

Model Checking FMI Co-simulation Using Timed Automata

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Abstract—The growing complexity of Cyber-physical Systems (CPSs) increasingly challenges existing methods and techniques. CPSs are often treated modularly to tackle both complexity and heterogeneity. A promising approach for verifying CPSs is to apply Functional Mock-up Interface (FMI) co-simulation techniques to obtain simulations of heterogeneous components in CPSs. However, the master algorithm for co-simulation may be livelock or deadlock. The architecture modelling of CPSs may also introduce an algebraic loop which is a feedback loop resulting in cyclic dependencies. To solve these problems, we propose a novel approach for model checking several properties of FMI co-simulation such as deadlock, liveness, reachability. We model the architecture of CPSs with SysML block diagrams, which captures the dependence of Functional Mock-up units (FMUs) and the orchestration of the master algorithm. To verify the system, we encode FMUs components and model three various master algorithms with timed automata separately. With the help of encoding, we verify the master algorithms for co-simulation and the absence of algebraic loops in the architecture with the model checker UPPAAL. To illustrate the feasibility of our approach, the case study water tank is presented. The experiment results show that our approach facilitates model checking FMI co-simulation. The novelty of our work is that our approach supports to analyse co-simulation behavior with model checking.

Keywords—Co-simulation, Master algorithm, Functional Mock-up Interface, Timed automata, Model checking.

I. INTRODUCTION

Cyber-physical systems (CPSs) are integration of computation with physical processes whose behavior is defined by both computational and physical parts of the system [1]. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. The heterogeneity is one of the main characteristics of CPSs. The components of CPSs are of various types, requiring interfacing and interoperability across multiple platforms and different models of computation. Verifying heterogeneous CPSs requires the use of heterogeneous simulation environments. One emerging industry standard is the Functional Mock-up Interface (FMI) [2] [3]. It is a standard to support simulation of complex systems composed of heterogeneous components, by coupling the different models with their own solver in a co-simulation environment.

The FMI standard was first developed in the MODELISAR project started in 2008 and supported by a large number of software companies and research centers. FMI offers the means

for model based development of systems and is particularly appropriate way to develop complex CPSs. The FMI standard supports both co-simulation and model exchange. In this paper, we focus on the co-simulation in FMI 2.0. Compared with the FMI 1.0, there are two important additions: *fmiGetFMUstate* and *fmiSetFMUstate*, which allow the master to copy and restore all states of an FMU slave. These two functions provide a basic mechanism for rollback. The soul of FMI-based co-simulation is a master algorithm (MA) [4], which specifies the orchestration the exchange of data among the FMUs during the whole co-simulation process. However, the master algorithm is not a part of the FMI standard. This implies that the user or tool vendor needs to develop a sophisticated orchestration algorithm for the problem at hand. Whether the master algorithm is deadlock or satisfies reachability? It should be analysed. There are three versions of master algorithms [3]: fixed step algorithm, rollback algorithm, predictable step size algorithm. Rollback and predictable step size algorithms are based on the extension of FMI 2.0, which supports the rollback and a predict function. P.G Larsen et al. [5] formally analysed the fixed step and rollback algorithms with the FDR3 refinement checker. However, there still lack effective method to verify FMI co-simulation. Based on our previous work, we found that the co-simulation is time-intensive. In this paper, we attempt to model the master algorithms with timed automata(TA) [6] and verify the algorithms with the model checker UPPAAL. Timed automata is a finite automata extended with a finite set of real-valued clocks, which is a classic formalism to specify time-related system. Besides, we also attempt to verify several properties of co-simulation such as deadlock, liveness and reachability. To achieve our goal, we propose a novel approach to model check FMI co-simulation with timed automata. Our main contributions are as follows:

- We propose a framework for verifying CPSs with model checking technology. To bridge the gap between FMU and the model checker. We encode FMU into timed automata with encoding rules. The orchestration between FMUs is modelled with a network of timed automata.
- We model and analyse three various master algorithms to ensure the correctness of the co-simulation process. With the help of UPPAAL, we analyse the reachability, livelock and deadlock of three master algorithms.
- The prototype for model checking co-simulation of CPSs is developing, which is integrated in our Mondana platform [7](<https://github.com/ECNU-MODANA/AL-Modana.git>). We have developed the

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The main novelty of our work, compared to the previous research, is that we propose to verify co-simulation with TA-based model checking. It has extensive tool supports. As far as we know, there is few existing approaches support TA-based model checking for FMI co-simulation. The remainder of this paper is organized as follows. In Section II, we briefly review the technical background including FMI, FMU and timed automata. Then, we present the technical road-map of our approach and how to encode FMU by timed automata with the help of their semantic mapping in section III. In section IV, we model three versions of master algorithms with timed automata and analyse their properties such as the livelock and deadlock. Section V presents a case study to demonstrate the feasibility of our approach. We model the architecture of the water tank with SysML block diagrams, and then obtains the FMUs components and connection of FMUs. We encode the FMUs with timed automata, and model check FMI co-simulation of the water tank with UPPAAL. Finally we position our work with respect to related work before concluding and discussing possible future extensions.

II. BACKGROUND

In this section, we present the syntax and semantics of FMU and timed automata separately. In order to verify the co-simulation of FMUs, we propose to encode FMUs by timed automata in subsection III.

A. FMU

FMU is the model component which implements the methods defined in the FMI API [9]. Here, we present the syntax and semantics of FMU. The aim is to encode FMU into timed automata based on their semantics.

Definition 1. FMU syntax We recall the definition of FMU. An FMU is a tuple $F = (S, U, Y, D, s_0, set, get, doStep)$, where:

- S denotes the set of states of F .
- U denotes the set of input port variables of F . Note that an element $u \in U$ is a variable, not a value, which ranges over a set of values \mathbb{V} .
- Y denotes the set of output port variables of F . Each $y \in Y$ ranges over the same set of values \mathbb{V} .
- $D \subseteq U \times Y$ denotes a set of input-output dependencies. $(u, y) \in D$ means that the output y is directly dependent on the value of u . The I/O dependency information is used to ensure that a network of FMUs does not contain cyclic dependencies, and also to identify the order in which all variables are computed during a step.
- $s_0 \in S$ denotes the initial state of F .
- $set : S \times U \times \mathbb{V} \rightarrow S$ denotes the function that sets the value of an input variable. Given current state $s \in S$, input variable $u \in U$, and value $v \in \mathbb{V}$, it returns the new state obtained by setting u to v .

- $get : S \times Y \rightarrow \mathbb{V}$ denotes the function that returns the value of an output variable. Given state $s \in S$ and output variable $y \in Y$, $get(s, y)$ returns the value of y in s .
- $doStep : S \times \mathbb{R}_{\geq 0} \rightarrow S \times \mathbb{R}_{\geq 0}$ denotes the function that implements one simulation step. Given current state s , and a non-negative real value $h \in \mathbb{R}_{\geq 0}$, $doStep(s, h)$ returns a pair (s', h') such that:
When $h' = h$, it indicates that F accepts the time step h and reaches the new state s' ;
When $0 \leq h' < h$, this means that F rejects the time step h , but making partial progress up to h' , and reach the new location s' .

Definition 2. FMU semantics Given the FMU $F = (S, U, Y, D, s_0, set, get, doStep)$,

The behavior of F depends on the functions $doStep$, which is a function of a timed input sequence (TIS). A TIS is an infinite sequence $v_0 h_1 v_1 h_2 v_2 h_3 \dots$ of alternating input assignments v_i , and time delays h_i . An input assignment is the value of function $v : U \rightarrow \mathbb{V}$. That is, v assigns a value to every input variable in U . A TIS denotes a running of FMU , which is an infinite sequence of quadruples (t, s, v, v') , where $t \in \mathbb{R}_{\geq 0}$ is a time instant, $s \in S$ is a state of F , v is an input assignment, and $v' : Y \rightarrow \mathbb{V}$ is an output assignment

TIS $:= (t_0, s_0, v_0, v'_0), (t_1, s_1, v_1, v'_1), (t_2, s_2, v_2, v'_2), \dots, (t_i, s_i, v_i, v'_i), (t_{i+1}, s_{i+1}, v_{i+1}, v'_{i+1}), \dots$ is defined as follows:

- $t_0 = 0$ and s_0 is the initial state of F .
- For each $i \geq 1$, $t_i = t_0 + \sum_{k=1}^i h_k$
- Given the current state s_i , the function set is used to set all input variables to the values specified by v . Then F reaches a new state s'_i . The function get is used to get the values of all output variables v'_i .
- We assume that $doStep(s_i, h_{i+1}) = (s_{i+1}, h_{i+1})$ based on the assumption that every h_i is accepted by F , F will reach the next state s_{i+1} .

B. Timed Automata

Timed automata (TA) [6] is a theory to model the behavior of real-time systems. It provides a powerful way to annotate state-transition graphs with many real-valued clocks. In this section, we introduce the syntax and semantics of timed automata.

Definition 3. Timed automata syntax A timed automaton is a tuple $A = (L, X, l_0, E_i, E_o, I)$, where:

- L is a finite set of locations;
- X is a finite set of clocks;
- $l_0 \in L$ is the initial state;
- The set of guards $G(x)$ is defined by the grammar $g := x \bowtie c \mid g \wedge g$, where $x \in X$, $c \in \mathbb{N}$ and $\bowtie \in \{<, \leq, \geq, >\}$. $E \subseteq L \times G(X) \times 2^X \times L$ is a set of edges labelled by guards and a set of clocks to be reset;
- E_i is a set of input events.

- E_o is a set of output events.
- $I : L \rightarrow G(X)$ assigns invariants to clocks.

A clock valuation is a function $v : X \rightarrow \mathbb{R}_{\geq 0}$. If $\delta \in \mathbb{R}_{\geq 0}$, then $v + \delta$ denotes the valuation such that for each clock $x \in X$, $(v + \delta)(x) = v(x) + \delta$. If $Y \subseteq X$, then $v[Y := 0]$ denotes the valuation such that for each clock $x \in X \setminus Y$, $v[Y := 0](x) = v(x)$ and for each clock $x \in Y$, $v[Y := 0](x) = 0$. The satisfaction relation $v \models g$ for $g \in G(x)$ is defined in the natural way.

Definition 4. Timed automata semantics The semantics of a timed automaton $A = (L, X, l_0, E, E_i, E_o, I)$ is defined by a transition system $L_A = (L, l_0, \rightarrow)$,

where $L = L \times \mathbb{R}_{\geq 0}^X$ is the set of locations, $l_0 = (l_0, v_0)$ is the initial location, $v_0(x) = 0$ for all $x \in X$, and $\rightarrow \subseteq L \times L$ is the set of transitions defined by :

- $(l, v) \xrightarrow{\epsilon(\delta)} (l, v + \delta)$ if $\forall 0 \leq \delta' \leq \delta : (v + \delta') \models I(s)$;
- $(l, v) \rightarrow (l', v[Y := 0])$ if there exists $(l, g, Y, l') \in E$ such that $v \models g$ and $v[Y := 0] \models I(l')$.

The reachability problem for an automaton A and a location l is to decide whether there is a state (l, v) reachable from (l_0, v_0) in the transition system L_A . As usual, for verification purposes, we define a symbolic semantics for timed automata. For universality, the definition uses arbitrary sets of clock valuations.

Consider a location l such that for any $t \in X$, for fixed constant $x \in X$, clock valuation $x + t \in X$. A possible execution fragment starting from this location is

$$(l, t) \xrightarrow{x_1} (l, t + x_1) \xrightarrow{x_2} (l, t + x_1 + x_2) \xrightarrow{x_3} (l, t + x_1 + x_2 + x_3) \xrightarrow{x_4} \dots$$

where $x_i > 0$ and the infinite sequence $x_1 + x_2 + \dots$ converges toward x .

III. OUR APPROACH

In this section, we present a novel approach to model and verify the properties of co-simulation with TA [10]. Besides, we propose encoding rules to encode FMU into timed automata. In section V, we will encode the FMUs of our case study with the network of TA, so that we can verify the case study with the model checker UPPAAL.

A. Framework of our approach

The schematic view of our approach is shown in Fig.1. At the design phase, we construct the architecture of CPSs with SysML block diagrams [11]. Each block represents a component and the communication between components is modeled with SysML connector. To simulate the whole system with co-simulation techniques, the block can be modeled with a Functional Mock-up (FMU) and the connector can be modeled with a master algorithm (MA). The MA orchestrate FMUs to accomplish the communication between FMUs. It is called *co-simulation* in our framework. To verify the correctness of the architecture, we encode each FMU component and model the master algorithm by timed automata, which facilitates the verification of livelock or deadlock with the model checker UPPAAL. [6].

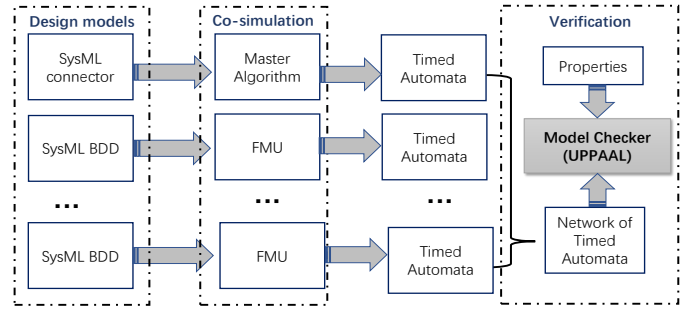


Fig. 1. A schematic view of our approach.

B. Encoding FMUs into timed automata

We find that there is a semantic gap between FMU and TA. The former focus on the execution sequence of FMU, which specifies the state change process with time elapsing. Essentially, the execution trace of TA is semantic equivalence to the execution sequence of FMU. Therefore, we encode FMU into TA to analyse the behavior of FMU components without exploring its internal structure. Given an FMU $F = (S, U, Y, D, s_0, set, get, doStep)$, we encode the FMU into a timed automaton $A = (L, X, l_0, E, E_i, E_o, I)$, the congruent relationship between them is as following:

- L is a set of finite states. Note that a location of A is the abstraction of a state in F .
- The initial location of TA l_0 which $x := 0 | x \in X$ is such that s is set to s_0 of F .
- Each input variable $u \in U$ ranges over $E_i \cup \{absent\}$.
- Each output variable $y \in Y$ ranges over $E_o \cup \{absent\}$.
- An input event in $e \in E_i$ is such that the function *set* of F sets the input variable u to a given value.
- An output event in $e \in E_o$ indicates that the function *get* of F gets the output variable y . The set of values in the E_i can be seen as Y of F .
- The communication between the network of TA is the same as the I/O dependencies information in FMU. $(u, y) \in D$ denotes that output y depend on input u . The output events also depend on the input events in TA.
- For any $e \in E$ of A , there is a transition $s \xrightarrow{e} s'$, which may be found after the function *doStep* is executing. For instance, if there is a transition $l \xrightarrow{e} l'$ in A , at the same time *doStep*(s, h) may be called which indicates that F accepts the time step h and reaches the new state s' . However, F maybe rejects the time step, if there is a rollback behavior happens, the transition in TA could be an edge $l' \xrightarrow{e} l$, which denotes that a location travels to the former location.

It is not easy to translate FMU to TA directly. Inspired by [9], we propose some encoding rules from FMU to TA. As we can see in the Fig.2, given a state s_i at t_1 in FMU, the operation *Dostep* makes FMU reach a new state s_{i+1} at $t_1 + step$. This situation can be encoded into a transition in

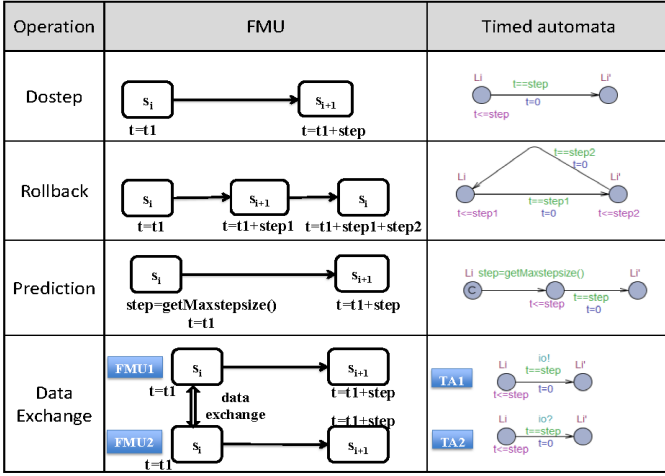


Fig. 2. Encoding rules from FMU to TA.

TA, in which a location L_i delays $step$ time and goes to a new location L'_i .

For the operation *Rollback*, given a state s_i at t_1 in FMU, the FMU will do a $step1$ to s_{i+1} at $t_1 + step1$, and then, the operation *rollback* makes FMU reach the former state s_i . For this situation, it can be encoded as: location L_i delays $step1$ time and reach a new location L'_i after a transition, next returns to the former Location L_i .

For the operation *prediction*, given a state s_i , FMU can get max step size ($step$) for next step, and then reach a new state s_{i+1} at $t_1 + step$. For TA, it gets max step size in location L_i , then it delays $step$ time and reach a new location L'_i .

For data exchange between two FMUs in state s_i at t_1 , they exchange data at t_1 and then do the same step to s_{i+1} . In TA, there will be a signal io to make the two FMUs do the same step from L_i to L_{i+1} after data exchange.

Although there are semantic gaps between FMUs and timed automata, we provide appropriate encoding rules to formalise FMU with timed automata. It lays the foundation for analyse FMI co-simulation with timed automata-based model checking. Limited to the length of this paper, we don't prove the correctness of encoding rules. We just encode FMU to TA manually, but the encoding process is semantic-preserve. In section V we apply these encoding rules to the water tank case study. Through the simulation results, we can find that the encoding rules does work well.

IV. MODELLING AND ANALYSIS OF MASTER ALGORITHM

The master algorithm (MA) provides the orchestration of FMUs, which denotes the co-simulation of various FMUs. To ensure the correctness of co-simulation execution process, it is necessary to verify certain properties of the master algorithm. In this section, we utilize timed automata to model three versions of master algorithms and verify some expected properties of master algorithm such as deadlock, liveness and reachability with UPPAAL.

A. I/O Dependency Information

When it comes to co-simulation, I/O dependency information [3] is inevitably required to be well considered. The master algorithm calls function *Set* to provide input value to an FMU and function *Get* to retrieve an output value. So it is essential to know which outputs of an FMU depend immediately on which inputs. In the design of a MA, the direct dependency information can be used to call the function *Set* and *Get* in a well-defined order. In FMI 2.0, this information can be provided using the element *ModelStructure* [12]. However, sometime there may be an algebraic loop in the dependency information, which may not converge. Since we are interested in non-diverging and deterministic composition of FMUs, we need to distinguish these two cases.

B. Master Algorithm

The master algorithm is to orchestrate the execution of different subsystems. Each subsystems serves as an FMU block whose simulation is triggered by a particular MA. FMUs can be seen as black boxes. FMU can be simulated independently until it needs to exchange data or implement synchronization. There are three versions of master algorithm, which is shown in Fig.3.

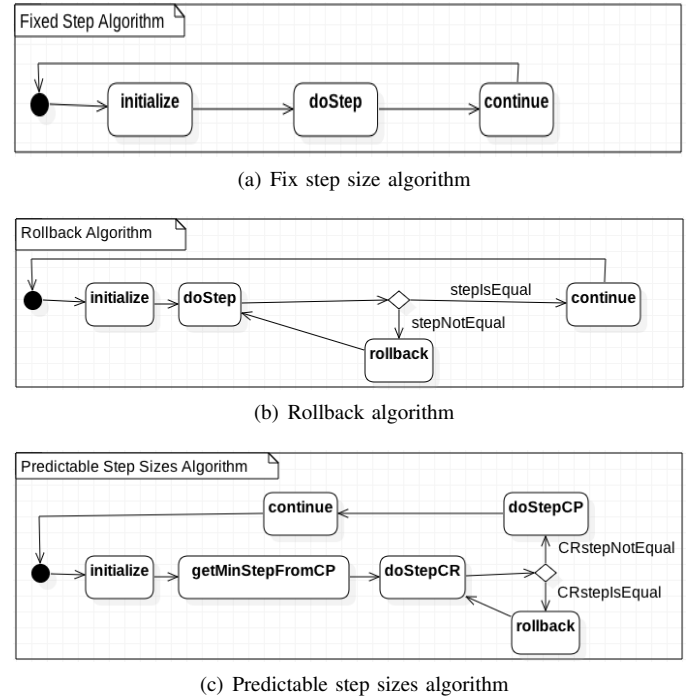


Fig. 3. Activity diagrams for three versions of master algorithms.

1) *Fixed Step Algorithm*: For fixed step algorithm, all FMUs have the same step size. When master algorithm calls *doStep* with the step size h , it will advance from a communication point t to the next communication point $t+h$. During the simulation step, an FMU with its own solver will simulate independently according to its input value and generate a running result as output value. MA will wait until all FMUs finish their simulation step and then get their output values to exchange data for preparing next simulation step. The activity diagram of fixed step algorithm is illustrated in Fig.3(a). There

are mainly three activities in the control flow: *initialize*, *doStep* and *continue*. In the fixed step algorithm [3], the process can maintain correctness when all FMUs are reliable. When some error happens during a simulation step, the process will be affected after the wrong simulation step. To overcome the shortcoming of the fixed step algorithm, it needs rollback mechanism.

2) *Rollback Algorithm*: There are some important features proposed in the FMI 2.0. It supports to save the FMU state if necessary and the saved state can be restored. For example, MA calls *doStep* on FMU_1 and FMU_2 while FMU_1 can accept the request or FMU_2 can reject it. If we save the state of FMU_1 and FMU_2 at the communicating point t , we can restore the scene after FMU_2 rejects *doStep*. The activity diagram of rollback algorithm is clearly shown in Fig.3(b). Compared with the fixed step algorithm, all FMUs are required to support *rollback* mechanism, that is, all FMUs need to return to the previous state if the simulation step sizes of all FMUs are not equal.

3) *Predictable Step Size Algorithm*: To improve the efficiency of MA, it is important to predict step size. So predictable step size algorithm is proposed. The function *GetMaxStepSize* was introduced to optimize the performance of rollback algorithm. This function returns the maximum step size and state flag of a predictable FMU. Maximum step is the largest step that a predictable FMU can perform. State flag includes *ok*, *discard* and *error*. *OK* denotes the predictable FMU can accept the simulation step size. *Discard* denotes the predictable FMU only implement partial step during simulation. *Error* denotes the predictable FMU can't continue the simulation because of its unacceptable state or unreasonable input value. Also, when *discard* and *error* happen, the FMU needs to rollback to the previous saved state. Whether an FMU is a predictable FMU or not should be indicated in FMU's *xml* file. Moreover, if an FMU supports rollback and predictable step size at the same time, the predictable step size algorithm only uses predictable ability to get the maximum step of a predictable FMU. On the other hand, a predictable FMU can accept any step size less than or equal to the maximum step returned by *GetMaxStepSize*.

First, the master algorithm chooses the maximum step size of all predictable FMUs and find the smallest communication step size h that all predictable step size can be accepted. Then, we save the states of all FMUs. MA calls *doStep(h)* on FMUs supporting rollback. The function *doStep()* will return the real performed step size. If all performed step sizes are equal to h , MA will call *doStep(h)* on FMUs. Otherwise, MA will find the smallest performed step h_{min} , then all FMUs will restore the state saved before the co-simulation. Finally, MA will invoke *doStep(h_{min})* on all FMUs. The control flow of predictable step size algorithm is shown in Fig.3(c). For example, *getMinStepFromCP* is an activity that MA will call *GetMaxStepSize* on all predictable FMUs to find their maximum simulation step size and then return the smallest one of them.

C. Modelling and Analysis of MA

UPPAAL [6] is a toolset for verification of real-time systems represented by (a network of) timed automata which

is extended with integer variables, structured data types, and channel synchronization. To verify the correctness of three versions of master algorithms, we model the master algorithms using timed automata in UPPAAL. The Fig.4 shows the timed automata model of three master algorithms, respectively. Fixed step algorithm has *Init*, *doStep* states and synchronize with FMU by channel *continue*. Rollback algorithm has *Init*, *DoStep*, and *Continue* states. If all FMUs don't have the same step size, rollback algorithm will communicate with FMUs by *rollback* signal, otherwise, it will send *continue* signal and move to *Continue* state. Predictable step size algorithm has *Init*, *find_CP_MIN*, *DoStep*, *writeCP* states. It obtains the minimal step size (i.e., *step2*) of FMUs supporting *GetMaxStepSize* function and the maximal step size (i.e., *step1*) of FMUs supporting rollback. If *step1* is greater than *step2*, FMUs receive *rollback* signal and return to *DoStep* state. Otherwise, FMUs receive *continue* signal and do the next step.

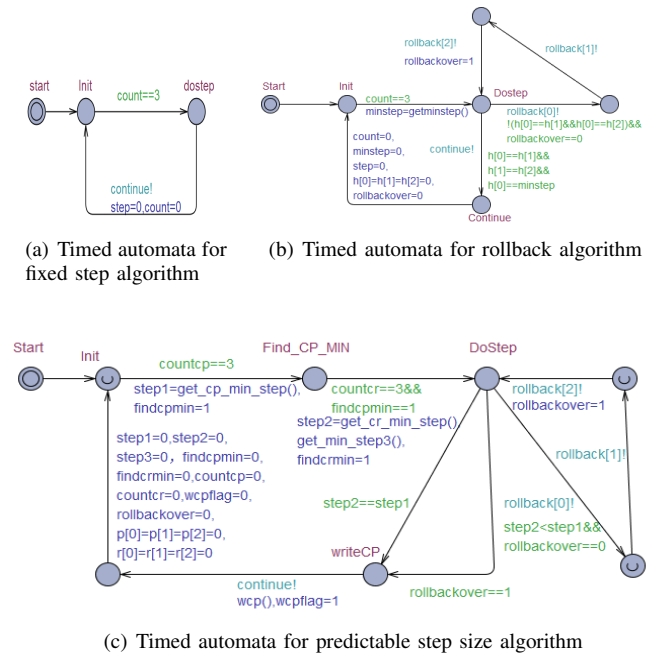


Fig. 4. Timed automata for three versions of master algorithms.

We verify the properties of master algorithms including reachability, liveness and deadlock. Experimental results are shown in Table I, where:

- $E\langle \rangle$ *master.dostep*, $E\langle \rangle$ *master.Continue* and $E\langle \rangle$ *master.writeCP* are reachability properties checking whether the model can reach these states;
- $master.Init \rightarrow master.dostep$, $master.Init \rightarrow master.Continue$ and $master.Init \rightarrow master.Continue$ are liveness property. If the master algorithm arrives at the former state, it eventually reaches the latter state;
- $A[]$ *not deadlock* is safety property, which means whether the model will be deadlock.

In Table I, we can find that the properties such as deadlock, liveness and reachability are satisfied, which proves that the correctness of co-simulation behavior. For example,

TABLE I. EXPERIMENTAL RESULTS

MA	Property	Result
Fixed Step	$A[] \text{ not deadlock}$	True
	$master.Init \rightarrow master.doStep$	True
	$E[] \text{ master.doStep}$	True
Rollback	$A[] \text{ not deadlock}$	True
	$master.Init \rightarrow master.Continue$	True
	$E[] \text{ master.Continue}$	True
Predictable	$A[] \text{ not deadlock}$	True
	$master.Init \rightarrow master.writeCP$	True
	$E[] \text{ master.writeCP}$	True

$A[] \text{ not deadlock}$ is satisfied, which means there is no deadlock in the execution of the master algorithm. $master.Init \rightarrow master.doStep$ is satisfied, which means if the model reach the former state *Init*, it will eventually reach the state *doStep*. $E[] \text{ master.doStep}$ is satisfied, which means there exists a reachable state *doStep*.

V. CASE STUDY

To illustrate our approach, we take an example water tank inspired by [13]. According to the I/O dependency information between FMUs, the architectural model for water tank is constructed using SysML. The aim of using SysML is to design the architecture of the system with a more high-level modelling language. It helps to show the components and their connections.

The water tank system is our running example. A source of water flows into the water tank whose water flows into the drain. The source is controlled by a valve; when the valve is open, the water flows into the water tank. The valve, managed by a software controller, is opened or closed stochastically or depending on the water level. There are three various water tank systems depending on various connections between controller, valve and tank.

A. Architecture Modelling in SysML

SysML is a general purpose domain-specific language (DSL) [14] for model-based systems engineering (MBSE) [15], which is originated as an initiative of the International Council on Systems Engineering (INCOSE) [16] in January 2001. SysML is implemented as a UML profile. The *Block Definition Diagram* (BDD) describes the system blocks and their features (structural and behavioural). The *Connection Diagram* (CD) describes the internal structure of blocks. The ports of blocks are connected by the connector. The I/O dependence of blocks describes the communication between blocks. SysML block diagrams are usually used to describe the architecture of systems.

Figure 5 shows the block definition diagram for the water tank system. The system consists of three blocks, i.e., *Valve*, *Tank* and *Controller*, in which *Valve* and *Tank* are physical components. *Controller* is the cyber component. Each component has its own input and output. For instance, the input interface of *Valve* is named as *vin*, which is used to input the *Open-Closed* signal. Figure 6 shows the connection diagram for the system. There are three cases for connections. The first case is that the system has one valve, one controller and one tank. The controller sends stochastic signals to control the valve on/off leading to various rate of water flow. The second case is that the signal from the controller is affected by the

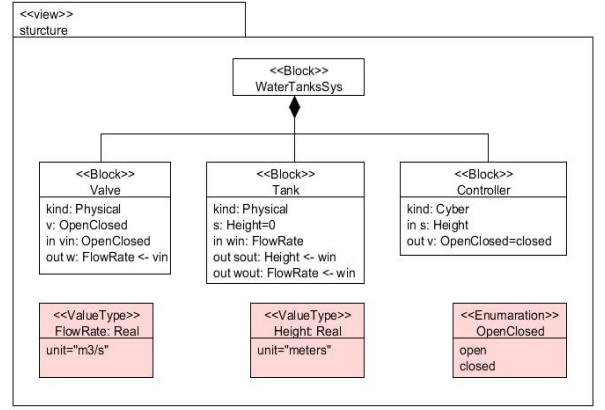


Fig. 5. SysML BDD for water tank system.

water level of the tank. The last case is on the basis of the first case and adds another tank2 which is affected by the flow rate of the tank1.

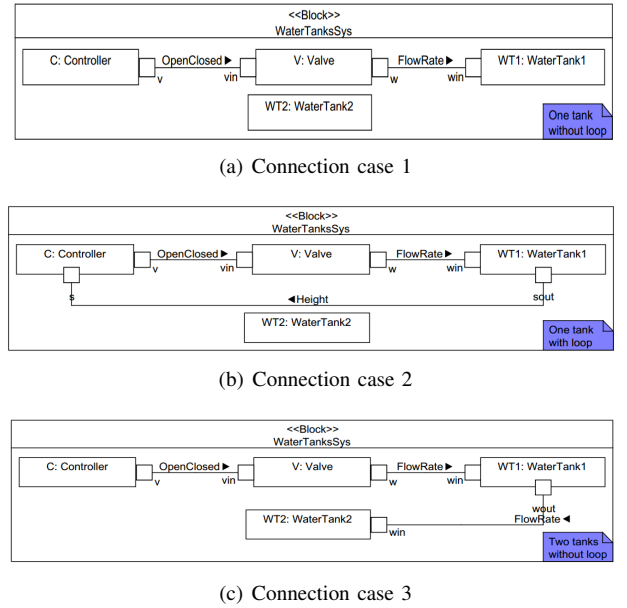


Fig. 6. SysML CD for water tank system.

We model the architecture with SysML which is a high-level modeling language. The SysML BDD shows the blocks of system and SysML CD shows the connection between blocks. In next section, we abstract each block as a FMU, and obtain the connection between FMUs based on the SysML CD.

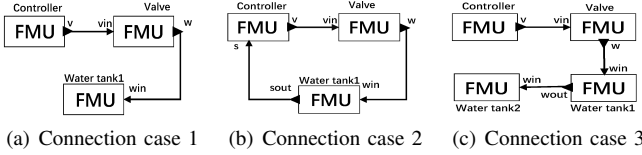
B. The FMUs Connection of Water Tank

Figure 7 is the FMUs and FMUs connection of water tank system. There are three connection cases between the FMUs according to the SysML CD in the previous section. The first case contains three FMU components (*Controller*, *Valve* and *Tank1*) and two channels (*v_vin*, *w_win*) as shown in Fig.7(a). The controller and valve are connected with channel *v_vin*. The valve and tank1 are connected with channel *w_win*. The second case is shown in Fig.7(b), there could be a channel

(a) Connection case 1

(b) Connection case 2

(c) Connection case 3



```

V → WI1[10]
(Unit, Rollback, Rollback, dostep)
WI1
(Unit, Rollback, Rollback, Rollback)
master
(dostep, Rollback, Rollback, Rollback)
rollback master → ControllerWI1
(dostep, reset, reset, reset)
V
(dostep, reset, Rollback, reset)
WI1
(dostep, reset, Rollback, Rollback)
Controller
(dostep, Rollback, Rollback, Rollback)
continue master → ControllerWI1

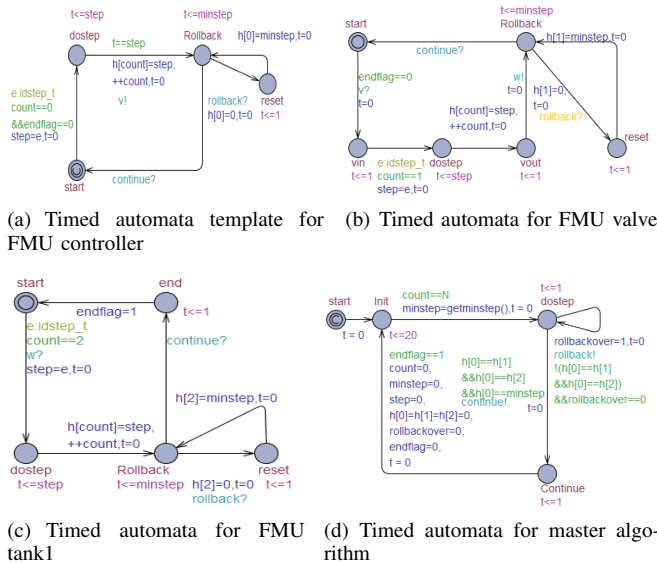
```

(a) Execution trace
(b) Execution sequence diagram

Fig. 9. The execution fragment of the co-simulation in UPPAAL.

Figure 8(a), 8(b), 8(c) are the templates for controller, valve and tank1 respectively, they model FMUs of the water tank, which support rollback function. These FMUs contain four key states, e.g., *start*, *dostep*, *Rollback* and *reset*. Figure 8(a) shows the template for controller which executes with random step size. It synchronizes with valve by signal *v* and transfers to *Rollback* state, and then waits for a signal from the master algorithm. Until the controller receives the *continue* signal, it does data exchange with other FMUs, and returns to *start* state. Otherwise, it receives *rollback* signal, once it obtains the minimize step size of all FMUs, it transfers to *Rollback* state. The states and transitions of valve and tank1 template are similar with the template of controller. Figure 8(d) shows the template for the master algorithm. Firstly, the master algorithm initializes the parameters, and then it gets minimize step size of FMUs until all FMUs visit *dostep*. Next, the master algorithm decides which signal should be sent according to the guard. If the step sizes of all FMUs are equal, the master algorithm will send *continue* signal, otherwise, send *rollback* signal.

Figure 9 is the execution fragment of the co-simulation in UPPAAL, we can find that valve sends a *w* signal to perform data exchange with tank1. After that, tank1 moves to *dostep* state. The master algorithm sends a *rollback* signal to all templates, which leads to all of them arrive at *reset* state. Finally, the master algorithm sends a *continue* signal to all FMUs. All templates return to *start* state, and then do the next step. The execution process shows that our models perform correctly.



In order to compare the behavior of three connection cases of water tank system presented in the previous subsection, we also model the other two connection cases in UPPAAL. We add a channel s in the templates for controller and tank1 of connection case 1 to model the connection case 2, as shown in Fig.10. We add a template *tank2* and channel $w2$ to model the connection case 3 as shown in Fig.11. In next subsection, we verify some properties of various connection cases to detect whether there is a loop dependence of the architecture.

- $E\langle \rangle$ *WT1.Rollback* and $E\langle \rangle$ *master.Continue* are reachability properties checking whether FMU *tank1*

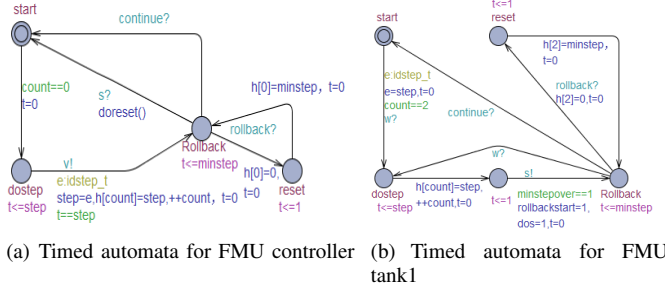


Fig. 10. Network of TA for connection case 2: $TA_controller \parallel TA_valve \parallel TA_tank1 \parallel TA_ma$.

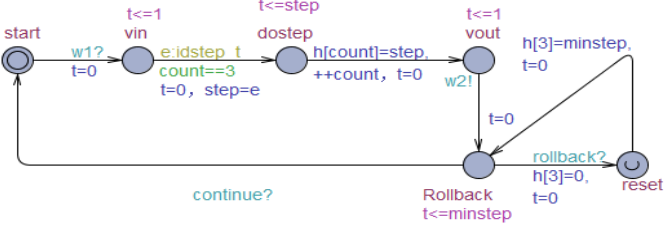


Fig. 11. Network of TA for connection case 3: $TA_controller \parallel TA_valve \parallel TA_tank1 \parallel TA_ma \parallel TA_tank2$.

can reach *Rollback* state and whether the master algorithm can reach *Continue* state respectively.

- $master.start \rightarrow master.Continue$ are liveness property. If the master algorithm arrive at *start* state, it eventually reaches *Continue* state.
- $A \parallel not\ deadlock$ is safety property checking whether the model will be deadlock.

The verification results are listed in Table II. We can find that all properties of connection case 1 and 3 are satisfied. It shows that our master algorithm works well and the composition of FMUs is determinate. However, the liveness and reachability properties of connection case 2 are not satisfied. We find that there is a algebraic loop which may be introduced with the I/O dependency in this connection case. The experimental results show that our approach is feasible and useful for model checking the FMI co-simulation. Here, we only focus on the detection of algebraic loop and the correctness of co-simulation. In the future work, we will consider eliminating the algebraic loop.

TABLE II. EXPERIMENTAL RESULTS

Connection case	Property	Result
Case 1	$E \langle \rangle WT1.Rollback$	True
	$E \langle \rangle master.Continue$	True
	$master.start \rightarrow master.Continue$	True
	$A \parallel not\ deadlock$	True
Case 2	$E \langle \rangle WT1.Rollback$	True
	$E \langle \rangle master.Continue$	False
	$master.start \rightarrow master.Continue$	False
	$A \parallel not\ deadlock$	True
Case 3	$E \langle \rangle WT1.Rollback$	True
	$E \langle \rangle master.Continue$	True
	$master.start \rightarrow master.Continue$	True
	$A \parallel not\ deadlock$	True

VI. RELATED WORK

For simulating CPSs [18], distinct simulation domains need to be integrated for a comprehensive analysis of the interdependent subsystems. Co-simulation [19] can maintain all system models within their specialized simulators and synchronizes them in order to coherently integrate the simulation domains. FMI [2] [12] is an industry standard which enables co-simulation of complex heterogeneous systems using multiple simulation engines. It has been adopted by the industry and academic. Jens Bastian et al. adopts fixed step size master algorithm to simulate heterogeneous systems in [20]. David Broman et al. discussed the determinate composition of FMUs for co-simulation. They extended the FMI standard to designs FMUs that enables deterministic execution for a broader class of models. Besides, rollback and predictable step size master algorithms are proposed in their work. In [21], Fabio Cremona et al. presents FIDE, an Integrated Development Environment (IDE) for building applications using FMUs. In our recent work, we have implemented the prototype *co-simulator* for continuous-time Markov chains (CTMCs) [22], discrete-time Markov chains (DTMCs) [23] and Modelica models in [24]. We also proposed an improved co-simulation framework that focuses on the capture of nearest future event to reduce the number of running steps and the frequency of data exchange between models. In short, the existing work focus on how to achieve deterministic execution of FMUs and improve the efficiency of master algorithms, however, there is few work to analyse master algorithms with formal methods. P.G Larsen et al. [5] presented formal semantics of the FMI described in the formal specification language CSP. They formally analyse the CSP model with the FDR3 refinement checker. Nuno Amalio et al. [13] presented an approach to verify both healthiness and well-formedness of an architecture design modelled with SysML. They attempt to check the conformity of component connectors and the absence of algebraic loops to ensure the co-simulation convergence. In [25], Mladen Skelin et al. reports on the translation of the FSM-SADF formalism to UPPAAL timed automata that enables a more general verification than currently supported by existing tools. Stavros Tripakis [9] discussed the principles for encoding different modelling formalisms, including state machines (both untimed and timed), discrete-event systems, and synchronous data flow, as FMUs. Compared to the existing work, the novelty of our approach is that it models the FMI co-simulation with timed automata. The execution of FMU and co-simulation is time related. It is naturally to use timed automata, due to its powerful describing ability of specifying time and extensive tool support.

VII. CONCLUSION AND FUTURE WORK

In this paper, we present a novel approach to model check the FMI co-simulation, which facilitates the formal verification of CPSs. It involves to model check the reachability, liveness and deadlock of three various master algorithms. Besides, the correctness of the system architecture is also analysed. We encode the FMU components and master algorithms with timed automata, so that properties of the co-simulation can be verified with UPPAAL. To illustrate the feasibility of our approach, the example water tank is discussed. Its architecture is specified with SysML block diagrams, from which the relevant FMU components are derived to co-simulate the system behavior. With the help of encoding, the network of timed automata for

the water tank system is built. The experiment results show that the co-simulation behavior of CPSs can be analysed effectively with model checking technology.

An interesting direction of future work is to analyse and compare the performance of various master algorithms. We will also study how to eliminate algebraic loop of the architecture. Besides, some industrial case studies will be conducted to check the scalability of our approach. The tool implement of co-simulation should also be improved further.

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