UPPAAL TIGA User-manual

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Abstract. UPPAAL TIGA is a tool to perform automatic synthesis of controllers for timed systems. This document is the user-manual of UPPAAL TIGA but should be read jointly with the UPPAAL tutorial [BDL04].

1 Introduction

TIGA is part of the UPPAAL toolbox for verification of real-time systems which provides several verification tools such as: UPPAAL[1] [BDL04] (Real-time Verification), CORA[2] [BLR05] (Real-time Scheduling), TRON[3] [LMN05] (Online Real-time Testing), TIGA[4] (Timed Games), COVER[5] (Test-case Generation) and TIMES[6] (Schedulability Analysis).

TIGA is implementing a real on-the-fly algorithm to synthesize winning strategies [LS98,CDF$^+$05]. Since our first prototype in 2005 [CDF$^+$05], TIGA has improved of several orders of magnitude and is now ready to deal with industrial case studies. Moreover, all the features of UPPAAL are now supported allowing the user to have a rich specification language (integer variables, templates, array of variables, ...) to create its models.

Our input models are specified through a network of Timed Game Automata [MPS95] (TGA) where edges are marked either controllable or uncontrollable (see Fig.1). This defines a two players game with on one side the *controller* (mastering the controllable edges) and on the other side the *environment* (mastering the uncontrollable edges). Winning conditions of the game are specified through TCTL formulae. By now, TIGA supports both reachability and safety games. Given a model and winning conditions, TIGA is able to say if 'yes' or

[1] http://www.uppaal.com
[2] http://www.cs.auc.dk/~behrmann/cora/
[3] http://www.cs.aau.dk/~marius/tron/
[4] http://www.cs.aau.dk/~adavid/tiga/
[5] http://user.it.uu.se/~hessel/CoVer/
[6] http://www.timestool.com/

'no' there is a strategy for the controller to win the game and can provide the strategy as an output if asked (option `-t0`).

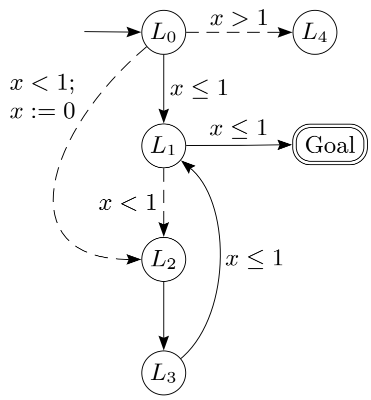


Fig. 1. An example of Timed Game Automaton.

The graphical user-interface has been augmented to deal with games models. Among other things, the simulator allows the user to play against the strategies synthesized by Tiga in order to give the understanding of what the strategy is.

This user-manual is covering the specificities of Tiga compared to the basic Uppaal tool. It is, then, strongly advised to start with the Uppaal tutorial [BDL04] to know about the basics of Uppaal before reading this document.

We first define our game model (section 2) and how to specify games (section 3), then we explain what are strategies, how to query for a controller and how to play with it and how to interpret results (section 4).

2 Timed Game Model

Our formalism is based on networks of Timed Game Automata (TGA) as described in [CDF$^+$05,MPS95]. Given a network of timed game automata we define two types of games, namely *reachability* and *safety* games. This section briefly recalls the definition of networks of timed game automata, reachability and safety games and the notion of strategy over a game. We suppose here that the reader is already familiar with timed automata as defined in [BDL04].

2.1 Timed Game Automata

Let C be a finite set of real-valued variables called clocks. We note $\mathcal{B}(C)$ the set of rectangular constraints φ generated by the grammar: $\varphi ::= x \sim k \mid \varphi \wedge \varphi$ where $k \in \mathbb{Z}$, $x \in C$ and $\sim \in \{<, \le, =, >, \ge\}$.

A *Timed Game Automaton (TGA)* is a timed automaton as defined in [BDL04] such that $\mathcal{A} = (L, l_0, C, \mathsf{Act}, E, I)$ with its set of actions $\mathsf{Act} = \mathsf{Act}_c \cup \mathsf{Act}_u$ partitioned into *controllable* (Act_c) and *uncontrollable* (Act_u) actions. L is the set of locations, $l_0 \in L$ the initial location, $E \in L \times \mathsf{Act} \times \mathcal{B}(C) \times 2^C \times L$ the transitions of the automaton and $I : L \rightarrow \mathcal{B}(C)$ the location invariants. Fig. 1. gives an example of a timed game automaton.

The semantics of a timed automaton $\mathcal{A} = (L, l_0, C, \mathsf{Act}, E, I)$ is defined as a labelled transition system $\langle S, s_0, \rightarrow\rangle$ where $S \subseteq L \times \mathbb{R}^C$ is the set of states, $s_0 = (l_0, \overline{0})$ is the initial state (where $\overline{0}$ is a clock valuation in which every clock value is 0) and $\rightarrow \subseteq S \times \{\mathbb{R}_{\geq 0} \cup \mathsf{Act}\} \times S$ is the transition relation such that:

- $(l, u) \xrightarrow{d} (l, u + d)$ if $\forall d' : 0 \leq d' \leq d \Rightarrow u + d' \models I(l)$
- $(l, u) \xrightarrow{a} (l', u')$ if $\exists e = (l, a, g, r, l') \in E$ s.t. $u \models g$ and $u' = [r \rightarrow 0]u$ and $u' \models I(l')$.

Timed game automata can be composed into networks over a common set of actions and clocks consisting of n timed game automata $\mathcal{A}_i = (L_i, l_0^i, C, \mathsf{Act}, E_i, I_i)$ where the set of actions over the network is given by $\overline{\mathsf{Act}} = \mathsf{Act} \times \mathsf{Act}$ and is such that $\overline{\mathsf{Act}} = \overline{\mathsf{Act}}_c \cup \overline{\mathsf{Act}}_u$ where $\overline{\mathsf{Act}}_c = \mathsf{Act}_c \times \{\mathsf{Act}_c \cup \{\tau\}\}$ and $\overline{\mathsf{Act}}_u = \overline{\mathsf{Act}} \setminus \overline{\mathsf{Act}}_c$. Note that this way of defining *controllable* and *uncontrollable* actions on the network gives precedence to the environment over the controller.

We also note a location of the system as a vector $\bar{l} = (l_1, \ldots, l_n)$. We extend the invariant functions such that $I(\bar{l}) = \wedge_{i \leq n} I_i(l_i)$. And we write $\bar{l}[l_i'/l_i]$ to denote the vector where the i^{th} element l_i of $\bar{l}$ is replaced by l_i'.

Semantics of a network of n timed game automata $\mathcal{A}_i = (L_i, l_0^i, C, \mathsf{Act}, E_i, I_i)$ is defined as a transition system $\langle S, s_0, \rightarrow\rangle$ where $S \subseteq (L_1 \times \cdots \times L_n) \times \mathbb{R}^C$ is the set of states, $s_0 = (\bar{l}_0, \overline{0})$ where $\bar{l}_0 = (l_0^1, \ldots, l_0^n)$, is the initial state and $\rightarrow \subseteq S \times \{\mathbb{R}_{\geq 0} \cup \overline{\mathsf{Act}}\} \times S$ is the transition relation such that:

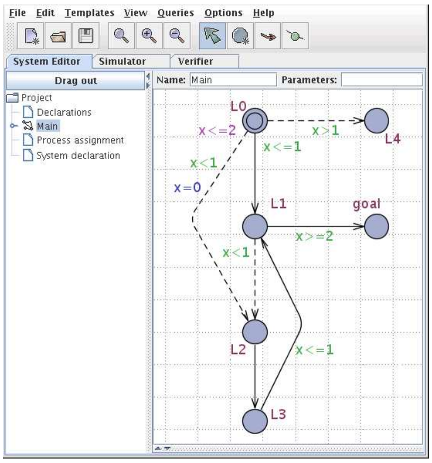
- $(\bar{l}, u) \xrightarrow{d} (\bar{l}, u + d)$ if $\forall d' : 0 \leq d' \leq d \Rightarrow u + d' \models I(\bar{l})$;
- $(\bar{l}, u) \xrightarrow{(a,\tau)} (\bar{l}', u')$ if $l \xrightarrow{a,g,r} l'$ s.t. $u \models g$ and $u' = [r \rightarrow 0]u$ and $u' \models I(\bar{l})$;
- $(\bar{l}, u) \xrightarrow{(a_i,a_j)} (\bar{l}'[l_i/l_i', l_j/l_j'], u')$ if $l_i \xrightarrow{a_i!,g_i,r_i} l_i'$ and $l_j \xrightarrow{a_j?,g_j,r_j} l_j'$ s.t. $u \models g_i \wedge g_j$ and $u' = [r_i \cup r_j \rightarrow 0]u$ and $u' \models I(\overline{l'})$.

2.2 The Modelling Language

Defining a timed game automata is achieved through a superset of the Uppaal modelling language. The only addition to the original language are the possibility to define "*uncontrollable*" transitions. Either through the graphical user interface (see Fig. 2, on the left) using the edge interface, or through the `ta` language using the "`-u->`" keyword (see Fig. 2, on the right). Note that transitions are assumed to be "*controllable*" by default and that priorities on transitions are simply ignored when synthesizing strategies.

3 Specifying Games

A game is given by a network of timed game automata $(\mathcal{A} = (\mathcal{A}_i)_{i>0})$ specifying the rules of the game and a formula (φ) specifying winning conditions defining the set of states that should be reached/avoided in order to win/lose the game.




```
process Main() {
clock x;
state L0 {x<=2}, L1, L2, L3, L4, goal;
init L0;
trans
  L0 -> L1 {guard x<=1;},
  L0 -u-> L2 {guard x<1;assign x=0;},
  L0 -u-> L4 {guard x>1;},
  L1 -> goal {guard x>=2;},
  L1 -u-> L2 {guard x<1;},
  L2 -> L3 { },
  L3 -> L1 {guard x<=1;};
}
system Main;
```

Fig. 2. TIGA GUI and XTGA syntax examples

3.1 Winning Games

Winning a game can only be achieved if the last transition leading to the goal state is controllable. For example, the automaton on Fig. 3.(a) is winning, on the contrary the automaton on the Fig. 3.(b) is losing. Intuitively this is because the opponent can decide to stay in the initial state forever without taking the transition leading to the goal state and let the controller with no other choice but its own.

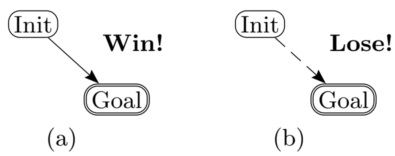


Fig. 3. Basic Examples of Winning (a) and Losing (b) Timed Game Automata.

The use of invariants might force the opponent to act, this can be simulated through an implicit controllable edge added when the upper limit of the invariant is reached. We will call this implicit extra transition a *forced transition*.

For example, the automaton on Fig. 4.(a) shows the original model, the automaton on Fig. 4.(b) makes the forced transition explicit making it clear why the model is winning[7]. Finally, the automaton on Fig. 4.(c) cannot be added a forced transition because there is already a possible controllable behavior when the automaton hit the invariant therefore this model is declared as losing.

[7] Note that forced transitions are always controllable.

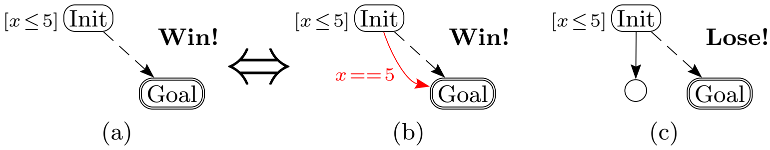


Fig. 4. Basic examples of forced transition: winning model (a), equivalent model with the implicit transition made explicit (b) and a losing model (c).

Finally, when dealing with synchronization and invariants some apparently strange behaviors might occurs. Indeed forced transitions might appear in components and be synchronized with others. The rule being to locally add forced transitions to each component and then to compose them all together. On Fig. 5.(a) we can see the original model of two synchronized automata, on Fig. 5.(b) the forced transition made explicit and finally on Fig. 5.(c) the full composition of the model (with the explicit forced transition).

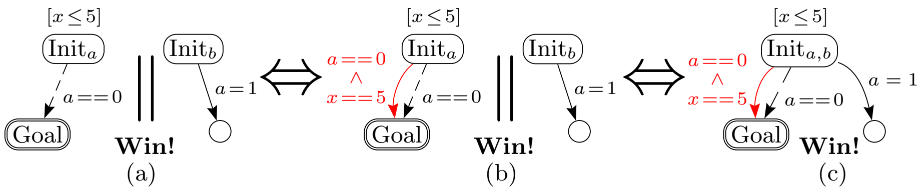


Fig. 5. Example of synchronisation with forced transitions: original model (a), forced transition made explicit (b), complete product with forced transition made explicit.

3.2 Winning/Losing Conditions

Specifying the game still requires to define what are the *winning conditions*. This is done through a slightly modified version of the UPPAAL query language. Given a timed game automaton $\mathcal{A}$, a set of goal states (`win`) and/or a set of bad states (`lose`), both defined by classical UPPAAL state formulae, four types of winning conditions can be issued. For all of them, the game is to find a controllable strategy f such that $\mathcal{A}$ supervised by f ensures that the controller:

- **Pure Reachability**:
  "**must** reach `win`"

```
control: A<> win
```

- **Strict Reachability with Avoidance** (Until):
  "**must** reach `win` and **must** avoid `lose`"

```
control: A[ not(lose) U win ]
```

– **Weak Reachability with Avoidance** (WeakUntil):
"**should** reach `win` and **must** avoid `lose`"

```
control: A[ not(lose) W win ]
```

– **Pure Safety**:
"**must** avoid `lose`"

```
control: A[] not(lose)
```

Note : Formulae not prefixed by "`control:`" are solved as in usual Uppaal. Also, the operators `A[p U q]` and `A[p W q]` are Tiga specific and are not supported by Uppaal.

Examples:

– `control: A<> Main.goal`
– `control: A[] not Main.L4`
– `control: A[ not Main.L4 W Main.goal ]`
– `control: A[ Main.x<2 U Main.goal ]`
– `control: A[ not(Main.goal and Main.x>2) U (Main.goal) ]`

3.3 Partially Cooperative Games

Partially cooperative games are defined by the fact that there are no winning strategy but reaching a maximal partition with winning strategy can be done with some help from your opponent. Once inside the maximal partition, you can enforce some condition whatever decide the oponnent. On Fig. 6, the maximal partition is the gray part and in order to reach it the controller has to rely on the environment to do some moves in his favor.

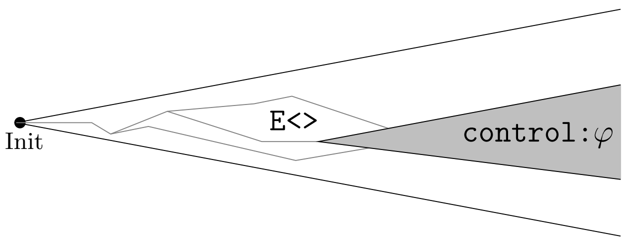


Fig. 6. Representation of `E<>control:`φ.

The syntax of this formula is given by:

– **Partial Cooperation**:
"**must** satisfy φ with the **least help** from the environment"

```
E<> control: φ
```

4 Strategy Synthesis

A *(controllable) strategy* is a function $f : L \times \mathbb{R}^C_{\geq 0} \rightarrow \mathsf{Act}_c \cup \{\lambda\}$ that constantly gives information as to what the controller should do during the course of the game. In a given situation, the strategy could suggest the controller to either "do a particular controllable action" or "do nothing at this point in time (λ)". A strategy is said to be a *winning strategy* if the controller supervised by the strategy always win the game whatever actions are chosen by the environment.

4.1 Existence of a Strategy

By default, TIGA first check whether there is or not a winning strategy for the timed game given a winning condition. On the example given Fig. 7, a winning strategy can be extracted for all the specified winning conditions except for the fifth one. Note that it is always better to start asking for existence because the process of strategy extraction is quite demanding and it would be useless to run such computation when the strategy can not be found.

```
#shell> verifytga concur05-1.{xml,q}
Options for the verification:
  Generating no trace
  Search order is breadth first
  Using conservative space optimisation
  Seed is 1156870160
  State space representation
    uses minimal constraint systems

Verifying property 1 at line 5
 -- Property is satisfied.

Verifying property 2 at line 11
 -- Property is satisfied.

Verifying property 3 at line 17
 -- Property is satisfied.

Verifying property 4 at line 23
 -- Property is satisfied.

Verifying property 5 at line 29
 -- Property is NOT satisfied.

Verifying property 6 at line 35
 -- Property is satisfied.
```

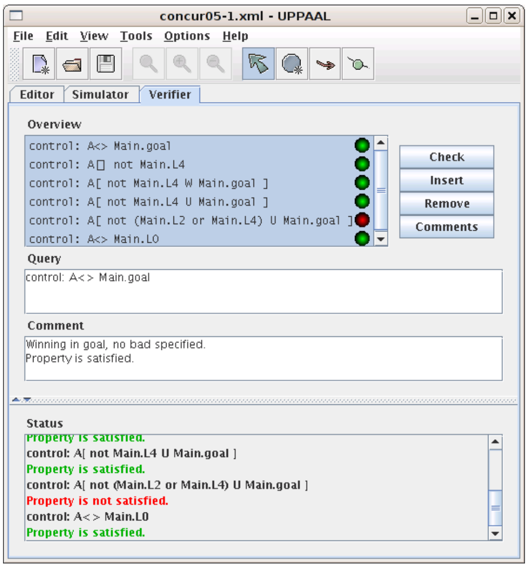


Fig. 7. TGA synthesis example and the TIGA GUI

4.2 Strategy Extraction (Option -t0)

The command line tool **verifytga** in the TIGA package can output a strategy for each given winning condition when used with the "-t0" option. If no such strategy exists, the dual strategy can then be computed by TIGA [8]. The extraction of a strategy can be triggered through a set of options specific to the TIGA engine:

```
-t <0|1|2>
    Generate diagnostic information on stderr.
      0: Some trace and output some strategy
-c <0|1>
    Print compact strategy
     0: Print one strategy for each discrete state
     1: Dump BCDD strategy for each transition
```

An example of such output is given for the `concur05-1.xml` example on Fig. 8 with the options "`-t0 -c0`".

```
State: ( Main.L0 )
While you are in (Main.x<1), wait.
When you are in (Main.x==1),
  take transition Main.L0->Main.L1 { x <= 1, tau, 1 }

State: ( Main.L1 )
While you are in (1<=Main.x && Main.x<2) || (Main.x<1), wait.
When you are in (2<=Main.x),
  take transition Main.L1->Main.goal { x >= 2, tau, 1 }

State: ( Main.L2 )
When you are in (Main.x<=1),
  take transition Main.L2->Main.L3 { 1, tau, 1 }

State: ( Main.L3 )
When you are in (Main.x==1),
  take transition Main.L3->Main.L1 { x <= 1, tau, 1 }
While you are in (Main.x<1), wait.
```

Fig. 8. Strategy Synthesized for `concur05-1.xml` for "`control: A<> Main.goal`".

4.3 Time Optimal Strategies

One may want not 'any strategy' but the most time efficient TIGA can find.

- **Time Optimality**:
  "**must** reach `win` **within less than u-g** time units and **must** avoid `lose`"

  `control_t*(u,g): A[ not(lose) U win ]`

[8] We plan to add an option "`-d`" (dual) to compute automatically the dual strategy.

Fig. 9 shows an example of use of `control_t*(u,g)`, where only the winning paths that can reach the winning location within $u-g$ are accepted thus allowing to forge a winning strategy based on this new winning conditions. Please note that the strategy that you play in the simulator has all its states constrained by $u-g$.

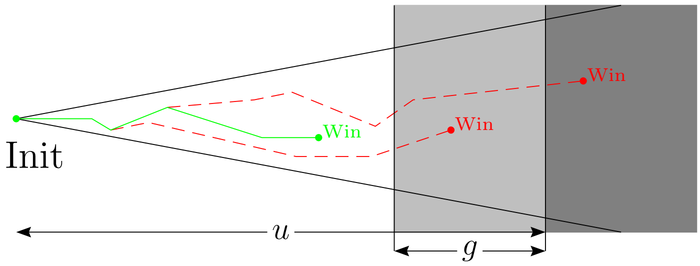


Fig. 9. Using the `control_t*(u,g):A[p U q]` expression.

Provided that TIGA stop on some winning-strategy for our property, we can give an always terminating approximation algorithm to refine the first winning strategy. Indeed, start with u being the minimum time needed to reach the winning state on the strategy outputted by TIGA and with $g=0$. Then, increase g until you reach a g' such that g' gives a winning strategy and $g'+1$ does not or do not terminate. This will provide you with the best strategy TIGA can give you (if not the optimal one).

Moreover, the u and g expression can be made more complex than constants. Indeed, it accepts the full C-like UPPAAL syntax with the limitations that u is evaluated once at the beginning so it should not depend on the current state or contain clock constraints, and g is evaluated on the current state but must be side-effect free, which is no clock constraints here as well. An adequate usage of the function `time2goal()` (quantifying the time left before reaching any goal state) can help a lot when searching for an optimal strategy. The formula would be: `control_t*(u,time2goal())`. Where `u` being the result of a non constrained search for strategy performed before. The `time2goal()` part will help here to prune a lot of non-optimal behavior and will help to reach time optimality.

4.4 Concrete Game Simulator

A new feature since UPPAAL TIGA 0.11 is the concrete simulator. Up to 0.10, the simulator was a symbolic one, you can now simulate your system based on concrete trace that you choose or that you can randomely fire throught the "Random" button.

Concrete simulator help you to select a transition to fire and then *at what time* it will be fired. The "*transition selection*" area is a clickable area where vertical axis displays the active transtion at this location and horizontal axis displays the time at which the transition will be fired. By clicking in a valid zone

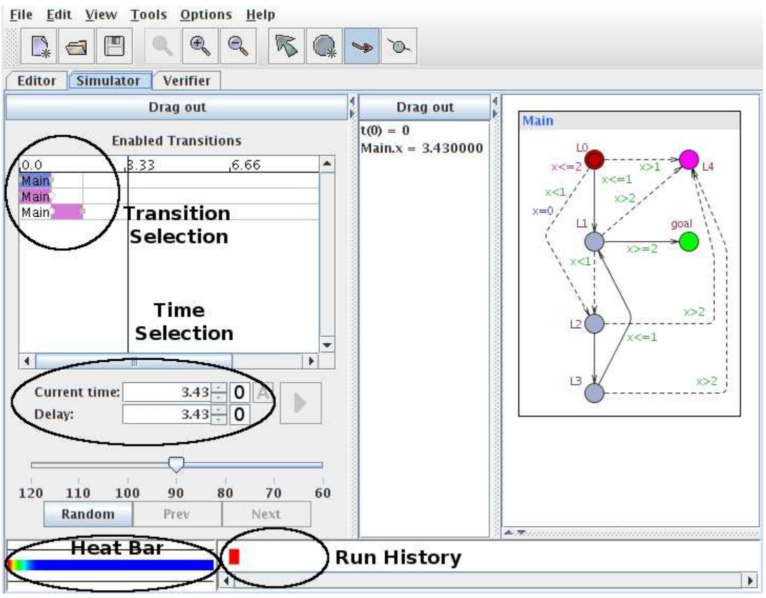


Fig. 10. TIGA concrete simulator with highlights on Transition selection, Time selection, Run History and Heat bar.

within this area make you select a precise transition and time for this transition. The time selected is displayed in the "*Time Selection*" area.

Two new graphical elements are also appearing in the new concrete simulator. One is the "*Run History*" area which allow a quick navigation in the history of the run that you explore. The gray part of an history item visualize the time elapsed within this state. Finally, the other element is the "*Heat Bar*" allowing to visualize the activity (rate of actions taken over the time). More blue it is, colder you are by waiting a lot in states. More red it is, hotter you are by performing a lot of actions in short time.

The concrete simulator is extremely useful at debug time to understand why a winning condition cannot be met. Playing against the dual strategy allow to test intuitive strategies or to discover tactics used by the environment to defeat the controller.

5 Conclusion & Further Works

TIGA is already fully functional and provide a full support of all the UPPAAL features plus an extended query language to specify winning conditions. TIGA is able to detect strategy existence and to synthesize it at will. An interactive simulator also allow the user to try out the strategy of the controller or the strategy of the opponent. Moreover, several industrial case studies [DJLR07,CDL07,LC04] have been conducted with success.

In [DJLR07], the synthesis capability of the tool has been combined with Simulink and Real-Time Workshop to provide a complete tool chain for synthesis, simulation, and automatic generation of production code. This work has been performed in collaboration with the company Skov A/S specializing in climate control systems used for modern pig and poultry stables.

Tiga has also been use to check for simulation between timed automata and timed game automata [CDL07]. Given two timed automata, the tool can check if one simulates the other and similarly for timed game automata with applications for controller synthesis with partial observability. This technique has been applied to the compositional verification of the ZeroConf protocol [GVZ06].

Our tool is being used in the AMAES project[9], a French national project on '*Advanced Methods for Autonomous Embedded Systems*'. Tiga has been applied for controlling the autonomous robot Dala [LC04] in charge of taking pictures and transmitting them back to Earth during limited transmission windows. It is desirable in such control problems to optimize the moves to save power.

In the near future we plan to improve efficiency of the state-space exploration again and to look at partial observability and focus on more and more real-life problems.

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