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Full Length Research Paper

A survey on applying different control methods approach in building automation systems to obtain more energy efficiency

Farinaz Behrooz[1]*, Abdul Rahman Ramli[2] and Khairulmizam Samsudin[2]

[1]Institute of Advanced Technology, Universiti Putra Malaysia, Serdang, Selangor, Malaysia, 43400, Malaysia.
[2]Department of Computer and Communications, Universiti Putra Malaysia, Serdang, Selangor, Malaysia, 43400, Malaysia.

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In this paper, the implementation of different control methodologies for controlling parameters of heating, ventilating and air-conditioning (HVAC) systems as a part of building automation systems were investigated. In the past few years, many researches have been done on application, structure and also efficiency of different methods to achieve saving more energy. Different control strategies were considered in terms of their advantages and disadvantages. In this research, fuzzy cognitive map (FCM) was recommended as a robust and simple method to decrease the energy consumption of HVAC systems. FCM is based on fuzzy logic and neural networks. FCM is a combination of the robust characteristics of these two methods. In this paper, the advantages of using FCMs have been indicated as a controller on the typical HVAC system among the other methods.

Key words: Fuzzy cognitive map, heating ventilating and air-conditioning system, control strategy, fuzzy logic, neural networks, conventional control.

INTRODUCTION

Due to increase in the nonlinearity and complexity of modern technological systems, it is difficult to find the mathematical model of system and analysis, using modelling and controlling of the complex systems. In spite of accuracy of conventional control methods, simplicity of intelligent and autonomous control systems causes the development of the new methods widely and also conventional methods are replaced by new methods. Intelligent and autonomous control systems are more attempts toward reaching more intelligence in buildings.

OVERVIEW OF INTELLIGENT BUILDING (IB)

In recent years due to the energy crises, the recognition of energy sources are limited and there is the tendency to have cleaner environment leading to development in using energy as optimally as possible and forming "building Energy Management Systems" (BEMS) in building sector (Nikolaou et al., 2002). According to Nikolaou et al. (2002), BEMS refers to a computerized system that tries to control energy consumption of every operation in a building. These operations may consist of heating, ventilation, lighting and indoor climate which may be controlled dependently or not based on the level of complication. Nevertheless, reaching to the optimum operation leads to count interrelation between the different parameters.

The development of information technology sharply increases the request for 'comfort living in environment and requirement for increased occupant control of their local environments' motivate the concept of "intelligent building" (Harrison et al., 1998; Kroner, 1997; Wigginton and Harris, 2002; Wong et al., 2005).Recently, the scope of the definition of IB has been extended to add 'learning

*Corresponding author. E-mail: fery_behrooz@yahoo.com. Tel: 006-017-6350970, 00989125272708.

ability' and 'performance adjustment from its occupancy and the environment' (Wigginton and Harris, 2002; Yang and Peng, 2001; Wong et al., 2005).In addition to reaction and change regarding conditions requisites, IB should be able to learn and adjust its performance according to occupancy and the environment(Wong et al., 2005). In other words, the concepts of self-correction or fault tolerance are regarded as necessary parts of "artificial intelligence" and also achieving the intelligence needed tools that resemble human intelligence methods, such as neural networks and fuzzy logic (Nikolaou et al.). According to Wong et al. (2005), the previous researches on intelligent building (IB) have dealt with three aspects of research including advanced and innovative intelligent technologies, performance evaluation methodologies, investment evaluation analysis.

A considerable amount of researches have been done on first category. According to Wong et al. (2005), these researches have focused on the advanced development of system integration, network protocol and building subsystem services, which include HVAC system, lighting system, fire protection system, life system, security system and communication system.

A large amount of IBs contain three levels of system integration as the top level (dealing with the provision of various features of normal and emergency building operation as well as communication management), the middle level (performing by the building automation system(BAS), energy management system(EMS), communication management system(CMS) and office automation (OA)system which control, supervise and coordinate the intelligent building subsystems), the bottom level (it contains subsystems) (Wong et al., 2005).Substantial amount of researches are allocated to the second category.

According to Wong et al. (2005), building performance evaluation is a crucial procedure which offers feedback function on the performance of building materials and components for future improvement and reference. Based on Wong et al. (2005), there has been few researches focus on evaluating economic and financial aspects of intelligent building, which is referred to as the investment feasibility evaluation of intelligent building projects. In other words, the development of intelligent buildings has been tangible and there has been much tendency to improve its limits and complexities. In general the intelligent building technology consists of the integration of four systems as a Building Automation System (BAS), a Telecommunications System (TS), an office Automation System (OAS), a Computer Aided Facility Management System (CAFMS) (Wong and So, 1997).

The main part of each Intelligent Building is a sophisticated BAS (Wong and So, 1997).The expansion of BAS includes information from all aspects of Building Systems, working toward the intelligent Building's goal (Kastner et al., 2005).

BUILDING AUTOMATION SYSTEM (BAS)

In recent years, the quality and complexity of mechanical and electrical systems in buildings have been increased. Integrated systems like building automation system are suitable alternatives to monitor, control and manage the modern structures with complex control functions (Stein and Reynolds, 2000). A BAS is an integration of subsystems like heating, ventilating and air-conditioning system (HVAC), lighting control, automatic fire alarm system and security system (Jiang, 2005). Carlson (1991) reported a BAS is a more effective and efficient control tool to be used for building. Automatic control of indoor parameters is provided by Building automation systems (BAS) (Kastner et al., 2005).According to Kastner et al. (2005), the core and root of BAS is the automation of heating, ventilation and air-conditioning systems in large functional buildings. The primary goals of using BAS are saving energy and decreasing the cost.

A BAS is an integration of several subsystems like heating, ventilating and air-conditioning (HVAC) control, illumination control, fire security system, security and access control, power monitoring and transportation control. The tasks of these subsystems are helping to understand and realize the situation of building performance, measuring building energy consumption, optimizing system running strategy and improving system management (Jiang, 2005). Comprehensive automation systems generally called BAS but still energy management system (EMS), building EMS (BEMS), building management system (BMS) or integrated BMS (IBMS) are habitually used which is referred to specific functional aspects of BAS. According to Merz et al. (2009), building automation is the computerized measurement, control and management of building services. Although, at first glance the building automation and the building control appear the same, by this definition building control is deduced as a part of building automation.After the early 1970s, while the oil price shocked everyone, the need for power-saving arose and highlighted the automation related to energy managing (Kastner et al., 2005).Control of active systems like HVAC was applied significantly for BEMS to save energy and cost (Doukas et al., 2007).

Introduction of HVAC systems

Regarding the above, the HVAC systems are active subsystems in BAS. Due to the great impact of HVACs systems on power and energy consumption, knowing the structure and operation of HVAC systems is becoming important (Tashtoush et al., 2005). According to Tashtoush et al. (2005) energy efficiency and indoor climate conditions are most important goals of designing HVAC systems. These include proper control strategies of the plant. A heating, ventilating and air conditioning system or in other words HVAC system consists of number of subsystems as indoor air loop, chilled water loop, refrigerant loop, condenser water loop, outdoor air loop (Lei et al., 2006; Wang et al., 2006). Due to a large number of dynamical variables in each loop, the HVAC system is a usual nonlinear time-variable multivariate system with disturbances and uncertainties (Lei et al., 2006; Wang et al., 2006).

As a result of complicated quality of an HVAC system, obtaining the mathematical model of HVAC is very difficult (Tashtoush et al., 2005) and also designing the proper controller becomes a big challenge (Lei et al., 2006; Wang et al., 2006). 50% of the total used energy in buildings is consumed by HVAC systems. Due to the much energy consumption by HVAC systems, designing the suitable controller could help save a considerable amount of energy (Huang et al., 2006).

DIFFERENT CONTROL STRATEGIES IN BUILDING AUTOMATION

One of the most important goals of developing control systems especially for buildings is minimizing of energy consumption (Dounis and Caraiscos, 2009). A considerable amount of literature has been published on different control systems in building automation. These studies classified the control techniques into the three categories: conventional methods (Classical methods, Digital methods, and Fuzzy methods), and computational intelligence techniques, agent-based intelligent control systems (Dounis and Caraiscos, 2009). It should be noted that overlapping between categories is unavoidable.

An overview of conventional control systems in buildings

Surveys such as that conducted by Dounis and Caraiscos (2009) have shown that conventional control systems in buildings have been carried out, using the following methods or some combinations of them: Classical controllers, Digital controllers and Fuzzy controllers.

Regarding the increase in the nonlinearity and uncertainty in recent building structures, mathematical description of the system has become more difficult or impossible by Classical control which is involved with mathematical models of the system that govern the relationships among system inputs and outputs. According to Bardossy et al. (1995), the base of automatic control is engineering control theory. Processing of inputs and feedbacks from the previous state is used by control algorithm to optimize the control of the system in the next time step. Due to measurement inaccuracies or incomplete observation of the process state, the control of complex processes is tremendously cumbersome (Bardossy et al., 1995). In other words, classical control and mathematical models are vulnerable to inaccurate and noisy inputs or feedbacks, making them disadvantageous.

According to Astrom and Wittenmark (1996) in digital control, a digital computer is used for real-time control of system. In contrast with classical control systems, digital control utilizes the digital or discrete technology instead of analog components. The major reason why analog technology was simply replaced by digital technology was cost. The numbers of control loops increase the cost of analog system, linearly. Despite the large initial cost of digital system, the cost of additional loop is small. Therefore digital control is suitable for large installation. Informational and technological development era increases the system’s complexity, involving system’s mathematical model and in addition integration of some systems is so difficult and sometimes impossible.

On the other hand, the control strategies like classical control which are used as mathematical model to define the relationship between inputs and outputs of system are very difficult to apply when dealing with mathematical model of non-linear or uncertain information systems. In comparison with other conventional methods fuzzy controllers offer better response and have been successfully applied in case of complex nonlinear and time varying conditions (Kristl et al., 2007).The design of fuzzy controllers is similar to human reasoning (Kristl et al., 2007). The advantage of this controller is linguistic model (Kristl et al., 2007) instead of mathematical models which are described by experts (Eftekhari and Marjanovic, 2003).

Importance of using fuzzy logic technique in BAS

As the complexity of electrical and mechanical systems in buildings increases, dealing with mathematical models of systems and making precise statement about their behaviour in mathematical model gets more difficult and sometimes impossible. On the other hand, the necessary thing in conventional controllers is mathematical model of system to define relationship between inputs and outputs. Therefore, due to difficulty in mathematical modelling of systems with nonlinear and uncertain information, fuzzy logic techniques have become advantageous compared to other conventional approaches.

Fuzzy logic techniques have been successfully used in most implementations due to the flexibility and intuitive use (Kristel et al., 2007). Fuzzy logic techniques are based on the system’s duty and control preferences rather than how the system works and it concentrates on the particular problem (Zhang, 2007). Therefore, for a complex, integrated, non-linear system such as a BAS, fuzzy logic techniques are used with simple mathematics to control the parameters in the building.

Fuzzy logic control versus other conventional controls

A considerable amount of literature has been published on classical control. These studies show that classical control is being applied in a large number of cases successfully. However, classical control is implemented in many cases, but in complicated systems with complicated mathematical model, a real system in real time can be described, barely. In order to solve this kind of problems, other control methods like fuzzy control have been used with simple mathematical model (Dounis and Caraiscos, 2009). Thus, for a complex, integrated, non-linear system, using the fuzzy logic techniques with simple mathematics is more efficient way to control the parameters in building. According to Zilouchian and Jamshidi, 2001, the comparison of control loop behaviour for set point with Direct Digital Controller and Fuzzy Logic Controller in order to optimizing the inner controller of HVAC-system shows fuzzy controller needs less control time versus Direct Digital Controller, for the same task. The big overshoot is a reason of large control time (T_c) in Digital controller. As a result of specific rules of fuzzy controller, process variables are brought to the new set point to avoid processing variable's overshooting. Based on Zilouchian and Jamshidi, 2001, the course of supplying temperature of cooling system with PLC and FLC performing system shows fuzzy control optimizes the system's performance. In order to discontinue operation of PLC system, it is observed such a wide error range of set point. By using fuzzy control, considerable improvement is shown in the system behaviour and reduces the cost of energy production. Zilouchian and Jamshidi (2001) investigated the heating system of the building to provide domestic hot water during summertime with Direct Digital Control system and Fuzzy system. Investigation shows for the same process that Heater by Direct Digital Control had four starts/stops while by fuzzy control had only one start/stop. For one thing heater by fuzzy control has less pollution effects and also it shows the improvement of the system. Releasing of the control mode of the heater by fuzzy controller is time-delay-oriented in which shooting the supply temperature over the set point is avoided and the number of the start/stop phases of the heater is reduced.

Shortcomings of BAS control according to the rule-based methodology

The accuracy of input variables and control outputs is an important criterion in control systems including fuzzy systems as addressed by Qiao et al. (2006). Although fuzzy models can treat uncertain and inaccurate information compared to their mathematical counterparts, accuracy is a major concern in most applications. In fuzzy rule-based methods for example, accuracy is related to the number of fuzzy grades in the membership functions. Although increasing the number of the fuzzy grades can provide higher accuracy, it also makes the number of rules increases exponentially which results into a longer block of rules. The numbers of rules which are necessary to represent a given control strategy with a given accuracy grow exponentially with the increase in accuracy (Yam et al., 1999). This has two major disadvantages: longer runtime which results in lower speed, and lack of real-time response. According to Bardossy et al. (1995), even if the speed does not play a central role in the controller, a reduced number of rules can often be realized at a lower cost. In other words, in rule-based implementation, the designer has to reasonably compromise between the system accuracy and speed, or totally forego either of these two due to actual or computational limits. It must be also noted that due to lower speed or longer runtime, fuzzy rule-based is far from the real-time control. Considering a typical BAS under fuzzy rule-based control, there are other shortcomings to be considered. There are usually four types of behaviours to be coordinated in BAS including safety behaviour, emergency behaviour, economy behaviour, and comfort behaviour. While the first three behaviours are usually predefined that is, by one or more experts, the comfort behaviour is dynamic and has to be learnt by the system with respect to the responses from the occupants in the building. Accordingly, several feedbacks have to be incorporated into the system for considering user's responses for generating appropriate control outputs. However, rule-base methods are not simply capable of receiving feedbacks for implementation of learning strategies (Park et al., 2000). According to Bardossy et al. (1995), in contrast to other fuzzy control techniques, fuzzy rule-based method is a quasi open loop procedure. Inclusion of feedbacks in development of the rules has to be avoided since it can exponentially increase the number of the rules. The main contribution of fuzzy modelling theory is its ability to handle many practical problems that cannot be adequately represented by conventional methods (Eftekhari and Katebi, 2008). However, pure rule-based systems such as the model of Eftekhari and Marjanovic (2003) are not so efficient. Such systems are still subjected to errors due to lack of corrective feedbacks from the environment. An effective idea is to incorporate feedback information through closed loop control techniques such as direct feedbacks or learning strategies (Eftekhari and Katebi, 2008).

Therefore, fuzzy rule-based methods are not advantageous in BAS control due to their difficulties in inclusion of feedbacks which is a must in any BAS implementation. Inclusion of feedbacks or the increase of system accuracy can simply cause an exponential growth in the number of the rules that is, a huge block of rules. The worse consequence of such problems is the reduction of computation speed and lack of real-time response. Although fuzzy rule-based techniques are advantageous over conventional methods, there might be better alternatives when it comes to closed loop control of BAS. The problem of inclusion of user feedbacks in fuzzy BAS control without much negative effect on computation speed has remained as a challenging problem.

Survey on Artificial Neural Networks (ANN)

According to Xu and Shin (2008), the generic method to map or represent input and output relationships or patterns of nonlinear functions or data through a single or multiple layers of an interconnected group of artificial neurons is called artificial neural networks or simply neural networks. On the other hand, the algorithms and architectures of artificial neural networks are based on neurobiological system (Daponte and Grimaldi, 1998). According to Lek and Guegan (1999), the ANN is like a black box with a great capacity in predicting models and all of the characters are described in an unknown situation and capable to train the ANN. ANN is an attractive choice to control the nonlinear systems due to robustness and its ability to map arbitrary nonlinear functions (Wu and Li, 2008). The structure of simple neural network consists of three types of neurons: the input, hidden and output neurons. In other words, neurons are very simple processors similar to the biological neurons in brain which are connected by weighted links to other neurons to pass signals. Also, the output signals are transmitted from the outgoing connection of neurons and the output signals split into the number of branches that transmit the same signal to the next layer's neurons as an input of the neurons. Each neuron computes the weighted sum of the inputs signals and compares the result with threshold value.

Importance of using Artificial Neural Network technique in BAS

Referring to Ghiassi and Saidane (2005), artificial neural networks are able to deal with both linear and nonlinear functional relationships. Nevertheless, neural networks are more implemented in nonlinear systems. Neural Networks advantages are: as many tasks could be performed by neural networks which could not by linear programs, the process can be continued when failure occurs without any problem due to the parallel nature, have ability to be implemented in many areas and applications, without any problem.

Shortcomings of BAS control according to the neural networks methodology

Although, they are more profitable advantages of neural networks, there are some disadvantages which cause decrease of the efficiency of this method. For example operating neural network requires training, due to the fact that different architecture of neural network from microprocessors needs to be emulated, and it takes long time to process large neural network. Due to the neural networks problems the need for efficient methodology to decrease the shortcomings of this method is reasonable.

Introduction of Fuzzy Cognitive Map (FCM)

Due to the development of technologies and also facing with complexity and nonlinearity behaviour of the systems, the need for new methods to analyse the behaviour of complex dynamical systems is arisen (Papageorgiou et al., 2004). Fuzzy Cognitive Maps have been implemented in many areas such as economy, sociology or virtual reality simulation as an alternative to expert systems (Huerga, 2002) or knowledge-based expert systems to analyse the complex systems (Khor and Khan, 2003).According to Khor and Khan (2003), Fuzzy Cognitive Map (FCM) first time was introduced by Kosko to model the causal relationship among concepts. In fact, Kosko extended the cognitive maps method, which was first introduced by Axelord, the political scientist to describe the methods to decision making in social and political science, by considering the fuzzy values instead of real values of concepts (Stylios and Groumpos, 2000; Kim et al., 2008; Bertolini, 2007). Kosko (1985) introduced the FCMs as fuzzy-graph structures which nodes are defined as concepts to represent causal reasoning according to the given scenario (Khor and Khan, 2003). In other words, condition or a characteristic of the system is represented by each concept (Aguilar, 2005). In general, FCMs are based on events, actions, goals, values and tendencies of the system (Stylios and Groumpos, 2000). As a matter of fact, FCMs method is combination of fuzzy systems and neural networks methods which contain the robust properties of both methods (Aguilar, 2005; Stylios and Groumpos, 2000).

Construction of Fuzzy Cognitive Map

The structure of fuzzy cognitive maps (FCMs) consists of nodes or concepts and also arcs between concepts to show the effect of concepts to each other. In other words, cause and effects of concepts have been shown by FCMs graph to define the system (Aguilar, 2005). According to definition of Fuzzy cognitive map, fuzzy values have been replaced instead of real values to concepts (Papageorgiou et al., 2004). The values of A_i represent the transformation of real values of concepts in the interval [0, 1]. The activation degree of each concept in the system at particular time is reflected by value of node. According to Aguilar (2005) the causal influences between the concepts are shown by graph's edges or arcs which are displayed by W_{ij} and also described by linguistic variables. It means that each weight between concepts takes value in range from -1 to 1 (Papageorgiou et al., 2004). According to Kosko (1986) and Aguilar (2005), the simple FCMs contain the trivalent values {-1, 0, +1} on weights, which -1 shows the negative effect, and 0 no relationship and +1 a positive causality. According to the above, in general the interactions between concepts are divided to three possible types. $W_{ij}>0$ indicates increase or decrease of A_i value which causes the same effect on A_j value; $W_{ij} = 0$ indicates no relationship between A_i and A_j; $W_{ij}<0$ indicates increase or decrease of A_i value which causes the reverse effect on A_j value (Stylios and Groumpos, 2000; Papageorgiou et al., 2004; Aguilar, 2005).

Mathematical model of Fuzzy Cognitive Map

Besides the graphical structure, FCM follows its mathematical model which consists of a 1×n state vector A which contains the values of the n concepts and also an n×n weight matrix which includes the weights W_{ij} of the causality between concepts. The number of concepts is indicated by n. The value of each concept depends on linked concepts with proper weights and also the previous value of concept. After transferring the fuzzy values to concepts, the $A_i^{new}=f\ (\Sigma A_j^{old}\times W_{ij})\ +A_i^{old}$ rule is used to calculate the activation level of A_i for each concept where A_i^{new} indicates the activation value of concept *i* at time t+1, A_j^{old} shows the activation value of concept *j* at time t and also *f* is a threshold function. There are two types of threshold functions which are applied in FCMs structure. The first one which is the unipolar sigmoid function to squash the content to the interval [0, 1] is $f(x) = 1/(1+e^{-\lambda x})$ and second one which has been utilized to transform the content in the interval [-1, 1] is $f(x) = \tanh(x)$ (Stylios et al., 2004).

CONCLUSIONS

In this paper, a review of control systems for energy management and comfort in buildings is presented. At the beginning of this paper, intelligent building is defined as achieving more comfort as well as energy management. To obtain intelligent buildings goals, using control strategies is unavoidable. Next, the different control systems and their advantages and disadvantages over control parameters of the buildings are inspected. According to investigation of control systems, the intelligent control systems are more developed for improving the energy efficiency in buildings. Finally, applying the combination of control techniques of fuzzy logic and neural networks is recommended to control buildings. The hybrid method of fuzzy logic and neural networks contain the robust characteristics of both methods. In addition, the shortcomings of both methods are omitted in this method. The robustness of FCMs is an important reason for choosing this method. Regarding the definition, characteristics and simplicity of mathematical model of FCMs, implementing the FCMs as a direct control is recommended in controlling the parameters in building automation systems to achieve more intelligence in building as well as more energy saving. As a result of the structure of FCMs, the run time of control process is declined. Due to the ability of FCMs in having learning strategy, the consumption of energy could be decreased. Due to the fact that, the energy sources are limited and energy crisis, saving more energy is an important goal for using building automation systems. Therefore, The FCMs as a direct control system are proposed in order to get to the objectives of decreasing run time of control process and saving energy.

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