

Case Study: Automated Fault Detection and Diagnostic Software



Phillip Burton Federal Building – San Francisco

INTRODUCTION

There is much interest in fault detection and diagnostics (FDD) as an integral tool to maintaining HVAC systems at their optimal performance and reliability. In addition, FDD supports continuous commissioning through its continuous performance monitoring functionality. Studies indicate that the use of FDD can result in 10-30% energy savings on an ongoing basis, support efficient maintenance practices, extend equipment life, and provide more consistent occupant comfort and indoor air quality. New FDD tools are entering the market that provide the needed functionality to help building managers achieve maximum performance and lowest energy cost.

Staff of the National Institute of Standards and Technology (NIST) have developed automated FDD (AFDD) software algorithms for air handling units (AHUs) and variable-air-volume (VAV) boxes. The software developed by NIST has been embedded in the controls at the Phillip Burton Federal Building in San Francisco, California and at Automated Logic Corporation (ALC) offices in Kennesaw, Georgia. In both cases, the software was embedded directly into the building's existing energy management and control system (EMCS). No additional software or hardware was required to implement the algorithms.

THE TECHNOLOGY

The technical basis for the FDD software is described in a July 2005 ASHRAE Journal article, "Fault Detection & Diagnostics for AHUs and VAV Boxes," by Jeff Schein and Steve Bushby. The article describes the basis for development of the AHUs Performance Assessment Rules and the VAV Control Chart algorithms. The concept behind the techniques is relatively simple:

- Use standard instrumentation on VAV boxes and AHUs to compare actual readings to expected performance.

- Determine possible diagnostic errors that could cause a deviation from the expected readings to the actual readings.
- From an array of tests determine the most likely cause (or multiple causes) of the error.
- Report the causes back to the EMCS for further investigation and possible mitigation.

To prevent false alarms or misdiagnoses the AFDD routines have to be tuned. The art in tuning the alarm thresholds is to set them broad enough to prevent nuisance alarms, but tight enough to catch control instabilities that could be fixed through better loop tuning. On the other hand, a poorly tuned control loop could cause fluctuations that are beyond the perception of the occupants, but are large enough to create significant wear on the actuators or higher energy costs.

To isolate the root cause (or causes) of a persistent problem, the NIST AFDD routines provide an array of tests that are performed in tandem. The tests for VAV boxes are shown in Figure 1 below. For example, one can see that a stuck or malfunctioning reheat coil valve is the only error that could trigger both a high zone temperature alarm and a coincident high discharge supply air temperature alarm. A malfunctioning VAV damper (whether from loop tuning, malfunctioning actuator or bad airflow sensor) is eliminated from consideration by the presence of the high discharge supply air temperature alarm. A malfunctioning VAV damper is detected by alarms on the airflow loop together with the zone space temperature alarms. These matrices of tests are the core of the NIST AFDD routines. The beauty of these tests is that they can be implemented by most programmable zone controllers. The logic is quite simple. It should be noted that not all commercial zone controllers are programmable. A class of low-cost zone controllers are merely "configurable;" these controllers have their programming embedded by the factory in memory and do not permit use of the algorithms.

This case study presents field experience with the Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program funded through California Energy Commission's Public Interest Energy Research (PIER) program.

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Possible Diagnoses

Alarm Description	Zone temperature sensor drift/failure	Airflow (DP) sensor drift/failure	Discharge temperature sensor drift/failure	Damper stuck or failed	Damper actuator stuck or failed	Reheat coil valve stuck or failed	Reheat coil valve actuator stuck or failed	AHU Supply air too warm	AHU Supply air too cool	Supply air static pressure too low	Scheduling conflict with AHU	Undersized VAV box	Tuning problem with airflow feedback control loop	Tuning problem with zone temperature feedback control loop	Inappropriate zone temperature setpoint	Minimum airflow setpoint too low	Minimum airflow setpoint too high	Maximum airflow setpoint too low	Maximum airflow setpoint too high	Sequencing logic error
High zone temperature alarm	X					X	X	X			X	X	X	X	X					X
Low zone temperature alarm	X					X	X		X		X	X	X	X	X		X			X
High airflow alarm		X		X	X					X			X							X
Low airflow alarm		X		X	X				X	X	X	X							X	X
Unstable airflow alarm		X		X	X				X	X	X	X				X				X
High discharge temperature alarm			X			X	X									X				
Low discharge temperature alarm			X			X	X													

Figure 1- Fault detection matrix for VAV boxes

A similar set of rules were developed by NIST for AHUs. These rules are depicted in Figure 2 below. It should be noted that each of these matrices has to be customized for the application. For instance the tests for a VAV box with reheat coils would differ from those for a dual-duct or cooling only VAV box. Similarly the presence of CO2 ventilation reset controls would need to be added to the tests for both the zone and AHUs controls. However, the logic of the tests is easy to extend.

Possible Diagnoses

Alarm Description	Supply Air Temperature Sensor Error	Return Air Temperature Sensor Error	Mixed Air Temperature Sensor Error	Outdoor Air Temperature Sensor Error	Leaking Cooling Coil Valve	Stuck Cooling Coil Valve	Undersized Cooling Coil	Fouled Cooling Coil	Chilled Water Supply Temperature Too High	Problem with Chilled Water Circulating Pump	Chilled Water not Available to Season	Leaking Heating Coil Valve	Stuck Heating Coil Valve	Undersized Heating Coil	Fouled Heating Coil	Hot Water Supply Temperature Too Low	Problem with Hot Water Circulating Pump	Leaking Mixing Box Damper	Stuck Mixing Box Damper	Controller Tuning Error	Controller Logic Error (Sequencing and Scheduling)
1 In heating mode, supply air temp should be greater than mixed air temp.	X																				
2 Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X																	
3 Heating coil valve command is fully open and supply air temp error exists.	X				X	X															
4 Heating coil valve command is fully open. If heating load increases, supply air temp will drift from setpoint.	X				X	X															
5 Outdoor air temp is too warm for cooling with outdoor air.	X			X																	X
6 Supply air temp should be less than return air temp.	X	X									X	X									
7 Supply and mixed air temp should be nearly the same.	X	X			X	X					X	X									
8 Outdoor air temperature is too cool for mechanical cooling with 100% outdoor air.	X			X							X	X						X	X		X
9 Outdoor air enthalpy is too great for mechanical cooling with 100% outdoor air.	X										X	X						X	X		X
10 Outdoor and mixed air temp should be nearly the same.		X	X															X	X		
11 Supply air temp should be less than mixed air temp.	X		X				X	X	X	X	X	X	X	X	X						
12 Supply air temp should be less than return air temp.	X	X					X	X	X	X	X	X	X	X	X						X
13 Cooling coil valve command is fully open and supply air temp error exists.	X				X	X			X	X	X	X	X	X	X						X
14 Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X				X	X			X	X	X	X	X	X	X						X
15 Outdoor air enthalpy is too low for mechanical cooling with minimum outdoor air.	X										X	X									X
16 Supply air temp should be less than mixed air temp.	X	X					X	X	X	X	X	X	X	X	X						
17 Supply air temp should be less than return air temp.	X	X					X	X	X	X	X	X	X	X	X						X
18 Outdoor air fraction (percentage of outdoor air) is too low or too high.		X	X	X																	
19 Cooling coil valve command is fully open and supply air temp error exists.	X				X	X			X	X	X	X	X	X	X						X
20 Cooling coil valve command is fully open. If cooling load increases, supply air temp will drift from setpoint.	X				X	X			X	X	X	X	X	X	X						X
21 Heating coil valve, cooling coil valve, and mixing box dampers are all modulating simultaneously.																					X
22 Heating coil valve and cooling coil valve are both modulating simultaneously.																					X
23 Heating coil valve and mixing box dampers are both modulating simultaneously.																					X
24 Cooling coil valve and mixing box dampers are both modulating simultaneously.																					X
25 Persistent supply air temp error exists.																					X
26 Mixed air temp should be between return and outdoor air temp (mixed air temp too great).		X	X	X																	
27 Mixed air temp should be between return and outdoor air temp (mixed air temp too low).		X	X	X																	
28 Too many mode switches per hour.																					X

Figure 2- Fault detection matrix for an AHUs

FIELD APPLICATIONS

Phillip Burton Federal Building

The Phillip Burton Federal Building is a 22 story, 1.4 million square foot, high-rise office building with nearly 1,200 dual-duct VAV boxes served by eight AHUs. The EMCS is a hybrid DDC system with an Alerton BACTalk system serving as the front end, control of the air-handling units and the majority of the zone controls. Three of the floors are controlled by an ALC WebCTRL system. This building was used as the first large-scale demonstration of the BACnet control protocol. Enovity Inc. manages operation and maintenance (O&M) of the building's mechanical and control systems and provides the Chief Engineer.

This building was selected as a pilot site for the NIST AFDD routines because of GSA's commitment to energy efficiency and the building operator's familiarity with the building controls. The Chief Engineer and the O&M contracting firm, have extensive experience with control system design, installation and programming. They maintain the building control systems themselves with minimal support from the local EMCS vendors. The AFDD algorithms were implemented in the Burton Building by the owner and the building operator.

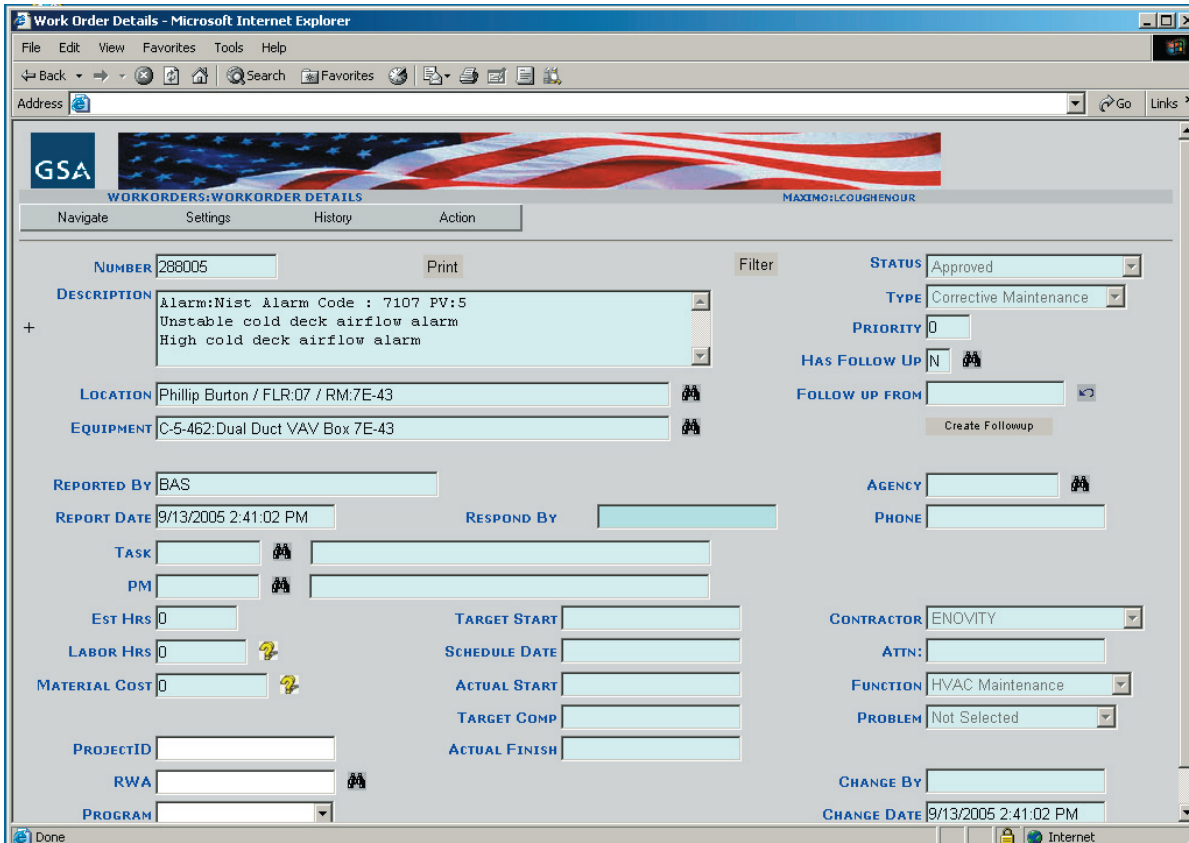
The addition of the AFDD algorithms was done over a six month period to fully implement and tune at this site. Part of this schedule was the coincident debugging and tuning of the underlying VAV box control algorithms that the building Chief Engineer was doing. The AFDD

routines were initially installed on two floors and gradually expanded to all floors as tuning was done to limit false alarms. According to the Chief Engineer, in the first few months they would get 10 to 20 faults per floor per day out of the approximately 60 boxes per floor. About half of the faults were either high or low temperature alarms with just a few relating to significant problems with the boxes. The remainder of the fault alarms were hot and cold deck damper and airflow alarms. At the end of the six months, the alarms were down to approximately 30 per day for the whole building. Of these, 11 VAV boxes had known deficiencies and were slated for repair or replacement. The Chief Engineer commented that the presence of AFDD algorithms helped him to detect errors in logic in his modifications of the dual-duct VAV box controls.

An interesting addition to this implementation of the NIST AFDD routines is the integration of the AFDD alarms into the building's computerized maintenance management system (CMMS) that generates and tracks work orders (see Figure 3). The alarms generated by the EMCS are fed into the work order database using standard SQL calls. This includes a diagnostic alarm message (in the Description field); the physical location of the device (under Location); the device name (under Equipment); and the date and time (under Report Date). In the example shown in Figure 3, two alarms were generated by the AFDD routines serving VAV box 7E-43: unstable airflow and high cold deck airflow. Both of these might be caused by problems with the VAV box airflow sensor. In one instance related by the Chief Engineer, a technician responding to a low airflow alarm discovered loose insulation that had fouled the box inlet flow sensor.

In addition to its commitment to energy efficiency, GSA is very interested in using these algorithms to provide proactive maintenance.

Figure 3- Example work order automatically generated by an AFDD alarm



In integrating the AFDD algorithms, some additional logic was required for the controls related to the handling of duplicate alarms, and reduction of false alarms. Code was added to the Maximo CMMS to reduce the burden duplicate work orders from unsolved anomalies. They also had to ensure that the VAV box alarms were disabled when the associated AHUs were shut down or a flood of alarms would be triggered.

The building's Chief Engineer is a strong advocate of the algorithms. Since the AFDD system has been installed, he has been able to target his preventative maintenance and proactively fix problems before the tenants notice them or before more energy cost is incurred. The O&M contract requires an annual inspection of all 1200 VAV boxes. In the past, this has required a daily routine of assigning technicians to physically inspect 6-8 boxes per day, regardless of their operating condition. With the AFDD system, technicians are being reassigned to provide maintenance on the boxes that are actually having problems.

"I can put my maintenance people right where they belong. This is a significant benefit to building operations"
-- Chief Engineer

This is a significant benefit to overall building operations. In fact, the system has identified a number of real problems including fouled airflow sensors, stuck dampers, frozen actuators, undersized boxes and improperly tuned loops. The Chief Engineer has tried out the AFDD algorithms on two AHUs and is planning to implement the AHUs algorithms in additional units. GSA implemented the VPACC to have a more sensible approach to VAV maintenance as much as for energy cost savings reasons.



ALC HEADQUARTERS BUILDING

ALC implemented both the VAV box and AHU algorithms on its headquarters building in Georgia. This building has several DX AHUs and a mixture of single duct VAV boxes with and without reheat. Only a subset of the reheat boxes have discharge air temperature sensors. The algorithms were programmed into the building's AHUs and VAV box controllers. The results of the FDD calculations were stored as fault codes that were trend logged. The trend logs were archived monthly and sent to NIST for review and comment. The AFDD routines found a number of real problems including a misplaced OSA temperature sensor, a broken compressor on a 4-stage DX AHUs, several sensors that were out of calibration, not enough heat on boxes that were at the far end of the distribution system, and one stuck damper. ALC's Director for Technical Services was pleased to note that they did not identify any VAV box damper hunting because they had been using ALC's proprietary algorithm for stable damper control.

ALC is writing a new version of its Eikon graphic programming tool that will include features to facilitate incorporation of the FDD algorithms into its applications language. ALC has already informed its dealer network that NIST staff is looking for additional field sites and will provide technical assistance to interested dealers upon request. Based on its experience ALC is planning to code the AFDD algorithms and make them available to the ALC dealers for their projects. ALC is also considering adding an option to require automatic fault detection and diagnosis control functionality to its CtrlSpecBuilder.com web site.

SUMMARY

"I would strongly recommend them in our O&M contracts with all our clients"
-- Enovity O&M Manager

The initial findings of the assessment have been very positive. From the two projects reviewed, the PIER-funded NIST AFDD algorithms appear to offer great hope for achieving sustainable performance and reliability. They are relatively simple to implement in code and they are being proven in the field in large commercial building applications. One of the outcomes of this project is a set of robust parameters that will largely eliminate the need for site-specific parameter tuning. For example, the ALC building, as well as newer test sites, have required little or no changes to the initial parameter values. Like all controls, they require some customization for the specific installation (e.g. VAV boxes with and without discharge air temperature sensors) and the parameters may need to be tuned to prevent false alarms. Based on the performance of the software so far, the GSA Region 9 office is planning to implement the algorithms in additional GSA-owned buildings.

It is quite promising that control manufacturers plan to implement these algorithms as part of the standard routines provided to their dealers. In addition to what ALC is planning, Alerton is preparing a release of the VAV box control chart algorithms to its dealers. In addition, Delta Controls, which is involved with a project at the Foley Federal Building in Las Vegas, Nevada, and Tour Andover Controls, have signed on with NIST to promote commercialization of the AFDD algorithms.

This case study was commissioned by the New Buildings Institute (NBI www.newbuildings.org) and completed by Taylor Engineering LLC. NBI is the Market Connections manager for the FDD program with specific responsibilities to provide commercialization support for each of the FDD products under development including the potential for FDD software and hardware to be incorporated into standard product offerings by vendors and in energy codes/standards including the California Title 24 Nonresidential Standards, ASHRAE and the International Energy Conservation Code. The FDD program is managed by Architectural Energy Corporation. The FDD program web site: www.archenergy.com/pier-fdd/

