Integrating Simulink into the Model-Checker Cosmos

Benoît Barbot[a], Béatrice Bérard[b], Yann Duplouy[c, d], Serge Haddad[d]

[a] LACL, Université Paris-Est Créteil
[b] Sorbonne Université, LIP6, CNRS UMR 7606, Paris, France
[c] IRT SystemX, Paris-Saclay, France
[d] LSV, ENS Paris-Saclay, CNRS, Inria, Université Paris-Saclay

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Cosmos

Description [Ballarini, Barbot, Duflot, Haddad, Pekergin 2015]

- Statistical model-checker for HASL over stochastic nets;
- Free software (GPLv3); C++, OCaml;
- Developers: Hilal Djafri (2009–2012), Paolo Ballarini (2010-2011), Benoît Barbot (since 2011), Yann Duplouy (2015–2018).

Main Applications

- Flexible manufacturing systems;
- Biological networks [Barbot, Kwiatkowska 2015];
- Embedded pacemaker model [Barbot, Kwiatkowska, Mereacre, Paoletti 2015].

Simulink®

Description

- Block diagram modeling and simulation for hybrid systems;
- Commercial software, embedded into MathWork's MATLAB.

Applications

- Advanced driver-assistance systems;
- Signal processing, etc.

Motivations

- Modeling cyber-physical systems:
  combining probabilistic features and differential equations;
- Providing semantics for Simulink models which increases the confidence in results;
- Improving efficiency;
- Lessening the dependency on MathWorks.

Outline

1 Semantics for Simulink

2 Integrating Simulink into Cosmos

3 Benchmarks

Challenges

Increasing the confidence

- Documentation is mostly informal;
- Development of models on what you think you know;

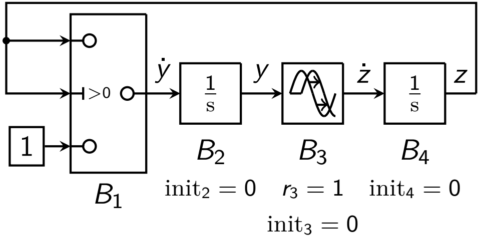
$\Rightarrow$ Necessity of a formal semantics.

Difficulties of such a formalisation

- Implementation of Integration
- Research of thresholds
- Managing blocks with delay

$\Rightarrow$ Necessity of an approximate formal semantics.

Overview of Simulink Syntax



- Simulation Interval: $\mathrm{Time} = [t_0, t_{\mathrm{end}}]$
- Signals: $\mathrm{Time} \to \mathbb{R}$ right-continuous;
- Characteristics of blocks:
  - continuous or discrete-time evaluation;
  - threshold crossings;
  - possible latency;

Providing an exact semantics

Trajectory: vector $\vec{w}$ of all values of output signals.

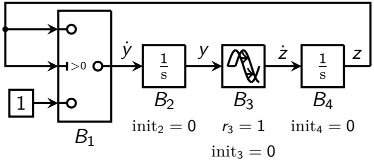
Establishing differential equation systems

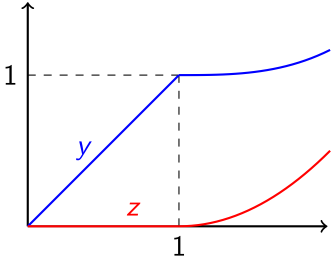
- *modes* for threshold crossings;
- *history* for blocks with latency.

Splitting the simulation interval: $\mathrm{Time} = \bigcup_{i=0}^{N-1}[t_i, t_{i+1}]$

- no sampling inside an interval $[t_i, t_{i+1}]$;
- positive latencies exceed $t_{i+1} - t_i$;
- "consistent" changes of modes between intervals.

Providing an exact semantics – Example





$$\text{Time} = [0,2] = [0,1] \cup [1,2]$$

Over $[0,1]$

$$\begin{cases} \dot{y}(t) = 1 \\ \dot{z}(t) = 0 \end{cases} \Longrightarrow \begin{cases} y(t) = t \\ z(t) = 0 \end{cases}$$

Over $[1,2]$

$$\begin{cases} \dot{y}(t) = z(t) \\ \dot{z}(t) = t - 1 \end{cases} \Longrightarrow \begin{cases} y(t) = (t-1)^3/6 + 1 \\ z(t) = (t-1)^2/2 \end{cases}$$

Accurate approximate semantics

Problem: Exact semantics is not operational;

Goal: Approximation of $\vec{w}$

Principle: Iterative construction of the sub-interval partition $\mathrm{Time} = \bigcup_{i=0}^{N-1} [t_i, t_{i+1}]$.

- Signal values stored at each t_i: array $W_{B,o}[i]$.
  Linear interpolation for intermediate values.
- Next evaluation time:
  - Adaptative Integration Step: Runge-Kutta-Fehlberg (ODE45)
  - Threshold crossing: interpolation of candidate time instants.

Outline

Challenges

Different kinds of simulation

- COSMOS (until now): simulation of stochastic discrete-event systems.
- Simulink : formalism (and tool) for continuous variable dynamic systems.

$\Rightarrow$ Extend COSMOS to simulate Simulink models communicating with stochastic systems.

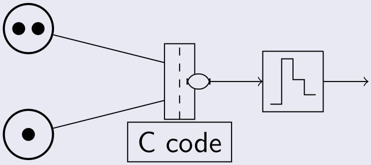
Communication between models

- How to transmit information ?
- How to schedule simulation events ?

Communication

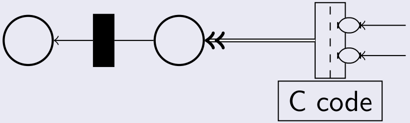
Interface transition for (Simulink) inputs

- Input place modification triggers firing;
- New content is read;
- C code computes output signals.



Interface transition for (Simulink) outputs

- Output places are connected by read arcs;
- Simulink step triggers firing;
- C code rewrites output places.



Principles of discrete-event simulation

Events

An event is composed of ID, absolute time, priority and tie.

Event Queue

Events are accordingly ordered in a queue (usual implementation: heap).

Simulation Loop

- Extract earliest event from event queue;
- Update state due to the event occurrence;
- Remove disabled events from queue;
- Add to the queue newly enabled events.

Observation. Simulink being sequential, it has a single event.

Simulation Loop for Cosmos/Simulink

Depending on the extracted event:

1. If it is a net transition firing:
    - Update marking;
    - Execute C code;
    - Generate new net events possibly including Simulink input transition firings.

Simulation Loop for Cosmos/Simulink

Depending on the extracted event:

1. If it is a net transition firing:
   - Update marking;
   - Execute C code;
   - Generate new net events possibly including Simulink input transition firings.
2. If it is a Simulink input transition firing:
   - Update Simulink signals;
   - Set up the Simulink event to current time.

Simulation Loop for Cosmos/Simulink

Depending on the extracted event:

1. If it is a net transition firing:
   - Update marking;
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2. If it is a Simulink input transition firing:
   - Update Simulink signals;
   - Set up the Simulink event to current time.
3. If it is the Simulink event:
   - Evaluate Simulink signals;
   - Put the Simulink event back at next Simulink simulation step;
   - Add Simulink output transition firings to event queue.

Simulation Loop for Cosmos/Simulink

Depending on the extracted event:

1. If it is a net transition firing:
   - Update marking;
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   - Update Simulink signals;
   - Set up the Simulink event to current time.
3. If it is the Simulink event:
   - Evaluate Simulink signals;
   - Put the Simulink event back at next Simulink simulation step;
   - Add Simulink output transition firings to event queue.
4. If it is a Simulink output transition firing:
   - Update output places of this transition.

Outline

A Model for Room Temperature

Single room with two heaters trying to keep temperature between 20°C and 25°C

Simulink model

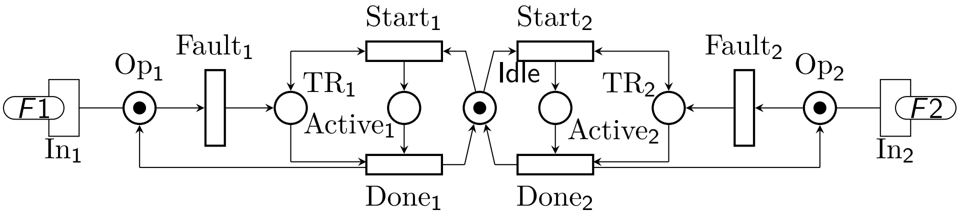
- Differential equations that compute the current temperature
- External temperature: sine wave 5-25°C
- Hysteresis blocks triggered off when above 25°C

Stochastic net

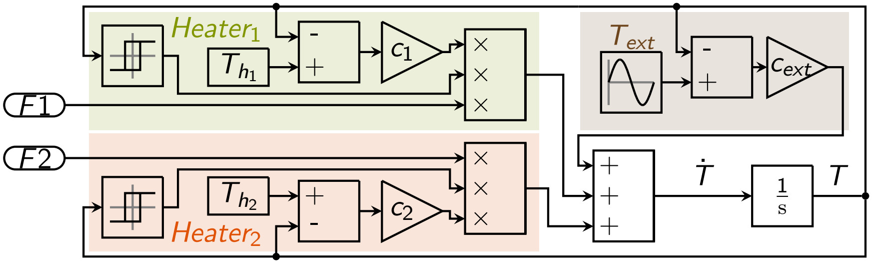
- Heater failures triggered by stochastic transitions;
- A single repairman;
- Repairing through transitions with deterministic time.

One-way communication: state of heaters transmitted to the Simulink model.

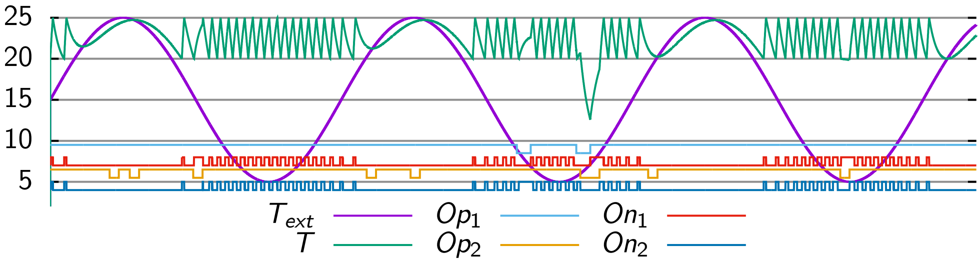
Model



$F1, F2 : \mathbb{B}$



Execution of the model



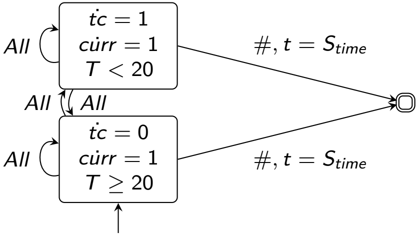
This data has been produced by COSMOS

Benchmarks

Performance Indices:

- I_1: average min. temperature
- I_2: elapsed time at target temperature
- I_3: average temperature
- I_4: average activity of heaters
- I_5: average repairman idling rate

Linear Hybrid Automaton (for Properties):



Indices	Original	Discrete Integration
I_1	[18.69 ; 18.72]	[18.27 ; 18.29]
I_2	[66.34 ; 67.22]	[92.92 ; 93.93]
I_3	[22.43 ; 22.45]	[22.48 ; 22.49]
I_4	[0.499 ; 0.501]	[0.488 ; 0.489]
I_5	[0.923 ; 0.925]	[0.923 ; 0.925]

Models	Build time	Sim. time
Orig	5.74s	6 885s
DTI	5.73s	1 145s
noSlx	1.31s	2s

Conclusion and Future Work

What has been done

- Simultaneous simulation of a stochastic net and a Simulink model;
- Possible Simulink standalone execution.

Future developments

- Increasing the number of supported blocks;
- Wrappers for multi-model simulation;
- Adding floating-point color support for nets.

Planned applications

- Evaluation of autonomous vehicle controllers into various vehicular environments;
- Analysis of strategies for energy consumption in data centers.

Thank you for your attention!