Building and Environment 73 (2014) 1–11

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Fault detection and diagnosis for buildings and HVAC systems using combined neural networks and subtractive clustering analysis

Zhimin Du*, Bo Fan, Xinqiao Jin, Jinlei Chi

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form
11 November 2013
Accepted 27 November 2013

Keywords:
Fault detection and diagnosis
Combined neural networks
Subtractive clustering analysis
Buildings

ABSTRACT

Various faults occurred in the buildings and heating, ventilation and air conditioning (HVAC) systems usually lead to more energy consumption and worse thermal comfort inevitably. The soft faults such as the sensor biases are difficult to discover in the real buildings. A robust diagnostics tool is presented to improve the energy efficiency and thermal comfort of buildings through removing various faults. The combined neural networks, integrating the basic neural network and auxiliary neural network, are developed to detect the abnormities in the air handling unit that is the widely used in commercial buildings. As a data mining technology, clustering analysis is used to classify the various faulty conditions adaptively in the buildings in this paper. Through subtractive clustering analysis, the different faults can be separated into different space zones in the data space. Besides the known faults in the library, the new unknown faults can be recognized and complemented into the faults library adaptively. The fixed biases, drifting biases and complete failure of the sensors and chilled water valve faults commonly occurred in the buildings are validated in this paper.

1. Introduction

The proper control of air handling unit (AHU) is essential to the energy efficiency of the buildings and heating, ventilation and air conditioning (HVAC) systems. There are some control loops in the air handling unit including the supply air temperature control, outdoor air flow rate control and supply fan speed control etc. To achieve higher operation efficiency, some optimal control strategies have been developed and applied. However, the effect of control strategies highly relies on the healthy control systems including sensors, controllers and actuators. In practical operation, unfortunately, these control elements usually experience various kinds of faults inevitably. The faults including biases of sensors, control command error, stuck of the air dampers or water valves always increase the energy consumption of the systems. Moreover, these faults may result in the poor thermal comfort, decrease of the facility life, or even safety accidents. Consequently, integrating suitable fault detection and diagnosis (FDD) in air handling unit is significant for higher efficiency of operation and energy savings.

Based on Annex25 [1] and Annex34 [2], many fault detection and diagnosis approaches have been developed and applied in HVAC systems that concerning various faults of sensors and facilities. As the most important components, the fault diagnosis in the air handling units and chillers has been paid more attention. In general, three kinds of fault diagnosis methods can be classified: the model-based, the rules-based and the data-driven methods.

Dexter [3] presented a fuzzy model to diagnose several faults in the air handling unit. Through comparing the outputs of the fuzzy model with those of the reference model, the faults occurred in the air handling unit can be diagnosed. Norford [4] developed a physical model to detect commonly occurred faults in the air handling unit. Castro [5] presented a physical model to detect the faults in the chillers. Wang [6] also presented the model-based strategy to diagnose the sensor faults in the chilling plant system. Yu and Li [7] presented a virtual model to estimate the supply air flow rate in the rooftop air-conditioning units. Employing the mass balance and energy balance, the physical residues can be calculated through comparing the outputs of the models with real measurements. Besides the physical diagnosis models, the gray-box [8] and black-box [9] models have also been developed to diagnose the chiller faults. Generally, the model-based methods [10–13] have been most widely developed in the HVAC systems. The well application of the model-based FDD method relies on the accurate mathematic physical models.

Different from the model-based method, the rules-based approach never need to construct the accurate mathematic models but expert knowledge or experience rules. Schein [14] presented the expert rules that are based on the mass balance

* Corresponding author. Tel.: +86 21 34206533.
E-mail address: duzhimin@sjtu.edu.cn (Z. Du).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.11.021

Nomenclature

T	temperature (K)
M	flow rate (kg/s)
C	control command
R	related coefficient
$RMSE$	root mean square error
$RMSPE$	root mean square percentage error
$MAPE$	mean absolute percentage error
n	data number
y	measured values
y_{pi}	predicted values
$\bar{y}$	mean of the measuring values
$\bar{y}_p$	mean of the predicted values
X	measuring matrix or vector
D	data density
AHU	air handling unit
HVAC	heating, ventilation and air conditioning
FDD	fault detection and diagnosis

Greek symbols

α	adjacent field
β	adjacent field with greatly reduced density
σ	statistic variance
λ	eigenvalue
ζ	weighting factor
ϕ	relative error
$\overline{\phi}$	combined relative error

Subscripts and superscripts

set	setpoint
sup	supply air
ws	supply water
wr	return water
w	water
p	prediction
m	measurement

and energy balance in the air handling unit. House [15] developed a series of the rules to judge the operation conditions of air handling unit. With the expert rules, the faults occurred in the air handling unit can be diagnosed successfully. Moreover, Visier [16] also constructed an expert system that is used to diagnose the faults in the school HVAC systems. The application of rules-based FDD methods depends on the rules constructed. One expert system is usually suitable for a special HVAC system. In addition, if the expert rules constructed for the real HVAC systems are not detailed enough, the diagnosis efficiency of this expert system may be limited.

As a new FDD method, recently, the data-driven approaches have been paid more attention in HVAC field. The data-driven method, such as principal component analysis [17–20], Fisher discriminant analysis [21], wavelet analysis [22,23] and neural network [24–26] etc., never need to build the accurate mathematic physical models or detailed experience rules. Actually, the data-driven FDD methods usually take advantage of the intrinsic relations among the various data. Through calculating the deep intrinsic mathematic relations of the variables, the normal and abnormal operation can be distinguished. When faults occur, the intrinsic relations among variables will be broken, which is different with that under normal conditions. Consequently, the faults occurred in the HVAC systems can be detected and diagnosed. Lee [24] presented a general regression neural network in the air handling unit. It can be used to diagnose the abrupt and performance degradation faults. Wang [25] developed a detection model-based on neural network in the variable air volume systems. The neural network can be used to diagnose the faults of outdoor air, supply air and return air flow rate sensors after training using operation data. In addition, Guo [27] presented a novel statistic machine-learning based method for FDD in HVAC systems. Later, Guo [28] further developed the strategy through combining a hidden Markov model to efficiently detect and diagnose the faults occurred in HVAC systems. Wu [29] presented a cross-level diagnosis method based on the spatial–temporal partition strategy to detect and diagnose the faults in HVAC system. Yang [30] presented the fractal correlation dimension logic to detect the temperature sensor faults in the air handling units. The data-driven FDD approaches are suitable for the situations that the operation data are sufficient and easy to obtain. There are still few efficient detection strategies for control faults in the control loops of air handling unit. The detection efficiency and diagnosis capacity for those typical control faults including small measuring biases of the control variables is not satisfied yet.

A fault detection and diagnosis strategy using combined neural networks and subtractive clustering analysis is presented in this paper. Combined basic and auxiliary neural networks are presented to detect the faults in the supply air temperature control loop in the building and HVAC system. The subtractive clustering analysis is used to diagnose the fault source through adaptive classification for the faults in the buildings.

2. System descriptions

2.1. Building and HVAC system

A typical HVAC system in the building is shown in Fig. 1. The supply air, the mixture of the outdoor air and recycle air, exchange heat and humidity with the chilled water in the air handling unit. The chilled water coming from the chillers is delivered by the pumps to the air handling unit. After being cooled down by the chilled water (in summer condition), the supply air is delivered to each air conditioning zone by the variable-speed supply fan. Moreover, the return air is divided into two streams by the variable-speed return fan. One stream is exhaust air to the outside of the building, and the other is recycled in the next air circulation.

2.2. Supply air temperature control loop and faults concerned

Several Proportion–Integral–Differential (PID) controllers are included in the HVAC system. These controllers, including the supply air temperature controller, outdoor air flow rate controller, supply fan speed controller and return fan speed controller, can be used to ensure the basic operation of the system.

The supply air temperature control loop (Fig. 2) is one of the most important control loops in the air handling unit. Through comparing the measurements of supply air temperature and its setpoint, the T_{sup} (supply air temperature) controller adjusts the chilled water valve locating at the inlet of the air handling unit to ensure proper supply air temperature for the users. Some faults including the biases of sensors, water valve stuck and controller faults may commonly occur in this control loop. These faults may affect the control process and lead to unwanted results. Consequently, the fixed bias of T_{wr} (return water temperature) sensor, the fixed bias of T_{sup} sensor, the drifting bias of T_{sup} sensor, the complete