FMICS+AVoCS 2017

Monday 18th September 2017
Torino, Italia

A unified formalism for monoprocessor schedulability analysis under uncertainty

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PROJET FINANCÉ PAR L'ANR - PROJECT FUNDED BY THE ANR

Context: Verifying critical real-time systems

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- Systems for which not only the correctness but also the timely answer is important

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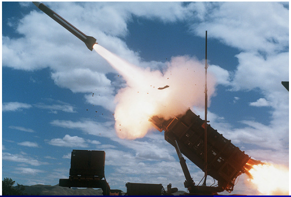
- Critical real-time systems:
  - Systems for which not only the correctness but also the timely answer is important
  - Failures (in correctness or timing) may result in dramatic consequences






Real-time system

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A task is characterized by:

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- W: its worst-case execution time
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Tasks have instances that can be activated...

- periodically
- sporadically (usually with a minimum interarrival time)
- or following more complex patterns (e. g., activation following the completion of another task instance)

Scheduler

Activated instances are queued

When the processor is idle, which instance in the queue should be executed?

$\rightsquigarrow$ decision made by the scheduler

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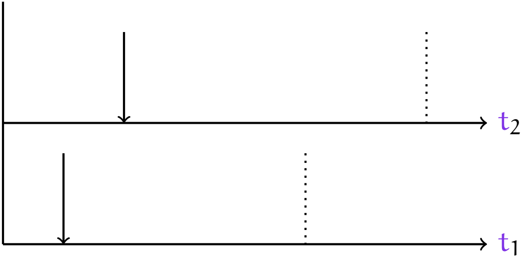
The scheduler can be preemptive

- The execution of a lower priority task can be interrupted when a instance of a task with higher priority is activated
- After completion of the higher priority task, the lower priority task resumes

Example: preemptive fixed priority scheduler (FPS)

Task	B	W	D	priority
t_1	3	3	4	low
t_2	2	2	5	high



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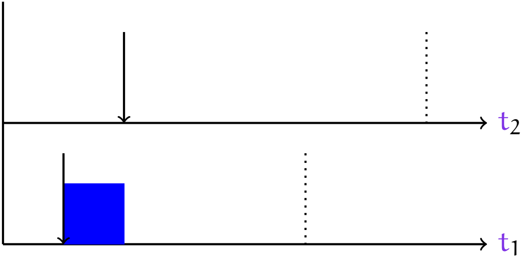

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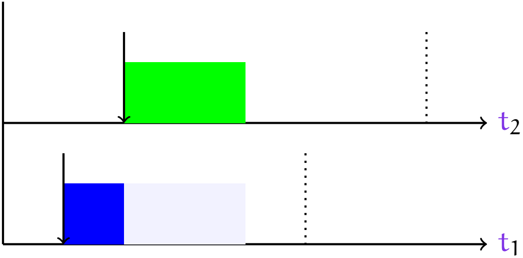

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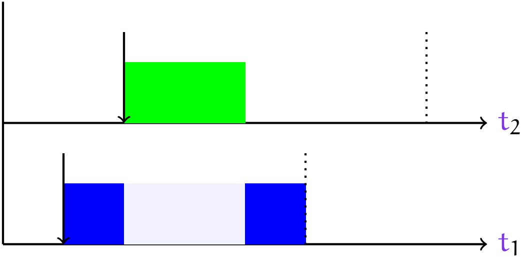

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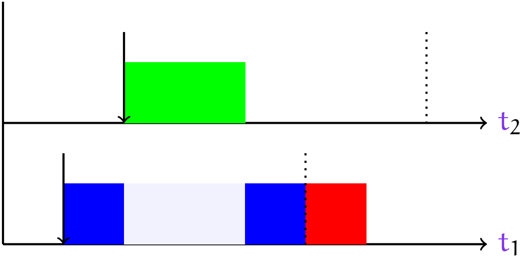

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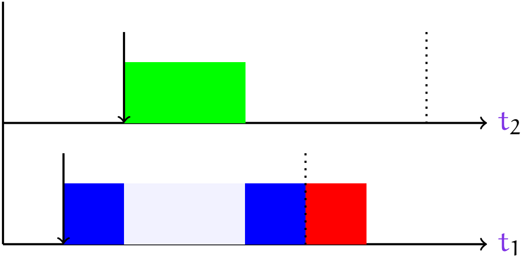

Task t_1 misses its deadline

Example: earliest deadline first (EDF)

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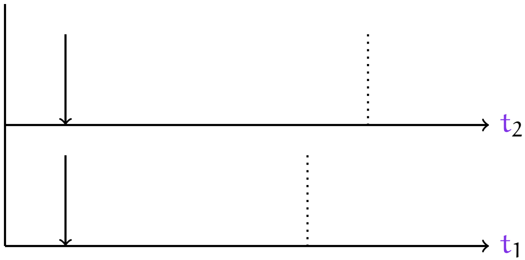

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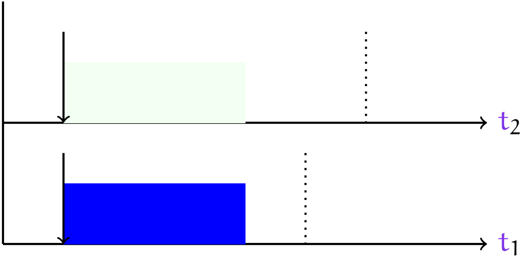

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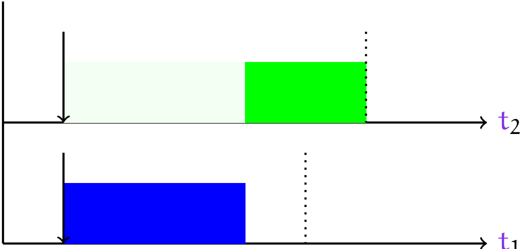

Example: shortest job first (SJF)

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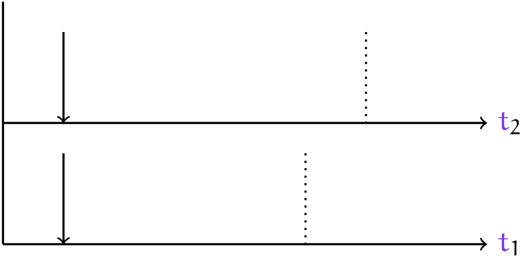

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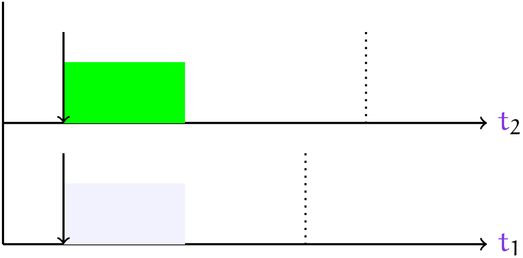

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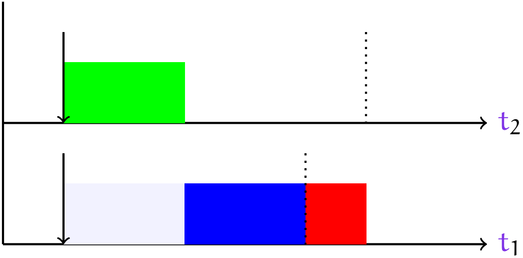

Task t_1 misses its deadline

Schedulability analysis

Definition (schedulability analysis)

Given a real-time system and a scheduling policy, the schedulability analysis checks whether the system is schedulable (i. e., all tasks meet their deadline) *for all possible behaviors*.

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All possible behaviors:

- Depends on the periods, interarrival rates, dependencies between tasks. . .

Problem: schedulability analysis under uncertainty

Problem: what if some timing constants (deadlines, execution times, periods, interarrival times...) are unknown or known with a limited precision?

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Objective

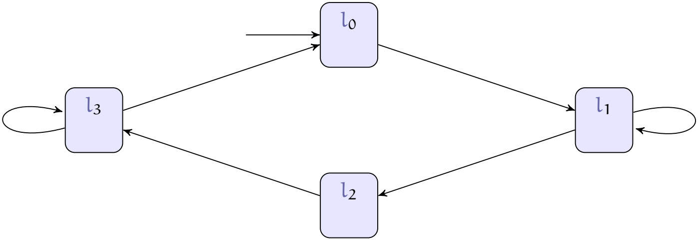
Propose a framework for the monoprocessor schedulability analysis of real-time systems under uncertainty

Outline

Outline: Parametric task automata

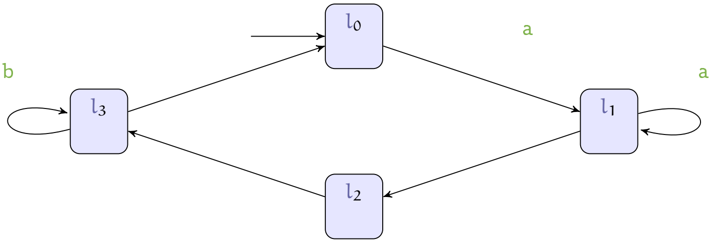
Task automaton (TaskA)

- Finite state automaton (sets of locations)



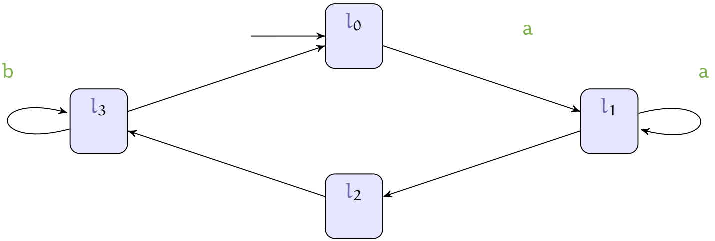
Task automaton (TaskA)

- Finite state automaton (sets of locations and actions)



Task automaton (TaskA)

- Finite state automaton (sets of locations and actions) with a set X of clocks as in timed automata [Alur and Dill, 1994]
  - Real-valued variables evolving linearly at the same rate



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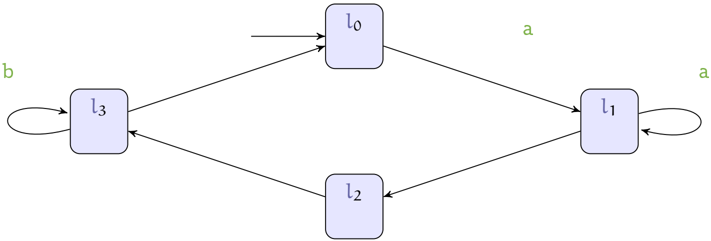

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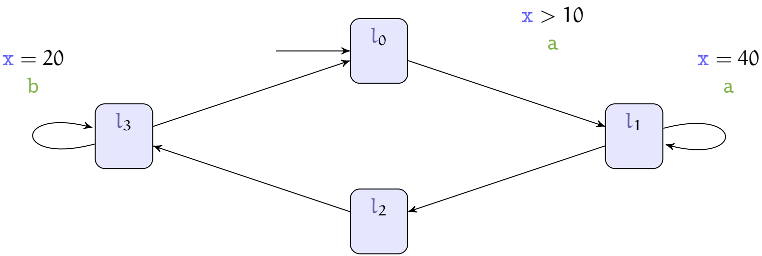

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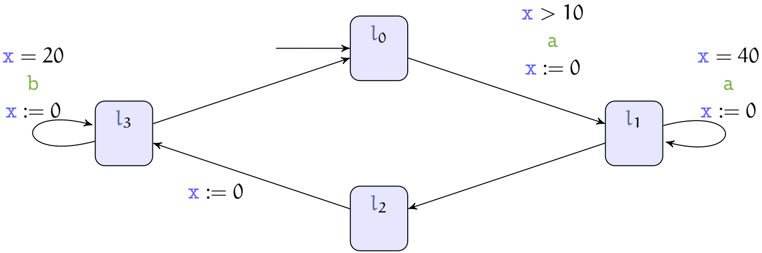

Task automaton (TaskA)

- Finite state automaton (sets of locations and actions) with
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  a set $\mathcal{T}$ of tasks [Norström et al., 1999, Fersman et al., 2007]
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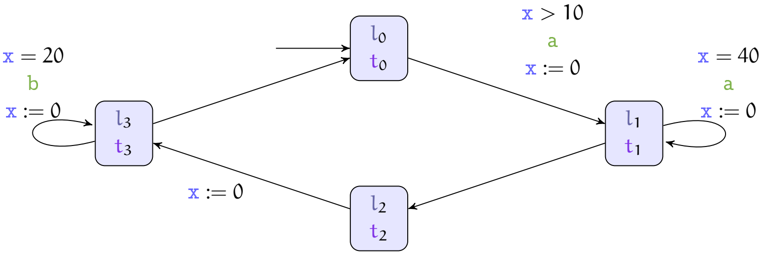


Concrete semantics of task automata

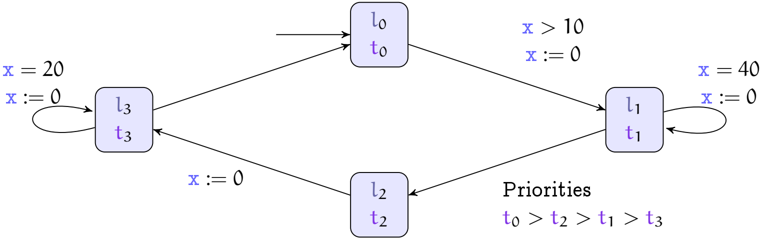
- Concrete state of a TaskA: triple (l, w, q), where
  - l is a location,
  - w is a valuation of each clock
  - q is a task queue made of instances of $\mathcal{T}$
    - Instance: task, remaining BCET and WCET, remaining deadline

  Example: $\left(l_1, \binom{x=1.2}{y=3.7}, \left[(t_0, 0, 0.5, 1.5), (t_1, 4, 4, 18.5)(t_1, 4, 4, 19.5)\right]\right)$

- Concrete run: alternating sequence of concrete states and actions or time elapse according to a given scheduler

Parametric task automaton (PTaskA)

- Task automaton



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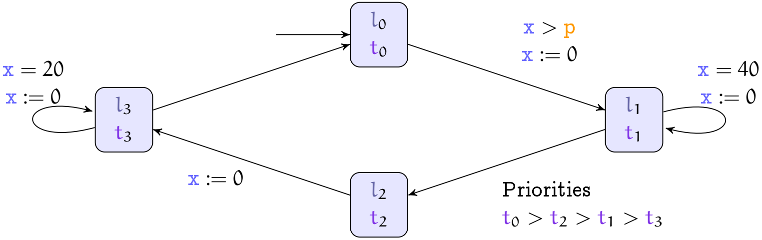
Parametric task automaton (PTaskA)

- Task automaton extended with a set P of timing parameters, that can be used
  - in the automaton, and/or
  - in the tasks B, W and D



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Problems of interest

Parametric task automata can model real-time systems...

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Some problems of interest

- For what values of the parameters is the system schedulable?
- Or even can we find at least one such valuation?
- Or is the system robustly schedulable? [Markey, 2011]

Outline: Decidability and undecidability

Decision problem

Schedulability-emptiness problem:

INPUT: A PTaskA $\mathcal{A}$ and a scheduling strategy Sch

PROBLEM: is the set of valuations v for which $v(\mathcal{A})$ is schedulable for strategy Sch empty?

An undecidability result

Theorem (Undecidability)

The schedulability-emptiness problem is undecidable for general PTaskA.

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Two reasons:

- Parametric task automata are at least as expressive as parametric timed automata [Alur et al., 1993] for which most non-trivial problems are undecidable [André, 2017]
- The schedulability of general non-parametric task automata is undecidable [Fersman et al., 2007] (in particular when using preemption)

Restricting a bit the formalism

Definition

A PTaskA has schedulable-bounded parameters if, for each task t, its worst-case execution time W is bounded in $[a, \infty)$ or $[a, b]$ with $a > 0$, and its deadline D is bounded in $[a, b]$, with $a, b \geq 0$.

Necessary to bound the task queue

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Definition

A PTaskA is an L/U-PTaskA if its parameters set is partitioned into lower-bound parameters (i. e., of the form $p < x$ or $p \leq x$) and upper-bound parameters (i. e., of the form $p > x$ or $p \geq x$).

Similar to L/U-parametric timed automata [Hune et al., 2002]

A decidability result

Theorem (Decidability)

The schedulability-emptiness problem is decidable for L/U-PTaskAs with schedulable-bounded parameters

1. *for non-preemptive* FPS *and* SJF, *and*
2. *non-preemptive* EDF *without parametric deadlines.*

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Proof idea

Reusing the encoding of [Norström et al., 1999, Fersman et al., 2007] together with a decidability result for L/U-parametric timed automata proved in [André, 2017]

Outline: Schedulability under uncertainty

Parametric schedulability with parametric TaskA

Parametric schedulability reduces to reachability synthesis

- "Synthesize parameter valuations for which a deadline violation is reachable"
- Transform to parametric stopwatch automata [Sun et al., 2013]
  - The PTaskA itself can be seen as a parametric timed automaton
  - Any common scheduler can be transformed into a parametric stopwatch automaton
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Undecidable in general… but we adopt a pragmatic approach and can use semi-algorithms or approximations

A practical encoding

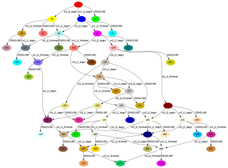
In practice, we use extensions of parametric stopwatch automata

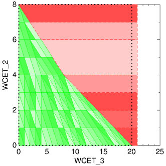
- Discrete global integer-valued variables (to model the queue)
- Extensive use of stopwatches
  - Also helps to reduce the state space!

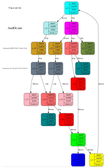
Automatic translation of the scheduler into the IMITATOR input format

IMITATOR

- A tool for modeling and verifying real-time systems with unknown constants modeled with parametric timed automata[Alur et al., 1993]
  - Communication through (strong) broadcast synchronization
  - Rational-valued shared discrete variables
  - Stopwatches, to model schedulability problems with preemption
- Verification
  - 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







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

A library of benchmarks

- Communication protocols
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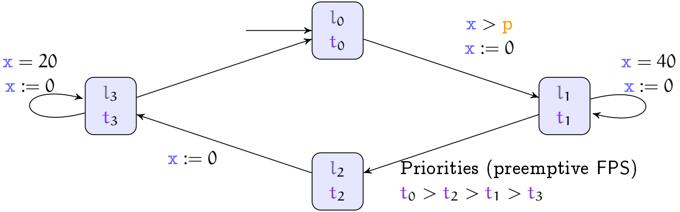
Try it!

www.imitator.fr

Parametric schedulability analysis



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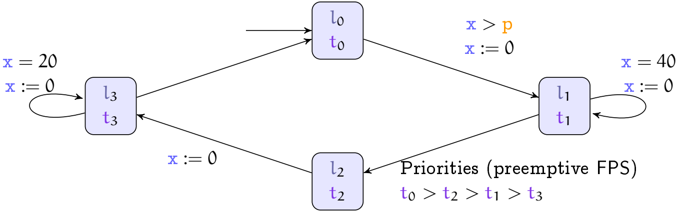
For which values of p and p' is the system schedulable?

Parametric schedulability analysis



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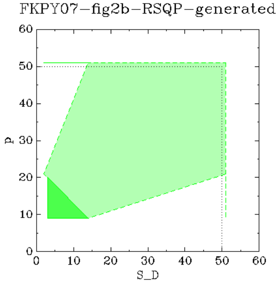
For which values of p and p' is the system schedulable?

$$p \geq 9 \wedge p' \geq 2 \wedge p + p' \geq 23$$
$$\vee$$
$$p \geq 9 \wedge p' \geq 3 \wedge p + p' < 23$$



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Methodology:

1. Replace any guard $x \leq c$ with $x \leq c + \epsilon$
2. Replace any guard $x \geq c$ with $x \geq c - \epsilon$
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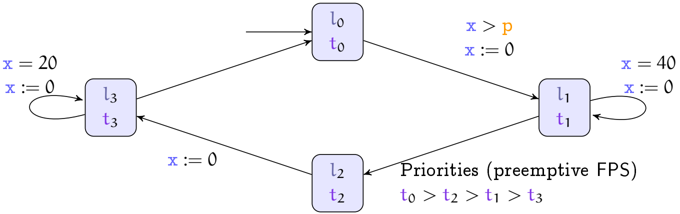
For our TaskA (fixing $p = 10$ and $p' = 4$), we get $\epsilon = 0$

Parametric schedulability and robustness



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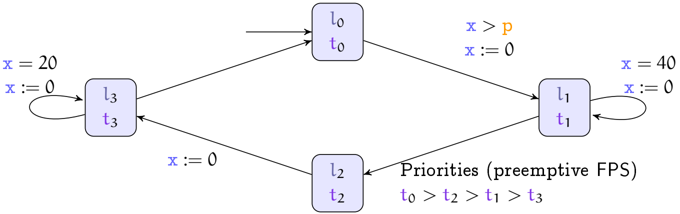
Parametric schedulability and robustness



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For which values of p is the system robustly schedulable?

$$p \geq 9 \wedge \epsilon = 0$$
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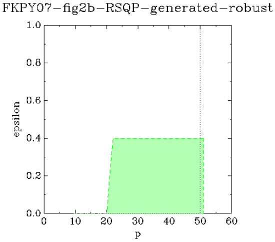
$$\epsilon \leq \frac{2}{5} \wedge p \geq 20 + 5\epsilon \wedge p \geq 19 + 8\epsilon$$



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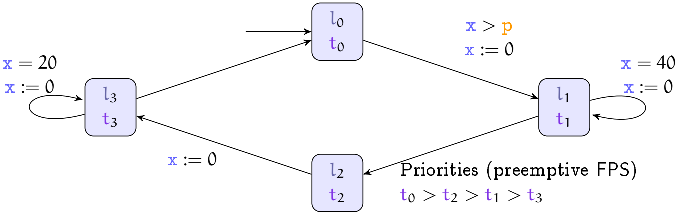

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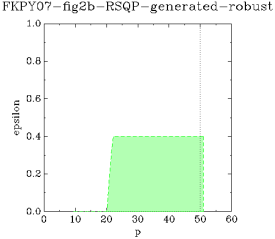


We even know by how the system is robust (depending on p and ϵ)

Outline: Conclusion and perspectives

Conclusion

Parametric task automata

- A unified, compact and expressive formalism to model and verify real-time systems under uncertainty
- ☹ Some undecidability results
- ☺ Some decidability results

Allow for

- Parametric schedulability
- Robustness analysis
- Robust parametric schedulability

Implementation in IMITATOR using an automated translation of the scheduler

Perspectives

Fill the decidability gap

- Still some unknown between decidability and undecidability results
- Our examples all fit into the undecidability cases... but analysis terminates with an exact answer

Design patterns for TaskA

- Allow to build periodic tasks, sporadic tasks... easily using predefined building blocks

Multiprocessor

- Extend the formalism to multiprocessor schedulability analysis

Mixed-criticality scheduling

Bibliography

References I

Alur, R. and Dill, D. L. (1994).
A theory of timed automata.
Theoretical Computer Science, 126(2):183–235.

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

André, É. (2017).
What's decidable about parametric timed automata?
International Journal on Software Tools for Technology Transfer.
To appear.

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.

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

References II

Fersman, E., Krcál, P., Pettersson, P., and Yi, W. (2007).
Task automata: Schedulability, decidability and undecidability.
Information and Computation, 205(8):1149–1172.

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.

Hune, T., Romijn, J., Stoelinga, M., and Vaandrager, F. W. (2002).
Linear parametric model checking of timed automata.
Journal of Logic and Algebraic Programming, 52-53:183–220.

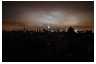
Markey, N. (2011).
Robustness in real-time systems.
In *SIES*, pages 28–34. IEEE Computer Society Press.

Norström, C., Wall, A., and Yi, W. (1999).
Timed automata as task models for event-driven systems.
In *RTCSA*, pages 182–189. IEEE Computer Society.

Sun, Y., Soulat, R., Lipari, G., André, É., and Fribourg, L. (2013).
Parametric schedulability analysis of fixed priority real-time distributed systems.
In *FTSCS*, volume 419 of *CCIS*, pages 212–228. Springer.

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)

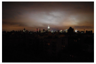
Allusion to the MIM-104 Patriot Missile Failure (Iraq, 1991)
28 fatalities, hundreds of injured
Computer bug: software error (clock drift)
(Picture of an actual MIM-104 Patriot Missile, though not the one of 1991)

Some success stories with 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

Licensing

Source of the graphics used I



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Author: David Shankbone
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Source of the graphics used II

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