Enhanced Distributed Behavioral Cartography of Parametric Timed Automata

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Context: Formal Verification of Timed Systems (1/3)

- Need for early bug detection
  - Bugs discovered when final testing: expensive
  - Need for a thorough modeling and verification phase
Context: Formal Verification of Timed Systems (2/3)

- Use formal methods

A model of the system

AG→

A property to be satisfied
Use formal methods

A model of the system

A property to be satisfied

Question: does the model of the system satisfy the property?
Context: Formal Verification of Timed Systems (2/3)

- Use formal methods

A model of the system

A property to be satisfied

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

Yes

No

Counterexample
Context: Formal Verification of Timed Systems (3/3)

- Problem: But *state space explosion* is always painful! Especially real-time systems.
Problem: But state space explosion is always painful! Especially real-time systems.

One solution:
- Extend to distributed fashion
Outline

1. Behavioral Cartography of Timed Automata

2. Distributing BC

3. State of The Art: Previous Distributed BC Algorithms

4. Enhanced Distributed BC Algorithm

5. Experimental Validation

6. Conclusion and Perspectives
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**Parametric Timed Automata (PTA)**

A formalism to model and verify concurrent real-time systems

[Alur et al., 1993]

- **x**: Clock
- **p**: Parameters allow to represent unknown values (e.g., a transmission delay or a timeout)
Behavioral Cartography (BC)

- **BC**: Partitions a parameter domain into tiles, i.e., parametric zones of uniform behavior [André and Fribourg, 2010]
- **Method**: enumerate integer points and generate a tile using an existing algorithm (the inverse method IM)
- All parameter valuations in a tile have the same possible behaviors (same “trace set”), and verify the same linear-time properties
Behavioral Cartography: Example
Behavioral Cartography: Example
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Behavioral Cartography: Example
An $n$-dimension analysis

Tile (constraints)

Parameter Valuation

Tile
(2 dimensions)

Tile
-Polyhedron
($n$ dimensions)
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Problem: BC is very slow! (up to several hours)
Goal: distribute BC on a cluster to increase the computation speed
Problem 1: the general shape of the Cartography is unknown in general. And the time to compute each tile varies a lot (more or less complex trace sets).
Distributing BC: Problems 2 and 3

Problem 2: two close points will very probably yield the same tile (loss of efficiency)
Distributing BC: Problems 2 and 3

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Problem 3: Should we stop a process when its reference point ("$\pi_2$") was covered by another tile ("$K_1$")?
Distributing BC: Problems 2 and 3

Problem 2: two close points will very probably yield the same tile (loss of efficiency)

Problem 3: Should we stop a process when its reference point (“$\pi_2$”) was covered by another tile (“$K_1$”)?
**Distributing BC: Problems 2 and 3**

**Problem 2:** two close points will very probably yield the same tile (loss of efficiency)

**Problem 3:** Should we stop a process when its reference point (“π₂”) was covered by another tile (“K₁”)?
Distributing BC: Problems 2 and 3

Problem 2: two close points will very probably yield the same tile (loss of efficiency)

Problem 3: Should we stop a process when its reference point (“π2”) was covered by another tile (“K1”)?
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Master Workers Scheme

Traditional Master-Worker communication scheme:  [André, Coti, Evangelista, 2014]

- **Workers**: ask the master for a point, and send the result (“tiles”) to the master
- **Master**: is responsible for **smart repartition** of data between the workers
Previous Point-based BC Algorithms

Point-based BC algorithms:

- **Sequential**: each point is sent to a worker sequentially
- **Random**: points selected randomly, then switches to Sequential
- **Shuffle**: similar to the Sequential, but the difference is that master must statically compute the list of all points, then shuffle all points, then store them in array (new)
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Subpart-based BC Algorithm Scheme

“Domain decomposition” scheme

- **Master**
  1. initially splits the parameter domain into **subparts** and send them to the workers
  - **Subpart**: a subdomain of the parameter domain
  2. when a worker has completed its subpart, the master splits another subpart, and sends it to the idle worker

- **Workers**
  1. receives the subpart from the master
  2. calls IM on the points of this subpart
  3. sends the results (tiles) back to the master
  4. asks for more work
Subpart-based Distribution Scheme: Initial Splitting

- Solved Problem 2! (prevent to choose close points)
- Prevent bottleneck phenomenon at the master side
  - Master only responsible for gathering tiles and splitting subparts
Enhanced Distributed BC Algorithm

Subpart-based Distribution Scheme: Dynamic Splitting

- Master can balance workload between workers

Worker2 (Finished)

Master (Splitting)

Worker1 (Working)

Master send split subpart to the worker2

Worker1 (Calling IM)
Violation Detection – Heuristic (1/2)

Violation detection: a mechanism to detect and stop process which is calling point in the covered tile.
Violation Detection – Heuristic (2/2)

- Solution proposed: stop immediately when the reference point ("\(\pi_2\)") is covered by another tile ("\(C_1\)"

- Workers have ability to self-detects violation

- Is an answer to the previous Problem 3 ("what to do when a point is covered by another tile?")

- Can be used for all previous algorithms
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**Implementation in IMITATOR**

- **IMITATOR** [André, Fribourg, Kühne, Soulat, 2012]
  - 26,000 lines of OCaml code
    - Including > 3,000 lines for the distribution algorithms
  - Relies on the PPL library for operations on polyhedra [Bagnara et al., 2008]
  - Available under the GNU-GPL license at www.imitator.fr
  - Stable version (2.6.2) integrated in CosyVerif [AHHKLLP13]

- Distributed version of IMITATOR relying on MPI
  - Using the OcamlMPI library for passing messages between Master and Workers
Implementation in IMITATOR

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- Distributed version of IMITATOR relying on MPI
  - Using the OcamlMPI library for passing messages between Master and Workers
  - … in which we found a bug!
Experimental Validation

Experimental conducted on a real cluster ("Magi") in the Paris 13 University
Average computation time for a set of case studies, for 4/12/32/64 nodes:

![Graph showing computation times for different configurations.]

Our new algorithm always outperforms existing algorithms.
From Amdahl’s law, we have $SpeedUp = \frac{T_s}{T_d}$ (Higher is better)

$T_s$: is run time with single process (sequential)

$T_d$: is run time with multi-processes (distributed)
**Efficiency Chart Diagram**

\[ \text{Efficiency} = \frac{T_s}{N \times T_d} = \frac{\text{SpeedUp}}{N} \]  
(Higher is better)

N: is number of processes ("nodes")

Efficiency decreases while number of processes increase

=> loss of efficiency
Conclusion and Perspectives

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Conclusion and Perspectives

- **Conclusion:**
  - Proposed a new efficient distributed algorithm (Subpart) for Behavioral Cartography
  - Proposed a new heuristic approach improving all BC distribution algorithms
  - Proposed solutions to our three problems
  - Implemented the new algorithm in IMITATOR

- **Future works:**
  - We will attempt to achieve a more efficient algorithm
  - Design an autonomous distribution scheme for BC
  - Improve heuristics
  - Try BC in GPU’s or CPU+GPU’s environment
  - ...and prove the deadlock-freeness of our master-worker communication scheme!
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The Parma Polyhedra Library: Toward a complete set of numerical abstractions for
the analysis and verification of hardware and software systems.
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)
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Source of the graphics used II

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