Towards Integrated Hybrid Modelling and Simulation Platform for Building Automation Systems; First Models for a Simple HVAC System

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Abstract

The aim of our research work is the development of an integrated platform for modelling and simulation of building operation systems. This platform uses hybrid automata which allows models for continuous and discrete behaviours. A model-driven hierarchical hybrid automata behaving in a multi-agent mode is adopted to provide an efficient and coherent modelling, it also facilitates system integration. The paper introduces the modelling framework and provides the first results for modelling and simulation of a simple Heating, Ventilating, and Air Conditioning (HVAC) system for a single room.

Keywords: Building Automation Systems, HVAC, Hybrid System Modelling, Embedded Middleware.

1 Introduction

The aim of a modern Building Automation System (BAS) is to enhance the functionality of interactive control strategies leading towards energy efficiency and a more user friendly environment. In this context, the BAS complexity is rapidly increasing due to the large number of objects deployed, e.g. sensors and actuators and also to the integration of complex control strategies for different physical effects, e.g. light and temperature. This integration is required because of the physical coupling of these effects.

System integration for BAS can be achieved using model-driven techniques. Indeed, constructing models using a compositional model-driven approach is becoming more critical, given the increased scale of systems that are being modelled, e.g. smart automation for large buildings or chip fabrication plants. In such cases, using a component-based tool can significantly improve the speed, and reduce the cost of modelling and verification. It can also help developing efficient optimizations.

On the other hand, computer simulation techniques can help to tackle the challenges due to the integration of large heterogenous systems; it is increasingly gaining importance as a tool for optimization and analysis of buildings and their control and energy systems.

Currently many software tools are dedicated to building performance simulation. Unfortunately they lack flexibility and transparent modelling of control strategies. What is needed is an integrated simulation platform that is able to simulate the user comfort and energetic aspects of a given building considering predictive control strategies. This is especially important when considering the heterogeneous nature of the systems involved in buildings.

The main challenge is to optimize energy usage while trying to provide adequate user comfort. Several research and industrial works have been dedicated to this topic, they use different approaches, e.g. Matlab/simulink [MAT,], hybrid systems[G. Labinaz, 1996], Petri net formalisms[L. Gomes, 2007] or finite state automata. Building energy simulation tools are also used to optimize energy usage. In

[P.E. Miyagi, 2002], [L. Gomes, 2007], two quite similar research works have developed integrated platforms that uses Petri Net for modelling and simulation of control strategies in Intelligent Building. In this context, the integration with other building systems can be achieved in a more systematic way considering a mechatronic approach (i.e. multidisciplinary concepts applied to the development of systems)

In this article we assume that building automation models can be represented using hybrid systems models [G. Labinaz, 1996], since hybrid systems can represent both the discrete-value and continuous differential-equation-based relations essential for such models. We show how we can use component-based hybrid systems to model and simulate HVAC controller and components. In previous work we have used the same framework for modelling lighting systems [A. Mady, 2009b]. We also have developed a first version of a code generator that can auto-generate embeddable code for a distributed sensor/actuator network [A. Mady, 2009a].

Our framework allows users to express preferences for interior lighting levels and temperature, and the control system accommodates such preferences over all occupants within a zone. For example, given a preferred temperature, the control system optimises energy usage by accurately controlling the heater only when a zone is occupied and external temperature is insufficient.

The remainder of the paper is organized as following: Section 2 introduces our modelling platform which uses compositional model-driven hybrid automata. In Section 3, we illustrate the integrated modelling framework through a simple HVAC controller for a single room, we also outline the simulation results. We end in Section 4 by giving a discussion of our work and outlining future perspectives.

2 Integrated Hybrid Modelling Platform

Hybrid systems are dynamic systems that exhibit both continuous and discrete behaviours. The continuous-time dynamics are modelled using differential equations whereas discrete-event dynamics are modelled by automata. They have the benefit of encompassing a larger class of systems within its structure, allowing for more flexibility in modelling dynamic phenomena. Building systems are a perfect example of hybrid systems where continuous and discrete dynamics are being used for modelling. For example heat dissipation and luminosity follow a continuous dynamics whereas presence detection is of a discrete nature.

In our work we show how we can use a component-based hybrid-systems modelling framework to generate models for simulation and verification. Using the CHARON tool [cha,], we assume that we can create/redesign a system-level model by composing components from a component library [G. Gssler, 2003], [J. Keppens, 2001]. We call a well-defined model fragment a component. We assume that each component can operate in a set of behaviour-modes, where a mode M denotes the state in which the component is operating. For example, a pump component can take on modes nominal, high-output, blocked and activating.

We define two classes of components: primitive and composite. A primitive component is the simplest model fragment to be defined. For such a component we specify the inputs I, outputs O, and functional transformation φ, such that we have $O = \varphi(I)$. A composite component consists of a collection of primitive components which are merged according to a set of composition rules [G. Gssler, 2003]. A set of (primitive/composite) components defines a component library. In this work we assume a component library consisting of sensors, actuators, human-agent models, and building components such as heaters, lights, windows, rooms, etc.

We demonstrate our approach on a simple heating model. This example illustrates the combination of discrete events behaviour (presence detection, control switch on/off) and hybrid properties for the heat dissipation control, i.e. where both discrete and continuous aspects are considered.

In the rest of the section we introduce the system architecture and we briefly describe the simulation platform. We end by giving a short introduction to the CHARON tool-set.

2.1 System Architecture

As shown in Fig. 1, the system design flow starts by defining relevant scenarios to be operated within the building. These scenarios are defined using the Unified Modelling Language (UML) [G. Booch, 1998]. The UML models are interpreted using specific models for simulations and analysis purposes. At this level we allow an optimization loop to optimize the model at an early stage of the development. When the simulation gives satisfactory results, the models are auto-translated into embeddable code to be deployed over a distributed sensor/actuator network.

The integration process is performed through the implementation of a model-/service-based middleware [K. Romer, 2002] platform allowing components connection and data exchange. All the different components of the architecture collaborate with the requirements module.

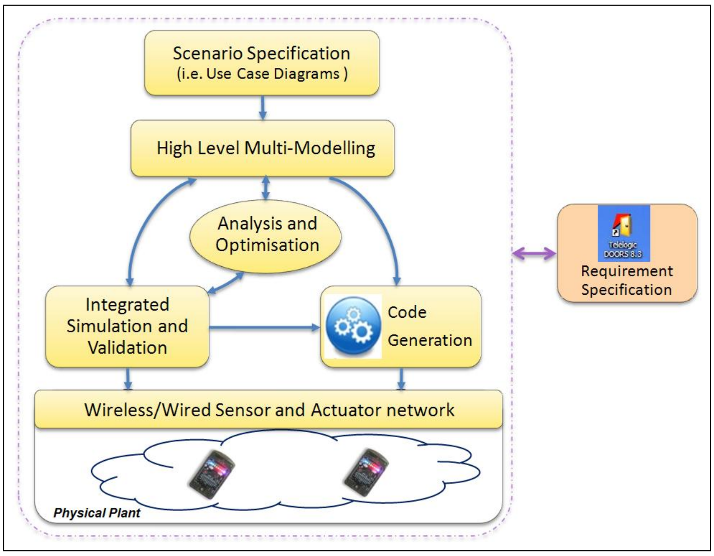


Figure 1: System Architecture

2.2 Modelling and Simulation Process

The first modelling steps consist of specifying the requirements and system behaviour through UML diagrams, for example Fig. 2 describes the use case for a simple HVAC system for a single room. This example is discussed in detail in Section 3.1. According to the UML specifications, we model each subsystem or service using hybrid automata. Most of the services are discrete-event-oriented, however some systems are dynamic and need to be modelled using hybrid systems.

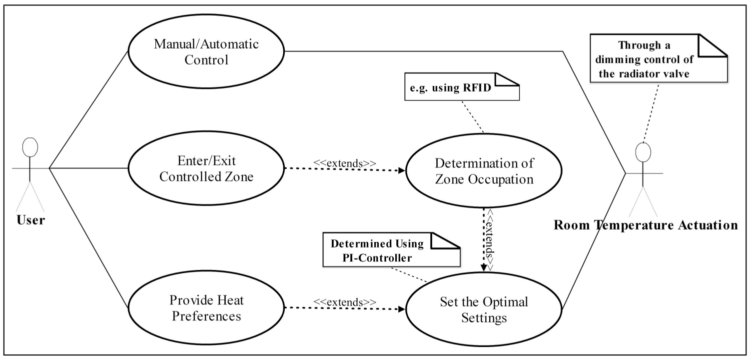


Figure 2: Use-case Diagram for the Heating System

CHARON offers several modelling features, in particular modularity and hierarchy which correspond to our modelling approach. To simulate the models, we must model the environment, e.g., the behaviour of the sensors and the people. The environment will provide a stimulus (control input) for the simulation. In our work we consider a preference model over lighting and temperature as well. For this, we have integrated the preferences inside the modelling; however, we have implemented an interface with constrain solver to handle complex preferences.

The overall model is built in incremental way. The whole system or part of it can be simulated by composing the relevant sub-systems as they would execute in reality, i.e. in sequence or in parallel. Once the models are built and the interface with the preference solver is set, the simulation is executed and the results can be analysed as given in Section 3.2.

2.3 CHARON tool

CHARON is a high-level language for modular specification of multiple, interacting hybrid systems, and was developed at the University of Pennsylvania [cha,]. The toolkit distributed with CHARON is entirely written in Java, and provides many features, including: a GUI (Graphical User Interface), a visual input language, an embedded type-checker, and a complete simulator. CHARON adopts a hierarchal modelling framework based on the statechart modelling technique. A hybrid system is described in CHARON as follows [Y. Hur, 2002]:
Architectural hierarchy: The architecture of systems is described with communicating agents. Those agents share information through shared variables or communication channels. Agents are either atomic or composite.
Behavioural hierarchy: A mode is a construct for the hierarchical description of the behaviour; it has well-defined control-, entry- and exit-points. Transitions between modes are enabled when a condition called guard becomes true. CHARON provides invariants governing when a continuous flow satisfies a condition, as well as differential and algebraic constraints representing continuous dynamics. The language also supports the instantiation of a mode for the reuse of mode definitions.
CHARON variables: CHARON provides two types of variables, continuous (analog) and discrete. Analog variables are updated continuously while time is flowing. Conversely, discrete variables are modified instantaneously only when the modes of an agent change.

3 Case Study: HVAC system for a single room

In this section, we model and simulate a simple HVAC system for a single room. The room model considers a radiator, a window and a wall facing the building façade. The controller sets the heater through a valve actuator only when the room is occupied and the external temperature is insufficient.

3.1 CHARON Modelling

The HVAC system has been modelled using CHARON in a hybrid multi-agent fashion [M. Hadjiski, 2007], [Y. Hur, 2002]. Following the scenario specification in Fig. 2, the system has been modelled using two kinds of agents as shown in Fig. 3. Firstly environment agents used to test the behaviour of the controller and to provide a stimulus (control input) for the simulation and second control agents that are used to model the behaviour of the control system.

For the environment modelling, as much as the modelling is close to reality, the controller can accurately be evaluated. In our model, we have considered four environments; Wall, Window, Radiator and Indoor Air [B. Yu, 2004], [KK. Andersen, 2000] as following:

1. *Wall Model*: One of the room walls is facing the building façade which implies heat exchanges between the outdoor and indoor environments. In general, a wall can be modelled using several layers, where more layers the wall is splitted, more realistic model is achieved. However considering too many layers will increase the complexity of the model. In our case, one layer has been

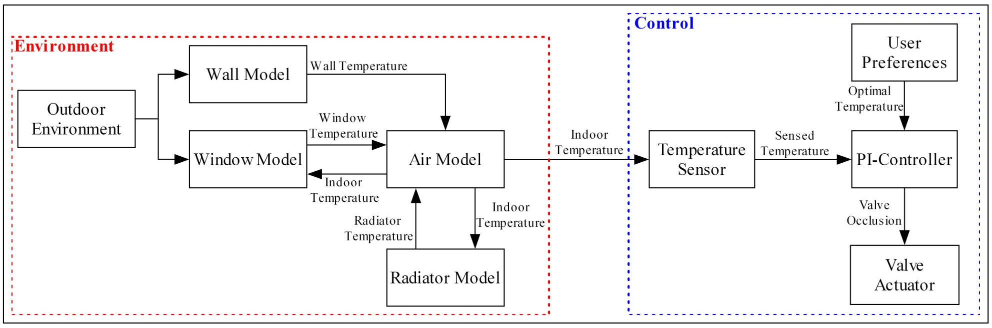


Figure 3: System Architecture for the HVAC Model

considered using the differential equation, Eq. 1.

$$\rho_{wall} V_{wall} c_{wall} \frac{dT_{wall}}{dt} = \alpha_{wall} A_{wall} (T_{external} - T_{wall}) \tag{1}$$

2. *Radiator Model*: One of the most popular heating devise is the radiator that uses the temperature deference between the water-in and water-out in order to heat the room. Moreover it exchanges temperature with its environment. Here we assume that the radiator is fixed on a wall that does not exchange temperature and hence it has negligible effect on the radiator, therefore the indoor air is the only effective component on the radiator as shown in equations: Eq. 2 and Eq. 3.

$$M_{water} c_{water} \frac{dT_{radiator}}{dt} = \dot{m}_{water} c_{water} (T_{waterin} - T_{waterout}) - Q \tag{2}$$

$$Q = Q_{air} = \alpha_{air} A_{radiator} (T_{radiator} - T_{air}) \tag{3}$$

3. *Indoor Air Model*: In order to model the indoor temperature propagation, all the HVAC components have to be considered as they exchange heat with the air inside the controlled room following the equations: Eq. 4, Eq. 5, Eq. 6, and Eq. 7.

$$\rho_{air} V_{air} c_{air} \frac{dT_{air}}{dt} = Q_{air} + Q_{wall} + Q_{window} \tag{4}$$

$$Q_{wall} = \alpha_{air} A_{wall} (T_{wall} - T_{air}) \tag{5}$$

$$Q_{air} = \alpha_{air} A_{radiator} (T_{radiator} - T_{air}) \tag{6}$$

$$Q_{window} = \alpha_{air} A_{window} (T_{window} - T_{air}) \tag{7}$$

4. *Window Model*: A window has been modelled to calculate the solar energy and the glass effects on the indoor environment. Since the glass capacity is very small, the window has been modelled as algebraic equation, Eq. 8, that calculates the heat transfer at the window node.

$$\alpha_{air} (T_{external} - T_{window}) + \alpha_{air} (T_{air} - T_{window}) + q_{solar} = 0 \tag{8}$$

In relation to control modelling, Fig. 4 shows the linear hybrid automata [Henzinger, 1996] of the main controller agent used to control the temperature inside the controlled room. Based on a PI-Controller [Cooper, 2008], the indoor temperature is adapted by actuating the radiator valve with the optimum occlusion degree in order to achieve the predefined user preference as explained in Eq. 9, Eq. 10, Eq. 11, and Eq. 12.

$$A(t+1) = A(t) + \alpha(t) \tag{9}$$

$$\alpha(t) = \begin{cases} \dfrac{S(t)-U(t)}{S(t)}, & \text{for } S(t) > U(t) + \epsilon \quad (10) \\ -1 \times \dfrac{U(t)-S(t)}{U(t)}, & \text{for } U(t) > S(t) + \epsilon \quad (11) \\ 0, & \text{for } |S(t) - U(t)| \leq \epsilon \quad (12) \end{cases}$$

Where:
$A(t)$: Actuation setting for the valve actuator.
$U(t)$: Sensed temperature.
$S(t)$: Optimal preference settings.
ϵ: Acceptable temperature margin.

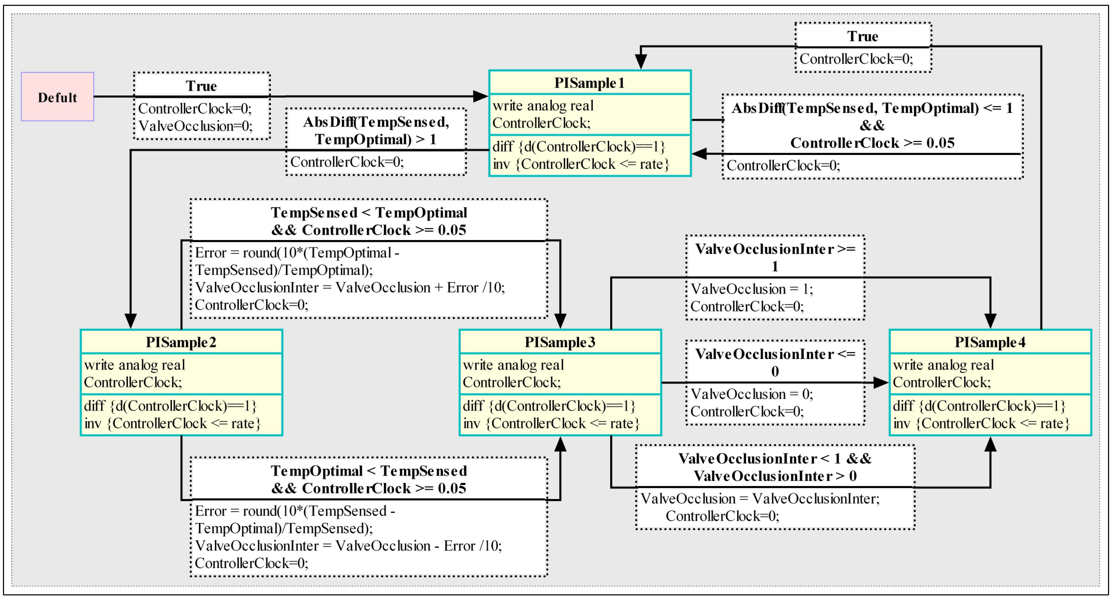


Figure 4: PI-Controller Hybrid Automata

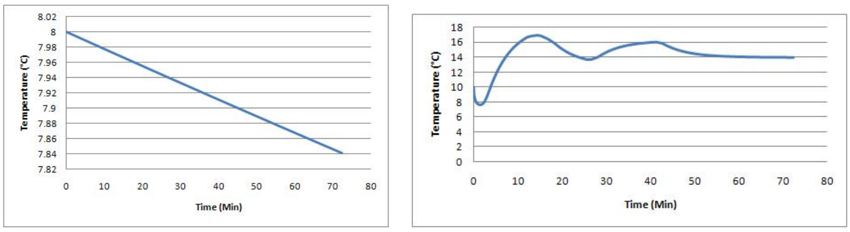
3.2 Simulation Results

In this section, we provide the simulation results for the HVAC system (Fig. 5). The Charon model described earlier and its environment have been simulated using the Charon simulation tool-set. Fig. 5(a) shows the wall temperature response, when the outdoor temperature (5 $^\circ C$) is less than the indoor one (8 $^\circ C$), the wall temperature follows a linear differential equation with a negative slope.

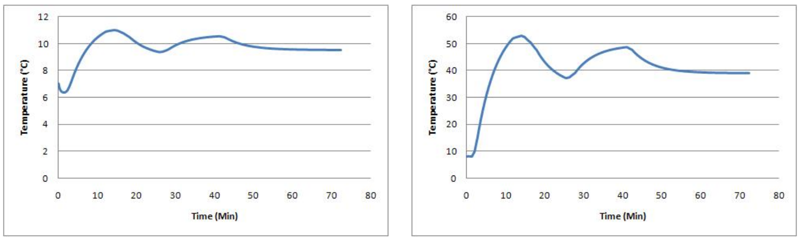
In the beginning, the actuation value of the radiator valve is equal to zero (Fig. 5(e)) that means the valve is completely closed and the controller still did not receive the current temperature value from the sensor, therefore the radiator temperature is equal to the initial room temperature (Fig. 5(d)). However the indoor temperature and the glass temperature are decreasing because the temperature decreasing rate at the wall is not overcome by heat from other components (Fig. 5(b), Fig. 5(c)). When the controller senses the indoor temperature, which is less than the optimal, it increases the valve actuation value to

80% occlusion and hence the air temperature increases as well. In order to reach the user preference (15 $^\circ C$), the controller refines the actuation value considering ± 1 $^\circ C$ acceptable margin.

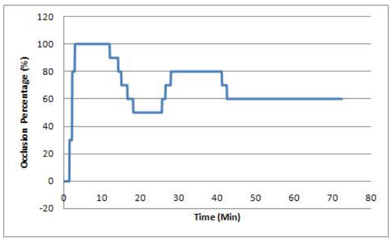
The simple models we have shown here can be easily applied to more complex HVAC systems since models of almost arbitrary complexity can compositionally be generated from the simple components. Hence the system can be easily scaled up (if the simulator can handle the complexity of larger systems). However, if embedded controls are generated by hand, scaling up becomes virtually impossible since it is not humanly possible to hand-generate the complex scenarios possible in large systems. Note also that modeling complexity depends also on the model's fidelity; hence, model fidelity of composed models can been increased (or decreased) by changing the component models to higher- (or lower-) fidelity models. Such changes of system-level model fidelity are also not possible when hand-generating controls.



(a) Wall Temperature (b) Indoor Air Temperature



(c) Window Glass Temperature (d) Radiator Temperature



(e) Actuation Percentage of Valve Occlusion

Figure 5: Simulation Results

4 Conclusions

In this paper we have introduced a platform for modelling and simulation of building operation systems. This platform is based on model-driven hierarchical hybrid automata which allows modelling for continues and discrete behaviours. We showed that hybrid systems simulation together with compositional model-driven techniques provides a key approach for efficient modelling and design for embedded models. In addition, this approach provides a clear mechanism for system integration.

As a future work, we intend to model and analyse an integrated system that involves lighting and heating control based on several factors including presence sensors, area occupancy, user preferences, etc. We also consider applying this approach to model, simulate and analyse more complex HVAC systems. This is possible since we are continually integrating existing library models and using reference models from the literature, rather than creating controls from scratch using hand-based approaches.

The benefit of model-based development for energy efficient controls constitutes an important research topic that we intend to pursue in future work. We plan to demonstrate the overall platform in the UCC Environmental Research Institute (ERI) building, which is the ITOBO Living Laboratory [ERI,] [ERI,].

5 Nomenclature

Symbol	Discerption	Unit
T_{wall}	Wall temperature	$^{\circ}C$
$T_{external}$	Outdoor temperature	$^{\circ}C$
$T_{radiator}$	Radiator temperature	$^{\circ}C$
T_{air}	Indoor temperature	$^{\circ}C$
T_{window}	Glass temperature	$^{\circ}C$
$T_{waterin}$	Water-In temperature to the radiator	$^{\circ}C$
$T_{waterout}$	Water-Out temperature from the radiator	$^{\circ}C$
ρ_{wall}	Wall density	kg/m^3
V_{wall}	Wall geometric volume	m^3
α_{wall}	Wall thermal conductance	$W/(m^2.K)$
α_{air}	Indoor air thermal conductance	$W/(m^2.K)$
M_{water}	Water mass	Kg
c_{water}	Water specific heat capacity	$J/Kg.K$
c_{air}	Indoor air specific heat capacity	$J/Kg.K$
c_{wall}	Wall specific heat capacity	$J/Kg.K$
$\dot{m}_{water}$	Water mass flow rate throw the radiator valve	Kg/s
Q	Pseudo-thermal state heat for the components attached to the radiator	J
Q_{air}	Indoor air pseudo-thermal state heat	J
Q_{wall}	Wall pseudo-thermal state heat	J
Q_{window}	Glass pseudo-thermal state heat	J
q_{solar}	Solar energy	w/m^2
$A_{radiator}$	Radiator geometric area	m^2
A_{wall}	Wall geometric area	m^2

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