by finding a winning strategy for certain games defined by the timed automata of Alur and Dill.



Consider a dynamical system P , whose presentation describes all its possible behaviours. A subset of the plant's behaviours, satisfying some criterion is defined as good or acceptable.

A controller C is another system which can interact with P in a certain manner by observing the state of P and by issuing control actions that influence the behaviour of P .

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└ Introduction

└ The problem

1. Kitchen robot
2. Selfdriven metro

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A controller C is another system which can interact with P in a certain manner by observing the state of P and by issuing control actions that influence the behaviour of P .



Introduction

The synthesis problem is then, to find out whether, for a given P , there exists a realizable controller C such that their interaction will produce only good behaviours.

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└ Introduction
└ The problem

The synthesis problem is then, to find out whether, for a given P , there exists a realizable controller C such that their interaction will produce only good behaviours.

Let's see some definition before dive in into the theorem and its proofs

Definition 1 (Plant)

A plant automaton is a tuple $\mathcal{P} = (Q, \Sigma_c, \delta, q_0)$ where

- ▶ Q is a finite set of states,
- ▶ Σ_c is a set of controller commands,
- ▶ $\delta : Q \times \Sigma_c \rightarrow 2^Q$ is the transition function
- ▶ $q_0 \in Q$ is an initial state

For each controller command $\sigma \in \Sigma_c$ at some state $q \in Q$ there are several possible consequences denoted by $\delta(q, \sigma)$.

Unlike other formulation of 2-person games, where there is an explicit description of the transition function of both players, here we represent the response of the environment as a non-deterministic choice among the transitions labeled by the same σ .

Definition 2 (Controllers)

A controller for a plant specified by $\mathcal{P} = (Q, \Sigma_c, \delta, q_0)$ is a function $C : Q^+ \mapsto \Sigma_c$. A simple controller is a controller that can be written as a function $C : Q \mapsto \Sigma_c$.

We are interested in the simpler cases of controllers that base their decisions on a finite memory.

Definition 3 (Trajectories)

Let \mathcal{P} be a plant and let $C : Q^+ \mapsto \Sigma_c$ be a controller. An infinite sequence of states $\alpha : q[0], q[1], \dots$ such that $q[0] = q_0$ is called a trajectory of \mathcal{P} if

$$q[i+1] \in \bigcup_{\sigma \in \Sigma_c} \delta(q[i], \sigma)$$

and a C -trajectory if $q[i+1] \in \delta(q[i], C[\alpha[0..i]])$ for every $i \geq 0$. The corresponding sets of trajectories are denoted by $L(\mathcal{P})$ and $L_C(\mathcal{P})$.

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For every infinite trajectory $\alpha \in L(\mathcal{P})$:

- ▶ $Vis(\alpha)$ denote the set of all states appearing in α
- ▶ $Inf(\alpha)$ denote the set of all states appearing in α infinitely many times

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For every infinite trajectory $\alpha \in L(\mathcal{P})$:

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Definition 4 (Acceptance Condition)

Let $\mathcal{P} = (Q, \Sigma_c, \delta, q_0)$ be a plant. An acceptance condition for \mathcal{P} is

$$\Omega \in \{(F, \square), (F, \diamond), (F, \diamond\square), (F, \square\diamond), (\mathcal{F}, \mathcal{R}_n)\}$$

where $\mathcal{F} = \{(F_i, G_i)\}_{i=1}^n$ and F, F_i and G_i are certain subsets of Q referred as the good states. The set of sequences of \mathcal{P} that are accepted according to Ω is defined as follows:

$$\begin{aligned} L(\mathcal{P}, F, \square) &= \{\alpha \in L(\mathcal{P}) : \text{Vis}(\alpha) \subseteq F\} \\ L(\mathcal{P}, F, \diamond) &= \{\alpha \in L(\mathcal{P}) : \text{Vis}(\alpha) \cap F \neq \emptyset\} \\ L(\mathcal{P}, F, \diamond\square) &= \{\alpha \in L(\mathcal{P}) : \text{Inf}(\alpha) \subseteq F\} \\ L(\mathcal{P}, F, \square\diamond) &= \{\alpha \in L(\mathcal{P}) : \text{Inf}(\alpha) \cap F \neq \emptyset\} \\ L(\mathcal{P}, \mathcal{F}, \mathcal{R}_n) &= \{\alpha \in L(\mathcal{P}) : \exists i \alpha \in \\ &\quad L(\mathcal{P}, F_i, \square\diamond) \cap L(\mathcal{P}, G_i, \diamond\square)\} \end{aligned}$$

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Definition 4 (Acceptance Condition)

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1. α always remains in F
2. α eventually visits F
3. α eventually remains in F
4. α visits F infinitely often
5. α visits F_i infinitely often and eventually stays in G_i

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Definition 5 (Controller Synthesis Problem)

For a plant \mathcal{P} and an acceptance condition Ω , the problem **Synth**(\mathcal{P}, Ω) is: Find a controller C such that $L_C(\mathcal{P}) \subseteq L(\mathcal{P}, \Omega)$ or otherwise show that such a controller does not exist.

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Definition 5 (Controller Synthesis Problem)

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Definition 6 (Controllable Predecessors)

Let $\mathcal{P} = (Q, \Sigma_c, \delta, q)$ be a plant and a set of states $P \subseteq Q$. The controllable predecessors of P is the set of states from which the controller can "force" the plant into P in one step:

$$\{q : \exists \sigma \in \Sigma_c \delta(q, \sigma) \subseteq P\}$$

We define a function $\pi : 2^Q \mapsto 2^Q$, mapping a set of states $P \subseteq Q$ into the set of its Controllable predecessors:

$$\pi(P) = \{q : \exists \sigma \in \Sigma_c \delta(q, \sigma) \subseteq P\}$$

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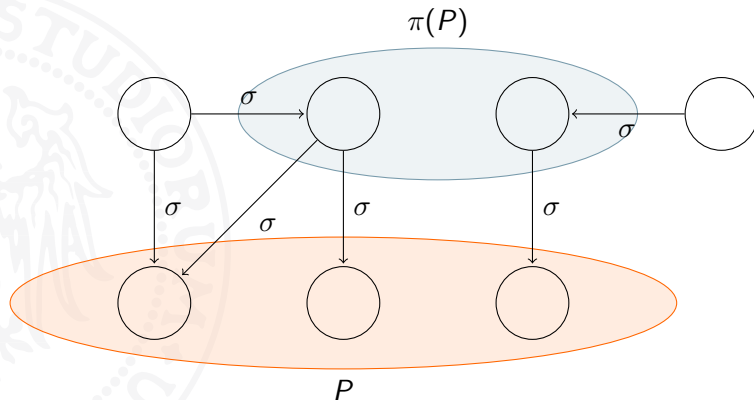
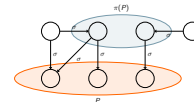
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└ Controllable Predecessors



the first one is not a controllable predecessor because it can have a bad consequence

Theorem 1

*For every $\Omega \in \{(F, \square), (F, \diamond), (F, \diamond\square), (F, \square\diamond), (\mathcal{F}, \mathcal{R}_n)\}$, the problem **Synth**(\mathcal{P}, Ω) is solvable. Moreover, if (\mathcal{P}, Ω) is controllable then it is controllable by a simple controller.*

Sketch of Proof

For a plant $\mathcal{P} = (Q, \Sigma_c, \delta, q_0)$ and an acceptance condition Ω , we denote $W \subseteq Q$ as the set of winning states, namely, the set of states from which a controller can enforce good behaviors according to Ω .

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└ Theorem**Theorem 1**

For every $\Omega \in \{(F, \square), (F, \diamond), (F, \diamond\square), (F, \square\diamond), (\mathcal{F}, \mathcal{R}_n)\}$, the problem **Synth**(\mathcal{P}, Ω) is solvable. Moreover, if (\mathcal{P}, Ω) is controllable then it is controllable by a simple controller.

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We can characterize this states by the following fixed-point expressions:

- $\square \nu W(F \cap \pi(W))$
- $\diamond \mu W(F \cup \pi(W))$
- $\diamond \square \mu W \nu H(\pi(H) \cap (F \cup \pi(W)))$
- $\square \diamond \nu W \mu H(\pi(H) \cup (F \cap \pi(W)))$
- $\mathcal{R}_1 \mu W \left\{ \pi(W) \cap \nu Y \mu H.W \cup G \cap (\pi(H) \cup (F \cap \pi(Y))) \right\}$

Then the plant is controllable iff $q_0 \in W$

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ν greatest
 μ least

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Then the plant is controllable iff $q_0 \in W$

```
W0 := ∅
for i := 0, 1, ... repeat
  Wi+1 := F ∪ π(Wi)
until Wi+1 = Wi
...
finally: W6 := F ∪ π(W5) = F ∪ π(F ∪ π(F))
```

Let see in more details how this works. Consider the case \diamond :

$W_0 := \emptyset$

for $i := 0, 1, \dots$ repeat

$W_{i+1} := F \cup \pi(W_i)$

until $W_{i+1} = W_i$

finally: $W_n := F \cup \pi(W_{n-1}) = F \cup \pi(F \cup \pi(\dots(F \cup \pi(F))))$

$W_0 := \emptyset$

$W_1 := F \cup \pi(W_0) = F \cup \pi(\emptyset) = F$

$W_2 := F \cup \pi(W_1) = F \cup \pi(F)$

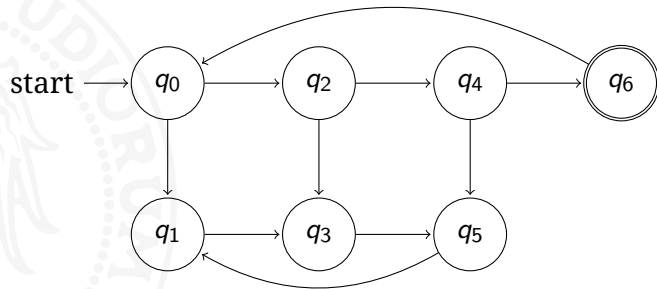
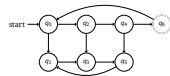
...

chain of operations

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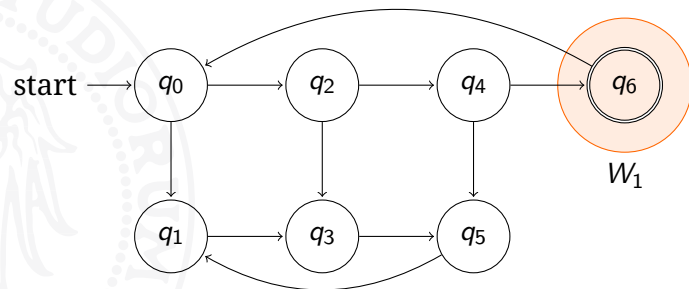
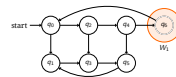


concluding the proof

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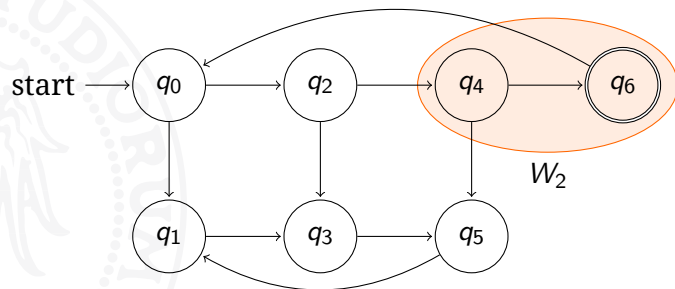


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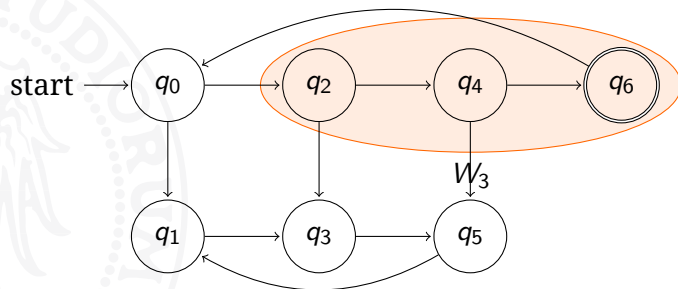
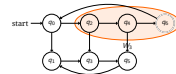


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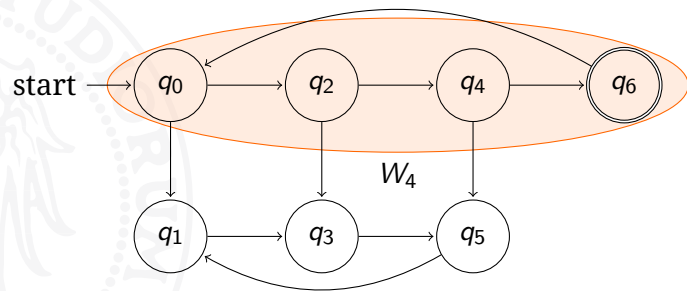
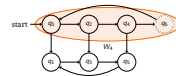


concluding the proof

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concluding the proof

In the process of calculating W_{i+1} , whenever we add a state q to W_i , there must be at least one action $\sigma \in \Sigma_c$ such that $\delta(q, \sigma) \subseteq W_i$.

So we define the controller at q as $C(q) = \sigma$.

When the process terminates, the controller is synthesized for all the winning states. \square

It can be seen that if the process fails, that is $q_0 \notin W$, then for every controller command there is a possibly bad consequence that will put the system outside F , and no controller, even an infinite state one, can prevent this.

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└ Conclusions

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the non determinism, the environment, is playing against us

Timed automata are automata equipped with clocks whose values grow continuously.

Let \mathcal{T} denote \mathbb{R}^+ and let $X = \mathcal{T}^d$ (the clock space).

The elements of X are $x = (x_1, \dots, x_d)$ and the d-dimensional unit vector is $\mathbf{1} = (1, \dots, 1)$

Definition 7 (Reset functions)

Let $F(X)$ denote the class of functions $f : X \mapsto X$ that can be written in the form $f(x_1, \dots, x_d) = (f_1, \dots, f_d)$ where each f_i is either x_i or 0.

The clocks interact with the transitions by participating in pre-conditions (guards) for certain transitions and they are possibly reset when some transitions are taken.

Since X is infinite and non-countable, we need a language to express certain subsets of X as well as operations on these subsets.

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Definition 8 (*k polyhedral sets*)

Let k be a positive integer constant. We associate with k three subsets of 2^X :

- ▶ \mathcal{H}_k : the set of half-spaces consisting of all sets having one of the following forms

- ▶ X
- ▶ \emptyset
- ▶ $\{x \in X : x_i \# c\}$
- ▶ $\{x \in X : x_i - x_j \# c\}$

for some $\# \in \{<, \leq, >, \geq\}$ and $c \in \{0, \dots, k\}$

- ▶ \mathcal{H}_k^\cap : the set of convex sets consisting of intersections of elements of \mathcal{H}_k
- ▶ \mathcal{H}_k^* : the set of k -polyhedral sets containing all sets obtained from \mathcal{H}_k via union intersection and complementation

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- ▶ \mathcal{H}_k^\cap : the set of convex sets consisting of intersections of elements of \mathcal{H}_k
- ▶ \mathcal{H}_k^* : the set of k -polyhedral sets containing all sets obtained from \mathcal{H}_k via union intersection and complementation

equals hash

For every k , \mathcal{H}_k^* has a finite number of elements, each of which can be written as a finite union of convex sets.

They are usually called *regions*

Definition 9 (Timed Automata)

A *timed automaton* is a tuple $\mathcal{T} = (Q, X, \Sigma, I, R, q_0)$ consisting of:

- ▶ Q a finite set of discrete states
- ▶ X a clock domain $X = (\mathbb{R}^+)^d$ for some $d > 0$
- ▶ $\Sigma = \Sigma_c \cup \{e\}$ an input alphabet (including a single environment action e)
- ▶ $I : Q \mapsto \mathcal{H}_k^\cap$ as the state invariant function
- ▶ $R \subseteq Q \times \Sigma \times \mathcal{H}_k^\cap \times F(X) \times Q$ is a set of transition relations each of the form $\langle q, \sigma, g, f, q' \rangle$ where:
 - ▶ q, q' in Q are states
 - ▶ $\sigma \in \Sigma$ is a command
 - ▶ $g \in \mathcal{H}_k^\cap$ is a guard condition
 - ▶ $f \in F(X)$ is a reset function

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A *configuration* of \mathcal{T} is a pair $(q, x) \in Q \times X$ denoting a discrete state and the values of the clocks.

Without loss of generality, we assume that for every $q \in Q$ and for every $x \in X$ there exists $t \in T$ such that $x + \mathbf{1}t \notin I_q$.

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A configuration of \mathcal{T} is a pair $(q, x) \in Q \times X$ denoting a discrete state and the values of the clocks.

Without loss of generality, we assume that for every $q \in Q$ and for every $x \in X$ there exists $t \in T$ such that $x + \mathbf{1}t \notin I_q$.

That is, the automaton cannot stay in any of its discrete states forever.

$x + \mathbf{1}t = (x_1, \dots, x_n) + (1, \dots, 1)t = (x_1 + t, \dots, x_n + t)$ The time has the same pace in all clocks

Definition 10 (Steps and Trajectories)

A step of \mathcal{T} is a pair of configurations $((q, x), (q', x'))$ such that either:

- ▶ $q = q'$ and for some $t \in T$, $x' = x + \mathbf{1}t$, $x \in l_q$ and $x' \in l_q$. In this case we say that (q', x') is a t -successor of (q, x) and that $((q, x), (q', x'))$ is a t -step.
- ▶ There is some $r = \langle q, \sigma, g, f, q' \rangle \in R$ such that $x \in g$ and $x' = f(x)$. In this case we say that (q', x') is a σ -successor of (q, x) and that $((q, x), (q', x'))$ is a σ -step

A trajectory of \mathcal{T} is a sequence $\beta = (q[0], x[0]), (q[1], x[1]), \dots$ of configurations such that for every i , $((q[i], x[i]), (q[i+1], x[i+1]))$ is a step.

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σ -steps includes the environment steps



We denote the set of all trajectories that \mathcal{T} can generate by $L(\mathcal{T})$.

Given a trajectory β we can define $Vis(\beta)$ and $Inf(\beta)$ as in the discrete case by referring to the projection of β on Q and use $L(\mathcal{T}, \Omega)$ to denote acceptable trajectories as in the discrete case.

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Definition 11 (Real time Controller)

A simple real time controller is a function $C : Q \times X \mapsto \Sigma_c \cup \perp$

We denote by $\Sigma_c^\perp = \Sigma_c \cup \perp$ the range of controller commands.

We also require that the controller is k -polyhedral, i.e., for every $\sigma \in \Sigma_c^\perp$, $C^{-1}(\sigma)$ is a k -polyhedral set.

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└ Real Time Controllers

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According to this function the controller chooses at any configuration (q, x) whether to issue some enabled transition σ or to do nothing and let time go by.

\perp equals bot

$C^{-1}(\sigma)$ means that the domain of C has to be a polyhedral set. We will see later that this condition is required in the proof.

Definition 12 (Controlled Trajectories)

Given a simple controller C , a pair $((q, x), (q', x'))$ of configurations is a C -step if it is either:

- ▶ an e – step
- ▶ a σ – step such that $C(q, x) = \sigma \in \Sigma_c$
- ▶ a t – step for some $t \in T$ such that for every t' , $t' \in [0, t)$, $C(q, x + \mathbf{1}t') = \perp$

A C -trajectory is a trajectory consisting of C -steps. We denote the set of C -trajectories of \mathcal{T} by $L_C(\mathcal{T})$.

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Definition 12 (Controlled Trajectories)

Given a simple controller C , a pair $((q, x), (q', x'))$ of configurations is a C -step if it is either:

- ▶ an e – step
- ▶ a σ – step such that $C(q, x) = \sigma \in \Sigma_c$
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A C -trajectory is a trajectory consisting of C -steps. We denote the set of C -trajectories of \mathcal{T} by $L_C(\mathcal{T})$.

Definition 13 (Real time Controller Synthesis)

Given a timed automaton \mathcal{T} and an acceptance condition Ω , the problem **RT-Synth**(\mathcal{T}, Ω) is: Construct a real-time controller C such that $L_C(\mathcal{T}) \subseteq L(\mathcal{T}, \Omega)$

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Definition 14 ($(t, \sigma) - \text{successor}$)

For $t \in T$ and $\sigma \in \Sigma$, the configuration (q', x') is defined to be a $(t, \sigma) - \text{successor}$ of the configuration (q, x) if there exists an intermediate configuration (\hat{q}, \hat{x}) such that (\hat{q}, \hat{x}) is a $t - \text{successor}$ of (q, x) and (q', x') is a $\sigma - \text{successor}$ of (\hat{q}, \hat{x}) .

Then we define a function $\delta : (Q \times X) \times (T \times \Sigma_c^\perp) \mapsto 2^{Q \times X}$ where $\delta((q, x), (t, \sigma))$ stands for all the possible consequences of the controller attempting to issue the command $\sigma \in \Sigma_c^\perp$ after waiting t time units starting at configuration (q, x)

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In order to tackle the real time controller synthesis problem we introduce the following definitions:

Note that this covers the case of (q', x') being simply a $\sigma - \text{successor}$ of (q, x) by viewing it as a $(0, \sigma) - \text{successor}$ of (q, x) .

Definition 15 (Extended Transition Function)

For every $t \in T$ and $\sigma \in \Sigma_c$, the set $\delta((q, x), (t, \sigma))$ consists of all the configurations (q', x') such that:

- ▶ (q', x') is a (t, σ) – successor of (q, x)
- ▶ (q', x') is a (t, e) – successor of (q, x) for some $t' \in [0, t]$

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- ▶ (q', x') is a (t, σ) – successor of (q, x)

- ▶ (q', x') is a (t, θ) -successor of (q, x) for some $t' \in [0, t]$

This definition covers successor configurations that are obtained in one of two possible ways:

some configurations result from the plant waiting patiently at state q for t time units, and then taking a σ -labeled transition according to the controller recommendation, the second possibility is of configurations obtained by taking an environment transition at any time $t' \leq t$

This is in fact the crucial new feature of real-time games - there are no turns and the adversary need not wait for the player's next move.

Definition 16 (Controllable Predecessors)

The controllable predecessors function $\pi : 2^Q \times 2^X \mapsto 2^Q \times 2^X$ is defined for every $K \subseteq Q \times X$ by

$$\pi(K) = \{(q, x) : \exists t \in T \exists \sigma \in \Sigma_c \delta((q, x), (t, \sigma)) \subseteq K\}$$

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As in the discrete case, we define a predecessor function that indicates the configurations from which the controller can force the automaton into a given set of configurations.

As in the discrete case, the sets of winning configurations can be characterized by a fixed point expressions similar to the discrete one over $2^Q \times 2^X$.

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Assume that $Q = \{q_0, \dots, q_m\}$. Clearly, any set of configurations can be written as $K = \{q_0\} \times P_0 \cup \dots \cup \{q_m\} \times P_m$ where P_0, \dots, P_m are subsets of X .

Thus the set K can be uniquely represented by a set tuple $\mathcal{H} = \langle P_0, \dots, P_m \rangle$ and we can view π as a transformation on set tuples.

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Thus the set K can be uniquely represented by a set tuple $\mathcal{H} = \langle P_0, \dots, P_m \rangle$ and we can view π as a transformation on set tuples.

Theorem 2 (Closure of \mathcal{H}_k^* under π)

if $\mathcal{H} = \langle P_0, \dots, P_m \rangle$ is k -polyhedral so is $\pi(\mathcal{H}) = \langle P_0, \dots, P_m \rangle$

Sketch of Proof

A set tuple \mathcal{H} is called k-polyhedral if each component P_0, \dots, P_m belongs to \mathcal{H}_k^* .

Wlog, we assume that for every $q \in Q, \sigma \in \Sigma_c$ there is at most one $r = \langle q, \sigma, g, f, q' \rangle \in R$. Let $\langle P'_0, \dots, P'_m \rangle = \pi(\langle P_0, \dots, P_m \rangle)$.

Then, for each $i = 0, \dots, m$ then set P'_i can be expressed as:

$$P'_i = \bigcup_{\langle q_i, \sigma, g, f, q_j \rangle \in R} \left\{ x : \exists t \in T \begin{pmatrix} x \in I_{q_i} \wedge x + \mathbf{1}t \in I_{q_i} \wedge \\ x + \mathbf{1}t \in g \wedge f(x + \mathbf{1}t) \in P_j \wedge (\forall t' \leq t) \\ \bigwedge_{\langle q_i, \sigma, g, f, q_k \rangle \in R} (x + \mathbf{1}t' \in g') \rightarrow f(x + \mathbf{1}t') \in P_k \end{pmatrix} \right\}$$

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A set tuple \mathcal{H} is called k-polyhedral if each component P_0, \dots, P_m belongs to \mathcal{H}_k^* .

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This ugly looking formula just states that $x \in P'_i$ if for some j, σ and t we can stay in q_i for t time units and then make a transition to some configuration in $\{q_j\} \times P_j$ while all other environment transitions that might be enabled between 0 and t will lead us to a configurations which are in some $\{p_k\} \times P_k$.



It can be verified that every P'_i can be written as a boolean combinations of sets of the form:

$$I_{q_i} \cap \{x : \exists t \in T \ x + \mathbf{1}t \in I_{q_i} \cap g \cap f^{-1}(P_j) \ \forall t' \leq t \ x + \mathbf{1}t' \in \overline{g'} \cup f'^{-1}(P_k)\}$$

for some guards g, g' and reset functions f, f' , where we use $f^{-1}(P) = \{x : f(x) \in P\}$.

Since timed reachability is distributive over union, i.e.,

$$\{x : \exists t \ x + \mathbf{1}t \in S_1 \cup S_2\} = \{x : \exists t \ x + \mathbf{1}t \in S_1\} \cup \{x : \exists t \ x + \mathbf{1}t \in S_2\}$$

it is sufficient to prove the claim assuming k -convex polyhedral sets.

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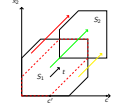
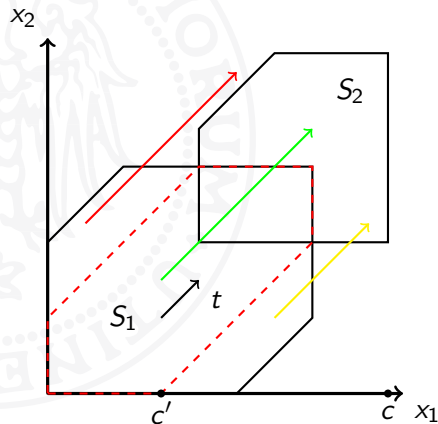
The domain of $f^{-1}(P) = \{x : f(x) \in P\}$ is \mathbb{R}^d

Real Time Case

So, what remains to show is that for any two k -convex sets S_1 and S_2 , the set $\pi_{t',t}(S_1, S_2)$, denoting all the points in S_1 from which we can reach S_2 without leaving S_1 , and defined as

$$\pi_{t',t}(S_1, S_2) = \{x : \exists t \ x + \mathbf{1}t \in S_2 \wedge \forall t' \leq t \ x + \mathbf{1}t' \in S_1\}$$

is also convex.





Theorem 3 (*Control Synthesis for Timed systems*)

Given a timed automaton \mathcal{T} and an acceptance condition

$$\{(F, \square), (F, \diamond), (F, \diamond\square), (F, \square\diamond), (\mathcal{F}, \mathcal{R}_n)\}$$

the problem **RT-Synth**(\mathcal{T}, Ω) is solvable

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Theorem 3 (Control Synthesis for Timed systems)

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Sketch of Proof

We have just shown that $2^Q \times \mathcal{H}_k^*$ is closed under π .

Any of the iterative processes for the fixed point equations (1) – (5) starts with an element of $2^Q \times \mathcal{H}_k^*$.

For example, the iteration for \diamond starts with $W_0 = Q \times F$.

Each iteration consists of applying Boolean set-theoretic operations and the predecessor operation, which implies that every W_i is also an element of $2^Q \times \mathcal{H}_k^*$ - a finite set.

Thus, by monotonicity, a fixed point is eventually reached.

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Thus, by monotonicity, a fixed point is eventually reached.

The strategy is extracted in a similar manner as in the discrete case. When ever a configuration (q, x) is added to W , it is due to one or more pairs of the form $([t_1, t_2], \sigma)$ indicating that within any $t, t_1 < t < t_2$ issuing σ after waiting t will lead to a winning position. Hence by letting $C(q, x) = \perp$ when $t_1 > 0$ and $C(q, x) = \sigma$ when $t_1 = 0$ we obtain a k -polyhedral controller.



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