ASHRAE Research Project Report 1587-RP

Control Loop Performance Assessment

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ASHRAE RP-1587 Control Loop Performance Assessment

Final Report

Prepared for
Project Monitoring Subcommittee
ASHRAE Technical Committee TC 1.4
Control Theory and Application

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Executive Summary

This is the final report for the control loop performance assessment project sponsored by ASHRAE. In this project, two single control quality factors (CQFs) in the context of building heating, ventilation and air-conditioning (HVAC) controls were developed and tested. These CQFs need to be objective, quantitative metric with simple-to-interpret criteria; additionally, they need to use only typically available data from HVAC control systems, such as the control loop output.

An extensive review of control loop performance assessment in various industries reveals that few studies are available to assess HVAC control loop performance. We systematically reviewed 35 indices and their associated methods of evaluating control loop performance, including their drawbacks and merits. Fourteen of these indices were selected to assess their performance on an air handler unit (AHU) heating coil outlet air temperature control loop using simulated data from a dynamic Modelica model. Based on the review and preliminary simulation results, two CQFs — the normalized Harris Index and Exponential Weighted Moving Averages (EWMA) — were recommended for further investigation. The first CQF (i.e., CQF-Harris) is based on the normalized Harris Index, together with a reversal index that detects control response trend reversal behaviors. The second CQF (i.e., CQF-EWMA) is the EWMA-based index along with the reversal index.

A CQF scale was developed to categorize HVAC control loop performance: excellent (A), good (B), fair (C), bad (D), and fail (F). For CQF-Harris, the scale is based on the ratio of control output variance to the minimum variance. For CQF-EWMA, the scale is based on the dimensionless error ratio between control output and the set point. The scale ranges are also given for the two CQFs. The proposed CQFs were implemented on simulated HVAC control loops through offline testing. A total of 16 simulated control loops (two sets) were assessed based on data from Modelica models. The first set of models is for the AHU heating/cooling coils. The

second set of models is for the dynamic VAV system with room models. This offline testing shows that the proposed CQFs can assess control loop performance with correct scales. Sensitivity analyses were conducted for CQF-Harris with respect to unmeasured disturbance (i.e., white noise) variance, moving window length, and sampling frequency. The results show that CQF-Harris is sensitive to unmeasured disturbance variance and to the length of the moving window, although it is less sensitive to the sampling frequency. The sensitivity analysis was also conducted for the CQF-EWMA with respect to the sampling frequency and unmeasured disturbance variance, and the results show that it is not sensitive to these two parameters.

The proposed CQFs were also tested using data from real control loops. A total of 213 real control loops were tested in six data sets. These loops covered VAV room air temperature control, AHU supply air temperature control, AHU static pressure control, water loop differential pressure control, and VAV airflow control, etc. The first four sets are from an office building in Chicago, Illinois. The fifth set is from the Iowa Energy Center's Energy Resource Station. The sixth set is from a classroom and laboratory building on campus at the University of Alabama. The test results show that the both CQFs are effective in assessing control loop performance. The assessments using these two indices are aligned with each other for the majority of the test cases.

Furthermore, sensitivity analyses for the real VAV control loops were conducted with respect to sampling frequency and length of the moving window. From the results, it is recommended that a moving window length of 80 or 100 minutes (i.e., 20 samples with a sampling frequency of four or five minutes) be used for VAV control loops. A weighted CQF for an evaluation of the averaged control loop performance over a given assessment time period is also proposed for the two CQFs with applications for real control loops.

Real-time field-testing with actual HVAC system and local VAV controllers were conducted at the Iowa Energy Center's Energy Resource Station. Both single maximum and dual maximum control logics were tested. Both proposed CQFs were able to be successfully programmed and downloaded to four real DDC (direct digital control) local controllers. The real-time CQFs values are consistent with those from offline Matlab computations. However, the effort in implementing CQF-Harris index was quite involved, and required significant computational resources for the controllers. It is recommended to adopt the CQF-Harris index for DDC controllers with a higher CPU power and larger memory, for example, higher than 2MB. It should be programmed by controller manufactures as a standard “calculation block”. Implementing the CQF-EWMA index on these DDC controllers was easy and straightforward, and can be implemented in most of modern DDC controllers by engineers who are familiar with DDC programming.

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Chapter 1 Introduction

1.1 Background

Heating, ventilation and air-conditioning (HVAC) systems are used to control environmental variables such as temperature and humidity in the built environment. Although some intelligent controllers (e.g. fuzzy logic controllers (Yen and Langari 1998) and pattern recognition adaptive controllers (Seem 1998)), have been developed over the past two decades, the most commonly used controller in HVAC applications remains the Proportional-Integral (PI) type (Seem 1998; Zhao et al. 2013b). Indeed, 95% of industrial controllers are of the Proportional-Integral-Derivative (PID) type even though most loops are actually PI-controlled (Aström 1995). The PI/PID controller has proven simple to implement and sufficient for most HVAC applications.

However, numerous studies show that, while effective in regulating the built environment, HVAC systems that poorly implement these controllers often use energy inefficiently (Barwig et al. 2002). Poorly performing control loops are a common issue across various industries and result in wasted energy, reduced occupant comfort, and excessive and unnecessary wear of actuators. In a 2000 Honeywell report (Edgar 2007), the author listed performance assessment numbers for installed controllers based on surveys. Of the 64% of controllers that utilized closed-loop feedback, 25% were rated as having excellent performance, 23% as acceptable, 34% as fair, and 16% as poor. Based on the data available, performance for HVAC control loops is even worse. Often, reduced performance in HVAC control loops is a result of manufacturer/field engineer/facility managers focusing on customers' desired indoor environment rather than on HVAC control loop performance. The focus on customers' desired environment contributes to wasted energy due to poor control loop performance in HVAC applications.

Cost and performance are always the biggest concerns in the HVAC industry. For engineers installing and commissioning a system, time spent tuning control loops can significantly add to the overall expense. Controllers are conventionally shipped with default tuning parameters that are determined through manufacturers' lab tests. Without retuning, those default parameters could result in poor control performance since the actual HVAC systems will, in practice, almost certainly have nonlinear and varying dynamics different from those at the manufacturers' test facilities (Federspiel and Seem 1996). Loads for a given HVAC system will often vary with time due to seasonal or job-schedule loads (summer vs. winter and weekday vs. weekend, for example). To better optimize performance, tuning parameters in the controller should be adjusted to accommodate such major process parameter variations. At this time, the tuning procedure commonly used in the HVAC industry is highly labor-intensive and subject to human error as stated in ASHRAE Guideline 11 (ASHRAE 2009). As an alternative, auto-tuning (Aström 1995) is emerging to automate the tuning of control loops in HVAC applications (Dexter et al. 1990; Dexter and Haves 1989; Zhao et al. 2012). Unfortunately, the HVAC industry does not have standard and quantifiable methodologies to test and verify the state of tuning and the performance of systems operating under closed-loop control. Current methods include proprietary schemes and labor-intensive manual methods.

Control loop performance assessment (CPA or CLPA) is an important step to guarantee the efficiency of automation systems. It is also a key step for deciding if the fault detection and diagnosis is necessary and if there is a need for subsequent tunings of control loops. A diagram of a typical procedure for control loop performance monitoring is shown in Figure 1.

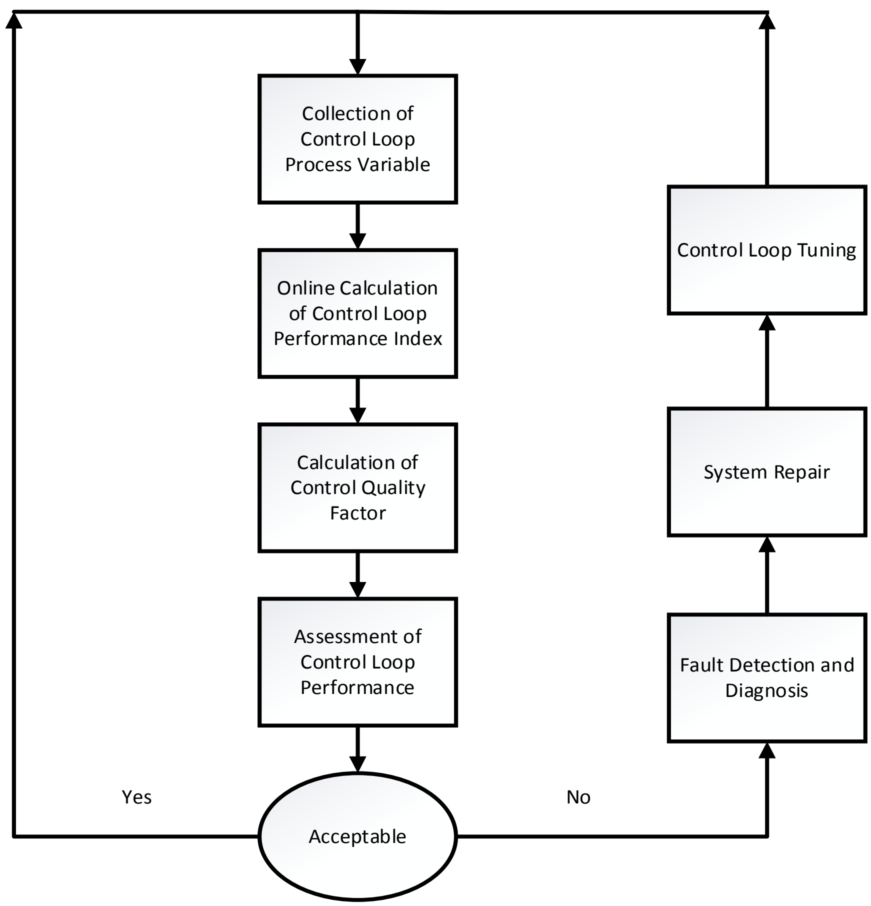

Figure 1 A Typical Procedure for Control Loop Performance Monitoring

The CPA has been an active topic for researchers and practitioners over the last three decades, especially in the process control industry. In the late 1980s, Harris (1989) introduced the Harris Index based on Minimum Variance Control (MVC) theory. Since then, this index has been widely used in the process control industry. Several commercially available packages (e.g. Honeywell's Loop Scout (Jämsä-Jounela et al. 2003)) were using the Harris Index for control loop performance assessment, mainly in the process control loops. New CPA indices have emerged in the process control industry over the last decade, especially in the refinery and oil industries. However, the complicated algorithms behind those CPA indices require significant computational resources, which may not be appropriate for applications in the HVAC closed loop performance assessment. HVAC control loop assessment usually requires a simple, fast evaluation algorithm due to the limited on-board memory of most HVAC controllers.

In addition, current CPA indices from the process control industry do not give definite assessment scales or criteria such as excellent, good, fair, bad and failed. Some CPA indices only have the lower bound such as an Integral of Absolute Error index (Hägglund (1995). In general, most of these existing CPA indices need a human-in-the-loop to decide if the control loop performance is acceptable or not.

In summary, there is a need for a comprehensive and systematic review of the state-of-the-art for control loop performance assessment to facilitate the development of an objective and quantitative index with simple-to-interpret criteria, namely, a Control Quality Factor (CQF) for HVAC applications. The focus of this CQF is assessment of normal loop operation after recovering from a disturbance. There is also a need in the field to develop assessment scales for the CQF regarding HVAC control loops.

The structure of this report is organized as follows:

- Review of Control Loop Performance Assessment
- Development of CQF
- Development of CQF Assessment Scales
- CQF Offline Testing for Simulated HVAC Control Loops
- CQF Offline Testing for Real HVAC Control Loops
- Weighted CQFs for Real HVAC Control Loops
- Online Field Testing for CQFs
- Conclusions

This is just a sample of the Final Report.

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