CoHLA: Design Space Exploration and Co-simulation Made Easy

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Abstract—The inherent multi-disciplinary nature of cyber-
physical systems makes it difficult to get early insight in key
system properties and trade-offs that have to be made. Our aim
is to support system architects of such systems by facilitating
the co-simulation of models from different disciplines and design
space exploration. This has been achieved by defining a domain-
specific language called CoHLA which allows a high-level de-
scription of a system architecture and simulation parameters to
be specified. A generator has been implemented that generates a
co-simulation of component models using an implementation of
the HLA standard. Component models that adhere to the FMI
standard can be incorporated easily. Moreover, CoHLA includes
primitives to express design space parameters and metrics; this
information is used to generate tooling for automated design
space exploration.

Index Terms—Domain Specific Language, Cyber-physical sys-
tems, Co-simulation, Design Space Exploration, HLA, FMI

I. INTRODUCTION

The development of a cyber-physical system (CPS) is a
complex multi-disciplinary process. It involves different dis-
ciplines to develop specific subsystems, all having their own
methods and workflows. To combine all these approaches
together into one development process can be very chal-
lenging. To overcome this problem, model simulation can
be helpful. However, different disciplines may use different
modelling techniques, which makes it hard to combine into
one simulation model representing the system as a whole. The
use of such co-simulations of models during the development
of industrial CPSs could help to speed up the development
process or to gain more insight in the working of the complete
system. These co-simulations could also improve the testing
process by supporting hardware-in-the-loop (HIL) or software-
in-the-loop (SIL) simulations. Early-stage co-simulation could
also provide additional insight in design decisions during
Design Space Exploration (DSE) [10].

For the construction and execution of co-simulations, stand-
ards such as the High Level Architecture (HLA) [1] and the
Functional Mock-up Interface (FMI) [4] were designed. FMI
aims for model interconnectivity by specifying a standard in-
terface that wraps a model in such a way that other simulato-
rs or modelling tools can read or execute them. The FMI standard
is supported by a wide range of tools, which enables the
connection of a wide variety of different types of models.

HLA is an interface standard that specifies a set of rules
for the definition and execution of co-simulations of models
created in different tools. An HLA implementation consists of
a Run-Time Infrastructure (RTI) together with a set of model
simulations. Each of these simulations is called a federate,
whilst the co-simulation is called a federation.

Although the definition of a co-simulation using HLA is
very useful, it is rather complex and time consuming [8][6]. An
HLA configuration is based on a configuration file, called the
Federation Object Model (FOM), which stores all information
about the connected federates and their attributes. Additionally,
each simulation requires a federate implementation specific
for the RTI implementation of HLA. This is particularly
time-consuming when the co-simulation changes frequently.
Consequently, constructing a co-simulation of a system using
HLA might be very costly.

Therefore, we aim for a model-based approach that enables
easy usage of HLA during the development of CPSs. Models
that are currently only being used for the design of specific
subsystems could also be used to get a better understanding
of the system design as a whole.

Additionally, we also aim for a clear separation and co-
simulation of models of hardware and models of software. Explicit modelling of the software architecture improves the
possibilities for concurrent development of a CPS. For this,
we will also provide support for co-simulating models cre-
ated in the Parallel Object-Oriented Specification Language
(POOSL) [15]. POOSL is particularly useful for rapid mod-
elling of software architectures and POOSL models can be
simulated using the Rotalumis simulator. Hence, the combi-
ation of these goals should greatly simplify the construction
of powerful HLA co-simulations. By supporting both the FMI
standard and POOSL as modelling tools, support for a wide
variety of modelling techniques is embedded in our method.

Our second goal is to provide an automated method to
perform DSE on a set of models to gain more insight in the
system as a composition of subsystems. This requires a
structured method to specify a design space together with a
set of performance metrics to be able to compare the results
of each of the executed design space configurations. The
simulation results and performance metric results should be
properly organised to support the system architect in making
the right design decisions. Automated execution of the system co-simulation over a design space could very well be done overnight so that the designers can proceed their work the next morning while having the most recent results.

A. Approach

To achieve the goals described above, we will continue our work on building a Domain Specific Language (DSL) to quickly construct HLA co-simulations [11]. This DSL is called CoHLA (Configuring HLA) and can be used to specify simulation models as federate objects, each of them having their own attributes, timing behaviour and simulator type. By means of the DSL, these objects can easily be reused and connected to each other to form a co-simulation of models. CoHLA also provides functionality to enable logging and to change model initialisation parameters. From a co-simulation instance defined in CoHLA, code is generated that can be integrated with an implementation of HLA. This concerns, for instance, wrapper code to allow the communication between an FMI-based simulation and RTI implementation. Currently, the generator of the DSL leads to code for use with OpenRTI. OpenRTI is an open-source implementation of the HLA standard written in C++. The DSL relies on a set of libraries written for OpenRTI to connect different types of models to the RTI. These libraries have been introduced in [11].

The approach proposed here is tested on a number of case studies. In this paper, we describe an academic system which was constructed such that it shares key characteristics with a confidential industrial case that we are working on in parallel.

B. Related work

There already is a number of tools and methods to explore the design space during the design of CPSs. The INTO-CPS [9] project is working on a tool chain that also focuses on co-simulating heterogeneous models of systems. INTO-CPS offers an analysis tool called Automated Co-model Analysis to perform design space exploration [7]. The analysis reports a number of objectives for each of the configurations to support comparison and design decisions. Since the INTO-CPS project greatly relies on a specified set of tools, it is difficult to change to another tool chain once using INTO-CPS. We intend to use existing standards to allow interchangeability between tool chains.

The OpenMETA [14] tool chain contains a number of tools that support quite extensive DSE [13]. The construction of a co-simulation of a bunch of models, however, is rather time consuming as it requires a lot of meta modelling. The tool chain also does not work with an existing co-simulation standard for heterogeneous sets of models.

Our research is also related to work that intends to facilitate the use of HLA and exploit the combination with the FMI standard. The SEE HLA Starter Kit [6] has been developed to make the construction of an HLA-based simulation less time consuming and error-prone. It provides a Java-based software framework to support the implementation of space simulators. The use of HLA’s RTI as a master for FMI compatible simulation components has already been proposed in [2]. [17] describes a mechanism to develop an HLA-compliant federate using a wrapper that connects a FMU to HLA. Similarly, Neema et. al. [12] have demonstrated an approach to integrate multiple FMUs [4] into one HLA co-simulation in which FMU containers are automatically wrapped as federates. The definition of a co-simulation still requires quite some effort because a number of meta-models have to be specified.

A few possibilities to combine HLA and FMI are discussed in [8]. Our CoHLA approach matches the adapter-based approach, using the FMI for co-simulation. Our main achievement is the automatic generation of wrappers and XML descriptions based on a concise instance of a DSL. A related tool that is capable of creating model-based co-simulations of systems based on generated federate code is SimGE [16]. The generated code, however, is limited to skeleton code and hence still requires some manual implementation steps.

II. Sample case: SliderSetup

To develop, evaluate and illustrate the proposed approach, a SliderSetup example was designed to reflect a number of problems that were encountered in an industrial case we are working on. The SliderSetup consists of two independent rails, each having a movable pin mounted, which is displayed in Figure 1. A motor for each pin allows it to move over its rail, which is 30 cm long. One rail is mounted at the bottom of a cage while the other is mounted at the top. Both pins are directed to the centre of the cage. Consequently, the pins can collide with each other in the middle.

The SliderSetup consists of five subsystems, which are displayed in Figure 2. Since both sliders and their controllers are exactly equal, the system consists of three different subsystems that should be developed. The components are all connected by wires.

- **Supervisory controller**: Controller running on an embedded board that provides setpoints and running modes to both motor controllers. The supervisory controller coordinates movements of both sliders of the SliderSetup.
- **Slider controller**: Controls a single slider motor by providing the electrical input for the motor. Receives

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1. [https://sourceforge.net/projects/openrti/](https://sourceforge.net/projects/openrti/)
setpoint information as input from the supervisory controller.

- **Slider**: The slider component contains a motor which receives electrical input from the controller and produces some kinetic action. It also contains a limit switch which sends a signal when the slider is close to the end of the rail.

For each of these subsystems a model is created. The supervisory controller was modelled using POOSL and is a discrete-time model. Both the slider controller and the slider were created in 20-sim\(^2\) and are discrete-time and continuous-time models respectively. The 20-sim models were exported to Functional Mock-up Units (FMUs), which are simulation containers using the FMI standard. An earlier case study, however, shows that the models could also be created in OpenModelica\(^3\) or any other modelling tool that supports exporting an FMU.

### III. CoHLA

This section starts with a brief description of the structure of our DSL approach as introduced in [11] and our steps towards the extension for automated DSE. CoHLA is developed using Xiext [5] together with a code generator developed using Xtend [3]. These tools are based on the Eclipse IDE\(^4\) and are suitable to create a custom language with a code generator, possibly for multiple targets.

#### A. Co-simulation definition in CoHLA

CoHLA can be used to define a co-simulation by specifying a number of simulation models and their connections. The main language constructs that are available to define a co-simulation are described below.

- **FederateClass**: Each simulation model should be specified in a FederateClass. An example for the Slider in the SliderSetup is displayed in Listing 1.

```plaintext
FederateClass Slider {
  TimePolicy RegulatedAndConstrained
  Attributes {
    Input Boolean enable
    Input Real encoder
    Output Boolean limit_switch
    Input Real motor
    Output Real position
  }
  Initialisables {
    Initialisable MaximumDistance *Maximum_distance* as Real
    Initialisable Position_realInitial *position_real.initial* as Real
  }
  SimulatorType FMU
  DefaultModel "SliderAxis.fmu"
  DefaultStep Time
  DefaultStepSize 0.00005
  DefaultLookahead 0.00001
}
```

Listing 1. FederateClass definition for the Slider in the SliderSetup.

It contains the type of simulator to use (line 14), the default model to use (line 15), some HLA-specific information (lines 2, 17 and 18) and the externally visible attributes in the model (lines 3 to 9). An attribute consists of an HLA sharing type, a type, and a name. Additionally, initialisation attributes can be defined for a FederateClass to specify some internal model attributes (lines 10 to 13) that can used to assign initial values.

- **Confederation**: A confederation is a co-simulation definition, consisting of a set of federate instances and their connections. A part of the SliderSetup Confederation is shown in Listing 2.

```plaintext
Confederation SliderSetup {
  Instances {
    Instance bottomSlider as Slider
    Instance topSlider as Slider
    Instance bottomController as Controller
    Instance topController as Controller
    Instance supervisoryController as HighLevelSliderController
  }
  Connections {
    Connection { bottomController.limit_switch <- bottomSlider.limit_switch }
    Connection { bottomController.encoder <- bottomSlider.encoder }
  }
}
```

Listing 2. Confederation definition of the SliderSetup.

Each federate instance should be given a unique name together with a FederateClass to specify its simulation model (lines 2 to 8). A set of connections can be created to specify how the attributes from different federate instances are connected (lines 9 to 12).

- **ClassInitialisation**: A ClassInitialisation consists of a number of values for initialisation attributes for a specific FederateClass. Such a ClassInitialisation can be applied to federate instances, see the Situation below. To allow re-usability, each ClassInitialisation is specified by a unique name. Listing 3 shows an example with name “onLimit”.

```plaintext
ClassInitialisation onLimit for Slider {
  Position_realInitial = "-0.15"
}
```

Listing 3. ClassInitialisation for the Slider model in the SliderSetup.

- **Situation**: A situation can be used to describe the initial states of federate instances in the federation. It applies given ClassInitialisations – containing initialisation values for attributes – on federate instances.

```plaintext
Situation customMPs {
  Apply customMP to bottomController
  Apply customMP to topController
  Apply onLimit to topSlider
}
```


Each situation consists of a set of ClassInitialisations that are applied on specific federate instances within the Confederation. The situation in Listing 4, for example, applies the Configuration “onLimit” that was given in Listing 3.
on the federate instance with the name topSlider. Multiple ClassInitialisations can be applied to a single federate instance, they will be applied in the order of appearance.

CoHLA supports code generation for OpenRTI. It is, however, relatively simple to add code generators for other HLA implementations. Simulation models following the FMI standard and POOSL models are supported. The OpenRTI libraries that were created also allow easy addition of a logger to the co-simulation.

From a co-simulation definition in CoHLA, a co-simulation project is generated. Such a project consists of two parts. The first part includes the HLA configuration file (FOM XML) together with a CMake\(^3\) project. The sources of the project are all C++ source and header files that depend on the OpenRTI libraries described earlier. For each of the FederateObjects defined in the co-simulation definition, code is generated that can be compiled to an executable. The code includes all handlers for sharing attributes, simulating the model and connecting to an RTI.

The second part consists of a Python\(^6\) script and a set of configuration files. The Python script allows the system architects to easily build and run the co-simulation using rather simple commands. The configuration files contain information about the attribute connections between federates and Situations that can be applied. The Python script ensures that all federates are being started according to the configuration specified by the system architect. This modular approach allows us to generate federate code only once, while being able to configure different co-simulations by only specifying another configuration file.

### B. Design Space Exploration

To define a design space to explore, initialisation attributes in CoHLA are very useful. As Situations and ClassInitialisations affect the initialisation values for federate instances, these can also be used to specify a design space. CoHLA has been extended by allowing the user to specify lists of different initialisation values for federate instances or attributes. As there are three methods to assign initialisation values, we also consider three different types of lists that can be used to define a design space.

- **Lists of initialisation values** are lists that specify specific values for initialisation attributes of a specific federate instance. For every initialisation attribute for every federate instance, such list may be given in a DSE definition.

  ```
  # Set bottomSlider.startPosition : "0.15", "0.05", "-0.05", "-0.14"
  
  Listing 5. Example of a list of initialisation values.
  ```

- **Lists of ClassInitialisations** are lists that specify ClassInitialisations that should be applied to a specific federate instance. A DSE definition may contain one list for every federate instance in the federation.

- **Lists of Situations** may contain situations that should be applied on the federation. Since a situation may apply ClassInitialisations to multiple federates, only one list per DSE definition is allowed.

  ```
  | Situations : situation1, situation2
  |
  Listing 7. Example of a list of Situations.
  ```

The exploration behaviour of the design space is described as either independent or linked.

<table>
<thead>
<tr>
<th>Federate</th>
<th>Attribute</th>
<th>Design Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Federate 1</td>
<td>Attribute A</td>
<td>x, y, z</td>
</tr>
<tr>
<td>Federate 2</td>
<td>Attribute B</td>
<td>a, b, c</td>
</tr>
<tr>
<td>Federate 2</td>
<td>Attribute C</td>
<td>q</td>
</tr>
<tr>
<td>Federate 2</td>
<td>Attribute D</td>
<td>u, v, w</td>
</tr>
</tbody>
</table>

Table I. Hypothetical Design Space.

Listing 8 displays a design space definition for the SliderSetup. The design space specifies two lists, each containing initialisation attribute values. The initialisation attributes are used to specify a starting position for the bottom slider and an initialisation speed for the supervisory controller. As the SweepMode is set to Independent, the design space has a size of \(20 \times 27 = 540\) possible configurations.

From this design space definition, a DSE configuration file is generated by the code generator. These configuration files can be used to easily perform a different DSE as described in Section III-A. The simulation results will be written to log files.

### C. Metrics

CoHLA DSE allows system architects to automatically execute different system configurations. Each of these system configurations result in some logging information that should be processed. Especially when the design space is rather large, this may be very time consuming. To overcome this

\(^3\)https://cmake.org/
\(^6\)https://www.python.org/
problem, we extended CoHLA with a method to specify performance metrics. At the end of each system configuration, each performance metric result is calculated and logged. After exploring the design space, all metric results are collected and logged to a separate file. This approach simplifies the comparison of different configurations in the design space by only comparing values of interest instead of processing all simulation data.

CoHLA currently supports four types of performance metrics that can be specified. These four types are briefly described below.

- **Error**: An error metric can be used to calculate the mean error for an attribute relative to another attribute. This metric can be useful to compare a measured value with a target value. Calculation of the mean squared error is also supported.
- **EndValue**: Returns the end value for a specific attribute. Optionally, the end value is returned as an absolute value, which is particularly useful to calculate the distance to the end value of a optionally referenced attribute.
- **Min/Max**: Returns the minimum or maximum value an attribute has reached during the simulation.
- **Timer**: A timer metric can be used to return the time when a condition is first met during the simulation. A condition consists of a comparison between an attribute value and a specified constant value.

Performance metrics must always be defined in a **MetricSet**, which is a set of metrics. A MetricSet requires a unique name and includes a measure time, which specifies the duration of a simulation that should be used to calculate the metric results. It should also contain one or more metrics. In addition to the configurable measure time, timer metrics can also be used as an end condition. These optional end conditions override the provided measure time and cause the simulation to stop once all timer metric conditions – that are flagged as end condition – are met. These flags are particularly useful to avoid unnecessary simulation after the behaviour of interest has finished.

Performance metrics must always be defined in a MetricSet. If a metric is not required the value for a specific metric is not stored.

Performance metrics can be specified using the **CoHLA Editor**. The editor provides a graphical interface for configuring metric sets and a comprehensive list of available metrics. The editor also supports the specification of end conditions for each metric set.

### Listing 9

Listing 9 shows the MetricSet “Initialisation” for the SliderSetup. A time to measure and two metrics are defined. The “InitialisationTime” timer metric returns the time when the supervisory controller first sets the SliderSetup as being initialised. As this metric is flagged to be an end condition, the simulation will be stopped when this condition is met. The minimum position of the bottom slider during this initialisation will be returned by the second metric.

```java
MetricSet Initialisation {
    MeasureTime: 300.0
    Metric InitialisationTime as Timer for supervisoryController.initialised == true (EndCondition)
    Metric MinBottomPosition as Minimum of bottomSlider.position
}
```

Listing 9. MetricSet to measure the initialisation speed of the SliderSetup.

When the slider passes the limit switch, a signal is triggered. Since the position of the limit switch is known to be at position -15 cm on the rail, the position of the slider is known from the moment the limit switch’s signal is triggered. However, after passing the limit switch, there is only 2 mm of rail left before hitting the hard limit, which should be avoided as it may introduce errors in the calibration of the system. We will use DSE for finding a suitable initialisation procedure that quickly initialises the system and does not collide with the hard limit of the rail.

Three types of control modes are supported by our controllers. The first mode (StrokeMode) requires a setpoint and a stroke time to be set. The controller then moves to the setpoint position in exactly the duration of the stroke time. Secondly, there is a mode that moves to a given setpoint as fast as possible (FastMode). The last mode that is supported requires
only a speed setpoint (FixedMode). The controller will then
move at the specified speed until the speed is changed.

As for the best initialisation method we seek, we can use
either of the three control modes. Therefore, we use DSE
to compare these three initialisation procedures with each other.
For all modes, we iterated over a small set of start positions
of the slider. For the StrokeMode, we will also iterate over
a set of stroke times to modify the movement speed. This will
also be done for the FixedMode, in which we can iterate over
different movement speeds.

For all three modes, the initialisation procedure consists of
the slider moving towards the limit switch and moving back
to position −10 cm when the limit switch is triggered. Once
this position is reached, the initialisation is finished. Expected
is that methods that initialise with a higher movement speed
are more likely to hit the hard limit. Therefore, DSE may help
us in finding a proper trade-off between speed and accuracy.

B. Implementation

Since not all modes require the same parameters, we will
split up the design space into three smaller design spaces in
CoHLA: one design space for each initialisation mode. For
each of the modes, four starting positions of the slider will
be simulated, being 0.15, 0.05, −0.05 and −0.14 m. As both
sliders and their controllers are exactly the same, the top slider
will already be located on the limit switch, so that we only
measure the initialisation time for one slider. Measuring the
initialisation time for only one slider decreases our design
space by a factor of 2.

Listing 10. DSE configuration for comparing initialisation procedures.

<table>
<thead>
<tr>
<th>DS Name</th>
<th>Attribute</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>StrokeMode</td>
<td>Starting position (m)</td>
<td>0.15, 0.05, −0.05, −0.14</td>
</tr>
<tr>
<td></td>
<td>Stroke time (s)</td>
<td>1.0, 1.5, 2.0, 2.5, 3.0</td>
</tr>
<tr>
<td>FastMode</td>
<td>Starting position (m)</td>
<td>0.15, 0.05, −0.05, −0.14</td>
</tr>
<tr>
<td></td>
<td>Movement speed (m/s)</td>
<td>0.04, 0.06, 0.08, 0.10, 0.12, 0.14, 0.16, 0.18, 0.20</td>
</tr>
<tr>
<td>FixedMode</td>
<td>Starting position (m)</td>
<td>0.15, 0.05, −0.05, −0.14</td>
</tr>
</tbody>
</table>

The metrics used to evaluate and compare the configurations
were already shown in Listing 9. The first metric checks
when the initialisation is finished and causes the simulation
to stop when this has been achieved, while the second metric
reports the minimum position that was reached. This minimum
position can be used to calculate the overshoot by subtracting
−15, which is the first position where the limit switch triggers.

C. DSE results

For all three design space definitions, the simulations were
automatically executed using the generated run script. Figure 4
shows the DSE results. System configurations that exceeded
the hard limit were ignored in the figure, because they did
not meet one of the requirements. Note that only one starting
position for the FastMode initialisation is displayed in the
results, because all other starting positions resulted in a large
overshoot. Based on the results displayed in Figure 4 the
following can be concluded.

- StrokeMode is typically faster in finishing the initialisation,
  except for when the starting position is very close to
  the limit switch, i.e., -14 cm.
- Strokemode results in a bigger overshoot than FixedMode
  when the starting position of the slider is far away from
  the limit switch.
- Movements speeds higher than 0.04 m/s are unsuitable
  in FixedMode, as they cause an unacceptable overshoot for
  starting position −5 cm and are therefore not displayed
  in Figure 4.

To select an initialisation procedure, a trade-off between
initialisation speed and overshoot should be made. Since the
initialisation procedure should never have an overshoot of
more than 2 mm, configurations exceeding this overshoot are not displayed. From these DSE results, it appears that either FixedMode using a movement speed of 0.04 m/s or StrokeMode using a stroke time of 1.5 s are most suitable to select. Using CoHLA to co-simulate the SliderSetup has proven to provide useful insights in the system’s internals during the design process. More than once, errors in the models of the controllers were found by running a co-simulation with a specific scenario that was not tested before. Additionally, the inclusion of DSE was only a small step once the system architecture was created in CoHLA and provided a tool to explore different implementation possibilities.

V. CONCLUSION

We presented CoHLA: a DSL that enables system architects to quickly define an HLA co-simulation of a system. It allows easy connection of models created in different modelling tools by supporting the FMI standard. CoHLA requires only minimal knowledge of HLA and FMI to construct a co-simulation and generates all ingredients required for running a co-simulation. A class definition of each simulation model and a specification of their connections are sufficient for CoHLA to generate configuration files, federate implementations and a script to easily run the simulation. Once the models of the SliderSetup were ready, defining the co-simulation of them only required half an hour of work.

This paper presents an extension that also brings automated DSE to CoHLA. A co-simulation definition in CoHLA can easily be extended with a specification of a design space and a set of performance metrics to support system designers to make design decisions. CoHLA generates a configuration file for each design space and set of metrics. These configuration files can be used to let the run script automatically execute all system configurations in the design space and output the metric results to a file.

After testing our approach on a sample system, we found that DSE was easy to use and it clearly showed the impact of selecting different initialisation procedures. In future work, we will improve the usability of CoHLA for performing automated robustness tests by adding fault injection. We will also aim for a method that allows easy distribution of the simulation executions. Although distributed simulation is supported by HLA, CoHLA currently does not provide easy setup of such a co-simulation. Additionally, CoHLA currently focuses on attribute sharing across federates instead of interaction by means of messages. It may be interesting to add support for this type of communication.

REFERENCES