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Sensor fault detection and its efficiency analysis in air handling unit using the combined neural networks

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ABSTRACT

The supply air temperature control is one of the most important controls in an air handling unit (AHU). Several advanced optimal strategies have been developed and integrated into this controller to ensure better thermal comfort and less energy consumption. However, common faults occurred in the control loop may lead to the optimal control target unachievable. In this paper, the dual neural networks combined strategy is presented to detect the faults of sensors in the supply air temperature control loop of air handling unit. Firstly, the basic and auxiliary neural networks, constructed based on the control relations and the correlation analysis among variables, are developed respectively. In addition, the basic and auxiliary neural networks are combined together through allocating the weighting factors of the two neural networks using the principal component analysis. Finally, the fixed bias, drifting bias, and complete failure of sensors, and coil water valve fault are tested. And the false alarm, missing alarm and detection time of each single neural network and the combined neural networks are analyzed in this paper.

1. Introduction

With the development of the heating, ventilation, and air conditioning (HVAC) systems, more and more advanced optimal control strategies have been developed for energy conservation and better thermal comfort. When those complicated strategies are integrated into the control systems, it is essential that each control component should be healthy. If the sensors, controllers or actuators have some faults, the purposes of those advanced strategies can be hardly achieved. The healthy and efficient control system is essential to the optimal operation of the whole HVAC systems. Unfortunately, typical control faults including the biases of sensors, control signal errors, and stuck of the actuators always exist in the HVAC systems. These control faults may decrease the control efficiency, disturb the operation of the facilities or even damage them, deteriorate the thermal comfort, waste the energy etc. Therefore, developing suitable fault detection and diagnosis (FDD) strategies for HVAC systems is an important way to prevent those undesirable results.

As the core component, chillers play essential roles in the HVAC systems. The detection and diagnosis methods for chiller faults have been widely developed. Reddy [1] presented an off-line linear parameter estimation method for chiller faults diagnosis. He assessed four different chiller FDD approaches using a generic evaluation method [2]. Castro [3] used both the experimental data and model predictions to evaluate the performance of the chiller for faults diagnosis. Jia [4] presented a characteristic physical parameter method to detect and diagnose the faults in chillers. Wang developed a physical residue based approach [5] and a statistic method based strategy [6] to diagnose the common sensor faults occurred in chillers.

Besides the chiller, the air handling unit (AHU) is also the important component in the HVAC systems, which is the heat exchange station between the air and water. AHUs directly influence the energy consumption of air conditioning systems as well as indoor air quality and thermal comfort in air-conditioned spaces. Therefore, FDD in AHUs also attracted intense research interests. Yoshida [7] developed a RARX model to online detect and diagnose the faults in the air handling unit. Lee [9] developed a neural network based strategy to realize the subsystem level fault diagnosis. Wang [8] presented a neural network based method to detect the outdoor air flow rate sensor faults. After that, Wang [10] further presented a condition-based adaptive statistic approach that can be used to detect and diagnose the various sensor faults. Norford [11] and Carling [12] also developed FDD strategies for the air handling units.

Recently, Yang [13] presented a set of expert rules to detect and diagnose the faulty sensors in air handling units. Wang [14] presented a system-level fault detection and diagnosis strategy in HVAC systems. The performance indices were introduced to indicate the performance status in the FDD scheme. Du [15] presented

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Nomenclature

d	relative humidity
$f()$	basic neural network
$g()$	auxiliary neural network
h	enthalpy(kJ/kg)
y	measuring or prediction values
$\bar{y}$	mean value of y
C	control signal
M	flow rate (kg/s)
N	number of input or output
R	related coefficient
T	temperature (°C)
X	measuring matrix
BP	back propagation
AHU	air handling unit
FDD	fault detection and diagnosis
PCA	principal component analysis
HVAC	heating, ventilation, and air conditioning
MAPE	mean absolute percentage error
RMSE	root mean square error
RMSPE	root mean square percentage error

Greek symbols

λ	eigenvalue
ξ	weighting factor
$\dot{\phi}$	combining relative error
Φ	relative error

Subscripts

sup	supply air
ws	supply water
wr	return water
w	water

Superscripts

p	prediction
I	input of neural network
O	output of neural network
mix	mixing air
set	set point

a FDD strategy using principal component analysis to diagnose the sensor faults in air handling units.

Generally, the FDD methods can be classified into three categories: the model-based, rules-based, and data-driven methods. The model-based FDD methods utilize physical or mathematical models [16–18] which are developed based on understandings of the process concerned. Through comparing the real process outputs with the predicted ones from the models, the residues are obtained that can be used to detect and diagnose the faults. The rules-based methods employ expert knowledge or experiential rules [19,20]. With a proper process of reasoning, a fault can be diagnosed through checking whether the abnormal symptoms match the expert knowledge or experiential rules. The data-driven FDD methods make use of historical operation data to capture the quantitative correlations among system variables. Less information about the system in concern is required except for historical data. The data-driven methods were adopted for FDD in HVAC systems recently [8,9,21–26] due to abundant data available from modern building automation (BA) systems. The data-driven methods developed include the neural network [8,9], wavelet analysis [21], and the statistic methods such as principal component analysis [23,26], Fisher discriminant analysis [24] etc.

The model-based methods can usually provide the most reliable FDD results if the models are precisely formulated. However, great efforts are needed to build accurate mathematical models of HVAC systems, because the processes in HVAC systems are always multivariable, nonlinear, and coupled with complicated heat and mass transfer. The precision of the models greatly influence the FDD efficiency when they are used in parallel with the real processes in a model-based FDD method. As for the rules-based FDD methods, it is comparatively easy to develop the rules and the reasoning processes are usually transparent. But, the rules utilized by a rules-based method are usually specific to a special system and special types of faults. The diagnosis will fail if the fault is beyond the rule database. The data-driven FDD methods are applicable in the situation where the operation data are sufficient and easy to obtain.

With the achievements mentioned above, however, there are still few efficient detection ways for small measuring biases in some important control loops of HVAC systems. The false alarm, missing alarm, and detection time during the detection process are seldom evaluated. And the detection efficiency for those small measuring biases of the control variables is not satisfied yet.

Based on this, in this paper, the basic and auxiliary neural networks are presented and combined to detect the measuring biases of sensors in the supply air temperature control loop of AHU. The auxiliary neural network, which can be used to improve the detection efficiency, is developed and integrated with the basic neural network. The false alarm ratio, missing alarm ratio, and detection time, which were seldom considered in previous research of FDD, are analyzed to validate the detection strategy.

2. Typical faults and characteristics in AHU

With the analysis of the typical faults and their characteristics, the target process can be understood that is beneficial to the construction of suitable detection strategies.

2.1. Typical faults in supply air temperature control loop

An air handling unit, shown in Fig. 1, is the important component of HVAC systems, where the process air is cooled and dehumidified to the supply air state through transferring heat to the chilled water and then delivered to the air conditioned space by the supply fan. One of the important control loops in AHU is the supply air temperature (T_{sup}) control loop, which directly influences the indoor air quality and thermal comfort in the space as well as the energy consumption of the air conditioning system. Fig. 2 shows the supply air temperature control loop adopting the PID (proportion-integration-differential) control. In this control loop, the PID controller compares the measurements of T_{sup} with its set-point ($T_{sup,set}$) and gives related control commands (C_w). The chilled water valve will be adjusted according to the control commands and the chilled water flow rate passing through the cooling coil will be changed. With the feedback control actions, the supply air temperature can be maintained near the desired set point.

In the T_{sup} control loop, there are several kinds of faults commonly occurred including the measuring biases of the sensors, unreasonable control set points, and water valve faults. In the air handling unit, some optimal strategies have been developed to decrease the energy consumption of the system. Obviously, the health of each part in the control loops, including the accurate measurement of the variables and the correct actions of the executives, is the premise of the optimal control.