A procedure for modeling of Holonic Control Systems for Intelligent Building (HCS-IB)

Robson M. da Silva¹,a, Julio Arakaki²,b, Fabricio Junqueira³,c, Diolini J. Santos Filho³,d, Paulo E. Miyagi³,e

¹Universidade Estadual de Santa Cruz, Ilhéus, BA, Brazil
²Pontifícia Universidade Católica de São Paulo, São Paulo, SP, Brazil
³Escola Politécnica da Universidade de São Paulo, São Paulo, SP, Brazil
⁴rmsilva@uesc.br, ⁵jarakaki@pucsp.br, ⁶fabri@usp.br, ⁷diolini.santos@poli.usp.br, ⁸pemiyagi@usp.br

Keywords: intelligent building, building control system, fault tolerance, holonic system, Petri net, system reconfiguration.

Abstract. Faults occurrence is inevitable in real world and a practical alternative approach is the reduction of fault consequences. Despite of this, the majority of buildings control systems do not have such mechanisms. Thus, this work proposes a procedure for the modeling of control systems for intelligent buildings which considers their functional specifications in normal operation, and in case of faults occurrence. The procedure adopts the concepts of discrete event system, holon, and Petri net and its extensions. It is presented some models derived from case studies, and mechanisms to fault-diagnosis, decision and reconfiguration.

Introduction

Intelligent building (IB) became an important infrastructure of modern productive plants dedicated to manufacturing products and executing services. In a typical IB environment there are systems such as HVAC (heating, ventilation and air conditioner) system, digital surveillance system, and access control and fire management system. In this work these systems are called as subsystems of the IB and in practical case there are heterogeneous. Despite this the designer of the IB should guarantee the interoperability among these subsystems. The concept of integrated systems is also fundamental to effectively combine the use of available resources in buildings control subsystems (BCS) [1, 2]. Moreover, a totally infallible system is unfeasible from practical viewpoint, once operational errors and faults occurrence is inevitable in systems conceived, constructed and operated by human [3]. Thus, the IB control subsystem must be provided with mechanisms of active fault-tolerant control (AFTC) that take account the system reconfiguration [4]. This reconfiguration is done by reallocation of resources and by choosing alternative ways of interactions among the processes [5]. These aspects define a complex behavior that confirms the necessity of a control architecture that integrates different functions for execution of a set of activities and of shared use of resources.

An agent is considered a software entity with enough intelligence that is capable of autonomous control actions and cooperation relationships by participating in associations’ agreements with other entities in order to meet its design objectives [6]. A multi-agent system (MAS), a system composed by two or more agents, can execute distributed intelligent supervisory control function with communication, cooperation and synchronization capabilities, among others, i.e., MAS can cover the behavior specifications of the IB subsystems and also the functional specification to be fulfilled by the overall system. A holon [7] is a special case of agent, an autonomous and flexible entity which is capable to act in its environment [8].

The integration of MAS and the holonic system (HS) paradigms [9] with mechatronics is currently presented as path for an intelligent automation of productive systems [10]. However, even recognizing that AFTC mechanisms are fundamental to improve the efficiency, flexibility, and robustness of control systems [5], the majority of BCS do not have such mechanisms, and there is few published material about the procedure to implement these functions for IBs [11]. Therefore, this work presents a procedure for holonic control systems modeling for intelligent building (HCS-
IB) considering their functional specifications in normal situation, and also in the occurrence of faults. The approach considers the AFTC requirements and IBs as a class of discrete event system [12]; and adopts the HS concepts and the application of Petri net [13], with their extensions.

Related Works

**Control Subsystem Modeling.** The buildings control subsystem (BCS) in IB must: a) attend the requirements of AFTC increasing the robustness and flexibility of the overall IB system; b) assures under any situation the fulfillment of the IB specifications in particular that related to safety; and c) adopt techniques that facilitate the organization of control tasks to ensure the integration between IB subsystems and their components.

The Petri net (PN) and their extensions have been successfully used in BCS for the modeling and analysis of the system structure and their dynamic behavior, as well as the specification of control strategies [3, 5, 14, 15]. Reference [3], for example, show that it is possible to develop models in PN through the characterization of patterns and detect faults through sensors signals.

In [16], the authors present models for faults diagnostic of discrete event system, where there is a mechanism called “diagnoser” that is modeled through an extended PN model. This approach suggest that in the decision phase of AFTC, some inference rules, based on reasoning [17], such as "if ... then ...else..." can be adopted in HCS-IB for specification of a mechanism called “decider”. Some authors define a homogeneous PN model which includes a single formalism to describe the overall IB system. Other authors use different formalism for each part of the IB system.

As this work consider practical system including abnormal situations the second approach is adopted, but to avoid the need of specialists for a great number of formalisms, only two based in PN are considered. To effectively model the dynamic behavior it is adopted a class of PN based on the place/transition PN, called extended PN, which were added timed transitions (terms related to PN are presented in Arial), inhibitor arcs and enabling arcs [18]. To construct these models an interpretation of channel/agent PN, called PFS (Production Flow Schema) [19], is used in the presentation of the proposed procedure showing the systematization of the modeling tasks; exploring the potential of methods and techniques that facilitate the structuring and detailing of the control functions that also facilitates the implementation phase.

**Holon, agent and holonic control system.** Holonic system (HS) is considered a framework useful for designing BCS with distributed architecture, while multi-agent system (MAS) is considered as a technique to develop software that can be used to implement HSs [20]. The result is a distributed intelligent automation system associated with the lowest layer of a HS. This MAS based control is called holonic control system (HCS). As main characteristic of this class of system can be addressed the fact that it is focused on the system behavior instead of the process-centered approach of conventional automation [21].

A survey showed that there are not many works applying the concept of holons or agents in BCS, but in the area of manufacturing systems already exists various proposals [10, 21, 22, 23]. In this work it is considered that, in terms of processes, IB and manufacturing system can both be seen as a productive system, and the theses works can the explored for this work.

In [24] a prototype of the holonic supervisory control and data acquisition (HSCADA) is presented and applied for IB, and according authors, it has the characteristics of flexibility, scalability, reconfiguration and integration. Reference [25] presents an IB control structure which is based on MAS and distributed architecture. Second the authors, this system not only effectively reduces energy consumption, but also gives full consideration to the users’ requirements with the environment. A MAS for security subsystem of a IB is presented in [26]. The proposal is evaluated through simulation and the authors consider that it achieve satisfactory results. In [27] it is presented a MAS for the design of control subsystem for IB. According to them, this MAS can be adapted to almost any building, and the implementation of the subsystem allows for dynamic reconfiguration of the agents without disrupting of the operation of the system.
Analyzing the above mentioned works it is possible to note that in most of these subsystems there is direct exchange of information in the request-response format between holons. However, a real holonic system must present a communication structure that assures the high level of holons autonomy, and functions essentially based on behavior. Therefore, in this case, a trading mechanism is more favorable than a request-response communication format between holons.

Other point is that there is no information about the use of a systematic procedure, to structure and rationalize the models development of the proposed architectures. Patterns emerge without an environment that facilitates the development of new models.

These studies also confirm that there are still a small number of known practical applications of HS technologies showing that there is a long way for a broad dissemination of these systems.

**Holonic Control System for Intelligent Building (HCS-IB)**

In HCS-IB, a Holon can be a physical (chiller, sprinkler, programmable controller, etc.) or logical (service, order, etc.) component. Each holon is responsible to perform different functions, and its individual behavior contributes with other holons to represent the whole system behavior. The proposed architecture (Fig. 1a) is divided in following levels: planning, ordination, supervision and local control. The holon of planning level (SSH - subsystem holon) contains the necessary knowledge for the general operation of IB and for choosing the general strategy that reaches the planned objective. The holon of ordination level (MH - manager holon) contains the knowledge to manage the execution of each productive strategy that results in a service. The holon of supervision level (SH – supervisor holon) contains all the knowledge to coordinate the holons of lower hierarchical levels, registering abilities of each component and offering services combined with other entities of control system. Its main function is to elaborate and implement optimized plans for holons under its coordination considering the system is operating without faults. The holon of local control level (OH – operational holon) represents the physical resources of building which has specific control devices for its operation, and determines the behavior of these resources in accordance with its objectives and abilities.

In the present work a mechanisms is introduced in the HCS-IB to allows the switching of control between two operational modes: the “stationary mode” where the control system is coordinated in a hierarchical way, i.e., MHs coordinate the optimized sequence of activities executed by SHs, that supervises the activities executed by OHs during normal situations of the system; and the “transient mode”, where to assure more system flexibility and agile behavior, OHs interact directly with MHs. For allocation of services or commands of OHs, during the “stationary mode”, MHs interact directly with OHs. In Fig.1b, the holarchies [9] are represented by ellipses. Note that a holon can belong simultaneously to different holarchies.
The application of AFTC concept in HCS-IB is divided in four phases (Fig. 1c) and they are present in each Holon independent of hierarchical level.

The “estimation phase” involves: the detection of symptoms, which can identify the existence of faults by the supervision of processes; and the fault isolation that is based on a model containing characteristics (type, statistical data, etc.) for identification of fault. When the detected symptoms do not allow any conclusion, the system should be programmed to identify the fault type for the most similar cases or to request external intervention.

The “planning phase” is to decide the reconfiguration. It is based on predefined priorities such as: reduction of the performance, shorter recovery time, etc., and on historical data, from where it is possible to measure the statistical significance of each type of fault in terms of frequency rate, recovery time, and operational cost.

The “execution phase” involves the sending of commands for the execution of the selected action plan. The last phase is the “learning phase”, which involves the storage of relevant data for use in further cases.

Therefore, the HCS-IB acts in accordance with the following rules: a) if <symptoms> then <selects fault>; b) if <selected fault> then <selects action>; c) if <selected action> then <activates reconfiguration>; and d) if <executed reconfiguration> then <store relevant data>.

Procedure for Modeling of HCS-IB

The modeling of HCS-IB (described in PFS in Fig.2) is structured in 4 stages: (1) stage 1 - analysis of requirements; (2) stage 2 - modeling; (3) stage 3 – analysis/simulation; and (4) stage 4 - implementation. These stages are subdivided in sub-stages and steps. In this paper, the focus is in stages 1 and 2 since, stage 3 is basically the use of methods and tools for evaluation of different situations of HCS-IB where verification and validation techniques for PN models can be applied, and stage 4 depends on specific application.

In the following explanation of each stage of the procedure it will be presented some examples of models derived from case studies applied to a commercial building of the Accenture company [28] in São Paulo city, Brazil.

**Stage 1 - Analysis of requirements**

In this stage, the objective is to define the specifications of BCS and its reconfiguration possibilities, and to characterize the interaction between parts of the system and its reconfiguration. This stage is divided in sub-stages.
a) Sub-stage 1.1 – identification of holons

This sub-stage involves the following steps: (i) identification of SSHs: SSHs are entities responsible for execution of services of each building subsystem. For instance: thermal comfort SSH, access control SSH, fire protection SSH, energy control SSH, vertical transportation SSH and communications network control SSH; (ii) identification of MHs: the management functions are defined. These functions can be classified into: initialization, operation, selection of operation mode, maintenance, faults treatment, finalization. These functions must also be classified by priority order. For IB, the following classification of priorities is adopted: “priority 6” - functions that involve dangerous situations toward humans, for instance gas leak or fire; “priority 5” - functions that involve productive activities as services to people; “priority 4” - functions associated to abnormal state variables, for example, high temperature; “priority 3” - functions related to local actions of faults reaction; “priority 2” - regular operational functions as starting devices; and “priority 1” - operational changes in environment, for example to modify temperature. The analysis of management functions defines the control strategies to be followed during the execution of IB services. The MHs are entities responsible for managing tasks in which control strategies have been implemented. A MH is defined for each control strategy; (iii) identification of SHs: the execution of control strategies involves, in general, a group of devices whose operations should be coordinated. SHs are entities responsible for this coordination of each group, which are represented for operational holons (OHs), for instance, the devices to maintain constant the flow of air in a duct; and (iv) identification of OHs: OHs are entities responsible for actuation, detection, command and monitoring functions. For example, functions performed by switches, buttons and selectors, keyboards and sensitive touch screens; actuation functions performed by drivers for chillers, cooling towers, motors, automatic doors and windows, valves, sprinklers, access turnstiles; detection functions performed by smoke detectors, temperature sensors, flow sensors, cameras, presence sensors; and monitoring functions performed through sonorous alarms, CFTV and displays. There are another element called “human OHs” to represent the man, such as operators, maintenance team and users.

b) Sub-stage 1.2 – specifications for AFTCS of IB

This activity focuses on the “estimation phase” (faults diagnostic) and the “planning phase” (decision) of AFTCS. The objectives here are: (a) listing the faults, (b) listing the diagnostics and decision specifications, and (c) writing faults treatment and reconfiguration strategies. This sub-stage begins with a survey main critical points of system that are accomplished identifying faults and characterizing those that affect the normal execution of indispensable functions. After this identification, the next step is to analyze which critical points are candidates for reconfiguration. The reconfiguration may be carried out if the function that presents compromised performance due the fault may recovered by the use of other resources or by changing some parameters of the failed component. The reconfiguration procedures must be planned considering all possible scenarios. These procedures are eligible during the execution, in mechanism of AFTCS, usually, considering the priority for those in that the drop of performance is minimized. It must be specified the acceptable degree of performance degradation for indispensable functions, for instance, redundant resources as ceiling fans reduce the thermal discomfort in case of fault in air temperature conditioning of HVAC subsystem. Thus, even with lower performance, additional components should be specified to permit the reconfiguration of the control system.

c) Sub-stage 1.3 – Specifications of interactions among holons

In this sub-stage, three interactive processes are considered in FTCS: “request of services”, “execution” of these services; and “reconfiguration” of the system in consequence of faults. It considers the direct communication between manager and operational holons in the allocation of commands to perform the services. This allows using of different control structures, resulting in faster reaction to disturbances.

Additional interactions that involve the transmission of specific commands for control of MHs, HOs, and control object are defined during the development of control system models. Figure 3 shows in PFS an extended PN an example of interactions between SSH and MH models. This example is a part of interactions that occurs in interactive process “request of services”.
d) Stage 2 – Modeling
This stage comprises the following sub-stages:

e) Sub-stage 2.1 – modeling of SSH
The PFS of SSH (Fig. 4a) shows that each initiated service generates a service planning. The activity requires execution model of each IB services.

f) Sub-stage 2.2 – modeling of MH
The PFS in Fig. 4b shows the sub-stage of modeling of MH. It comprises the activities [modeling of strategies], and [execute strategy]. The first one involves modeling the control strategies of the IB services. The second one consists in elaborating the plans to implement the control strategy to provide the requested service. The activity [elaborates plan of allocation of new orders], allocates the orders received in the available resources. The activity [executes orders] comprises the sending of orders to OHs.

g) Sub-stage 2.3 – modeling of SH
The SH is responsible for coordinating OHs. The SH coordinates the activity of holons under its domain in normal operation (without faults). When a fault occurs, the OHs may have to interact locally. The PFS of sub-stage of modeling of SH is represented in Fig. 4c.

h) Sub-stage 2.4 – modeling of OH
The OH represents the resources, such as operators, access controllers and chillers. OHs manage the behavior of these resources in accordance with its objectives, characteristics and abilities. The PFS of modeling of OH is represented in Fig. 4d.

i) Sub-stage 2.5 – modeling of control object
In order to detail the dynamics of the system, the operation of each component of control object of HCS-IB must be represented in extended PN, to model the dynamic of the components, as illustrated in Fig. 5a.

j) Sub-stage 2.6 – modeling for AFTCS of IB
The fault occurrence must be represented in models of operational (OHs) and management (MHs) holons. Thus, the faults related to OHs and MHs are modeled in this stage, as well as the mechanisms for diagnosis and faults decision. In Fig. 5b is presented an example of reconfiguration, and in Fig. 5c, an example of “diagnosier” and “decider” development is depicted.

There are six steps to model the “diagnosier”: (i) construction of control strategies models in extended PN

![Fig. 3. Example of interactions.](image-url)

...
Fig. 4. PFS of holons modeling.

Fig. 5. AFTCS functions modeling examples.
Conclusions

This paper presents a procedure for modeling HCS-IB considering not only normal operations but also faults occurrence. The procedure focuses on active fault-tolerant control (AFTC) requirements, with especial attention on the system reconfiguration. The modeling process is based on Petri net (PN) and its extensions – the PFS (production flow schema) is used to structure the development of models components and in the presentation of the proposed procedure. The proposed architecture with their mechanisms, it enables to implement a hierarchical or heterarchical control structure, and react to faults in a more agile way.

This work synthesizes project in [29], which involves the edition, simulation and validation of PN models for control system of productive systems. For development and evaluation of the proposed procedure it was applied in case examples of commercial building. The resulting model analysis was conducted with PN tools for edition and structural analysis. The behavior and quantitative analysis was performed through simulation techniques associated with PN properties. For practical implementation, the resultant models are interpreted as the specifications of control programs to be executed in computers (for supervisor and upper levels functions) and programmable controllers (for local control level functions).

Acknowledgment

The authors are grateful to following institutions that assisted financially different parts of this research: UESC, FAPESB, USP, CAPES, CNPq.

References


A Procedure for Modeling of Holonic Control Systems for Intelligent Building (HCS-IB)
10.4028/www.scientific.net/AMR.383-390.2318