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CASE STUDY: DEVELOPING INTELLIGENT BUILDING USING COLOURED PETRI NET

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Abstract. *Advances in mechatronic in the last decades have motivated the development of new capabilities of the intelligent building. Considering that in these systems new interaction emerge through the functionalities of different devices that are not treated by conventional modeling techniques, it is important the study of new modeling approaches to address the complexity of these systems. This is fundamental to evaluate the interaction between the functionality devices and to ensure an adequate specification of the system. In this paper we proposed a novel approach to model and simulate an intelligent building. The procedure adopts a component-based approach that enables the reuse of the models developed. To illustrate the main features of this approach, we presented a hypothetical example of an intelligent building. This system is integrated by three systems: HVAC, lighting and security system.*
Keywords: *Intelligent building, discrete event system, Coloured Petri net, discrete simulation.*

1. INTRODUCTION

The evolution of intelligent buildings (IB) has been considerable over the last decades because of technological development in the areas of microelectronics, communication networks and control paradigms that enable the reduction of energy consumption and environmental impact during construction and operation of the building (Flax, 1991, Liu and Yao, 2010). The IB can be characterized as a system with the capacity to recognize and adapt to the surrounding and the activities of the user, with the objective of making various decisions and perform actions autonomously, according to different situations (Aarts and Grotenhuis, 2011).

From the viewpoint of technological innovation, the IB has emerged as a new paradigm in the scenario of building automation. These systems are composed of a large number and variety of electronic devices, distributed in the physical environment. These devices, characterized by having a high computing and communication power, have the capacity to adapt automatically to a changing environment and the user preferences (le, et al., 2006). These characteristics enable a new universe of applications and interactions between users and the environment (Medeiros, 2008).

One of the current challenges in the scientific community related to the development of IB is the need to create solutions to address the complex interactions between the large quantities of interconnected devices that integrate its control system. Complex interaction is a feature of the system in which the representation of the global behavior cannot be done in a strictly sequential way, even knows the individual behavior of each component. The functionalities of each device can be easily described by a set of sequential activities. However, the IB is integrated by several devices with high computing and communication power. These devices operate in a cooperatively way through an intensive exchange of data. The design of IB is not a trivial task. Disregarding some important interactions between devices that integrate the control system can lead to specification errors or malfunction, endangering the integrity of users and physical facilities. Therefore, it is important that the control logic of the component must be rigorously specified and verified prior to its implementation to ensure an errorless control system.

The modeling of the IB involves the systematization of the knowledge of how these environments operate, i.e., what are the activities performed by its components and how they interact. In this context, the behavior of the devices that integrates the IB can be described as the evolution of discrete states, as a consequence of instant events. For instance, some of the events that may occur are: activation or deactivation of smart presence sensors, opening and closing automatically the doors and windows, activation or deactivation of the emergency devices, etc. This kind of system is called Discrete Event Dynamics System (DEDS), and for which have been developed different approaches to modeling and analysis (Miyagi, et al., 2002).

In recent years, there were several proposals to develop software solutions for an IB (Bettini, et al., 2010, Augustin, et al., 2006, Chen, et al., 2003). Although these studies have contributed to the development of this research area, these approaches do not allow adequately represent the dynamic behavior of the system. In this sense, many studies consider behavior of the IB as discrete event systems and the Petri net have been used as a formal tool to model and analyze their behavior.

In this sense, in Kaneshiro et al., (2010), it was presented a novel approach to specify the control network system in an intelligent building. The models of the activities and interaction between the devices of the control system were supported by models in Petri nets. In Sgarbi and Tonidandel (2006), it was presented a study to create a control system for smart houses. This control uses dynamical rules that changes according to the behavior of the inhabitants. This paper aims to contribute to the development of a new approach for the design of the IB, where the control system can adapt dynamically according to the context of the users and the environment.

This paper is organized as follows: section 2 presents the fundamental concepts of colored Petri nets and in section 3 it is presented the procedure for modeling and analyzing the behavior of the IB. In section 4, an application example of the proposed procedure is discussed. Finally, in the last section, it is presented the main conclusion of this work.

2. COLOURED PETRI NET

The Petri net (PN) was initially developed in 1962 by Carl Adam Petri in his doctoral thesis at the University Kommunication mit Automaten of Darmsdadt in former West Germany (Jensen, et al., 2009). It is a graphical and mathematical tool for modeling, analyzing and designing systems with parallel, concurrent, asynchronous and non-deterministic process, especially those characterized by discrete states that change abruptly by events assumed to be instantaneous. The PN allows modeling typical situations of distributed systems, such as asynchrony, concurrency, causality, conflict processes and resources sharing.

When describing the behavior of the IB by means of traditional Petri nets, known as a place-transition, the interpretation of its graphic description may be difficult due to the total number of structural elements (places, transitions and directed arcs) that the resulting model of the system can to achieve. However, there is an extension of Petri nets known as Coloured Petri nets (CPN) which is understood as a high level Petri net that combines the Petri net place-transition and a programming language (Jensen, et al., 2007). The Petri net provides a graphical environment and supports the formal description of the system and the programming language facilitates the definition and data processing. Thus, a compact and parametric model can be created. This type of PN allows the construction of hierarchical models that can condense and facilitate the description of the system. In this paper, it is adopted a modular approach based on CPN, which it is considered that a complete system could be divided into independent functional modules, which interact with each other by means of message exchange in a communication network. Then, all these models are integrated into a global system model. From this model, it can be possible to analyze the behavior of the system, like the identification of some undesirable conditions, such as the presence of states in which the system is blocked (deadlock) or the identification of some specification errors previously to the implementation, preventing problems in later stages of the project.

3. MODELING PROCEDURE PROPOSED

The purpose of this chapter is to present a systematic procedure to specify the IB. Initially, to illustrate the organization and interaction of elements that integrate the control system it is proposed a distributed architecture of the control system. Then, it is presented a sequence of steps that systematizes the development control system according to this architecture. The modeling procedure can be used as a support to improve existing IB or to develop new ones. The collaboration between the building systems are performed through the publication and subscription of data topics, available in the control network. The proposed modeling procedure uses a component-based approach to build the control system, aimed at facilitating the construction of large systems. The modeling procedure uses decoupled and distributed architecture. In this way, it is facilitated by the insertion of new components, since they need only connect to the network control by subscription of data topic. Each time that these data are available, the control network provides this information to the subscribed devices.

3.1 Distributed architecture of the IB

The global control of the system emerges from the interaction between the control devices, so that collaboration is carried out in a parallel and distributed way, without the existence of a master-slave relationship. The control system is made up of control devices which can be grouped to form subsystems. The complexity of the global control of the IB is distributed among the control devices that perform a local control. These devices are autonomous, have a partial view of the system under control and can interact with each other via a control network. In this architecture, it is proposed the Publish/Subscribe communication (Eugster, et al., 2003) to establish the cooperation between the control devices. The procedure consists of an interactive sequence of six steps, in which the completion of a step can lead to the revision of the previous steps.

Step 1: Requirements of the IB

In this initial modeling stage, the scope and the main features of the IB are identified and defined. In order to discover, prioritize, negotiate and document the requirements of the IB, it is important the participation of the stakeholders involved in the project. The documentation of the requirements is done through an informal description of the characteristics of the system.

Step 2: Specification of strategies to be modeled

The goal of this step is to define all the activities of the control devices, which act in a cooperatively way in order to achieve the objective defined in Step 1. The collaboration between the control devices is performed through the sharing of information necessary for the implementation of control strategies.

This step is divided into the following activities:

1. Group the control devices according to the subsystem to which it belongs.
2. Identification of facilities and devices that are under the command of the control devices.
3. Assignment of the functionality of each control device. This activity is subdivided into the following steps:
    - The sequence of control activities;
    - The identification of conditions for the initiation of control activities;
    - The identification of conditions for the completion of control activities.

Step 3: Data topic definition

Due to the control devices have partial information of the global behavior of the system, they need to interact between them to perform activities in a collaborative way. In order to perform the activities described in the previous step, it is necessary that the devices can communicate with each other. In this stage, we propose the use of the communication paradigm publish/subscribe, which in general terms is based on asynchronous exchange of messages, grouped by topic (Eugster, et al., 2003). The topics are tuples consisting of an identifier and a data type. The devices that send information to a particular topic in the communication network of the IB are called producers and devices that declare their interest in receiving information from a given topic are called consumers. The devices are not directly coupled to each other, and the process of collaboration between them is performed through the publication and subscription of data topics. The control network is responsible for managing the process of receiving and delivering the messages.

Step 4: Construction of the components

In this stage, the basic components of the control devices are constructed, considering its reuse in the development of other devices. These components are modeled using CPN. These models can be hierarchically structured as a collection of connected modules. Thus, it is possible to reduce the development time of system models.

Step 5 Structural modeling of the control system

At this stage, it is developed a CPN model of the control system considering the input and output parameters of the system. This model is important because it allows a better understanding of stakeholders involved in the project in order to know the system requirements and the activities of the control system devices.

Step 6: Analysis of the models

Once obtained the functional models, in this step is carried out the analysis of the structure and behavior of the models. The purpose of this step is to verify and validate if the models attend adequately the requirements specified in the previous steps. Initially, a structural analysis of the system is done based on the study of properties of the "place/transition Petri net” (Murata, 1989). However, for a better understanding of the dynamics of the control system, it is important to perform the simulation of the models that represents the IB. The simulation processes allows the analysis of the consequences of the system specifications, unexpected behavior under certain circumstances, and even, discover new features that were not specified in previous steps.

4. APPLICATION EXAMPLE

This section presents an idealization of an IB which is integrated by three systems: HVAC, lighting and surveillance system. In this example, only the main features of these systems were studied. This control system can be useful for users who move frequently within the building. In the case of a hospital, for example, it is important to know and track the location of the medical specialist. In Fig. 1 it is presented the layout of the IB modeled. The localization of sensors used by the IB, such as security, lighting and HVAC system is presented.

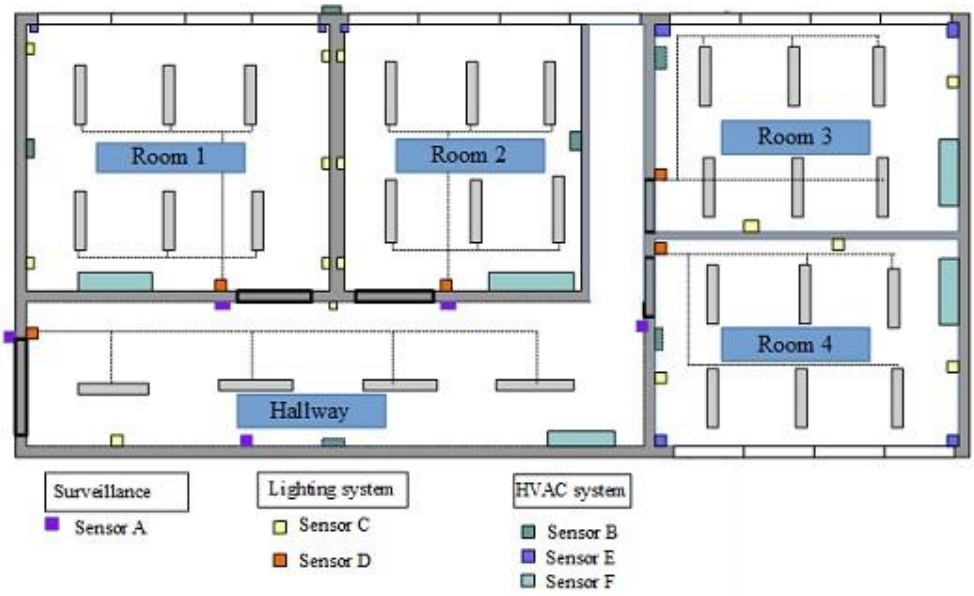

Figure 1. Layout of the IB

Step 1: Requirements of the IB

We identified the follow requirements the IB must perform:

- The surveillance system constantly tracks the user location in the building.
- The database system storage the user's preference, such as lighting and temperature level.
- The lighting system adjusts the light intensity according to the user's preference.
- The HVAC system maintains the temperature in the room according to the user preference. To perform this requirement, the internal temperature and external temperature of the room is measured.

In Tab. 1 it is illustrated some strategies the HVAC must perform. The options were configured, based on the logic AND between condition 1 and condition 2. For instance, if the outside room temperature is 30 degrees, the room temperature is 28 degrees and the user preference is 25 degrees, then the windows must be closed, the air conditioning is turned on and the heater is turned off, as it can see in option 6 (Tab. 1).

Table 1. Strategies of HVAC system

Adjustment Options	Settings (Logic AND)		Actuator Control		
	Condition 1	Condition 2	Heater	Air Conditioning	Windows
Option 1	Tpref=Tint	Tpref=Text	OFF	OFF	CLOSE
Option 2	Tpref=Tint	Tpref>Text	OFF	OFF	CLOSE
Option 3	Tpref=Tint	Tpref<Text	OFF	OFF	CLOSE
Option 4	Tpref<Tint	Tpref=Text	OFF	OFF	OPEN
Option 5	Tpref<Tint	Tpref>Text	OFF	ON	CLOSE
Option 6	**Tpref <Tint**	**Tpref<Text**	**OFF**	**ON**	**CLOSE**
Option 7	Tpref >Tint	Tpref=Text	OFF	OFF	OPEN
Option 8	Tpref>Tint	Tpref>Text	ON	OFF	CLOSE
Option 9	Tpref>Tint	Tpref<Text	ON	OFF	CLOSE

Step 2: Specification of strategies to be modeled

The activities that the IB must perform in order to satisfy the requirements specified in step 1 is presented in Tab. 2.

Table 2. Specification of strategies

System	Publish	Subscribe	Control
Surveillance	• Identification • Location of users		
Data Base	• Light preference • Temperature preference		
Lighting		• Lighting preference • Room • Lumens per area of the room.	• Adjustment of lighting intensity.
HVAC		• Temperature preference • Room • Internal and external temperature • Windows	• Adjustment of internal temperature.

Step 3: Definition of topics

The communication between the four systems is handled using a control network, according to the Fig. 2. The security system publishes into the control network the location of the user in one of the room in the building. The colored arrows represent the flow of information interchanged between the network and the systems. Data Base system storage the lighting and temperature user preference. This system is subscribed to the user and publishes into the network the lighting and temperature preference. The Lighting system is subscribed to the light preference and the room. With this information, the room is illuminated according to the user preference. And the HVAC system is subscribed to room and temperature preference. After ordering the internal and external temperatures, it performs the adjustment based on this information.

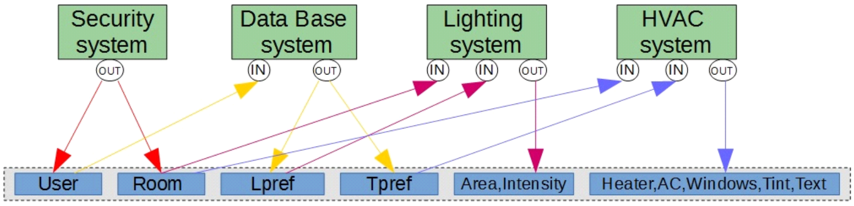

Figure 2. Communication between the four systems

Step 4: Construction of functional models

These components are modeled and simulated using the software CPNTools [12]. For example, in Fig. 3 it is modeled the sensor responsible to track the user in the building. The transition "Sensor A" represents an identification sensor, such as a biometric reader or a facial recognition sensor. This figure represents one of the functional models that integrate the Security system, described previously.

When this transition fires, a mark with the room, user and scan cycle is send to the output place "(room, user, K)".

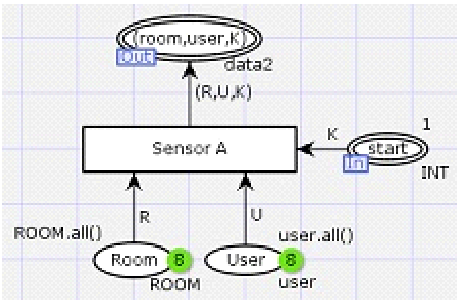

Figure 3. Model of sensor responsible to track the user in the building

The data base system is subscribed to the topic information "user" and publishes into the control network the user preference using the output place "Lpref, Tpref". Figure 4 represents this model.

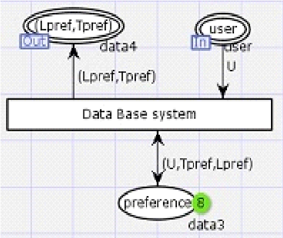

Figure 4. Figure "Data Base System"

In the control network, this information will enable a transition called "Tpref, Lpref" that will split this data in two parts: one contains temperature preference to the HVAC system and another part with the lighting preference to the lighting system. Fig. 5 presents one part of the control network.

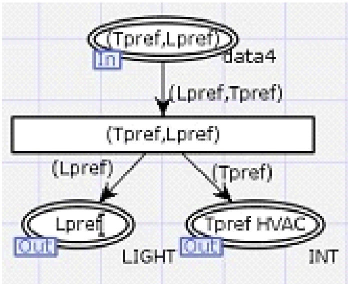

Figure 5. User´s preference

The HVAC system is subscriber to the topic information "room" and "Tpref HVAC". Internally, this system measures the internal and external temperature of the room using the transition "Temperature sensor", as represented in Fig. 6.

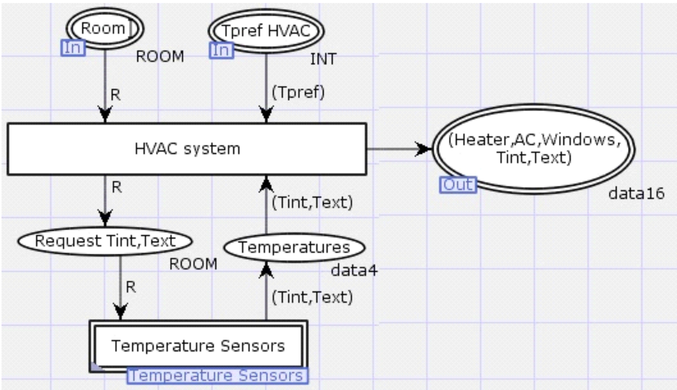

Figure 6. HVAC system

Based on this information the control system chooses the best adjust among 9 options. After this operation, it will publish in the control network the final state of the heater, air conditioning, windows, internal and external temperatures. This data can be used, for example, for evaluation of consumption of energy.

Step 5: Structural modeling of the IB

The operating cycle of the control system is represented in Fig. 7. Initially, the IB is subjected to stimuli by means of the transition "Input data". This module represents: the identification and localization of users who enter into any room and the number of the cycle. That information is sent to the module 'Process' using the interfaces: K, U, R, Tpref and Lpref. In this module it is implemented the control strategies defined in step 2. Once finalized these control strategies, the result of this process is obtained in the way of output data through the communication interfaces K(Cycle), R(Room), A(Area), I(Intensity), Tint, Text, X(Heater), Y(air Conditioning), Z(windows). After all the output data are obtained, it is initiated another operation cycle of the IB.

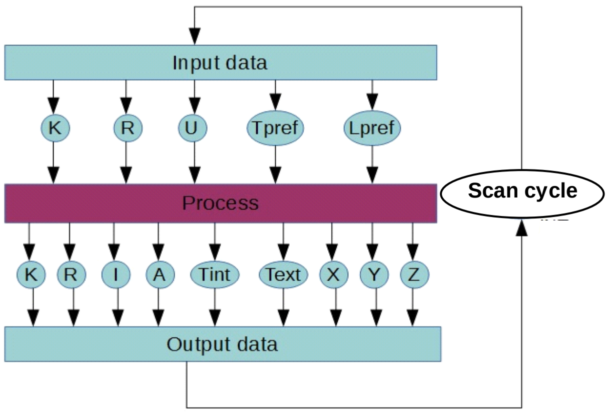

Figure 7. Operating cycle of the IB

Internally, the module "Process" is constituted by devices, developed in step 3, as shown in Fig. 8. In this figure, the communication between devices is performed through the topics of data. For example, the "surveillance" receives the data input through the gateway $(K, R, U)_{(in)}$. This data is processed by the system which publishes this information in the module "Topic Data" through the exit gateway $(R, U)_{(out)}$. The devices which declare interest in receiving this information are subscribed to the topic through the entrance gateway $R_{(out)}$ or $U_{(out)}$.

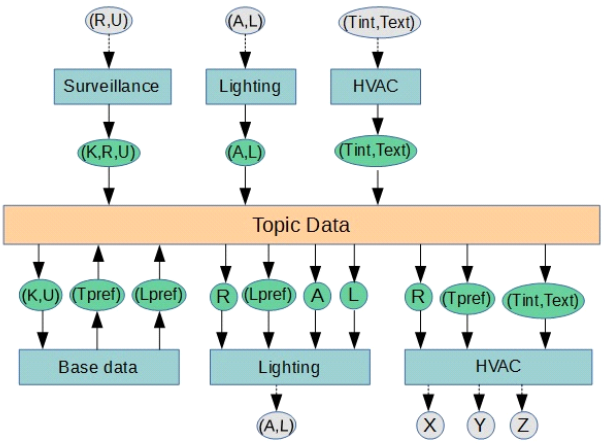

Figure 8. "Process" model

Step 6: Analysis of the models

In this step, it is verified if the models represent adequately the functional specifications of the IB, defined in previous steps. The software CPNTools was used to the simulation of these functional models. During the edition of the models, the software can indicate if there is already any structural error. The analysis of the specifications is performed by simulation, which allows experimenting and testing based on different scenarios based on specific initial conditions. The simulation also allows the understanding of the system behavior under different conditions, ensuring a better understanding by the people involved in the project. Better understanding of the system can lead to the emergence of new ideas aimed at improving the proposed system.

Next, it is presented an example of the questions (Q) that can be studied from the simulation of the system and their corresponding answers (A) derived from the analysis of the model:

Q1. Is the system able to make detailed lighting and temperature adjustment?

A1. Yes, the system is able to control the lighting in different areas of the room or by automatic control or special way. In the HVAC system, we have 9 pre-set scenarios according to the user preference, outside temperature and internal temperature.

Q2. Is it possible to establish new user's preferences for the system according to their use?

A2. No. Currently, the system only receives new data preferences when they are imported from an external database.

Q3. Is it possible for the IB register more than one user getting into one of the rooms?

A3. Yes, the system can recognize the input from multiple users, but given the diversity of interests among all of them in the room, control over the settings options should only be done by the responsible for the room.

The questions Q2 and Q3 motivate future modifications of the model, aiming to improve the functional characteristics of the system.

5. CONCLUSION

In this paper it was presented a study case to systematize the modeling of the IB control. This work provides an approach to help engineers and researchers in the project related to this kind of environment. The proposed procedure uses the publish/subscribe paradigm to establish communication between the devices that integrate the control system. The CPN was used to specify the features of the IB and the interaction between the different devices that integrates this system. The proposed approach uses a modular structure for the development of models. Thus, it is possible the creation of modules from smaller elements and reuse them in other parts of the model. Additionally, through simulation it is possible to know in detail the characteristics of the system, unexpected behavior and other aspects that are not always explicitly defined in their requirements. Thus, the simulation model allows studying and improving the model and the alternative scenarios, aimed at constant evolution of the system.

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