Intelligent Technologies for Energy Efficiency and Comfort in a Building Environment

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Abstract – In this work we present a multi-agent control system that can be applied to a building environment in order to obtain energy conservation and occupants' comfort. The system consists of a number of local controllers-agents that are coordinated by an intelligent supervisor. The proposed architecture is based on the concept of intelligent agents that has been introduced recently in the area of artificial intelligence.

Index Terms – controller-agent, comfort, building, multi-agent control system, intelligent coordinator.

I. INTRODUCTION

International Energy Agency (**http://www.iea.org**) has found that in Europe buildings use about 35% of the total energy consumed. Also, the construction sector of the economy covers one eighth of the total economic activity in European Union (EU). More than eight million people work in the construction sector in EU [22]. The intense activity in the building construction, combined with the need for energy conservation and the need for environmental protection, demand more rational design of the buildings. Moreover, EU has recently issued a new directive regarding energy conservation in buildings [22]. This directive dictates member countries to adopt stricter specifications and regulations for efficient use of energy in buildings.

The way energy conservation problem in buildings was faced in 70's and 80's resulted mostly in design and construction of buildings without paying much attention to the conditions of life inside buildings. However, people spend about 80% of their lives inside buildings. So, achieving comfort conditions, namely thermal and visual comfort, and good air quality, in a building is very important and has direct implication to the productivity of the occupants and indirect implication to the energy efficiency of the building [21,22].

The aforementioned reasons led researchers to the development of building intelligent management systems (BIEMS), mainly for big buildings like offices, hotels, and public and commercial buildings. BIEMS have been introduced in order to monitor and control the environmental parameters of a building and to minimize energy consumption and cost. Fuzzy techniques have been applied to a significant number of cases in BIEMS [1,2,3,5-13,15,17-21]. In parallel with the development of BIEMS, special emphasis to bioclimatic architectures of buildings has been given. Bioclimatic architecture aims at the construction of bioclimatic buildings (solar buildings) that take advantage of solar radiation, daylight, and natural flow of air, thus achieving in some extend natural heating and passive cooling. In recent years, several buildings with bioclimatic architecture have been constructed in Greece [22].

The quality of occupants' living, in other words the comfort conditions, are determined by three basic factors: thermal comfort, visual comfort, and indoor air quality (IAQ). Thermal comfort is specified by the index PMV (Predictive Mean Vote) defined in [16] and visual comfort is specified by the level of illumination (measured in lux). Indoor air quality is mainly affected by the concentration of CO_2 in the building [5,19]. CO_2 concentration comes from the presence of occupants and from a variety of pollutants inside the building.

In order to achieve comfort conditions, the following actuators (sub-system) have to be controlled:

- Shadowing systems that control the in-coming solar radiation and daylight. They also reduce glare.
- Openings (windows) that regulate natural ventilation. In turn, natural ventilation affects thermal comfort and indoor air quality.
- Artificial lighting systems that give visual comfort.
- Heating/Cooling systems.

The combined and coupled control procedure of the above systems requires optimization of the operation of each control sub-system, under the basic assumption that the sub-systems are normally co-operating and conflicts are avoided. Optimal operation of the system can be obtained by employing expert human operators. In this work we give the guidelines for an architecture of a multi-agent control system that incorporates the knowledge of the operators. The proposed system consists of an intelligent supervisor which coordinates the operation of the sub-systems which are now local intelligent controllers-agents. The basic characteristics of a multi-agent control system for indoors microclimate and energy management in buildings are: a) It provides high priority to techniques for passive

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heating/cooling and ventilation, aiming also at energy conservation. b) It incorporates occupants' preferences for comfort. c) It minimizes energy consumption.

A basic characteristic of the advanced control systems, in combination with computational intelligence, is their ability to operate with symbolic language and inexact and fuzzy logic, which humans understand easily. Computational Intelligence has been applied extensively in industry. Hundreds of power plants all over the world have used such techniques successfully. Because in complicated systems mathematical modelling cannot easily represent the dynamics of a real system in real time, Computational Intelligence techniques, like Fuzzy Logic (human approximate classification and reasoning), Neural Networks (the neurophysiology of human brain), and Genetic Algorithms (Darwinian evolutionary laws) are used to solve problems raised in managing such systems.

The organisation of this paper is as follows. Section II describes the architecture of a multi-agent control system for a building environment. Finally, Section III offers some conclusions.

II. ARCHITECTURE OF A MULTI-AGENT CONTROL SYSTEM FOR A BUILDING ENVIRONMENT

Techniques that divide a problem in smaller sub-problems that in consequent are solved, are called divide-and-conquer techniques. They consist also a top-down process. In general, there are not standard or classical methods for optimal division of a problem in smaller sub-problems. Each complex problem has its own peculiarities and its analysis may reveal proper ways to divide it in sub-problems. So, people try to invent heuristic techniques for the solution of such complex problems.

In our work, solution of the sub-problems is obtained by designing controllers-agents that are based on fuzzy logic and can be optimized by using genetic algorithms. The controllers-agents are coordinated by an intelligent supervisor. The coordination of the operation of the controllers-agents is an important procedure, because it leads to the normal operation of the whole system. In other words, it solves the original problem.

Agent is a new concept introduced recently in the area of computer science. An agent is a computer system situated in some environment and that is capable of autonomous action in this environment in order to meet its design objectives [24]. It has been used extensively in the field of Artificial Intelligence and is closely related to the subject of distributed problem solving [17].

An intelligent agent is a computer system that is capable of flexible autonomous action in order to meet its design objectives [24]. With the characterisation "flexible" we mean that the system must be: responsive, proactive and social. The main difference of an Intelligent Agent (IA) from the agent is the flexible autonomous action. An intelligent agent consists of a virtual entity (software) that mainly has the following properties:

a) It has the ability to communicate and interact with its environment.
b) It is able perceive local environment.
c) It is guided by basic objectives.
d) It develops feedback behaviours.

The strategy for designing of a multi-agent control systems consists roughly of three steps [23]:

1. **Structuring:** Decompose the whole problem in a set of independent partial problems.
2. **Solving individual subproblems:** Solve the partial problems by designing a controller-agent that knows how to complete a particular task that solves the partial problem.
3. **Combining individual solutions:** Combine the set of implemented agents into a coherent whole by properly coordinating the activities of the agents.

A. Decomposition of the problem of energy efficiency and comfort in buildings

The goal of obtaining comfort conditions and simultaneously energy conservation is solved by the development of intelligent systems. In the present work, we propose the use of an intelligent and enriched supervisor that will coordinate the optimal cooperation of local controllers-agents. This result of this is that total control is achieved, occupants' preferences are satisfied, conflicts are avoided, and energy consumption is conditionally minimized. In a building, the controlled variables are:

- The Predictive Mean Vote (PMV).
- The illumination level (in lux).
- The CO_2 concentration (in parts per million, ppm).

Also, the following actuators are used:

- The heating/cooling system of the building.
- The window openings.
- The shadings.
- The lighting.

In order to control the operation of the building, three local intelligent field controllers are developed and optimized by using Genetic Algorithms [14]. These three lower level field controllers are called controller-agents (CA) and are guided by a higher level Intelligent Coordinator. Generally, a controller with feedback is designed to satisfy a performance criterion, however a controller-agent is associated with localization, that is a controller-agent has a partial representation of the overall problem. The idea is presented in the following Figure 1:

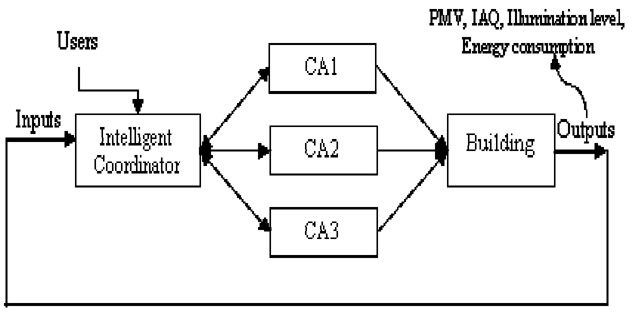

Fig. 1. Interconnection between the controlled system, the controllers-agents and the intelligent coordinator.

Inputs and outputs to the local controller-agents are:

Controller CA1: **Input:** illumination level, **Outputs:** shadowing and electric lighting.
The indoor illumination level is determined by the electric lighting and the daylight. The incoming daylight is strongly affected by the shadowing.
Controller CA2: **Inputs:** PMV and external temperature, **Outputs:** shadowing, window openings, and heating / cooling system.
Controller CA3: **Inputs:** CO_2 concentration and its rate of change, **Outputs:** window openings.

The communication operation of a controller-agent with its environment is sketched in Figure 2. More specifically, for controller-agent i, (i=1,2,3,) in Figure 2 shows the set of measurements (inputs), the control actions (outputs), the activation signal $w_i = f(inputs_i, q_i)$, where variable q_i denotes the state of the controller-agent, and the acknowledge signal α_i that makes the controller-agent active (q_i=1) or inactive (q_i=0).

In every sampling period (time step) each controller-agent performs a set of communication tasks. First, it receives a sample of measurements and uses it to calculate the activation signal w_i and send it to the coordinator / supervisor. This signal denotes that the controller wants to become active or inactive. When the coordinator receives all activation signals from the controllers, makes its decision and sends acknowledge signals back to controllers-agents. If a controller-agent receives a positive acknowledge, it becomes or stays active, otherwise it becomes or stays inactive. Finally, if a controller-agent is active it calculates the control action and sends it to the actuators.

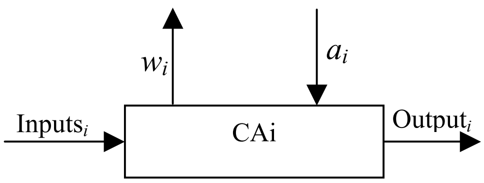

Fig. 2: Communication operation of a controller-agent.

B. Structure of the intelligent coordinator

The proposed intelligent coordinator receives as inputs PMV, IAQ, illumination level, energy consumption, occupants' preferences, and the activation signals from the controllers-agents. It then performs two specific tasks using a master-slave coordination mechanism. Each task requires a separate intelligent agent (IA). The dependency between the two tasks is that the lower agent (slave) operates only when it receives an activation signal from the upper agent (master) [23,24,4].

- The first IA (IA_1), called master agent, evaluates the energy efficiency of the building and comfort. The master agent monitors of occupants' preferences with the determination of the comfort reference points. By equipping master agent with qualitative fuzzy rules, the inference engine machine produces reference signals that activate IA_2. The rules that are used have the form IF – THEN. A typical example of this type of rule is:

IF {Energy consumption is small AND Comfort is accepted} THEN {IA_2 is inactive}.

- The second IA (IA_2), called slave agent, compensates the interaction of the subsystems being controlled and manages to avoid conflicts between them as, for example, between natural ventilation and mechanical cooling, between natural ventilation and heating, between shadowing and heating or cooling, between decrease of direct solar radiation with shadowing and visual comfort, etc. Very often, the evaluation of control strategies is based on subjective criteria. So, IA-2 uses linguistic rules that stem from physical laws [10,13,11,12,9] and an inference engine that generates an compensation policy. This policy is decisive to the increase of the system's performance. An example of a rule used by IA_2 is:

IF {w_1 is small AND w_2 is big AND w_3 is medium} THEN {$a_1 = 0$ AND $a_2 = 1$ AND $a_3 = 1$}.

where a_1, a_2, a_3 are the acknowledge signals and w_1, w_2, w_3 are the activation signals. The linguistic variables small, medium and big are fuzzy variables of w_i.

The two IA's can be viewed as parts of a integrated real time decision support system that proposes compensation actions in order to increase energy efficiency of the building, to minimize the conflicts that arise from the simultaneous operation of the controllers and to satisfy the occupants' preferences by obtaining thermal and visual comfort.

The above analysis shows that intelligence of the whole system is embedded not only in the controllers-agents but also and mainly in the procedure of their communication.

C. Organization diagram

The final result of designing a multi – agent control system is a hierarchical organization of intelligent agents which is called organization diagram. In essence, the organization diagram is a model that represents the operation of a multi-agent control system. The organization diagram of the overall control algorithm for the control problem in a building environment is depicted in Fig. 3. The whole control system is obtained by using a master–slave coordination mechanism. The intelligent agent IA_1 is the master one and the intelligent agent IA_2 is the slave one. The controllers-agents CA1, CA2 and CA3 at the bottom of the diagram are also called field controllers or elementary controllers, because they mainly execute algorithms for the control applied directly to the actuators. The organization diagram exposes the interaction between sub-problems which is implemented by the coordination mechanism. In the lower level, coordination is local with dynamic priority of each controller-agent. In effect, this priority is determined by IA_2.

D. Implementation methods for multi-agent control systems

The controllers-agents are activated when some conditions determined by the coordinator are satisfied, otherwise they stay inactive. Such a coordination mechanism can be implemented with a variety of methodologies like fuzzy logic, markov chain models, finite state automata, learning automata, dependencies organization [4], etc. that express the decision logic.

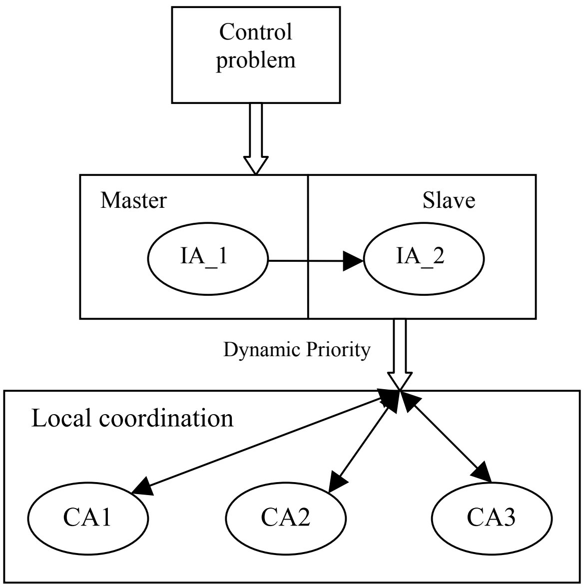

Fig. 3. Organization diagram of the control algorithm in a building environment.

III. CONCLUSIONS

In this work we examined the possibility of the design and implement of a multi-agent control system with that uses intelligent technologies in order to solve the complex problem that arises from the need to obtain energy conservation and comfort conditions in a building. The complex control system can be designed by using a divide and conquer strategy. This approach results in a control system that is composed of a set of controllers–agents that are coordinated by an intelligent coordinator. This coordinator can be realized as a supervisor scheme that contains the decision logic to the controllers–agents. The decision logic may be defined by the use of fuzzy logic or finite-state automata.

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