Embedded Controllers for Increasing HVAC Energy Efficiency by Automated Fault Diagnostics

Jiří Vass, Jana Trojanová, Radek Fišera, Jiří Rojíček
Automation & Control Solutions (ACS) Laboratories
Honeywell
Prague, Czech Republic
{Jiri.Vass, Jiri.Rojicek}@Honeywell.com

Abstract— **This paper illustrates the use of embedded controllers for improving energy efficiency of commercial buildings. The next generation of intelligent controllers (such as Honeywell JACE controllers) will be capable of automatically diagnosing the faults and degradations of the Heating, Ventilation & Air Conditioning (HVAC) equipment. This paper gives an example of a diagnostic algorithm for air-handling units (AHUs), and also emphasizes the importance of data pre-processing (cleansing) to obtain reliable diagnostic results. Early detection of HVAC faults can reduce the wastage of heating/cooling energy and improve the comfort of building occupants.**

Keywords-HVAC; AFDD; embedded controller

I. Introduction

Due to increasing energy prices, building owners have become more interested in optimizing energy usage of their buildings. A major energy consumer in commercial buildings is the HVAC equipment, such as boilers, chillers, air-handling units, and their auxiliary devices (fans, pumps, valves, etc.). Therefore, correct (fault-free) operation of the HVAC equipment, together with intelligent HVAC control, is an attractive way to achieve significant energy savings and reduce CO2 emissions.

Saving energy in both commercial and industrial sector is one of the key areas where Honeywell generates its revenue. To increase HVAC energy efficiency, Honeywell is developing solutions to automatically detect any issues causing energy wastage and/or comfort compromise, such as: (a) *abrupt hardware faults* (stuck damper, leaking valve, frozen sensor), (b) *long-term performance degradation* (boiler fouling, heat exchanger scaling, air filter clogging), (c) *control inefficiencies* (oscillatory control signals, permanent setpoint offset, improper utilization of outdoor air, simultaneous heating and cooling, etc.). All detected issues are graphically depicted using intuitive online software (showing the layout of each HVAC equipment), and can be also aggregated over time to generate an automated diagnostic report (with various charts summarizing energy usage, comfort level, equipment performance, etc.). This paper contributes to the area of HVAC fault detection, which represents one of the approaches for reducing energy costs of buildings.

Building automation is one of the areas where embedded devices are used for monitoring and control of energy usage. In large building complexes (enterprises) the distributed control architecture is commonly used. An intelligent embedded controller (integration controller) communicates with (a) the supervisory system, i.e. workstation with Building Management System (BMS), such as Honeywell EBI (Enterprise Buildings Integrator™) and (b) the local (unitary or plant) controllers (responsible for control of individual pieces of equipment, such as boiler, AHU, VAV, lighting). Honeywell embedded controllers (e.g. JACE controllers [1] based on the Niagara^AX framework) are capable of integrating various building sub-systems, such as HVAC, lighting, security, fire, access control, etc. The JACE (JAVA® Application Control Engine) controllers are based on a small, compact platform allowing to integrate the functions of control, supervision, data logging, alarming, scheduling and network management with the internet connectivity and web serving capabilities. It enables the user to control and manage external devices over the internet, as well as to observe real-time information using web-based graphical views. From the energy usage viewpoint, the most important functionality of JACE controllers is the supervision of local controllers responsible for HVAC control, lighting control and power monitoring. Moreover, the next generation of embedded controllers will be also capable of performing the AFDD (Automated Fault Detection & Diagnostics) of HVAC equipment in order to minimize the energy wastage caused by abrupt mechanical faults and gradual equipment degradations.

II. AFDD Algorithm for Air Handling Units

This paper gives a specific example of the AFDD algorithm for air-handling units. The example also illustrates that data pre-processing can be the key differentiator between a good and poor AFDD algorithm, hence a special attention is paid to the data cleansing module.

Fig.1 shows a block diagram of the AFDD algorithm consisting of four main modules (detailed description of each module is beyond the scope of this paper and can be found in [2]). The data cleansing module validates the correctness of raw input data (sensor data, control signals) and classifies the data into two categories: valid or invalid. This module increases the robustness of the AFDD system by protecting it against raw errors, and thus avoiding incorrect diagnoses.

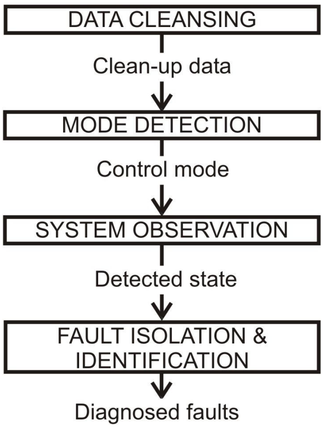

Figure 1: AFDD system for air-handling units (taken from [2]).

Typical examples of invalid sensor data are abrupt errors (outliers, missing values), while control signals are regarded as invalid in case of oscillations (large periodic fluctuations of the amplitude).

The AFDD algorithm is based on APAR (AHU Performance Assessment Rules), which is a heuristic technique (first proposed by Schein et al. [3]) based on a set of *expert rules* derived from mass and energy balances [3]. This rule-based approach can detect abrupt mechanicals faults (e.g. stuck damper, leaking valve) and other typical problems, such as communication failures and wrong control logic.

A typical diagnostic rule (for AHU operating in the heating mode) is as follows: if the supply air temperature is below its setpoint, and the heating control signal is 100% (i.e. heating valve is commanded to a fully open position), then the possible faults can be: a) stuck heating valve, b) heating failure, c) stuck/leaking cooling valve. The rules are mutually exclusive and cover all possible combinations of the input data (typically temperatures, setpoints and control signals). When a certain rule is satisfied, the probability (relevance) of the corresponding fault(s) is increased. The fault relevance is aggregated in time, which allows applying the methods of reasoning [4] in order to isolate the most likely fault. Also note that the diagnostic rules can be further enhanced by the fuzzy approach (defining fuzzy borders instead of "strict" thresholds).

The AFDD algorithm provided correct results when applied to data *without* errors, such as outliers, missing data, out-of-range data, etc. However, when applied to real data from a real building, it was unable (in some cases) to correctly diagnose the actual fault. The most common reason was an oscillating control signal that resulted in unreliable fulfillment of the expert rules. The AHU is a system with slow dynamics (e.g. after opening the heating coil valve it takes several minutes until the air temperature starts increasing). In case of an unstable control loop (e.g. control signal for heating valve oscillates between 0 and 100%), the delay caused by system dynamics is adversely affecting the system observation (i.e. when some diagnostic rule is applied the system is already in a different state). As a result, the AFDD algorithm provided unreliable system observation that resulted in wrong diagnostics. To overcome this problem, we have developed a data cleansing method capable of detecting outliers (in sensor data) and oscillations (in control signals), as shown in Fig. 2.

The outlier detector is based on EWMA (Exponentially Weighted Moving Average). For detecting the outliers, sensor signal is high-pass filtered (using EWMA), then its three-sigma limits are computed, and only the samples within these limits are regarded as valid. The oscillation detector utilizes the fact that oscillations have a periodic character, and thus increase the high-frequency content of the signal. At the same time, its variance σ^2 also increases due to a wider range of signal amplitudes. Therefore, oscillations are detected by low-pass filtering the signal (using EWMA) and comparing the standard deviation of the original and filtered signal (denoted as σ_x and σ_y, respectively). The control signal is regarded as invalid when $\sigma_x > C \cdot \sigma_y$, where C is a positive constant controlling the sensitivity of the detector. Whenever this method detected some invalid data no diagnostic rules were applied, hence the fault relevance (of all faults) was not updated. As a consequence, the calculated fault relevance became more reliable (unaffected by invalid data) and the fault reasoning method provided more consistent results.

Fig.3. illustrates an example of a fault-free AHU with an oscillating control signal (as depicted in Fig.2). The AFDD algorithm consists of 3 stages: *state observation*, *fault detection*, and *fault relevance aggregation*. If the data cleansing would not be applied (left column in Fig.3), the observation of the abnormal behavior would result in detection of multiple faults. These incorrect detections affect the outcome of the gradual fault aggregation and non-existing (hoax) faults are diagnosed. Therefore, the use of the data cleansing module protects the fault reasoning module from making wrong decisions when the data are invalid.

III. CONCLUSION

This paper illustrated the use of embedded systems for increasing energy efficiency of commercial buildings by detecting faults and degradations in the HVAC equipment. A specific example of diagnosing mechanical faults in air handling units was given. The corresponding AFDD algorithm is optimized for use in intelligent embedded controllers, such as Honeywell JACE controllers. The paper also emphasized the importance of data preprocessing to obtain better diagnostic results.

REFERENCES

[1] Tridium, Inc. "Tridium Solutions Guide", 29 pages. *http://www.tridium.com*

[2] J. Trojanova, J. Vass, K. Macek, J. Rojicek and P. Stluka, "Fault Diagnosis of Air Handling Units," in Proc. SafeProcess 7th IFAC International Symposium on Fault Detection, Supervision and Safety of Technical Processes, Barcelona, Spain, 2009..

[3] J. Schein, S.T. Bushby, N.S. Castro, J.M. House, "Rule-Based Fault Detection Method for Air Handling Units," ., Energy and Buildings. 38, p 1485-1492, 2006.

[4] J. Kukal, K. Macek, J. Rojicek and J. Trojanova, "From Symptoms to Faults: Temporal Reasoning Methods," Proc. 2009 Int. Conference on Adaptive and Intelligent Systems, Klagenfurt, Austria, 2009.

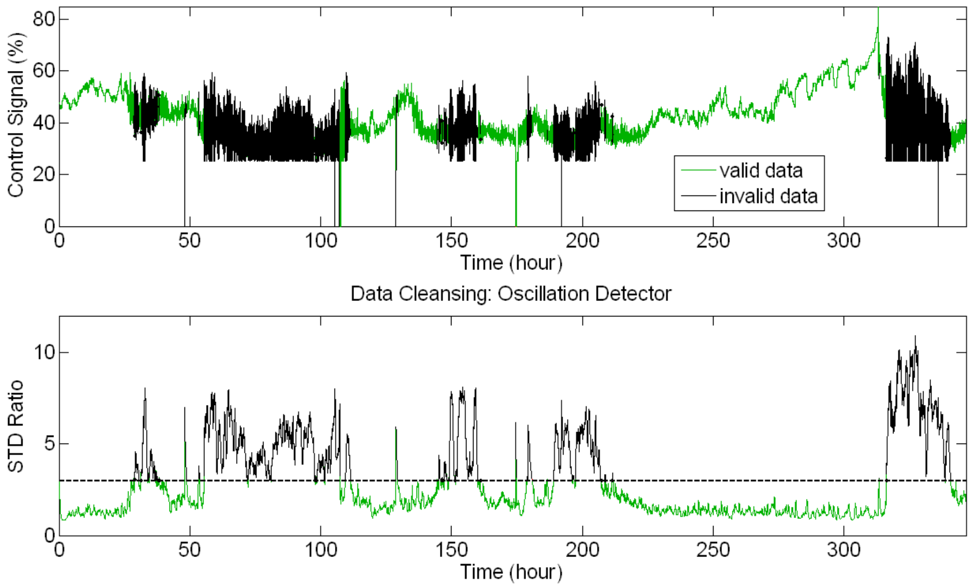

Figure 2: Data pre-processing to detect oscillations in control signals: the bottom figure shows a statistical indicator (based on standard deviation and low-pass filtering) whose high value (above the threshold) corresponds to oscillating (i.e. invalid) control signal (shown by black color in the top figure).

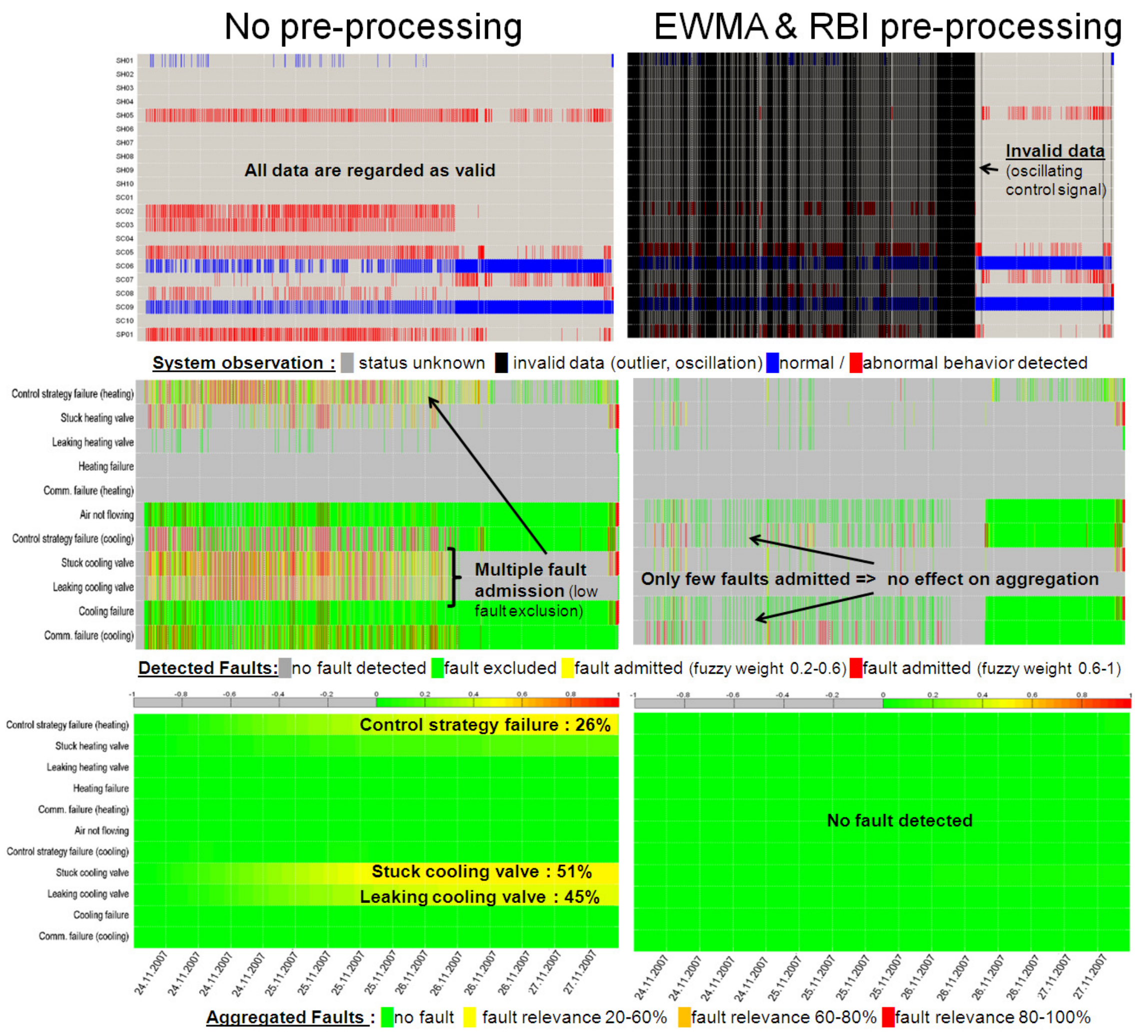

Figure 3: AFDD algorithm consisting of 3 stages: state observation (top row), fault detection (middle row), and fault relevance aggregation (bottom row). Without data pre-processing (left column images), all data are regarded as valid, which causes the AFDD algorithm to produce misleading results (non-existing faults are detected). When using data pre-processing (right column images) to detect invalid data (oscillations, outliers), the AFDD algorithm produces correct diagnosis (because fault relevancies are not updated when invalid data are detected).