OPTIMIZING FAULT INJECTION IN FMI CO-SIMULATION THROUGH SENSITIVITY PARTITIONING

Mehrdad Moradi

Department of Electronics-ICT
University of Antwerp - Flanders Make
Antwerpen, Belgium
mehrdad.moradi@uantwerpen.be

Cláudio Gomes

Department of Mathematics-Computer Science
University of Antwerp, Antwerpen, Belgium
claudio.gomes@uantwerpen.be

Bentley James Oakes

Department of Mathematics-Computer Science
and Department of Electronics-ICT
University of Antwerp - Flanders Make
Antwerpen, Belgium
bentley.oakes@uantwerpen.be

Joachim Denil

Department of Electronics-ICT
University of Antwerp - Flanders Make
Antwerpen, Belgium
joachim.denil@uantwerpen.be

ABSTRACT

As society and industry relies more on Cyber-Physical Systems (CPS), any malfunctions can have unforeseen catastrophic failures. Fault Injection (FI) techniques perturbed a model of a CPS with the intention of causing a failure and measuring the robustness of the CPS. Naturally, the success of a FI simulation depends on three factors: (i) realism of the faults injected; (ii) how quickly the faults cause catastrophic failure; and (iii) fidelity of the model used.

In this paper, we propose to improve the success rate of FI studies by addressing each one of these factors: we develop an algorithm that leverages traditional Sensitivity Analysis (SA) in hybrid systems to reduce an infinite fault search space to a optimal finite set (factors i,ii), and we use co-simulation as the model integration technique (factor iii). We evaluate our contribution on the power window system developed by MathWorks®.

Keywords: Fault-injection, Co-simulation, Functional Mock-up Interface (FMI) standard, Sensitivity analysis, Hybrid Systems.

1 INTRODUCTION

Cyber-physical systems should be robust against failure, specially in safety critical systems. For testing robustness, FI has become an important tool. FI consists of perturbing the system (either its inputs, or internal components) and observing the impact in the system's behavior (Pintard, Fabre, Kanoun, Leeman, Pintard, Fabre, Kanoun, Leeman, Roy, Injection, Pintard, Fabre, and Kanoun 2017). Naturally, this is an expensive process if applied to physical prototypes of the system. As

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such, most FI studies are currently performed on models of the CPS (Kooli and Di Natale 2014, Svenningsson, Vinter, Eriksson, and Törngren 2010).

According to (Yu and Johnson 2003), faults have three main configuration dimensions: the *type*, *location*, and *value*. These configuration points induce a *fault space*, which, when combined with the complexity of a CPS, creates an infinite space of fault candidates. Even for reasonably simple systems, as we shown in Section 3, it is hard to predict the system's reaction to failure. The success of an injected fault depends on three factors:

Realism the probability of the fault during the system operation;
Impact the kind of failure produced by the fault; and
Fidelity whether the model accurately reproduces the abnormal behavior of the system (in addition to the normal behavior).

Contributions In this paper, we propose a technique to increase the success of a FI study, by proposing solutions to the above factors.

In order to improve the realism of faults, we support uncertain faults. For example, the voltage drop across a brushed DC Motor (caused by wear of the brushes) increases at an uncertain rate over time. We support the uncertain voltage drop and postulate that there is a realistic value in the interval between no voltage drop and total voltage drop.

An uncertain fault represents a possibly infinite set of possible faults, which makes it harder to tackle the fault coverage. To address this, we make use of traditional SA of hybrid systems (e.g., see (Barton and Lee 2002, Hiskens, Member, and Pai 2000)) to find sets of faults that cause similar system (abnormal) behavior. These sets can then abstracted as a single fault, since all faults in the set share the same impact.

High fidelity models are expensive to build. To improve the fidelity factor, we use *co-simulation*. Co-simulation is a technique to compute the behavior of a coupled system through the coordination of simulators of the corresponding subsystems (Gomes, Thule, Broman, Larsen, and Vangheluwe 2018, Kübler and Schiehlen 2000, Hafner and Popper 2017, Palensky, Meer, Lopez, Joseph, and Pan 2017). The simulators are consist of Functional Mock-up Units (FMU), essentially black boxes, that they are coupled using a master algorithm which communicates with each simulator via its interface. The simulators communicate via a standardized interface. An example of such an interface is the FMI Standard (FMI 2014, Blockwitz, Otter, Akesson, Arnold, Clauss, Elmqvist, Friedrich, Junghanns, Mauss, Neumerkel, Olsson, and Viel 2012) which we are using in this paper.

The paper is organized as follows. Background information is provided in Section 2, with our case study presented in Section 3. Section 4 describes the elements of our technique, while Section 5 demonstrates applies this technique to the case study. Related work to our approach is found in Section 6. Finally, Section 7 presents a brief conclusion of our approach and future research directions.

2 BACKGROUND

This section will briefly introduce the concepts required for this paper and provide the reader with further reading. Note that these concepts ae exemplified in Section 3.

2.1 Hybrid Automata

Hybrid Automata is a formalism used to model hybrid systems, which are systems that exhibit continuous behavior, interleaved with discontinuous mode changes. Informally, a hybrid automaton contains input, state, and output variables, and multiple modes connected by transitions. Each mode contains a system of differential algebraic equations, involving input, state, and output variables. Each transition is a directed edge contains a trigger condition, and an action. The trigger condition represents an inequality relating state and I/O variables. The action encodes changes to the made to state and I/O variables, when the transition takes place.

In this paper, we adopt the *must-fire* semantics of hybrid automata. That is, a transition between a source mode and a target mode is triggered when the current mode of the automaton is the source mode, and as soon as the trigger condition of the automaton becomes true. The initial state of the automaton is always given. For a formal definition of hybrid automata, see (Navarro-López and Carter 2011, Henzinger 2000, Frehse 2015).

2.2 Sensitivity Analysis

Sensitivity analysis is a broad family of techniques that help identify the impact of changes to a model (Saltelli 2004, Hutcheson and McAdams 2010). Here, we focus on local trajectory SA of hybrid systems. In essence, when applied in a co-simulation setting, this technique consists of comparing a perturbed co-simulation with a non-perturbed one, for each possible parameter or initial state. The results give a measure of the relative importance of each parameter, under the assumption that the change is small. For continuous systems, this assumption is reasonable, but not for hybrid automata (Hiskens, Member, and Pai 2000), which is why we adapt the technique to be usable in a co-simulation of hybrid systems.

Literature like (Saltelli 2004, Hutcheson and McAdams 2010) have a comprehensive overview of SA, and for efficient implementations of the technique in hybrid systems, we refer readers to (Barton and Lee 2002, Hiskens, Member, and Pai 2000, Galán, Feehery, and Barton 1999).

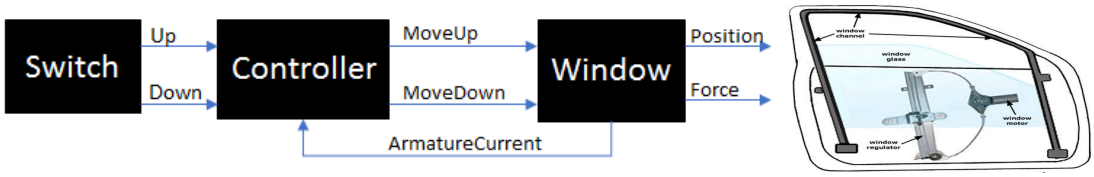
3 MOTIVATING EXAMPLE

In this section, we introduce a simplified model of a power window control system. This example will be used throughout the paper to exemplify the techniques that we propose.

3.1 Description of Power Window

The model of the power window system, illustrated in Figure 1a, is a hybrid system. It is comprised of a software controller and a model of the physical window as FMUs. The component `window_system` in Figure 1a is continuous, while the controller is discontinuous. Controller is responsible for ensuring the safe operation of the window. In particular, it should detect obstructions to the window movement, such as an object being compressed when the window is closing, and act to ensure that no harmful forces are exerted on the obstruction.

In this paper, we will focus on a single scenario for the power window: the driver continuously pushes the `move-up` button of the window interface. However, the techniques developed here can be applied to any system. Figures 2a and 2b show the behavior of the system. In both figures, the top plot shows armature current on the *direct current* (DC) motor, the second plot shows the window's



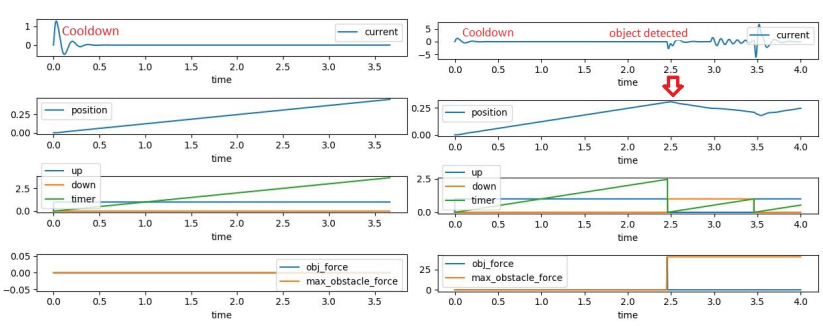
(a) A power window model in Simulink®.

(b) A closing window with obstacle (Glass 2018).

Figure 1: The power window motivating example.

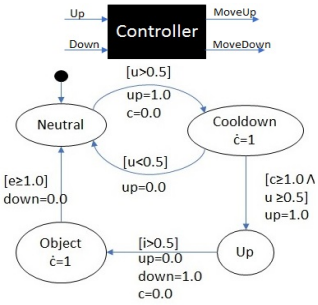
vertical position. Third plot shows the instructions of the control system to the DC motor, and last one is the force to the object.

As can be seen from the plots in Figure 2, whenever there is any obstruction to the movement of the window, be it coulomb friction (cf. Figure 2a, interval $[0s, 0.5s]$), or the presence of an object (cf. Figure 2b, interval $[2s, 10s]$), the armature current in the DC motor spikes. The control system therefore uses the armature current to detect whether something has obstructed the movement of the window. To avoid false positives, there is a *cool-down* period of about one second after the controller instructs the motor to move the window up before an obstacle can be detected.



(a) Obstacle is absent.

(b) Obstacle is present.



(c) Simplified hybrid automata of software controller.

Figure 2: Power window traces and hybrid automata.

Figure 2c shows the simplified hybrid automata of the software controller[1]. The controller has four main modes of operation: `Neutral`, `Cooldown`, `Up`, and `Object`. The u variable represents the driver/passenger commands, and the $up/down$ variables represent the controller commands (to the motor). The c variable represents an internal clock, and the i represent the armature current reading. The conditions in brackets are monitored constantly and trigger the mode transition as soon as the condition becomes true.

3.1.1 Specifications for Correct Behavior

The power window system has to satisfy the requirements described in (Prabhu and Mosterman 2004). In this paper, we select two main requirements. (i) Window fully opened/closed within 4s; and (ii) The force to detect when an object is present should be less than 100 [N]. Careful examination of Figures 2a and 2b shows that the power window system satisfies both these requirements.

[1] In the results section, we apply techniques to the full example.

3.1.2 Faults to Inject

As an example fault, consider the real-world operation of the power window. As the brushes in the DC Motor wear down over time, the current passing through them meet more resistance. This causes a voltage drop on the motor, which makes it operate more slowly.

A realistic fault is therefore to adjust the operating voltage of the DC Motor. However, uncertainty lies in how much voltage is decreased. For illustrative purposes, we suppose that the voltage lies in the interval $[7,12]$, where 12 is the normal operation voltage. Such fault can be represented as a hybrid automaton with a single state setting the output to a value in the interval $[7,12]$, which is then connected to the window system's voltage parameter.

3.1.3 Sensitivity

We exemplify the sensitivity of the specification (i) with respect to fault introduced above. Figure 3 shows two co-simulations: one where the DC Motor operates with $12V$ (normal behavior), and another where it operates with $7V$.

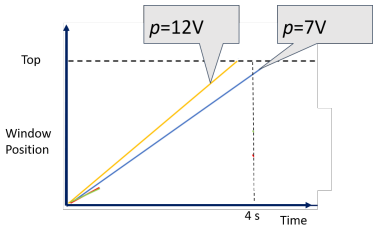


Figure 3: Sensitivity of the motor Simulink®model.

Assuming that the system is continuous with respect to the voltage parameter in the interval $[7,12]$, we can estimate the sensitivity of the time it takes to close the window o w.r.t. the voltage parameter as $\frac{\partial o}{\partial V} \approx (-1-1)/(7-12)$. This value can then be used to estimate the voltage drop $V_0 \in [7,12]$ that is the specification breaking point, that is, $o(V_0) \approx 0$: $V_0 = 12 - o(7)/\frac{\partial o}{\partial V}$.

Our technique will assist the user in configuring the faults by determining the ranges of parameters under which the continuity assumption holds, and therefore specification breaking points can be identified.

4 APPROACH FOR CONFIGURING FAULT INJECTION

In this section, we describe our technique using the power window as a running example. Before detailing the main contribution, we explain how the faults and specifications are defined. To make our exposition clearer, we will assume that there is a single fault to be injected, with a single uncertain parameter, and a single specification being measured.

The faults and specifications are FMUs as detailed in (FMI 2014), orchestrated in a co-simulation. By assuming that the co-simulations presented in this paper exhibit perfect accuracy, any disturbance on the behavior computed by the co-simulation is due to the faults, and not to the co-simulation algorithm. For the power window system, Figure 4 illustrates the co-simulation scenario and FMUs that we use.

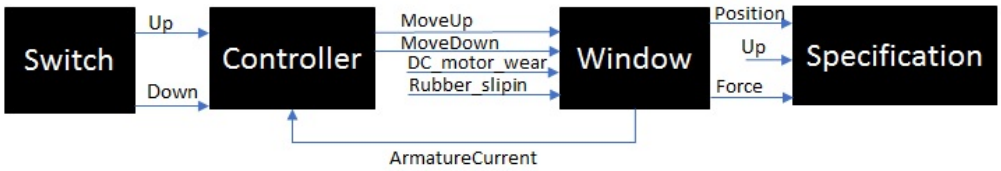
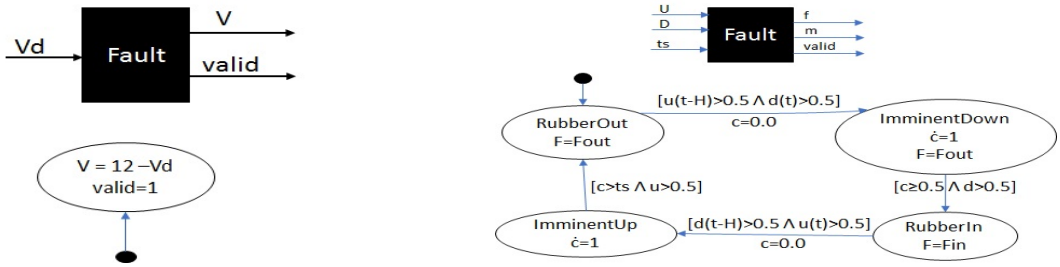


Figure 4: Power window FMU in co-simulation.



(a) Voltage drop fault implementation.

(b) Rubber fault implementation.

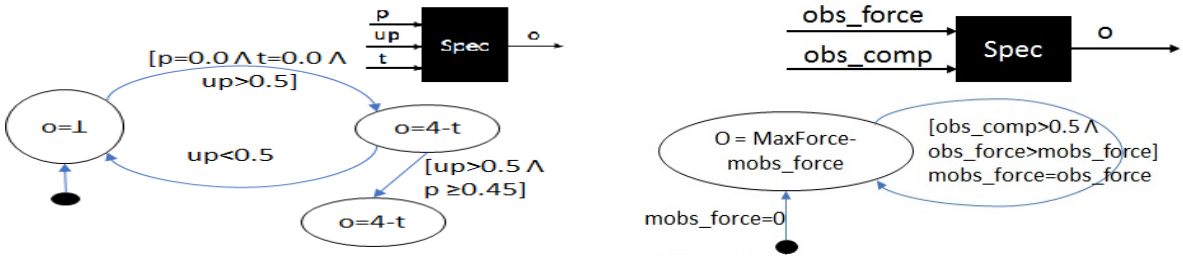
Figure 5: Fault implementations and their interface.

4.1 Defining the Faults

Each fault is assumed to have at least one input that allows us to control the fault intensity (or deactivate the fault). Note that the fault intensity does not mean that more intensity leads to more specification failure. As for outputs, we assume that each fault discloses its discrete mode signal, and whether the fault is valid or not. The validity is important because faults can have complex pre-conditions. For example, the DC motor voltage drop fault, introduced in Section 2.2, is represented as a hybrid automaton in Figure 5a. As a more complex example, consider the rubber seal slipping into the door, as the window moves down in Figure 5b. The effect is an adjustment of the friction on the window movement. In the figure, f_{out} is a constant denoting the normal friction of the rubber, f_{in} is the friction caused by the rubber slipping into the door, and H corresponds to the co-simulation step size, so that $d(t-H)$ refers to the value of signal d at the previous co-simulation step. To keep the explanation simple, the uncertainty in this fault is captured only by the input t_s, which controls the timing of the rubber slipping out of the door. The fault is valid unless the co-simulation causes it to deadlock.

4.2 Defining the Specifications

In order to automatically measure the degree to which a co-simulation satisfies the specifications, we will assume the existence of an oracle for each specification, that receives values computed in the co-simulation, and outputs a specification measure, or $\perp$, in case such a measure is not applicable (i.e., the pre-conditions are not satisfied), and a signal encapsulating its internal discrete mode. For example, Figure 6a shows one such interface as an FMU and a possible implementation as a hybrid automaton. In the figure, p denotes the position of the window, up is the controller command signal, t is the time, and o is the measure of the specification. The output $o \geq 0$ means the co-simulation satisfies the specification, and violates it otherwise. Note that the oracle will produce a measure of the specification (different than $\perp$) only when the window moves from fully open to fully closed.



(a) Four second specification.

(b) Object force specification.

Figure 6: Implementation example of specifications

4.3 Parameter Interval Partitioning

The first part of our technique lies in identifying the fault intensity intervals for which the behavior of the co-simulation does not change substantially. We consider two co-simulation traces to be substantially different if the sequence of discrete modes of at least one FMU is different. Given a co-simulation trace, we define the aggregated untimed sequence of modes as the set product of all discrete mode signals converted to untimed sequences, preserving only causality. For example, the aggregated untimed version of the discrete mode signals *up* and *down* plotted in Figure 2b is $(1,0),(0,1),(1,0)$. This operation allows us to define an equivalence relation: two co-simulation results are equivalent iff their aggregated untimed sequence of modes is the same. With these definitions, our technique is described next.

Procedure 1. *Given a co-simulation scenario that includes a fault and a specification FMU:*

1. *Let $N \in \mathbb{N}$ be a parameter given by the user;*
2. *Let the fault intensity input p be in the range $[0,1]$ with 0 being the lowest intensity and 1 being the highest;*
3. *Let $P = \{p_0, p_1, \ldots, p_N\}$ be a set where $p_i = \frac{i}{N}$;*
4. *For each $p_i \in P$:*
   (a) *Run cosim with fault intensity p_i;*
   (b) *Let o_i be the resulting specification measure;*
   (c) *Let m_i be the resulting aggregated untimed sequence of discrete modes of all FMUs (including specification and fault);*
5. *Create a partition of P according to the equivalence relation defined above. In other words, p_i and p_{i+1} are equivalent iff m_i is equivalent to m_{i+1}.*
6. *Return the partition.*

An example application of Procedure 1 is given in Section 5. We assume that every FMU in the co-simulation scenario discloses it's interval mode as a signal. The above procedure relies this assumption,and it allows us to compute the sensitivity.

4.4 Determining Sensitivity

Given a partition created with Procedure 1, and two values p_i and p_{i+1} in the same set, we have following equation. Furthermore, within the same set of equivalent fault intensity values, traditional optimization techniques can be applied to find the maximum, minimum, and zero of the specification.

$$\frac{\partial o}{\partial p} \approx \frac{o_{i+1} - o_i}{p_{i+1} - p_i}. \tag{1}$$

4.5 Ranking and Configuring Faults

From each equivalence class of fault intensity parameter, we pick the value that minimizes the specification measure, which is then ranked against the best of the other classes. Until now we have explained technique for a single fault intensity parameter and a single specification. Extending this to multiple specifications is trivial: Procedure 1 stores the results of multiple specification measures, and Equation (1) becomes a vector. Note however that the discrete modes of each specification has to be taken into account. When these are different, we postulate that the sensitivity is infinite.

The case of multiple faults is the same as the case with a single fault having multiple intensity parameters, so we consider only the former. When multiple faults are given, Procedure 1 is applied to each one individually. The ranking is then performed as described above. The next section gives examples of this procedure.

5 RESULTS

In this section, we apply Procedure 1 to the power window system introduced in Section 3. We consider only the fault where rubber slips into the window, as detailed in Figure 5b, and the object compression specification, introduced in Section 3.1.1 and detailed in Figure 6b. In Figure 6b, `MaxForce`$= 100$ is a constant, and the `mobs_force` keeps track of the maximum force exerted on the object, whenever it is being compressed (signaled by the input `obs_comp`).

Figure 7 shows the co-simulation results for increasing values of fault intensity parameter t_s. As can be seen, when $t_s \in [0.0, 0.7]$, there is no substantial difference in the behavior. That is, the discrete modes (software controller, and object being compressed) do not change. However, when $t_s = 0.8$, in Figure 7d, there is a specification violation (object force exceeds $100N$). This violation deserves clarification: as the motor is drawing more current to move the window up under extra friction, when the rubber slips out, an impulse in the window movement, and subsequent oscillations, occur.

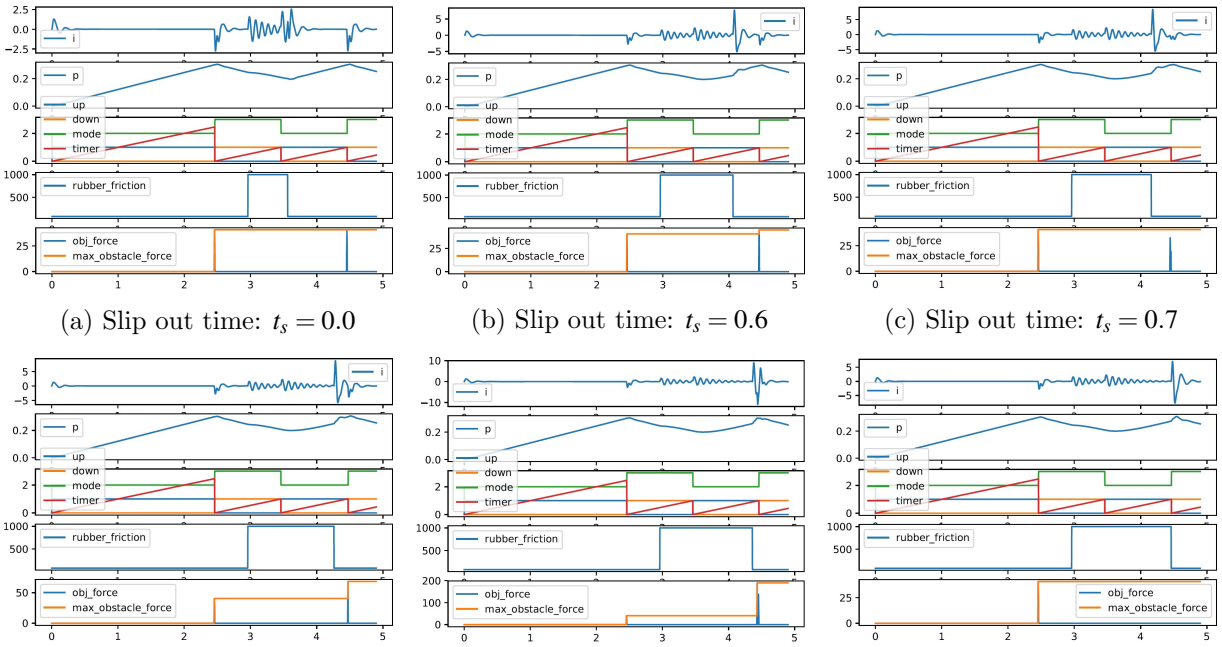
6 RELATED WORK

To the best of our knowledge, there is no work that uses an interval partitioning technique like the one we propose in Procedure 1 to guide FI in FMI co-simulation. Related work can be found in methods, techniques and tools that leverage SA.

The work in (Hiskens, Member, and Pai 2000) presents a technique to compute the trajectory SA for a hybrid system, more specifically described using differential-algebraic-discrete (DAD) models. The work in (Galán and Barton 1998) uses earlier results to elicit a classification of optimization problems for hybrid systems. It focuses on using the sensitivity for solving an optimization problem. In contrast, in our work, we leverage SA when the sequence of modes of the nominal trajectory, and its perturbed trajectory, are the same. Hence, if an event ceases to exist due to the perturbation, we conclude that the sensitivity to that perturbation is infinite.

Furthermore, different techniques are available to compute the sensitivities in different formalisms and tools. E.g. (Han and Mosterman 2013) proposed a method that enables direct SA on system models via an implementation in the Simulink software. The approach relies on the existing ordinary differential equation solver of Simulink and the block-by-block analytic Jacobian computation to provide the analytic Jacobian for solving the sensitivity equations.

Authors in (Kane, Fuhrman, and Koopman 2014) describe a monitor to detect faulty system behavior with run-time verification using hardware-in-the-loop. They study the system under faults



(a) Slip out time: $t_s = 0.0$ (b) Slip out time: $t_s = 0.6$ (c) Slip out time: $t_s = 0.7$

(d) Slip out time: $t_s = 0.8$ (e) Slip out time: $t_s = 0.9$ (f) Slip out time: $t_s = 1.0$

Figure 7: Rubber Slip fault analysis results.

such as random bit flips, random value injections, and exceptional value injections. In order to verify the system, they use a domain-specific language for monitoring. An important argument they use is the fact that any run-time monitors require access to the source code, and this is not feasible with commercial systems. To avoid this problem, we use the FMI Standard. The monitor they propose uses properties specified in Metric Temporal Logic (MTL).

7 CONCLUSION

In this paper we proposed a method based on SA in the FMI co-simulation to improve FI. This method differs from previous studies in two key ways. First, this framework uses SA to understand system behavior. Then, according to notion about signals and the destructive value of each signal, the framework can semi-automatically configure FI by reducing the fault space.

Second, using co-simulation provides advantage for FI such as performing simulation in heterogeneous system and eliminating Intellectual Property (IP) concerns specially in industrial use cases. In addition, co-simulation provides the developer the flexibility to optimize and increase the fidelity of the simulation in the future by proving more advanced solvers and models.

7.1 Risks

Limitation of our exploratory study need to be acknowledged, most notably the Procedure 1. In this paper we divide simulation time to N points, and this number regulate accuracy and performance of algorithm. Therefore, user have to adjust performance/accuracy trade off. Furthermore, disclosing discrete modes of hybrid system will affect the algorithm which in this paper we use our knowledge about system.

In addition, there's no information telling the user how to map domain faults to parameter faults in the co-simulation. This type of mapping relates to the knowledge about system implementation, mathematical formula and the experience of user of FI, and is an area of our future work.

7.2 Future Work

Future research could address a number of additional issues. For example, an open area is using verification of temporal logic for monitoring the specifications in FI. With this verification, the framework does not need to create a FMU for specifications, reducing user effort.

The current framework performs many co-simulation runs for SA from time zero until the end. Reusing a part of simulation for further simulation would increase performance, such as using branching co-simulation to avoid redoing calculations. Information for this branching methodology could be taken from the FI timing.

In this paper, we inject one faulty FMU per simulation. Future research will investigate multiple point FI, including injecting sequences of faults. Additionally, sensitivity regarding delay should be taken into account. Tools like Jittebug and Jittertime (Lincoln and Cervin 2002) can perform this analysis in Simulink. These areas are helpful in the analysis of real-time system and their behaviour. In (Christopher Frey and Patil 2002), the authors describe some methods for SA and automatic differentiation which is a method for local analysis of large systems, which aligns with our purpose. In addition, for modeling hybrid system we can use impulsive system as in (Gomes, Van Tendeloo, Denil, De Meulenaere, and Vangheluwe 2017).

Allowing for injecting and configuring the faults will enhance our framework. A solution to this is the use of a domain-specific language which could guide FI to a specific part of model with the fault parameters that the user intends to simulate.

Other domains like model-based testing are also related to FI. We can use their methodology for finding the best order of scheduling co-simulation to optimize the run time. Moreover, FI will be more challenging if we consider implementation limits on co-simulation. For example, if vendors implement the power window controller in two Electronic Control Units (ECU), these ECUs can run software concurrently. If they lose synchronization, they can glitch the power window armature. Therefore, taking the implementation method into account will provide an exact simulation result for users.

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AUTHOR BIOGRAPHIES

MEHRDAD MORADI is a PhD student at the University of Antwerp (Belgium). The topic of his PhD is the fault injection and co-simulation. His email address is mehrdad.moradi@uantwerp.be and his web address is https://www.uantwerpen.be/nl/personeel/mehrdad-moradi.

CLÁUDIO GOMES is a PhD student at the University of Antwerp (Belgium). The topic of his PhD is the foundations of co-simulation. His email address is claudio.gomes@uantwerp.be and his web address is http://msdl.cs.mcgill.ca/people/claudio.

BENTLEY JAMES OAKES is a post-doctoral researcher at the University of Antwerp (Belgium). His research focuses on the engineering of domain-specific languages and formal verification. His email address is bentley.oakes@uantwerpen.be.

JOACHIM DENIL is an Assistant Professor in the University of Antwerp and member of the Cosys-lab. His main research interest is multi-paradigm modelling of software-intensive systems. His email address is joachim.denil@uantwerpen.be and his web address is http://msdl.cs.mcgill.ca/people/joachim.