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Design and Implementation of an Intelligent Fuzzy Logic Controller (FLC) for Air Handling Unit (AHU) for Smart House

[1]Momoh-Jimoh E. Salami, [1]M.M Rashid and [2]Noor Mohammad

[1]Department of Mechatronics Engineering, Faculty of Engineering, International Islamic University Malaysia, Gombak 53100, Kuala Lumpur, Malaysia
[2]Department of Biotechnology Engineering, Faculty of Engineering, International Islamic University Malaysia, Gombak 53100, Kuala Lumpur, Malaysia

Abstract: Intelligent Building Automation System (IBAS) is one of the heaviest researched areas motivated by the continuous high demand on economically-effective systems that are designed to provide a desirable controlled space for various organizations. IBAS has been developed along with the rapid sophistication of the information and control technologies in this study. The main objective of the continuous effort is to provide an intelligent monitor and control of various facilities within the building so as to offer its users or occupants with effective security, improved productivity, human comfort, and efficient energy management. Heat, Ventilation and Air Conditioning (HVAC), Lighting Systems, Life and Safety System, and Access Control are some of the typical systems that formed IBAS in most modern building. HVAC and Lighting systems constitute the major energy consumer in an entire building that focuses particularly on the improvement of monitor and control of these systems.

Key words:

INTRODUCTION

Buildings are designed and constructed for various purposes. The structures and services they offer vary and as time goes they become more complex which results in costly operation and maintenance. System management and maintenance problems can be attributed to the poor monitoring and control strategy for the systems serving the building purposes. This problem opens the door to develop an effective control strategy for an entire building and this system is called building automation system (BAS). The problems in the building services keep growing along with the increasing complexity of occupants' activities and thus BAS has been further improved to what is now called intelligent building automation system (IBAS). Since early 70s, many researchers have been conducted in the area of building automation system (BAS) in an attempt to find more effective solutions to cater for the high demand of energy conservation while maintaining efficient building operation and services. At the early stages of the research work on this field there were traces of rapid improvement driven by the tremendous growth of microcomputer and later the personal computer (PC). As a result control strategies have evolved from pneumatic to conventional digitally-driven controller. The development of direct digital controller (DDC) revolutionizes the way modern building is controlled. Its increasing capability and capacity to embed real-time controller has opened wide range of control strategies. The expansive readiness of open standard communication protocol has even placed the building control system to higher level of automation. This situation permits the implementation of more sophisticated building control system (Heinemann 2000). Subsequently, efforts have been made further until the realization of embedding 'intelligence' into building automation system can be achieved. Consequently, many researchers have been taking part in an innovative design of IBAS that can provide solution to some of the above mentioned problems. Although significant contribution in the field of IBAS can be traced back to the past years, there are still many potential improvements that can be made. HVAC and Lighting systems controller is an outstanding example as these systems are highly nonlinear in nature. Because these systems dominate mostly the services a modern building is built for, their controllers must be well designed so they can deliver the desirable performances. For this reason, this report tries to investigate and evaluate the use of fuzzy logic controller for HVAC and Lighting Systems.

Corresponding Author: Momoh-Jimoh E. Salami, Department of Mechatronics Engineering, Faculty of Engineering, International Islamic University Malaysia, Gombak 53100, Kuala Lumpur, Malaysia.

The main problem addressed by this research work is the improvement of HVAC and Lighting Systems performance in order to provide a comfortable environment while reducing the systems energy consumptions. It is known that the above-mentioned systems consume roughly 50 percent of the world energy consumption as related by Imbabi (1990). Alternatives solution to this problem have been made in the past years but, despite the advancement of microprocessor, and later PC technologies, HVAC and Lighting system operation in commercial and industrial building is still an inefficient and high energy consumption process. Classical control technique used for these systems such as ON/OFF controller and the conventional Proportional-Integral-Derivative (PID) controllers are still very popular because of their low cost. However, in the long run, these controllers are expensive because they operate at very low energy efficiency levels. To realize the usefulness of the conventional strategy, there has been a growing interest in the formulation of thermal comfort models that can be used to control HVAC systems (Fanger 1972, Gagge 1986, and Sherman 1985). To compute the indoor thermal comfort level, the environmental variables must be measured at a location close to the occupant and the activity level and the clothing insulation must be known which in most application not possible. Attempts have been made (Sherman 1985) to overcome the underlying problem on the iterative process by calculating sensation index to simplify the model. However, many researchers have found that the modified model can only be valid in laboratory condition. Fanger and ISO proposed in (Fanger 1972) to use tables and diagrams to simplify the calculation of the thermal comfort sensation in practical application. This method has to be done by manual selection of the environmental variable setpoints that will provide optimal indoor thermal comfort. But this is difficult to use from the practical point of view as it requires detailed knowledge of the HVAC control techniques. Furthermore, good performance of the conventional controller is achieved only if the parameters of this control match with the operating condition of the system (Dexter 1985, So 1996 and 1997). So (1996) reported that when a well-tuned PID is applied to other system with other operating parameter, the system performance becomes poor and energy consumption increases dramatically. In practice, the parameters of HVAC system are always changing due to many factors such as weather, occupants' activities and lighting being some of the typical example. In other words, the air condition system is a complex nonlinear system with multi-factors, long delay, strong inertia, dynamic, random and heavy disturbance. Due to these reasons, the accurate mathematics model is hard to make out, so the performance of common control theory can hardly be satisfying. Even if a control model could be made, control parameter tuning is another big challenge. A number of controllers used in industries today runs with factory settings, which normally gives poor performance. One of the reasons for this is that the commissioning time is often very time consuming. Jason (1998) proposed a solution using single-zone thermal model provided by House (1991) as a case study. Jason proposed the used of neural network to identify a process model by inverse system identification approach. The design was to control HVAC by regulating the mixture of heat and cold air in the controlled environment. This is achieved by regulating the heat input in the heat exchanger, the volumetric air flow, and the position of the return air damper. However, the main problem here is that there are few parameters which are neglected including the thermal losses between components and humidity of the air. In practical situation, thermal losses or gain between components always occurs due to the variation of pressure-temperature relationship within the components. Humidity is very crucial to take into consideration since it determines the quality of the environment and the balancing of the thermal load. Another technique to minimize HVAC energy consumption was proposed by Chow (2001). The design was focused on the control of cooling system (chiller) using neural network. Chiller is an integral part of HVAC that needs to be interfaced with the other components in order to optimize the overall performance of the system. In other words, an ideal control for a chiller alone cannot practically provide an optimal control option for HVAC system. One of the very significant processes in HVAC is the mixture of the fresh air with the returned air (recycle air). This process determines the quality of the air mass being conditioned and since the performance of chiller controller depends on the condition of the air entering heat-exchanger, which is an integral part of the chiller, the enthalpy of the air must be as low as possible to minimize the HVAC energy consumption. This particular problem of HVAC is addressed in this report.

Significance of the Problem:

This report proposes a new method which is the control of air handling unit (AHU) using fuzzy logic controller (FLC). The main advantage of the proposed technique is that instead of controlling the cooling and heating supply to the controlled space, it controls the airflow by properly modulating AHU MDs and fans. In this approach, the system performance can be optimized by allowing a proper mixture of the fresh air and the conditioned air without necessary adding excessive cold air in order to maintain temperature in the controlled space. The developed controller is incorporated with tuning mechanism so as to improve its performance in response to the dynamic process. Integration of lighting system with conventional HVAC system improves HVAC system performance by the reduction of unnecessary source of load (light).

Design Implementation and Procedure:

A) Ahu Control Design:

The main objective in the AHU design is to ensure that the enthalpy of the mixed air before it enters the heat-exchanger is as low as possible for cooling process and as high as possible for heating process. Enthalpy is the property of the air whose quality is dependent on air properties such as temperature and relative humidity. In other words, enthalpy is a function of temperature and humidity levels. Air is a mixture of various gases and water vapor. When it is to reduce the temperature of air (cooling), its energy content per unit mass (enthalpy) is reduced. In the process, temperature and humidity level must be taken into account. To achieve the desirable cooling process, which ideally must be quick as much as possible, the temperature and humidity level of both the fresh and recycled air have to be measured before these two airstreams are mixed and then enters the heat-exchanger. Figure 1 shows the AHU diagram having the dampers marked by D1, D2, D3 and heat-exchanger marked by HWR (heat water retur) and HWS (heat water supply) for heating process and CHWR (chilled water return) and CHWS (chilled water supply) for cooling process. In the AHU process, fresh air enters and modulated by D1 and recycled air enters and modulated by D2. D3 is used as balancing damper to modulate the amount of recycled that is allowed to exit from the AHU for in some cases it is required to mix more recycled air with fresh air. If the fresh air contains large amount of vapor as compare to gas (high humid) it requires more energy to cool it down since gas molecules give up their energy faster than the vapor molecules. For this situation, if the recycled air is less humid as compare to fresh air, then the mixed air should content more recycled air than the fresh air as long as the relative humidity in the controlled space is within the acceptable range. This is the case that is not given an account in the previous works and therefore addressed in this research work. To achieve that purpose, fuzzy logic controller has been designed and developed. This controller is composed of two components namely the pseudo slave fuzzy logic control (pSFLC) and fuzzy control tuning mechanism (FCTM). The pSFLC is identical to direct FLC, however its membership function is tuned online by FCTM. The pSFLC is a two-input and single-output controller. The two inputs are the deviation from setpoint error, e(t), and error rate Δe(t). FCTM has the same inputs as pSFLC and has single-output whose value alters the universal discourse of the pSFLC output membership function online. The operational structure of the control loops is shown in Figure 2. The initial rules and input/output membership functions of these control loops are heuristically created and is established based on observation made in capturing the behavior of the system. Since this approach can be used only for approximate process identification, manual iterative tuning is required to improve the system performance based on rise time, overshoot and steady state. The center and slopes of the input membership functions in each region is adjusted so that the corresponding rule provides an appropriate control action. There is need to modify the output membership function as well to adjust the rules governing the output universe of discourse. After the tuning is done, the initial pSFLC parameters, namely the input and output membership functions, and the rules are established. Expectedly, well-tuned controller degrades due to nonlinear process therefore the controller must be kept tuned at all the time to maintain its good performance. This can be achieved by incorporating the FCTM. Passino and Yurkovich (1998) indicated the idea that a fuzzy controller can be tuned by re-scaling its output membership function. This method is implemented by introducing gain g0 between the fuzzy controller and the controlled devices (dampers and fans) shown in Figure 2. The value of this gain is equal to 1 for the original choice of the membership function and therefore when the value of this gain changes is not equal to 1 the value of control signal instantaneously changes. With the presence of various sources of thermal load in the conditioned space as well as in the AHU itself, the controller should provide appropriate command signal to the damper motors and the fans to achieve a desirable system response. This research investigates the feasibility of online tuning of fuzzy controller via scaling-factor method and is applied in AHU process. The main objective with this control architecture is to minimize the enthalpy of the mixed airstream so that the heat exchanger (cooling/heating) system consumes less energy while at the same time the desired temperature at the controlled environment is maintained. This approach is achievable by properly modulating the mixing dampers position so the mixture of outside and return airstreams can be optimized by having the bare minimum of the mixed air enthalpy. This rationale is simply motivated by the fact that the cooling rate for air is not only dependent on dry bulb temperature but also the water vapor content of the air. If the vapor content is less, the higher the cooling rate. The AHU operation shown in Figure 3 begins with the measurement of seven variables namely supply air relative humidity (RH_s), return air relative humidity (RH_r), outside air temperature (T_o), supply air temperature (T_s), mixed air temperature (T_{ma}), zone temperature

(T_z) and zone tempature setpoint (T_{zref}). The measured T_o is compared with the outside air high limit temperature (T_{OHL}) and if T_{OHL} exceeds T_o cooling process begins with the T_z being compared with T_{zref}. If T_z exceeds T_{zref} then it proceeds to the sequence shown in Figure 4, otherwise the sequence Figure 5 is followed. At this stage, the measured mixed air temperature T_{ma} is compared with T_{maref} which is calculated using the formula below:

$$T_{maref} = h_{ma}/c_p \tag{1}$$

$$h_{ma} = \frac{\dot{m}_o h_o + \dot{m}_r h_r}{\dot{m}_o + \dot{m}_r} \tag{2}$$

Where h is enthalpy of the airstream and $\dot{m}$ is mass flow rate which is assumed to be proportional to the opening of the damper. The subscript o, r, and ma denotes outside air, return air and mixed air respectively. The values of the independent h(s) are calculated by:

$$W = 0.62xp/(P_{atm} - p) \tag{4}$$

$$p = RH(\%)xp_s/100 \tag{5}$$

$$p_s = 610.78x\exp(T/(T+238.3)x17.2694) \tag{6}$$

$$h = (1.007xT - 0.026) + Wx(2501 + 1.84T) \tag{7}$$

Where T – temperature
W – humidity ratio
p – atmospheric pressure
p_s – saturation pressure of water vapor

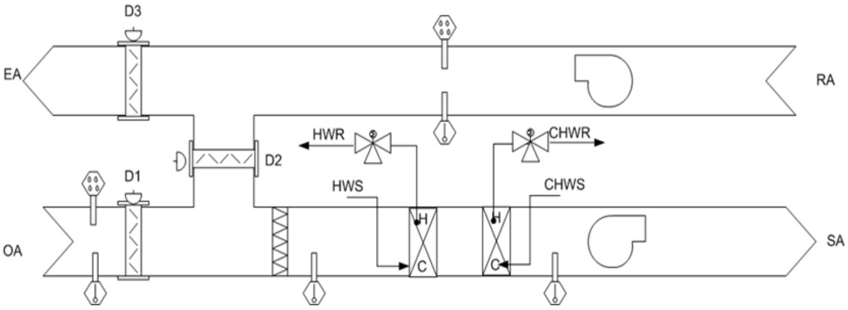

Fig. 1: Diagram of the AHU

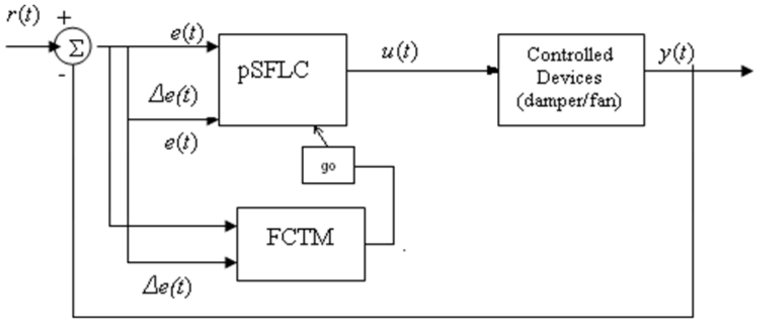

Fig. 2: Structure of Fuzzy Logic Controller

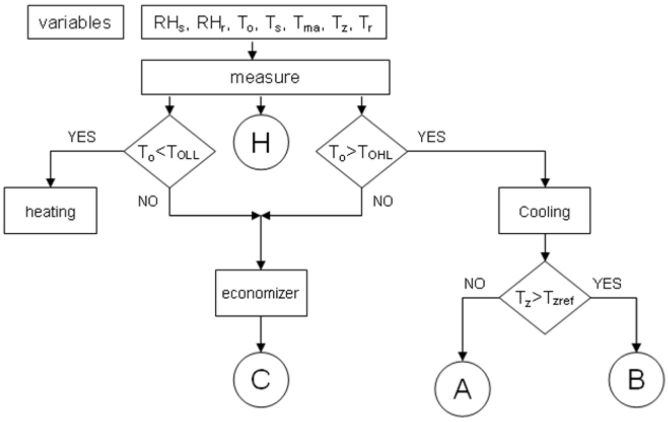

Fig. 3: Typical AHU sequence of operation

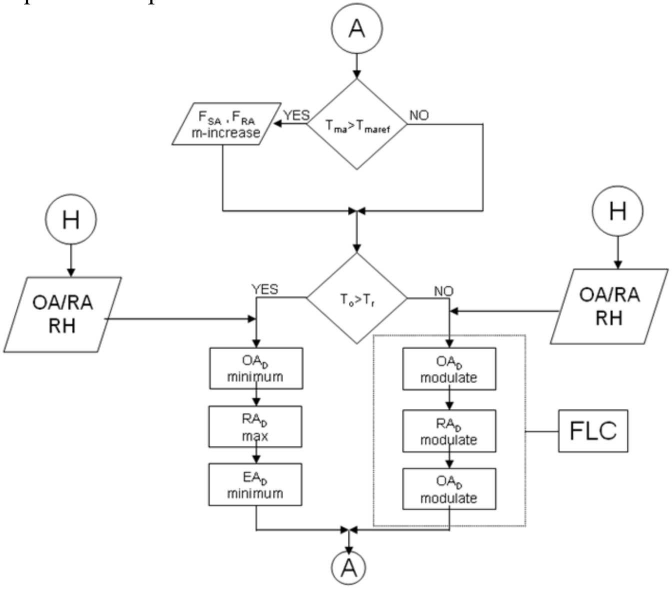

Fig. 4: AHU control sequence when T_z exceeds T_{zref}

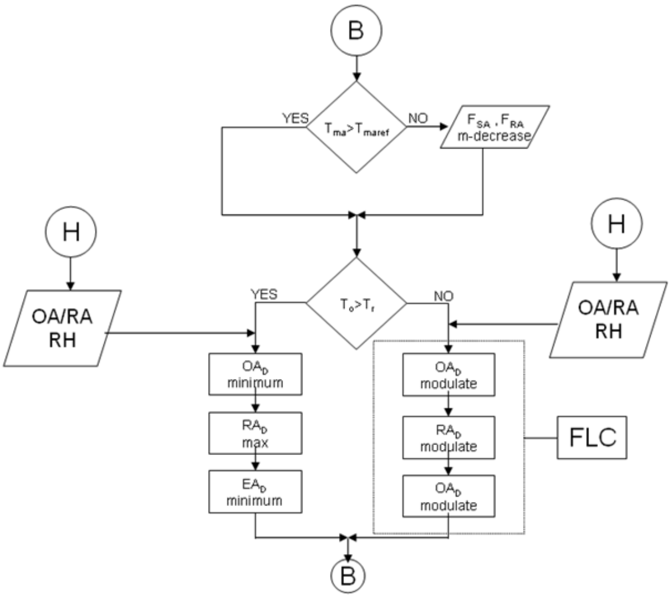

Fig. 5: AHU control sequence when T_z below T_{zref}

b) FLC Implementation for Lighting System:

Lighting could be implemented either natural or artificial or a combination of the two methods depending on space requirements. There are areas where natural lighting seems to be useful during the daytime; however in this situation one may still requires artificial lighting when bad weather occurs. On the other hand there are areas where only artificial lighting can be applied. But whatever may the case it may be necessary to control lighting system as it exhibits nonlinearity if we are concerned about the conservation of energy. There are cases where unnecessary excessive lighting takes place due to poor control strategy or maybe people would just think of ON/OFF control to be satisfactory. This problem can be noticed in many different places, for instance in large buildings large numbers of light bulbs generate huge amount of wasted energy. These bulbs are usually powered up by fixed amount of current though there are times it could be lowered to meet the sufficient lighting requirements. Unfortunately most of the existing lighting controllers do not seem to have been designed for time-varying lighting requirements. This research work proposed lighting controller with two components namely Boolean logic control (LC) and fuzzy logic controller (LFLC) as shown in Figure 6. The LC component uses infra red technology for occupant detection and switches the light on/off upon detection. LFLC uses light detector and measures lighting level (or light intensity) and compares it with the desired light level. The deviation of the measured value from the desired value, eLI (t), prescribes whether to increase or decrease the amount of current that gives energy to the light bulb. Therefore the proposed LFLC has two inputs namely the error eLI (t) and the rate of change of this error, ΔeLI (t), and single output uc(t) as an actuating signal.

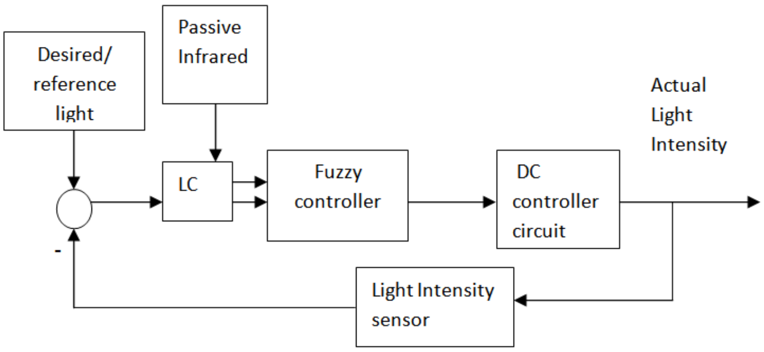

Fig. 6: Overall structure of the proposed lighting system controller

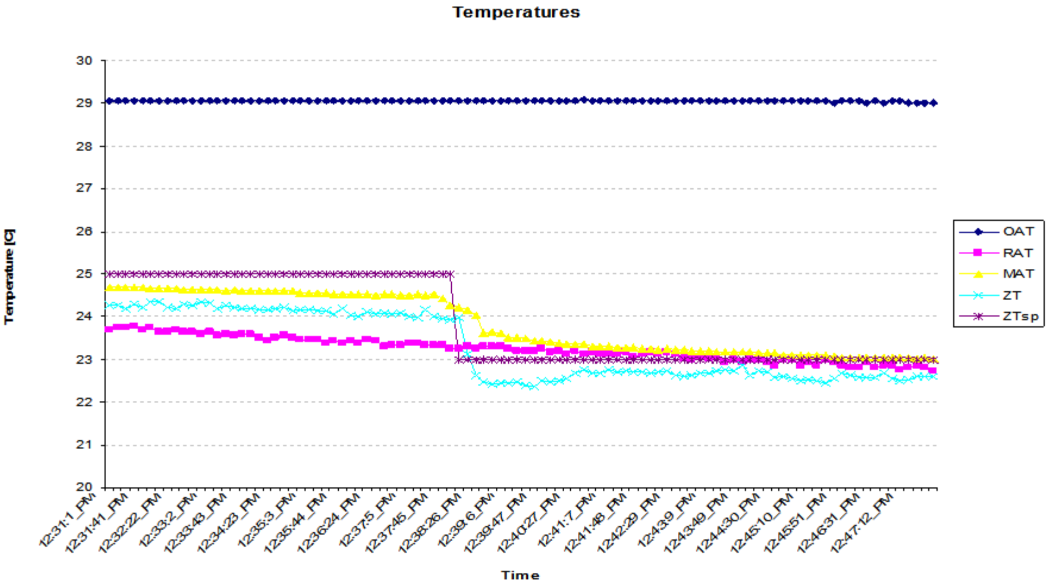

Fig. 7: Temperature profile case 1

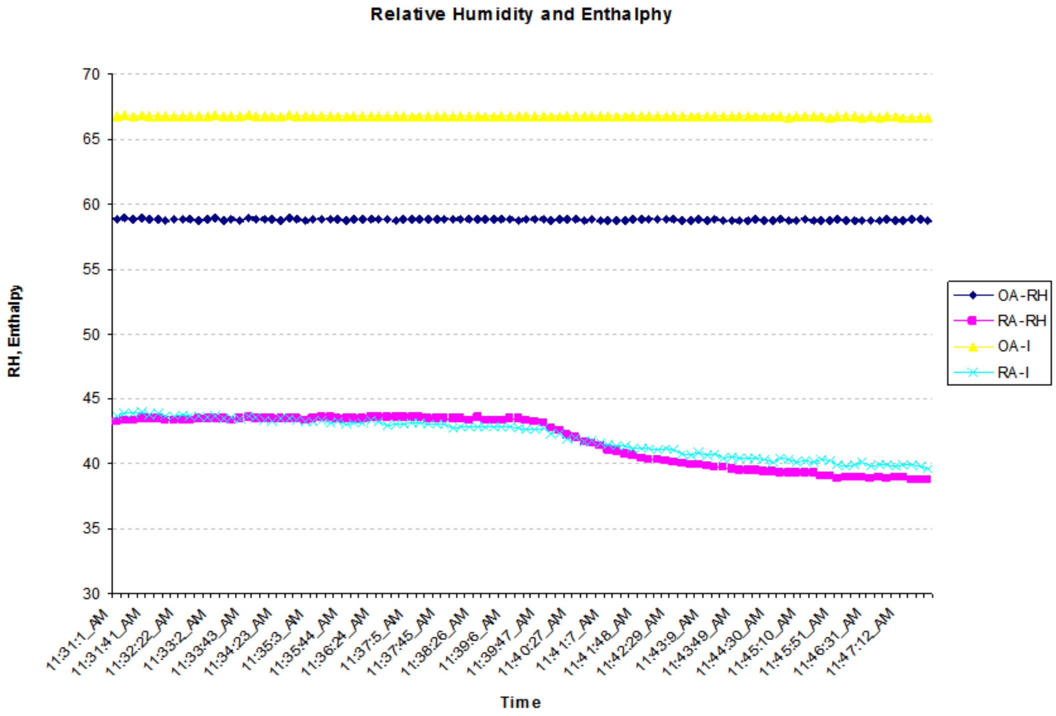

Fig. 8: RH and Enthalpy profile case 1

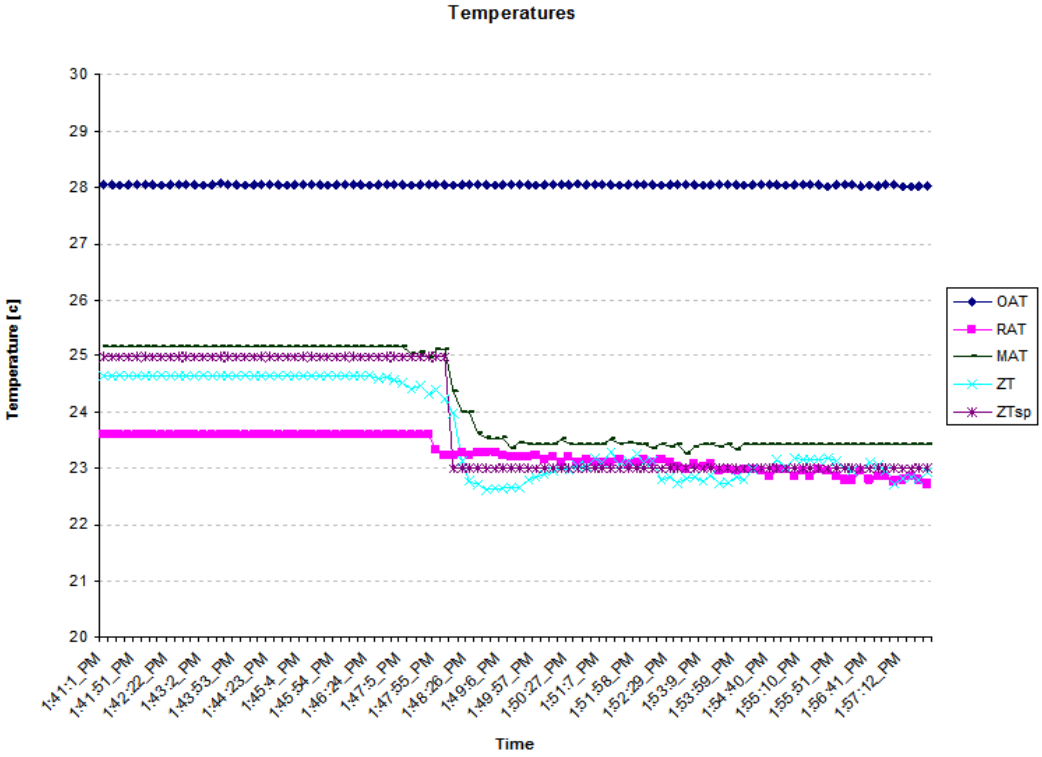

Fig. 9: Temperature profile case 3

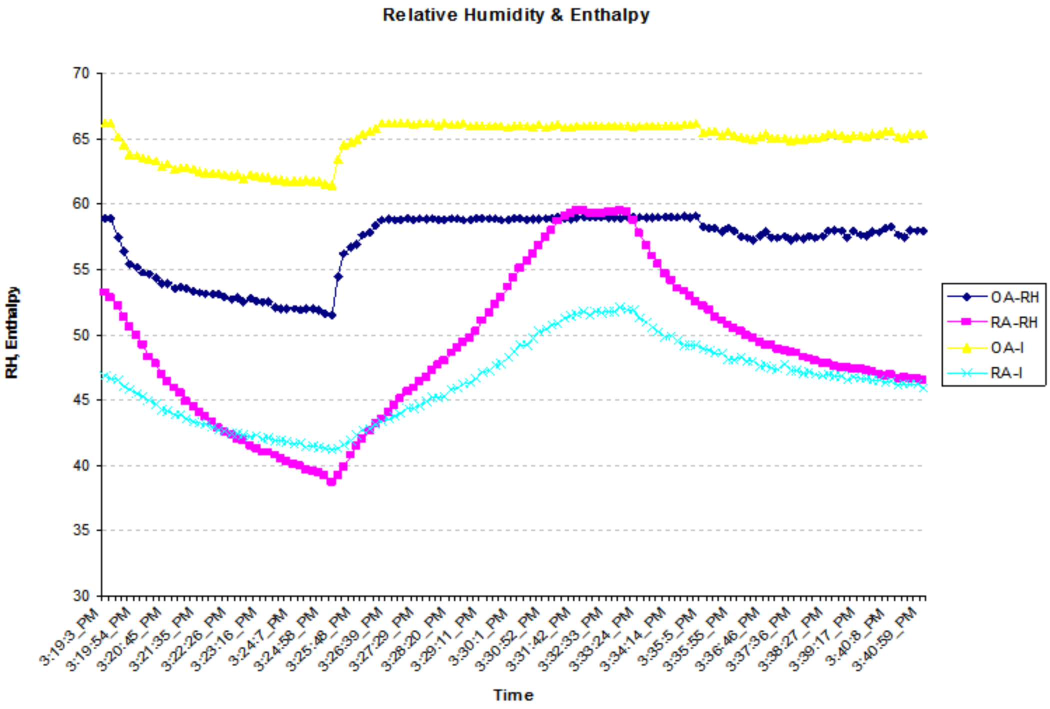

Fig. 10: RH and Enthalpy profile case 3

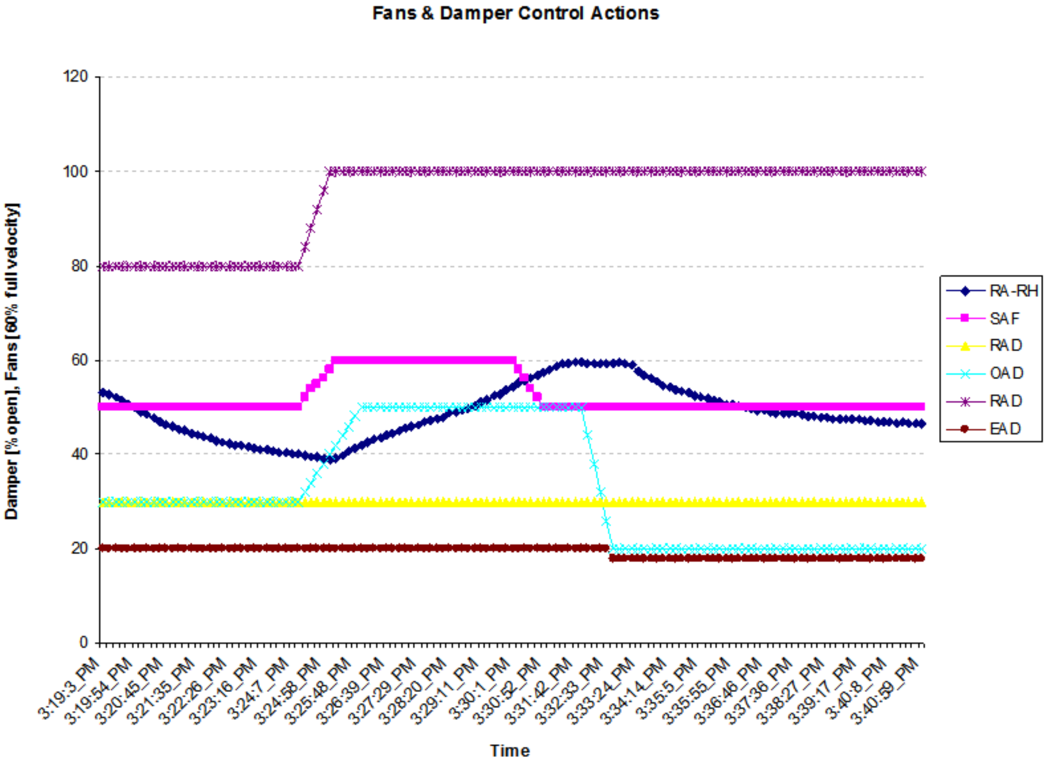

Fig. 11: Control Actions profile case 3

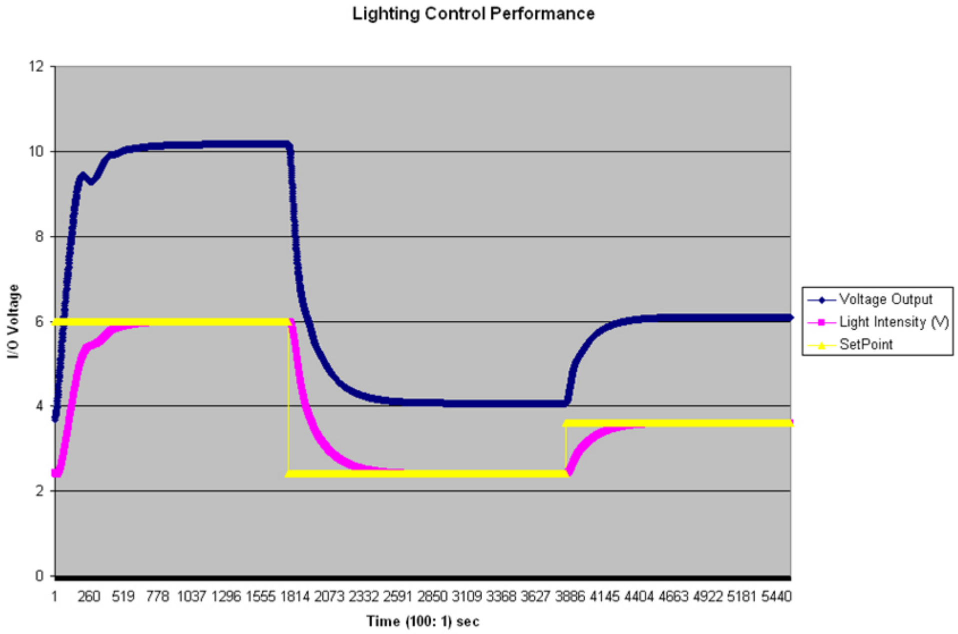

Fig. 12: Performance of LFLC

RESULTS AND DISCUSSION

a) AHU Performance:

The results obtained from the experiments are found to be convincing that when temperature and relative humidity of air are taken account for controller parameters the performance of the HVAC system is improved. This is achieved with the implementation of self-tuning fuzzy logic controller. Evaluation of AHU performance begins from Figure 7 through 12. Firstly, the controller without online tuning was tested and temperature profile is shown in Figure 7. A step was input to the system in which the zone temperature was altered from 25°C to 23°C. The same procedure was repeated with the controller auto-tuned. By inspection, Figure 7 and 9 show significant difference. Although without online tuning the performance seems to be better in terms of steady state error as shown Figure 7, the controller with online tuning exhibits a better performance in terms of transient response and overshot because the steady state error falls within the accepted range (±0.5°C). In terms of energy consumption, both the performance profiles have to be observed. In actual application, the results shown here may not seem to be sufficient enough because HVAC uses pumps (for chiller and boiler) and fans which are the main component installation that consume more energy. However, our main contribution in enhancing HVAC controller lies in the manipulation of air properties entering heat transfer coil which is achievable by minimizing the enthalpy of this airstream. This process depends on the control interaction between fans and mixing dampers. Figure 8 shows only the state of RA and OA enthalpy whilst MA enthalpy is directly proportional to the OA and RA enthalpy. The enthalpy shown in Figure 8 was the effect of the dampers modulating control action i.e., (i) OAD was modulated from 30-20%, (ii) EAD was modulated from 25-18%, and (iii) RAD was modulated from 80-100% whereas fans remain at their initial speed. This result indicates that MA enthalpy can be reduced by modulating the mixing dampers alone. In this experimental setup, the rate of heat transfer is assumed to be dependent only on the MA enthalpy because there is no such a coil installed in the ductwork that MA would pass through, instead cooled air mixes with MA with constant flowrate and temperature. In this case, the state of the MA directly affects that of the zone temperature. However, if AHU downstream process is involved the reduced MA enthalpy will cause an increase in the rate of the heat transfer from the coil, and hence HVAC control performance is improved. ASHRAE has indicated that the acceptable level of relative humidity (RH) in an occupied space should be within 40-60%. Therefore, HVAC controller must act to combat the fluctuating RH due to internal and external disturbances. There are times when both fans and mixing dampers require control command. For example in Figure 10, at a given time RA-RH (which also in the zone RH) falls below the lower limit and to bring back the RH within the accepted range would not be achieved by modulating the dampers alone. Figure 11 provides the control action profile for the RH and enthalpy condition shown in Figure 9. The controller must keep OA and RA enthalpy at minimum level no matter how much the RHs fluctuate and at the same time, the zone temperature is within the accepted level as well. With the RHs and enthalpy being manipulated as shown in Figure 10, dampers and fans are altered accordingly as shown in Figure 11 and the zone temperature has not been sacrificed. From these figures one could say that the proposed control architecture for HVAC is therefore very useful in actual application.

b) Lighting System Performance:

Figure 12 shows the response of the lighting fuzzy logic controller. There are three lines representing the light intensity setpoint, the light brightness measured values, and the control output signal. When the lighting reference (setpoint) changes, the controller changes the voltage supply to the lighting source (light bulb) until the measured value approaches the setpoint. It can be seen that the transient response is high with zero steady state error and overshoot. This diagram demonstrates that fuzzy logic controller is effective and practical for lighting systems.

Conclusion:

The results shown in this experimental evaluation of the proposed systems have showed that this intelligent moinitoring system is able to provide effective security, improved productivity and human comfort with an efficient energy management. The performance of HVAC can be practically improved when enthalpy, instead of temperature alone, is considered specifically for airstream entering heat transfer coil. The main reason is that the rate of heat transfer depends on the energy content (enthalpy) of air and because air is composed or gas and water vapor, its enthalpy can be affected by several factors namely the concentration of moist, the pressure and temperature. The results have also demonstrated that proper regulation of an AHU dampers and fans plays very important role in achieving desired indoor environment with minimal usage of energy. This control scheme can be achieved using fuzzy logic system. Fuzzy logic system is also the best option for lighting system control. Overall, fuzzy logic controller has been successfully implemented for nonlinear systems such as HVAC and Lighting Systems.

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