Runtime verification of real-time applications using trace data and model requirements

Progress Report Meeting
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Raphaël BEAMONTE   Michel DAGENAIS

Distributed Open Reliable Systems Analysis Lab
Computer and Software Engineering Department
École Polytechnique de Montréal

Introduction

- Low-overhead tracing is available
- But trace analysis requires users to have kernel knowledge
- So what about automating the analysis ?
  - CAE suggested to verify applications' execution using specifications
  - Ericsson is working towards programming at model level
  - **Why couldn't we do both?**
- $\Rightarrow$ model-based constraints

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Analyzed case

Occasional missing of deadlines

Problem

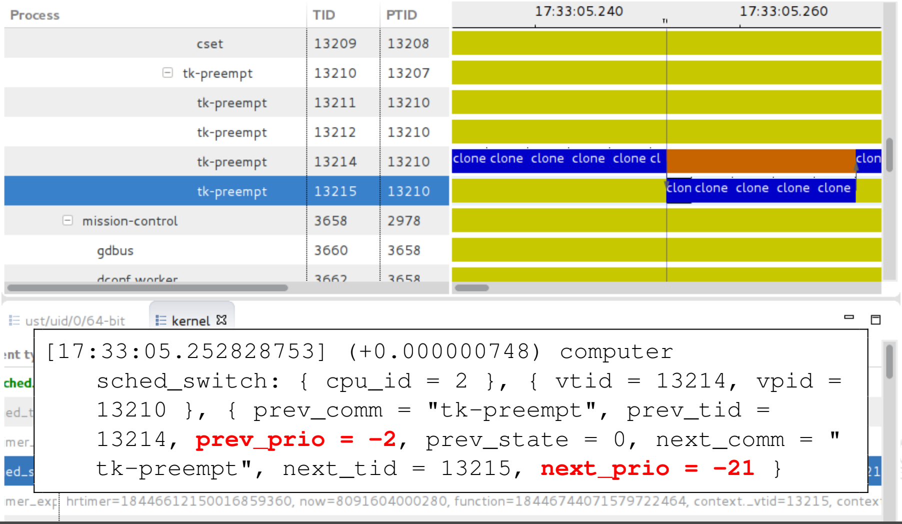
In a task that appears a lot of times, some deadlines are missed occasionnaly.

Analysis

What happened on the kernel side when the deadlines were missed ?

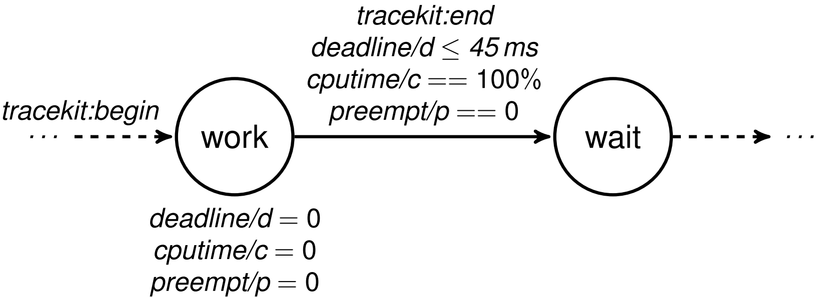
Analyzed case

Occasional missing of deadlines



Analyzed case

State machine representation



State machine representation of `tk-preempt`'s work using constraints to check if our process spent at most 45 ms working, used 100 % of the CPU time and was not preempted during its critical real-time task

Analyzed case

State Chart XML representation

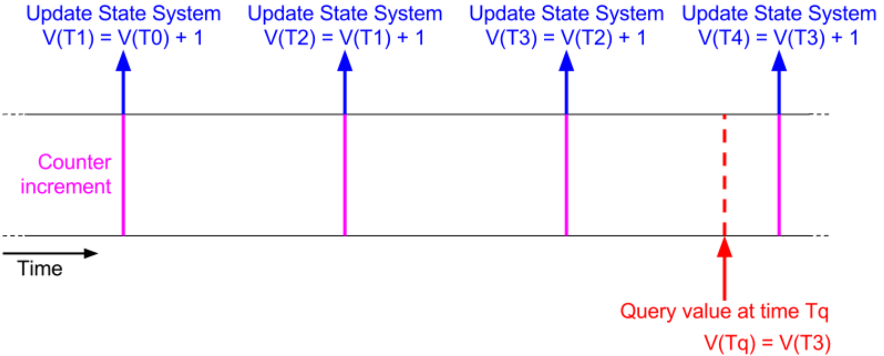
```
<?xml version="1.0" encoding="UTF-8"?>
<scxml xmlns="http://www.w3.org/2005/07/scxml" version="1.0">
    <initial>
        <transition event="tracekit:begin" target="work"/>
    </initial>

    <state id="work">
        <onentry>
            <assign location="deadline/d" expr="0"/>
            <assign location="preempt/p" expr="0"/>
            <assign location="cputime/c" expr="0"/>
        </onentry>

        <transition event="tracekit:end" target="wait"
                cond="deadline/d &lt;= 45ms; preempt/p == 0;
                    cputime/c == 100%"/>
    </state>

    <state id="wait">
    </state>
</scxml>
```

Internal state system

- Used to store the state of different metrics per PID through time
- Three categories of variables:
  - Independent from the current state (state system free)
  - Counters
  - Timers
- Variables are categorized according to the number of queries needed to get their value at a given time: 0, 1 or 2

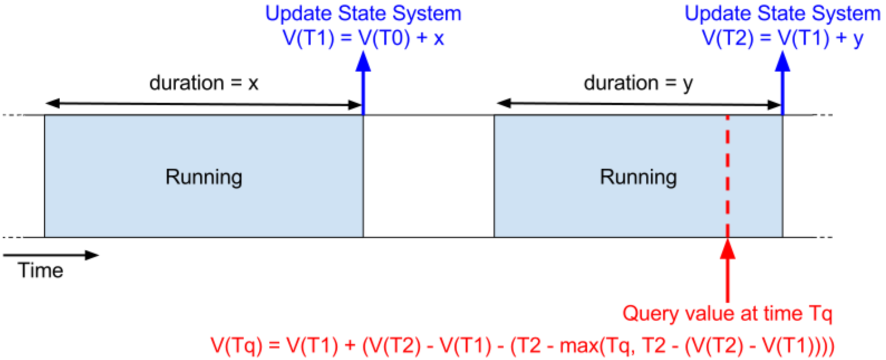
Internal state system

Counters



Internal state system

Timers



Constraint verification

How it is done

- Done when following a transition
- Consider T_{init} is the timestamp of the variable initialization and T_{trans} the timestamp of the event setting off the transition
- Consider $V(T_x)$ the value of the variable in the state system at timestamp T_x
- The variable value for constraint verification will be $V(T_{trans}) - V(T_{init})$

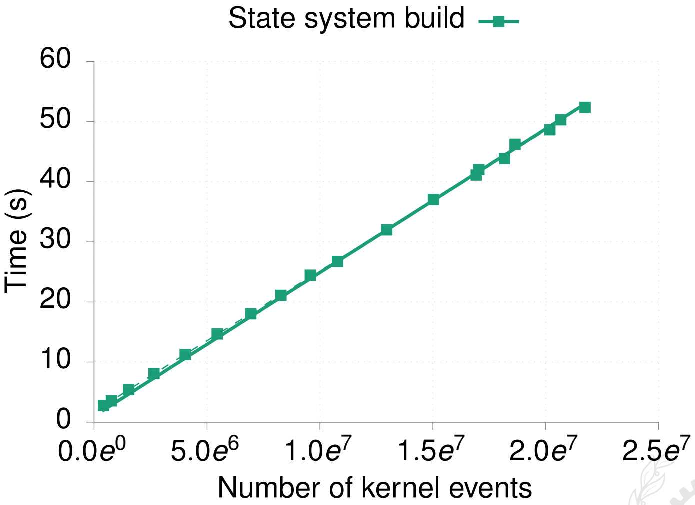
Constraint verification

Constraints status: VALID vs. INVALID vs. UNCERTAIN

```
Received tracekit:begin at 18:27:53.173 147 428
    Entering state: Work
    Variables:
        - deadline/d = 0
        - cputime/c = 0
        - preempt/p = 0
Received tracekit:end at 18:27:53.218 552 778
    Entering state: Wait
    Constraints:
        - deadline/d <= 45ms [INVALID] value: 45.4054ms
        - cputime/c == 100% [INVALID] value: 99.9806%
        - preempt/p == 0 [INVALID] value: 1
```

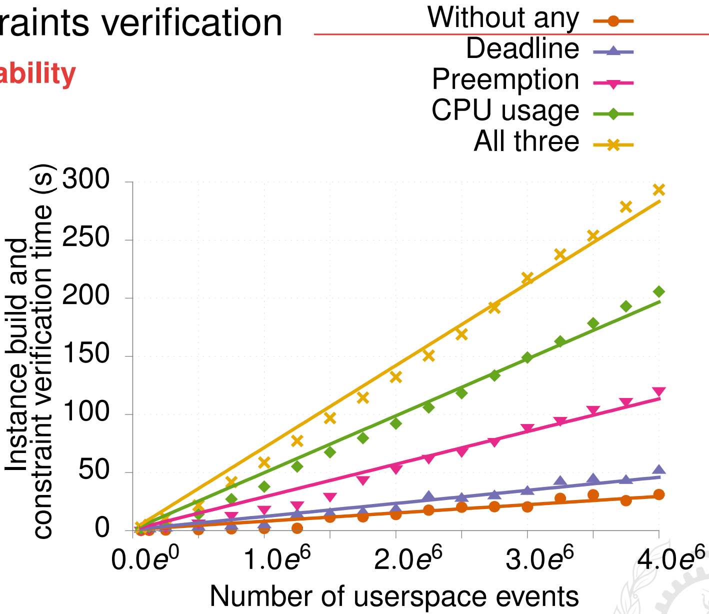
Constraints verification

Scalability



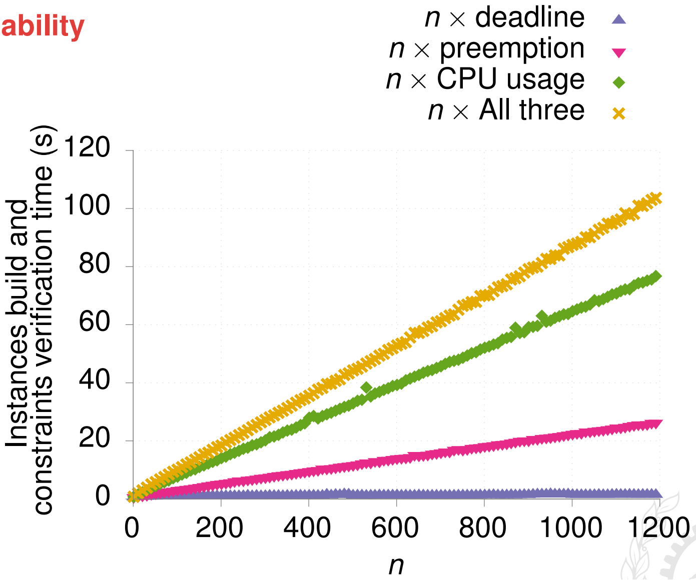
Constraints verification

Scalability



Constraints verification

Scalability



Constraints analysis

- Now we know where are the problems. But we'd like to know why there was a problem!
- Step 1: Data extraction
  - Depends on the category of variable
  - Aims to extract relevant data for next step
- Step 2: Data organization
  - Depends on the category of variable
  - Aims to identify the normal and abnormal behaviors and regroup them
- Step 3: Algorithm application
  - Different approaches for absolute (e.g. $== 0$) and relative (e.g. < 2) constraints
  - Same algorithm used no matter the category of variable

Algorithms

Absolute

- Each element is part of the problem: each occurrence adds to the responsibility of that element

```
1 different constraint(s) with invalid status on 31021 different instances
Constraint preempt/p == 0 (wait) has been invalid 2036 times

Process should not have been preempted.
Processes identified as potential cause of constraint violation:
   -------------------------------------------------------------------
   | Task        | TID   | Occurrences | Responsibility | Max. Prio. |
   |=================================================================|
   | tk-preempt  | 13215 |        1905 |       93.5658% |        -21 |
   | watchdog/2  |    32 |         144 |        7.0727% |       -100 |
   -------------------------------------------------------------------
   Total preemption occurrences identified: 2049

   In 100.0% of cases, the process which preempted had a higher priority.
```

Algorithms

Relative

- Amongst the elements, some are part of the problem, some not.
- We need to identify what should have been instead.

```
1 different constraint(s) with invalid status on 31021 different instances
Constraint preempt/p < 2 (wait) has been invalid 13 times

Invalid preempting tasks list [tk-preempt 13215, watchdog/2 32] has been encountered
     13 times
Preempting tasks lists identified as potential expected list instead of this invalid
     one:
   ---------------------------------------------------------------
   | Preempting tasks list | Distance | Occurrences | Weight     |
   |=============================================================|
   | [tk-preempt 13215]    |        1 |        1892 |   90.0956% |
   | []                    |        2 |       28984 |   86.8090% |
   | [watchdog/2 32]       |        1 |         131 |   46.5711% |
   ---------------------------------------------------------------
```

Algorithms

Relative

```
1 different constraint(s) with invalid status on 31021 different instances
Constraint cputime/c > 99% (wait) has been invalid 1905 times

Invalid interruption list {PREEMPTED, tk-preempt 13215=1} has been encountered 1884
     times
Interruption lists identified as potential expected list instead of this invalid one:
---------------------------------------------------------------
| Valid interruption list | Distance | Occurrences | Weight   |
|=============================================================|
| []                      | 1        | 28984       | 95.0000% |

Invalid interruption list {PREEMPTED, tk-preempt 13215=1, PREEMPTED, watchdog/2 32=1}
      has been encountered 21 times
Interruption lists identified as potential expected list instead of this invalid one:
-------------------------------------------------------------------------------------
| Valid interruption list                       | Distance | Occurrences | Weight   |
|===================================================================================|
| [[PREEMPTED, watchdog/2 32, [860.0, 13400.0]]]| 1        | 131         | 95.0000% |
| []                                            | 2        | 28984       | 94.5501% |
```

Algorithms

Relative

- **Distance** = edit distance (only add or delete, not replace) between valid and invalid lists of elements

$$
\begin{array}{rll}
[a, b, c]\text{to } [a, b] & (d = 1) & \text{remove } c \\
\text{to } [a] & (d = 2) & \text{remove } b \\
\text{to } [\,] & (d = 3) & \text{remove } a \\
\text{to } [e] & (d = 4) & \text{insert } e
\end{array}
$$

- **Occurrences** = number of times we encountered that valid list of elements

Algorithms

Relative

Weight = weight as computed by:

$$W_i = W_{r\,i} - P$$

With the uncertainty penalty $P = F_C \times \left(1 - \frac{1}{N_{valid}}\right)$ $(F_C = 0.1)$

And the relative weight $W_{r\,i}$:

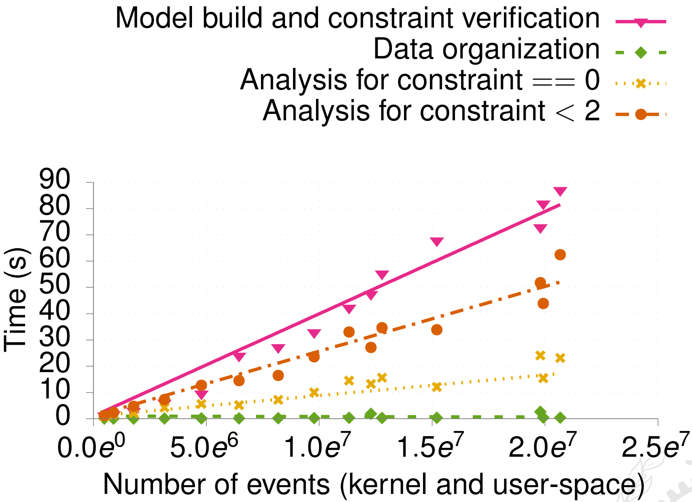
$$W_{r\,i} = \frac{O_i}{\sum_{d_j \leq d_i} O_j} \times \frac{d_i}{\max(1, s)} + \frac{s - d_i}{\max(1, s)}$$

With:

- O_i the number of occurrences of the valid list i
- d_i the distance between this list and the invalid one
- $\sum_{d_j \leq d_i} O_j$ the sum of O_j for all list j with $d_j <= d_i$
- s the size (or number of elements) of the invalid list

Constraints analysis

Scalability



Conclusion

- New approach using constraints to automatically detect problems using traces
- Overview of how we verify constraints
- Algorithms to do a more thorough analysis of the constraints violations
- Linear scaling of the approaches used
- Future work:
  - Finish the implementation of the analysis algorithm (counters and timers done, state system free variables to go)
  - Track 3 of the Ph.D. $\Rightarrow$ from trace to model-based constraints

Thank you.
Any question?

raphael.beamonte@polymtl.ca

Slides:

www.dorsal.polymtl.ca/~rbeamonte/dorsal-pm-dec2015.pdf