

SPECIFICATION FOR REAL-TIME CONTROL USING HYBRID SYSTEMS IN BUILDING AUTOMATION SYSTEMS

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ABSTRACT

The actual controllers used in building performance simulation have traditionally been devoted to continuous dynamical systems, where both plant and controller are usually modelled by differential equations. But a good model to use for control system design is one that captures quite enough the important characteristics of the system such as dynamics, disturbances and so on. To explore this potential, this paper addresses a new approach to building automation systems that utilizes hybrid systems. In fact hybrid systems are crucial for solving complex problems and for the design of real-time controllers that can be used to automatically regulate HVAC (Heating, Ventilation and Air-Conditioning) systems and building components. Statecharts are also used for modelling building system behaviour in the structural analysis paradigm, in order to achieve a comfortable indoor climate while fulfilling operating constraints. Particularly, this paper concerns the relevance and reliability of integrating control and building performance simulation environments by run-time coupling, over TCP/IP protocol suite. In addition, this paper involves a case-study with two important steps; first consists of experiments obtained in TU Delft test-cell, and then simulation results are obtained with the use of run-time coupling approach.

INTRODUCTION

The theoretical studies are wonderful things but from the perspective of practicing them, it is very often difficult to properly build systems that operate in the real world. In Building Automation Systems (BAS), an open distributed control systems composing of various components (sensors and actuators), control systems and an open network interconnecting them, is used to ensure the communication of information with a central computer through routers. For assuring the control analysis and performance of various building equipments and components with the important data exchange on the network, as depicted

on figure 1, the simulation of this distributed control systems is required. The main goal of BAS is the automation of HVAC (Heating, Ventilation and Air-Conditioning) and lighting systems in order to provide a healthy, comfortable and productive indoor environment while minimizing energy consumption, and to control them in an efficient and rational way (see Yahiaoui et al. 2005). They also perform tasks such as access control, energy management while reducing green house gas emissions, and fault detection and diagnoses. In case a BAS configuration exploits information between central computer and sub-stations (or terminals) through different network protocols like LonWorks and BACnet, it is necessary to use a router since those protocols utilize different network representations (see e.g. Kastner et al. 2005).

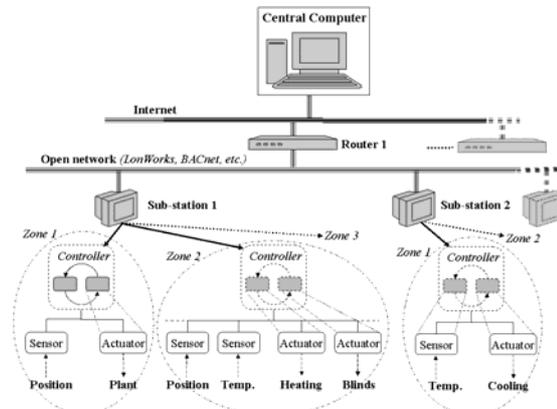


Figure 1 Architecture of Building Automation Systems (BAS).

One important complexity in cooperative simulation between the controller model and the plant model of BAS is that most current software tools developed for building performance simulation are of limited use since do not have a flexible way of dealing with control strategies. With this regard, there is no single control method or conventional control application that can solve all the challenges encountered in buildings. An integral approach is, then developed and implemented in order to simulate the comfort and energetic aspects of building design in combination

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with any control strategies. This approach is therefore based on distributed control modeling and building performance simulation environments by run-time coupling. In this approach, building model and its control system, which are separated and exchange data through Internet socket during simulation can be located on different kinds of hosts. As a result, model-based advanced control methods such as optimal control, fuzzy logic, predictive control and so on; which are fast, accurate and robust can now be performed for building performance simulation.

In addition to building performance simulation, control systems of plants and building dynamics require specific methods of specification that can verify the sequence of motions of those plants. Structural methods are useful for a real-time control to easily handle building applications. Although HVAC systems consist of physical (mechanical, hydraulic, electrical, etc.) components and exhibit a mix of discrete and continuous behavior, hybrid systems are essential because they are characterized by interacting continuous-time dynamics (modeled by differential equations) and discrete-event dynamics (modeled by automata). Nevertheless, a hybrid automaton is a Finite State Machine (FSM) formalism extended with states and events. While a perspective used for complex systems consists to divide a system into a set of sub-systems such as sensors, actuators, plant and control laws; the complexity of sub-systems (or components) can in turn be divided into a set of sub-components, and so on. To overcome the parallelism and the dependence of the actions of two or more concurrent sub-systems that can exponentially increase the number of states and transition in hybrid model, StateCharts developed by Harel (1987) can in effect be used as a visual formalism for the specification and modeling of building complex systems. The importance of the modeling with hybrid systems has been demonstrated in various applications such as aeronautic (Tomlin et al. 1998), automobile (Lygeros et al. 1998), etc. As a result, the concept of *Hybrid StateCharts* integrating discrete logic events and continuous time dynamics in natural way is proposed in order to model and design real-time controllers for integrated building systems.

A simple hybrid StateChart model for a building heating system is depicted in figure 2. This heating system has two variables T_{sp} and T_{in} and two discrete states *A* and *B*, which they refer to the mode of the system. Both states evolve continuously and are described by differential equations. Another variable $T_{deadband}$ is fundamentally used for the motion that can represent the system internal parameters for real-time specification (e.g. the sensitivity of the controller, the delay of the controlled variable response, and etc.). the automaton starts by default

in state *B* where the heater is off. At transition from the state *B* to the state *A* happens once the value of the internal temperature T_{in} drops below the reference temperature T_{sp} and this must happens just after this transition is verified. When this transition happens, the value of the internal heating rate increases instantaneously within the variable heat flux at between 0 (when the heater is completely off) and 100% (when the heater is fully on). The transition back to the state *B* happens once the internal temperature T_{in} is above the set-point T_{sp} .

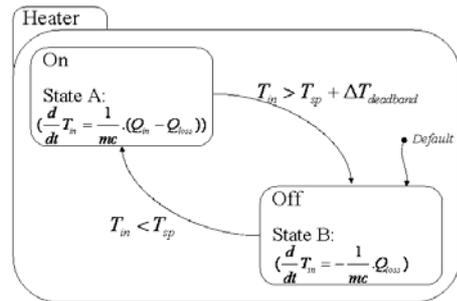


Figure 2 The building heating system StateChart

Now it should be clear that this system involve the management of two important steps: first consists of logical making decision (e.g. when a transition happens), and the second is continuous state evolution (e.g. which heat rate needed accordingly). A hybrid control system is therefore used to accomplish proper solutions when complex building systems need to be controlled correctly. Furthermore to alleviate inherent complexities of building control systems such as making decision, learning about occupants, adapting suitable control behaviors, such problems including needs and constraints, can in effect be decomposed and modeled as systems of multiple (intelligent) agents (Wooldridge, 1999). Also Lygeros (et al. 1996) presented a methodology for designing hybrid controllers for large scale with multi-agent systems based on optimal control and game theory. In this paper, an agent is defined as a control system (or a zone process controller as shown in figure 1), which is capable of sensing and computing and acting while fulfilling environmental and operating constraints. The design of those agents can be enhanced so that they act within a flexible autonomous manner to optimize the attainment of their objectives and to affect their surroundings in a desired manner.

The first part of this paper presents a brief description of motivation. The next part elaborates the reasoning behind our hypothesis that distributed control and building performance simulation software by run-time coupling will facilitate integrated performance assessment by predicting the overall effect of innovative control strategies for integrated building systems. Then, an analysis to the specification of multi-agent architecture for integrated building

systems is described. This is followed by the synthesis relevant to the design of hybrid control for integrated building systems in feedback structure. The last essential part of this paper ends with a case study resulting on a balance between theoretical aspects and practical applications.

MOTIVATION

The principal motivation for this work is to proposing a cooperative multi-agent architecture using hybrid systems for Intelligent Buildings (IB) of the third generation (see e.g. Sharples et al. 1999). This third-generation Intelligent Buildings is formed when Building Automation Systems (BAS) is based on the capacity of learning about the building environment and its occupants in order to adapt suitable control loops and appropriate set-points accordingly for the current situation. In (Sharples et al. 1999) work, three-generation Intelligent Buildings have been described. The first-generation consists of several control systems or sub-systems in which they operate independently to each other. The second-generation takes place when BAS exploits networks to assure distributed control systems, and the third-generation have in addition to previous (first and second) generations, an extra functionality that arises from the application of intelligent control systems.

Although multi-agent systems (or agent-based models) are used in the design of Artificial Intelligence (AI), Information Communications Technology (ICT) and so on; a multi-agent architecture can also be used for designing and modeling distributed autonomous agents exploited in a building environment. In the case of BAS, a cooperative between the controller and the mechanical plant model is required to verify the sequence of motions of the system. Hence, it further understood that a simulation is strongly needed in order to evaluate the control behavior of a building environment and to illustrate how distributed multi-agents can react in building design. In this paper, the main goal aims to derive a useful, general approach to the design of hybrid multi-agent systems for complex systems. This is important for the third-generation Intelligent Buildings (IB) to assure the control performance of distributed building systems in the BAS coordination. In fact by interconnecting building control systems via a network, it becomes possible either to control remotely from the management level (i.e. from the central computer). Another important key concepts of development BAS is distributed building control systems that should initially concentrate on design requirements and fundamental principles encountered. A methodology based on hierarchical semantics of multi-agent hybrid systems can now be developed to cover various design stages including modeling, simulation,

analysis, implementation, and monitoring of building control systems in building design.

However, difficulties in implementing appropriate controllers in buildings motivate us to investigate hybrid StateCharts based on a simple building application as a solution to controlling building HVAC systems, in which time delays, nonlinearities, constraints and so on can be addressed. In addition, integrating hybrid systems together with model based modern (or intelligent) control techniques in the form of multi-agent hybrid systems can solve the complexity of problems when agents disagree.

DISTRIBUTED CONTROL & BUILDING PERFORMANCE SIMULATION

One key of the issues facing us when we want to simulate a building modeling plus environmental control systems is that frequently certain system components and/or control features can be modeled in one simulation environment while models for other components and/or control features are only available in other simulation software. In other words, there is domain specific software for building performance simulation (BPS), which is usually relatively basic in terms of control modeling and simulation capabilities (e.g. ESP-r, TRNSYS). On the other hand, there exists domain for control modeling environments (CME), which is very advanced in control modeling and simulation features (e.g. Matlab/Simulink). To alleviate the restricted issue mentioned above, it is essential to reason behind our hypothesis that marrying two approaches by run-time coupling would potentially enable integrated performance assessment by predicting the overall effect of innovative control strategies for integrated building systems.

Previous (in Yahiaoui et al., 2003 and Yahiaoui et al., 2005), it has been described that a promising approach to run-time coupling between ESP-r and Matlab/simulink is an IPC (Inter-Process Communication) using Internet sockets. This approach performs distributed simulation by a network protocol in order to exchange data between building model and its controller, as it almost happens in a real situation. Both building model and its controller which are separated and work together through run-time coupling can be located on different kinds of hosts in which the performance simulation is much faster than using a single computer. Consequently, the development of this new advent would potentially enable new flexible functionalities of building control strategies that are not yet possible.

During simulation, commands and data are transmitted between ESP-r and Matlab/Simulink. If for instance the building model (i.e. ESP-r) has to send its current measured process to its controller (i.e. Matlab/ Simulink) with TCP/IP-stream, a method

called encodes them and transmits them with a defined control sequence via TCP/IP to a method received. This then receives the control sequence, decodes data from TCP/IP-stream format and sends data to the recipient (Matlab/ Simulink). When the controller has to send back the actuated process to its building model via TCP/IP, the same procedure is followed in this case, as shown on figure 3.

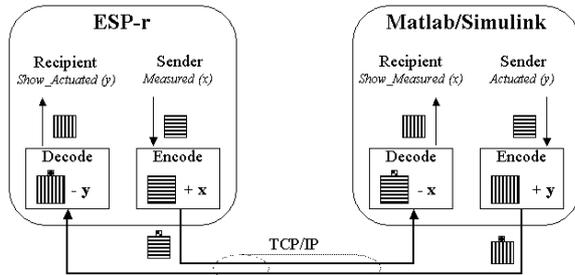


Figure 3 Distributed control modeling and building performance simulation environments

In the current implemented approach of run-time coupling between ESP-r and Matlab, it is ESP-r which starts simulation. Indeed, Matlab is launched at every ESP-r time-step as a separate process. If the connection between ESP-r and Matlab breaks down the data to be exchanged cannot be transferred until the communication between them is reconnected. More detail about distributed building domain specific and domain independent software tools by run-time coupling can be found in (Yahiaoui et al., 2004 and Yahiaoui et al., 2005).

ANALYSIS TO MULTI-AGENT SYSTEM SPECIFICATION

Before delving into the specific specification of interactive control systems and building performance, this section describes first how the analysis of a building can be mapped to the design of multi-agents models. The methodology based multi-agents systems engineering (e.g. DeLoach et al. 2001) is similar to traditional software engineering methodologies. In this paper, the methodology follows the basic steps of the *waterfall* process model as it is the most relevant diagram applied in software development industry. It is structured a cascade of phases, where the output of one phase constitutes the input of the next one. One of the key advantages of this diagram is that it clearly identifies number of relevant phases where a development of multi-agent architecture passes through. The phases of this process model are described with some importance to be adapted for the current research, but several versions of this diagram can be established with different fields (see e.g. Cheong et al. 2005). Those phases can also appear in any other process model such as V diagram, spiral model and so on, and include:

- User requirements – collecting of occupant’s needs for the control system (or agent) to be;
- System requirements – specifying the requirements into a set of functionalities and proprieties (i.e. like climatic conditions, changes ...) to be provided by the agent to be;
- Design of multi-agent architecture to be;
- Implementation of multi-agent architecture;
- Verification and acceptance of multi-agent systems for operation in building environment.

Although requirements analysis for an agent system is typically translated into a set of goals to be pursued by that agent, the development of multi-agent systems is involved in those phases. Using this approach, it is clear that an agent role in conjunction with a link between tasks (or sub-agents), as shown in figure 4, determines the behavior of each the sub-agent will have. Nevertheless, external events need to be captured from the tasks to coordinate in the design of the agent so that it can behave consistency with the initial concurrent tasks. Internal events should be captures in the design as well. However, based on this approach, figure 4 illustrates how the role models in the analysis phase are transformed to multi-agent systems in the design phase as well as the relationship between multi-agents.

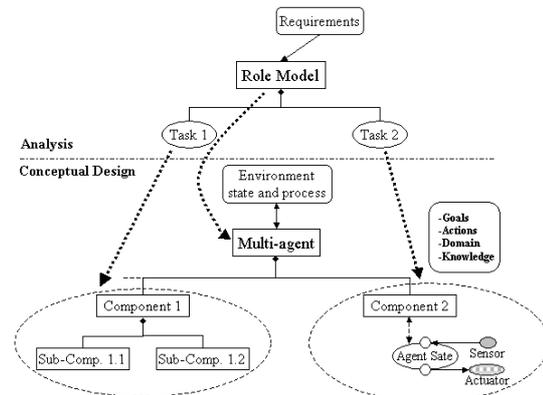


Figure 4. Multi-agents in a building environment

The formal specification of compositional architectures for role models is based on task-based approach to the design of multi-agent systems. As a result of task analysis, hierarchical role models are specified at different levels of abstraction, as the interaction between tasks. Each task can be assigned to one or more agents. Agents themselves perform one or more (sub-) tasks, either in parallel or sequentially. The agents can be designed with a knowledge base to behave by certain intelligence.

MATHEMATICAL FORMULATION

In this section, an application for a building case-study model is presented as shown in figure 5. This application comprises a test cell unit of dimensions $(3.15 \times 3.85 \times 2.6 \text{ m}^3)$ constructed in TU Delft with

light construction materials that has for the purpose to investigate different causes that influence the indoor environment of passive solar buildings. Those causes can include natural ventilation, radiant or solar heat gain and heat loss coefficient.

HEATING SYSTEM

A mathematical simple model of the heating system plant is represented as the rate change of the temperature difference in the heat flow Q_{in} supplied by the heater, and the heat rate Q_{loss} lost through the wall insulation, related by the following equation:

$$mc \frac{d}{dt}(T_{in} - T_{out}) = Q_{in} - Q_{loss} \quad (1)$$

where m is the building mass (Kg), c is the average specific heat ($J/Kg.K$), Q_{loss} and Q_{in} are heat flow rates (J/s or W), and T_{in} and T_{out} are inside and outside temperatures ($^{\circ}C$).

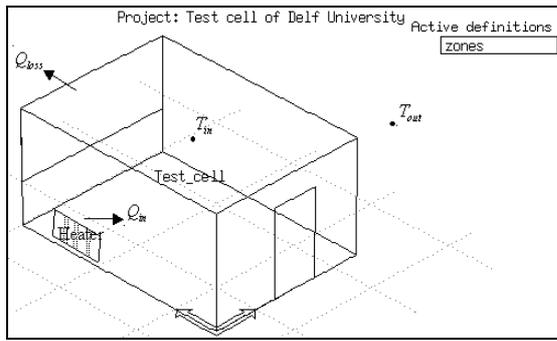


Figure 5. TU Delft test-cell case study

When the outside temperature T_{out} is constant (or very slowly varying), the relation given by equation (1) can become, $mc \frac{d}{dt}(T_{in}) = \frac{V_h^2}{R} - Q_{loss}$ (2)

where V_h is the heater voltage, and R is the electric resistance of the heater.

The rate of heat Q_{loss} lost through the wall insulation is proportional to the temperature difference across the insulation, in which it is given by $Q_{loss} = U_0(T_{in} - T_{out})$ (3)

where U_0 is a heat loss coefficient (W/K)

Submitting from equation (3) into equation (2) gives a relation in form of the state-space representation, which is as follow:

$$\frac{d}{dt}T_{in} = -\frac{U_0}{m.c}T_{in} + \frac{1}{m.c}Q_{in} + \frac{U_0}{m.c}T_{out} \quad (4)$$

where the $\frac{U_0}{m.c}T_{out}$ factor is the effect of the disturbance input.

The value of c for this example consisted of using common proprieties for air temperature in which it is taken from table with respect to the average temperature of the building in wintertime, as mentioned in (ETB, 2005). On the basis of this table, c is something like $1.005 (kJ / Kg.K)$. The value of m is also calculated with respect to density ρ , which is in the order of $1.205 (Kg/m^3)$. The heat loss coefficient U_0 is calculated in relation of U-value defined by each area in relation with all areas of the room.

MULTI-AGENT MODELING

In the design phase of multi-agents, the role model is taken in the analysis phase after having defined requirements which are specified in both problem and functional terms. Then an agent paradigm is produced where complex systems are partitioned into simple sub-problems that have limited mutual dependencies. However system decomposition and design of individual agent can sometimes be a problem since it is important to make decisions, hybrid systems can in effect be suitable in decomposition as they support capabilities in decision making. In the case of BAS as shown in figure 1, building zones are represented to explain how distributed control systems work in building. Practically, a building zone contains a controller which forces a building system to behave in a desired way in order to achieve a certain goal. Even though a building zone disposes more than one controller, the objective is the same where system goals need to be accumulated. In order to ensure that all system goals are being satisfied, each role must be played by at least one agent where a traceable link is provided from the goals in the analysis phase to the agents in design phase.

Formally, an agent is described as $A = \langle M, V, I \rangle$, which consists of a set V of variables, a set I of initials states and a set M of modes. The set of variables V are partitioned into input and output variables. The set of initial states I specifies possibles initialisations of the variables of the agent and can further be used to correct the assignments of value to the variables. The set of modes M represent the behavior of the agent in the system design.

In the context of BAS, each sub-station can be connected to several zones and each zone dispose at least of one controller when a distinct operation is required. In that fact, the controller is an agent and the operation of this controller is defined on agent.

When sub-station is connected to more than one zone, agents are composed in parallel. The parallel agents execute concurrently and communicate through shared variables. To enable communication between agents, shared variables can be defined as global so that the agents distribute information without confusion. Finally, the communication between controllers located in different building zones is performed and distributed control systems in BAS environment can be simulated.

SYNTHESIS OF HYBRID CONTROLLER

With model-based distributed control modeling and building simulation environments, the control algorithms are designed and performed offline building models of which the simulation can be ran on two computers. Hence, a generic control diagram depicting the interaction between the controller and its environment plus the building model is shown in figure 6. Finally it should be noted that the control systems (or controllers) implemented for collecting experiments in Testcel are the same carried out in building performance simulation.

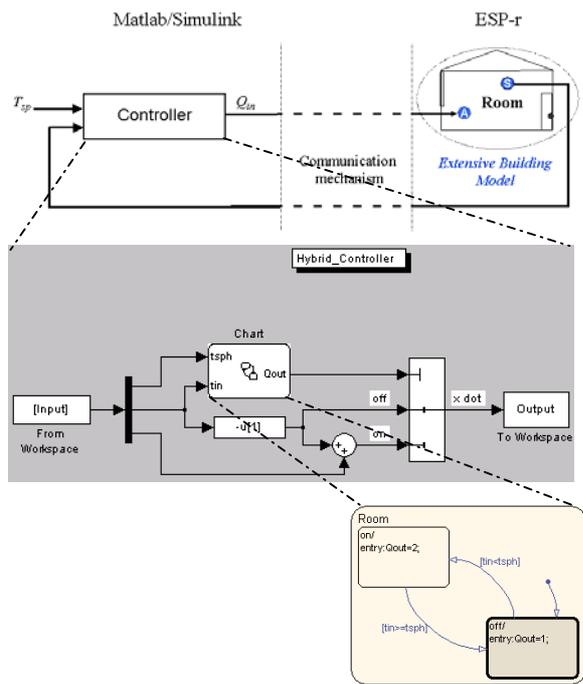


Figure 6. A prototype hybrid control system for building plant model

Both Simulink and Stateflow are used as graphical languages. In addition, Matlab is used for control and data-flow applications that mix continuous and discrete-time domains. Those tools are based on a particular mathematical formalism, language and necessary to analyze and simulate the design of a hybrid system. Figure 6 illustrates also a graphical environment for the hybrid controller developed for building heating system.

In order to integrate multi-agent systems in building performance simulation, the synthesis of model-based hybrid system is presented in a way that can be generalized to compose a specification of multi-agent architecture for integrated building systems. The formalism of Statecharts with hybrid systems is used in order that a chart can represent an agent. Although, a StateChart frame lies a hybrid automaton where states represent feasible actions of the hybrid controller, each state can therefore constitute a hybrid sub-system which in turn is the sub-agent.

BUILDING TEST CELL: -CASE STUDY

The current case study is illustrated to investigate an application with two objectives. The first consists of comparing between experiments and simulation results obtained by the same model-based hybrid controller within the same time step of 1mn/hour. The second qualifies the importance of the run-time coupling approach when it involves advanced control applications in building performance simulation.

EXPERIMENTS

A test cell built in TU Delft with light construction materials is used with the aim of designing measurements by controlling the indoor temperature in a building. In consequence, sensors are installed more or less all over different places in the room to provide timely detection of potential temperature changes where the indoor temperature is the average of all measures collected by those sensors.

A model-based hybrid controller developed for real-time specification is implemented to actuate the electrical heater of 1750 (W) with proper amount of power appropriate for a current situation through a data acquisition located in the room during experimental results, presented in figure 7.

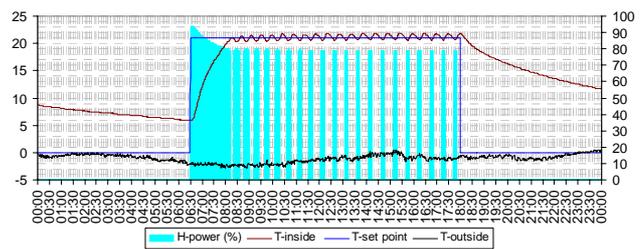


Figure 7. Experimental results

SIMULATION RESULTS

A test-cell building model is implemented in ESP-r with new databases created to represent and carry out the same material proprieties that are practically used in the construction of the room, shown in figure 5. The climate measurements are partially integrated as well, but ESP-r considers their values on an hourly basis. The simulation results, shown in figure 8 are obtained typically within the same model-based hybrid controller implemented on the same (Matlab/

Simulink) environments respectively, as shown in figure 6, which is actually realized for experimental applications. Though the run-time coupling described approach above is used to exchange data between ESP-r and Matlab, Matlab is synchronously launched at every ESP-r time step as a separate process during occupied period (from 6:30 to 18 o'clock).

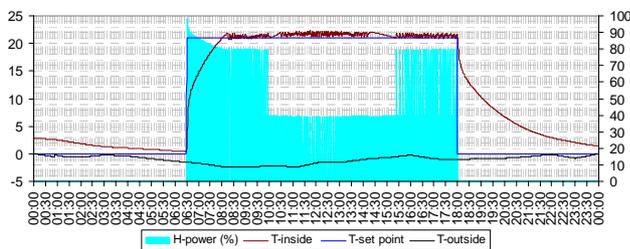


Figure 8. Simulation results

A detailed comparison between experiments and simulation results shows that there are small changes in both responses of the controller used for the indoor temperature in the test cell. Those changes are due to the climate data that highly influence the temperature inside the test cell. In fact this outside temperature is a disturbance that makes changes over time and the controller designed does not takes action to suppress sensitive input noise, which causes chattering at short intervals of few seconds only. However, the controller designed can filter noises if it uses an estimator that operates simultaneously causes with negative values. In addition, hybrid systems can be easily coupled with model-based modern control techniques to eliminate any changes that disturbs a system (see e.g. Sazonov, 2003).

Another point to highlight in comparing experiments and simulation results is that the responded signals (or controlled variables) in both figures (7 and 8) are not very close to each other. This is due to ESP-r, which considers the climate on an hourly base and due probably to theoretical approximations used sometimes to represent closely practical issues. Nevertheless, the controller designed maintains the measured indoor temperature with few variations small and brief around the set-point.

CONCLUSIONS

A new approach to building automation systems that utilizes hybrids systems is presented in order to design real-time controllers that can automatically regulate building equipments and components. This type of approach is implemented and experimented within a building model, and tested in simulation within the use of run-time coupling approach developed by means of distributed control modeling and building performance simulation environments.

The use of multi-agent systems for intelligent control in buildings can have a great potential. This potential

may well rely on a dynamic autonomy control to be introduced in buildings where it can have a large impact on saving costs. It can also reduce the complexity of distributed control systems used in BAS. For such reasons, it is considered that multi-agents based on hybrid systems can be suitable to design intelligent control models for complex building systems.

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