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# TiPEX: a tool chain for Timed Property Enforcement during eXecution

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**Abstract.** The TiPEX tool implements the enforcement monitoring algorithms for timed properties proposed in [1]. Enforcement monitors are generated from timed automata specifying timed properties. Such monitors correct input sequences by adding extra delays between events. Moreover, TiPEX also provides modules to generate timed automata from patterns, compose them, and check the class of properties they belong to in order to optimize the monitors. This paper also presents the performance evaluation of TiPEX within some experimental setup.

## 1 Enforcement of Timed Properties

Runtime enforcement extends runtime verification [2] and refers to the theories, techniques, and tools aiming at ensuring the conformance of the executions of systems under scrutiny w.r.t. some desired property. As shown in Fig. 1, an enforcement monitor (EM) modifies an (untrustworthy) input sequence of events into an output sequence that complies with a property. To be as general as possible, we consider that the enforcement monitor is placed between an event emitter and an event receiver, which can be considered to be e.g., a program or the environment. In [1], we introduced runtime enforcement for timed properties modeled as timed automata. An extensive comparison between runtime enforcement of timed properties and related work is provided in [1].



Fig. 1: Usage of an enforcement monitor at runtime

### 1.1 (Deterministic) Timed Automata

A lot of ongoing research efforts are related to the verification of real-time systems by means of e.g., model-checking, testing, and runtime monitoring. Central to these techniques is the use of timed automata (TAs) [3] as a formalism to model requirements or systems. One of the most successful tools for the verification of real-time systems is UPPAAL [4,5]. UPPAAL is based on the theory of TAs and comes with a somewhat standard syntax format for the definition of TAs.

In this paper, we consider timed properties as languages that can be defined by deterministic TAs. We introduce TAs [3] via the example in Fig. 2.

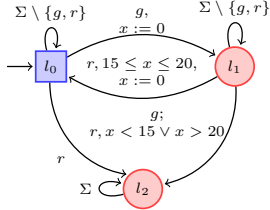


Fig. 2: A TA

The set of locations is  $\{l_0, l_1, l_2\}$ ,  $l_0$  is initial (incoming edge), and accepting (blue square). The alphabet of actions is  $\Sigma = \{r, g\}$ . A finite set of real-valued clocks is used to model time ( $\{x\}$ ). A transition between locations (e.g.,  $l_1$  to  $l_0$ ) consists of i) an action (e.g.,  $r$ ), ii) a guard specifying a clock constraint (e.g.,  $15 \leq x \leq 20$ ), and iii) a reset of some clocks (e.g.,  $x := 0$ ). This TA defines the requirement “Resource grants ( $g$ ) and releases ( $r$ ) should alternate, starting with a grant,

and every grant should be released within 15 to 20 time units (t.u.)”. Upon the first  $g$ , the TA moves from  $l_0$  to  $l_1$ , and resets  $x$ . From  $l_1$ , if  $r$  is received and  $15 \leq x \leq 20$ , then the TA moves to  $l_0$  and resets  $x$ , otherwise it moves to  $l_2$  (where it is stuck). The semantics of a TA can be defined by timed words recognized by the TA, i.e., sequences of timed events (pairs of actions and delays) reaching accepting locations.

## 1.2 General Principles of Timed Enforcement

Enforcement monitors proposed in [1] have the ability of *delaying events* to produce a correct output sequence. At an abstract level, an EM for a property  $\varphi$  can be seen as a function from timed words to timed words. An EM operates online and should thus satisfy some *physical-(time) constraints*: i) new events can only be appended to the tail of output words, and ii) any event should be input before being output. An EM should be *sound*: it should only output events that contribute to an output word in  $\varphi$ , and otherwise produce an empty output. An EM should be *transparent*: it should keep the order between events. Finally, an EM should be *optimal*: it should release events as soon as possible.

To ease their design, implementation, and correctness proofs, EMs are described at different levels of abstraction in [1]. An *enforcement algorithm* further concretises the description of an EM as an algorithmic implementation of an enforcement monitor. One of TiPEX’s modules implements the enforcement algorithms in Python (see Sec. 2).

*Runtime enforcement on an example.* We provide some intuition on the expected behavior of EMs via an example (see [1] for formal details): enforcing the property defined by the TA in Fig. 2. Let us consider the input sequence  $\sigma = (3, g) \cdot (10, r) \cdot (3, g) \cdot (5, g)$ , where the delay of each event indicates the time elapsed since the previous event or system initialization:  $g$  is received at  $t = 3$ ,  $r$  at  $t = 13$ , etc. Upon receiving the first  $g$ , the EM cannot output it because the event alone does not satisfy the requirement (and the EM does not know yet the next events). Upon receiving action  $r$ , then it can output action  $g$  followed by  $r$ , as it can choose appropriate delays for both actions while satisfying timing constraints. Hence, the output delay associated with  $g$  is 13 t.u. However, the EM cannot choose the same (input) delay for  $r$ , because the property would not be satisfied. Consequently, the EM chooses a delay of 15 t.u., which is i) the minimal delay satisfying the constraint, and ii) is greater than the corresponding delay in the input sequence. When the EM receives the second  $g$  at  $t = 16$ , it releases it as output. Since the next action observed at  $t = 21$  is not  $r$ , it becomes impossible for the EM to output a correct sequence. Hence, after  $t = 21$ , the output remains  $(13, g) \cdot (15, r)$ .

*Contributions and outline.* This paper provides an implementation and test harness of enforcement algorithms. The major improvements (over the initial implementation [1]) provided in this paper are as follows:

- We implemented synthesis of EM for any regular property (while the implementation in [1] supports only safety and co-safety properties) and provide complimentary details on the implementation of EM.<sup>4</sup>
- We implemented a test harness that generates and composes TA.
- We experiment optimized version of EM synthesis for safety and co-safety properties and show performance improvements through experiments.

The paper is organised as follows: Sec. 2 presents the architecture and functionalities of TiPEX, Sec. 3 discusses the evaluation results; and Sec. 4 draws conclusions.

## 2 Overview and Architecture of TIPEX

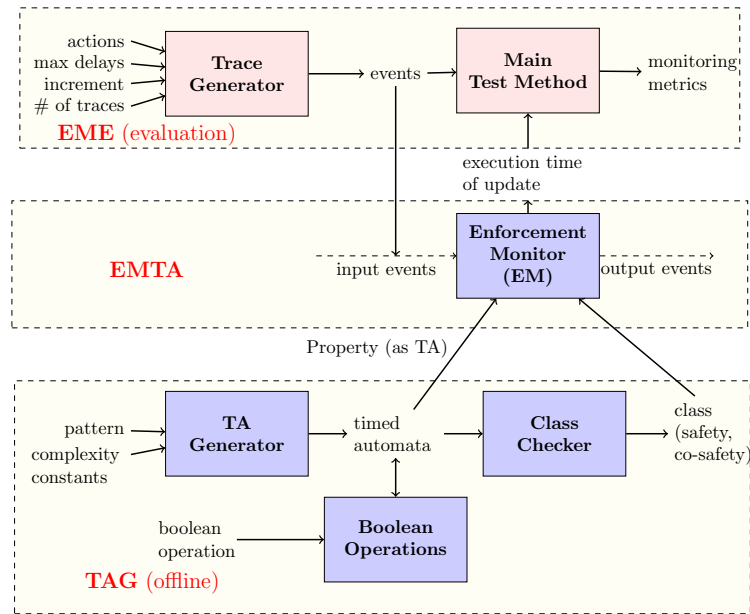


Fig. 3: Overview of TIPEX tool

TiPEX is a tool of 1,200 LLOC in Python and consists of three modules (see Fig. 3). Module *Enforcement Monitor from Timed Automata* (EMTA) consists in an implementation of the enforcement algorithms described in [1]. Module *Enforcement Monitor Evaluation* (EME) is a test harness for the performance of enforcement monitors, with functionalities such as a trace generator. Module *Timed Automata Generator* (TAG) provides functionalities such as generating and composing TAs (which can be also used in other contexts than enforcement monitoring). Module TAG provides a TA (defining the

<sup>4</sup> Regular properties are the ones that can be defined by TA. Safety (resp. co-safety) properties are the prefix-closed (resp. extension-closed) languages. See [1] for more details.

requirement) to module EMTA, and information such as the class to which the timed automaton belongs. The functionalities of this module are used offline (i.e., prior to monitoring). TAG manipulates TAs described in UPPAAL [5] model written in XML. TAG and EMTA make use of the UPPAAL pyuppaal and DBM libraries, respectively.<sup>5</sup>

## 2.1 Module EMTA

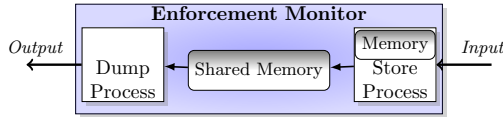


Fig. 4: Implementing an EM

Module EMTA is the core functionality. It implements enforcement monitors by two concurrently running processes called as *store* and *dump*, communicating via shared memory as shown in Fig. 4. The shared memory contains the corrected sequence that can be released as output. The memory is realized as a queue, shared by the processes *store* and *dump*, where process *store* adds events with corrected delays. Process *dump* reads events stored in the shared memory and releases them as output after the required amount of time. Process *store* also makes use of another internal memory (not shared with any other process), to store the events that cannot be yet corrected (to satisfy the property).

EMTA takes as input a TA and one trace. The most important part of module EMTA is the *store* process which computes optimal output delays for input events by exploring the TA. This computation relies on function Update. The *dump* process of monitors are algorithmically simple and lightweight from a computational point of view.

---

### Algorithm 1 Update( $\sigma_{mc}, q$ )

---

```

allPaths  $\leftarrow$  computeReach( $\sigma_{mc}, q$ )
accPaths  $\leftarrow$  getAccPaths(allPaths)
if accpaths = {} then
    return(ff,  $\sigma_{mc}$ )
else
     $\sigma'_{mc}$   $\leftarrow$  getOptimalWord(accPaths,  $\sigma_{mc}$ )
    return(tt,  $\sigma'_{mc}$ )
end if

```

---

Function Update (see Algo. 1) checks if an accepting state is reachable in the TA from the current state  $q$ , upon a delayed version of the sequence of events  $\sigma_{mc}$  provided as input. In case if an accepting state is reachable, then it computes optimal delays. It returns a timed word of same length as  $\sigma_{mc}$  and a Boolean indicating the result of this reachability analysis. Function computeReach computes all the reachable paths from the current state  $q$  upon events in  $\sigma_{mc}$ . These paths are computed using forward analysis, zone abstraction, and operations on zones such as the resetting of clocks and intersection of guards [4]. Function getAccPaths takes all the paths returned by computeReach and returns a subset of them that end in an accepting location. A path is accepting if the location in its last state belongs to the set of accepting locations of the input TA. Function getOptimalWord takes all the accepting paths and a sequence  $\sigma_{mc}$  and computes optimal delays for events in  $\sigma_{mc}$ . This function first computes an optimal delay for each event, for all accepting paths. Finally, it picks a path among the set of accepting paths whose sum of delays is minimal, and returns it as the result. If the set of accepting paths is empty, then function Update returns **ff** and  $\sigma_{mc}$ . Otherwise, it returns **tt** and the optimal word computed using getOptimalWord.

<sup>5</sup> The UPPAAL libraries are provided by Aalborg Univ. at <http://people.cs.aau.dk/~adavid/python/>.

We now briefly describe the implementation of process *store*. It first parses an input model and performs the necessary initialization. As seen in Sec. 1, an EM may not output events immediately after they are received. Consequently, process *store* also uses an internal memory ( $\sigma_{mc}$ ) to store events. Each event  $(t, a)$  of the trace in order is appended to the internal memory, and function Update is invoked, with the current state information and the events in the internal memory ( $\sigma_{mc} \cdot (t, a)$ ). If function Update returns **ff**, then the monitor waits for the next event. If function Update returns **tt** and  $\sigma'_{mc}$ ,  $\sigma'_{mc}$  is added to the shared memory (since it contributes to a correct sequence and can be released as output). Before continuing with the next event, the process *store* updates the current state information, and internal memory.

## 2.2 Module EME

Module EME is a test harness of 150 LLOC to: i) validate through experiments the architecture and feasibility of enforcement monitoring, and ii) measure and analyze the performance of function Update of process *store*. The architecture of module EME is depicted in Fig. 3.

Module *Trace Generator* takes as input the alphabet of actions, the range of possible delays between actions, the desired number of traces, and the increment in length per trace. For example, if the increment in length per trace is 100, then the first trace is of length 100 and the second trace of length 200 and so on. For each event, module Trace Generator picks an action (from the set of possible actions), and a random delay (from the set of possible delays) using methods from the Python random module.

Module *Main Test Method* uses module *Trace Generator* to obtain a set of input traces to test module EM. It sends each sequence to the EM, and keeps track of the result returned by the EM for each trace. Module EM takes as input a property (defined as a TA) and one trace, and returns the total execution time of function Update to process the given input trace. In process *store*, the execution time of Update is measured. Process *store* keeps track of the total time of Update, by adding the time measured after each event to the total time, which is returned as a result of invoking process *store*.

## 2.3 Module TAG

*Motivations.* TAG facilitates the translation of informal requirements into formal models by automating the process of generating TAs. Using TAG, one can generate several (meaningful) TAs of some pattern, with varying complexity which can be used as input models for testing EMs. Note, TiPEX can be also used with manually generated TAs.

Consider the requirement “*There cannot be more than 100 requests in every 10 t.u.*”. The TA defining this requirement has more than 100 locations and associated transitions, and manually modeling it (for example using a graphical editor) is tedious and time consuming. Using TAG, the corresponding TA can be obtained almost instantly, just by providing some pattern, time constraint, and actions. TAG also implements the algorithms for the composition of TAs using Boolean operations (defined in [3,1]).

Figure 3 presents the architecture of TAG. Note that the modules inside TAG are loosely coupled: each module can be used independently, and can be easily extended. In the following, we detail each sub-module.

**Generating Basic Timed Automata.** Module *TA Generator* generates TAs based on some parameters: the *pattern* specifying the form of the TA among those defined in [6];

some *complexity constant* specifying the number of transitions and locations, the maximal constant in guards, and some action alphabets.

*Supported patterns.* Currently, the tool supports generation of automata for the requirements of the following forms (see [6]):

- *Absence:* In every consecutive time interval of *TIME\_CONSTRAINT\_CONSTANT* t.u., there are no more than *COMPLEXITY\_CONSTANT* actions from *ACTION\_SET1*.
- *Precedence with a delay:* A sequence of *COMPLEXITY\_CONSTANT* actions from *ACTION\_SET1* enable actions belonging to *ACTION\_SET2* after a delay of at least *TIME\_CONSTRAINT\_CONSTANT* t.u.
- *Timed bounded existence:* There should be *COMPLEXITY\_CONSTANT* consecutive actions belonging to *ACTION\_SET1* which should be immediately followed by an action from *ACTION\_SET2* within *TIME\_CONSTRAINT\_CONSTANT* time units.

**Composing Timed Automata.** Module *Boolean Operations* builds a TA by composing two input TAs using Boolean operations (see Fig. 3). All boolean operations are supported. In particular, operations *Union* and *Intersection* are performed by building the synchronous product of the two input TAs, where, in the resulting automaton, each location is a pair, and the guards are the conjunctions of the guards in the input TA. For operation *Union*, accepting locations are the pairs where at least one location is accepting in the input TAs, and for *Intersection* operation, both the locations in the corresponding input TAs are accepting. See [3] for formal details.

**Identifying the Class of a Timed Automaton.** Module *Class Checker* takes as input a TA and determines the class of the property it defines:<sup>6</sup> *safety* (resp. *co-safety*) if the constraints of a safety (resp. co-safety) TA are satisfied, and “*other*” otherwise. With the class information, one can use simplified enforcement algorithms (see Sec. 3).

### 3 Performance Evaluation

We focus on the performance evaluation of function *Update*, the most computationally intensive step as discussed in Sec. 2.1. Experiments were conducted on an Intel Core i7-2720QM at 2.20GHz CPU, with 4 GB RAM, and running on Ubuntu 12.04 LTS. The reported numbers are mean values over 10 runs and are represented in seconds. To compute the average values, 10 runs turned out to be sufficient because, for all metrics, with 95 % confidence, the measurement error was less than 1 %.

The considered properties follow different patterns [6], and belong to different classes. They are recognized by one-clock TA since this is a current limitation of our implementation. We however expect the trends exposed in the following to be similar when the complexity of automata grows.

- Property  $\varphi_s$  is a safety property expressing that “*There should be a delay of at least 5 t.u. between any two request actions*”.
- Property  $\varphi_{cs}$  is a co-safety property expressing that “*A request should be immediately followed by a grant, and there should be a delay of at least 6 t.u between them*”.

<sup>6</sup> A TA defining a safety (resp. a co-safety) property is said to be a safety (resp. a co-safety) TA. In a safety (resp. co-safety) TA, transitions are not allowed from non-accepting (resp. accepting) to accepting (resp. non-accepting) locations. For formal details, see [1].

- Property  $\varphi_{re}$  is a regular property, but neither a safety nor a co-safety property, and expresses that “*Resource grant and release should alternate. After a grant, a request should occur between 15 to 20 t.u.*”.

Table 1: Performance analysis.

$\varphi_s$		$\varphi_{re}$		$\varphi_{cs}$	
$ tr $	$t\_Update$ (sec)	$ tr $	$t\_Update$ (sec)	$ tr $	$t\_Update$ (sec)
10,000	9.895	10,000	16.354	100	3.402
20,000	20.323	20,000	32.323	200	13.583
30,000	29.722	30,000	48.902	300	29.846
40,000	40.007	40,000	65.908	400	53.192
50,000	49.869	50,000	83.545	500	82.342
60,000	59.713	60,000	99.088	600	120.931
70,000	72.494	70,000	117.852	700	169.233

*Results and analysis.* Results of the performance analysis for  $\varphi_s$ ,  $\varphi_{cs}$ , and  $\varphi_{re}$  are reported in Table 1. Entry  $|tr|$  (resp.  $t\_Update$ ) indicates the length of the considered traces (resp. the total execution time of function Update).

As expected, for the safety property ( $\varphi_s$ ), we can observe that  $t\_Update$  increases linearly with the length of the input trace. Moreover, the time taken per call to Update (which is

$t\_Update/|tr|$ ) does not depend on the length of the trace. This behavior is as expected for a safety property: function Update is always called with only one event which is read as input (the internal buffer  $\sigma_{mc}$  remains empty). Consequently, the state of the TA is updated after each event, and after receiving a new event, the possible transitions leading to a good state from the current state are explored.

For the co-safety property ( $\varphi_{cs}$ ), the considered input traces are generated in such a way that they can be corrected only upon the last event. Notice that  $t\_Update$  is now quadratic. For the considered input traces, this behavior is as expected for a co-safety property because for an input sequence of length  $|tr|$ , function Update is invoked  $|tr|$  times, starting with a sequence of length 1 that is incremented by 1 in each iteration.

For the regular property ( $\varphi_{re}$ ), the considered input traces are generated in such a way that it can be corrected every two events. Consequently, function Update is invoked with either one or two events. For the considered input traces,  $t\_Update$  is linear in  $|tr|$ , and thus the time taken per call to Update (which is  $t\_Update/|tr|$ ) does not depend on the length of the trace. For input traces of same length, the value of  $t\_Update$  is higher for  $\varphi_{re}$  than the value of  $t\_Update$  for  $\varphi_s$ . This stems from the fact that, for a safety property, function Update is invoked only with one event.

*Implementation of simplified algorithms for safety properties.* As explained in [1], for safety properties, the internal memory is never used, since the decision of whether to output an event or not has to be taken when receiving it. Thus, the functional definition can be simplified, and consequently the enforcement monitors and algorithm can be also simplified. The simplified algorithm is also implemented in TiPEX, and experiments were conducted using several safety properties (see [1] for details and evaluation results). From the results in [1], we can notice that for safety properties, using the simplified algorithm gives better performance. The time taken per call to Update reduces by around 0.2 milliseconds using the simplified algorithm.

*Remark 1.* More experimental results used to assess the influence of the size, class, and pattern of a property on the monitoring metrics are available in [1,7].

## 4 Summary and Discussion

TiPEX implements and assesses the enforcement monitoring algorithms for timed properties in [1]. It demonstrates the practical feasibility of our theoretical results.



TiPEX consists of 3 modules. Module EMTA consists of functionalities to synthesize enforcement monitors from a TA, and module EME is a test harness for monitors. Module TAG consists of features to automatically generate TAs from some input data such as the actions, pattern, and time constraint constant. To the best of our knowledge, there is no available tool to help formalizing real-time requirements. As shown in the examples, the input data required by TAG can be easily inferred from the informal description of a requirement. Moreover, TAG composes TAs using Boolean operations, and identifies the class of a given TA.

Assessing the performance of runtime enforcement monitors is crucial in a timed context as the time when an action happens influences satisfaction of the property. We also evaluated the performance of enforcement monitors for several properties, and considering very long input executions. As our experiments in Sec. 3 show, the computation time of the monitor upon the reception of an event is relatively low. For example, for safety properties, one can see that, on the used experimental setup, the computation time of function `Update` is below 1ms. Moreover, given some average computation time per event and a property, one can determine easily whether the computation time is negligible or not for an application domain in consideration. By taking guards with constraints using integers above 0.1s, one can see that the computation time can be negligible in some sense as the impact on the guard is below 1%, and makes the overhead of enforcement monitoring acceptable.

For co-safety and regular properties, the computation time of function `Update` depends on the property and the input trace. For example, for a co-safety property with a loop in a non-accepting location, the execution time of `Update` depends on the length of the minimal prefix of the input sequence allowing to reach an accepting state.

Finally, note that while the monitoring algorithm implemented in EME is used with traces, it is an online algorithm. To use TiPEX within a system for online runtime enforcement, one needs to define the implementation of the delaying of an action in the monitored system by, for instance, suspending the thread performing the delayed action.

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## A Demonstration of TiPEX

We illustrate the features of TiPEX discussed in the paper via some examples. All the source files with examples, prerequisites, and some documentation are available at:

```
http://srinivaspinisetty.github.io/Timed-Enforcement-Tools/
```

### A.1 Modules EMTA and EME

In the following subsections, we describe how to test the input-output behavior of an enforcement monitor, and how to collect performance data for a property.

**Testing the Behavior of an Enforcement Monitor** We present how the input-output behavior of enforcement monitors for some properties is tested. We consider three example properties (used in Sec. 3). We also provide the TAs defining these properties in UPPAAL format (.xml files) inside the source folder.

- **Example\_Safety.xml** defines a safety property expressing that a safety property expressing that “*There should be a delay of at least 5 t.u. between any two request actions*”.
- **Example\_CoSafety.xml** defines a co-safety property expressing that “*A request should be immediately followed by a grant, and there should be a delay of at least 7 t.u. between them*”.
- **Example\_Response.xml** defines a regular property, and expresses that “*Resource grant and release should alternate. After a grant, a request should occur between 15 to 20 t.u.*”. Note that this property is neither a safety nor a co-safety property.

To test the functionality, with these properties for some input traces, simply run the test script `testFunctionality.py` (available inside the source folder). For each property, the input trace provided and the output of the EM is printed on the console. On the console, we can observe that for each property, for the provided input, the output satisfies the property (soundness) and the other constraints (transparency, optimality).

**Collecting Performance Data** We explain via an example how the main test method is invoked via Python command line to collect performance data for a property (see Fig. 5). The steps are the following:

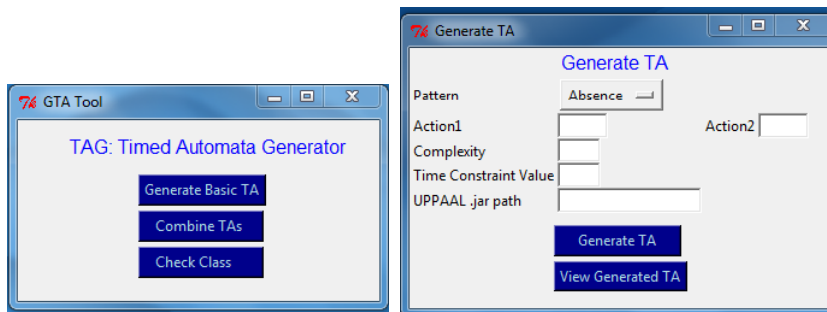
- Import the `MainTest` module.
- Specify the property by indicating its path. “`Example_Safety.xml`” is the property in this example, which is a UPPAAL model stored as “.xml”.
- Specify the accepting locations in the input TA. For instance, by typing “`accLoc=['S1', 'S2']`”, one specifies that the set of accepting locations in the input TA is  $\{S1, S2\}$ .
- Specify the possible actions. For instance by typing “`actions = ['a', 'r']`” one specifies that the set of actions is  $\{a, r\}$ .
- Define the range of possible delays.
- Invoke method `testStoreProcess` in module `MainTest`, providing the following arguments in order: property, accepting locations, actions, delays, # traces incr.

```

@srinivas:~/eclipseWork/EMTA+EME
srinivas@srinivas:~/eclipseWork/EMTA+EME$ python
Python 2.7.6 (default, Mar 22 2014, 22:59:38)
[GCC 4.8.2] on linux2
Type "help", "copyright", "credits" or "license()" for more information.
>>> import MainTest
>>> property="Example_Safety.xml"
>>> accLoc=["S1", "S2"]
>>> actions=['a','r']
>>> delays=[1,2,3,4,5]
>>> MainTest.testStoreProcess(property,accLoc,actions,delays,2,1000)
Test results..[(2000, 1.1357380628585816, 0.0005678690314292907), (1000, 0.508677339553833, 0.000508677339553833)]
>>>

```

Fig. 5: Collecting performance data.



(a) TAG GUI.

(b) Generate TA GUI.

Fig. 6: GUI.

“#traces” is the number of traces used for testing (3 in the example above), each trace varying in length, and “incr” is the increment in length per trace (1,000 in the example above). As shown in Fig. 5, a list of triples (trace length, total execution time of the Update function, average time per call of the Update function) is returned as the result.

## A.2 Module TAG

Module TAG has a basic GUI. The following lines demonstrate how to launch the GUI via Python command line.

- Browse to the folder containing the source code.
- Execute the script `GUI_TAG_Tool.py` entering the following line in the command prompt `python GUI_TAG_Tool.py`.
- A GUI will be launched (shown in Fig. 6a), using which the user can select to generate a basic TA, or to combine TAs, or to check the class of a TA.

We demonstrate how to use each feature via an example.

**Generating Basic Timed Automata** We present some TAs generated using module *TA Generator*. Clicking “Generate Basic TA” launches the GUI shown in Fig. 6b. To generate a TA defining the requirement “*In any time interval of 10 t.u., there cannot be 3 or more a actions*”, the values of the input parameters provided the tool are:

- *PATTERN* = absence,

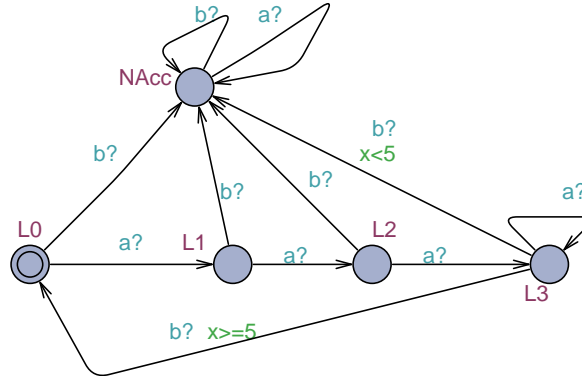


Fig. 7: Automaton belonging to the precedence pattern.

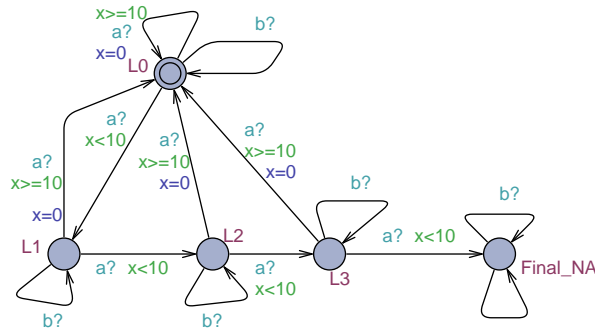


Fig. 8: Automaton belonging to the absence pattern.

- $COMPLEXITY\_CONSTANT = 3$ ,
- $TIME\_CONSTRAINT\_CONSTANT = 10$ ,
- $ACTION1 = a$ , and  $ACTION2 = b$ .

Figure 8 shows the representation in UPPAAL. In this TA, L0 is initial location,  $\{L0, L1, L2, L3\}$  is the set of accepting locations, and the only non-accepting location is Final\_NA. In L0, upon action a, if the value of clock  $x \geq 10$ , then the clock  $x$  is reset and the TA remains in the same location. We can see that the TA moves to a non-accepting (trap location) Final\_NA upon 3 a actions within 10 time units. To generate a TA defining the requirement “A sequence of 3 a actions enables action b after a delay of at least 5 t.u.”, the values of the input parameters provided to the tool are:

- $PATTERN = precedence$ ,
- $COMPLEXITY\_CONSTANT = 3$ ,
- $TIME\_CONSTRAINT\_CONSTANT = 5$ ,
- $ACTION1 = a$ , and  $ACTION2 = b$ .

Figure 7 shows its representation in UPPAAL tool. In this TA, L0 is the initial location,  $\{L0, L1, L2, L3\}$  is the set of accepting locations, and the only non-accepting location is NAcc. We can see that from locations L0, L1, and L2, if a b action occurs then the TA moves to the trap state, since 3 preceding a actions are missing.

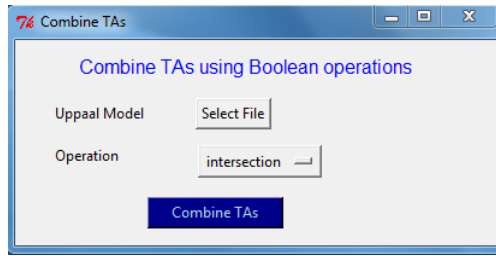


Fig. 9: Combine TA GUI.

**Composing Timed Automata** Clicking “Combine TAs” launches the GUI shown in Fig. 9. Clicking “Select File” button allows the user to select a input UPPAAL model. The input UPPAAL model (stored as .xml) selected by the user, should contain two input TAs (defined as two different templates). Note that in the input TAs, names of accepting locations should be prefixed by “Final”. The user should select an operation. The resulting TA will be written as another template in the UPPAAL model file given as input by the user.

Let us now see an example of the resulting TA obtained after combining two TAs using the *Boolean Operations* functionality. The two input TAs are shown in Fig. 10a and Fig. 10b. Figure 10c shows the resulting TA after combining the two input TAs using Union operation.

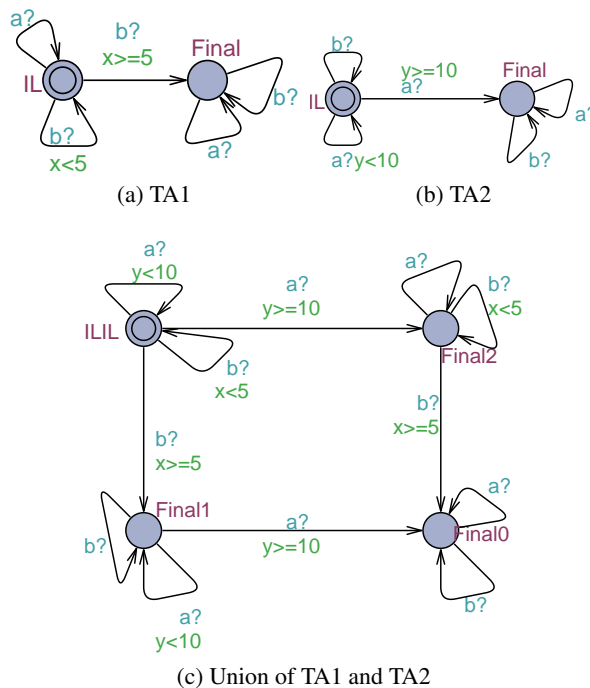


Fig. 10: Example: Combining TAs using Boolean operations.