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A probabilistic approach to diagnose faults of air handling units in buildings

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ABSTRACT

Air handling unit (AHU) is one of the most extensively used equipment in large commercial buildings. This device is typically customized and lacks quality system integration which can result in hardwire failures and control errors. Air handling unit Performance Assessment Rules (APAR) is a fault detection tool that uses a set of expert rules derived from mass and energy balances to detect faults in air handling units. APAR is computationally simple enough that it can be embedded in commercial building automation and control systems and relies only upon sensor data and control signals that are commonly available in these systems. Although APAR has advantages over other methods, for example no training data required and easy to implement commercially, most of the time it is unable to provide the root diagnosis of the faults. For instance, a fault on temperature sensor could be bias, drifting bias, inappropriate location, or complete failure. In addition a fault in mixing box can be return and/or outdoor damper leak or stuck. In addition, when multiple rules are satisfied, the list of faults increases. There is no proper way to have the correct diagnosis for rule based fault detection system. To overcome this limitation, we proposed Bayesian Belief Network (BBN) as a diagnostic tool. BBN can be used to simulate diagnostic thinking of FDD experts through a probabilistic way. In this study we developed a new way to detect and diagnose faults in AHU through combining APAR rules and Bayesian Belief network. Bayesian Belief Network is used as a decision support tool for rule based expert system. BBN is highly capable to prioritize faults when multiple rules are satisfied simultaneously. Also it can get information from previous AHU operating conditions and maintenance records to provide proper diagnosis. The proposed model is validated with real time measured data of a campus building. The results show that BBN correctly prioritize faults that are verified by manual investigation.

1. Introduction

Heating, ventilation and air conditioning (HVAC) equipment commonly fails to satisfy performance expectations envisioned from design due to problems caused by inadequate maintenance, improper installation, or equipment failure. These problems of faults include mechanical failures such as dampers or actuators, stuck broken or leaking valves; control problems related to frozen or biased sensors, poor feedback loop tuning of incorrect sequencing logic; fouled heat exchangers; design errors; or inappropriate operation intervention. By identifying and diagnosing faults to be repaired, FDD techniques can benefit building owners by reducing energy consumption improving operation and maintenance and increasing effective control over environmental conditions in occupied spaces. Approximately 50% of a commercial's building energy consumption is associated with HVAC systems [1] and more specifically Air handling unit's (AHU) energy consumption counts for around 40% of industrial sites total energy consumption [2] because of its inefficient operation. Overall it is estimated that HVAC energy consumption accounts for 10–20% of total energy consumption in developed countries with AHU associated energy use associated with the majority of this [3]. The energy potential saving of FDD is estimated at 10–40% of HVAC energy consumption depending on the age and condition of the equipment, maintenance practices, climate and building use [4]. In this study we tried to detect and diagnose faults of AHU through a probabilistic way by combining expert rules and Bayesian Belief Network (BBN). Based on the literature reviews and survey results we identified the parameters of BBN. In addition, we trained, verified and tested our model with real time measured data.

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Nomenclature

Tco	Changeover temperature
T_{RA}	Return air temperature
T_{OA}	Outdoor air temperature
T_{MA}	Mixed air temperature
T_{SA}	Supply air temperature
E_t	Threshold parameter accounting for errors in temperature measurements
E_f	Threshold parameters accounting for errors related to airflows
Tsf	Temp. rise with supply fan
Trf	Temperature rise across return fan
$T_{SA,S}$	Supply air set point
U_{CC}	Cooling coil control signal
U_{HC}	Heating coil control signal
Q	Outdoor air fraction
MT_{MAX}	Maximum allowed mode transition per hour
E_C	Threshold parameter for cooling coil valve control signal

2. Litarature review

There were lots of researches conducted on FDD of AHU and VAV in the last decades. Most of them are focused on AHUs. Among data driven based models, Principle component analysis is most commonly used to detect and diagnose sensor faults like fixed bias, drifting bias or complete failure. Wang ([5–9]), Jigtan [10], Wu [11], li [12], Du ([13–15]) developed PCA based FDD method for Air Handling Unit (AHU), variable air volume box and centrifugal chiller. Three kinds of diagnostic methods were used in those studies, Q-contribution plot, joint angle analysis (JAA) and Fisher discriminant analysis (FDA). However, it is found that Joint angle analysis (JAA) is more efficient than Q-contribution plots in diagnosing complex faults. The studies focused on both simulation and field data.

The main advantage of principle component analysis is less training data is required than other data driven approaches. However, sensor fault diagnostic process through PCA can be affected by component faults because PCA is not totally robust against component faults. Also, joint angle analysis (JAA) requires fault library which is tough to get in real field application [16].

The use of artificial neural network (ANN) as FDD strategy was developed as early as 1996. Wang [17] first used artificial neural network (ANN) to detect and diagnose faults in AHU. The later study proposed two stages ANN, one is to detect the abnormality in the system and other is to isolate the subsystem. Residuals of different parameters are given as input and the trained network was used to diagnose root cause of the faults. Later lee [18] developed General regression neural network (GRNN) trained with normal operating data to predict the parameters. The deviation of actual data from predicted value considered as a sign of fault. Recently, Du ([19], [20] and [21]) developed ANN model incorporated with wavelet and/or fractal data preprocessing tool. Data preprocessing tools were used to increase the efficiency of Artificial Neural Network. Most of the studies require faulty dataset for diagnostic process.

A.L Dexter [22] used fuzzy model to detect faults in AHU. The model was validated using both simulated and experimental data. In this study both normal and faulty data are used to create the reference models which are used to detect and diagnose the faults. The advantage of this method is no faulty data's from the actual system is necessary for training. Only simulation data's were enough to complete the training process.

Yun [23] developed Hidden Markov Model (HMM) to detect and diagnose the faults in AHU. Both normal and faulty data are used to train different HMMs for both detection and diagnosis. Data's from ASHRAE RP project was used to validate the model. Later in 2012 Wang used Bayesian network to diagnose the faults of both VAV and chiller. In that study no normal or faulty data's are used to train the model. Prior probabilities are used based on the survey results of different VAV boxes and chiller. As no training data's are used this model can be used in different real time FDD analysis. Support vector machine (SVM) also can be a very effective tool to detect and diagnose root cause of the faults. Du [24] used support vector regression to detect and diagnose sensor faults of AHU.

Apart from data driven methods and expert rules, Kumar [25], Narayanaswamy [26], Lee [27], Liang [28], Uk Lee [29], Salsbury [30], Wang (2001), Salesbury [31] used model based method to detect and diagnose the faults of AHU. In those studies, energy modeling, first principle based models; physics based models and linear models (ARX, RARX) are used. In the energy modeling procedure abnormality in the energy consumption was considered as indication of fault. Also in other model based FDD studies [32–35] a parameter is predicted by model and then some residual analysis was done. If the residue exceeds a threshold then a fault is detected.

Pakanen [36] used an online diagnostic test where the deviation from the normal operating data is a sign of fault and later by analyzing different sub process data fault was isolated. Field data was used to validate the experiment. Table 1 provides a list of different methods.

In summary, many of the methods usually provide good fault detection results. However, in certain cases fault may cause similar symptoms and also propagate to other components. So, it becomes very hard to provide proper diagnosis. For example, a fault in mixed air temperature can influence parameters like cooling coil and damper signal etc. Therefore, it is more reasonable to provide probabilities of faults at given symptoms in FDD results. Symptoms can be considered as abnormal parameter change or residual analysis, expert rules etc. Here, in this study we tried to use expert rules (APAR) as symptoms of faults. APAR is a well-established set of rules by NIST that are able to trigger an alarm if the system is running abnormally means if any fault happens. FDD of AHU can be very efficient and effective if the FDD strategy can work in a similar way as that used by FDD experts. In this study diagnostic thinking of experts is simulated by a Bayesian Belief network (BBN), where APAR rules are used as symptoms of fault.

3. Methodology

3.1. Typical AHU system

Fig. 1 shows a typical AHU with air loop measurement. The control loops of a typical AHU include damper control, temperature control and pressure control. The fresh air through the fresh air damper is mixed with the return air with recirculation air damper. Advanced control strategies are implemented to provide adequate outdoor air ventilation and suitable supply air temperature and indoor pressure, and to minimize energy use. PID controllers are

Table 1
Review of different AHU FDD methods.

Reference	*Method*
[58,11,59,60,12,27,13,14,61,5,6,8]	PCA
[21,20,19]	ANN
[24,28]	SVM
[23]	HMM
[61,62]	Bayesian
[29,31,25,30,13,27,26,28]	Model based
[63,64,56,37]	Expert rules
[36]	Online diagnostic test
[65,66]	fuzzy logic