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Advanced Control Solutions for Building Systems

Petr Stluka* Karel Mařík* Petr Endel*

* *Honeywell ACS Global Laboratories, Prague, Czech Republic*
e-mails:petr.stluka, karel.marik, petr.endel@honeywell.com

Abstract: The path of an innovative technology from the research stage to the validation in real test beds and subsequent commercialization and wider deployment may not always be straightforward. Multiple domain-specific constraints need to be considered and properly addressed. In case of the advanced control solutions for building's Heating Ventilation and Air Conditioning (HVAC) systems, one needs to keep in mind limitations given by the legacy control hardware, typical instrumentation levels, and overall cost-to-benefit ratio. The paper is written from the corporate R&D perspective and discusses methodological and practical aspects of design, validation and implementation of advanced control solutions in the application domain of commercial buildings. All issues are illustrated based on experience from the development of two different technologies: an embedded solution for control performance monitoring and a cloud-based supervisory control for HVAC systems.

1. INTRODUCTION

Today's Building Management Systems provides monitoring and control capability for multiple sub-systems including HVAC, electrical systems, fire systems, security systems and others. They play an essential role in realization of an "intelligent building", which can be defined from many different perspectives: for instance this can be a building that provides the most convenient environment to its occupants, offers a high level of automation, delivers top energy and environmental performance, provides high availability of managed spaces, or everything together. The recent technology trends in the area of building automation enable the development of new types of advanced solutions. The main trends can be generally characterized as follows:

Cloud computing enables the retention of more detailed data about the facility as well as integration of the automation data with other business data (Everett et al., 2013). This in turn enables more powerful building analytics, which can be further improved through Big Data technologies to better inform end users and decision-makers responsible for the operation of the building.

Embedded Intelligence. More computational power and intelligence residing directly in building automation devices will enable an extensive set of self-commissioning, self-tuning, self-diagnostic and correction, and even self-configuring features (Hartman, 2012).

Interoperability. The demand for interoperability between various solutions is driving many industry standards, including Building Information Model (BIM), Haystack, gbXML and similar standards for energy management, and additional protocols and standards for Asset Management (Hamil, 2012).

End-user experience. There is a growing focus on human factors and end-user experience that is driving innovative concepts relying on an active occupants' engagement, such as the Social Building (Irwin, 2013) or the Collaborative Energy Management and Control (Lu et al., 2012).

Development of new control and optimization capabilities for building systems is reflecting the above trends at a continually increasing extent, but at the same time, any new designs have to take into account all traditional barriers and challenges for deployment of these solutions, from which we would like to highlight the following three (Marik et al., 2011).

Legacy automation systems may cause problems in several aspects. Firstly, serious interoperability issues arising from the wide variety of proprietary protocols can make integration of multiple systems from different companies a challenge. Then also control strategies for legacy controllers are often coded in programming languages that do not allow easy modularization of the code, and therefore do not support easy reuse from one application to another.

Instrumentation level in a typical building is not always sufficient for implementation of advanced control solution. Flow sensors - for both air flow and water flow measurement – are typically not available, which makes it difficult to setup models based on enthalpy balances. Similarly, the lack of meters and sub-meters for electricity and gas can severely limit the calculation of energy costs and objective functions used by the optimizers.

Cost-to-benefit ratio remains one of the major limitations. Total cost associated with implementation of an advanced monitoring or control solution includes setup and configuration cost, maintenance cost, cost of additional sensors, and cost of potential hardware retrofits. Desire for an attractive return of investment usually disqualifies complex solutions requiring significant engineering effort to configure and install the solution, as well as to maintain it in long-term.

The paper discusses two innovative solutions – one in the category of embedded intelligence, the other related to cloud-based building automation – while emphasizing important methodological and practical aspects of the solution design, validation, and transition into commercial environment. The text is structured in a way that the Sections 2 and 3 first summarize technical concepts of the control performance monitoring and cloud-based supervisory control solutions. This is then followed by the methodological overview in Section 4, which provides insights into main aspects of the development process.

2. CONTROL PERFORMANCE MONITORING

2.1 Problem Description

A typical HVAC control project requires installation and tuning of multiple PI controllers. Usually there is a little time for manual tuning and also the installers often do not have a rigorous control engineering background. As the result, the control loops are often not properly tuned. In addition, the commissioning during one season leaves loops operating in another season, non-linear HVAC behavior causes poor control at some operating points, and the disturbances are significant. Due to these reasons even the good control quality can deteriorate in time - the comfort is then often violated, the energy is wasted or the actuators are worn out.

Because of that there is a need to monitor the control performance after the installation and identify the poor behavior of loops to prevent those negative effects. There are hundreds of control loops in a building, so the preferred solution is to perform monitoring on the lower level and on-line, without need of data transfer, storage and off-line evaluation.

Existing solutions represent offline analysis of the data in order to classify the performance of loops. Those tools focus more on deeper engineering analysis, and they often do not provide quick reference needed by field engineers. Existing online analysis tools focus on particular aspects of poor controller tuning (e.g. oscillatory or sluggish control), not presenting generalized performance indicator nor wider diagnosis.

2.2 Concept and Requirements

The main idea of performance monitoring of HVAC controllers is to assess and diagnose the behavior of wide variety of control loops to provide information, alert or prioritization in cases when the control quality has deteriorated or the actuators do not behave in a standard way due to valve stiction, backlash, or other faults. The diagnosis is done directly in the controller in order to trigger the loop tuning mechanism, which re-tunes the controller if the cause of poor behavior can be addressed by proper tuning. The status information can also be collected by a higher level monitoring software, which can provide status reports with aggregated statistics.

Based on this description the main requirements of the solution can be summarized as follows. The algorithm should have low memory requirements (recursive algorithms are preferred), it should not provide false alarms, and it should be applicable to a variety of loops in a building. From the user interaction perspective, the solution should be easy to set-up and capable to provide results in an intuitive way, while suggesting or invoking the correct action.

2.3 Methods Used

To meet the solution requirements the performance indices and oscillation detection methods were employed and further augmented by diagnostics, whose results were then merged to form aggregated performance measures. All indices were designed to be computed recursively.

The predictability index, based on minimum variance index (Harris et al., 1999, Horsch et al., 1999), reflects how well the controller error is predictable. In an ideal case the controller error should be white noise, because any model of it can be used for improving the control. For that purpose the auto-regressive model of the controller error is formed, and compared in terms of lower prediction error variance to the better of two elementary models – naive predictor and error variance. The predictability index is defined as

$$PI_{pred} = 1 - \frac{\sigma_{mv}^2}{\min(\sigma_{NP}^2, \sigma_{error}^2)}, \tag{1}$$

where σ_{mv}^2 is the prediction error variance of the model of controller error, σ_{NP}^2 is the prediction error variance of the naive predictor, and σ_{error}^2 is the variance of the controller error. The value of index close to one represents the poor loop performance. The same numerical logic applies to other indices as well.

The fluctuation index is designed to detect high frequency quasi-periodic behavior with low amplitudes in controller output, which causes extensive wear of the actuators (e.g. heating and cooling valves), and it is defined as

$$PI_{fluct} = 1 - \frac{\sigma_{error}^2}{\sigma_{NP}^2}, \tag{2}$$

where σ_{NP}^2 is the prediction error variance of the naive predictor, and σ_{error}^2 is the variance of the controller error.

The offset index detects offset in controller error based on (Rhinehart, 1995), defined as

$$PI_{off} = 1 - \frac{\sigma_{NP}^2}{MSE}, \tag{3}$$

where σ_{NP}^2 is the prediction error variance of naive predictor, and *MSE* is mean square error of controller error.

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