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ASSESSING MEASUREMENTS FOR FEEDFORWARD CONTROL

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Abstract

A method is presented for assessing disturbances in SISO loops. The method indicates if the SISO loop under consideration will benefit from an addition of feedforward control from a measured disturbance. The method uses minimal process knowledge and is based on measurement from normal operation.

1 Introduction

The economic demands of today pose harder performance objectives for the industry. The quality related work has increased, but few have realized the importance of control engineering in the improvement chain.

In the process industry there are several hundreds of control loops in a typical plant. In studies in North America [5, 3] it was reported that only 20% of the loops were performing better in automatic mode than in manual mode, 30% of the installed controllers operated in manual, and 25% were still running with default parameters. The large amount of controllers, and limited resources in the maintenance and instrumentation departments, imply the need for automatic tools which identify loops which offer potential improvement.

The reason why the control loops are performing badly varies. There may be faulty equipment, badly tuned controllers, and wrong controller structures. First poorly performing equipment in the loops should be identified. Such a tool have been presented recently [6]. After that the tuning is addressed. Time and frequency domain performance evaluation can be found in [1, 7], and stochastic performance assessment in [9, 8].

If, when the loop has been tuned and the equipment in the loop maintained, the performance still is unsatisfying a change of structure must be considered. Both the process structure and the control structure may be changed. We will here address the latter case, and in particular the addition of feedforward control action.

The control structure question has been addressed in, for example, [10, 4] for feedforward control as an addition to a feedback loop. In [10] an approach based on models and cross-correlations was presented, and in [4] a stochastic approach was formulated.

2 Background

In many process control industries the plants contain a large amount of variables and control loops. In many cases the causal dependencies between the variables are difficult to understand.

In our study, the starting point has been a SISO system and an additional measurable signal, x (see Figure 1). The question is to decide if the signal has a relation to the loop, the nature of this relation, and if the signal could be used to improve the performance of the loop.

If the additional signal is classified as an additive disturbance, it may be used for feedforward. Multiplicative disturbances can be used for ratio control or gain scheduling. If the signal is a measurement in between the process input and the process output, it can be used for disturbance rejection in a cascade controller.

In this paper we will discuss the case when the extra signal is a measurable additive disturbance, $x = d$.

3 The Feedforward Case

Our interest lies in estimating where the disturbance enters the process, and conclude whether we can use it

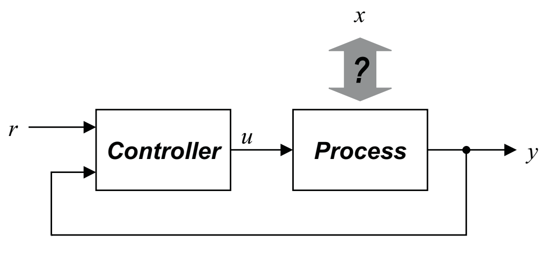

Figure 1: A SISO system and an additional signal

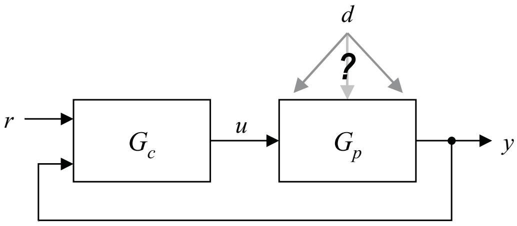

Figure 2: SISO system affected by measurable load disturbance with unknown entry point.

for feedforward control or not.

The interesting case is when the disturbance enters early. If the disturbance enters late, both the feedback controller and the feedforward controller will take action. This can result in degraded performance, if not suitable measures are taken.

In Figure 2 a system description can be found where G_c and G_p are the transfer functions for the controller and the process respectively. The reference signal is denoted r, the controller output u, the process output y, and the measurable disturbance d. The process output's dependence on the process inputs u and d is

$$y = G_p u + G_d d \tag{1}$$

The disturbance and the controller output have different transfer functions since the disturbance might have some external dynamics before it enters the process (see Figure 3). Depending on where the disturbance enters, the common factor of G_p and G_d will vary. This common factor will be denoted G_{p2}.

$$y = G_{p2}(G_{p1}u + G_{d1}d) \tag{2}$$

We will use the notation *entry point* to refer to how large common factor G_p and G_d have.

If the disturbance enters *before* the process it corresponds to when the disturbance enters at the same point as the control signal. Hence, $G_{p2} = G_p$, and

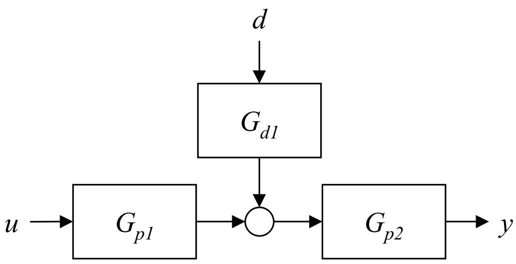

Figure 3: The transfer functions of the process and the disturbance may have a common factor

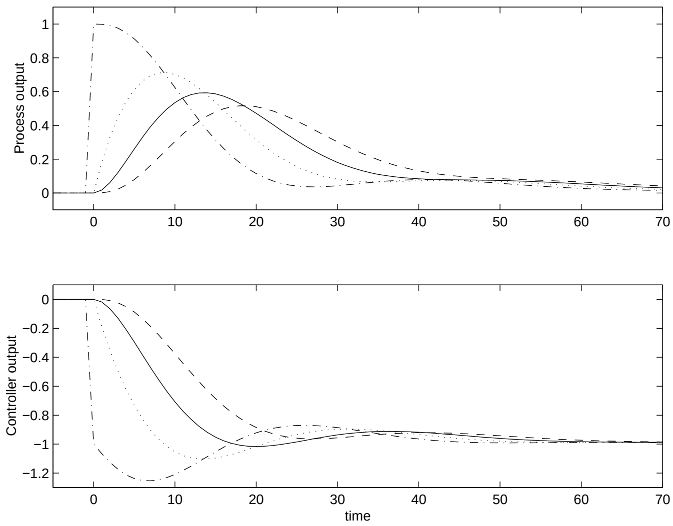

Figure 4: The load effect on the loop signals when the disturbance enters before (dashed), early in (solid), late in (dotted), and after (dash-dotted) the process.

$G_{p1} = 1$. When the disturbance enters *after* the process, G_p and G_d in Equation (1) have no common factor. Hence, $G_{p1} = G_p$, and $G_{p2} = 1$.

3.1 Preliminary assumptions

The controller structure and parameters are considered known. Moreover, the reference (set-point) signal, the controller output, the process output, and the unclassified signal are measured.

The unclassified signal, x, has been identified as an additive disturbance, denoted d, which initially will be a unit step. Initially we will also assume full knowledge of the process model, G_p. The process used in the simulations is a third order system with unit gain and all time constants equal to five. The PID controller used is tuned according to the λ-tuning procedure [2], with a λ-factor of one. The static gain of both G_p and G_d will, in the preliminary discussion, be one.

These preliminary assumptions are relaxed in Sec. 5.

3.2 The idea

The idea is to compare a disturbance influence on the loop with two references. In Figure 4 the effect of a step disturbance is shown for four different entry points.

We have chosen the extreme cases when the disturbance enters before and after the process, see Figure 5, to constitute these references. Since the effect of a load disturbance results in an offset in the control signal, $u(t)$, and a peak in the process output, $y(t)$, we have chosen the control signals as references. By com-

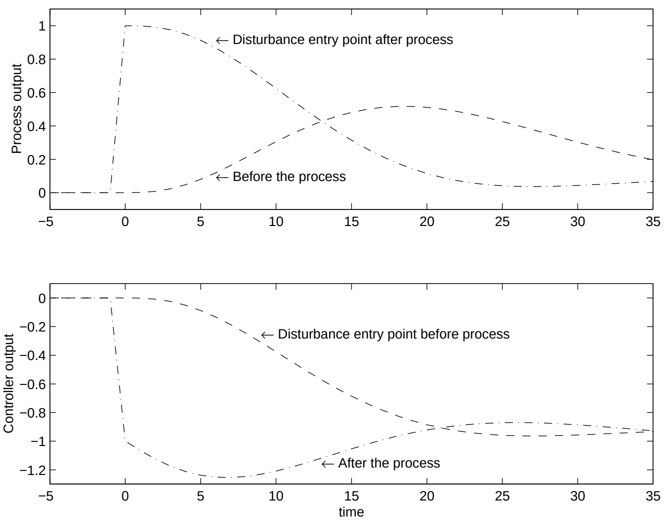

Figure 5: The two cases which will be used as references. The cases are when the disturbance enters before (dashed) and after (dash-dotted) the process.

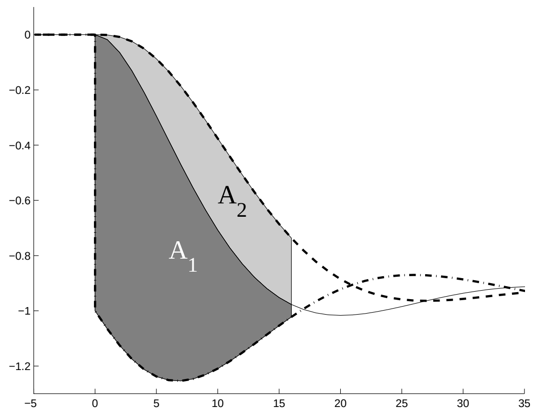

Figure 6: The areas of interest in the comparison

paring the controller signals for the different cases, we can classify a new measured signal.

There are many ways to compare, and we have chosen to make the comparison with areas. The area in between the two reference signals constitutes a reference area, to which the area between the *after*-reference and the measured signal under investigation is compared.

In Figure 6 the area belonging to the newly measured signal, is labeled A_1, and the reference area is the sum of the two areas, $A_1 + A_2$. The feedforward index is the ratio between A_1 and the reference area.

4 The Feedforward Index

The prerequisites for calculating the feedforward index are the time horizon, and the references.

4.1 The time horizon of the index

The time horizon over which the index is calculated should cover the transient phase of the process response of the original SISO loop. Looking at Figures 4 and 5, and keeping in mind that the process transfer function is $1/(1+5s)^3$, it can be seen that, in this case, an appropriate choice would be in the order of 15 s.

We have chosen the average residence time as the time-window for the calculation. The average residence time for a system, is defined as [2]:

$$T_{\text{ar}} = \frac{\int_0^\infty (s(\infty) - s(t))dt}{K} \tag{3}$$

where $s(t)$ is the step response of the open-loop system, and K is the static gain. For a three parameter model, $Ke^{-sL}/(1+sT)$, the average residence time is $T_{\text{ar}} = T + L$. Methods of moments can also be used to calculate the average residence time, or it can be estimated from measurements [2]. It is worth pointing out that T_{ar} is independent of the controller tuning.

4.2 Obtaining references

The references are initially generated through simulation. The system simulated consist of a controller corresponding to the one in the control system, and a model of the process. The measured disturbance is introduced before and after the process model, and the controller output is registered for the two cases.

4.3 The index

The index is defined as

$$\eta_{\text{FF}} = \frac{\int_0^{T_{\text{ar}}} (u(t) - u_{\text{after}}(t))\, dt}{\int_0^{T_{\text{ar}}} (u_{\text{before}}(t) - u_{\text{after}}(t))\, dt} \tag{4}$$

The feedforward index η_{FF} ranks the disturbance d's suitability from 0 to 1. See also section 5.3.

4.4 Simulation example

The index will now be demonstrated by an example where a unit step disturbance enters at four different locations in the process.

Consider the process used previously. The process transfer function is $G_p(s) = 1/(1+5s)^3$. There is no external disturbance dynamics, i.e. $G_{d1} = 1$. The disturbance is a unit step.

The controller output response to the step disturbance is shown in Figure 7. The reference signals were generated by simulation using a model identical to the process. The indices were calculated to 1.00, 0.74, 0.39, and 0.00 for the before, early, late and after cases, respectively. These values will be used as a comparison in the forthcoming examples.

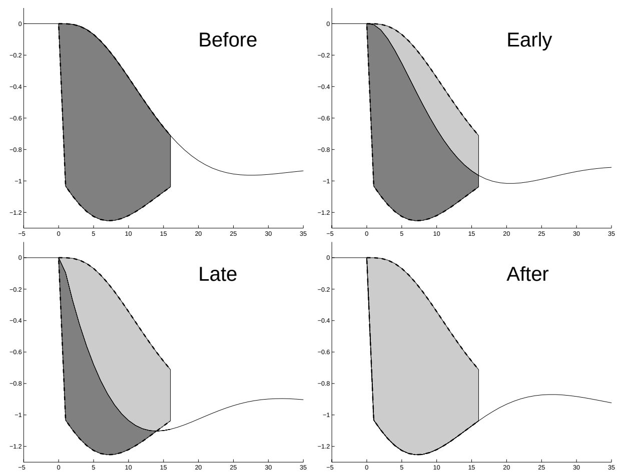

Figure 7: The effect of a step disturbance for the different entry points (as indicated in the figures).

The value of the index when feedforward control is recommended, or not, depends on the implementation structure of the feedforward part. A larger value indicates that the disturbance, d, is suitable as a feedforward control signal. We propose 0.7 as a general threshold for suggesting the use of feedforward.

5 Relaxations

In this section, the assumptions made previously will be discussed. We will, using some examples, analyze the robustness of the index presented.

5.1 Normalization

Until now the static gain of G_d and G_p have been one, and the disturbance magnitude has also been one. This is of course an unrealistic assumption. The effect if the process has a different gain, or G_{d1} has a gain other than one, will be a shift in the the controller output. The solution is a normalization of the signals in the calculation of the index.

Consider the case when $G_{p2} = 2/(1+5s)^2$ and $G_{d1} = 3$. The controller's response to the disturbance will then be three times as large as before, it's reference-response, u_{after}, to the *after*-disturbance is halved, while u_{before} remains unchanged, see Figure 8.

To handle this, the controller output, $u(t)$, and the reference for the after case, $u_{\text{after}}(t)$, are scaled according to

$$\bar{u}(t) = \frac{G_p(0)\Delta d_{\text{ref}}}{G_d(0)\Delta d_{\text{meas}}} u(t) \qquad (5)$$

$$\bar{u}_{\text{after}}(t) = G_p(0) u_{\text{after}}(t), \qquad (6)$$

where the Δd_{meas} correspond to the magnitude of the measured disturbance and Δd_{ref} to the disturbance used for reference generation.

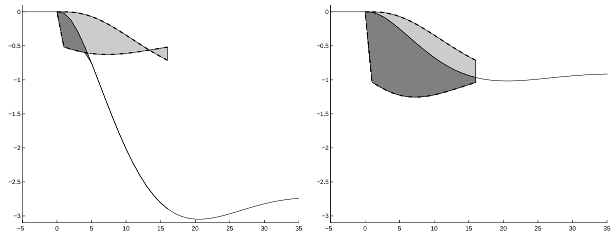

Figure 8: The influence of the gains is clearly visible in the left figure. In the right figure the measured signal and the after-reference are scaled.

The modified index includes the scaled measured control output, $\bar{u}(t)$, and the scaled *after*-reference, $\bar{u}_{\text{after}}(t)$,

$$\eta_{\text{FF}} = \frac{\int_0^{T_{\text{ar}}} (\bar{u}(t) - \bar{u}_{\text{after}}(t))\, dt}{\int_0^{T_{\text{ar}}} (u_{\text{before}}(t) - \bar{u}_{\text{after}}(t))\, dt} \qquad (7)$$

The modified index was calculated to 1.00, 0.73, 0.39, and 0.00, which is compliant with previous results.

5.2 The shape of the disturbance

The example in Sec. 4.4 has a step disturbance. We cannot expect the disturbances to be so kind. We will here use a ramp disturbance, $d(t) = 0.02t, t > 0$, on the same process.

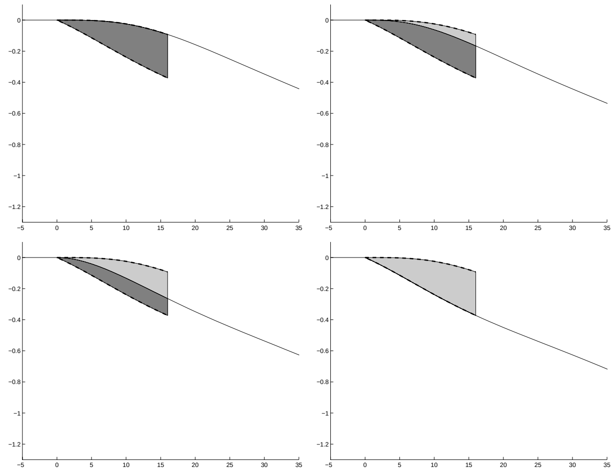

Figure 9: The effect of a ramp disturbance for the different entry points

The axes of Figure 9 are intentionally the same as used in Figure 7 to show the difference in size of the areas used for calculating the index. The index now is: 1.00, 0.82, 0.50, and 0.00.

The example shows that the method works also for dis-

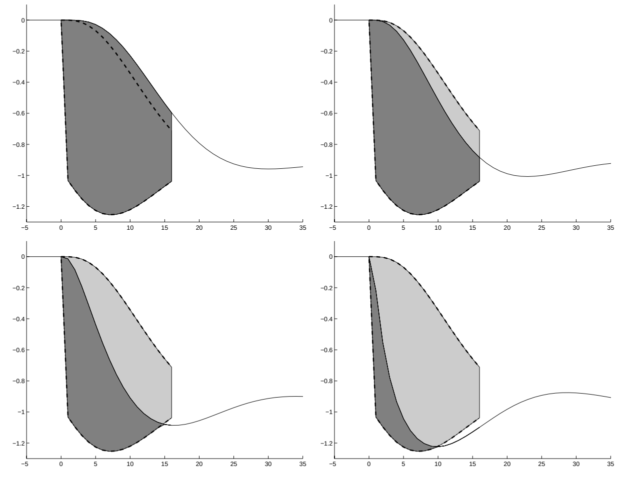

Figure 10: Dynamics in the disturbance pre-filter for different disturbance entry points

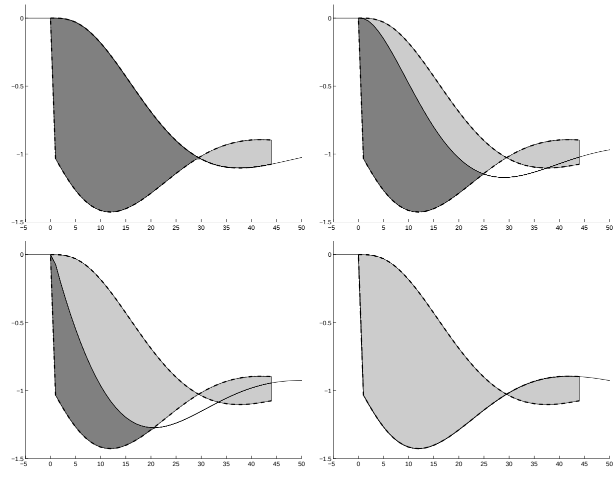

Figure 11: The effect of a too aggressively tuned controller.

turbances that are not steps, as long as they are fast enough compared to the process dynamics.

5.3 Filtered disturbance

We have previously treated the case when the gain of G_d was not unity. Here, we extend this by also allowing dynamics in G_{d1}. This represents additional dynamics in between the measurement point of d and where this disturbance enters the process in consideration.

In the following example the additional dynamics are $G_{d1} = 1/(1 + 2s)$. The simulation results are shown in Figure 10.

The resulting indices was 1.10, 0.87, 0.58, and 0.20. The values don't conform with those of previous examples. The index for the *before*-case is larger than one due to the unmodeled dynamics of G_{d1} in Equation (2). However, the high indices clearly indicate that the process would benefit from a feedforward controller.

5.4 Badly tuned controller

Here, the controller is aggressively tuned using a model which is faster than the true process. The control design is based on a model with all time constants equal to five, the same as before. The true process has, however, all time constants equal to 7. The disturbance is once again a step disturbance.

The indices are 1.00, 0.76, 0.43, and 0.00. The indices are remarkably close to the ones in Sec. 4.4.

5.5 The reference model

The reference values can be generated using a model of the process. In this situation it is of interest to see how

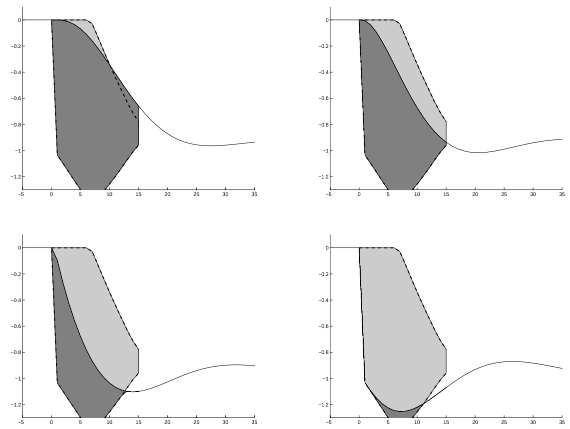

Figure 12: The effect of using a three parameter model for reference generation. Compare with Figure 7

robust the index is to model error. We will here use a three parameter model of the process to generate the references. The model was fitted to the process and is $\hat{G}_p = e^{-6.3s}/(1 + 8.66s)$.

The indices are 0.99, 0.81, 0.54, and 0.16, for the four cases of entry point. The values are again reasonably close to the ones obtained in Sec. 4.4.

6 Implementation Aspects

The prerequisites so far is that we need the controller outputs for the two reference cases, as well as the average residence time of the process.

How can the controller output references be generated? There are several ways to obtain them, for example by manual experiments, letting the controller do the ex-

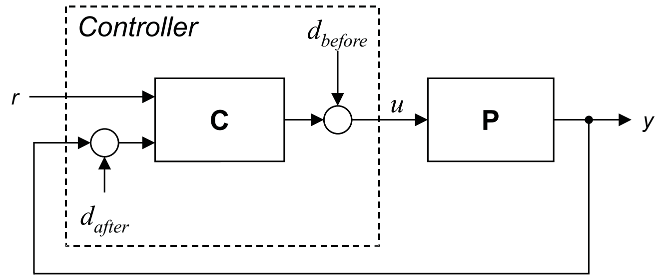

Figure 13: Generation of reference signal by introducing disturbances to signals in the controller

periments (after operators approval) by introducing the (measured) disturbance, or through calculation (simulation) using a process model

The analysis time can be estimated from measured data by methods of moments [2]. The controller can introduce the disturbance to its internal signals. In Figure 13 a schematic view of such generation is shown. The early case corresponds to an addition to the controller output, and the late case to an addition to the measured process output. The forced disturbance that is used to generate the references can correspond to the measured disturbance signal, or a step disturbance. The latter case when the reference disturbance is a unit step has the objective to record the references once, and then through transformation adapt them to the present disturbance situation. This avoids unnecessary experiments on the real process system.

Two things must be included in the calculation of the feedforward index Equation (7) when the references are generated by a unit step. The Δd-factor in Equation (5) shall correspond to normalization of the magnitude of the measured disturbance, and a transformation of the references should be done, corresponding to the G_{d1} in Equation (2) in order to give the step the correct shape.

If a process model is available the reference signals can be generated through simulation. Then the true disturbance can be introduced to generate the references.

7 Conclusion

The feedforward index presented can be used in manual evaluation of control loops or in a supervisor. The index indicates if feedforward control action should be added. Future activities will include an estimation of the improvement of adding a feedforward controller to a process. Since it may be costly to change the control structure in reality, an estimate of the improvement can be of help in the decision.

We will in the framework include integrating processes, other control structures, for example cascade control, and disturbances that affect the loop multiplicatively. An industrial case study will be done to test the method on industrial process data. For this study, the question of transformations of the references arises. The transformation corresponds to the scaling in Sec. 5.1, but here the disturbance dynamics are important.

The intention is to incorporate this method in a tool together with control loop performance monitoring.

References

[1] K. J. Åström. “Assessment of achievable performance of simple feedback loops.” Int. J. of Adaptive Control and Signal Processing, **5**, pp. 3–19, 1991.

[2] K. J. Åström and T. Hägglund. PID Controllers: Theory, Design and Tuning. Instrument Society of America, Research Triangle Park, NC, second edition, 1995.

[3] W. Bialkowski. “Dream versus reality: A view from both sides of the gap.” Pulp and Paper Canada, **94:11**, pp. 19–27, 1993.

[4] L. Desborough and T. Harris. “Performance assessment measures for univariate feedforward/feedback control.” The Canadian Journal of Chemical Engineering, **71**, pp. 605–616, 1993.

[5] D. B. Ender. “Process control performance: Not as good as you think.” Control Engineering, **40:10**, pp. 180–190, September 1993.

[6] T. Hägglund. “A control-loop performance monitor.” Control Engineering Practice, **3:11**, pp. 1543–1551, 1995.

[7] T. Hägglund. “Automatic detection of sluggish control loops.” Control Engineering Practice, **7**, pp. 1505–1511, 1999.

[8] T. Harris, C. Seppala, and L. Desborough. “A review of performance monitoring and assessment techniques for univariate and multivariate control systems.” J. of Process Control, **9**, pp. 1–17, 1999.

[9] T. J. Harris. “Assessment of control loop performance.” Canadian Journal of Chemical Engineering, **67**, pp. 856–861, 1989.

[10] N. Stanfelj, T. E. Marlin, and J. F. MacGregor. “Monitoring and diagnosing process control performance: The single-loop case.” Ind. Eng. Chem. Res., **32:2**, pp. 301–314, 1993.