Automated mode Coverage Analysis for Hybrid Automata using OpenModelica

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Outline

Introduction
- Model-based testing
- Coverage criteria
- Hybrid automata

Mode coverage
- Definition
- Why mode coverage and not MC/DC?

Use case from Volvo Cars
- The model
- Generating the modes
- Mode coverage results

Outline

Model-based testing

- An industrial Cyber-Physical System (CPS) is typically safety-critical.
- The *continuous dynamics* makes the system impossible to test efficiently using standard software testing methods.

Coverage criteria

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Coverage criteria

From software testing, we know of different (code) coverage criteria, for example:

- Statement coverage
- Branch coverage
- Condition coverage
- Mixed Condition/Decision coverage (MC/DC)

Coverage criteria

if $u_1 > 0$ **then**
$\dot{x}_1 = -2u_1u_2x_1$
else
$\dot{x}_1 = -5u_1u_2x_1$
end if
if $u_2 > 0$ **then**
$\dot{x}_2 = -7u_1u_2x_1$
else
$\dot{x}_2 = -u_1u_2x_1$
end if

Table: Test input that gives full MC/DC.

time	u_1	u_2	Stability
0	1	1	stable
1	-1	-1	stable

Hybrid automata
Example

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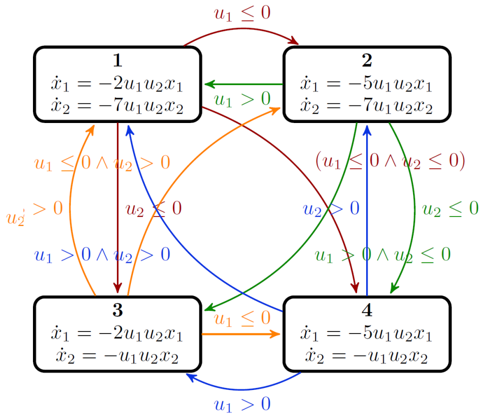

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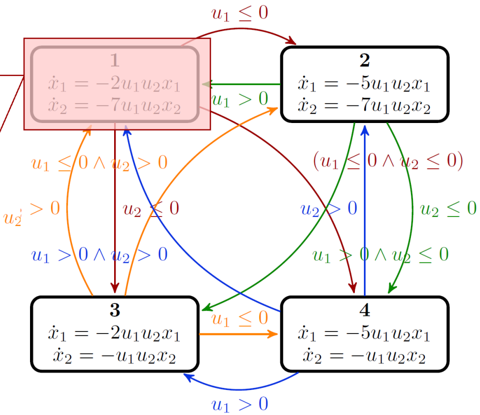

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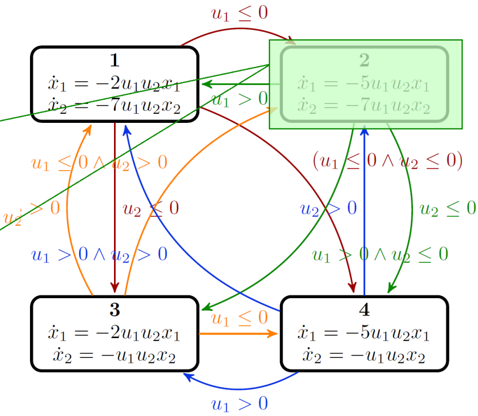

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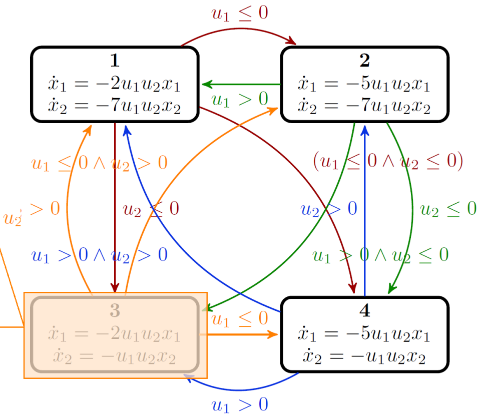

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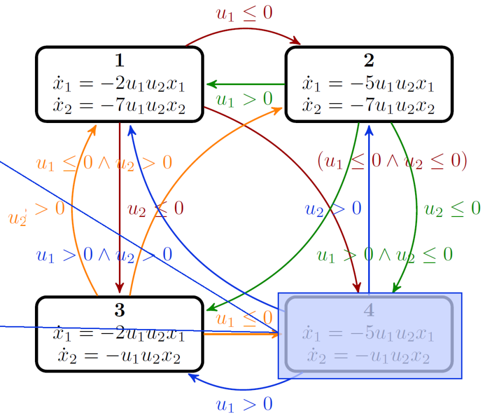
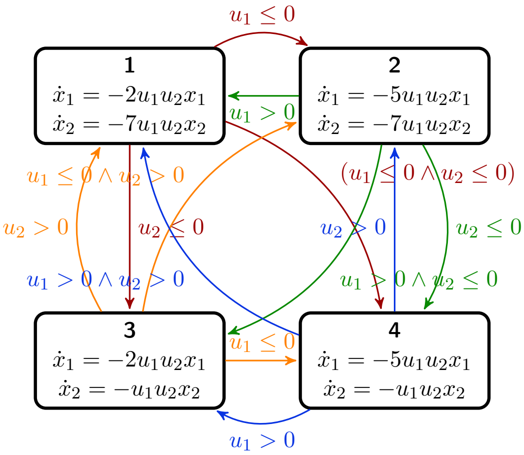


Hybrid automata
Example

- $X = \mathbb{R}^2$ and $V(X) = \{x_1, x_2\}$,
- $Q = \{1, 2, 3, 4\}$,
- $U = \mathbb{R}^2$ and $V(U) = \{u_1, u_2\}$,
- E: Arrows,
- F: Equations,
- G: Arrow labels,
- R: The set of identity functions.



Outline

Definition

Test case, test suite

A ***test case*** $\xi(t) = (u(t), (q(t), x(t))$ is the time-varying signal containing the input $u(t)$ applied to the hybrid system, together with the resulting hybrid states.

A ***test suite*** $\Xi = \{\xi_1, \xi_2, \ldots, \xi_N\}$ is a set of test cases executed on the hybrid system.

Definition
Set of visited modes

The ***set of visited modes*** $Q_{case} \subseteq Q$ for a *test case* ξ is defined as

$$Q_{case}(\xi) = \{q(t) | (\exists t \in [0, T])[(q(t), x(t)) \in \xi]\} \tag{1}$$

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$$Q_{suite}(\Xi) = \bigcup_{i=1}^{N} Q_{case}(\xi_i) \tag{2}$$

Definition

Mode coverage, relative mode coverage

The ***mode coverage*** of a test suite Ξ of the hybrid automaton containing Q is defined as

$$Coverage(\Xi) = \frac{|Q_{suite}(\Xi)|}{|Q|}. \tag{3}$$

Let $c_q(\xi)$ be the total time spent in mode q in ξ, and let $C(\xi)$ denote the total time spent in all modes in ξ. The ***relative mode coverage*** η of the mode $q \in Q$ in the test suite $\Xi = (\xi_1, \xi_2, \ldots, \xi_N)$ is defined as

$$\eta = \frac{\sum_{i=1}^{N} c_q(\xi_i)}{\sum_{j=1}^{N} C(\xi_j)} \tag{4}$$

Why mode coverage and not MC/DC?

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Why mode coverage and not MC/DC?

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$$\xi = \Xi = (\left(\begin{bmatrix} 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix} \right), \begin{bmatrix} 1 \\ 4 \end{bmatrix}, \left(\begin{bmatrix} x_1(0) \\ x_1(1) \end{bmatrix}, \begin{bmatrix} x_2(0) \\ x_2(1) \end{bmatrix} \right))$$

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- $Coverage(\Xi) = \frac{|\{1,4\}|}{|\{1,2,3,4\}|} = \frac{2}{4} = 0.5$,

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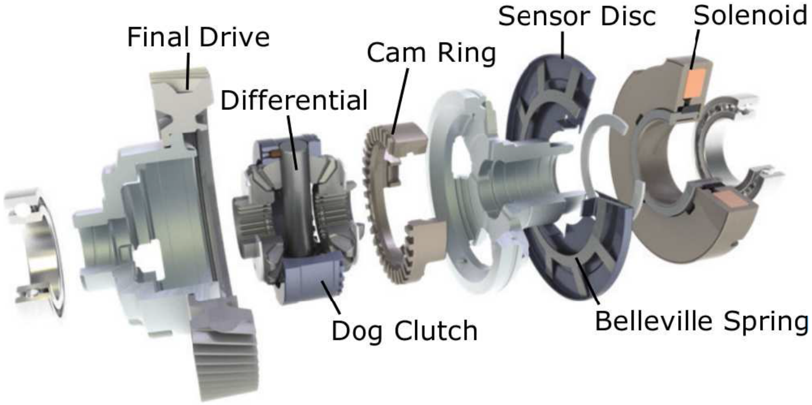
- $\eta_1 = \eta_4 = \frac{1}{2} = 0.5$,
- $\eta_2 = \eta_3 = 0$.

Why mode coverage and not MC/DC?

- From our toy example, we get full MC/DC coverage but only 50% mode coverage
- Mode coverage can give additional insight for complex models

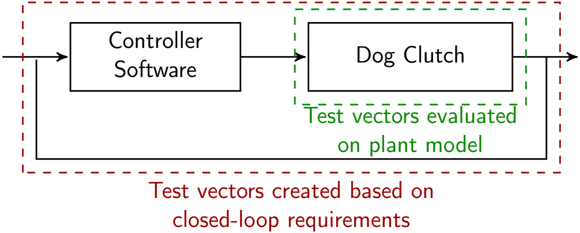
Outline

The model


Final Drive
Differential
Cam Ring
Sensor Disc
Solenoid
Dog Clutch
Belleville Spring

The model

- We use mode coverage to analyze previously created test vectors
- 175 test vectors
  - 25 created manually by engineers
  - 150 created automatically using Testweaver

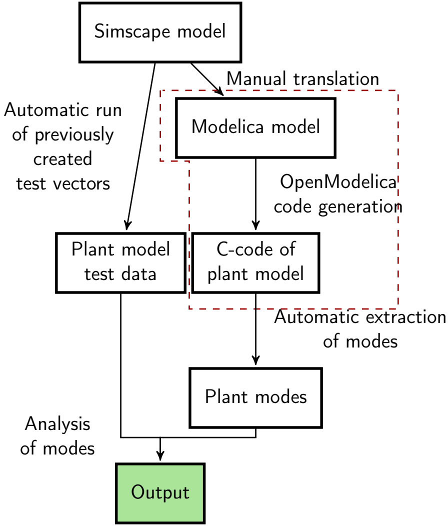


Generating the modes
Using an SMT solver

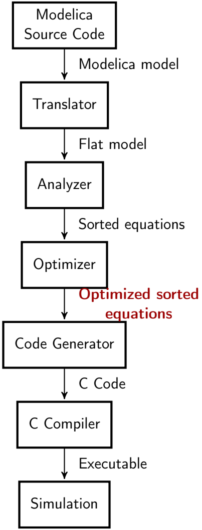
- The conditions for equations to be executed can be formulated using first-order logic
- Conflicting conditions lead to unreachable modes
- These unreachable modes are removed by an SMT Solver

Generating the modes

Overview of approach

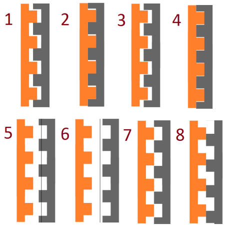


Generating the modes
OpenModelica's role

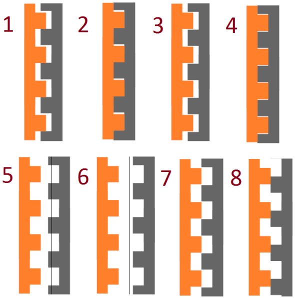


Generating the modes
Characteristics of generated modes

- The automatically generated modes are interpreted as physical configurations
- Automatically generate 34 modes, our modelling gives 8 physical configurations
- The difference is mainly due to Boolean variables defining the system state more precisely without changing physical appearance

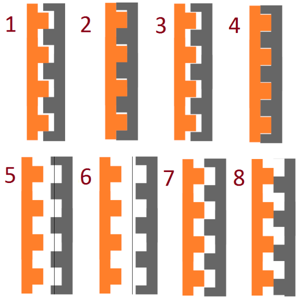


Mode coverage results



Physical configuration	η_{man}	η_{auto}	η_{tot}
1	0.336%	0%	0.228%
2	0.066%	0%	0.045%
3	1.111%	0.623%	0.954%%
4	0.103%	2.988%	1.031%
5	97.814%	96.386%	97.356%
6	0%	0%	0%
7	0%	0.003%	0.001%
8	0.570%	0%	0.385%
Mode coverage:	75%	50%	87.5%

Mode coverage results



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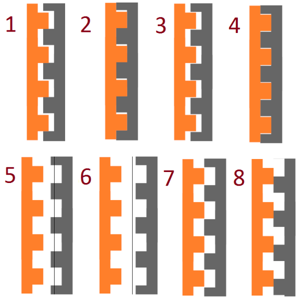
- Configuration 6 is never visited

Mode coverage results



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- Configuration 6 is never visited
- System spends large amount of time in configuration 5

Mode coverage results
Conclusions

- Analysis of mode coverage and relative mode coverage can give insights into how well a system is exercised by a test suite
- In some ways, mode coverage is more detailed than e.g. MC/DC
- We can generate modes automatically thanks to OpenModelica and the Z3 SMT solver

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