# SL2SX Translator: From Simulink to SpaceEx Models

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## ABSTRACT

The tool Matlab/Simulink is a numerical simulation environment that is widely used in industry for model-based design. Numerical simulation scales well and can be applied to systems with highly complex dynamics, but it is also inherently incomplete in the sense that critical events or behavior may be overlooked. The application of formal verification techniques to Simulink models could help to overcome this limitation. Set-based verification tools such as *SpaceEx* use as underlying formalism hybrid automata, which are semantically and structurally different from Simulink models. To address this issue, we are building the tool *SL2SX* for transforming a subset of the Simulink modeling language into a corresponding SpaceEx model. Our method is designed to preserve the syntactic aspects of a given Simulink diagram: the resulting SpaceEx model shows the same hierarchical structure and preserves the names of components and variables. Placeholders with the correct interface are provided for unsupported Simulink blocks, which can then be translated manually. We illustrate the tool *SL2SX* and the verification of the transformed models in SpaceEx on two examples provided by the Mathworks example library.

## 1. INTRODUCTION

*Matlab/Simulink* [17] is a software tool widely used in industry to model and simulate physical systems. For modeling, it provides a set of standard blocks from which one can hierarchically create a block diagram of the system. For simulating, it provides an extensive library of solvers, each of which determines the time of the next simulation step and applies a numerical method to solve the set of ordinary differential equations arising from the model. Different from simulation, formal verification can provide complete coverage, and hence it can be used to ensure whether or not a model meets a requirement. To apply formal verification techniques, it is necessary to switch from a *simulation model* to a *verification model.* Such a transformation needs to take into account the inherent differences between the two classes of models. Typically, a simulation model contains details that need to be abstracted away for the verification model. A verification model can be enriched with nondeterminism to check the system behavior for a whole range of parameters, disturbances, user inputs, etc. Simulink uses *must semantics*, also called *urgent* or *ASAP* semantics, meaning that a transition must be taken as soon as its guard is satisfied. Verification models, such as hybrid automata (HA), are typically defined with *may semantics*, in which the system can delay the transition as long as the invariant (staying condition) is satisfied. This may affect the quality of the model transformation, resulting in overapproximations, and the complexity of the model, resulting in state space explosion. Simulink lacks an actual formal description of its semantics. For the basic blocks one can resort to their ideal mathematical interpretation, but a wide variety of complex blocks is included in the standard Simulink library, many of which are beyond direct translation to functional models such as hybrid automata. Clearly, the process of translating a Simulink diagram into a verification model is not an easy task, and a fully automatic approach seems to be not plausible.

Verification tools like SpaceEx [10] use *Hybrid Automata (HA)* [11] as models and check safety properties using reachability algorithms. Our goal is to make the tool SpaceEx applicable to Matlab/Simulink models. The SpaceEx verification language is able to preserve the structure and the hierarchy of a Simulink diagram, using *basic* and *network* components (a single hybrid automaton and a network of them, respectively). Preserving the structure of the simulation model is not just a secondary aspect because, as described in [26], the structure has a profound impact on several aspects of safety-critical model development. In this paper, we present the tool *Simulink to SpaceEx Translator (SL2SX)* that takes a Simulink model (in xml format) as input, and generates a network of hybrid automata in a format compatible with *SpaceEx* verification tool. Since the SX format closely resembles the mathematical definition of hybrid automata (modulo template and parameter instantiations), SX models can be automatically translated for other verification tools based on hybrid automata. The HyST translation tool [4] provides translations from SX to the verification tools Flow* [7], dReach [12], HyCreate [3], and HyComp / HyDI [9].

Our translation is based on the ideal interpretation of Simulink semantics [14]. The translation preserves all structural aspects of the Simulink diagram. Moreover, the translator preserves the names of blocks, variables, and components, as well as the graphical positions and dimensions of blocks. The must semantics of Simulink are handled by enhancing SpaceEx with *urgent conditions* [21]. A restriction of our approach is that SpaceEx is currently limited to piecewise constant and piecewise affine dynamics.

The translation process of *SL2SX* is not fully automatic, meaning that the SpaceEx model needs to be completed manually by adding hybrid automata to model blocks for which no translation is given. The tool aids in the completion process by adding placeholders with proper interface for the missing blocks. Having the mechanical aspects of the model transformation being carried out by a tool reduces errors and results in a model that can be easily compared with the Simulink diagram, due to the preservation of structure and names of blocks and variables. The tool *SL2SX* together with models in this paper are available online [20].

A variety of different approaches to verify Simulink models has been reported in literature. The tools *HyLink* [15] and *GreAT* [1] translate a Simulink diagram into hybrid automaton expressed by intermediate formats (i.e. *hybrid input/output automata (HIOA)* [22] and *hybrid system interchange format (HSIF)* [24], respectively). Both formalisms are not able to model hierarchy and must semantics. The tool *Checkmate* [23] provides a Simulink toolbox containing additional blocks that the designer is allowed to use. A Simulink model thus obtained is then translated into the special class of *Polyhedra Invariant Hybrid Automata (PIHA)* [8]. The PIHA formalism uses ordinary differential equations (ODE) to express the dynamics, hyperplanes for guard transitions and only identity as update functions. Hierarchy can not be handled, and moreover the PIHA may semantics cause overapproximation when modeling must transitions. Other formalisms than hybrid automata are also used. In [25], the discrete part of a Simulink model is translated to a pushdown automaton defined by the *SAL transition system language* [5], while the differential equations arising from the Simulink component are converted into difference equations. The resulting model is a discretization of the original. The tool *S2H* [28] translates Simulink models into the *Hybrid CSP (HCSP)* formalism [13], based on the separation of variable definitions, process definitions, assertion definitions and goals to be proved. This results in a loss of compositional properties and the obtained model may be hard to compare with the original. The tool *HySon* [6], performs set-based simulation with "imprecise" or "uncertain" inputs directly on a Simulink model. The aim is to compute a good approximation of the set of all possible Simulink executions. Being based on numerical simulation methods, HySon is able to handle systems with both nonlinear dynamics and guards, and zero-crossing events are properly treated. We expect that for certain classes of systems, SpaceEx, whose algorithms are highly optimized for piecewise affine dynamics, can outperform the more general algorithm of HySon. A direct comparison is not possible since HySon is not publicly available.

## 2. SIMULINK, HYBRID AUTOMATA AND SPACEEX

We briefly introduce the modeling language of Simulink, the formalism of hybrid automata and the SpaceEx verification tool, highlighting the features relevant to the translation process.

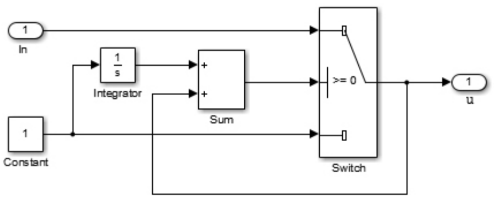


**Figure 1: A Matlab/Simulink block diagram**

### 2.1 Simulink Models

Simulink is an environment for simulation and model-based design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of blocks that let one design, simulate, implement, and test a variety of time-varying systems. The modeling language lacks a formal and rigorous definition of its semantics, usually estimated by either the ideal or the numerical simulation interpretation [14]. A Simulink design is represented graphically as a diagram consisting of inter-connected Simulink blocks. It represents the time-dependent mathematical relationship between the inputs, states, and outputs of the design. Figure 1 depicts an example of Simulink diagram, whose signal that drives the switch blocks is modeled by the hybrid dynamics $\dot{x} = c + u$, when $x \geq 0$, and $\dot{x} = c$ otherwise (where $x$ is the integrator output).

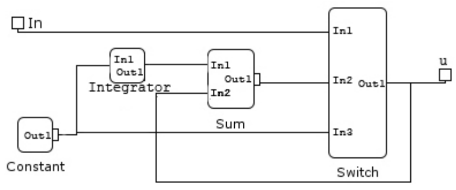
The follows definition derives from [2]. A Simulink model $SL = \langle D, B, C \rangle$ consists of the following components:

- A set $D$ of *variables*, partitioned into input variables $D_I$ and output variables $D_O$.
- A set $B$ of Simulink *blocks*. Each block $b \in B$ has inputs, outputs, and parameters. The input and output variables are associated with input and output ports. A Simulink block can be itself a Simulink Diagram; such a block is called a *subsystem*.
- An ordered relation $C \subseteq B \times B$ represents *connections* between blocks. A connection $c = \langle b, b' \rangle \in C$ connects an outport of $b$ with an inport of $b'$ and represent the flow of the data between the corresponding variables of $b$ and $b'$.

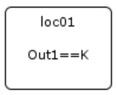
Simulink uses *must semantics*, meaning that discrete events happen as soon as possible a given condition (guard) is satisfied (also referred as *urgent* or *as-soon-as-possible (ASAP)* semantics).

### 2.2 Hybrid Automata

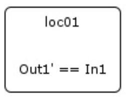
*Hybrid automata* [11] are a verification modeling formalism that combines discrete states (modeled by locations) with continuously evolving, real-valued variables. The discrete states and the transitions from one state to another are described with a finite state-transition system. A change in discrete state can update the continuous variables and modify the set of differential equations that describes how variables evolve with time. Hybrid automata are nondeterministic, which means that different futures may be available from any given state. Rates of change or variable updates can be described by providing bounds instead of fixed numbers. Incomplete knowledge about initial conditions, perturbations, parameters, etc. can easily be captured in this way. A specific source of nondeterminism is due to the *may semantics*.



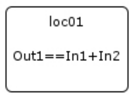
(a) network component



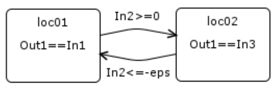
(b) HA for "constant"



(c) HA for "integrator"



(d) HA for "sum"



(e) HA for "switch"

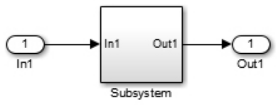
**Figure 2: SpaceEx model for the Simulink diagram in Figure 1**

This means that a transition may happen at any time the associated guard is satisfied, but it may also be delayed as long as the invariant (staying condition) of the discrete state is satisfied. Hybrid automata with urgency conditions allow the definition of a urgency condition for each location. A must transition can be easily encoded by adding its guard as urgent condition to the source location. For the class of LHA, an exact reachability algorithm is available [21].

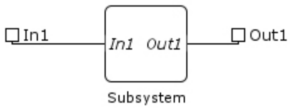
## 2.3 SpaceEx

SpaceEx is a development platform for verification algorithms based on hybrid automata. of a system, modeled by the SpaceEx definition language. The SpaceEx verification engine provides specific reachability algorithms, called *scenarios*, and each of them may come with its own set representation, apply to its own class of models, and produce a different kind of output. The scenarios include a formally exact algorithm for piecewise constant dynamics (PHAVer), two variations of template-based approximate reachability algorithms for piecewise affine dynamics (LGG and STC), and a simulation algorithm that mimics reachability analysis by random sampling of the initial states.

A SpaceEx model is similar to the standard hybrid automata, syntactically extended with hierarchy and templates. A SpaceEx model consists of one or more *components*. Each component has a set of *formal parameters*, like *continuous variables*, *constants*, and synchronization labels. A formal parameter is part of the *interface* of a component, unless it is declared as *local* to the component. There are two types of components: *Base Components* correspond to a single hybrid automaton, and *Network Components* allow the instantiation one or more components (base or other network components), possibly assigning values to their constants. A network component is a parallel composition of its subcomponents. When instantiating a component $A$ in network $B$, one must specify what happens to each of the formal parameters in its interface. This is called a *bind*. Every formal parameter of $A$ must be bound to either a formal parameter of $B$ or to a numeric value. Components inside $B$ can be connected by binding their variables to the same symbols in $B$. Because of the acausal semantics, the variables binding does not distinguish source and destination (non-oriented connection). Figure 2(a) depicts a SpaceEx model of the Simulink model in Figure 1, whose components are the hybrid automata in Figures 2(b)–2(e).



(a) Simulink subsystem



(b) SX component

**Figure 3: The translation from a Simulink subsystem to an SX component preserves the interface**

Formally, a SpaceEx model $SX = (Comp, Bind)$ has

- a set $Comp$ of SpaceEx *components*, partitioned into the set $Comp_b$ of basic components and the set $Comp_n$ of network components. Each component $b \in Comp$ has a set of formal parameters, including a set of variables $Var_b$. For lack of space, we omit the discussion about synchronization labels and local variables.
- a relation $Bind \subseteq Comp_n \times Comp$ that associates each network component with a set of components (including other networks components). Each variable of a component associated to a network, is also a variable of the network. For each $(n, c) \in Bind$, a mapping $Map_{n,c} : Var_c \to Var_n$ associates to each basic variable a network variable.

## 3. FROM SIMULINK TO SPACEEX

The translator analyzes a Simulink model $SL = \langle D, B, C\rangle$ and produces a SpaceEx model $SX = (Comp, Bind)$. $B$ is the set of Simulink blocks and $C$ the set of connections between blocks. Each basic Simulink block (i.e., not a subsystem) is associated to a SpaceEx basic component, while each subsystem is modeled by a network component. Simulink connections are expressed by mapping related variables. Because Simulink connections are oriented, while SpaceEx mappings are not, this task requires some additional considerations as explained in Section 3.3.

An unsupported block is represented by a placeholder with the correct interface. The placeholder is a basic component, with all the necessary variables and mappings, consisting of an empty hybrid automaton.

### 3.1 Translating Blocks

For each block $b_i \in B$, such that $b_i$ is not a subsystem, an inport or an outport, the translator adds to the set $Comp_b$ the corresponding SpaceEx basic component (an hybrid automaton) with same the name of $b_i$. For each input and output of $b_i$ a variable is added to $Var_b$. If $b_i$ is an inport or an outport, then the translator adds to the network component containing $b_i$ a corresponding variable with the same name.

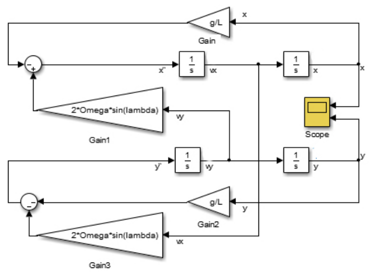
A continuous Simulink is represented by a hybrid automaton with a single location, where the algebraic constraints are included in the invariant and any ODEs are included in the flow. If the Simulink block contains different modes, e.g., the switch block, each mode is represented by a location, and urgent transitions with appropriate guard conditions model the switching. SpaceEx allows only nonstrict guards for urgent transitions, since strict urgent guards are ill defined in continuous time. For example, consider the trajectory $x(t) = t$. A transition that must be taken as soon as $x(t) > 0$ makes sense in the discrete time steps taken by a simulator, but in dense time there is no earliest point at which $x(t) > 0$. We use the numerical interpretation of the Simulink semantics, which corresponds to the set of traces generated by the simulation engine through numerical interpretation. Under this interpretation, similarly to the *guard enlargement* considered by *Almost ASAP* semantics [27], a strict guard can be relaxed and scaled according to the minimum difference $d$ between the values that variables may assume before and after an integration step. Clearly, $d$ depends on the time step $\delta$. Theorem 1 in [14] guarantees that as $\delta$ approaches to zero, the numerical interpretation converges to the ideal interpretation. Moreover, $d$ converges to the machine epsilon *eps*. A strict guard of the form $x > 0$ (resp., $x < 0$) is translated into a nonstrict guard of the form $x \geq eps$ (resp., $x \leq -eps$).

## 3.2 Translating Subsystems

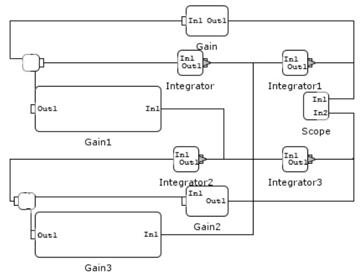
For each subsystem block $b \in B$, we add to the set $Comp_n$ a network component with the same name. In this case, the translator keeps track of the Simulink blocks $b_i$ that belong to $b$. Then, for each $b_i$ that is not an inport or an outport, the bind $(b, b_i)$ is added to the set *Bind*. Semantically, the block is translated to the parallel composition of the hybrid automata from its subcomponents. Note that SpaceEx carries out the parallel composition on the fly, so that only reachable locations are instantiated. This typically avoids the construction of the full product automaton, which can be prohibitively large.

## 3.3 Translating Block Connections

Once components are added to the network, it is necessary to decode the set of block connections $C$. The main issue for this task is due to the acausal semantics of SpaceEx, where connections among variables are not oriented. Let $c_{ij} = (b_i, b_j) \in C$ be a Simulink connection that links the output of the *source* block $b_i$ to the input of the *destination* block $b_j$, inside subsystem $b_s$ and let $b'_i$, $b'_j$ and $b_n$ be the SpaceEx components used to model $b_i$, $b_j$ and $b_s$, respectively, and $Out_i$ and $In_j$ be the variables used to model source and destination of $c_{ij}$. By definition of SpaceEx model, $Map_{n,i}$ contains the mapping between $Out_i$ of $b'_i$ and $Out_i$ of $b_n$, while $Map_{n,j}$ contains the mapping between $In_j$ of $b'_j$ and $In_j$ of $b_n$. To model $c_{ij}$ it is necessary to map $Out_i$ and $In_j$ to the same variable. This is done by mapping the destination variable to the source variable. If the source $Out_i$ is connected to many destinations $In_z$ (i.e. there exists at least another $c_{iz} = (b_i, b_z) \in C$), the translator replaces each mapping in $Map_{nz}$ that involves variable $In_z$, by the mapping between $In_z$ and $Out_i$. This technique does not preserve the names of variables that model outports, which is one of our goals. An outport can be only a destination, and hence the corresponding variable will be replaced by the variable that corresponds to the source. In order to fix this issue, an additional step replaces, for each mapping $Map_{n,i}(Out_i) = Out_j$ such that $Out_i$ is an outport, all the mappings $Map_{n,z}(x) = Out_j$ by $Map_{n,z}(In_z) = Out_i$, where $x$ is a variable that models a source. At the end of this task, all variables $Out_i$ modeling outports appear in the network interface. The block interface is therefore preserved, as illustrated in Figure 3.



(a) Simulink model



(b) translated SX model

**Figure 4: Models for the Foucault pendulum.**

## 4. CASE STUDIES

We illustrate the translation with two Simulink models from the Mathworks examples library and show results obtained with SpaceEx on the translated SX models.

## 4.1 Foucault Pendulum

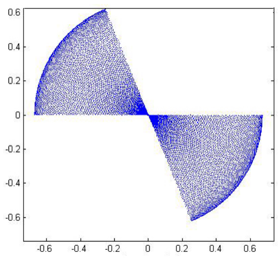
Figure 4(a) shows a Simulink model of a Foucault pendulum, taken from the Mathworks examples library [19]. The *SL2SX* translator produces a complete SpaceEx model, shown in Figure 4(b), without manual intervention.

The translator also extracts simulation parameters from the Simulink file and stores them in a configuration file for SpaceEx. Figures 5(a) and 5(b) show simulation runs obtained by Simulink and SpaceEx, starting from an initial pendulum length of $x = 0.67$.

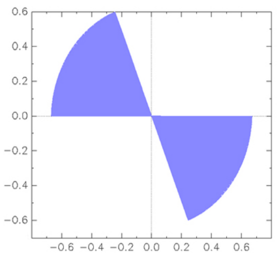
To demonstrate the results of a reachability analysis with SpaceEx, we relax the initial condition to the interval $x \in [0.669, 0.671]$. We show the overapproximation obtained by running two different analysis algorithms of SpaceEx. Figure 5(c) shows the output of the LGG algorithm for a flowpipe tolerance of 0.01, and Figure 5(d) shows the result of the STC algorithm for a flowpipe tolerance of 0.5. Both sets are obtained with bounding box template directions and bounding the time horizon in the model to 6 hours. The LGG scenario takes 8.1 seconds, while the STC scenario takes 5.4 seconds.

## 4.2 Automotive Suspension

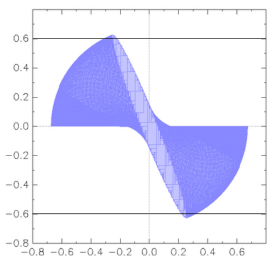
Figure 6 shows a simplified half car model for Simulink, taken from [18]. The model is a hybrid system, since it includes two step blocks. Figure 6(a) shows the main Simulink diagram, while Figure 6(b) depicts the Simulink subsystem



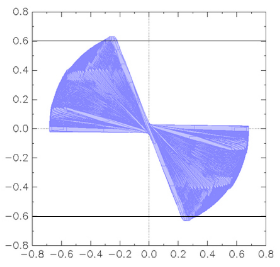
(a) Simulink simulation



(b) SpaceEx simulation



(c) reachable states with SpaceEx/LGG (tol=0.01)



(d) reachable states with SpaceEx/STC (tol=0.5)

**Figure 5: Simulation and reachability analysis for the position of the Foucault Pendulum**

that models the suspension.

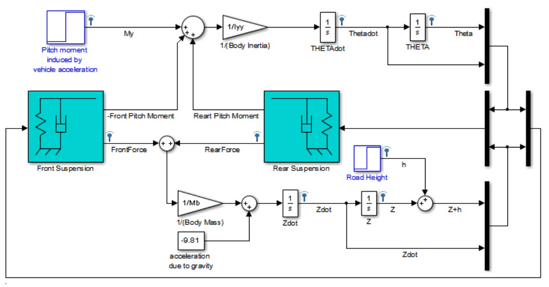
The *SL2SF* translator produces an incomplete SX model, since the Simulink model includes blocks that are currently unsupported (i.e. step, mux and demux). The user needs to remove the components for mux and demux, and directly map the involved variables. This requires the introduction of an input variable for all components connected to the mux input. Then these variables are mapped to the variables that model the source connection of the mux. Figure 6(c) shows the SX main system after modeling (removing and variables mapping) the mux/demux blocks. The user also needs to build a hybrid automaton to model the unsupported step block. Such manual completions are not necessarily very involved; a simple model for the step block is shown in Figure 9.

Figure 7 shows simulations from Simulink and SpaceEx, with step time set to 0.01 and with the front pitch initially at zero. Figure 8 shows the reachable states for the vertical bounce over a time horizon of 10 seconds, starting with a front pitch in the interval $[0, 0.3]$. The LGG algorithm takes 0.55 sec and the STC algorithm 0.41 sec.

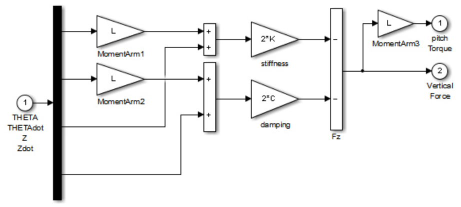
## 5. CONCLUSIONS AND FUTURE WORK

The SL2SX translation tool takes care of the mechanical, but error-prone, aspects of constructing a hybrid automaton model from a Simulink source. The resulting model preserves the structure and basic graphics, and provides placeholders for components that need to be completed manually. The SX model format closely resembles the standard hybrid automaton formalism. It can be read directly by the verification platform SpaceEx, and fully automatic translations to a variety of tools are already available via the translation tool HyST [4].

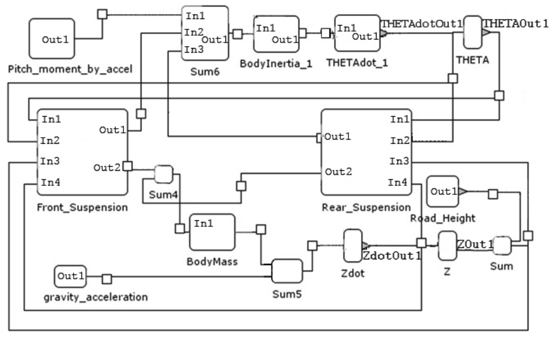
Future work will be directed at providing support for more blocks from various Simulink libraries, as well as translating Stateflow components [16].



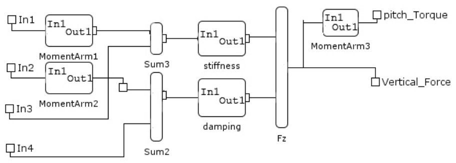
(a) Simulink main system



(b) Simulink suspension subsystem



(c) SX main system.



(d) SX suspension subsystem

**Figure 6: A half car model**

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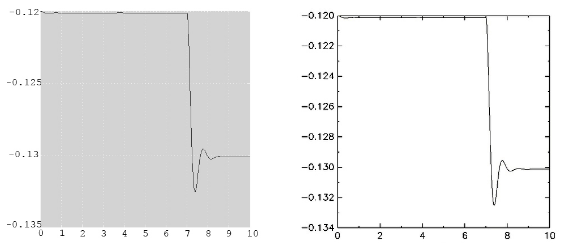
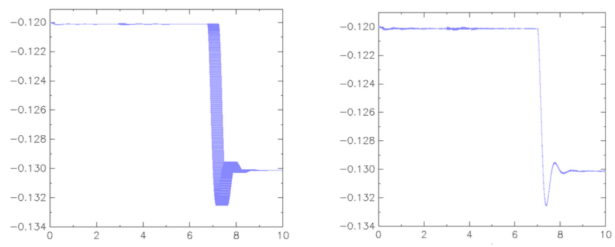


(a) Simulink simulation. (b) SpaceEx simulation.

**Figure 7: Vertical bounce for the suspension models, with the front pitch initially at zero**



(a) reachable states with SpaceEx/LGG (tol=0.001) (b) reachable states with SpaceEx/STC (tol=0.001)

**Figure 8: Reachable states of the vertical bounce, starting with the front pitch in a given interval**

S. Owre, H. Rueß, J. Rushby, V. Rusu, H. Saïdi, N. Shankar, E. Singerman, and A. Tiwari. An overview of SAL. In *LFM'00*. NASA Langley Research Center, 2000.

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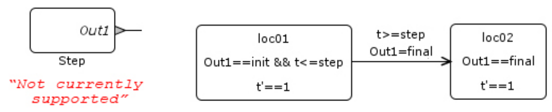

(a) placeholder (b) manually completed HA model

**Figure 9: Example unsupported block: Step**

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