Integration of heterogeneous components for co-simulation

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Keywords: Heterogeneous models, Simulation, Formal verification, Integration, System design

Abstract: Because of their complexity, embedded systems are designed with sub-systems or components taken in charge by different development teams or entities and with different modeling frameworks and simulation tools, depending on the characteristics of each component. Unfortunately, this diversity of tools and semantics makes the integration of these heterogeneous components difficult. Thus, to evaluate their integration before their hardware or software is available, one solution would be to merge them into a common modeling framework. Yet, such a holistic environment supporting many computation and computation semantics seems hard to settle. Another solution we investigate in this paper is to generically link their respective simulation environments in order to keep the strength and semantics of each component environment. The paper presents a method to simulate heterogeneous components of embedded systems in real-time. These components can be described at any abstraction level. Our main contribution is a generic glue that can analyze in real-time the state of different simulation environments and accordingly enforce the correct communication semantics between components.

1 Introduction

Complex embedded systems are commonly designed using several modeling approaches and tools, because of the different nature of sub-systems, and because of the use of tiers to provide equipments. Integrating such heterogeneous is known as complex because of the diversity of models. Yet, ideally, this integration stage should be done as early as possible in the development process of these systems to verify, e.g., that the interfaces and main data exchanged are as expected, and can provide the expected overall functions.

Since forcing all partners of a product to use the same modeling languages or simulation techniques is a too hard constraint, integration of components designed within disparate formalisms necessitates a methodology for interconnecting these varying formalisms. A first way to do would be to glue the different meta-models of the components in order to build a unique (meta-)model from which integration verifications can be performed. This has already been shown in the scope of components for which their models of computation are quite similar [Zhao et al., 2020]. Yet, when they are too different, a second approach can be used: connecting these components at simulation level. This paper aims to address this challenge, concentrating specifically on data exchanges between components. The objective is to guarantee the enforcement of the correct communication semantics.

In this paper, we define a method and techniques to allow to integrate a set of models designed with different frameworks and simulated using their own simulator, with no modification on their simulation engine. To maintain a real-time co-simulation of these different simulators where they interoperate in realistic scenarios, we propose a generic ”simulation glue” based on a distributed event streaming platform to join heterogeneous simulators together. After having defined this glue, the paper illustrates in a more concrete way how SystemC and TTool components can be co-simulated, using Apache Kafka as the distributed event streaming platform.

2 Related Work

In the area of heterogeneous distributed systems analysis, e.g., [Basu et al., 2006, Liboni and Deantoni, 2020], most of the works are based on co-simulation, but not many of them can support both simulation and formal validation in the same framework. For coupling two or more simulation tools in a co-simulation envi-
3 Simulating heterogeneous models

This section presents our contribution: a new framework for the integration of heterogeneous components using a simulation integration platform. This integration platform is agnostic to the simulation technology, as long as it supports the communication semantics described in this section.

Figure 1: Communication between models and the distributed event streaming platform

3.1 Component model

A model defines components interconnected with ports. A model supports 4 types of ports: internal input ports $I_i$, external input ports $I'_j$, internal output ports $O_k$ and external output ports $O'_l$. A model $M$ has $m$ internal input ports, $n$ external input ports, $p$ internal output ports and $q$ external output ports as shown in Fig. 1. We assume that the objective is to co-simulate a set of components $C$. We assume that the simulation engine of each $c \in C$ can already handle communications internal to $c$. Thus, in this paper, we focus on external input ports $I'_j$ and external output ports $O'_l$.

In this paper, we consider two modeling frameworks and their corresponding meta-models: TTool [TTo, 2023] and SystemC. The former can be used to capture SysML components that can be simulated with the internal simulator [Knorreck et al., 2009] of TTool to prove safety and performance properties. The latter uses components written in C++ and simulated with the SystemC simulation engine.

3.2 Distributed event streaming platform

We assume that a facility, part of our contribution, can stream events to distributed senders/receivers so as to ensure data can be sent and received, in real-time, by the simulation engines of components.

Apache Kafka. Apache Spark, Apache Kafka, Apache Flink and Spring Cloud Data Flow are examples of streaming platforms. We decided to rely on Apache Kafka to forward messages between simulation engines. Indeed, Kafka supports many computing platforms and can also handle distributed and event-based communications. Yet, Kafka cannot natively support the communication semantics usually found in modeling frameworks for embedded systems, for instance the exchange of values via FIFOs. Yet, Kafka supports the notion of broker: a broker contains a set of topics, and each topic has a set of
partitions that can be considered as an infinite FIFO buffer. To send messages to a partition, we rely on producers. A producer can send messages to different partitions in different topics. Consumers can receive messages from partitions. Partitions are configured at co-simulation setup.

3.3 Communication

In Fig. 1, we give an example of the simulation integration between 3 models via a distributed event streaming platform, where:

- Model $M_1$ has 2 external input ports $I_1^1$ and $I_1^2$ and 2 external output ports $O_1^1$ and $O_2^1$.
- Model $M_2$ has 2 external input ports $I_1^1$ and $I_1^2$ and 1 external output port $O_1^1$.
- Model $M_3$ has 1 external input port $I_1^1$ and 2 external output ports $O_1^1$ and $O_2^2$.

The distributed event streaming platform must ensure communications, for example from external output $O_1^1$ of $M_2$ to external input $I_1^2$ of $M_2$.

Fig. 2 depicts the general approach of our contribution. First, we assume that a user wants to co-simulate at least two models having possibly different meta-models. From those models, our contribution automatically updates these models to allow them to interact with our co-simulation framework. Then, using these Co-simulation models, we start the corresponding simulation of each model at the same time. We assume we can access to the simulation trace of each simulation when they are running: what is of interest for us is obviously to identify all the potential read or write transactions on external ports. Indeed, the co-simulator retrieves information that being sent or received on each port. When data is ready to be sent on an external output port, our co-simulator ensures data are forwarded to the corresponding external input port while enforcing the communication semantics, e.g., finite or infinite FIFO, exchange of values or exchange of a quantity of information.

Fig. 3 zooms on the co-simulation box shown in Fig. 2. The co-simulator is in charge of stream routing. For each model, the co-simulator manages the sending and receiving of data from the event streaming platform depending on the port type and the current status of ports.

3.4 Co-simulation models

The purpose of modifying the original models is to facilitate communication between the simulation of a model and the co-simulation. Co-simulation models are automatically generated from the original model.

The Co-simulation models are automatically generated from a given model.

Algorithm to create a Co-simulation TTool model, as shown in Fig. 2. A TTool model consists of two views: a functional view and a hardware view. In the functional view, SysML blocks are used to describe the functions and their communication. The behaviour of each function is given with an Activity Diagram. Functions can communicate together using two different facilities: event and data channels. Events can be used to exchange control values. Data channels are used to capture the exchange of a quantity of information. In the hardware view, functional blocks are allocated to blocks representing hardware components: processors, buses and memories. Functions are to be allocated to execution components (e.g., processors), and data communication are mapped to buses and memories. Events are not mapped since the traffic induced by control signals is usually considered as negligible. Events and data channels support different semantics, such as finite FIFO, infinite FIFO, etc.

Handling a communication (events, data) with a model external to TTool means that the hardware platform modeled in TTool must contain a input/output hardware device from which all system components can be reached. This is how this is achieved in embedded systems: a communication interface must be used for input and output operations with the environment.

As a consequence, sending information to a component external to the TTool’s model means that transactions on memories and on buses leading to the communication interface device must be taken into account when simulating the TTool model. Thus, when connecting TTool’s simulator with another simulator, we decided to add one hardware I/O device per output or input channel, and the necessary connection to buses and memories of the hardware part of the TTool model. Moreover, we map to each hardware device one function $f_{ce}$. The activity diagram of $f_{ce}$ features a main loop, which is infinite. In the case of an input device, the loop contains a wait event operator that makes it possible to receive the number of samples to be read (i.e., the quantity of information). The wait event is followed by a read channel operator. In the case of an output device, the infinite loop had a send event to send to the destination the number of samples to be read, and then a write operator. Algorithm 1 formalizes the different steps necessary to prepare a TTool model for external co-simulation: this includes creating the new functions $f_{ce}$ and their behavior, creating the hardware I/O devices $p_{ce}$, con-
Co-simulation
Simulation of Model 1
Model 1
Trace of Model 1

Co-simulation Model 1

Automatic adjustment

Co-simulation Model 2

Automatic adjustment

Co-simulation Model n

Automatic adjustment

Simulations
Simulation of Model 2
Simulation of Model n

Traces
Trace of Model 2
Trace of Model n

Glued Models/Event streaming platform

Figure 2: An overview of the proposed approach

Figure 3: Zoom in the "Co-simulation" box

necting them to the corresponding bus, and connecting the new ports (ports of $f_e$) to the corresponding sending or receiving functions.

4 Implementation of our approach

An example of Generating automatically a Co-simulation Tool model. Let’s consider an example with 3 external input ports (“evt_1”, “comm_1” and “comm_2”) and 2 external output ports (“evt_2” and “comm_3”). The top part of the functional view in Fig. 4 and the top part of the architecture in Fig. 6 depict functional components and the allocation of components to the related architecture, respectively.

The application of Algorithm 1 to this model automatically transforms the component view to the one given at the bottom of Figure Fig. 4. Similarly, the activity diagram of the new task of the external channel “comm_1” is shown in Fig. 5, the activity diagrams of the tasks of the external channels “comm_2” and “comm_3” are similar to that of the channel “comm_1”, but its of “comm_3” has a channel read operator instead of the channel write operator. Also, bottom part of Figure Fig. 6 depicts the new hardware architecture.

Automatic handling of communication semantics via Kafka. The general idea behind our contribution is to automatically create the necessary Kafka partitions to handle the communication semantics, e.g., to manage the number of events or data samples in transit between two external ports. We associate to each component ports consumers and producers.
Figure 4: Top: The original Task diagram of the initial model. Bottom: The auto-generated task diagram of the Co-simulation model.

Figure 5: The auto-generated activity diagram for Channel `comm_1`.

A consumer intends to collect values from partitions, while a producer add information to partitions. Finally, our co-simulation framework is based on a set of partitions handled by Kafka and a set of producers and consumers.

We now review how the different communication semantics of data channels and events can be handled by the co-simulation framework ("Co-simulation" box in Fig. 2). For space reason, the paper focuses on one data channel communication semantics: **Blocking Read Blocking Write (BRBW)**. An other communication semantics of type: **Block Read Non Blocking Write with finite FIFO for events (BRNBW)** can be found in section 4 of [Jerray et al., 2023].

**Blocking Read, Blocking Write Channel.** Let's consider a model built upon two components `c1` and `c2` exchanging data with an external communication. `c1` has an "external output" port `comm_1` of type "blocking write channel", `c2` has an "external input" port `comm_2` of type "blocking read channel". Because they are external, these two ports must exchange data via our approach to provide a blocking-read blocking-write channel communication. The approach is configured as follows.

Fig. 7 depicts the communication between `c1` and `c2` and presents the different producers and consumers that are used to enforce the correct communication semantics between them.

First of all, a topic denoted `T` with two partitions `p1` and `p2` is created to apply the correct communication semantics between `c1` and `c2`. `p1` indicates the current number of samples that can be consumed by `c2` while `p2` contains the number of samples that has been already read by `c2`.

For `c1`, we create a producer `pr_1` that puts in `p1` the number of samples that have been written. The producer `pr_1` detects the written samples by analyzing in real-time the simulation trace of `c1`. `c1` relies on `p2` via consumer `co_1` to know how many samples have been already read by `c2` to figure out how many samples can be transmitted to `p1`. 
For $c_2$, we create a consumer $co_2$ to get from $p_1$ the number of samples that has been written by $pr_1$, and we use a producer $pr_2$ to send in $p_2$ the number of samples that have been read based on the simulation trace of $c_2$. So, the consumer $co_2$ is blocked until a new element is added to $p_1$ or a read is performed by $c_2$.

Algorithm 2 features how the channels at output side (component $c_1$) are handled for a BRBW channel and Algorithm 3 shows how to handle channels at input side (component $c_2$) for a BRBW channel.

Co-simulation of TTool SysML and SystemC models. We show how our approach can be used to co-simulate components designed in TTool (SysML) and others designed in SystemC. A ZigBee decoder serves as case study: we use the version described in [Enrici et al., 2017]. ZigBee is a wireless communication scheme adapted to low-power devices.

In this example, we have divided the ZigBee decoder into 5 components (Source, symbol2ChipSeq, Chip2Octet, CW, and Sink) where Source, Chip2Octet and Sink are modeled and simulated by TTool while symbol2ChipSeq and CW are modeled and simulated using SystemC. All the external channels, in this example, are of type blocking read blocking write (FIFO of size 2) and the external events are of type blocking read, no blocking write with infinite FIFO. Also, we set the size of samples to 13.

After model improvement, our approach starts all five simulation engines (one for each component), thus including all the necessary Kafka consumers and producers.

The description of case study and the results can be found in section 5 of [Jerray et al., 2023].

5 Conclusion

In this paper, we highlighted the need to integrate components together without common modeling languages nor heavy model transformations. Thus, we presented a method that allows to co-simulate, in real-time, embedded systems with heterogeneous components while respecting usual communication semantics between the components to be integrated. Our approach is based on simple model updates, on Kafka,
and on the use of consumers and producers.

We have applied our method applies to mid-size systems such as Zigbee.

Having a distributed co-simulation has a cost in term of simulation time: we intend to lower the extra latency as much as possible: an option is to experiment with more modeling and simulation environments like AADL.

Algorithm 1: Algorithm of the creation of the Co-simulation TTool model

```c
for each
i_inpput_channel in list_input_channels do
disconnect_port_from_origin_side
(i_input_channel); /* Disconnect the external
port from its origin. */
create_new_task(); /* Create new task for the
external input channel. */
connect_port_to_new_task(i_input_channel);
/* Connect the external port to the new task. */
add_event(i_input_channel); /* Add an event
to the new task, this event will retrieve data from
the co-simulator using the avs command that allows
to add signals to a given event. */
associate_activity_diagram_to_task
(i_input_channel); /* Create the activity
diagram of the new task that contains an infinite
loop with a read event to get the data sent by the
co-simulator followed by a write channel to insert
the data to the model. */
add_CPU_in_architecture(i_input_channel);
/* Add a new CPU in the architecture and associate
the created task to it. */
link_CPU_to_bus(i_input_channel); /* Link
the new CPU to the main Bus. */
end
for each
i_output_channel in list_output_channels do
disconnect_port_from_destination_side
(i_output_channel); /* Disconnect the
external port from its destination. */
create_new_task(); connect_port_to_new_task(i_output_channel);
add_event(i_output_channel);
associate_activity_diagram_to_task
(i_output_channel); /* Create the activity
diagram of the new task that contains an infinite
loop with a read event, followed by a read channel
to remove samples from the channel. */
add_CPU_in_architecture(i_output_channel);
link_CPU_to_bus(i_output_channel);
end
```

Algorithm 2: Algorithm of the output side
(component c1) for a BRBW channel

```c
search ←
ssearch_write_trans_in_trace(channel_name);
/* Check if there is a write transaction of
this output channel in the trace. */
if search is True then
nb_samples_written ←
get_from_trace_number_of_samples_written
(channel_name); /* Parse, from the
trace, the number of samples of the
external output channel that has been
written. */
send_message(pr2, T); 0,
 nb_samples_written); /* Send the number
of samples in pr1 of T created for this
channel using its producer pr1. */
end
nb_samples_read_by_c2 ←
read_first_message_no_blocking(co1);
/* Check if there is a new message in pr1 since
the last consumption and return the value of the
first new message (element). */
if nb_samples_read_by_c2 != "" then
exec_command("avs "+
name_of_event_created_for_channel_output
+ " 1 " + nb_samples_read_by_c2);
/* Add the number of samples obtained from
pr1 to the event of the new task that was
created for the output external channel.
Thanks to the avs command of the simulator
that allows to add virtual signals for a
given event. By adding the number of the
samples read by c1 to the event a read
transition will be succeeded to remove the
obtained number of samples from the output
channel buffer. */
end
```

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```plaintext
Algorithm 3: Algorithm of the input side (component c2) for a BRBW channel

1. check_new_data ← check_new_data_in_topic(channel_name);
   /* Check if there is new data since the last consumption
    * in p1 of the topic T that was created for this channel. */
2. if check_new_data is True then
   3. read_first_message_blocking(co2);
      /* Consume the first new message since the last
       * consumption and return the number of
       * samples found in p1 using the consumer co2
       * created for this input channel. */
   4. exec_command("avs "+
      name_of_event_created_for_channel_input
      + " 1 " + nb_samples); /* Add the number
         of the new samples obtained from p1 to the
         event of the new task that was created for
         the input external channel (for example the
         event goTM in Fig. 5). By adding
         the number of the samples written by c1 to the
         event, a write transition will be
         succeeded to add the obtained number of
         samples to the input channel buffer. */
   5. end
   6. search ← search_read_trans_in_trace(channel_name);
      /* Check if there is a read transaction of this
       * input channel in the trace. */
   7. if search is True then
      8. nb_samples_read ←
         get_from_trace_number_of_samples_read
         (channel_name); /* Parse, from the
            trace, the number of samples of the
            external input channel that has been read.
            */
      9. send_message(pr2, T, 1,
         nb_samples_read); /* Send the number of
            read samples in p2 of the topic T using the
            producer pr2. */
   10. end
```