Online Testing of Real-time Systems Using UPPAAL: Status and Future Work

Kim G. Larsen, Marius Mikucionis, and Brian Nielsen

Department of Computer Science, Aalborg University
Fredrik Bajers Vej 7B, 9220 Aalborg Øst, Denmark
{kgl,marius,bnielsen}@cs.auc.dk

Abstract. We present the development of T-UPPAAL — a new tool for online black-box testing of real-time embedded systems from non-deterministic timed automata specifications. It is based on a sound and complete randomized online testing algorithm and is implemented using symbolic state representation and manipulation techniques. We propose the notion of relativized timed input/output conformance as the formal implementation relation. A novelty of this relation and our testing algorithm is that they explicitly take environment assumptions into account, generate, execute and verify the result online using the UPPAAL on-the-fly model-checking tool engine.
This paper introduces the principles behind the tool, describes the present implementation status, and future work directions.

1 Introduction

The goal of testing is to gain confidence in a physical computer based system by means of executing it. More than one third of typical project resources is spent on testing embedded and real-time systems, but still it remains ad-hoc, based on heuristics, and error-prone. Therefore systematic, theoretically well-founded and effective automated real-time testing techniques is of great practical value.

1.1 Model Based Testing

Testing conceptually consists of three activities: test case *generation*, test case *execution* and *verdict assignment*. Using model based approach, a behavioral model can be interpreted as a specification that defines the required and allowed observable (real-time) behavior of the implementation. It can therefore be used for automatic generation of sound and (theoretically) complete test suites.

An embedded system interacts closely with its environment which typically consists of the controlled physical equipment (the plant) accessible via sensors and actuators, other computer based systems or digital devices accessible via communication networks using dedicated protocols, and human users. A major task of the embedded system development is to ensure that it works correctly in its real operating environment. Due to lack of development resources it is not feasible to validate the system for all possible environments. Also it is not necessary if the system environments are known to a large extent. However, the requirements to the system and the assumptions made about the environment should be clear and explicit.

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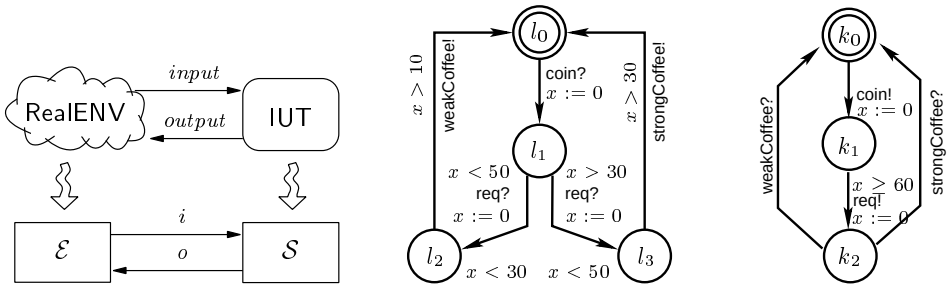


(a) Abstraction of an embedded system. (b) Example Specification $\mathcal{S}_c$. (c) Example environment $\mathcal{E}_c$.

Fig. 1. Embedded system and example models.

We denote the system being developed IUT, and its real operating environment RealENV. These communicate by exchanging $input$ and $output$ signals (seen from the perspective of IUT). Using a model-based development approach, the environment assumptions and system requirements are captured through abstract behavioral models denoted $\mathcal{E}$ and $\mathcal{S}$ respectively, communicating on abstract signals $i \in A_{in}$ and $o \in A_{out}$ corresponding (via a suitable abstraction) to the real $input$ and $output$. This setup is depicted in Figure 1(a).

1.2 Online Testing

Test cases can be generated from the model offline where the complete test scenarios and verdicts are computed apriori and before execution. Another approach is *online (on-the-fly) testing* that combines test generation and execution: only a single test primitive is generated from the model at a time which is then immediately executed on the IUT. Then the produced output by the IUT as well as its time of occurrence are checked against the specification, a new test primitive is produced and so forth until it is decided to end the test, or an error is detected. An observed test run is a timed trace consisting of an alternating sequence of (input or output) actions and time delays.

There are several advantages of online testing: 1) testing may potentially continue for a long time (hours or even days), and therefore long, intricate, and stressful test cases may be executed; 2) the state-space-explosion problem experienced by many offline test generation tools is reduced because only a limited part of the state-space needs to be stored at any point in time; 3) online test generators often allow more expressive specification languages, especially wrt. allowed non-determinism in real-time models.

Non-deterministic specification allows great flexibility in modeling. The implementation model can be precise, following the exact computation. If the exact implementation model becomes so large or complex that it cannot be interpreted online in real-time, it may be replaced by a more abstract one, where the functional and/or timed behavior is more important than the computation result itself. Moreover, the model can be a mixture of abstraction and precision where its needed. If desired, the observed trace can then be analyzed offline against the detailed implementation model.

1.3 Relativized Online Testing

The goal of relativized conformance testing is to check whether the behavior of the IUT is correct (conforming) to its specification $\mathcal{S}$ when operating under assumptions $\mathcal{E}$ about the environment. We propose relativized timed input/output conformance relation between model and IUT which coincides with timed trace inclusion taking the environment behavior into account.

The environment models the use of the system whereas the implementation specification models the required and allowed system behavior. An online test generation tool uses the environment model to generate relevant input stimuli sequences to the implementation. Thus, from a testing perspective the environment model functions as a *load generator* or environment simulator. Similarly, the test tool uses the implementation model to check whether the actual observed (timed) input-output sequences are legal according to the implementation relation. The implementation specification $\mathcal{S}$ thus *monitors* the implementation and functions as a *test oracle*. Figure 2 shows the test setup of relativized online testing, where the real environment is substituted by testing tool behaving according to the model of environment and monitoring based on the model of implementation.

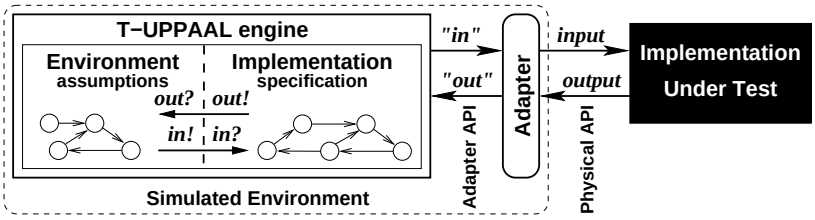


Fig. 2. Test setup in online relativized testing.

Modeling the environment explicitly and separately and taking this into account during test generation has several advantages, which we are going to elaborate further in this section.

The test generation tool can synthesize only *relevant* and *realistic scenarios* for the given type of environment, which in turn reduces the number of required tests and improves the quality of the test suite.

The test engineer can use the environment model to *guide* the test generator to more specific situations of interest. This can be used to concentrate on positive behavior testing of early prototypes rather than all possible situations for robustness testing. Later, testing can be based on a more generic environment which allows any input sequences required for negative and stress-testing. Further, the implementation model often contain parts that may be hard to reach by a random chance and a more intelligent guiding is needed. Finally, it allows the test engineer to guide testing on specific parts of the specification, either for *regression testing* or *debugging*.

A separate environment model makes it easy to test the system under *different assumptions* and *use patterns*. It is sometimes the case that the same basic controller is reused in a slightly different setup, e.g. temperature regulator in refrigeration plants and incubation houses, embedded software in PC CD-ROM controller and portable CD players, etc.. The implementation can be designed to work in a number of different environments and might never be used in their strange superposition at the same time. Relativized testing allows to concentrate on different functionality aspects which are identified in application usage patterns. Also it is worth mentioning that our assumption that the implementation models are input enabled can be relaxed; they need only be input enabled in the specific assumed environment. This eases the construction of the model.

From a testing tool implementation point of view, the online testing consists of *environment simulation* and *verdict assignment*, which are quite independent tasks concentrating on different models in the system specification: simulation mainly follows the model of environment, deals with test generation and execution and therefore is time critical, while test oracle is focusing on possible violations in the implementation model and therefore can be postponed to a time where there are more processing power or time available. We can separate the simulator and oracle into two processes, potentially running on different hosts or even postponing verdicts to offline trace analysis.

1.4 Related Work

Model based test generation for real-time specifications has been investigated by others (see e.g., [6, 9, 11, 13, 14, 18, 21, 22, 27, 28, 30]), but remain relatively immature.

A solid and widespread implementation relation used in model based conformance testing of untimed systems is the input/output conformance relation by Tretmans [32]. Informally, input/output conformance requires that, for all traces in the specification, the implementation never produces an output not allowed by the specification, and that it never refuses to produce an output (stays quiescent) when the specification requires one.

As also noted in [18, 21] a timed input/output conformance relation can be obtained (assuming input enabledness) as timed trace inclusion between the implementation and its specification. Our work further extends this to a *relativized* conformance relation taking environment assumptions explicitly into account. In [32] the specification is permitted to be non-input enabled (thus making the conformance relation non-transitive in general) in order to capture environmental constraints. However, this requires explicit rewriting of the specification when different environments are to be used. Following the seminal work [19] our approach is based on an separate model of the environment. In particular, once conformance has been established with respect to a particular environment we can automatically conclude conformance under more restricted environments. Also, when the IUT is to be used in different environments, it suffices to test it under the most liberal environment assumptions. Furthermore, relativized conformance is transitive.

Model based *offline testing* is often based on a coverage criterion of the model like in [13,15], on a test purpose as e.g. [17, 18], or a fault-model as [11, 14]. When specifications allow non-determinism, the generated test cases cannot simply be a sequence, but take the form of *behavior trees* adaptive to implementation controlled actions, e.g different outputs or timing. Therefore, most offline test generation algorithms explicitly determinize the specification [10, 17, 27]. However, for expressive formalisms like timed automata this approach is infeasible because in general they cannot be determinized [2] and their unobservable actions cannot always (and when they can it may be very costly) be removed [34]. Much work on timed test generation from timed automata therefore restricts the amount and type of allowed non-determinism. Some works [11, 13, 30] completely disallow non-determinism, whereas others [18, 27] restrict the use of clocks, guards or clock resets. However, in many cases it is important to allow non-determinism, because 1) specifications are often given as a parallel composition of model-components, 2) it allows the implementor some freedom, and 3) the tester is usually concerned with abstract requirements rather than concrete details of the IUT. Note that in particular for real-time systems it may be crucial to allow specification of timing uncertainty, e.g., that an output is expected in some interval of time (e.g., between 1 and 5 time units from now), but not

exactly when. Timed automata model this by a non-deterministic choice of letting time pass or outputting an event.

In contrast, online testing is automatically adaptive and only implicitly determinizes the specification, and only partially up to the concrete trace observed so far. The (untimed) online testing algorithm proposed by Tretmans et. al. in [4, 36] continually computes the set of states that the specification can possibly occupy after the observations made so far. Based on this the tester can at any time decide to either perform one of the inputs enabled in the specification, or wait for output from the implementation, and then check whether the output (or its absence) is allowed in the state-set. Online testing from Promela [36] and LOTOS specifications for untimed systems have been implemented in the TORX [35] tool, and practical application to real case studies show promising results [4, 33, 35]. However, TORX provides no support for real-time. Our work generalizes the TORX approach to timed systems and to the handling of the explicit environment assumptions. We allow a quite generous (non-deterministic) timed automata language. In addition, we compute the state-set symbolically to track the (potentially dense) timed state space.

Online testing from unrestricted non-deterministic timed automata using symbolic state-set computation [29] was first published by Krichen and Tripakis [21]. We implement a similar approach by extending the UPPAAL model-checker resulting in an integrated and mature testing and verification tool. Our work (originating from [7, 24, 26]; an abstract appeared in [25]) is different from [21] in that 1) the exact timed automata language variant is different and includes separable environment models, 2) we propose a relativized version of timed input/output conformance, 3) our algorithm (presented in much greater detail) generates tests relevant only for the specified environment, and 4) is shown to be sound and complete under certain assumptions, and finally 5) we provide experimental evidence of the feasibility of the technique.

1.5 Contributions

In this paper we describe a tool for online testing of real-time systems. Our main contributions are the notion of *relativized timed input/output conformance* and an implementation of a *symbolic algorithm* in testing tool T-UPPAAL, which is based on UPPAAL model checking engine. T-UPPAAL performs online testing of timed systems from a (possibly densely timed and potentially non-deterministic) timed automata model of the IUT and its assumed environment. Under a certain testing hypothesis, we prove that our algorithm is complete (in a precise probabilistic sense) and sound. Furthermore, we apply T-UPPAAL to a medium sized case that demonstrates good error detection potential and very encouraging performance. We describe the status and future work of our testing concept and implementation.

2 Test Specification

This section formally presents our semantic framework, and introduces TIOTS, timed automata, and our relativized input/output conformance relation.

2.1 Timed I/O Transition Systems

We assume a given set of actions A partitioned into two disjoint sets of output actions A_{out} and input actions A_{in}. In addition we assume that there is a distinguished unobservable action $\tau \notin A$. We denote by A_τ the set $A \cup \{\tau\}$.

Definition 1. *A timed I/O transition system (TIOTS) $\mathcal{S}$ is a tuple $(S, s_o, A_{in}, A_{out}, \rightarrow)$, where S is a set of states, $s_0 \in S$, and $\rightarrow \subseteq S \times (A_\tau \cup \mathbb{R}_{\geq 0}) \times S$ is a transition relation satisfying the usual constraints of* time determinism *(if $s \xrightarrow{d} s'$ and $s \xrightarrow{d} s''$ then $s' = s''$) and* time additivity *(if $s \xrightarrow{d_1} s'$ and $s' \xrightarrow{d_2} s''$ then $s \xrightarrow{d_1+d_2} s''$), $d \in \mathbb{R}_{\geq 0}$, where $\mathbb{R}_{\geq 0}$ denotes non-negative real numbers.*

Notation for TIOTS. Let $a, a_{1\ldots n} \in A$, $\alpha \in A_\tau \cup \mathbb{R}_{\geq 0}$, and $d, d_{1\ldots n} \in \mathbb{R}_{\geq 0}$. We write $s \xrightarrow{\alpha}$ iff $s \xrightarrow{\alpha} s'$ for some s'. We use $\Rightarrow$ to denote the τ-abstracted transition relation such that $s \stackrel{a}{\Rightarrow} s'$ iff $s \xrightarrow{\tau}{}^* \xrightarrow{a} \xrightarrow{\tau}{}^* s'$, and $s \stackrel{d}{\Rightarrow} s'$ iff $s \xrightarrow{\tau}{}^* \xrightarrow{d_1} \xrightarrow{\tau}{}^* \xrightarrow{d_2} \xrightarrow{\tau}{}^* \cdots \xrightarrow{\tau}{}^* \xrightarrow{d_n} \xrightarrow{\tau}{}^* s'$ where $d = d_1 + d_2 + \cdots d_n$. We extend $\Rightarrow$ to sequences of actions and delays in the usual manner.

We assume that the TIOTS $\mathcal{S}$ is strongly *input enabled* and *non-blocking*. $\mathcal{S}$ is strongly input enabled iff $s \xrightarrow{i}$ for all states s and for all input actions i. $\mathcal{S}$ is non-blocking iff for any state s and any $t \in \mathbb{R}_{\geq 0}$ there is a timed output trace $\sigma = d_1 o_1 \ldots o_n d_{n+1}$ such that $s \stackrel{\sigma}{\Rightarrow}$ and $\sum_i d_i \geq t$. Thus $\mathcal{S}$ will not block time in any input enabled environment.

To model potential implementations it is usefull to define the properties of *isolated outputs* and *determinism*. We say that $\mathcal{S}$ has isolated outputs if whenever $s \xrightarrow{o}$ for some output action o, then $s \not\xrightarrow{\tau}$ and $s \not\xrightarrow{d}$ for all $d > 0$ and whenever $s \xrightarrow{o'}$ then $o' = o$. Finally, $\mathcal{S}$ is deterministic if for all delays or actions α and all states s, whenever $s \xrightarrow{\alpha} s'$ and $s \xrightarrow{\alpha} s''$ then $s' = s''$.

An observable *timed trace* $\sigma \in (A \cup \mathbb{R}_{\geq 0})^*$ is of the form $\sigma = d_1 a_1 d_2 \ldots a_k d_{k+1}$. We define the observable timed traces $\mathsf{TTr}(s)$ of a state s as:

$$\mathsf{TTr}(s) = \{\sigma \in (A \cup \mathbb{R}_{\geq 0})^* \mid s \stackrel{\sigma}{\Rightarrow}\} \tag{1}$$

For a state s (and subset $S' \subseteq S$) and a timed trace σ, s After σ is the set of states that can be reached after σ:

$$s \;\mathsf{After}\; \sigma = \{\, s' \mid s \stackrel{\sigma}{\Rightarrow} s' \,\}, \quad S' \;\mathsf{After}\; \sigma = \bigcup_{s \in S'} s \;\mathsf{After}\; \sigma \tag{2}$$

The set $\mathsf{Out}(s)$ of observable outputs or delays that can occur in $s \in S' \subseteq S$ is defined as:

$$\mathsf{Out}(s) = \{\, a \in A_{out} \cup \mathbb{R}_{\geq 0} \mid s \stackrel{a}{\Rightarrow} \,\}, \quad \mathsf{Out}(S') = \bigcup_{s \in S'} \mathsf{Out}(s), \tag{3}$$

Timed Automata [2] is an expressive and popular formalism for modelling real-time systems. Let X be a set of $\mathbb{R}_{\geq 0}$-valued variables called *clocks*. Let $\mathcal{G}(X)$ denote the set of *guards* on clocks being conjunctions of simple constraints of the form $x \bowtie c$, and let $\mathcal{U}(X)$ denote the set of *updates* of clocks corresponding to sequences of statements of the form $x := c$, where $x \in X$, $c \in \mathbb{N}$, and $\bowtie \in \{\leq, <, =, >, \geq\}$. A *timed automaton* over (A, X) is a tuple (L, ℓ_0, I, E), where L is a set of locations, $\ell_0 \in L$ is an initial location, $I : L \to \mathcal{G}(X)$ assigns invariants to locations, and E is a set of edges such that $E \subseteq L \times \mathcal{G}(X) \times A_\tau \times \mathcal{U}(X) \times L$. We write $\ell \xrightarrow{g,\alpha,u} \ell'$ iff $(\ell, g, \alpha, u, \ell') \in E$.

The semantics of a timed automaton is defined in terms of a TIOTS over states of the form $s = (\ell, \bar{v})$, where ℓ is a location and $\bar{v} \in \mathbb{R}^X_{\geq 0}$ is a clock valuation satisfying the invariant of ℓ. Intuitively, there are two kinds of transitions: delay transitions and discrete transitions. In delay transitions, $(\ell, \bar{v}) \xrightarrow{d} (\ell, \bar{v} + d)$, the values of all clocks of the automaton are incremented by the amount of the delay, d. Discrete transitions $(\ell, \bar{v}) \xrightarrow{\alpha} (\ell', \bar{v}')$ correspond to execution of edges $(\ell, g, \alpha, u, \ell')$ for which the guard g is satisfied by $\bar{v}$. The clock valuation $\bar{v}'$ of the target state is obtained by modifying $\bar{v}$ according to updates u and satisfies the invariants on ℓ'.

Figure 1(b) shows a timed automaton specifying the requirements to a coffee machine. It has a facility that allows the user, after paying, to indicate his eagerness to get coffee by pushing a request button on the machine forcing it to output coffee. However, allowing insufficient brewing time results in a weak coffee. Waiting less than 30 time units definitely results in weak coffee, and waiting more than 50 definitely in strong coffee. Between 30 and 50 time units the choice is non-deterministic, meaning that the IUT/implementor may decide what to produce. After the request, it takes the machine an additional (non-deterministic) 10 to 30 (30 to 50) time units to produce weak coffee (strong coffee). The timed automaton in Figure 1(c) models a potential (nice) user of the machine that pays before requesting coffee and wants strong coffee thus requesting only after 60 time units.

TIOTS Composition. Let $\mathcal{S} = (S, s_0, A_{in}, A_{out}, \rightarrowtail)$ be an input enabled, non-blocking TIOTS. An *environment* $\mathcal{E}$ for $\mathcal{S}$ is itself an input enabled, non-blocking, TIOTS $\mathcal{E} = (E, e_o, A_{out}, A_{in}, \rightarrowtail)$. Here E is the set of environment states and the set of input (output) actions of $\mathcal{E}$ is identical to the output (input) actions of $\mathcal{S}$. The parallel composition of $\mathcal{S}$ and $\mathcal{E}$ forms a *closed system* $\mathcal{S} \parallel \mathcal{E}$ whose observable behavior is defined by the TIOTS $(S \times E, (s_0, e_0), A_{in}, A_{out}, \rightarrow)$ where $\rightarrow$ is defined as

$$\frac{s \xrightarrow{a} s' \quad e \xrightarrow{a} e'}{(s,e) \xrightarrow{a} (s',e')} \qquad \frac{s \xrightarrow{\tau} s'}{(s,e) \xrightarrow{\tau} (s',e)} \qquad \frac{e \xrightarrow{\tau} e'}{(s,e) \xrightarrow{\tau} (s,e')} \qquad \frac{s \xrightarrow{d} s' \quad e \xrightarrow{d} e'}{(s,e) \xrightarrow{d} (s',e')} \tag{4}$$

The timed automata $\mathcal{S}_c$ and $\mathcal{E}_c$ respectively shown in Figure 1(b) and 1(c) can be composed in parallel on actions $A_{in} = \{\mathsf{req}, \mathsf{coin}\}$ and $A_{out} = \{\mathsf{weakCoffee}, \mathsf{strongCoffee}\}$ forming a closed network[1].

2.2 Relativized Timed Conformance

In this section we define our notion of conformance between TIOTSs. Our notion derives from the input/output conformance relation (ioco) of Tretmans and de Vries [32, 36] by taking time and environment constraints into account. Under assumptions of input enabledness our relativized timed conformance relation coincides with relativized timed trace inclusion. Like ioco, this relation ensures that the implementation has only the behavior allowed by the specification. In particular, 1) it is not allowed to produce an output at a time (too late or too early) when one is not allowed by the specification, 2) it is not allowed to omit producing an output when one is required by the specification by delaying more than allowed. Thus, timed trace inclusion offers the notion of time-bounded quiescence [8] that—in contrast to ioco's conceptual eternal quiescence—can be observed in a real-time system.

Definition 2. *Given an environment $e \in E$ the e-relativized timed input/output conformance relation rtioco_e between system states $s, t \in S$ is defined as:*

$$s \,\mathsf{rtioco}_e\, t \quad \text{iff} \quad \forall \sigma \in \mathsf{TTr}(e).\, \mathsf{Out}\big((s,e)\ \mathsf{After}\ \sigma\big) \subseteq \mathsf{Out}\big((t,e)\ \mathsf{After}\ \sigma\big)$$

Whenever $s \,\mathsf{rtioco}_e\, t$ we will say that s is a correct implementation (or refinement) of the specification t under the environmental constraints expressed by e. Under the assumption of input-enabledness of both $\mathcal{S}$ and $\mathcal{E}$ we may characterize relativized conformance in terms of trace-inclusion as follows:

[1] To avoid cluttering the figures we have not made them explicitly input enabled; for the unspecified inputs there is an undrawn self looping edge that merely consumes the input without changing the location.

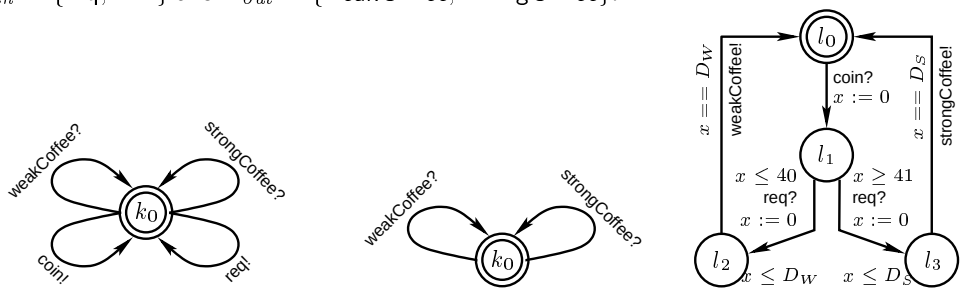
Lemma 1. *Let $\mathcal{S}$ and $\mathcal{E}$ be input-enabled with states $s, t \in S$ and $e \in E$ respectively. Then*

$$s \ \mathsf{rtioco}_e \ t \quad \text{iff} \quad \mathsf{TTr}(s) \cap \mathsf{TTr}(e) \subseteq \mathsf{TTr}(t) \cap \mathsf{TTr}(e)$$

Thus if $s \ \mathsf{rtioco}_e \ t$ does not hold then there exists a trace σ of e such that $s \stackrel{\sigma}{\Rightarrow}$ but $t \stackrel{\sigma}{\not\Rightarrow}$. Given the notion of relativized conformance it is natural to consider the preorder on environments based on their discriminating power, i.e. for two environments e and f:

$$e \sqsubseteq f \quad \text{iff} \quad \mathsf{rtioco}_f \subseteq \mathsf{rtioco}_e \tag{5}$$

(to be read f is more discriminating than e). It follows from the definition of rtioco that $e \sqsubseteq f$ iff $\mathsf{TTr}(e) \subseteq \mathsf{TTr}(f)$. In particular there is a most (least) discriminating input enabled and non-blocking environment U (O) given by $\mathsf{TTr}(U) = (A \cup \mathbb{R}_{\geq 0})^*$ $\left(\mathsf{TTr}(O) = (A_{out} \cup \mathbb{R}_{\geq 0})^*\right)$. The corresponding conformance relation rtioco_U (rtioco_O) specializes to simple timed trace inclusion (timed output trace inclusion) between system states. In Figure 3(a) and Figure 3(b) the most-discriminating and the least-discriminating environments are given when $A_{in} = \{\mathsf{req}, \mathsf{coin}\}$ and $A_{out} = \{\mathsf{weakCoffee}, \mathsf{strongCoffee}\}$.



(a) most-$\sqsubseteq$ environment $\mathcal{E}_U$. (b) least-$\sqsubseteq$ environment $\mathcal{E}_O$. (c) IUT: $\mathcal{I}(D_S, D_W)$.

Fig. 3. Implementation of coffee machine

2.3 Examples

The specification machine $\mathcal{S}_c$ and environment $\mathcal{E}_c$ were described in Section 2.1. The (deterministic) implementation $\mathcal{I}(D_S, D_W)$ in Figure 3(c) produces weak coffee (strong coffee) after less than 40 time units (more than 41 time units) and an additional brewing time of D_S (resp. D_W) time units. Observe that any trace of the implementation $\mathcal{I}(40, 20)$ (in any environment) can be matched by the specification; hence $\mathcal{I}(40, 20)$ $\mathsf{rtioco}_{\mathcal{E}_U}$ $\mathcal{S}$. Thus also $\mathcal{I}(40, 20)$ $\mathsf{rtioco}_{\mathcal{E}_c}$ $\mathcal{S}_c$. In contrast $\mathcal{I}(70, 5)$ $\not\mathsf{rtioco}_{\mathcal{E}_U}$ $\mathcal{S}_c$ for two reasons: 1) it has the timed trace $\mathsf{coin} \cdot 30 \cdot \mathsf{req} \cdot 5 \cdot \mathsf{weakCoffee}$ that $\mathcal{S}_c$ does not, i.e., it may produce weak coffee too soon (no time to insert a cup); 2) it has the trace $\mathsf{coin} \cdot 50 \cdot \mathsf{req} \cdot 70$ not in $\mathcal{S}_c$ meaning that it produces strong coffee too slowly. Assume now that the strong coffee error is fixed, and that the machine $\mathcal{I}(40, 5)$ is used in the restricted environment of nice users $\mathcal{E}_c$. Here, despite the remaining weak coffee error in $\mathcal{E}_U$, $\mathcal{I}(40, 5)$ $\mathsf{rtioco}_{\mathcal{E}_c}$ $\mathcal{S}_c$ because $\mathcal{E}_c$ never requests weak coffee.

3 Test Generation and Execution

We present the main algorithm, its soundness and completeness proof, and how to implement it.

3.1 The Main Algorithm

The input to Algorithm 1 is two TIOTSs $\mathcal{S} \parallel \mathcal{E}$ respectively modelling the IUT and environment. It maintains the current reachable state set $\mathcal{Z} \subseteq S \times E$ that the test specification can possibly occupy after the timed trace observed so far. Knowing this, state estimate allows it to choose appropriate test primitives and to validate IUT outputs.

Algorithm 1 Test generation and execution: $TestGenExe(\mathcal{S}, \mathcal{E}, \mathsf{IUT}, T)$. $\mathcal{Z} := \{(s_0, e_0)\}$.

while $\mathcal{Z} \neq \emptyset \wedge \sharp iterations \leq T$ **do** switch(*action*, *delay*, *restart*) randomly:
- *action*: `// offer an input`
  - **if** $\mathsf{EnvOutput}(\mathcal{Z}) \neq \emptyset$
    - randomly choose $a \in \mathsf{EnvOutput}(\mathcal{Z})$
    - send a to IUT
    - $\mathcal{Z} := \mathcal{Z}$ After a
- *delay*: `// wait for an output`
  - randomly choose $\delta \in \mathsf{Delays}(\mathcal{Z})$
  - sleep for δ time units and wake up on output o
  - **if** o occurs at $\delta' \leq \delta$ **then**
    - $\mathcal{Z} := \mathcal{Z}$ After δ'
    - **if** $o \notin \mathsf{ImpOutput}(\mathcal{Z})$ **then return** *fail*
    - **else** $\mathcal{Z} := \mathcal{Z}$ After o
  - **else** `// no output within` δ `delay`
    - $\mathcal{Z} := \mathcal{Z}$ After δ
- *restart*: `//reset and restart`
  - $\mathcal{Z} := \{(s_0, e_0)\}$
  - **reset** IUT

if $\mathcal{Z} = \emptyset$ **then return** *fail*
else return *pass*

The tester can perform three basic actions: either send an input (enabled environment output) to the IUT, wait for an output for some time, or reset the IUT and restart. If the tester observes an output or a time delay it checks whether this is legal according to the state set. The state set is updated whenever an input is offered, or an output or delay is observed. Illegal occurrence or absence of an output is detected if the state set becomes empty which is the result if the observed trace is not in the specification. The functions used in Algorithm 1 are defined as: $\mathsf{EnvOutput}(\mathcal{Z}) = \{a \in A_{in} \mid \exists (s,e) \in \mathcal{Z}.e \xrightarrow{a}\}$, $\mathsf{ImpOutput}(\mathcal{Z}) = \{a \in A_{out} \mid \exists (s,e) \in \mathcal{Z}.s \xrightarrow{a}\}$, and $\mathsf{Delays}(\mathcal{Z}) = \{d \mid \exists (s,e) \in \mathcal{Z}.e \overset{d}{\Rightarrow}\}$. Note that EnvOutput is empty if the environment has no outputs to offer. Similarly, Delays cannot pick at random from the entire domain of real-numbers if the environment must produce an input to the IUT model before a certain moment in time. We use the efficient reachability algorithm implementation [3] to compute the operator After. It operates on bounded symbolic states, checks for inclusions and thus always terminates even if the model contains τ action loops.

3.2 Soundness and Completeness

Algorithm 1 constitutes a randomized algorithm for providing stimuli to (in terms of input and delays) and observing resulting reactions from (in terms of output) a given IUT. Assuming the

behavior of the IUT is a non-blocking, input enabled, deterministic TIOTS with isolated outputs the reaction to any given timed input trace $\sigma = d_1 i_1 \ldots d_k i_k d_{i+1}$ is completely deterministic. More precisely, given the stimuli σ there is a unique $\rho \in \mathsf{TTr}(\mathsf{IUT})$ such that $\rho \uparrow A_{in} = \sigma$, where $\rho \uparrow A_{in}$ is the natural projection of the timed trace ρ to the set of input actions.

Under a certain (theoretically necessary) testing hypothesis about the behavior of IUT and given that the TIOTSs $\mathcal{S}$ and $\mathcal{E}$ satisfy certain assumptions, the randomization used in Algorithm 1 may be chosen such that the algorithm is both complete and sound in the sense that it (eventually with probability one) gives the verdict "fail" in all cases of non-conformance and the verdict "pass" in cases of conformance. The hypothesis and assumptions are based on the results on digitization techniques in [31][2] which allow the dense-time trace inclusion problem between two sets of timed traces to be reduced to discrete time. In particular it suffices to choose unit delays in Algorithm 1 (assuming that the models and IUT share the same magnitude of a time unit).

Theorem 1. *Assume that the behavior of* IUT *may be modelled*[3] *as an input enabled, non-blocking, deterministic TIOTS with isolated outputs. Furthermore assume that* $\mathsf{TTr}(\mathsf{IUT})$ *and* $\mathsf{TTr}(\mathcal{E})$ *are* closed under digitization *and that* $\mathsf{TTr}(\mathcal{S})$ *is* closed under inverse digitization. *Then Algorithm 1 with only unit delays is sound and complete in the following senses:*

1. *Whenever* $TestGenExe(\mathcal{S}, \mathcal{E}, \mathsf{IUT}, T) = fail$ *then* $\mathsf{IUT}\ \not{\mathsf{rtioco}}_{\mathcal{E}}\ \mathcal{S}$.
2. *Whenever* $\mathsf{IUT}\ \not{\mathsf{rtioco}}_{\mathcal{E}}\ \mathcal{S}$ *then* $\mathsf{Prob}\big(TestGenExe(\mathcal{S}, \mathcal{E}, \mathsf{IUT}, T) = fail\big) \xrightarrow{T \to \infty} 1$ *where* T *is the maximum number of iterations of the while-loop before exiting.*

Proof. See [20]

From [16, 31] it follows that the closure properties required in Theorem 1 are satisfied if the behavior of IUT and $\mathcal{E}$ are TIOTSs induced by closed timed automata (i.e. where all guards and invariants are non-strict) and $\mathcal{S}$ is a TIOTS induced by an open timed automaton (i.e. with guards and invariants being strict). In practice these requirements are not restrictive, e.g. for strict guards one can always scale the clock constants to obtain arbitrary high precision.

3.3 Symbolic State-set Computation

The concrete realization of Algorithm 1 is described in [20]. We use (well established) symbolic constraint solving techniques to represent sets of clock valuations compactly by so-called zones.

A zone over a set of clocks X is a conjunction of clock in-equations of the form $x_i - x_j \prec c_{i,j}$, $x_i \prec c_{iu}$, and $c_{il} \prec x_i$, where $\prec \in \{<, \leq\}$, $c_{i,j}, c_{il}, c_{iu}$ are integer constants including $\pm\infty$, and $x_i, x_j \in X$. A *symbolic state* is a pair $\langle \bar{\ell}, Z \rangle$ consisting of a vector $\bar{\ell}$ of locations for each parallel automaton and the zone Z. Z denotes a set of clock valuations, i.e., a symbolic state represents a set of concrete states: $\langle \bar{\ell}, Z \rangle = \{(\bar{\ell}, \bar{v}) \mid \bar{v} \in Z\}$.

The required symbolic algorithms are similar to those used for model checking [1, 3] except that only states up to a certain time limit need to be computed. This is most easily accomplished by introducing an auxiliary clock t that is set to zero whenever an observable action occurs.

[2] We refer the reader to [31] for the precise definition of digitization and inverse digitization.

[3] The assumption that the IUT can be modelled by a formal object in a given class is commonly referred to as the *test hypothesis*. Only its existence is assumed, not a known instance. In particular it may be extremely large, and structurally totally unrelated to the specification.

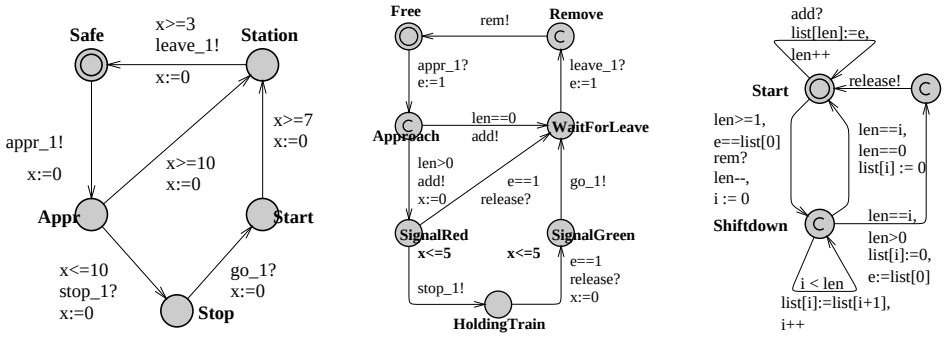
4 Experiments

We implemented our algorithm by extending the mature UPPAAL model-checker tool to the testing tool T-UPPAAL. Besides a graphical timed automata editor, UPPAAL provides an efficient implementation of the needed basic symbolic operations. Unlike UPPAAL, T-UPPAAL does not store the reached state space, but only the current symbolic state set. We allow the full UPPAAL timed automata language, including non-deterministic (action and timing) specifications and discrete variables. The IUT is connected to T-UPPAAL via an adapter component translating abstract I/O actions into their real representation, and sends (receives) them to (from) the IUT.

This section presents the results of the first set of experiments using our implementation. The purpose is to give an indication of the feasibility of our technique in terms of applicability, error detection capability, and performance in terms of state-set size and computation time.

4.1 Test Specification

For our experiment we used a slightly changed and adopted specification of a simple railway control system originally published in [37] and found in UPPAAL distribution. A rail-road intersection controller monitors trains on a set of rail-road tracks with a shared track segment, e.g. a train-station. Its main objective is to ensure that only one train occupies the shared segment at a time, and to grant access in arrival order. In this setup we assume 4 tracks, and for simplicity 1 train per track at a time. Trains on track i signal the controller when they approach and leave the station using signals appr_i and leave_i respectively. When train i approaches an occupied station the controller is required to issue a stop_i within 5*mtu* (model time units), and is similarly required to issue go_i within 5*mtu* after the station becomes free.



(a) Train 1 of 4. (b) Controller 1 of 4. (c) Queue

Fig. 4. Test specification for train controller: trains as environment, controller and queue as implementation.

The environment assumption model consists of 4 concurrent timed automata each modeling the assumed behavior of a train. The model for train 1 is shown in Figure 4(a); the remaining trains are identical except for the train-id. The model of the IUT requirements consists of 4 concurrent train control automata (Figure 4(b)) tracking the position of each potential train, and one queue automaton tracking their arrival order (Figure 4(c): list is an array of integers, and i is an index into the array). We use UPPAAL syntax to illustrate timed automata. Initial locations are

marked using a double circle. Edges are by convention labeled by the triple: guard, action, and assignment in that order. The internal τ-action is indicated by an absent action label. Committed locations are indicated by a location with an encircled "C". A committed location must be left immediately as the next transition taken by the system. Finally, bold-faced clock conditions placed under locations are location invariants.

The complete test specification is a reasonably large and nontrivial first experiment: it consists of 9 concurrent timed automata, 8 clocks, and a sequential queue data structure.

4.2 Implementation Under Test

The IUT is implemented as an approximately 100 line C++ program following the basic structure of the specification. It uses POSIX Threads and POSIX locks and condition variables for multi-threading and synchronization. It consists of one thread per train, and queue data structure whose access is guarded by mutual exclusion and condition variables. In the experiment, the IUT runs in the same address space as the T-UPPAAL tool, and input and output actions are communicated to and from the driver/adapter via two single place bounded buffers.

In addition we have created a number of erroneous mutations based on the *assumed* correct implementation (**M0**):

M1: The $\mathtt{stop}_3$ signal is issued 1*mtu* too late.
M2: The controller issues $\mathtt{stop}_1$ instead of $\mathtt{stop}_3$.
M3: The controller never issues $\mathtt{stop}_3$
M4: The controller uses a bounded queue limited to 3 trains. Thus, the fourth train overwrites the third train in the queue.
M5: The controller uses LIFO queue instead of FIFO.
M6: The controller ignores $\mathtt{appr}_3$ signals if a train arrives before 2*mtu* after entering the location Free.

4.3 Error Detection Capability

The experiments are run on a 8x900 MHZ Sun Sparc Fire v880R workstation with 32 GB memory running Sun Solaris 9 (SunOS 5.9). T-UPPAAL runs on one CPU whereas the IUT may run on one or more of the remaining. T-UPPAAL itself does not require these extreme amount of resources, and it runs well on a standard PC, but a multiprocessor allows T-UPPAAL and the IUT to run in parallel as they would normally do in a black-box system level test.

To allow for faster and more experiments and reduce potential problems with real-time clock synchronization between the engine and IUT, the experiments are run using a simulated clock progressing when both T-UPPAAL and the IUT needs to let time pass. Each mutant is tested 1100 times each with an upper time limit of 100000*mtu*. All runs of **M1-6** mutants failed and all runs of **M0** passed with timeout for testing. The minimum, maximum, and average running time and number of used input actions are summarized on the left side of Table 5.

The results show that all erroneous mutants are killed surprisingly quickly using less than 100 input actions and less than 2100*mtu*. In contrast the assumed correct implementation **M0** was not killed and was subjected to at least 3500 inputs stimuli and survived for more than 300 times longer than other mutants in average. In conclusion, the results indicate that online real-time testing may be a highly effective technique.

Table 5. Error detection and performance measures:

Mu-	Error detection capability						State-set size				Execution time, μs			
	Input actions			Duration, *mtu*			After(delay)		After(action)		After(delay)		After(action)	
tant	Min	Avg	Max	Min	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max
M1	2	4.8	16	0	68.8	318	2.3	18	2.7	28	1113	3128	141	787
M2	2	4.6	13	1	66.4	389	2.3	22	2.8	30	1118	3311	147	791
M3	2	4.7	14	0	66.4	398	2.2	22	2.7	30	1112	3392	141	834
M4	6	8.5	18	28	165.0	532	2.8	24	3.1	48	1113	3469	125	936
M5	4	5.6	12	14	89.8	364	2.8	24	3.3	48	1131	3222	146	919
M6	2	14.1	92	0	299.6	2077	2.7	27	2.9	36	1098	3531	110	861
M0	3565	3751.4	3966	10^5	10^5	10^5	2.7	31	2.9	46	1085	3591	101	950

4.4 Performance

Based on the same setup from Section 4.3 we instrumented T-UPPAAL to record the number of symbolic states in the state-set, and the amount of CPU time used to compute the next state-set after a delay and an observable action. The right side of Table 5 summarizes the results. The state-set size is in average only 2-3 symbolic states per state-set, but it varies a lot, up to 48 states. In average, the state-set sizes reached after performing a delay appear larger than after an action. In average it costs only $1.1ms$ to compute the successor state-set after a delay, and less than $0.2ms$ after an action. Thus it seems feasible to generate tests from much larger specifications, obviously depending on the scale of time units.

To examine these variations in greater detail and the dependency of computation time on state-set size, we created the scatter plot in Figure 6, also including the regression line of the mean. The figure shows the distribution of After(delay) successor computation time of as function of state-set size. The figure shows graphically by far that most of the population of state-set sizes are concentrated below 5 symbolic states, and that very few are larger than 25. We found a similar, but less dispersed, pattern for After(action) successor computation time.

Figure 7 plots the average successor state computation time as function of the state-set size. The After(delay) computation time appear to depend linearly on the state-set size, where as After(action) appear even sub-linear. But this conclusion is uncertain because only few measurements points are available for large state-set sizes. The scatter plot in Figure 7(a) shows the average of After(delay) successor computation times as function of state-set size. Figure 7(b) displays After(action) with a similar pattern as After(delay), but is about 10 times cheaper to compute (varies between 0.4 and 1 ms).

In conclusion, the performance of our technique looks very promising and appears to be fast enough for many real-time systems. Obviously, more experiments on varying size and complexity models are needed to find the firm limitations of the technique.

4.5 Industrial Case Study

We applied T-UPPAAL on a first industrial case study provided by Danfoss Refrigeration Controls Division. The system under test is an Electronic Cooling Controller (EKC) for industrial cooling plants. Its main objective is to keep the refrigerator room air temperature at a user defined set point by switching a compressor on and off. It monitors the actual room temperature, and sounds an alarm if the temperature is too high (low) for too long a period. In addition it

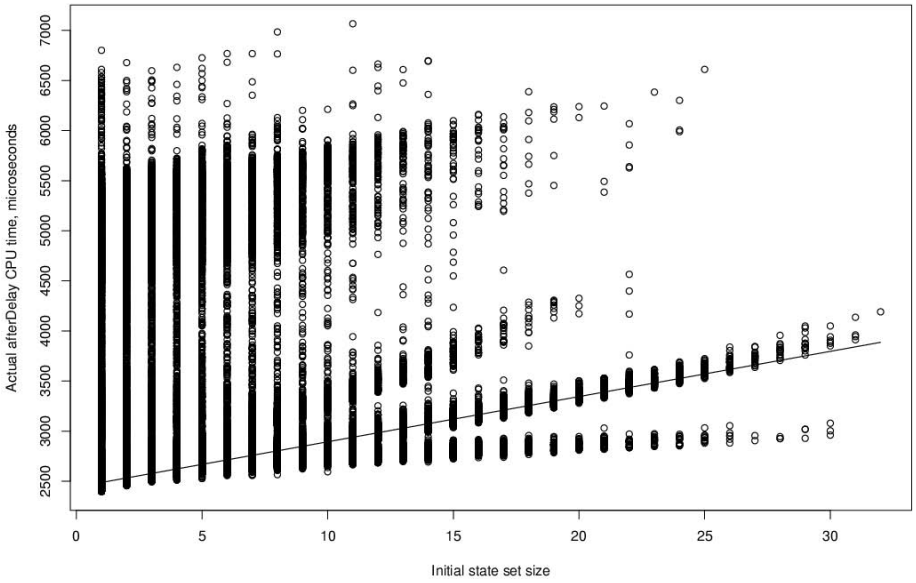
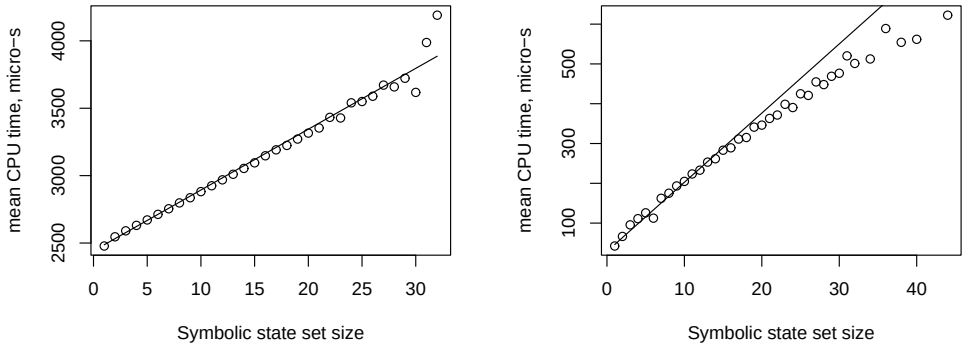


Fig. 6. Distribution of After(delay) state-set successor computation on state-set size.



(a) After delay. (b) After action.

Fig. 7. The scatter plots of average CPU time per state-set size with linear regression lines.

offers a myriad of features (e.g. defrosting and safety modes in case of sensor errors) and approximately 40 user set-able parameters. Figure 8 depicts the photo of EKC unit.

The EKC obtains input from a room air temperature sensor, a defrost temperature sensor, and a two-button keypad that controls approximately 40 user set-table parameters. It delivers output via a compressor relay, a defrost relay, an alarm relay, a fan relay, and a LED display unit showing the currently calculated room air temperature as well as indicators for alarm, error and operating mode.

Figure 9 shows a simplified view of control objective, namely to keep the temperature within *setPoint* and *setPoint*+*differential*. The regulation is to be based on an weighted averaged room

Fig. 8. Photo of EKC unit on a desk.

temperature T_n calculated from periodically sampling the air temperature sensor such that a new sample T is weighted by 20% and the old average T_{n-1} by 80%:

$$T_n = \frac{T_{n-1} * 4 + T}{5}$$

A certain minimum duration must pass between restarts of the compressor, and similarly the compressor must remain on for a minimum duration. An alarm must sound if the temperature increases (decreases) above (below) *highAlarmLimit* (*lowAlarmLimit*) for *alarmDelay* time units. All time constants in the EKC specification are in the order of seconds to minutes, and a few even in hours.

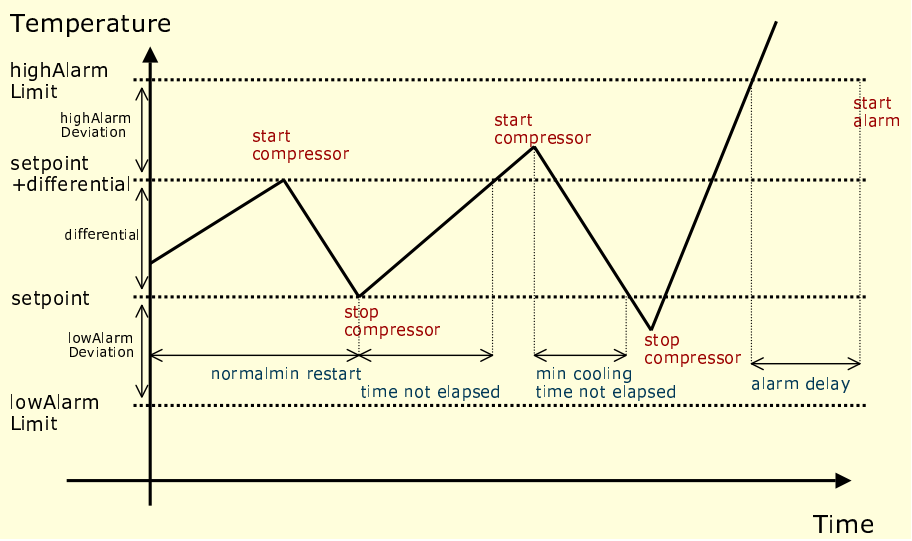


Fig. 9. Main Control Objective of an EKC is to maintain temperature within bounds.

Test Interface. The test interface defines how the IUT can be controlled and observed. Danfoss proposed to test the EKC by reading and writing its parameter database. Nearly every input, output or system parameter is stored in a so-called parameter database in the EKC, essentially a parameter id indexed table that contains the value, type and permitted range of each variable. The parameter database is accessible from a PC host computer first via a LON network from the EKC to a EKC-gateway, from there via a RS-232 bus to the PC host, and finally via protocol software implemented as a Microsoft COM object. We implemented adaptation software allowing T-UPPAAL running on a UNIX host to interact with the COM object via a TCP/IP connection. In addition the adaptation translated changes in the parameter database into events and vice versa.

The model. We modeled a central subset of the functionality of the EKC as a network of UPPAAL timed automata, namely basic temperature regulation, alarm monitoring, and defrost modes with manual and automatic controlled (fixed) periodical defrost (de)activation. The allowed timing tolerances and timing uncertainties introduced by the adaptation software is modeled explicitly by allowing output events to be produced within a certain error envelope, typically 2 seconds. The model consists of the main components depicted in Figure 10, and explained below:

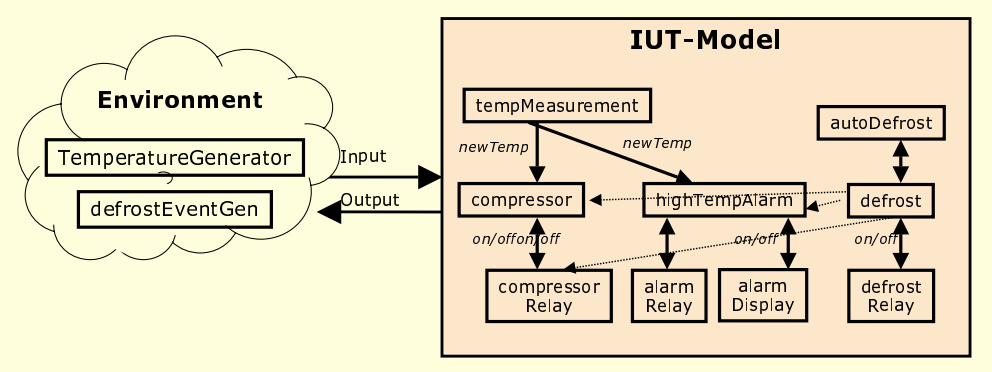


Fig. 10. Main timed automata components in model

Compressor controls the compressor relay based on the estimated room temperature, alarm and defrost status.

Defrost Controls the events that must take place during a defrost cycle.

Auto Defrost automatically engages defrost mode periodically, according to a user setting. In this mode the compressor and alarm handling functions are disengaged until *delayAfterDefrost* time units have elapsed.

Relay automata model a digital physical output (compressor, defrost alarm, alarm display) that when given command switches on (respectively off) within a certain time bound.

Temperature Generator (part of the environment) simulates the variation in room temperature, currently either as a sinus curve or randomly.

Defrost Event Generator (part of the environment) randomly issues manual defrost on/off commands.

Experiences. Our preliminary experiences shows that it is possible to accurately model the behavior of EKC like devices as timed automata and use the resulting model as a test specification for online testing. It is also possible to model only selected desired aspects of the system behavior, i.e. a complete and detailed behavioral description is not required for system testing. However making the model was not trivial because the system specification was generally incomplete and ambiguous. This meant that much time was spent on questioning Danfoss engineers, qualified guessing, and reverse engineering. We conclude that explicit modeling is a strong method of understanding and capturing the required system behavior. Once the behavior is understood we find it important to simulate and verify the model to ensure that it has the intended behavior; some errors were introduced in the model and detected by spurious behavior of the resulting test run.

We also learned that the provided test interface is not ideal. Originally the AK-online software is designed for basic monitoring and changing configuration of the EKC rather than testing. It lacks controllability of some physical sensor inputs and synchronization features with the tester. We are collaborating with Danfoss to propose a better test interface for new generation EKCs with improved control and observation.

Before the submission deadline of this report we encountered numerous test runs where the EKC disengages defrosting earlier than expected. According to Danfoss a possible explanation is that the EKC uses a low resolution timer with a precision of around 5 seconds to control defrosting, whereas the model expects 2 seconds. It remains to be seen if this can explain all failing test runs, but it indicates that our method indeed *can* detect such timing errors.

5 Status and Future Work

T-UPPAAL is based on symbolic model-checking techniques based on different bound matrices, which are efficiently implemented in the UPPAAL verification engine. The test specification can be created through a user friendly UPPAAL timed automata network graphical editor. The environment and the IUT separation is specified by defining the observable communication channels between them. In addition, for testing, T-UPPAAL needs an adapter (loaded as dynamic library) to connect to the IUT.

The tool implementation has been released to the public and the latest T-UPPAAL versions can be downloaded for non-commercial use at [23]. The experiments can be re-examined and a few more examples can be tried out using scripts from the distribution.

Our first experience with online timed-model-based testing has been encouraging so far. We observed promising error detection capabilities having just random guiding techniques and the model-checking engine provided us with fast enough reachability algorithms—not just to generate tests online—but also to execute them, analyze and compute the conformance verdict in real-time. The abstract and non-deterministic test specification minimized the effort in modeling and testing various event and timing combinations. Non-determinism proved to be useful to deal with some practical issues like uncertainty in floating point computation, possible timing drifts and could even partially substitute the basic value passing.

Test generation improvements. Although generally successful, our first applications also revealed the lack of certain modeling features, e.g., for interprocess communication since UPPAAL channels define only handshake communication and data sharing via global variables which

need to be categorized into IUT and environment in the T-UPPAAL framework. During testing an input action has to be (non-deterministically) selected and/or pre-computed in the model of environment. We plan to improve the *value passing* by implementing variable value binding to channel synchronization. To improve the data selection, a special types of variables could be introduced. Further, it would be interesting to combine with state of the art testing data generators (e.g. GAST [12]) from symbolic specifications, especially when complex C-like data structures are soon to be available in UPPAAL engine.

Some specifications happen to contain (probabilistically) narrow passages that may be hard to reach by a randomized algorithm. Moreover it is not trivial to detect such bottlenecks while modeling. To *improve the guiding* in such cases, we plan to combine the results from offline test case generators by converting the generated test traces into models of the environment. Specifically for online testing, there are even bigger expectations from online model coverage analysis described below.

Although the test runs can be long, there is still too little support implemented for estimating the confidence of successful test runs and the tester is left in doubt whether all behavior combinations have been tried out. To complement this lack of confidence, a *coverage of the system model* can be measured according to various criteria. The coverage of structure, variables usage, and functional behavior for UPPAAL specifications has recently been proposed in [5, 13] and are awaiting to be implemented for online testing. However the coverage criteria for real-time properties need more fundamental research.

When a test run fails the tester needs to find out why test failed and what parts of specification were potentially violated, i.e. the *test failure diagnostic information* needs to be provided and most preferably automatically. To provide this knowledge we propose to analyze the evolution of the state-set, more specifically dead-ends which are cut off by observable actions and branching points which start alternative histories of computation. The coverage estimate of the system model by various test traces can provide probabilistic clue of what went wrong according to specification. In some cases, the coverage of the executed IUT code can be examined too and the erroneous parts spotted when a failing test run is identified.

Test execution improvements. One of the main problems for the real-time system developer is the uncontrollable progression of time. Mainly there are two ways of designing real-time applications to be time-aware: schedule events based on absolute clock values or schedule events based on offset from previous (internal or observable input/output) events. Both approaches have their pros and cons, but the later may have timing drifts. The situation becomes even more complicated if the system is built mixing both approaches are used. We propose to introduce timing uncertainties in input/output event observation in order to *synchronize model clocks* with the ones in IUT, which requires further future research.

So far the testing algorithm proved to be efficient enough for online execution, but still the performance is unpredictable because of highly varying state-set size, which may strain time synchrony. Therefore,*more sophisticated algorithms* could be used to allow state-set precomputation in advance, faster algorithms allowing testing of larger specifications and/or with finer time units. One alternative is to investigate whether the tool should be separated into two parts, the environment simulator and test oracle (monitor). This would allow finer computing power distribution in time. Moreover, test oracle can be extended to a fully equipped monitor: at the same time as analyzing the trace with the implementation model, it can mark the model

coverage and gather diagnostic information. The model coverage facts can be converted (online or offline) into guiding hints for (slightly) later testing. The diagnostic information can help developers in identifying the possibly violated parts of specification.

Figure 11 shows the information flow and breakdown into functional blocks of our envisioned online testing tool: the *test specification* consists of the environment model MEnv and the implementation model MImp composed in parallel, the online testing tool separated into *emulator* (as environment simulator) and *monitor* (as test oracle) and extended with test *selector* for smart *guiding* based on *coverage facts* produced by *monitor*; generated test *traces* (from offline *case generator*, *model checker* or from online testing *diagnostic information*) are loaded as environment models through trace *converter*.

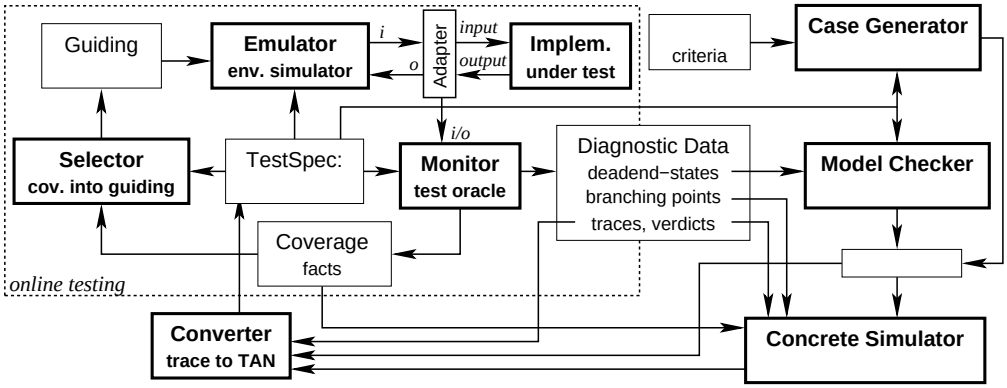


Fig. 11. Data flow in online testing: active processes are in bold and passive storages are in normal font.

6 Conclusions

We have presented the T-UPPAAL tool and approach to testing of embedded systems using real-time online testing from non-deterministic timed automata specifications. Based on an experiment with a non-trivial specification we conclude that our notion of relativized input/output conformance and our sound and complete randomized online testing algorithm appear correct and feasible. We further conclude that our algorithm is implementable, and T-UPPAAL tool implementation shows encouraging results both in terms of error detection capability and performance of the symbolic state-set computation algorithm. However, further work and real-life applications are needed to evaluate the algorithm and the tool in detail.

Besides practical application, we plan to improve the tool in several directions. For instance, to estimate model coverage of the trace and use it to guide the random choices made by the algorithm and investigate their impact on the error detection capability. Also we plan to include observation uncertainty into our algorithm (i.e., outputs and given stimuli classified in an interval of time rather than a time instance), to improve clock synchronization between T-UPPAAL and the implementation, and a value passing mechanism to make tool easier to adopt.

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