Online Testing of Real-time Systems Using UPPAAL

Kim G. Larsen, Marius Mikučionis, Brian Nielsen

{ kgl, marius, bnielsen } @cs.aau.dk

CISS — Center for Embedded Software Systems
BRICS — Basic Research in Computer Science
Aalborg University

Outline

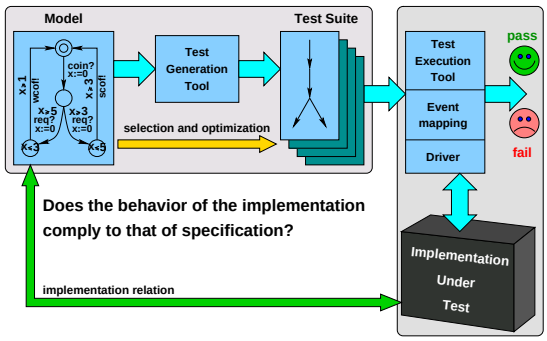
Online testing using UPPAAL: NWPT'03, FATES'04, EMSOFT'05.

- Formal framework of timed conformance testing of black-box:
  - Classical model-based black-box testing.
  - Test setup: from system and specification to testing.
  - Relativized timed input/output conformance relation.
  - Ordering of environments by discriminating power.
- Online Real-time Test Generation
  - Symbolic techniques from UPPAAL.
  - Online testing algorithm animated.
  - Real-time mapping to model and back.
- Evaluation: performance, industrial study, light controller demo.
- Conclusions and future work.

Motivation for Automated Testing

- What is testing?
  - checking the *quality* (functionality, reliability, ...) of an *object*
  - by performing *experiments*
  - in a *controlled* (and systematic) way.
- Testing is the *main* validation *technique* used by industry:
  - 10-20 errors per 1000 lines of code.
  - 30-50% of development time and cost in embedded software.
  - Testing is still ad-hoc, based on heuristics, and error prone.
- "Testing is routine, tedious and boring work" – let *machines* do it.
- But! Testing requires most of *development skills*.
- Verification vs. testing: abstract *models* vs. *real* world.
- Conformance testing is *undecidable*.

Classical Model-based Testing Framework



- *Model*-based, *black*-box, *conformance* testing.
- *Timed*, *online* (on-the-fly generation and execution in real-time).

Related Work

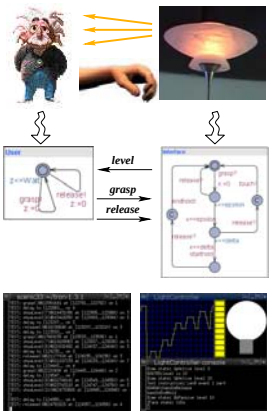
This work is based on the following ideas:

- UPPAAL model-checking algorithms for timed systems (1994).
- Jan Tretmans' testing theory (un-timed, quiescence) (1999).
- TORX testing tool framework (un-timed, w/o environment) (2000).
- Digitization techniques, T.A.Henzinger, Z.Manna, A.Pnueli (1992), J.Ouaknine, J.Worrell (2003).

Other close works:

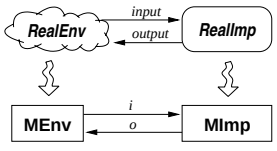
- Time-optimal test cases for RTS, A.Hessel, K.G.Larsen, B.Nielsen, P.Pettersson, A.Skou (2003).
- Black-box conformance testing for RTS, M.Krichen, S.Tripakis (2004).
- Test generation framework for quiescent RTS, L.B.Briones, E.Brinksma (2004).

Modelling and Testing with UPPAAL TRON



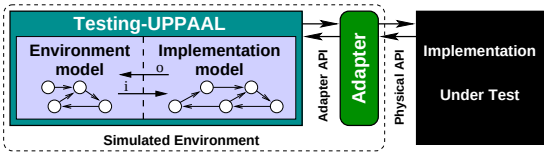
- Modelling a (closed) system:
  - Selected aspects.
  - Use abstraction.
  - Formal notations: UPPAAL TA.
  - Automatically analyze and test.
- Tester acts as environment where:
  - Specification: $Env \| IUT$,
  - IUT model acts as oracle,
  - Load/guiding model is Env,
  - Generate only relevant inputs,
  - Modular and flexible.

Test Setup: System ⇒ Model ⇒ Online Testing



- Imp is (weakly) *input enabled*.
- *Clear* and *explicit* Env assumptions.
- Imp||Env forms a *closed* system.
- *Observable* input/output actions.

- Testing with general Env is *expensive* and often *unnecessary*.
- *Flexible*: only relevant behavior (Env change, guiding, debug).



- Online generation allows *long* and otherwise *exhaustive* tests.

Relativized Timed Input/Output Conformance

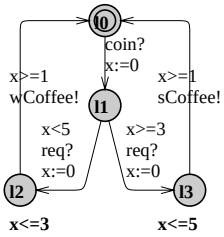
- Idea: extend ioco (J.Tretmans) from TORX with time and env.
- Timed trace e.g.: $\sigma = coin? \cdot 5 \cdot req? \cdot 2 \cdot weakCoffee! \cdot 9 \cdot coin?$
- $\mathrm{TTr}(s)$ – set of *timed traces* from state s: $\{\sigma \in (A \cup \mathbb{R}_{\geq 0})^* \mid s \stackrel{\sigma}{\Rightarrow}\}$
- Timed trace *inclusion* as conf. relation: $\mathrm{TTr}(i) \subseteq \mathrm{TTr}(s)$
- *No illegal* output and *legal* output is observed at *right time*.
  $\mathrm{Out}(P) \stackrel{def}{=} \bigcup\{\alpha \in (A_{out} \cup \mathbb{R}_{\geq 0}) \mid p \in P.\ p \stackrel{\alpha}{\Rightarrow}\}$
- Relativized Timed Input/Output Conformance:
  $s\ \mathrm{rtioco}_e\ t \stackrel{def}{=} \forall \sigma \in \mathrm{TTr}(e).\mathrm{Out}((e,s)\ \mathrm{After}\ \sigma) \subseteq \mathrm{Out}((e,t)\ \mathrm{After}\ \sigma)$

$$s\ \mathrm{rtioco}_e\ t \iff \mathrm{TTr}(s) \cap \mathrm{TTr}(e) \subseteq \mathrm{TTr}(t) \cap \mathrm{TTr}(e)$$

- Environment *ordering*. f is more discriminating than e:

$$e \sqsubseteq f \stackrel{def}{=} \mathrm{rtioco}_f \subseteq \mathrm{rtioco}_e$$

Test Specification: Timed Automata Networks

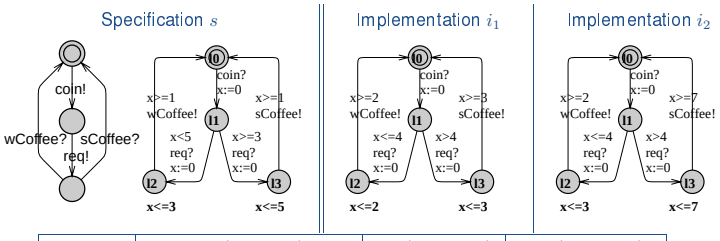


Timed automaton over A is $\langle L, l_0, X, D, E, I\rangle$:

- L – set of *locations*,
- $l_0 \in L$ – the *initial* location,
- X – set of real-valued *clocks*,
- D – bounded integer *variables*,
- $I : l \mapsto G(X)$ – location *invariant* mapping,
- $E \subseteq L \times G(X) \times A \times 2^{R(X)} \times L$ is a superset of directed *edges*: $l \xrightarrow{g,a,r} l'$ iff $\langle l, g, a, r, l'\rangle \in E$.

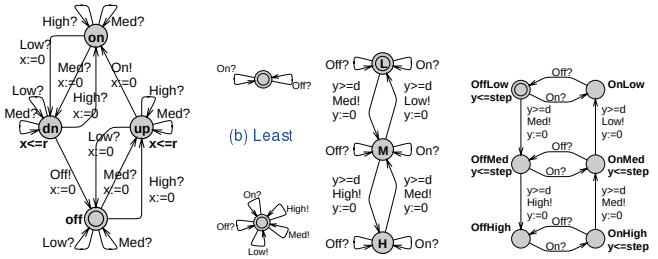
- Has *Labeled Transition System (LTS)* semantics.
- I/O, internal and timing *non-determinism* allow modelling parallelism, abstraction and possible time slacks.
- Test Spec: $\langle (\mathcal{E}_1||\mathcal{E}_2||\ldots||\mathcal{E}_n) \;||\; (\mathcal{I}_1||\mathcal{I}_2||\ldots||\mathcal{I}_n),\ A_{in},\ A_{out},\ T\rangle$

Timed I/O Conformance Relation Example



Trace, σ	Out$(s$ After $\sigma)$	Out$(i_1$ After $\sigma)$	Out$(i_2$ After $\sigma)$
$c \cdot 2$	$\mathbb{R}_{\geq 0}$	$\mathbb{R}_{\geq 0}$	$\mathbb{R}_{\geq 0}$
$c \cdot 4 \cdot r \cdot 1$	$\{wCoffee, sCoffee\} \cup [0, 4]$	$[0, 1]$	$[0, 2]$
$c \cdot 4 \cdot r \cdot 2$	$\{wCoffee, sCoffee\} \cup [0, 3]$	$\{wCoffee, 0\}$	$\{wCoffee\} \cup [0, 1]$
$c \cdot 5 \cdot r \cdot 3$	$\{sCoffee\} \cup [0, 2]$	$\{sCoffee, 0\}$	$[0, 4]$
$c \cdot 5 \cdot r \cdot 5$	$\{sCoffee, 0\}$	$\emptyset$	$[0, 2]$

Discriminating Power of Environments



(a) Cooling controller. (c) Most (d) Inertial (e) Responsive

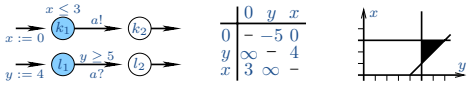
Most ⊒ Inertial ⊒ Responsive ⊒ Least

Consider trace: $0 \cdot \mathbf{Med}! \cdot 0 \cdot \mathbf{High}! \cdot 0 \cdot \mathbf{Med}! \cdot 0 \cdot \mathbf{Low}? \cdot r \cdot \ldots$

Symbolic Techniques from UPPAAL

- *Action* transition: $\langle \bar{l}, z\rangle \xrightarrow{a} \langle \bar{l}', (z \wedge g)_r \wedge I(\bar{l}')\rangle$ **iff**: $l \xrightarrow{g,a,r} l'$ is a-action transition and $z \wedge g \neq \emptyset$,$(z \wedge g)_r \wedge I(\bar{l}') \neq \emptyset$.
- *Delay* transition: $\langle \bar{l}, z\rangle \xrightarrow{\delta} \langle \bar{l}, z^{+\delta} \wedge I(\bar{l})\rangle$ **iff** $z^{+\delta} \wedge I(\bar{l}) \neq \emptyset$.
- *Zone* is a conjunction of clock constraints of the form: $\{x_i - x_j \prec c_{ij}\} \cup \{a_i \prec x_i\} \cup \{x_j \prec b_j\}$ where $\prec \in \{<, \leq\}$
- *Difference bound matrix* – compact representation.
- Symbolic state set $\mathcal{Z} = \{\langle \bar{l}_1, z_1\rangle, \ldots, \langle \bar{l}_n, z_n\rangle\}$

$$z = [(y - x \leq 4) \wedge (y \geq 5) \wedge (x \leq 3)]$$



Randomized Test Generation and Execution Online

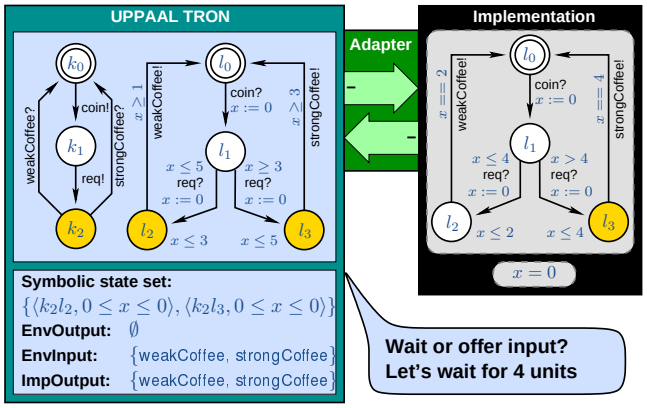
while $\mathcal{Z} \neq \emptyset \wedge \sharp iterations \leq T$ **do** choose randomly:

1. **if** EnvOutput$(\mathcal{Z}) \neq \emptyset$ // offer an input
   randomly choose $a \in$ EnvOutput$(\mathcal{Z})$
   send a to IUT
   $\mathcal{Z} := \mathcal{Z}$ After a
2. randomly choose $\delta \in$ Delays$(\mathcal{Z})$ // wait for an output
   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 $o \notin$ ImpOutput$(\mathcal{Z})$ **then return fail**
   else $\mathcal{Z} := \mathcal{Z}$ After o
   else $\mathcal{Z} := \mathcal{Z}$ After δ // no output within δ delay
3. $\mathcal{Z} := \{(s_0, e_0)\}$, **reset** IUT //reset and restart

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

sound and complete in limit

Testing Online in Action



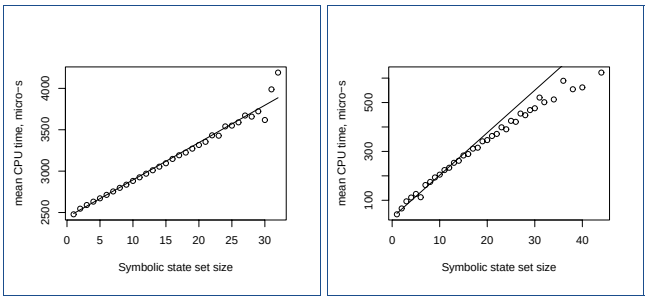
Error Detection Capability: Mutant Experiment

- Specification: train-gate example of 9 timed automata.
- Implementation: 4 threads with a shared queue in C++.
- 7 mutants: M1-M6 with seeded error, M0 correct.

Mutant	Number of input actions			Duration, *mtu*		
	Min	Avg	Max	Min	Avg	Max
M1	2	4.8	16	0	68.8	318
M2	2	4.6	13	1	66.4	389
M3	2	4.7	14	0	66.4	398
M4	6	8.5	18	28	165.0	532
M5	4	5.6	12	14	89.8	364
M6	2	14.1	92	0	299.6	2077
M0	3565	3751.4	3966	10^5	10^5	10^5

Computing Performance (means)

after delay after action

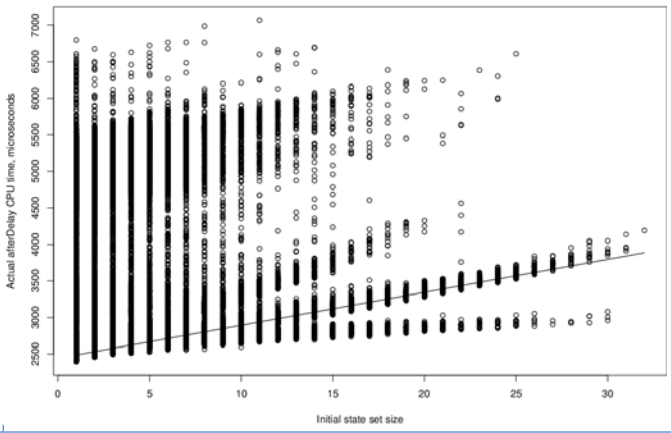


Benchmark Data: Summary

- Executed on Sun SPARC, 8x900MHz, 32GB RAM, Sun Solaris 9.

Mu-	Number of states in $\mathcal{Z}$				CPU execution time, μs			
	After (delay)		After (action)		After (delay)		After (action)	
tant	Avg	Max	Avg	Max	Avg	Max	Avg	Max
M1	2.3	18	2.7	28	1113	3128	141	787
M2	2.3	22	2.8	30	1118	3311	147	791
M3	2.2	22	2.7	30	1112	3392	141	834
M4	**2.8**	24	**3.1**	**48**	1113	3469	125	936
M5	**2.8**	24	**3.3**	**48**	1131	3222	146	919
M6	2.7	27	2.9	36	1098	3531	110	861
M0	**2.7**	31	2.9	**46**	**1085**	3591	**101**	950

Performance Unpredictable: instances



Danfoss Case Study: EKC – Refrigeration Controller

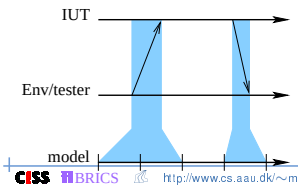
Time Mapping to the Model and Back

- Reachability algorithms for *afterDelay* and *afterAction*:

$$\text{Closure}_{\delta\tau}(\mathcal{Z}, d) = \bigcup_{0 \le \delta \le d} \left\{ \langle \bar{\ell}', z' \rangle \mid \langle \bar{\ell}, z \rangle \in \mathcal{Z},\ \langle \bar{\ell}, z \rangle \xrightarrow{\delta} \langle \bar{\ell}', z' \rangle \right\}$$

$$\mathcal{Z} \text{ After } d = \left\{ \langle \bar{\ell}, z' \rangle \mid \langle \bar{l}, z \rangle \in \text{Closure}_{\delta\tau}(\mathcal{Z}, d),\ z' = \left(z \wedge (t == d)\right)_{t:=0} \right\}$$

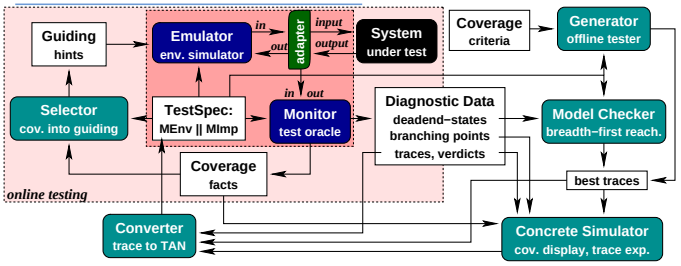
- Everything above works well in controlled-time.
- But in real world, communication doesn't happen instantaneously.
- Clocks at Env/tester and IUT may drift.
- Models of queues and drifts contain non-determinism.



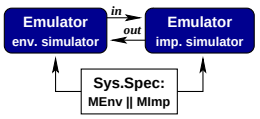
Concluding Remarks

- Online real-time testing theoretically *sound* and *complete in limit*.
- Environment assumptions should be *known* and *explicit*.
- Relativized conformance allows to *minimize cost* of testing.
- *Implemented* in TRON using *efficient* algorithms from UPPAAL.
- Encouraging *error detection* capability and *performance*.
- TRON allows *abstract* and *non-deterministic* specifications.
- *Extreme* non-determinism may degrade performance.
- Testable environments are limited by CPU and comm. latency.
- IUT models just need to be deadlock free and input-enabled.

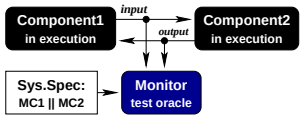
Summary and Future Work



Prototyping via simulation:



Execution monitoring:



Future Work

- Research tasks:
  - Clock synchronization, latency, jitter.
  - Coverage estimation, use coverage in guiding.
  - Diagnostics, fault location.
  - Model learning during experiment.
  - Relativized conformance in interface compatibility: unit testing.
- Engineering tasks:
  - New UPPAAL features (broadcast, committed, U-Code).
  - Termination of testing (specify property expressions?).
  - TRON in monitoring, testing via simulation and monitoring.
  - Relativized conformance in *practice*: specialized applications of generalized controllers, test-case guiding, debugging.
  - Industrial case studies.

Download...

UPPAAL TRON is available for research and non-commercial use at:

http://www.cs.aau.dk/∼marius/tron

Thank You!