Model-Independent Fault Detection and Diagnostics For VAV Terminal Units

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ABSTRACT

A new tool for performing fault detection and diagnostics for variable air volume (VAV) terminal units has been successfully developed and tested. The Model-Independent Fault Detection and Diagnostics tool was developed without the use of a traditional model-based preprocessor. Instead, the FDD analysis is performed using performance indices that can be evaluated using only design information and measured values. This eliminates the need to "train" the tool for each individual system and should expedite real-world implementation of the tool. Appropriate fault threshold values have been determined through a combination of simulation and laboratory testing. To date, the tool is capable of detecting and diagnosing nearly 40 different failure modes for pressure-independent VAV terminal units. Detection of numerous other failure modes is possible, including simultaneous multiple failure modes, although the tool cannot currently diagnose these cases.

Introduction

Medium-to-large-sized commercial buildings have complex mechanical and lighting systems, often run by energy management control systems (EMCS). While more information than ever regarding the operation of these systems is available today, most building operators lack the time and training necessary to fully utilize this information. Hence, problems arise in the operation of these systems that often go undetected or undiagnosed, leading to substandard energy performance. Building systems researchers and members of the HVAC industry are beginning to address this problem; they have produced several technologies that can assist building operators in maintaining good building performance. Some of the major blocks in implementing these technologies, however, are the capital costs, time consumed, and level of effort required.

To overcome these obstacles, a new tool for performing fault detection and diagnostics (FDD) for variable air volume (VAV) terminal units has been successfully developed and tested. The development focus for the Model-Independent Fault Detection and Diagnostics Tool (MIFDD) was to avoid the use of models in the FDD preprocessors. Typically, a model-based FDD approach requires that a tool be calibrated, or "trained," for each individual system. This process generally requires large amounts of historical data that had been recorded when the system was operated in the absence of any known failure modes. Often these data are unavailable or are cost prohibitive to obtain. By avoiding the use of models, implementation of this tool in real-building environments should be easier and less expensive.

A similar approach to fault detection has been completed for large, built-up air handling units (Lee et al. 1996a). As part of this work, residual values for seven different parameters were calculated under steady-state operating conditions. This work was expounded upon to develop diagnostic capabilities using an artificial neural network (ANN) classifier (Lee et al. 1996b). While laboratory results were promising, field testing in real buildings met with limited success due in part to the large time and cost-constraints associated with training the diagnostics model for use in a new environment (House 1999).

Tool Development

Development of MIFDD was completed in five different stages: (1) simulation of identified failure modes, (2) parameter identification, (3) classification of model-independent performance indices, (4) identification of appropriate threshold values, and (5) fault detection and diagnostics. Details regarding the work completed during each of these steps are presented in this section.

Simulation of Identified Failure Modes

A pressure-independent VAV terminal unit with optional baseboard reheat was chosen as the basis for tool development. This type of system was selected because of its prevalence in existing commercial buildings and because many other types of terminal units are similar to this design, allowing for the easy future adaptation of the tool to other terminal unit configurations.

Pressure-independent VAV terminal units provide a constant primary airflow rate (F) to the zone for a given zone controller output (U_1) regardless of the static pressure in the main supply duct. These units provide a constant primary airflow rate (F) to the zone for a given zone temperature by controlling (C) the position of the primary air damper motor (DM). Reheat capabilities can also be added to this type of terminal unit through either a heating coil in the box itself or through the control of a baseboard heater valve (V) located in the zone. Figure 1 presents a schematic representation of the VAV terminal unit simulated during development of MIFDD.

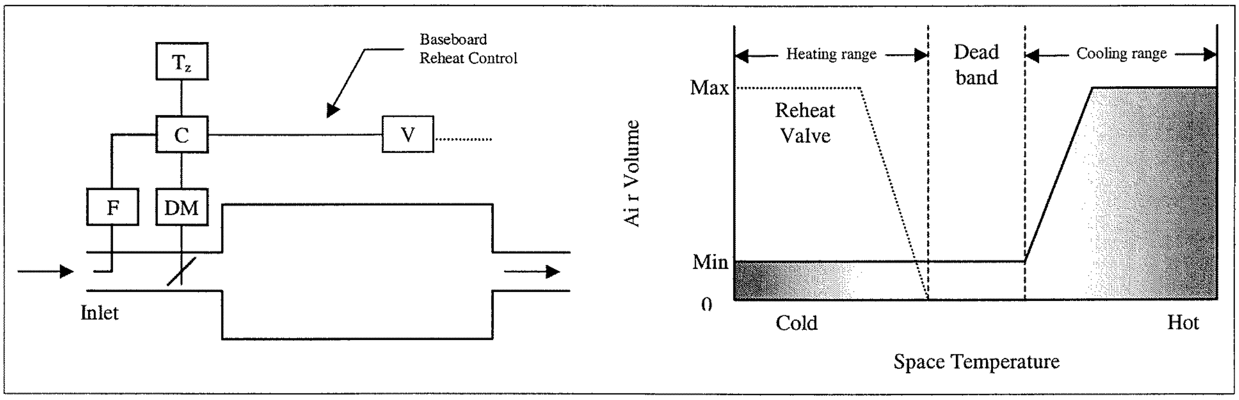

Figure 1. Pressure independent VAV terminal unit

A typical master/slave control algorithm was simulated for the control of the VAV terminal unit. The primary air damper portion of this control algorithm is illustrated in Figure 2. T_z is the measured zone temperature and is controlled to the *Set point* temperature. *F* represents the measured airflow rate and *DM* is the damper actuator motor used to control the position of the VAV damper. Control blocks C_1 and C_2 were simulated with PID algorithms. A separate PID controller was used for control of the baseboard reheat.

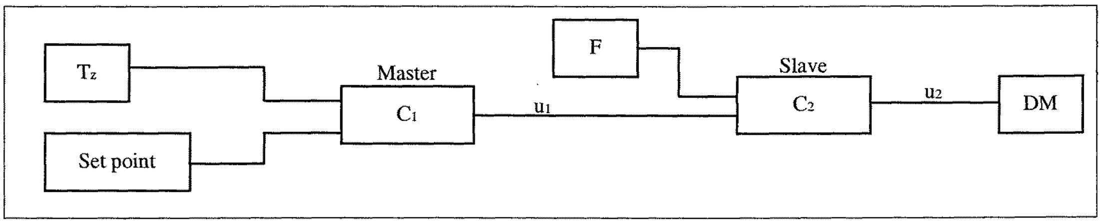

Figure 2. Simulated VAV terminal unit control logic (reheat control not shown)

Since simulation algorithms were developed only for a VAV terminal unit and not an entire building, the load profile for the zone served by the VAV terminal unit was generated separately using DOE-2. To capture the effects of various failures over the entire operating range of the terminal unit, the load profile developed included both a design cooling day and a design heating day. A weeklong load profile was built based on an annual DOE-2 simulation of a typical medium-sized office building located in San Francisco, California. Building loads were calculated in 30-second intervals for the weeklong load profile. Default commercial building occupant, lighting, and plug load densities and schedules from the VisDOE libraries were used in this process.

Expert knowledge was used to identify over forty different possible failure modes for pressure-independent VAV terminal units. System designers, manufacturers, building owners and operators were questioned to develop this comprehensive list. Failure modes were classified by one of the three following categories:

1. Mechanical failure, such as a broken actuator
2. Sensor failure, such as a temperature sensor out of calibration
3. Control failures, such as poor PID tuning on a control loop

Using the load profile described above, the VAV terminal unit model was run under each of the identified failure modes and the system outputs recorded.

Parameter Identification

To identify the parameters that are available from VAV terminal units in typical commercial buildings, interviews were conducted with both equipment manufacturers and building operators. From these interviews, a list of typically available parameters was compiled. The parameters used in the development of MIFDD are listed in Table 1. Of the thirteen parameters used for the development process, two are likely not to be present in most commercial installations: the primary damper position feedback and the reheat valve position feedback signals. These two values were included in the development to increase the robustness of MIFDD; however, MIFDD is capable of performing FDD activities on VAV terminal units that contains *any* subset of these parameters.

Table 1. System parameters used in MIFDD development

Parameter	Signal Type	Units
Zone Temperature	Feedback	°F
Cooling Start/Stop	Control	0/1
Primary Damper Position	Control	%
Primary Damper Position	Feedback	%
Zone Air Flow Rate	Control	CFM
Zone Air Flow Rate	Feedback	CFM
Reheat Start/Stop	Control	0/1
Reheat Valve Position	Control	%
Reheat Valve Position	Feedback	%
Supply Air Temperature	Control	°F
Supply Air Temperature	Feedback	°F
Supply Duct Static Pressure	Control	inW.G.
Supply Duct Static Pressure	Feedback	inW.G.

Model-Independent Performance Indices

Using the system parameters listed in Table 1, *residual* and *fault* flags that could be calculated without the use of models or historical data were identified. These performance indices are flags in the sense that they have discrete values. A *residual* flag can have a value of 0 (measured value greater than expected), 1 (normal), or 2 (measured value less than expected). *Fault* flags can either be 0 (normal) or 1 (unexpected operating condition).

In the context of MIFDD, a residual is defined to be the difference between the "expected" and the "measured" value. Expected values may come from set points, controller output, equipment nameplate data, or a combination of these values. For example, the identified zone air temperature residual is calculated as follows:

Zone Temp Residual = Zone Temp Set Point – Measured Zone Temp

This value was then used to set the appropriate residual flag value by comparing the residual to the threshold value.

One example of a *fault*, or unexpected operating condition, in MIFDD is when the measured zone temperature is too high and the airflow rate is not at a maximum value, with these limits defined by the appropriate threshold values. These "faults" should not be confused with the failure modes that may be the actual cause of these unexpected operating conditions. In all, 11 *residual* and 19 *fault* flags were identified. Complete listings and descriptions of each of these model-independent residuals and faults are presented in Tables 2 and 3, respectively.

Table 2. Model-independent residual flags

Residual #	Status	Residual Flag Description
1	high	The measured primary damper position was greater than expected
	low	The measured primary damper position was less than expected
2	high	The terminal unit was unexpectedly providing cooling
	low	The terminal unit was not providing cooling when expected
3	high	The terminal unit was unexpectedly providing the minimum amount of cooling
	low	The terminal unit was not providing the minimum amount of cooling when expected
4	high	The terminal unit was unexpectedly providing the maximum amount of cooling
	low	The terminal unit was not providing the maximum amount of cooling when expected
5	high	The measured reheat valve position was greater than expected
	low	The measured reheat valve position was less than expected
6	high	The baseboard unit was unexpectedly providing heating
	low	The baseboard unit was not providing heating when expected
7	high	The baseboard unit was unexpectedly providing the maximum amount of heating
	low	The baseboard unit was not providing the maximum amount of heating when expected
8	high	The measured primary air flow rate was greater than expected
	low	The measured primary air flow rate was less than expected
9	high	The measured zone temperature was greater than expected
	low	The measured zone temperature was less than expected
10	high	The measured supply air temperature was greater than expected
	low	The measured supply air temperature was less than expected
11	high	The measured supply duct static pressure was greater than expected
	low	The measured supply duct static pressure was less than expected

Table 3. Model-independent fault flags

Fault #	Fault Flag Description
1	The terminal unit control was asking for simultaneous heating and cooling
2	Measured parameters indicated that simultaneous heating and cooling was occurring
3	The primary air flow rate control signal was less than the minimum allowable
4	The measured primary air flow rate was less than the minimum allowable
5	The primary air flow rate control signal was greater than the maximum allowable
6	The measured primary air flow rate was greater than the maximum allowable
7	Control signals indicated a request for heating when the reheat was not enabled
8	Control signals indicated a request for cooling when the cooling was not enabled
9	The measured zone temperature was low and system was calling for full heating
10	The measured zone temperature was low and full heating was measured
11	The measured zone temperature was low and system was not calling for full heating
12	The measured zone temperature was low and full heating was not measured
13	The measured zone temperature was high and system was calling for full cooling
14	The measured zone temperature was high and full cooling was measured
15	The measured zone temperature was high and system was not calling for full cooling
16	The measured zone temperature was high and full cooling was not measured
17	The zone air flow rate control signal was unsteady
18	The primary air damper control signal was unsteady
19	The reheat valve control signal was unsteady

As previously stated, MIFDD is capable of operating using any subset of the parameters listed in Table 1. However, as the number of available parameters is reduced, the detection and diagnostic capabilities of MIFDD are also reduced. Table 4 illustrates the dependency of each residual and fault flag to the available system parameters. For example, Table 4 shows that the "Zone Temperature" is required to evaluate residual 9 and faults 9-16. Residual 9 is the zone temperature residual and faults 9 through 16 relate to failures modes dependent upon the value of the zone temperature (as can be seen from Tables 2 and 3, respectively).

Table 4. Residual and fault flag input parameter dependencies

Parameter	Residuals											Faults																		
	1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Zone Temperature (F)[1]									✓											✓	✓	✓	✓	✓	✓	✓	✓			
Cooling Start/Stop (C)[2]																			✓											
Primary Damper Position (C)	✓																												✓	
Primary Damper Position (F)	✓																													
Zone Air Flow Rate (C)		✓	✓	✓				✓				✓		✓		✓			✓					✓		✓		✓		
Zone Air Flow Rate (F)		✓	✓	✓				✓					✓		✓		✓								✓		✓			
Reheat Start/Stop (C)																		✓												
Reheat Valve Position (C)					✓	✓	✓					✓						✓		✓		✓								✓
Reheat Valve Position (F)					✓	✓	✓						✓								✓		✓							
Supply Air Temperature (C)										✓																				
Supply Air Temperature (F)										✓																				
Supply Duct Static Pressure (C)											✓																			
Supply Duct Static Pressure (F)											✓																			

[1] Feedback signal

[2] Control signal

Threshold Values

Establishing the correct threshold value is a critical step in any fault detection algorithm. If the thresholds are too low, the number of false alarms will be high and building operators may choose to ignore the warnings. If the thresholds are too high, actual system failures may not be detected, resulting in sub-optimal control. Serious and expensive equipment failure, in addition to reduced indoor air quality and occupant comfort, could also result if system failures are not caught in time. The key to establishing acceptable thresholds is choosing values that balance these two extremes. Appropriate threshold values for MIFDD were established using a three-step process:

1. Minimum threshold values were identified from simulation of system operating in the absence of any failure modes.
2. Minimum threshold values were then identified from laboratory test data of a system operating in the absence of any failure modes.
3. Final threshold values were taken as the maximum of the previous two values. In a select few cases, threshold values were increased slightly to account for higher accuracy equipment present in the laboratory that would not be expected in a typical commercial building environment.

Appropriate threshold values in step 1 and 2 were determined using a simplified divided difference algorithm. The criteria for identifying acceptable thresholds was the smallest value that would detect and diagnose imposed failure modes without causing any false alarms.

To further reduce the possibility of false alarms, a dynamic trending capability was added. This feature tracks the status of each residual and fault flag for the past "n" time steps and behaves similar to a running average function. An alarm threshold is specified that requires a certain percentage of these past "n" flags to be at an abnormal state before a failure is detected. This default trendsize for MIFDD is 20 time steps with the alarm threshold set to 75%. For example, in a system with a scan rate of 1 minute, the zone temperature residual will be calculated each minute. If the trendsize is 20 time steps and the alarm threshold is 75%, then during 15 of the past 20 minutes, the zone temperature residual must be abnormal before the tool will detect a failure.

Despite these steps, it may be necessary to modify the threshold values slightly for individual systems. MIFDD was designed to allow for user modification of the default threshold values if necessary. Further testing of MIFDD in a real world environment will help to identify which, if any, threshold values must be modified. Thresholds that are closely related to the scan rate of a system are the most likely candidates for modification.

Fault Detection and Diagnostics

At each scan rate, the values of the residual and fault flags are combined into one pattern. This pattern consists of 30 characters, the first 11 representing the values of the residual flags (0, 1, or 2), and the last 19 representing the values of the fault flags (0, 1). If any of these flags differ from the normal operating condition (1 for residual flags, 0 for fault flags), then a possible failure mode has been detected. To diagnose the cause of the failure, the tool attempts to match the current pattern with patterns of known failure modes. This library of failure patterns was established from the 40+ simulated failures. If the tool is unable to find an exact match for the current pattern, it will tell the operator what residual and/or fault flags differed from expected in order to provide a starting point for operator diagnosis of the possible failure.

As stated earlier, it is not necessary to have available all the parameters used to develop MIFDD (see Table 1) in order to use it. Prior to performing the FDD analysis on an input file, the tool reviews the available parameters as specified by the user. It then uses these available parameters to develop the library of failure patterns unique for the specified parameters. In this way, MIFDD is not limited to only those terminal units with extensive monitoring points available.

At the current stage of development, MIFDD is designed for use offline using input files containing recorded system data. Future development efforts will incorporate the use of MIFDD in a real-time environment, using data collected through a central energy management control system and delivered through an appropriate gateway.

Laboratory Testing

Testing of the tool in a laboratory environment was conducted for two reasons: (1) to verify—and modify if necessary—the threshold values identified during simulation development and (2) to analyze the tool's FDD capabilities by inducing known fault conditions in the laboratory environment.

The laboratory system consists of two air handlers, four VAV boxes and a return fan. The central air system component is a single zone, draw-thru, built-up air handling unit. This air handling unit is comprised of, in order, an outside air economizer, a filter bank, a chilled water coil, a hot water coil, and a variable speed drive supply fan. The main air handling unit supplies medium pressure conditioned air to the variable air volume terminal units serving the zones. A second air-handling unit located up stream of the main air handler provides control of ventilation air conditions supplied to the main air-handling unit. The system also includes a variable speed drive return fan. Chilled glycol is supplied to the system by a 70-ton screw compressor chiller with an air-cooled condenser for heat rejection.

Laboratory data were collected and analyzed in 10-second increments. Table 5 lists the recommended default threshold values determined using the previously described process.

Table 5. Threshold values

Threshold Description	Minimum Simulation Threshold	Minimum Laboratory Threshold	Recommended Threshold Value
Zone temperature [°F]	1.6	0.75	1.75
Supply air temperature [°F]	N/A[1]	0.75	1.75
Supply static pressure [in W.G.]	N/A[1]	0.00	0.05
Minimum controllable airflow rate [% of design air flow rate]	2.5%	0%	10%
Airflow rate threshold [% of design air flow rate]	1%	5%	5%
Damper position [% open]	0%	2%	2%
Reheat valve position [% open]	0%	N/A[2]	2%
Primary air flow rate control signal stability [% of design air flow]	0.5%	1%	1%
Primary damper position control signal stability [% open]	0%	0.5 %	2%
Reheat valve position control stability [% open]	3%	N/A[2]	3%

[1] Primary air control was not simulated

[2] Baseboard reheat was not tested in the laboratory

Six different failure modes, in addition to a system operating in the absence of any failures, were tested in the laboratory. Three different mechanical failures, two sensor failures, and one control failure were tested. Table 6 presents a description of these failures and how they were implemented in the laboratory.

Table 6. Failure modes investigated in the laboratory

Ref. #	Failure Mode	Failure Location	Failure Cause	Notes
0	Normal operation	N/A	N/A	Normal operation evaluated to validate and modify threshold values
1	Mechanical failure	Primary air damper	Burnt-out actuator motor	Simulated in lab by locking damper at a constant position
2	Mechanical failure	Supply air temperature	Primary air temperature increased	Supply air temperature increased to from 55°F to 60°F
3	Mechanical failure	Supply duct static pressure	Supply duct static pressure decreased	Supply duct static pressure decreased from 1.85 in W.G to 0.90 in W.G.
4	Sensor failure	Primary air damper position sensor	Communication failure	Sensor value locked at 0.0
5	Sensor failure	Zone temperature sensor	Sensor drift	Measured values from sensor increased by 5°F in control system
6	Control failure	Master PID controller	Poor tuning	Proportional gain of controller increased by a factor of 8

```
Output file for Vavbox1-1a.dat
*****************************************************************************************
 Fault Pattern:        1111XXX1111XX0000X0XXXX000000X
 Fault Description:    Normal operation

 Start Time:           23-Aug-99  10:00:20 AM
 Stop Time:            23-Aug-99  10:10:30 AM
*****************************************************************************************
 Fault Pattern:        0111XXX1111XX0000X0XXXX000000X
 Fault Description:
    The measured primary damper position was greater than expected

  Possible Failure Mode  Possible Failure Location  Possible Cause
 ===================== ========================= ======================================
 Sensor Failure         Primary Damper Positioner  Communication/Complete Failure
 Sensor Failure         Primary Damper Positioner  Drift
 Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor
 Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator
 Sensor Failure         Primary Damper Positioner  Excessive Signal Noise/Vibration

 Start Time:           23-Aug-99  10:10:40 AM
 Stop Time:            23-Aug-99  10:33:29 AM
*****************************************************************************************
 Fault Pattern:        1111XXX1111XX0000X0XXXX000000X
 Fault Description:    Normal operation

 Start Time:           23-Aug-99  10:33:39 AM
 Stop Time:            23-Aug-99  10:39:10 AM
*****************************************************************************************
 Fault Pattern:        2111XXX2111XX0000X0XXXX000000X
 Fault Description:
    The measured primary damper position was less than expected
    The measured primary air flow rate was less than expected

 Possible Failure Mode  Possible Failure Location  Possible Cause
 ===================== ========================= ======================================
 Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator
 Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor

 Start Time:           23-Aug-99  10:39:20 AM
 Stop Time:            23-Aug-99  10:43:50 AM
*****************************************************************************************
 Fault Pattern:        2111XXX2011XX0000X0XXXX000100X
 Fault Description:
    The measured primary damper position was less than expected
    The measured primary air flow rate was less than expected
    The measured zone temperature was greater than expected
    The measured zone temperature was high and full cooling was not measured

 Possible Failure Mode  Possible Failure Location  Possible Cause
 ===================== ========================= ======================================
 Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor
 Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator

 Start Time:           23-Aug-99  10:43:59 AM
 Stop Time:            23-Aug-99  10:48:29 AM
*****************************************************************************************
 Fault Pattern:        2112XXX2011XX0000X0XXXX100100X
 Fault Description:
    The measured primary damper position was less than expected
    The terminal unit was not providing the maximum amount of cooling when expected
    The measured primary air flow rate was less than expected
    The measured zone temperature was greater than expected
    The measured zone temperature was high and system was calling for full cooling
    The measured zone temperature was high and full cooling was not measured

 Possible Failure Mode  Possible Failure Location  Possible Cause
 ===================== ========================= ======================================
 Mechanical Failure     Primary Air Damper         Burnt-out Actuator Motor
 Mechanical Failure     Primary Air Damper         Foreign Object/Bent Actuator

 Start Time:           23-Aug-99  10:48:39 AM
 Stop Time:            23-Aug-99  12:00:00 PM
```

Figure 3. Sample FDD output file

For each of the six failure modes investigated in the laboratory, MIFDD was able to correctly detect faulty operating conditions and diagnose likely causes for the particular failures.

Sample FDD Report

A copy of the FDD summary report generated for a laboratory test run is presented in Figure 3. In this test, the terminal unit was operating normally; then at 10 a.m., the motor on the primary air damper actuator failed. At this time, the damper was approximately 20% open. Early during the two-hour test, the damper was stuck open further than necessary, although the zone temperature was maintained within acceptable limits. As the cooling load increased in the space, the zone temperature also increased. The sample output shows the capability of MIFDD to detect and diagnose possible causes for the failed actuator motor under a variety of operating conditions.

Conclusions

Initial simulation and laboratory testing of the fault detection and diagnostic capabilities of MIFDD shows very promising results. Further testing of the tool in real-building environments is necessary, however, to provide a thorough demonstration of its usefulness. Fine tuning of the threshold values may be necessary for each building due to the wide variety of system types and data recording capabilities. Thresholds dependent on the scan rate of a system are the most likely candidates for modification.

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