OBJECT-ORIENTED MODELING OF VIRTUAL LABORATORIES FOR CONTROL EDUCATION

Carla Martin [*] **Alfonso Urquia** [*]
Sebastian Dormido [*]

[*] *Dept. Informática y Automática, E.T.S. de Ingeniería Informática, U.N.E.D., Juan del Rosal 16, 28040 Madrid, Spain. {carla,aurquia,sdormido}@dia.uned.es*

Abstract: The combined use of Ejs, Matlab/Simulink and Dymola (with Modelica language) has been successfully applied to set up virtual labs for control education. The tasks completed to achieve this goal are discussed in this manuscript: (1) the development of a novel modeling methodology adequate for interactive simulation; (2) the object-oriented design and programming of JARA: a Modelica library of dynamic hybrid models of some fundamental physical-chemical principles; (3) the description of the JARA physical models in a way suitable for interactive simulation; and finally (4) the implementation of the virtual labs. This is illustrated by means of two case studies. *Copyright ©2005 IFAC*

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1. INTRODUCTION

Virtual laboratories, supporting interactive simulations, are effective pedagogical resources for control education (Dormido, 2004). During the interactive simulation run, the students can change the value of the model inputs, parameters and state variables, perceiving instantly how these changes affect to the model dynamic. Interaction possibilities enhance the students' understanding. The students take an active role in the learning process, and this promotes their motivation to study the subject.

Virtual laboratories can be implemented by combining the use of three software tools: Ejs, Matlab/Simulink and Dymola (with Modelica language). This approach takes advantage of the best features of each tool (Martin *et al.*, 2004*b*). Ejs' capability for building interactive user-interfaces composed of graphical elements, whose properties are linked to the model variables (Esquembre, 2004). Matlab/Simulink's capability for modeling automatic control systems and for model analysis. Modelica's capability for physical modeling (http://www.modelica.org), and finally Dymola's capability for simulating hybrid-DAE models (Dynasim, 2002). Next, the fundamentals of Ejs and its use together with Matlab/Simulink and Dymola are briefly discussed.

1.1 Fundamentals of Ejs

Ejs is a open source, Java-based tool intended to program web-based virtual labs. It can be freely downloaded from http://fem.um.es/Ejs/. Ejs guides the user during the definition of the virtual lab, and it automatically performs all the tasks required to generate the virtual-lab code: a Java application or an applet.

Ejs is based on a simplification of the "model - view - control" paradigm. The virtual-lab definition is structured in the following three parts: (1) *introduction*: html pages including educational content related with the virtual-lab topic; (2) *model*: dynamic model whose interactive simulation is the virtual-lab basis; and (3) *view*: user-to-model interface.

The *view* is intended to provide a visual representation of the model dynamic behavior and to facilitate the user's interactive actions on the model. Ejs includes a set of ready-to-use visual elements, that allows easy creation of the virtual-lab view. The graphical properties of the Ejs' view elements can be linked to the model variables, producing a bi-directional flow of information between the view and the model. Any change of a model variable value is automatically displayed by the view. Reciprocally, any user interaction with the view automatically modifies the value of the corresponding model variable.

Ejs virtual-labs can run: (1) stand-alone; (2) in conjunction with Matlab/Simulink; and (3) in conjunction with Matlab/Simulink and with Dymola. In the first case, Ejs gives the user a procedure to define the model, and provides a set of built-in ODE solvers to simulate it. In the second case, the virtual-lab model can be partially or completely described using Matlab code and Simulink block diagrams. In the last case, Modelica models can be embedded within a Simulink block: the DymolaBlock block. This block can be found in the Simulink's library browser. It is an interface to the C-code generated by Dymola for the Modelica model (Dynasim, 2002). DymolaBlock block can be connected to other Simulink blocks and also to other DymolaBlock blocks.

1.2 Contributions of this paper

This software combination approach has been successfully used to program a set of virtual labs for chemical process control. To achieve this goal, the following four tasks have been completed:

(1) *Proposal of a modeling methodology intended for interactive simulation* (Martin *et al.*, 2004*b*). This methodology states how a Modelica model can be formulated to suit interactive simulation.
(2) *Object-oriented design and programming of JARA* (Urquia, 2000; Urquia and Dormido, 2003). JARA is a library of dynamic hybrid models of some fundamental physical-chemical principles. Its main application is the modeling of physical-chemical processes in the context of automatic control.
(3) *Re-formulation of JARA physical models in a way suitable for interactive simulation* (Martin *et al.*, 2004*a*). The modeling methodology proposed in Task (1) has been applied. The JARA library version, that is written in Modelica language and intended for interactive simulation, is JARA 2i.
(4) *Implementation of the virtual labs.* The physical models of the controlled chemical plants have been composed using JARA 2i. The controllers have also been modelled using Modelica language. Plant and controller models have been translated using Dymola, and embedded within Simulink's DymolaBlock blocks. The views of the virtual labs have been programmed using Ejs.

The modeling methodology proposed in Task (1) is discussed in this manuscript. Its application to the implementation of the virtual labs is illustrated by means of the following two case studies: (1) the control of an industrial boiler; and (2) the control of a batch chemical reactor.

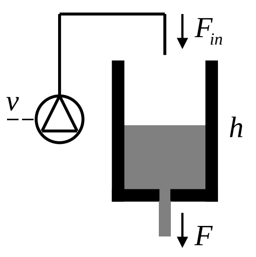
2. MODELING FOR INTERACTIVE SIMULATION USING MODELICA

A modeling methodology adequate for interactive simulation using Ejs, Matlab/Simulink and Dymola is proposed. It takes advantage of the modeling and simulation capabilities of Modelica and Dymola. The common characteristics of the models intended for interactive simulation are discussed in this section. Next, the proposed modeling methodology is briefly described. Further details can be found in (Martin *et al.*, 2004*b*).

2.1 Characteristics of the interactive models

The proposed methodology states how a Modelica model can be formulated to suit interactive simulation using Ejs, Matlab/Simulink and Dymola. The obtained Modelica model fulfills the following requirements (Martin *et al.*, 2004*b*):

(1) *Computational causality of the interface.* In order to embed the Modelica model within a Simulink block, the computational causality of the Modelica model interface needs to be explicitly set. In other words, interface variables needs to be classified into inputs and outputs.
(2) *Interactive changes on the model state.* As a result of the user interaction, the interactive model needs to support instantaneous (discontinuous) changes in the value of the state variables. In general, different choices of the model state variables are possible. Therefore, several choices of the state variables need to be simultaneously supported by the interactive model, in order to provide alternative ways of describing the state changes.



$$\frac{dV}{dt} = F_{in} - F$$
$$F = a\sqrt{2gh}$$
$$V = Ah$$
$$F_{in} = kv$$

Fig. 1. Model of a process

(3) *Changes on the interactive parameters.* Time-independent properties of the system are usually represented by model parameters. However, sometimes one of the interactive-simulation goals is studying the dependence between the model dynamic behavior and the value of these properties. In this case, the property value can be instantaneously changed by the user's action, remaining constant between consecutive interactive changes. These variables of the model are called *interactive parameters.* Changes in the value of the interactive parameters can have different effects depending on the state variable selection. As a consequence, interactive models need to support interactive changes in the value of the interactive parameters, for different choices of the state variables.

Example 1. The model shown in Fig. 1 will be used to illustrate these requirements (Martin *et al.*, 2004*b*). The voltage applied to the pump (v) is an input variable. The cross-sections of the tank (A) and the outlet hole (a), the pump parameter (k) and the gravitational acceleration (g) are time-independent properties of the physical system. The liquid volume (V) and level (h), and the liquid flows (F and F_{in}) are time-dependent properties.

Possible choices of the model state-variables include: $e_1 = \{h\}$, $e_2 = \{V\}$, $e_3 = \{F\}$; where e_i represents one particular choice of the state variables. If the user wants to change interactively the level value (h), the appropriate choice is $e_1 = \{h\}$. Likewise, if the user wants to change V, then the right choice is e_2, and if he wants to change F, then e_3. The model should support the following feature: every time the user needs to change the state value, the user decides to represent it in terms of a change in either the volume or the height or the flow. Different choices are possible during a given interactive simulation run.

Changes in the value of interactive parameters can have different effects depending on the state variable choice. For instance, consider an instantaneous change in the tank cross-section (A). If the state variable is the liquid volume (V), then the change in A produces an instantaneous change in the value of the liquid height (h) and flow (F), while the liquid volume remains constant. On the contrary, if the state variable is the height or the flow, these magnitude values do not change as the result of an instantaneous change in A. In this case, the volume does change.

2.2 Modeling methodology

The proposed modeling methodology for interactive simulation consists in the following steps:

(1) *Physical modeling.* Object-oriented modeling of the system using Modelica language. For explanation purposes, lets suppose that this model is called *physicalModel.*
(2) *State selection control.* Modelica supports the user's control on the state variables selection, via the *stateSelect* attribute of Real variables (Otter and Olsson, 2002). This attribute values include *never* (the variable will never be selected as state variable) and *always* (the variable will always be used as a state). This Modelica feature allows controlling the model state selection by means of a Boolean array. The following example tries to illustrate it.

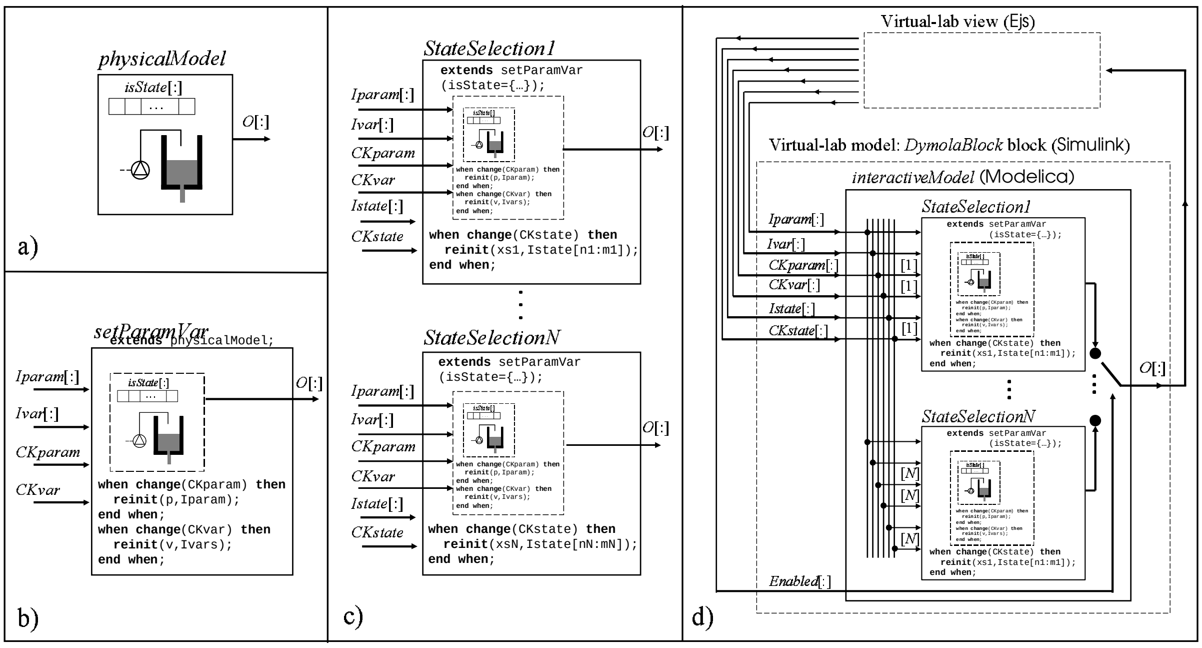
Example 2. State selection of the model in Fig. 1 can be accomplished as shown below, by means of the Boolean vector *isState.* For instance, if *isState* is set to the value {false, true, false} when instantiating the physical-model, then the volume (V) is selected as a state variable.

```
model tank
  Real h (stateSelect = if hIsState
                   then StateSelect.always
                   else StateSelect.never);
  Real V (stateSelect = if VIsState
                   then StateSelect.always
                   else StateSelect.never);
  ...
end tank;

model pipe
  Real F (stateSelect = if FIsState
                   then StateSelect.always
                   else StateSelect.never);
...
end pipe;

partial model physicalModel
  parameter Boolean[3] isState;
  tank tank1 ( hIsState      = isState[1],
               VIsState      = isState[2] );
  pipe pipe1 ( FIsState      = isState[3] );
...
end physicalModel;
```

The Boolean vector *isState* controls the state selection (see Fig. 2.a). The output-variable array (O[:] in Fig. 2) contains the variables representing the actual value of the state, in addition to the other variables linked



```
extends physicalModel;
when change(CKparam) then
  reinit(p,Iparam);
end when;
when change(CKvar) then
  reinit(v,Ivars);
end when;
```

```
extends setParamVar
(isState={…});
when change(CKstate) then
  reinit(xs1,Istate[n1:m1]);
end when;
```

```
extends setParamVar
(isState={…});
when change(CKstate) then
  reinit(xsN,Istate[nN:mN]);
end when;
```

Fig. 2. Schematic description of the modeling methodology

to the view elements. Ejs uses the value of this output array (i.e., $O[:]$) to refresh the control-lab view.

(3) *Interactive parameters.* The interactive parameters are defined in *physicalModel* as constant state variables (i.e., with zero time-derivative). The interactive changes in the value of these parameters are implemented by re-initializing their values. The state re-initialization is performed using *when*-clauses and a built-in Modelica operator: *reinit(x,expr)*. It re-initializes an state variable (x) with the value obtained of evaluating an expression (*expr*), at an event instant.

(4) *Input variables.* The model symbolic manipulations performed by Dymola to formulate the model according to a given state selection can require differentiating an input variable (Martin *et al.*, 2004*b*). In this case, an error is produced: Dymola cannot differentiate an input variable. A valid approach consists in defining the input variables in *physicalModel* as constant state-variables. The changes in the value of these variables are implemented by re-initializing their values.

In conclusion, an analogous solution is applied to the input variables and the interactive parameters. The zero time-derivatives are included in the *physicalModel* model. A new model is defined: *setParamVar*. It inherits *physicalModel* and contains the *when*-clauses and *reinit* operators to change the value of the interactive parameters and input variables. Four input variables are used to model the changes in the value of the interactive parameters and input variables (see Fig. 2.b): two signal arrays (*Iparam*[:], *Ivar*[:]) containing the new values, and two signals (*CKparam* and *CKvar*) for triggering the re-initialization events.

(5) *State-variable choices.* As many models (*stateSelection1*, *stateSelection2*, ...) are defined as different state-variable choices are needed (e_1, e_2, ...). Each of these models inherits *setParamVar* (*isState* array is set to the value adequate in each case) and contains a *when*-clause and a *reinit* operator to change the value of the corresponding state-variable array. Two input variables are used to model the interactive changes in the state: *Istate*[:] and *CKstate* (see Fig. 2.c). The array *Istate* contains the values used to reinitialize the model state. The signal *CKstate* is used to trigger the state re-initialization event.

(6) *Interactive model.* The interactive model is defined (*interactiveModel* model in Fig. 2.d) and embedded within a Simulink's DymolaBlock block. It is composed of all the models defined in the previous step (i.e., *stateSelection1*, ..., *stateSelectionN*). The value of the input array *Enabled*[1:N] is set by Ejs (see Fig. 2.d), and it selects which output is connected to the output signal (O[:]).

3. CASE STUDY I: CONTROL OF AN INDUSTRIAL BOILER

The interactive simulation of an industrial boiler has been implemented, by the combined use of Ejs, Matlab/Simulink and Modelica/Dymola (Martin *et al.*, 2004*a*). The mathematical model of

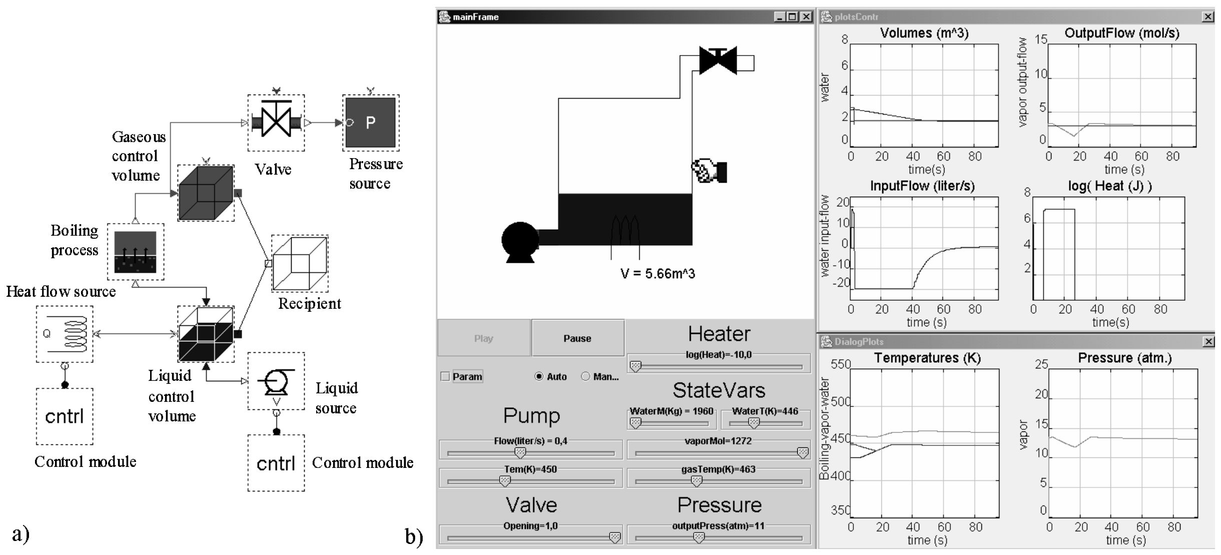


Fig. 3. a) Boiler model composed using JARA 2i; b) View of the virtual lab implemented using Ejs

the boiler is found in (Ramirez, 1989). The input of liquid water is placed at the boiler bottom, and the vapor output valve is placed at the top. The water contained in the boiler is continually heated. The diagram of the boiler model, composed using JARA 2i, is shown in Fig. 3a. Two control volumes are considered: (1) a control volume containing the liquid water stored in the boiler; and (2) a gaseous control volume containing the vapor. The vapor volume is equal to the difference between the boiler-recipient inner volume and the water volume. The boiling is a transport phenomena represented by a model connecting both control volumes. The heat-flow into de boiler, the pressure at the valve output and the water pump are modeled using JARA source models.

The Ejs view of the boiler virtual-lab is shown in Fig. 3b. The plant has been modeled using JARA 2i (Martin *et al.*, 2004*a*). The user can interactively choose between two control strategies: manual and decentralized PID. The control system has been modeled using Modelica: a PID is used to control the water level and another PID is used to control the vapor flow. The manipulated variables are the pump water-flow and the heater heat-flow respectively. The parameters of these PID controllers can be changed interactively. In addition, the value of the model state-variables (mass and temperature of the water and the vapor), parameters (inner volume of boiler), and input variables (temperature of the input water, valve opening and output pressure) can be changed interactively during the simulation run.

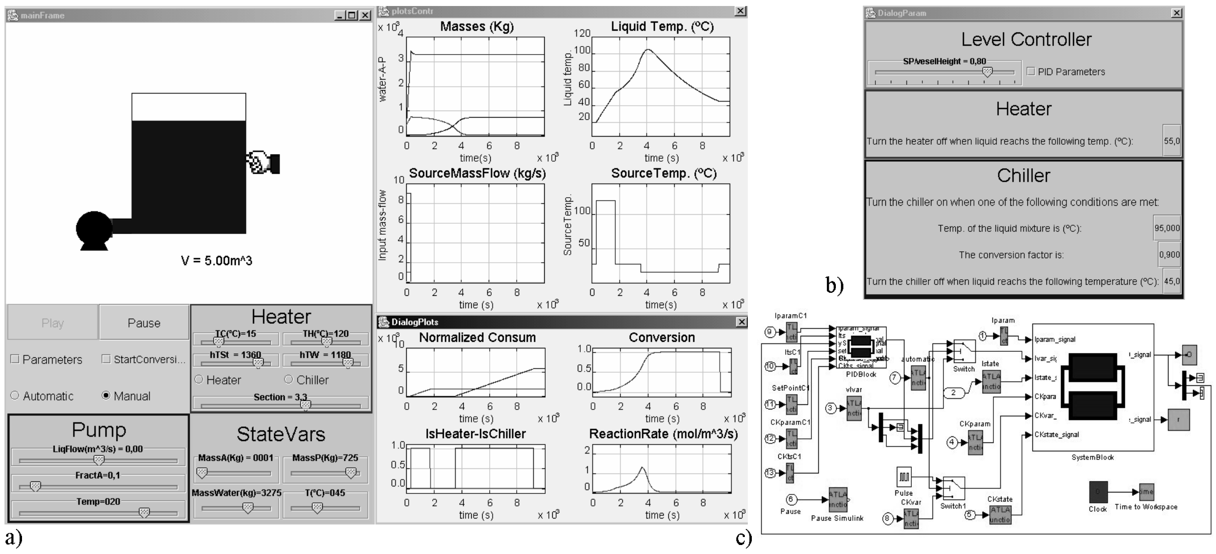
4. CASE STUDY II: CONTROL OF A BATCH CHEMICAL REACTOR

The model of the batch reactor has been adapted from (Froment and Bischoff, 1979). In a batch reactor having a volume V, an exothermic reaction $A \rightarrow P$ is carried out in the liquid phase. The reactor contains a heat exchanger and it can be operated with steam and with cooling water. The Simulink model of the reactor and its control system is shown in Fig. 4c. The Modelica models of the plant (composed using JARA 2i) and the controllers are embedded within the *SystemBlock* and *PIDBlock* blocks respectively.

The virtual-lab view is shown in Fig. 4a. The main window (on the left side of Fig. 4a) contains the schematic diagram of the process (above) and the control buttons (below). Both of them allow the user to experiment with the model. The user can interactively choose between manual and automatic control. The automatic control is intended to perform the following operation policy (see Fig 4b):

(1) Fill up the reactor with the reacting liquid. The inflow is controlled by a PID.
(2) Preheat to certain temperature, and let the reaction proceed adiabatically. The heat exchanger is controlled by another PID.
(3) Start cooling when either the maximum allowable reaction temperature occurs or the desired conversion is reached, and cool down to the desired temperature.
(4) Empty the reactor.

The value of the PID-controller parameters, the temperatures defining the operation policy and the desired conversion can be changed interactively. Also, the value of the model state-variables (i.e., the temperature and mass of the reaction



Level Controller

SPVeselHeight = 0,80

Heater

Turn the heater off when liquid reachs the following temp. (ºC): 55,0

Chiller

Turn the chiller on when one of the following conditions are met:

Temp. of the liquid mixture is (ºC): 95,000

The conversion factor is: 0,900

Turn the chiller off when liquid reachs the following temperature (ºC): 45,0

Fig. 4. a) Ejs' view of the virtual lab; b) Window menu to determine the policy of operation; c) Simulink model of the virtual lab

mixture, and the concentration of A and P), the model parameters (i.e., the reactor volume and section, the area of the heat exchanger, and the physicochemical data of the steam and cooling water), and the input variables (i.e., the inflow temperature and concentration) can be changed interactively during the simulation run. The secondary windows on the right side of Fig. 4a contain plots showing the evolution of some relevant process variables.

5. CONCLUSIONS

A novel modeling methodology adequate for interactive simulation has been proposed. It allows easy creation of the virtual labs, by combining the use of Ejs, Matlab/Simulink and Dymola (with Modelica language). This approach has been successfully applied to the implementation of the JARA 2i library. The use of Modelica language has reduced considerably the modeling effort and it has permitted better reuse of the models. The use of JARA 2i, Ejs and Matlab/Simulink to develop virtual labs for control education has been illustrated by means of two case studies.

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REFERENCES

Dormido, S. (2004). Control learning: Present and future. *Annual Reviews in Control* **28**, 115–136.

Dynasim (2002). *Dymola. User's Manual. Version 5.0a.* Dynasim AB. Lund, Sweden.

Esquembre, F. (2004). Easy Java Simulations: a software tool to create scientific simulations in Java. *Computer Physics Communications* **156**, 199–204.

Froment, G.F. and K.B. Bischoff (1979). *Chemical reactor analysis and design.* John Wiley & Sons. New York.

Martin, C., A. Urquia and S. Dormido (2004*a*). JARA 2i - A Modelica library for interactive simulation of physical-chemical processes. In: *Proc. European Simulation and Modelling Conference.* pp. 128–132.

Martin, C., A. Urquia, J. Sanchez, S. Dormido and F. Esquembre (2004*b*). Interactive simulation of object-oriented hybrid models, by combined use of Ejs, Matlab/Simulink and Modelica/Dymola. In: *Proc. 18th European Simulation Multiconference.* pp. 210–215.

Otter, M. and H. Olsson (2002). New features in Modelica 2.0. In: *Proc. 2nd International Modelica Conference.* pp. 7.1–7.12.

Ramirez, W.F. (1989). *Computational Methods for Process Simulation.* Butterworths Publishers. Boston.

Urquia, A. (2000). Modelado Orientado a Objetos y Simulación de Sistemas Híbridos en el Ámbito del Control de Procesos Químicos. PhD thesis. Dept. Informática y Automática, UNED, Madrid, Spain.

Urquia, A. and S. Dormido (2003). Object-oriented design of reusable model libraries of hybrid dynamic systems. *Mathematical and Computer Modelling of Dynamical Systems* **9**(1), 65–118.