A Structuring Mechanism for Embedded Control Systems using Co-modelling and Co-simulation

Xiaochen Zhang and Jan F. Broenink

Centre for Telematics and Information Technology, University of Twente, Enschede, The Netherlands

Keywords: Model Structuring, Collaborative Modelling, Co-simulation, Embedded Control System.

Abstract: In most embedded control system (ECS) designs, multiple engineering disciplines and various domain-specific models are involved, such as embedded software models in discrete-event (DE) domain and dynamic plant model in continuous-time (CT) domain. In this paper, we advocate collaborative modelling and co-simulation to verify different aspects of the system as a whole before implementation. This paper proposes a development approach and structuring mechanism for CT-intensive ECS designs using co-modelling and co-simulation techniques. Based on this approach, an integrated co-model can be developed and refined using different domain-specific languages and tools. Influences from one domain to the other can be simulated via co-simulation and analysed in both perspectives. Our structuring and development process has been applied to a mobile robot using this co-simulation technique. We have experienced that structuring the co-modelling process allows us to produce co-models an co-simulations effectively. Future work is on checking for model inconsistencies during collaboration, and provide approaches to deal with this.

1 INTRODUCTION

The nature of embedded control systems determines that multiple engineering disciplines and various domain-specific models are often involved. The conventional way of modelling such system is to divide the system into different engineering domains and assign them to different domain experts.

However, there are some disadvantages to use this modelling paradigm. Due to the differences between, for instance, the software modelling tool Overture (Overture Community, 2010) and the dynamic system modelling tool 20-sim (Controllab Products, 2010), distinct aspects of the system are modelled separately. After both developments are finished and verified, the system can be integrated and tested on the real setup or using a prototype.

The late integration may cause fatal problems since the impacts on each other are usually exposed late when integration phase is reached. It will be very costly and error-prone if engineers have to redesign the system and change the actual device. In addition, the lack of system-level support and communication between domain experts may lead to entirely different assumptions of the same system.

Hence, we advocate collaborative modelling and co-simulation for complex embedded control systems, as being developed in the DESTECS project (DESTECS, 2010). Integration can then be applied at early stage of the development, and the system can be verified as a whole before deploying to the real setup. In our co-modelling and co-simulation terminology, an embedded control system consists of a discrete-event model (*DE model*) implementing the software and a continuous-time model (*CT model*) implementing the physics parts of the system, and the combination is called a *co-model*.

In order to construct a dependable and reusable co-model, we propose a structuring mechanism and design process to support the co-modelling and co-simulation techniques.

In this paper, we restrict ourselves to dynamic-intensive embedded control systems, in which the dynamic behaviour is more essential for the total behaviour than the software logic. The complementary approach, in which the software logic is more essential is discussed in (Fitzgerald et al., 2012).

In this paper, Section 2 gives a brief introduction to the technologies we used. Section 3 proposes the structuring mechanism and design process to support the development of a CT-intensive co-model. A case study is followed and described in Section 4 to show how to apply our approach in practice. Finally, Section 5 gives the conclusion and a forward look.

Zhang X. and F. Broenink J. (2012).
A Structuring Mechanism for Embedded Control Systems using Co-modelling and Co-simulation.
In *Proceedings of the 2nd International Conference on Simulation and Modeling Methodologies, Technologies and Applications*, pages 131-136
DOI: 10.5220/0004059801310136

2 BACKGROUND

In order to achieve multidisciplinary modelling, the CT/DE domains in our case, different modelling paradigms and tools are required. This section introduces the basic technologies and concepts we used in our approach.

2.1 Bond Graphs and VDM

Bond graphs (Paynter, 1961) are labeled and directed graphs, in which vertices represent submodels, and edges, called *bonds*, represent an ideal energy connection between the submodels. Different than block diagrams, the bonds in bond graphs also represent a bi-directional connection. For different physical domains, such bi-directional connections are specified as voltage and current, force and velocity, etc. Bond graphs are domain independent which means that systems from different physical domains (e.g. electrical, mechanical, hydraulic, etc.) can be modelled using the same type of graphs.

In our case, the 20-sim dynamic systema modelling tool is used. It supports besides bond-graph models also block-diagram models to cover the information domain, which means that besides modelling the CT part, it is also possible to model DE elements.

The Real-Time Vienna Development Method (VDM-RT) (Bjorner and Jones, 1978) is an object-oriented language and used for modelling and analysing of real-time embedded systems from a discrete-event point of view. It allows explicit modelling of computation times on virtual networked processors (Verhoef et al., 2006). Operations can be implemented as periodic threads which run concurrently. VDM-RT is supported by the Overture tool built on top of the Eclipse platform and provides a textual environment to model the discrete-event aspect of embedded control systems.

2.2 Co-simulation and Co-modelling

A precondition of co-modelling and co-simulation CT/DE models is that two domain models must be able to talk to each other and exchange information. For a continuous-time simulation, the state of the system changes continuously with respect to time. For a discrete-event simulation, only the points in time at which the discrete state of the system changes are computed. The co-simulation engine supported by the DESTECS tool is used to interact with the DE/CT models to perform co-simulation. A synchronisation scheme is the basis of the co-simulation engine, taking care of the simultaneous execution of DE and CT models and keeping their local simulation time synchronised (Fitzgerald et al., 2012).

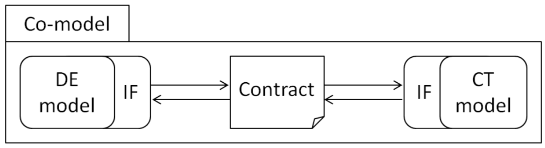


Figure 1: Conceptual view of a co-model.

Information sharing is achieved by defining shared *variables*, *parameters* and *events* in the co-simulation *contract* (see Figure 1). For example, a discrete-event controller may control the continuous-time velocity of an automobile by writing a steering signal to an actuator. The *steering signal* can then be considered as a shared variable which is defined in the contract. Each domain model is connected to the contract by attaching to a *model interface (i.e. IF)*. A model interface defines the shared properties of the model that can be accessed externally.

In order to support the co-simulation technique, we propose a structuring mechanism for the development of dynamic intensive embedded control systems. Our intention is to, besides promote collaborative modelling and simulation, also streamlining the co-model creation process and ensure cross-domain model consistency when constructing a co-model.

3 MODEL STRUCTURING AND DESIGN STEPS

To support efficient development of a reliable co-model using co-simulation technique is the ultimate goal of our approach. The ideal way of applying co-modelling and co-simulation is to: (1) partition the DE/CT parts of a system and assign them to domain experts; (2) concurrently develop the DE/CT models based on the same abstraction and assumptions of the system thus no need to worry about inconsistencies between them; (3) both models are finished or reach a certain level of maturity at the same time, such that the co-model can be constructed and simulated using co-simulation; and finally, (4) analyse the co-simulation result and apply *stepwise refinement* or *detailed engineering* (Broenink et al., 2007) if necessary, see Figure 2.

However, most embedded control systems in reality do not always contain evenly distributed complexity on two domains. One side may be more obvious or easier to abstract than the other. Especially for motion control systems, the dynamic behaviours and control algorithms are often more important and complex

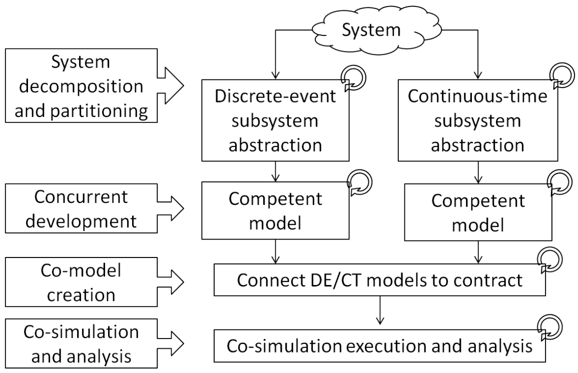


Figure 2: Ideal development process using co-modelling and co-simulation.

than the logic controller. Therefore, our approach is to support the development of CT-intensive systems and construct a co-model from this point of view. The complementary DE-intensive development approach using co-simulation can be found in (Fitzgerald et al., 2012)

3.1 System Level Structuring

Coping with system-level complexity and decomposition is a major non-functional requirement behind all embedded control system designs and developments. A CT-intensive system-level structuring mechanism is needed to help with these non-functional / informal problems of a system. Figure 3 illustrates the system level structure from a CT perspective in order to test an initial co-model. This structure is adapted from the embedded control system architecture in (Broenink et al., 2010). It consists of three submodels, the *DT Controller*, I/O hardware and the *Dynamic plant*, that are modelled using CT formalism initially.

The I/O (e.g. sensors and actuators) is treated separately in this structure because of its specific role in the design trajectory. Inside the DT controller submodel, the *Loop controller* represents a controller that directly communicates with the I/O and governs the response of the plant model. For complex dynamic systems, the control algorithms are usually complex as well. So it makes sense to model the loop controller together with the plant to verify the dynamic behaviour, and deploy it on the virtual CPU at the DE side for analysing the performance of the controller.

The supervisory controller and safety layer (i.e. the dashed blocks in Figure 3) are more suitable to model using DE formalism. A CT model interface can then replace the entire DT controller submodel and connect to the DE model through the contract to construct a co-model.

We recommend this structure because it allows

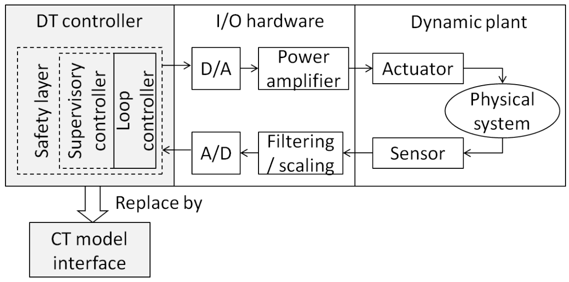


Figure 3: CT-first system level structuring mechanism for co-model integration.

different sensor, actuator and loop, sequence, supervisory controller implementations. Continuous-time, discrete-time or discrete-event controllers can easily be replaced by a CT model interface to connect to the co-simulation contract. Following this structuring mechanism, three steps are required to accomplish the co-model construction:

- Dynamic plant modelling and control law design.
- DT controller migration.
- Co-model integration.

Stepwise refinement is supported and design decisions can be made at all stages of the development processes listed above. This implies that modellers can start with simple dynamic models and thus apply simple control algorithms. Once the simulation result fulfils the system requirements, more detailed information can be added.

This structuring and development approach can shorten the process of co-model integration. Both domain modellers are able to see the performance of the system in their own perspective. Inconsistencies can be examined and solved in early stages of the design process. The following subsections describe each step of development.

3.2 Modelling and Control Law Design

For many embedded control systems, various physical domains are often involved, such as the electrical domain, the rotational/translational mechanical domain, etc. that are interconnected to express different parts of the system. So the structure of a dynamic model can be further decomposed into *submodels* of different mechanical parts, physical domains or functional subsystems, and keep large-scale system organized.

Depending on different design requirements, analogue (continuous in time) or digital (discrete in both time and amplitude) loop controllers can be used in the system. In most cases, if it is decided to use a digital controller in the design, the control laws in the

```
externals
  real global import actuator_value;
  real global export sensor_value;
equations
  // import from DE
  io_pwm = actuator_value;
  // export to DE
  sensor_value = io_encoder;
```

Figure 4: An example of CT model interface for connecting to the co-simulation contract.

CT model should be implemented in the discrete-time domain instead of the continuous one, because the control algorithms will be eventually moved and deployed on a virtual digital computer in the DE model supported by the DESTECS tool, or in an actual microcomputer in the real device.

A continuous-time value from the dynamic plant model cannot be computed using the discrete-time formalism. The analog-digital conversion can be done by means of sensors/actuators or A/D converters, and modeled in the I/O submodel.

When the control algorithm is ready, the plant model can be connected to the DT controller via the I/O submodel and simulated in the 20-sim tool to verify the performance of the system. At this stage, the 20-sim model is ready for the next step towards migration.

3.3 Migration and Replacement

A *model interface* in our terminology defines the part of the model which can be accessed externally, i.e. shared variables and design parameters. Shared information can be exchanged between models through the model interface by the DESTECS tool. An example of the CT model interface is illustrated in Figure 4, in which the `actuator_value` and `sensor_value` are shared variables between DE and CT models and can be accessed by DE model externally. The CT model imports the steering value from the DE controller and assigns it to the variable `io_pwm` such that this signal can pass across domains, vice versa.

The DT controller designed in the previous phase can be replaced by the CT model interface without changing anything in the I/O and plant submodels. The model interface connects the I/O submodel from the CT side to the co-simulation contract, assuming the shared variables between the interface and the contract have the same identity name, data type and range. These will be checked by the tool in order to keep two domain models consistent.

3.4 Co-model Integration

This paper focuses on CT-intensive systems co-model design, so hereby we assume that the DE model is ready for co-simulation, and the DT controller developed in the CT model has been moved to the DE side and implemented as a time-triggered loop controller. The contract shall be specified at this stage of the development.

An important issue of cross-disciplinary modelling and co-model creation is that both domain models have to be developed based on the same assumption of the system. For instance, when running the co-simulation, the sampling time or discrete-time interval in the CT simulator should be the same as set in the DE model; assumptions on the size of a wheel or the direction (e.g. positive-negative, clockwise-counterclockwise) of a velocity between DE/CT models should be the same. Any syntactic or semantic inconsistencies may cause wrong behaviours of the system. So the DE/CT model interfaces and the contract have to clearly indicate all shared information. Communications are often required at this stage in case requirement changes may cause cross-domain inconsistencies.

4 EXAMPLE: JIWYONWHEELS

Following the structuring mechanism and development process, a case study is presented in this section to show how to apply our approach in practice and its advantages.

4.1 System-level Structure and Dynamic System Modelling

The JiwyOnWheels robot (pronounce as "Jiwy [djee; wai] on wheels") is a mechatronic setup for carrying and moving a camera around to take pictures. The main goal is to design a stable and accurate robot control system with fast response time. The dynamic behaviour and control algorithms part of this design are rather essential for the overall behaviour, so our CT-intensive structuring approach is used here to achieve co-simulation.

The development of this system can be decomposed into three subsystems similar as Figure 3, the *Controller*, *IO* and *Plant*. A *Joystick* is implemented inside the controller as a motion profile for the movements. Using this structure, the system boundary and subsystem functions can be easily indicated.

The dynamic behaviour of the robot can be further decomposed into different physical domains. The

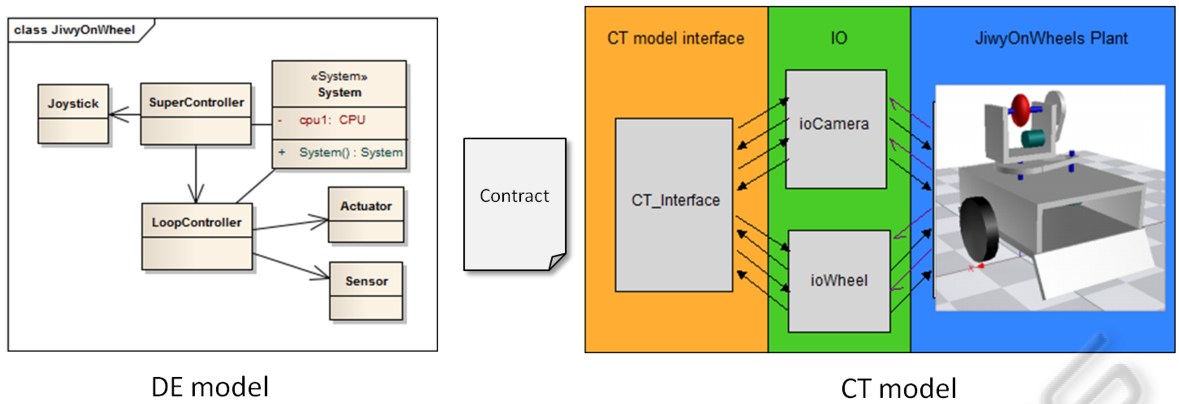


Figure 5: JiwyOnWheels from co-model perspective.

most dominant properties of the system are the movement of the cart with two wheels and the rotation of the camera mounted on top. All components are connected to each other by electrical and/or mechanical ports and this behaviour is modelled using bond graphs. The corresponding control algorithms, e.g. digital PID controllers in our case, can be designed. The digital/analog conversion is modelled as A/D converters with necessary scaling in the IO submodel.

4.2 Migration

When the CT model is competent enough to be used to construct a co-model, the step of migrating the DT controller can start. The controller submodel can be replaced by the CT model interface directly without changing the IO and plant submodels, see Figure 5. Signals shared between the DT controller and the IO submodel are now shared between the CT model interface and IO submodel.

In order to test the performance of the digital controller on different hardware platforms, the DT controller has to be moved from the CT model to DE model to be deployed on different architectures supported by the DESTECS tool.

The migration requires converting the DT controller to a time-triggered DE controller using the VDM formalism. It is implemented as a periodic thread that reads the signals from the sensors and writes to the actuators, shown as the `LoopController` class on the left side of Figure 5. The *SampleTime* defined in the time-triggered `LoopController` has to be the same as set in the CT simulator to ensure both models are executed at the same co-simulation time.

In order to describe real-time behaviour in the DE model, the `System` class is constructed to handle the creation of a virtual `CPU` and the deployment of the `SuperController` and `LoopController`.

In this case study, the DE model is simply designed as an event-triggered supervisory controller, a time-triggered loop controller and a joystick that gives steering signals to the robot. More complex DE models, such as distributed `CPU`'s running different controllers and connected through a `BUS`, can be studied and developed in depth when required.

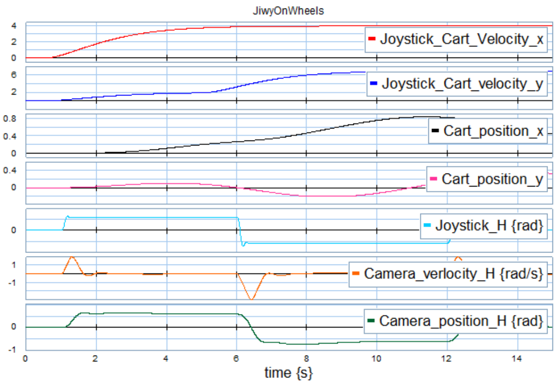
4.3 Co-model Integration and Result

Finally, the co-model (see Figure 5) is created by defining the contract in the DESTECS tool and executed using the co-simulation engine. All shared information between the DE/CT models of JiwyOnWheels is defined in the contract. Figure 6 illustrates the final co-simulation results in the CT simulator, in which the steering signals are generated from the DE model as user inputs from the joystick. The rotation of the camera and the movement of the cart are controlled by the time-triggered DE controller through co-simulation. Figure 6(b) shows the trajectory of the robot movement.

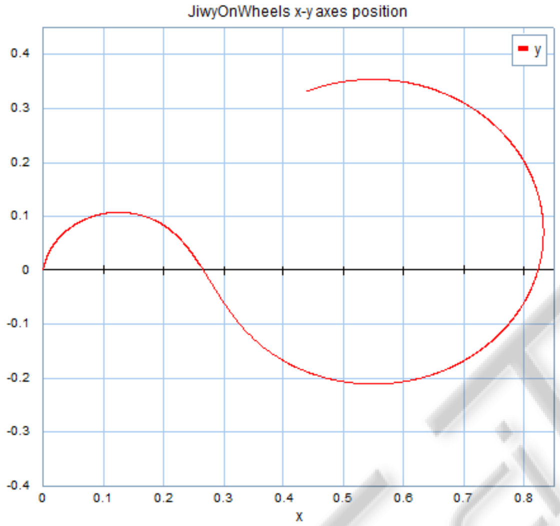
5 CONCLUSIONS

In this paper, we have proposed a structuring mechanism and design process to support the development of continuous-time intensive ECSs using collaborative modelling and co-simulation techniques. Based on this approach, complex embedded control systems can be decomposed into continuous-time (CT) models and discrete-event (DE) models and further developed using their own domain-specific languages and tools. Co-simulation can then be achieved by connecting these two models through the co-simulation contract and DE/CT model interfaces.

Another key feature of our approach is that it allows modellers to design the digital loop controllers



(a) Co-simulation results: the velocity / position of cart movement; the velocity / position of camera rotation.



(b) JiwyOnWheels simulated position, x versus y.

Figure 6: JiwyOnWheels co-simulation results.

in the CT model, and then migrate them to the DE model using the time-triggered (TT) DE formalism. Doing so, the dynamics of the controller can be designed and tuned in the CT domain, and in turn, the performance of the controller on different hardware architectures can be tested in the DE domain. In addition, the same controller/plant models can be reused easily. We also have described a CT-intensive case study which demonstrates how to apply this structuring approach and the co-model creation process.

When using collaborative modelling and co-simulation techniques, many challenges may encounter, such as the inconsistency issues caused by different modelling knowledge across domains or lack of communications between domain experts. Our future work will focus on addressing and solving these challenges and prevent inconsistencies between domain models while using co-simulation.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 248134 (project DESTECS).

REFERENCES

Bjorner, D. and Jones, C. (1978). The vienna development method: The meta-language. *Lecture Notes in Computer Science*.

Broenink, J. F., Groothuis, M. A., Visser, P., and Bezemer, M. M. (2010). Model-driven robot-software design using template-based target descriptions. In Kubus, D., Nilsson, K., and Johansson, R., editors, *ICRA 2010 workshop on Innovative Robot Control Architectures for Demanding (Research) Applications*, pages 73 – 77. IEEE.

Broenink, J. F., Groothuis, M. A., Visser, P., and Orlic, B. (2007). A model-driven approach to embedded control system implementation. In Anderson, J. and Huntsinger, R., editors, *Proceedings of the 2007 Western Multiconference on Computer Simulation WMC 2007, San Diego*, pages 137–144, San Diego. SCS, San Diego.

Controllab Products (2010). The 20-sim dynamic modelling tool website. http://www.20sim.com.

DESTECS (2010). The DESTECS project website. http://www.destecs.org.

Fitzgerald, J. S., Larsen, P. G., Pierce, K. G., and Verhoef, M. (2012). A formal approach to collaborative modelling and co-simulation for embedded systems. *Mathematical Structures in Computer Science*, vol(no):1–25. To be published.

Overture Community (2010). The Overture Tool project website. http://www.overturetool.org.

Paynter, H. (1961). *Analysis and design of engineering systems*. MIT Press, Cambridge, MA.

Verhoef, M., Larsen, P., and Hooman, J. (2006). Modeling and validating distributed embedded real-time systems with vdm++. *FM2006: Formal Methods*.