On-line Monitoring And Fault Detection

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Modern energy management and control systems have alarm and trend features that allow building operators to monitor and troubleshoot building systems. The alarm feature can provide nearly immediate feedback when, for instance, a sensor value is outside specified limits. Using the trend feature, building operators can view graphs of sensor and controller output versus time. In the case of an alarm, information obtained using the trend feature can assist the operator in isolating the cause of the alarm. However, it can be difficult to select the alarm limits. If the limits are too narrow, the building control system likely will issue a number of false alarms and building operators eventually will ignore them. If the limits are too wide, faulty conditions will tend to go unnoticed because alarms are not issued.

Although alarm and trend features provide significant monitoring and troubleshooting capabilities, challenges remain. The size and complexity of building systems has led to data overload at the operator workstation. Tools and algorithms are needed to consolidate the information that arrives at the workstation into a clear picture of the system status.

This article describes one such algorithm for monitoring control performance and presents laboratory and real building data from variable-air-volume (VAV) boxes that demonstrate the utility of the algorithm for isolating faults. This algorithm, referred to as the control performance monitor, compresses large volumes of data into a small number of indices that can be used to quickly assess the performance of control loops. Indices also can be computed that allow building operators to identify actuators and valves that are wearing out prematurely due to excessive movement. The algorithm is computationally efficient and requires only limited memory for archiving data. Thus, it can reside in local digital controllers.

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Control Performance Monitor

Figures 1 and *2* provide an overview of the function of the control performance monitor and its implementation. *Figure 1* is a block diagram of a digital control system that has a control performance monitor. The feedback controller adjusts the actuator to bring the sensed value for the process output toward the setpoint. Simultaneously, the control performance monitor collects data and computes indices that quantify the control system performance and that can be accessed over the communication trunk.

Figure 2 depicts control performance monitors residing in digital controllers at various locations on the communication trunk. Although the performance indices could be computed in a central computer, there are several advantages to performing these computations in local digital controllers.

First, network communication speed makes it difficult to refresh all data points at the operator workstation at the same rate at which local digital controllers are sampling and controlling a particular control loop (in many cases this can be every second). Computing the performance indices at the local digital controllers and downloading values on a hourly or daily basis alleviates this bottleneck.

Second, by distributing the processing, the amount of processing performed at the operator workstation is reduced. A third advantage is that a service person can connect a portable computer to the network and read the performance indices for various controllers. This is important for control systems that do not have an operator workstation on the communication trunk.

Finally, there are times when the communication network is not connected or is malfunctioning. After the network communication is re-established, a building operator could determine quickly the performance of the control system by pulling data from the local digital controllers.

This article focuses on two performance indices. The first provides an

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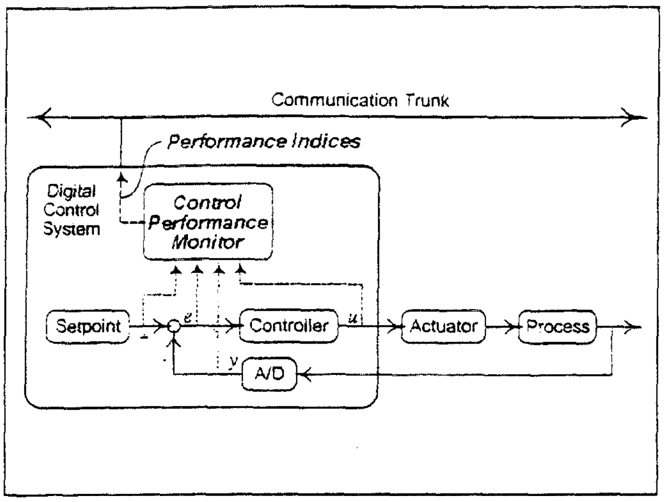

Figure 1: Single loop feedback control system with control performance monitor.

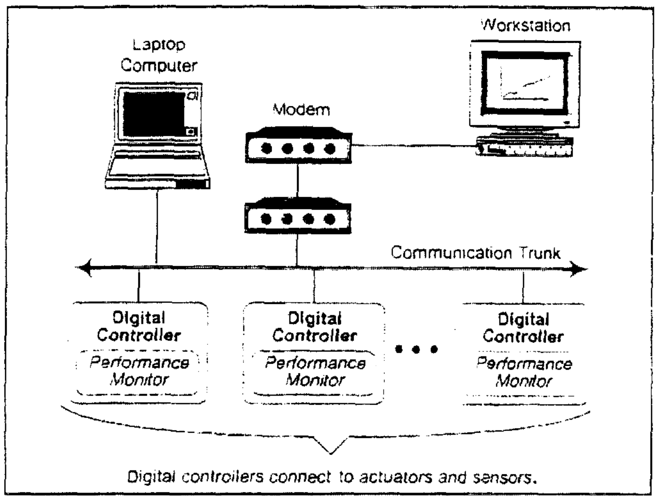

Figure 2: Network of digital controllers with performance monitors.

estimate of the process error (or simply error), defined as the setpoint value of the process output minus the measured value of the process output. This index provides an indication of how well the controller maintains the process output at its setpoint value, with values near zero indicating good control. The second performance index provides a measure of the average duty cycle of an actuator. A large value of average duty cycle is an indication of unstable control that could cause the actuator to wear out prematurely.

The performance index for the absolute value of the error is determined from

$$|\bar{e}_t| = |\bar{e}_{t-T}| + \lambda\left(|e_t| - |\bar{e}_{t-T}|\right) \quad (1)$$

where $|\bar{e}_t|$ is the exponentially weighted moving average (EWMA) of the absolute value of the error at time t, $|\bar{e}_{t-T}|$ is the EWMA of the absolute value of the error at time $t - T$ where T is the sampling time of the digital controller, λ is the exponential smoothing constant, and e_t is the error at time t.[1] $|\bar{e}_t|$ is a measure of how well the controller has maintained the process output at the setpoint value over a period of time. This performance index will be large for both persistent errors and for control systems where the process output oscillates around the setpoint.

The performance index for duty cycle is determined from

$$\bar{d}_t = \bar{d}_{t-T} + \lambda\left(d_t - \bar{d}_{t-T}\right) \quad (2)$$

where $\bar{d}_t$ is the EWMA of the duty cycle at time t, $\bar{d}_{t-T}$ is the EWMA of the duty cycle at time $t - T$, and d_t is the duty cycle between time t and $t - T$. (The duty cycle at time t is the fraction of time an electric actuator has been operating between time t and $t - T$.) A large value of $\bar{d}_t$ would indicate that mechanical components (such as actuators, valves, or dampers) are moving excessively and could wear out prematurely.

There are a number of additional performance indices that can be used to assess control performance, including the process error, process output, valve and damper control signals, and the number of starts, stops and reversals of an actuator. Each provides useful information for both assessing the control performance and for troubleshooting when a fault is detected.

The main challenge to using *Equations 1* and *2* is the selection of the proper smoothing constant, λ. If λ is too large, the performance indices will take on large values following a load disturbance or setpoint change. If λ is too small, the time required to detect a fault will be excessive. The following guideline can be used to select a smoothing constant that will give a good estimate of the control performance:

$$\frac{T}{20t_s} < \lambda < \frac{T}{5t_s} \quad (3)$$

where t_s is the settling time of the control system. The settling time is the time required for the process output to settle to and remain within $\pm\,\delta$ of the final value. Common values for δ are 1%, 2%, or 5% of the size of the setpoint change.[2,3] Note that the selection of λ depends only on the dynamics of the control loop and the sampling time of the digital controller. Hence, if a single control loop is considered (e.g., the flow control loop in a VAV box controller), *Equations 1* and *2* would use the same value of λ.

Conventional moving averages have a fixed-length-sliding window of data with each data point contributing equally to the average. EWMAs weigh recent values more heavily than past values. The smaller the value of λ, the greater the influence of past values on the EWMA. When $\lambda = T/(X \cdot t_s)$ where X is an arbitrary number, approximately 63.2% of the weighting in the computation of the EWMA is assigned to the data between times t and $t - X \cdot t_s$.

Another important difference between conventional moving averages and EWMAs is the amount of data that must be stored to make the computations. For EWMAs, *Equations 1* and *2* show that only the previous value of the EWMA must be stored. Other terms in these equations are current values. Con-

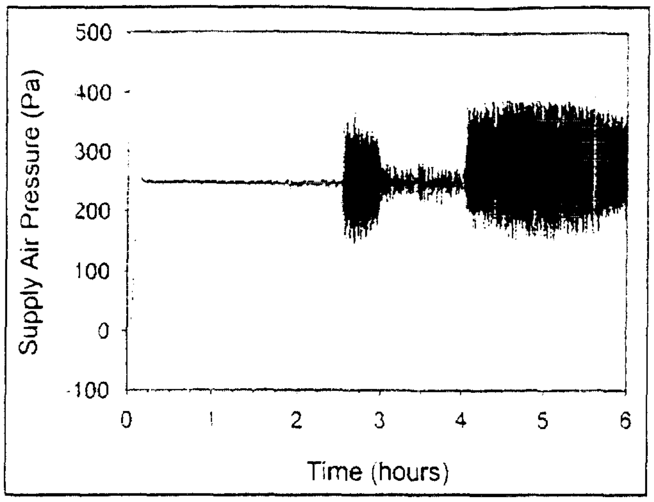

Figure 3: Static pressure during laboratory test.

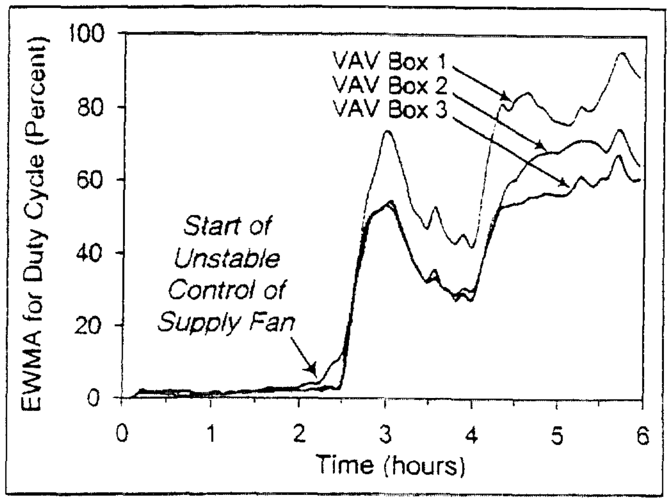

Figure 4: EWMA of the duty cycle during laboratory test.

ventional moving averages based on the past n values of a variable must store all n values. This storage savings can become important when attempting to implement numerous performance indices in a controller with limited memory.

VAV Laboratory Results

Yoshida described a number of faults that cause pressure-independent VAV systems to fail.[4] Examples include stuck dampers and actuators, fouling of the reheat coil, improper installation of the reheat coil valve, incorrect readings from the flow measurement station, drifting of the zone temperature sensor, and oscillating VAV dampers caused by poor controller tuning.

Laboratory tests were performed to assess the capability of the control performance monitor to identify symptoms in VAV boxes subjected to faults. The laboratory system consisted of a VAV air-handling unit (AHU) that supplied air to three VAV boxes. The faults introduced consisted of a stuck damper in one of the VAV boxes, and an unstable supply fan control loop. (The supply fan was controlled to maintain the static pressure in the supply duct at a fixed setpoint value and, therefore, would affect all VAV boxes served by the AHU.) The stuck damper fault was detected easily by observing that the EWMA for the absolute value of the flow error for that particular VAV box increased as the zone load changed.

Figure 3 shows the supply air pressure during the test for the unstable static pressure control. Data for the initial two and one-half hours of the test show that the controller is performing well and is maintaining the supply air pressure at the setpoint value of 249 Pa (1 in. of water). The controller gain was then increased by a factor of 4.5, causing the static pressure to oscillate. The oscillations of the static pressure caused the dampers in the VAV boxes to move excessively.

Figure 4 shows the EWMAs for the duty cycle of the three VAV boxes. Notice the obvious increase in the EWMAs caused by the oscillation of the dampers. Hence, this EWMA can be used to identify actuators that are likely to fail prematurely due to excessive movement.

AHU Laboratory Results

The AHU system described in the previous section also was tested to assess the capability of the control performance monitor to detect six other AHU faults. The faults introduced consisted of a complete failure of the supply fan, a complete failure of the return fan, a stuck cooling coil valve, a complete failure of the supply air thermocouple, a complete failure of the supply airflow station, and a complete failure of the return airflow station. Plots of the performance indices versus time showed that the performance monitor successfully identified the presence of a fault in each case.[5]

VAV Field Test Results

The utility of the performance indices is best demonstrated by examining their implementation in a real building application. In one particular building, a subcontractor installed new digital controllers for 24 dual-duct VAV boxes. The subcontractor and building engineer were confident that the VAV controllers were installed correctly and operating properly. The controlled variables were sampled every 1.5 seconds. The smoothing constants for the flow error and temperature error were 0.000833 and 0.000104, respectively. An average duty cycle was determined from the last time the controller was reset. The figures that follow represent a snapshot of the operation of the 24 VAV boxes at a particular point in time.

Figure 5 shows the normalized flow error for the 24 VAV boxes. To normalize the flow error, the EWMA of the absolute value of the flow error was divided by the design maximum flow rate for cooling. The normalized flow errors for Boxes 16 and 18 are significantly larger than those for the other boxes. Further investigation revealed a defective capacitor in the electric motor for Box 16. Box 18 was found to have an incorrectly installed electric damper actuator. Specifically, it had been locked to the damper shaft 90 degrees from the correct position causing the VAV box to be wide open when the VAV controller issued a closed command, and to be completely closed when the VAV controller issued a command for full flow.

For the fault-free VAV boxes (i.e., all boxes except 16 and 18),

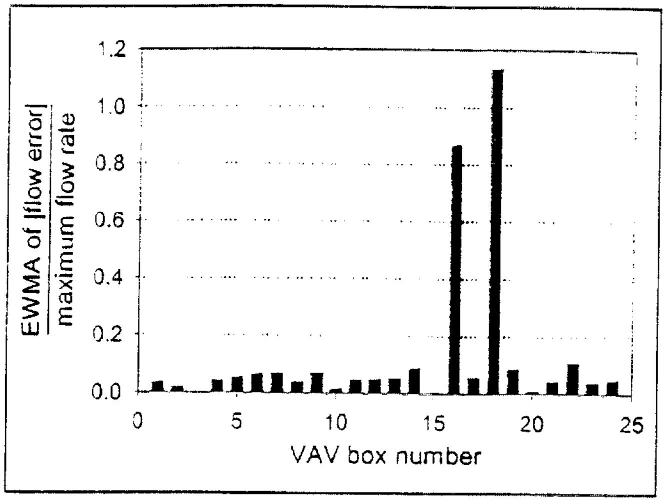

Figure 5: EWMA of the normalized flow error for the field-installed VAV boxes.

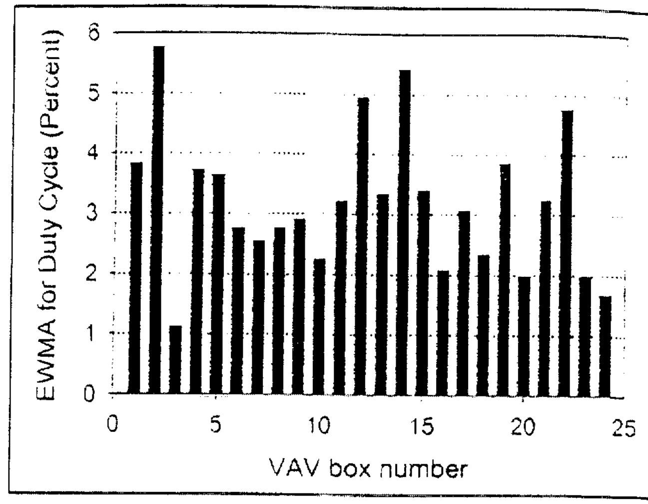

Figure 6: EWMA of the duty cycle for the field-installed VAV boxes.

the average normalized flow error was 0.047 and the standard deviation was 0.027. For VAV Boxes 16 and 18, the normalized flow errors were 0.866 and 1.136, respectively. These flow errors are 30 and 40 standard deviations larger than the average value for fault-free boxes.

Figure 6 shows the EWMA for the duty cycle of the 24 VAV boxes. There appears to be no significant outlier in the duty cycle data. If the large normalized flow errors seen in *Figure 5* were due to unstable control, then larger than normal duty cycle values would also be observed for these boxes.

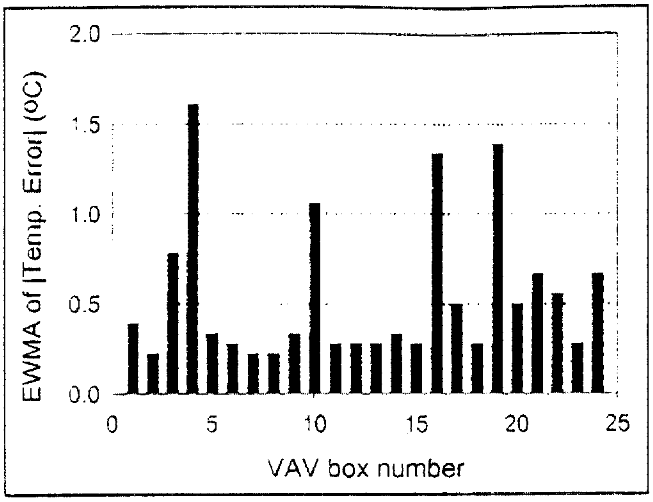

Figure 7: EWMA of the absolute value of the temperature error for the field-installed VAV boxes.

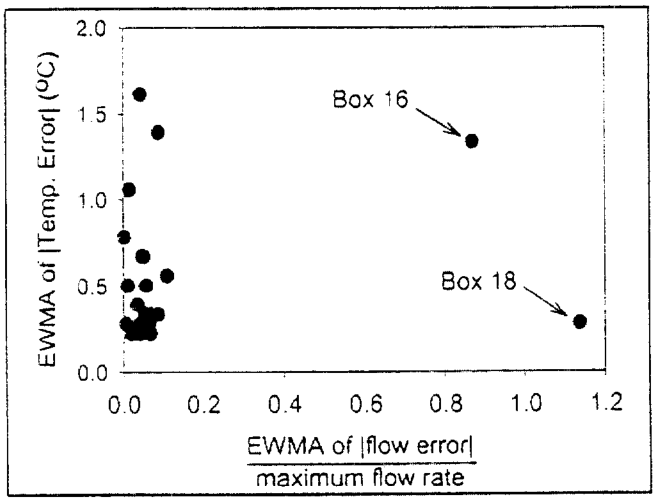

Figure 8: EWMA of the absolute value of the temperature error versus EWMA of the normalized flow error for the field-installed VAV boxes.

Figure 7 shows the EWMA of the absolute value of the temperature errors for the 24 VAV controllers. The temperature errors indicate that four or five VAV boxes could be operating in the presence of faults (Boxes 3, 4, 10, 16 and 19). *Figure 8* is a plot of the EWMA of the temperature errors versus the EWMA of the normalized flow errors. This figure can help a building operator prioritize maintenance for boxes with the high-normalized flow errors by identifying which of the boxes has the highest temperature error and, therefore, the highest likelihood of uncomfortable occupants. Although Box 18 has a larger flow error than Box 16, Box 16 probably should be examined and repaired first because of the large temperature error associated with this box. The controllers for Boxes 3, 4, 10 and 19 should be monitored further to determine if they require maintenance.

Conclusions

Performance indices computed using EWMAs make it practical to simultaneously monitor the recent performance of large numbers of digital controllers because they effectively compress performance data. This was demonstrated with real building data from pressure-independent VAV boxes. Because the EWMA algorithm is numerically efficient and requires very little memory, it can be used in today's digital control systems to compute performance indices on-line. There are several possible uses of the performance indices:

- The performance indices can be used to compare the performance of similar controllers. By comparing performance indices, a building operator can easily identify faulty systems. Also, the performance indices can provide an early indication of systems that may prematurely wear out due to excessive actuator movement.
- The performance indices can be used in a real-time fault detection system. A fault could be determined by comparing the performance indices with thresholds determined from expert knowledge or statistical quality control.[6]
- A diagnostic system can be developed that uses patterns of the performance indices to identify causes of a fault.

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