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Control Techniques in Heating, Ventilating and Air Conditioning (HVAC) Systems

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Abstract: Problem statement: Heating, Ventilating and Air Conditioning (HVAC) systems are among the main installations in residential, commercial and industrial buildings. The purpose of the HVAC systems is normally to provide a comfortable environment in terms of temperature, humidity and other environmental parameters for the occupants as well as to save energy. Achieving these objectives requires a suitable control system design. **Approach:** In this overview, thermal comfort level and ISO comfort field is introduced, followed by a review and comparison of the main existing control techniques used in HVAC systems to date. **Results:** The present overview shows that intelligent controllers which are based on the human sensation of thermal comfort have a better performance in providing thermal comfort as well as energy saving than the traditional controllers and those based on a model of the HVAC system. **Conclusion:** Such an overview provides an insight into current control methods in HVAC systems and can help scholars and HVAC learners to have the comprehensive information about a variety of control techniques in the field of HVAC and therefore to better design a proper controller for their work.

Key words: HVAC, thermal comfort, fuzzy control, neural network

INTRODUCTION

The primary goals of control strategies for the Heating, ventilating and Air Conditioning (HVAC) systems are to maintain occupants' thermal comfort and energy efficiency[1]. Thermal comfort is a vague and subjective concept and varies from one person to another. Research done by American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHARE) during last years identified the most important parameters that influence thermal comfort as Temperature, Relative Humidity, Air Velocity and Radiant Temperature. However, activity level and clothing insulation of occupants are effective in thermal comfort, but they are variable and usually not measurable.

On one hand, HVAC systems are used for comfort purposes, hence categorized in Comfort System, On the other hand, it's been well established that the consumption of energy by the HVAC equipment in commercial and industrial buildings constitutes 50% of the world energy consumption[2-5]. Therefore, HVAC systems are also classified in Energy Management Systems (EMS).

The HVAC system is a typical nonlinear time-variable multivariate system with disturbances and uncertainties[6], so it is very difficult to find a mathematical model to accurately describe the process over a wide operating range.

MATERIALS AND METHODS

The design of controller for HVAC systems is a big challenge for practical engineers[6]. Many control methods have been proposed in HVAC systems from traditional controllers to advanced and recently intelligent controllers during the last years[1-3,5-8]. The present research constitutes a thorough review of the variety of the control methodologies as used in the area of HVAC systems. Such a review will help pave the way for an HVAC engineer to better design the system.

Thermal comfort model: This model was represented by Fanger and includes two sets of parameters: environmental and personal[9]. Environmental parameters are air temperature, radiant temperature, air velocity and relative humidity, whereas personal parameters are activity level and clothing insulation. First, these six factors must be measured or estimated

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and then the Predicted Mean Vote (PMV) index will be calculated. PMV was proposed by Fanger in 1970, used to predict the mean thermal sensation vote on a standard scale for a large group of people[8]. This index is a real number and comfort conditions are achieved if the PMV belongs to the [-0.5 0.5] range[9]. Figure 1 shows the Fanger model structure[10].

However, since the human sensation of thermal comfort is a subjective evaluation that changes according to personal preferences, the development of an HVAC control system on the basis of the PMV model had proven to be impossible[11-13]. In practice, in the majority of HVAC control systems instead of comfort level control through PMV index, two main climatic parameters temperature and relative humidity are controlled through Comfort Field in the ISO h,x diagram as the set point[9]. A temperature set point of 22°C and a relative humidity set point of 45% with a deviation of ±2°C and ±15% RH are common for rooms and workplaces[14]. The ISO h,x diagram is shown in Fig. 2.

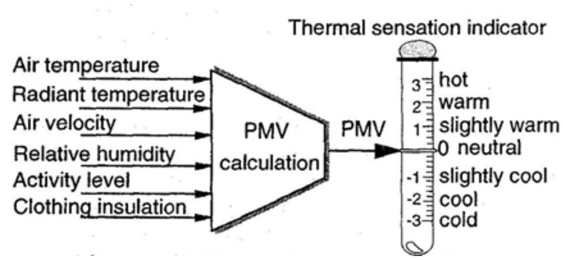

Fig. 1: PMV index and thermal sensation indicator (Fanger model)

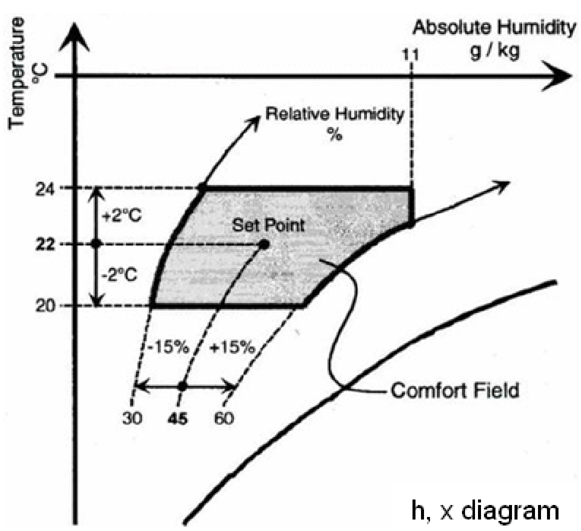

Fig. 2: ISO Comfort Field

HVAC systems characteristics: The most important specifications of HVAC systems -which are as inherent part of all thermal systems - are Time lags. There are several types of time lags in HVAC systems such as distance-velocity lag, exponential lag and capacity lag. The distance-velocity lag is the time between a signal being sent to an element and the element starting to respond, arising from the finite speed of propagation of the signal. An exponential lag occurs when the change with time in the output from an element or system (resulting from the application of a step change in the Input signal to that element or system), is of simple exponential Form. This lag may be defined as a capacity for storing energy which may be on the demand side of the process such as heated water in a tank, or on the supply side such as the hot water in the primary heating coils[15].

HVAC process has several nonlinear components like temperature and humidity which are nonlinear and extremely interrelated[16,17]. Moreover, actuators like valves and dampers which perform control actions are nonideal and nonlinear and these nonlinear factors must be identified and compensated for in the design of the controller.

Another problem is variable condition of HVAC systems. These variations arise from changeable climatic conditions and variation in occupants' activities which change significantly and periodically from day to night and from season to season[17].

An HVAC system is basically an MIMO system. However, sometimes it may be considered as an SISO system in the design of the controller, but if the aim was full control of the system, the interaction between temperature control and humidity control loops is important and must be taken into consideration.

Control modes in HVAC systems: Many control modes are used in HVAC systems which are categorized in three main groups: 1-Traditional Controllers, 2-Advanced Controllers, 3-Intelligent Controllers

Traditional controllers: Traditional control mode includes two subgroups: On/Off control and PID. The simple structure and the low initial cost are the benefits of traditional controllers and make them the first choice in the control of HVAC systems.

On/Off control provides only two plant outputs, maximum (on) or zero (off). The control sensor usually takes the form of an on/off thermostat, humidistat and pressure switch [15]. On/off control is a simple and low-cost method and it does not have enough accuracy and quality. Figure 3 shows the action of an on/off controller[15].

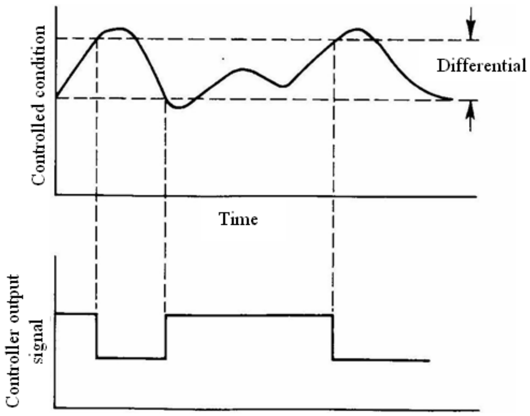

Fig. 3: Action of an on/off controller

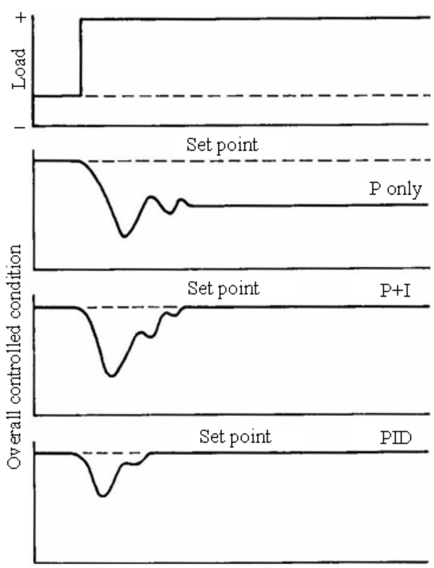

Fig. 4: Action of a PID controller

Proportional, Integral and Differential (PID) control has been commonly used in many HVAC applications[18]. There are a number of advantages in using PID control, such as its simplicity of implementation. The distinct effect of each of the three terms in the PID functions is probably the most important impetus for its survival in the world of ever sophisticated modern control algorithms[19]. Several types of Proportional, Integral and Derivative controllers (P, PI, PID) are used in the control of HVAC systems.

The Proportional plus Integral plus Derivative (PID) control combines the advantages of (P+I) control with derivative to combat sudden load changes, while maintaining a zero offset under steady state conditions[15] (Fig. 4).

However, traditional controllers have the relatively acceptable functions, but due to the low efficiency and the high maintenance, it proves to be of high cost. Therefore, advanced controllers are replaced which produce more thermal comfort and use lower energy consumption.

Advanced controllers: Advanced control modes are categorized in three subgroups as Auto-tuning PID, Modern and Nonlinear Controllers and Optimal Controllers.

The tuning procedure of a PID controller can be a time-consuming, expensive and difficult task[20,21]. Auto-tuning relieves the pain of manually tuning a controller. PID auto-tuning means automatically determining PID parameters without human intervention[22]. Generally, auto-tuning PID controllers utilize two kinds of algorithms: Model-based algorithms in which the parameters of the PID controller are related to the parameters of a transfer-function model of the plant[23]; Empirical rule-based algorithms in which the parameters of the PID controller are determined by a set of heuristic rules[23]. Although Self-Tuning Control (STC) can offer many advantages and are normally superior to the PID control, this approach is limited to large range applications because model identification is required as initial step, together with model parameter identification in real time mode. Since air conditioning is a complicated process and air-conditioned space is subject to disturbance, the model may not be well identified[17].

Since HVAC system is essentially a nonlinear system, a number of Nonlinear Controllers are designed and utilized in HVAC systems since the 80's. Some of these controllers made use of direct nonlinear control methods, as for example Serrano and Reyes who presented a nonlinear disturbance rejection state feedback controller for an HVAC system. They showed that the disturbance rejection controller is capable of reducing the effect of thermal loads (disturbances) on the thermal space and hence being more effective in keeping comfort conditions[24].

Others convert a nonlinear HVAC model to a linear model via an algebraic transformation. Semsar *et al*., employed the feedback linearization and Back-Stepping methods for the control and disturbance decoupling in HVAC systems[25].

As stated earlier, two primary goals in the control of HVAC systems are occupants' comfort and energy efficiency. In most cases, the achievement of one of these goals requires that the other be sacrificed to a certain extent. If the relative importance of the two goals can be established, optimal control can be used to determine the minimum operating cost for the system to achieve the desired comfort level[26]. Optimal control of single-zone building and HVAC systems has been studied extensively. In comparison to conventional control strategies, optimal control has been demonstrated to have the potential for energy savings of 12-30%[27].

Intelligent controllers: This category of controllers includes Neural Network based and Fuzzy Logic based Controllers. Since the HVAC systems are MIMO, nonlinear and time-varying systems, Intelligent Controllers seem to be the most proper choices for the control of these systems. Moreover, since the human sensation of thermal comfort is vague and subjective, fuzzy logic theory is well adapted to describe it linguistically depending on the state of the thermal comfort dependent variables[10]. In the following, First Intelligent controllers based on the neural network are inspected and then intelligent controllers based on fuzzy logic are considered.

Neural network (NN) as a whole is applied extensively in the control of HVAC systems, but there are two neural network based control systems used more commonly as Neural Network based Predictive Controller and Direct Neural Network Controller. In the Neural Network based Predictive Controller, the NN is exploited for the system model construction used in the controller regulating in the nonlinear systems (Fig. 5). This method is also named identification technique. There are two system identification approaches: forward system identification and inverse system identification

The procedure of training a neural network to represent the forward dynamics of a system is often referred to as the forward system identification approach[28]. A schematic diagram of this process is shown in Fig. 6. The neural network is placed in parallel with the system and the error e between the system outputs y and network outputs y is used to train the network. This represents a classical supervised learning problem for which the teacher (i.e., the system) provides target values (i.e., system outputs) directly in the output coordinate system of the learner (i.e., the network model)[29].

In an inverse system identification approach, a network is trained in an effort to model the inverse of the plant mapping[28]. One of the simplest approaches, known as direct inverse system identification, is shown schematically in Fig. 7. A synthetic training signal S is introduced to the system and the system output y is used as the input to the network. The network output is compared to the training signal and this error is used to train the network[30].

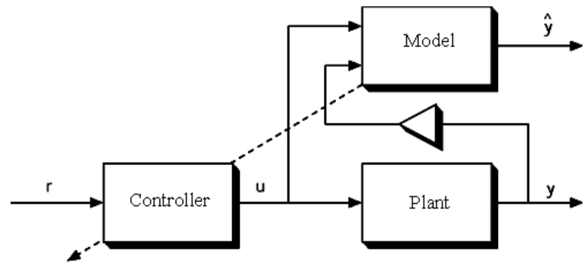

Fig. 5: Neural Network based Predictive Controller

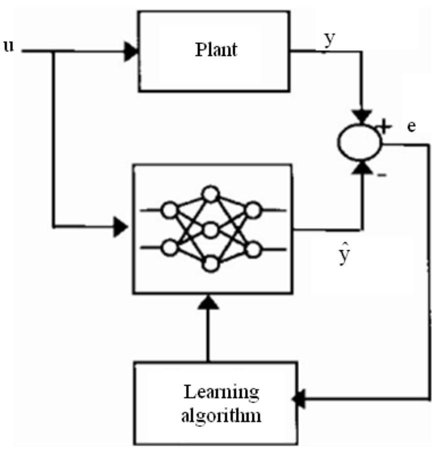

Fig. 6: Forward system identification

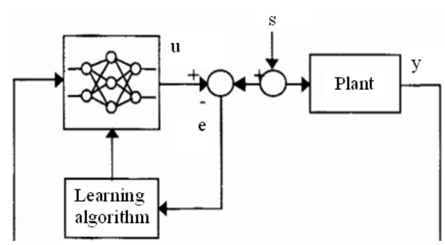

Fig. 7: Direct inverse system identification

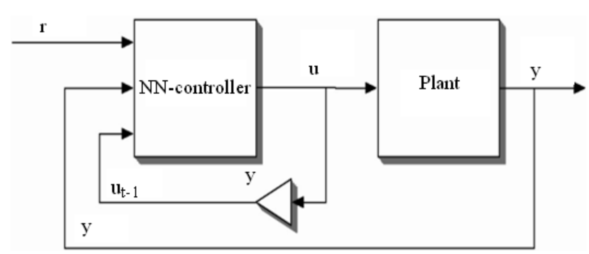

Fig. 8: Direct neural network controller

The idea of the Direct Neural Network Controller is very simple. The control diagram is shown in Fig. 8. It is an output feedback controller with a neural network at the core of the controller. The direct neural network controller does not need training of a plant model. Instead, the controller itself is trained. This is done on simulation runs of the complete system. Hence a careful choice of the training scenario is of importance.

The main problems in HVAC systems are variable conditions, intense nonlinear factors, interaction between climatic parameters, variation in system parameters and impossibility of accurate modeling of the system.

In terms of the problems stated above, fuzzy logic control will be an excellent controlling choice. Since fuzzy logic control is based on the operational experience of human expert, the system is robust to changes in environment[17]. The main advantage of fuzzy logic controllers as compared to conventional control approaches resides in the fact that no mathematical modeling is required for the design of the controller. Fuzzy controllers are designed on the basis of the human knowledge of the system behavior[10]. In the following, a fuzzy control system based on the human sensation of thermal comfort designed by Hamdi and Lachiver in 1998 is introduced[10].

In their study, it has been pointed out that controllers that directly regulate human's thermal comfort have advantages over the conventional thermostatic controller[11-13]. The main advantages are increased comfort and energy savings. The fuzzy modeling of thermal comfort could be of importance in the design of such a control system that regulates Thermal Comfort Levels (TCL) rather than temperature levels. The TCL-based fuzzy controller establishes the desired setpoint values of the environmental variables to be supplied to the HVAC system and distributed in the building to create a comfortable indoor climate.

Figure 9 shows the block diagram of the HVAC control system architecture based on the TCL. The TCL-based fuzzy system starts with the evaluation of the indoor thermal comfort level depending on the state of the six parameters mentioned before as the air Temperature (Ta), Relative Humidity (RH), air Velocity (Vair), mean radiant temperature (Tmrt), the Activity Level of occupants (MADu) and their clothing insulation (Icl). Then, if the estimated thermal comfort level is out of the comfort range, the control algorithm will provide the air temperature and the air velocity setpoints that should be supplied to the HVAC system in order to create indoor thermal comfort.

Once the TCL is calculated, it is compared to the user's actual thermal sensation in order to improve the fuzzy approximation of the specific User's Thermal Comfort Level (UTCL) on-line. The on-line adaptation

Table 1: Fuzzy evaluation of the temperature range in which the thermal sensation is neutral

	Activity level		
Clothing insulation	Low	Medium	High
Light	Very high	High	Medium
Medium	High	Medium	Low
Heavy	High	Low	Very low
Very Heavy	Medium	Low	Very low

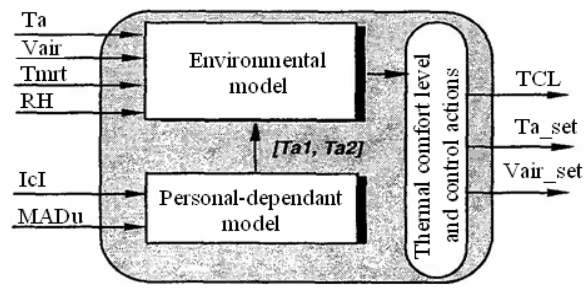

Fig. 9: TCL-based fuzzy system

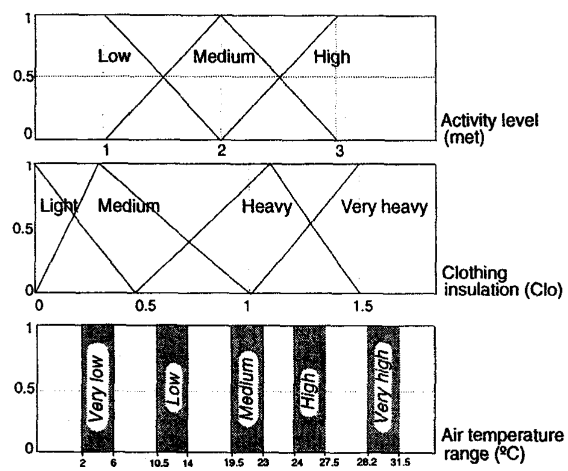

Fig. 10: Membership functions used in the personal-dependant fuzzy subsystem

of the thermal comfort model is justified by the fact that each occupant possesses different attributes that will affect his or her thermal comfort due to biological variance. Fuzzy rule base and membership function of this system is shown in Table 1 and Fig. 10.

RESULTS AND DISCUSSION

From the several different control techniques studied, it was determined that those based on the intelligent methodology offer better performance. In fact, in the work of Hamdi and Lachiver in 1998[10], three controllers were considered for a given HVAC system and their performance were compared.

Table 2: Performances of the three HVAC control systems for one day simulations

	No. of comforts hours [per-day]	Energy consumption	Savings
Constant setpoint thermostat	5 h a day	8.25 kWh	
Night setback thermostat	10 h a day	7.10 kWh	14%
TCL-based fuzzy system	24 h a day	6.6 kWh	20%

The controllers include the constant setpoint thermostat, night setback thermostat and TCL-based fuzzy system. The criteria for comparison were the number of comfort hours and the level of energy consumption. The results are shown in Table 2. These results indicate that the TCL-based fuzzy system had a superior performance leading to smaller energy consumption than the other two methods while maintaining a greater number of comfort hours.

CONCLUSION

The variety of control methodologies as applied in the control of HVAC systems were reviewed and investigated in the present study. Conventional control methods are still the first choice in HVAC systems today. Their traditional use is due to their simplicity of implementations and low initiation cost. However, these methods suffer from a high cost of maintenance and energy consumption. An alternative approach would be to revert to the more modern and intelligent methodologies. It is noted that thermal comfort is inherently a vague issue in humans since they have different definitions for comfort. Therefore, intelligent controllers which are based on the human mind are essentially more reliable and hence apt to providing thermal comfort in the control of HVAC systems. In addition, fuzzy-neural controllers are normally more energy efficient as well.

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