Statistical Model Checking for SystemC Models

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Executive summary

- PMC: state space exploration is infeasible for large systems
  - Partial Order Reduction
  - Symbolic Model Checking
  - SAT-based Bounded Model Checking
  - Predicate Abstraction
  - Counterexample Guided Abstraction Refinement
- SMC: often easier to simulate a system
- Our goal: provide probabilistic guarantees of correctness of stochastic SystemC models using a number of simulations
  - How to define an execution trace?
  - How to generate each execution trace?
  - How many simulation runs to make?

An example

- Message's length and FIFO's buffer are fixed (i.e. of 10)
- Producer writes 1 character to the FIFO with probability p_1 every 1 time unit
- Consumer reads 1 character from the FIFO with probability p_2 every 1 time unit
- Quantitative analysis: What is the probability that messages are transferred completely within 15 time units during 10000 time units of operation?
- Qualitative analysis: Is this probability at least 0.6?

A solution - PMC

- Given a stochastic model $\mathcal{M}$ such as a Markov chain
- A property φ expressed in Bounded Linear Temporal Logic (BLTL) and a probability threshold $\theta \in (0,1)$
- Does $\mathcal{M}$ satisfy φ with probability at least θ?

$$\mathcal{M} \models \mathsf{Pr}_{\geq\theta}(\varphi)$$

Example: messages are transfered completely within T_1 time units during T time units of operation

$$\mathsf{G}_{\leq \mathsf{T}}((\mathsf{c\_read} = \ '\&') \rightarrow \mathsf{F}_{\leq \mathsf{T}_1}(\mathsf{c\_read} = \ '@'))$$

PMC - Scalability

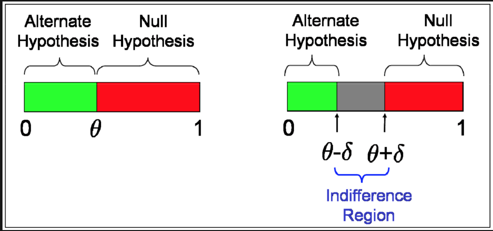
- PMC is infeasible for large systems due to the state space exploration
  - PMC employs symbolic model checking which can scale to $\sim 10^{100}$ states
  - Scalability depends on the structure of the system
- PMC does not work directly with SystemC models
  - Formal model is sometime much over-approximated. It cannot capture the concrete implementation of the system
- Example: PRISM checker created at Oxford and Birmingham

Another solution - SMC

- Associate the ith execution trace with a random variable B_i having a Bernoulli distribution,
  $\Pr[B_i = 1] = p, \Pr[B_i = 0] = 1 - p$
- An observation $b_i = 1$ if the trace satisfies the property, $b_i = 0$, otherwise
- Decide between two hypotheses:
  - Null hypothesis: H : $p \geq \theta$
  - Alternate hypothesis: K : $p < \theta$
- Or estimate the probability p instead of hypothesis testing
  - Simulation is feasible for many more systems
  - Easier to parallelize
  - Answers may be wrong. But error probability can be bounded (i.e. at most $\alpha \sim 0$)
  - Simulation is incomplete

SMC - Existing work

- [Younes et al. 06, CMU] use Wald's Sequential Probability Ratio Test
- The simple null hypothesis $H_0 : p \geq p_0 = \theta + \delta$
- The simple alternate hypothesis $H_1 : p < p_1 = \theta - \delta$



- [Plasma Lab, Inria] checker uses MonteCarlo method, Chernoff and Hoeffding bounds, etc. to estimate the probability

$$\tilde{p} = \frac{1}{n}\Sigma_{i=1}^{n} b_i \text{ st } \Pr[|\tilde{p} - p| < \delta] \geq 1 - \alpha$$

BLTL

- An extension of LTL with time bounds on temporal operations (i.e. $\varphi_1 \mathrm{U}_{\leq \mathrm{T}} \varphi_2$)
- The semantics of BLTL for a trace suffix $\omega^k = (s_k, t_k), (s_{k+1}, t_{k+1}), \ldots$ is defined as follows

  $\omega^k \models \mathit{true}$ and $\omega^k \not\models \mathit{false}$
  $\omega^k \models p, p \in \mathrm{AP}$ iff $p \in \mathrm{L}(s_k)$
  $\omega^k \models \varphi_1 \wedge \varphi_2$ iff $\omega^k \models \varphi_1$ and $\omega^k \models \varphi_2$
  $\omega^k \models \neg\varphi$ iff $\omega^k \not\models \varphi$
  $\omega^k \models \varphi_1 \ \mathrm{U}_{\leq \mathrm{T}} \ \varphi_2$ iff there exists an integer i such that

    $\omega^{k+i} \models \varphi_2$
    $\Sigma_{0<j\leq i}(t_{k+j} - t_{k+j-1}) \leq \mathrm{T}$
    for each $0 \leq j < i, \omega^{k+j} \models \varphi_1$

SystemC model state

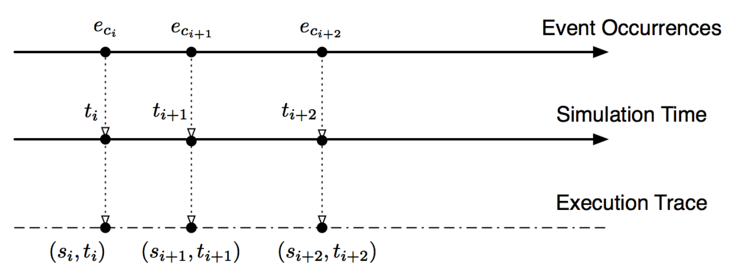
A state is an evaluation of variables which represent

- Simulation kernel state
  - Current phase of the simulation scheduler (i.e. delta-cycle notification, simulation-cycle notification)
  - Events notified during the execution of the model
- SystemC model state: full state of the C++ code
  - All module's attributes,
  - Location of the program counter (i.e. executed statement, function call)
  - Call stack (i.e. function parameters and return values)
  - Status of module processes

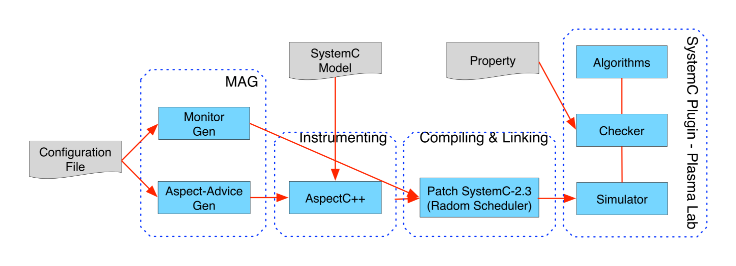
Note: external libraries are considered as block boxes

Temporal resolution

- Is a set of Boolean expressions, called temporal events, defined over the simulation kernel states, location of the program counter, and processes' status
- Whenever a temporal event is true, a new state is sampled
- A time unit is duration between two event occurrences
- States are snapshots of system at event occurrences



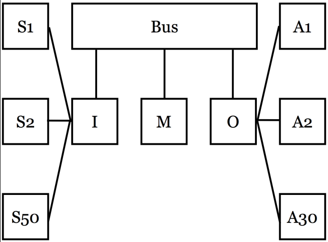
SMC for SystemC models



- MAG: automatically instruments SystemC model with the help of AspectC++ in order to generate the traces and communicate with the checker
- SystemC plugin: communicates with the instrumented model and applies appropriate statistical algorithms provided by Plasma Lab

Case study - Dependability analysis

- 50 groups of 3 sensors, 30 groups of 2 actuators
- Main, input and output processors communicate via a reliable bus



Component	Mean time
Sensor	*1 month*
Actuator	*2 months*
Transient Fault	*1 day*
Processor	*1 year*
Reboot to Repair	*30 seconds*

Dependability analysis

- Time to failure of sensors, actuators and processors and time to repair of I/O processors can be modeled by exponential distributions
- The reliability is modelled as a Continuous Time Markov Chain (CTMC)

  Sensor group: 4 states

  Actuator group: 3 states

  Main processor: 2 states

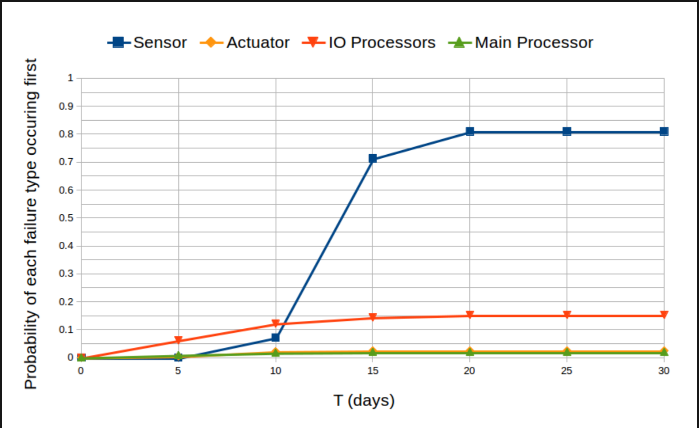
  I/O processors: 3 states (including 1 state of transient failure)

  The model has $4^{50} \times 3^{30} \times 2 \times 3^{2} \sim 2^{150}$ states

Results

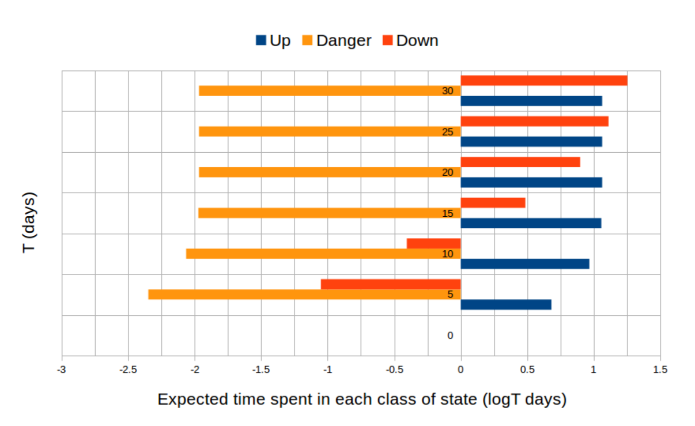
The probability that each of the 4 failure types is the cause of system shutdown in the first T time of operation

$$\text{shutdown} = \bigvee_{i=1}^{4} \text{failure}_i \quad \neg\text{shutdown}\,\mathrm{U}_{\leq T}\,\text{failure}_i$$

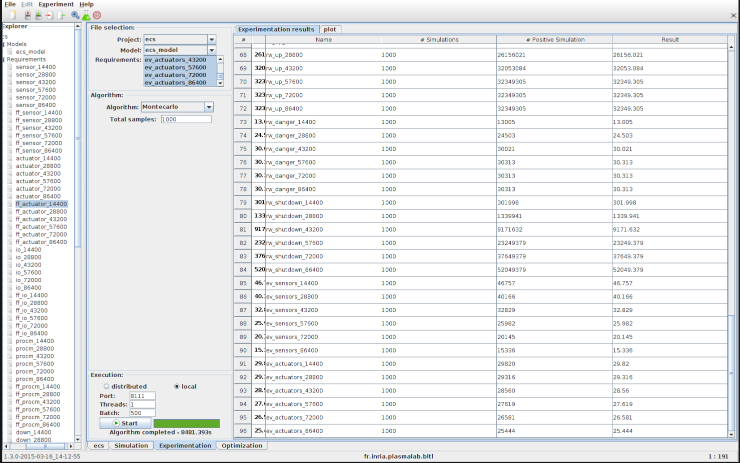


Results

- The expected amount of time spent in each of the states: "up", "danger" and "shutdown"
- $X_{\leq T}$reward_c returns the mean of reward_c after T time of execution



Tool in action



https://project.inria.fr/pscv/

Conclusion

- An introduction about Statistical Model Checking
- Some evidences that SMC scales to large systems
  - SystemC models
  - Simulink models [Clarke et al. 09, CMU]
- Initial experiments on SystemC for dependability analysis are carried out

Future work

- More SystemC examples
- Parallel implementation of the statistical analyzer
- Consider the implementation of a random scheduler for SystemC kernel