École Temps-Réel 2017

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IMITATOR dans une coquille de noix

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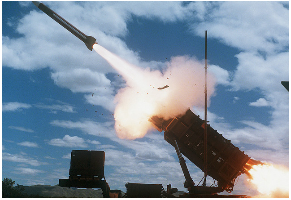
Context: Verifying complex timed systems

- Need for early bug detection
  - Bugs discovered when final testing: expensive
  - $\rightsquigarrow$ Need for a thorough specification and verification phase



Outline

Outline: Parametric timed automata in a nutshell

Beyond timed model checking: parameter synthesis

- Verification for one set of constants does not usually guarantee the correctness for other values

- Challenges
  - Numerous verifications: is the system correct for any value within $[40; 60]$?
  - Optimization: until what value can we increase 10?
  - Robustness [Markey, 2011]: What happens if 50 is implemented with 49.99?
  - System incompletely specified: Can I verify my system even if I don't know the period value with full certainty?

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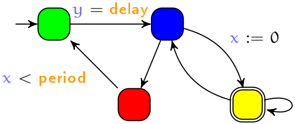
- Parameter synthesis
  - Consider that timing constants are unknown constants (parameters)

timed model checking



$\overset{?}{\models}$

 is unreachable

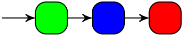
A model of the system

A property to be satisfied

- Question: does the model of the system satisfy the property?

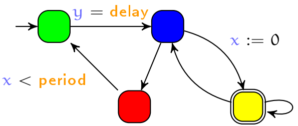
Yes

No



Counterexample

Parametric timed model checking



$\overset{?}{\models}$

 is unreachable

A model of the system

A property to be satisfied

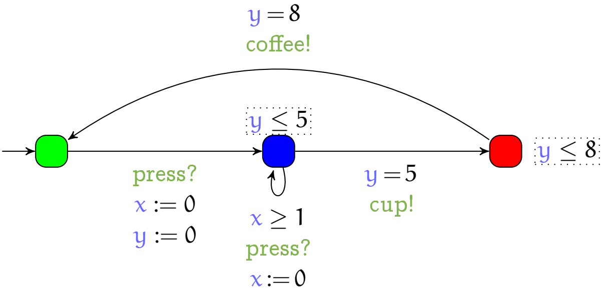
- Question: for what values of the parameters does the model of the system satisfy the property?

Yes if. . .

$$2\text{delay} > \text{period} \land \text{period} < 20.46$$

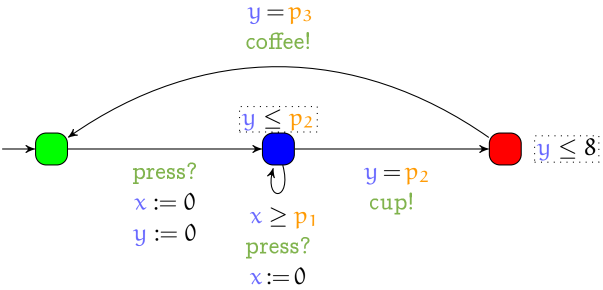
Parametric Timed Automaton (PTA)

- Timed automaton (sets of locations, actions and clocks)



Parametric Timed Automaton (PTA)

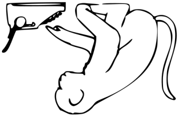
- Timed automaton (sets of locations, actions and clocks) augmented with a set P of parameters [Alur et al., 1993]
  - Unknown constants compared to a clock in guards and invariants



Outline

IMITATOR

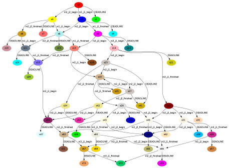
- A tool for modeling and verifying real-time systems with unknown constants
- Input language: parametric timed automata extended with
  - Communication through (strong) broadcast synchronization
  - Rational-valued shared discrete variables
  - Stopwatches, to model schedulability problems with preemption

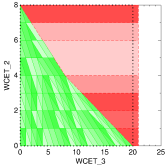


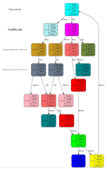
Features of IMITATOR

- Algorithms implemented in IMITATOR
  - Computation of the symbolic state space
  - (non-Zeno) parametric model checking (using a subset of TCTL)
  - Language and trace preservation, and robustness analysis
  - Parametric deadlock-freeness checking
  - Behavioral cartography

- Graphical output







Inside IMITATOR

- Entirely programmed in OCaml
- Polyhedral operations computed using the Parma Polyhedra Library [Bagnara et al., 2008]
- Free and open source software: Available under the GNU-GPL license

IMITATOR: download and benchmarks

Under continuous development since 2008 [André et al., 2012]

A library of benchmarks

- Communication protocols
- Schedulability problems
- Asynchronous circuits
- . . . and more

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Try it!

www.imitator.fr

Some success stories using IMITATOR

- Modeled and verified an asynchronous memory circuit by ST-Microelectronics
  - Project ANR Valmem
- Parametric schedulability analysis of a prospective architecture for the flight control system of the next generation of spacecrafts designed at ASTRIUM Space Transportation [Fribourg et al., 2012]
- Formal timing analysis of music scores [Fanchon and Jacquemard, 2013]
- Solution to a challenge related to a distributed video processing system by Thales

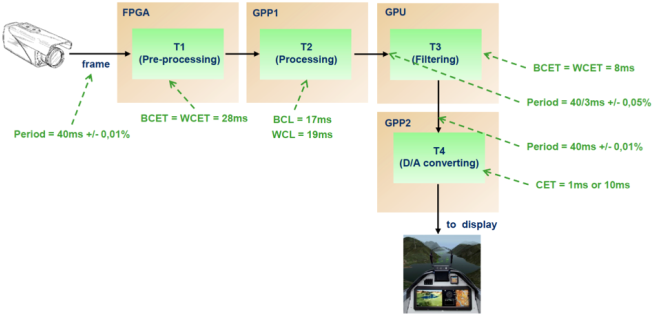
Outline

The FMTV 2015 Challenge (1/2)

Challenge by Thales proposed during the WATERS 2014 workshop
Solutions presented at WATERS 2015

System: an unmanned aerial video system with uncertain periods

- Period constant but with a small uncertainty (typically 0.01 %)
- Not a jitter!



The FMTV 2015 Challenge (2/2)

Goal

Compute the end-to-end BCET and WCET times for a buffer size of $n = 1$ and $n = 3$

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- ☹ Not a typical parameter synthesis problem?
  - No parameters in the specification

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Goal

Compute the end-to-end BCET and WCET times for a buffer size of $n = 1$ and $n = 3$

☹ Not a typical parameter synthesis problem?

- No parameters in the specification

☺ A typical parameter synthesis problem

- The end-to-end time can be set as a parameter… to be synthesized
- The uncertain period is typically a parameter (with some constraint, e. g., $P1 \in [40 - 0.004, 40 + 0.004]$)

Methodology

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Note: not eliminating parameters allows one to know for which values of the periods the best / worst case execution times are obtained.

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6. Exhibit the minimum and the maximum

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To build the PTA model

- Uncertainties in the system:
  - $P1 \in [40 - 0.004, 40 + 0.004]$
  - $P3 \in [\frac{40}{3} - \frac{1}{150}, \frac{40}{3} + \frac{1}{150}]$
  - $P4 \in [40 - 0.004, 40 + 0.004]$

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- Parameters:
  - P1_uncertain
  - P3_uncertain
  - P4_uncertain

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  - $P4 \in [40 - 0.004, 40 + 0.004]$
- Parameters:
  - P1_uncertain
  - P3_uncertain
  - P4_uncertain
- The end-to-end latency (another parameter): E2E
- Others:
  - the register between task 2 and task 3: discrete variable $reg_{2,3}$
  - the buffer between task 3 and task 4: $n = 1$ or $n = 3$

Simplification

- T1 and T2 are synchronised; T1, T3 and T4 are asynchronised
  - (exact modeling of the system behaviour is too heavy)

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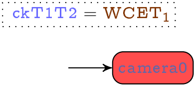
- T1 and T2 are synchronised; T1, T3 and T4 are asynchronised
  - (exact modeling of the system behaviour is too heavy)
- We choose a single arbitrary frame, called the target one
- We assume the system is initially in an arbitrary status
  - This is our only uncertain assumption (in other words, can the periods deviate from each other so as to yield any arbitrary deviation?)

The initialization automaton



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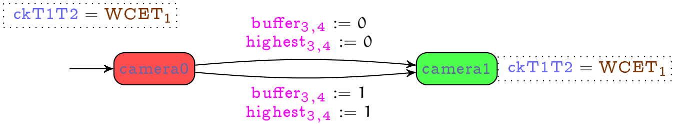

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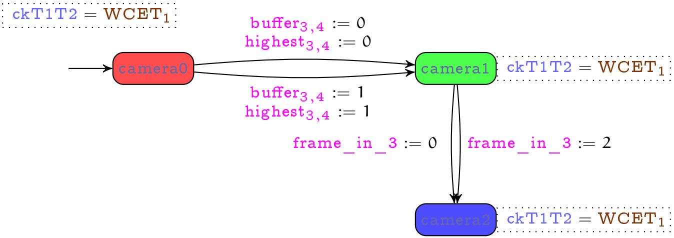

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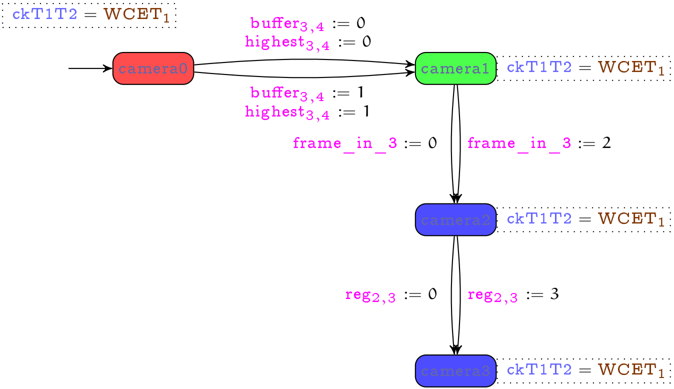

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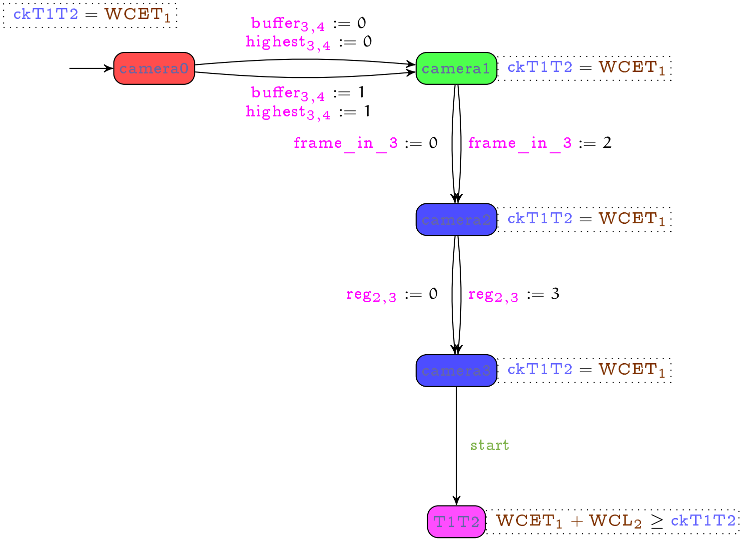

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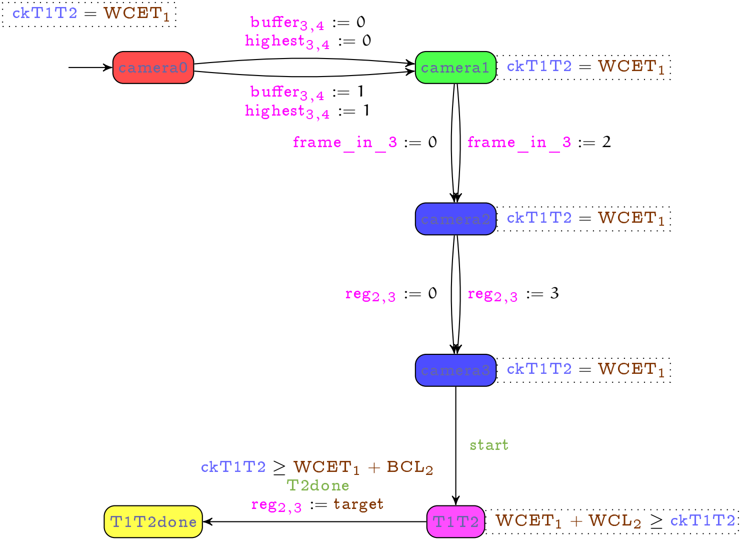

Task T3

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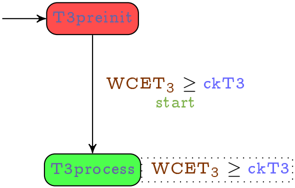
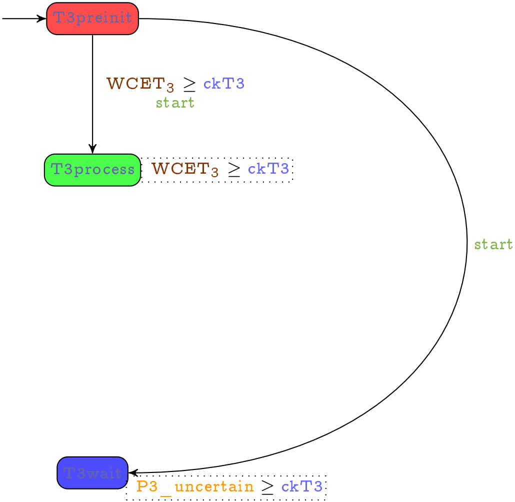
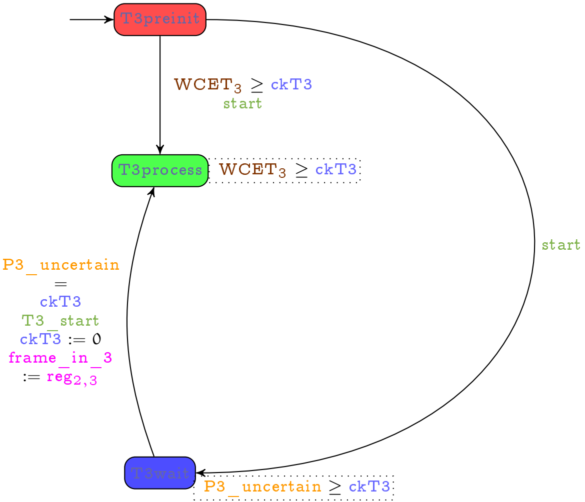


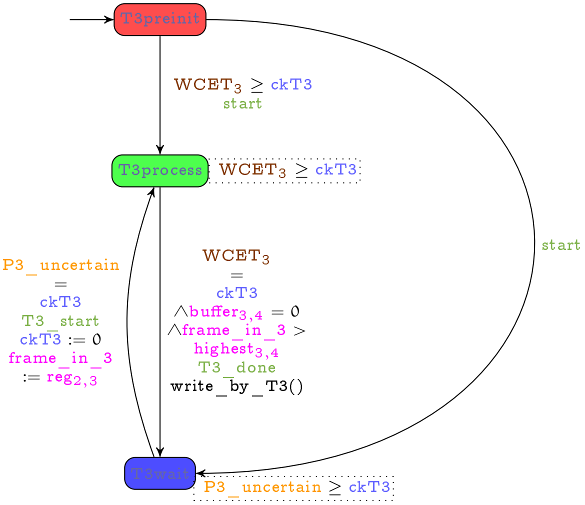
Task T3


T3preinit
WCET3 ≥ ckT3
start
T3process
WCET3 ≥ ckT3
start
T3wait
P3_uncertain ≥ ckT3

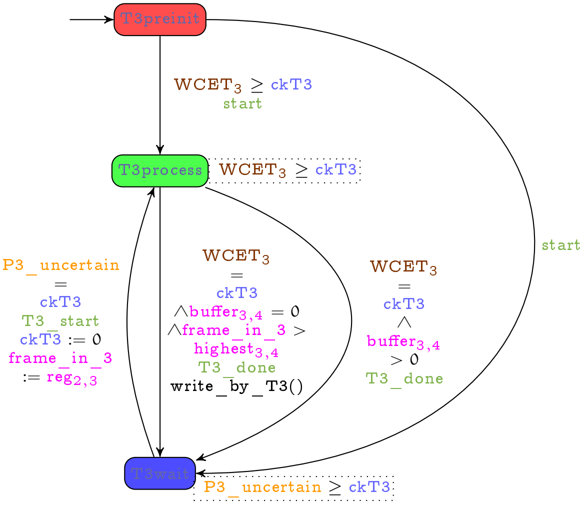
Task T3


T3preinit
WCET_3 ≥ ckT3
start
T3process
WCET_3 ≥ ckT3
start
P3_uncertain
=
ckT3
T3_start
ckT3 := 0
frame_in_3
:= reg_{2,3}
T3wait
P3_uncertain ≥ ckT3

Task T3


T3preinit
WCET3 ≥ ckT3
start
T3process
WCET3 ≥ ckT3
start
P3_uncertain
=
ckT3
T3_start
ckT3 := 0
frame_in_3
:= reg2,3
WCET3
=
ckT3
∧buffer3,4 = 0
∧frame_in_3 >
highest3,4
T3_done
write_by_T3()
T3wait
P3_uncertain ≥ ckT3

Task T3


T3preinit
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T3process
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buffer3,4
> 0
T3_done
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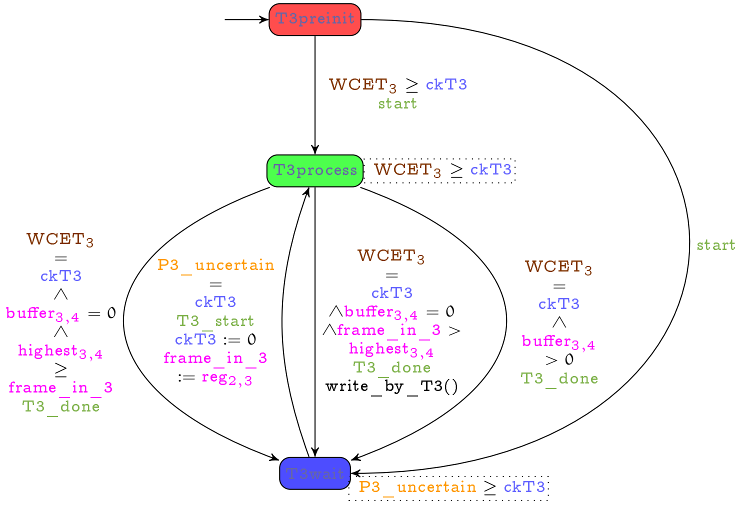
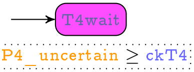
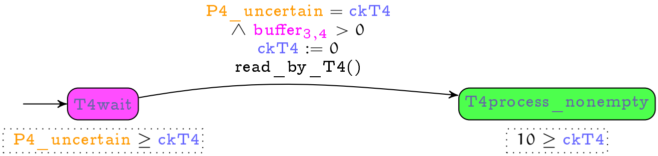
Task T3


T3preinit
WCET_3 ≥ ckT3
start
T3process
WCET_3 ≥ ckT3
start
WCET_3 = ckT3 ∧ buffer_{3,4} = 0 ∧ highest_{3,4} ≥ frame_in_3
T3_done
P3_uncertain = ckT3
T3_start
ckT3 := 0
frame_in_3 := reg_{2,3}
WCET_3 = ckT3 ∧buffer_{3,4} = 0 ∧frame_in_3 > highest_{3,4}
T3_done
write_by_T3()
WCET_3 = ckT3 ∧ buffer_{3,4} > 0
T3_done
T3wait
P3_uncertain ≥ ckT3

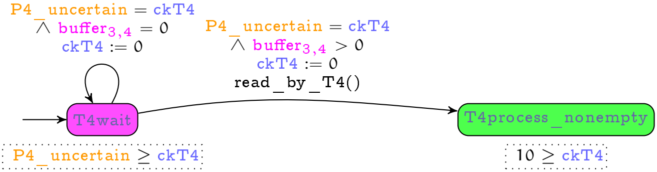
Task T4



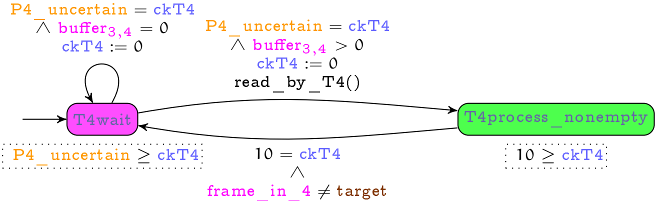
Task T4


P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 ≥ ckT4

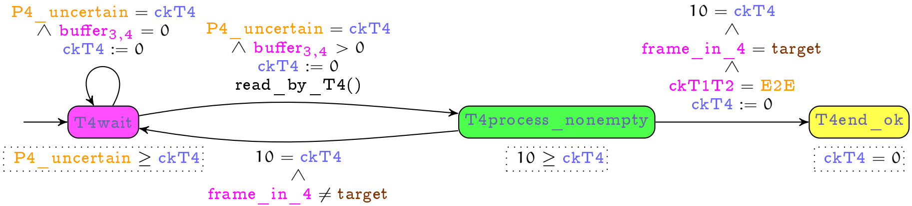
Task T4


P4_uncertain = ckT4
∧ buffer_{3,4} = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer_{3,4} > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 ≥ ckT4

Task T4


P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
T4wait
T4process_nonempty
P4_uncertain ≥ ckT4
10 = ckT4
∧
frame_in_4 ≠ target
10 ≥ ckT4

Task T4


P4_uncertain = ckT4
∧ buffer3,4 = 0
ckT4 := 0
P4_uncertain = ckT4
∧ buffer3,4 > 0
ckT4 := 0
read_by_T4()
10 = ckT4
∧
frame_in_4 = target
∧
ckT1T2 = E2E
ckT4 := 0
T4wait
T4process_nonempty
T4end_ok
P4_uncertain ≥ ckT4
10 = ckT4
∧
frame_in_4 ≠ target
10 ≥ ckT4
ckT4 = 0

Results

E2E latency results for $n = 1$ and $n = 3$

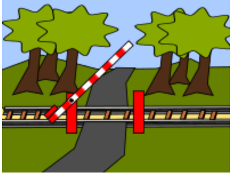
	$n = 1$	$n = 3$
min E2E	63 ms	63 ms
max E2E	145.008 ms	225.016 ms

Results obtained using IMITATOR in a few seconds

Outline

Outline of the practical session

1. Perform parameter synthesis for a railway crossing system



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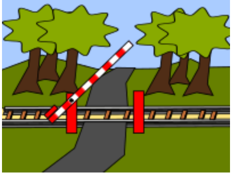

2. Specify and verify the coffee machine

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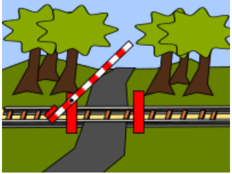


2. Specify and verify the coffee machine

3. . . . and if you are fast: a free bonus exercise!

Bibliography

References I

Alur, R., Henzinger, T. A., and Vardi, M. Y. (1993).
Parametric real-time reasoning.
In *STOC*, pages 592–601. ACM.

André, É., Fribourg, L., Kühne, U., and Soulat, R. (2012).
IMITATOR 2.5: A tool for analyzing robustness in scheduling problems.
In *FM*, volume 7436 of *LNCS*, pages 33–36. Springer.

Bagnara, R., Hill, P. M., and Zaffanella, E. (2008).
The Parma Polyhedra Library: Toward a complete set of numerical abstractions for the analysis and verification of hardware and software systems.
Science of Computer Programming, 72(1–2):3–21.

Fanchon, L. and Jacquemard, F. (2013).
Formal timing analysis of mixed music scores.
In *ICMC (International Computer Music Conference)*.

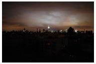
Fribourg, L., Lesens, D., Moro, P., and Soulat, R. (2012).
Robustness analysis for scheduling problems using the inverse method.
In *TIME*, pages 73–80. IEEE Computer Society Press.

References II

Markey, N. (2011).
Robustness in real-time systems.
In *SIES*, pages 28–34. IEEE Computer Society Press.

Additional explanation

Explanation for the 4 pictures in the beginning



Allusion to the Northeast blackout (USA, 2003)
Computer bug
Consequences: 11 fatalities, huge cost
(Picture actually from the Sandy Hurricane, 2012)

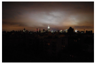
Error screen on the earliest versions of Macintosh

Allusion to the sinking of the Sleipner A offshore platform (Norway, 1991)
No fatalities
Computer bug: inaccurate finite element analysis modeling
(Picture actually from the Deepwater Horizon Offshore Drilling Platform)

Allusion to the MIM-104 Patriot Missile Failure (Iraq, 1991)
28 fatalities, hundreds of injured
Computer bug: software error (clock drift)
(Picture of an actual MIM-104 Patriot Missile, though not the one of 1991)

Licensing

Source of the graphics used I



Title: Hurricane Sandy Blackout New York Skyline
Author: David Shankbone
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Author: Przemub
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Author: imcomkorea
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Source of the graphics used II

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Author: LadyofHats
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Title: Smiley green alien big eyes (cry)
Author: LadyofHats
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Title: Krups Vivo F880 home espresso maker
Author: Mike1024
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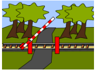

Title: Skizze eines offenen Bahnüberganges
Author: MichaelFrey
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