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Control Structure Assessment in an Industrial Control System

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Abstract This paper describes the implementation of a structure assessment method in an industrial control system. The method uses available signals to evaluate if a given signal can be used for additional feedforward control action to improve the performance of a control loop.

1. Introduction

During the last decade much research has been done on monitoring control loop performance using normal operating data, see for example [2] for a survey. Several performance assessment products are now available on the market, and their usage in the industry is increasing. With this in mind, a tool for analysing the control loop structure has been developed. This tool is based on mainly measurements, and not rigorous models of the process.

The goal is to incorporate this tool in an environment for control loop and structure assessment. Such a tool could be used to determine whether the control loops are well tuned, to verify if an appropriate control strategy has been chosen, and, when not, to hopefully get a measure on how much better control is achievable using another control strategy.

A tool for control structure assessment has been implemented in ABB's new control system Control$^{\mathrm{IT}}$. The tool is able to evaluate if feedforward control action should be added to a SISO loop. Given the signals of the loop and one or several extra measurable signals, the tool evaluates the influence of these extra signals on the loop. The tool estimates, by comparing areas, where the disturbance enters in the process. The result is presented as an index. The indices of different loops can be compared in order to focus the maintenance on the most needing control loops.

The tool for assessing additive disturbances and their use for feedforward control action was presented in [4]. In this paper the aspects of implementing the tool in a commercial control system are discussed. First the assessment method is presented, then in Section 3 the implementation environment is discussed. In Section 4 the safety logic required for operation in an industrial control system is described. In Section 5 some experiments are presented, and finally some conclusions are presented along with ideas of future work.

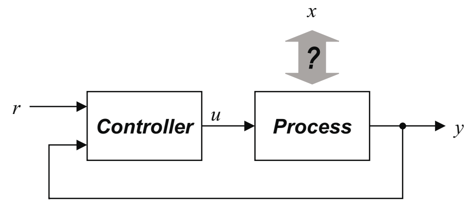

Figure 1 A SISO system and an additional signal

2. Assessment Method

The starting point for this research project is an ordinary control loop in the process industry. The loop is assumed to be tuned, which is reasonable when most control systems offer a tuning feature. In addition to the signals present in the loop, an measurable signal, x, is available, see Figure 1. The nature of this additional signal is not considered to be known, but it is of interest to determine its effect on the control loop.

2.1 The Feedforward Index

By analysing the transient responses the tool evaluates the influence on a single control loop from an additional measurable signal.

The index gives an idea of where in the process the disturbance enters, and is based on a comparison between the time constants of the process and disturbance paths.

2.2 Definition

The idea is to compare the controller's response, $u(t)$, to a disturbance, with two reference responses. The references are the controller's response to the same disturbance entering before and after the process respectively, i.e. the two extreme entry points of a disturbance in the control loop. The two control reference responses are denoted $u_{\text{before}}(t)$ and $u_{\text{after}}(t)$.

The index calculation consists of taking the ratio between an area depending on the measured disturbance, and a reference area. The area between the two reference responses constitutes the reference area. The disturbance dependant area is the area between the *after*-reference and the response due to the disturbance, see Figure 2.

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The signals need to be scaled before calculating the index, as reported in [4]. The scaling is depending on the process gains, the size of the measured disturbance, Δ_{dist}, and the size of the disturbance used to generate the references, Δ_{ref}.

Let the static gain of the transfer functions from the controller output to the process output and the gain from the disturbance to the process output be denoted by $P(0)$ and $D(0)$, respectively. The scaled measured control output is then defined as $\bar{u}(t) = P(0)\Delta_{\text{ref}}/(D(0)\Delta_{\text{dist}})u(t)$ and the scaled *after*-reference as $\bar{u}_{\text{after}}(t) = P(0)u_{\text{after}}(t)$. The index is now given by the following equation

$$\eta_{\text{FF}} = \frac{\int_0^{T_{\text{ar}}} \left(\bar{u}(t) - \bar{u}_{\text{after}}(t)\right) dt}{\int_0^{T_{\text{ar}}} \left(u_{\text{before}}(t) - \bar{u}_{\text{after}}(t)\right) dt} \tag{1}$$

where T_{ar} is the average residence time, which for a first-order plus deadtime model is the sum of the time constant and the deadtime.

An index close to or larger than one indicates a signal that enters before or early in the process. Such disturbances can preferably be used in an additional feedforward control action in order to improve the performance of the loop. Disturbances receiving indices close to zero are considered to enter late in the process and they are best handled by feedback control.

2.3 Simulated example

The process consists of three first-order filters, each with a time constant of five, and unit gain. The disturbance entry points are before the process, between the first and second filter, between the second and third filter, and after the process. The effect of a unit step disturbance, entering the process at different locations, is shown in Figure 3, together with the calculated indices.

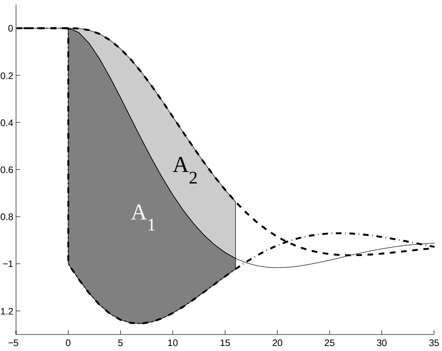


Figure 2 Comparison of control signals. The response to the disturbance is shown in solid, the after-reference is dash-dotted, and the before-reference is dashed. The area generated by the disturbance is labelled A_1, and the reference area is the sum of the two areas, $A_1 + A_2$. The feedforward index is the ratio between A_1 and the reference area.

2.4 Reference generation

The references can be generated in at least three ways. The first case involves generation of the references experimentally from a unit step disturbance. Two experiments are performed where disturbances are introduced in the controller, C, before and after the process, P, see Figure 4. A linear relation between a fictive unit step disturbance and the measured disturbance is calculated once a disturbance has been detected. This linear model is used to transform the references so that the index can be obtained. For more details concerning this approach see [5]. While the transformation of the shape of the disturbance is a linear transformation, the change of controller parameters is non-linear. Therefore it is assumed that the controller will have a fixed operating point. If it changes, new references must be recorded once the controller is tuned at the new operating point.

The second approach consists of performing experiments on the process when a disturbance has been measured. The measured disturbance is played back to the process in order to obtain the references. This approach is not attractive since it upsets the process during the evaluation phase.

The third way requires a simple process model, for example a first-order plus deadtime model, describing the relationship between the controller output and the process output. The controller parameters and structure are considered known. The references are generated by simulations with the measured disturbance as input.

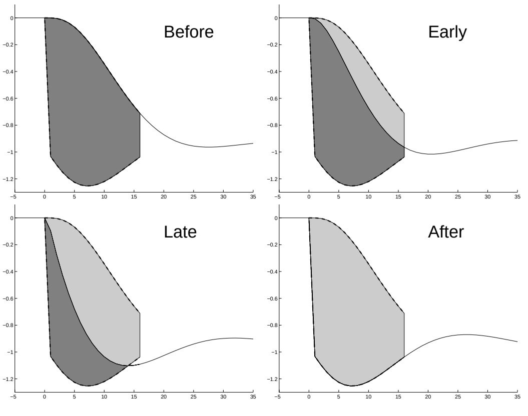


Figure 3 The effect of a step disturbance for the different entry points in the process (as indicated in the figures). The indices were calculated to $1.0, 0.74, 0.36$ and 0.0, in the order from before to after.

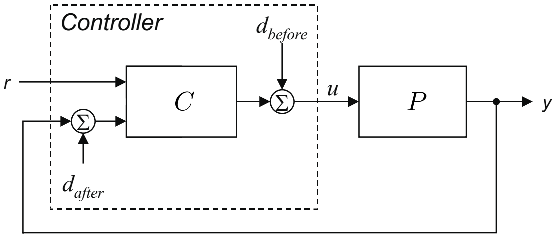


Figure 4 Schematic view over generation of reference signal by introducing disturbances to signals in the controller

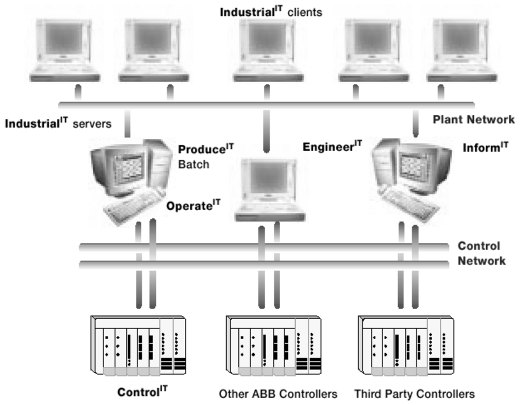


Figure 5 The assessment tool may reside in a controller, but also on the server/client levels above. The latter choice offer the possibility for usage with older products as well as third party controllers.

In the experiments presented in Section 5 the references were obtained through simulations.

3. Implementation Environment

The control structure assessment tool has been implemented in Control$^{\text{IT}}$, ABB's new family of control hardware, software and tools.

Two different ways to implement the tool have been considered. The first approach is to implement the assessment method in the controller software, and the second is to place it at the server-level above, see Figure 5, for example in the Operate$^{\text{IT}}$ Process Portal operator station.

If the implementation resides at the server level it is possible to use third party products like Matlab for numerical calculations. If the tool resides in the controller the implementation is done in one of the IEC 61131-3 languages, e.g. Structured Text. In both cases the results are displayed in an operator station, but the data used may differ. The methods implemented in the controller have direct access to the data whereas calculation residing on the server-level are depending on the information availability and data transfer speed of the OPC (OLE for Process Control) connection.

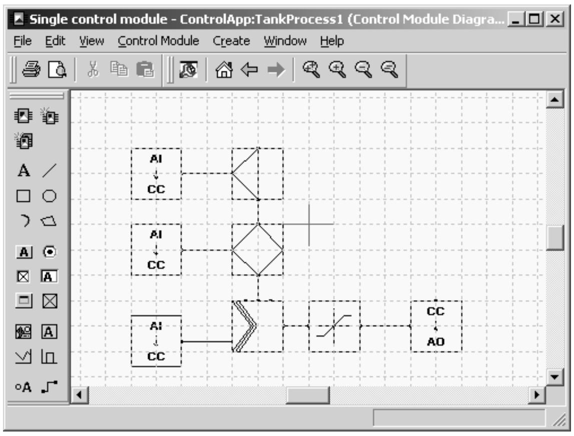


Figure 6 The assessment modules are inserted in the control diagram in the Control Builder-tool. Bottom row shows the following modules, from left to right; an analog input, a PID controller, a limiter, and an analog output. On top of the controller is a assessment master module and an assessment slave module connected in series.

In this feasibility study the implementation is done inside the controller. The information available on the different levels and CPU load will determine the future location of the tool. It might also be possible to have some part of the method in the controller, and the rest on the level above.

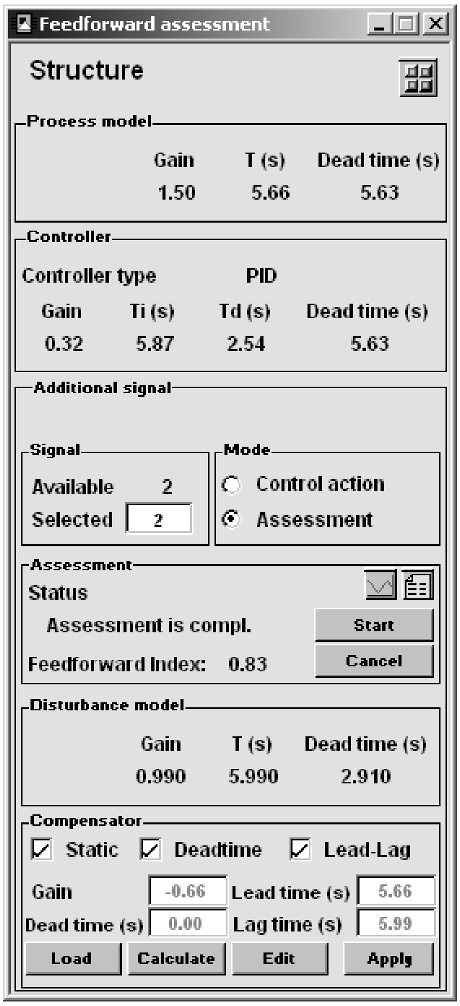
3.1 Engineering environment

In the engineering tool the different control modules are graphically connected. The control modules are an extension of the IEC 61131-3 standard to offer support for object-oriented programs. A control module is a container for both application programs and graphical objects.

The implementation is divided into two types of modules, one master module and one slave module. To both the master and the slave modules it is possible to connect one signal, and another slave module, see Figure 6. There is thus no theoretical limit in the amount of signals that can be connected for assessment. For each signal, there is a feedforward compensator. This compensator has a static gain, a lead-lag filter, and a delay. Depending on the information available a compensator is proposed after an assessment.

3.2 Operator Environment

A main user interface gives the operator an overview of the loop variables, as well as one of the additional signals available. The user can select one signal and bring up a new window,



Process model

Gain	T (s)	Dead time (s)
1.50	5.66	5.63

Controller

Controller type PID

Gain	Ti (s)	Td (s)	Dead time (s)
0.32	5.87	2.54	5.63

Additional signal

Signal

Available 2
Selected 2

Mode

○ Control action
● Assessment

Assessment

Status
Assessment is compl.
Feedforward Index: 0.83

Disturbance model

Gain	T (s)	Dead time (s)
0.990	5.990	2.910

Compensator

☑ Static ☑ Deadtime ☑ Lead-Lag

Gain -0.66
Lead time (s) 5.66
Dead time (s) 0.00
Lag time (s) 5.99

Figure 7 The user interface for additional assessment information. The outcome of the assessment is presented in the lower half of the window.

see Figure 7, with more information about the signal and the current feedforward control action associated with it.

4. Implementation Issues

Implementing an assessment tool in an industrial control system implies that it should be capable of delivering reliable results. A supervisor, consisting of safety logic, must reassure the proper functionality of the tool so it remains trustworthy. The dialog with the operator must be as simple as possible, but provide enough information so that the person conducting the assessment can trust the results.

During an assessment the data is first logged and then compared to simulated references when calculating the index. If another disturbance affects the loop, or the setpoint is changed, when logging, this data can obviously not be used for evaluation. Other events that may disqualify data is if the controller parameter is changed during an assessment.

In order to calculate the feedforward index some process models must be estimated. Identification of process parameters is needed for the reference generation. This may require resampling of the data, since a controller in a control system of today often is sampled so fast that a continuous framework can be used for design and analysis. Moreover the gain in the disturbance path is used for scaling of the data during index calculation. When an additional signal is indicated for feedforward use, these process parameters are used for proposing an initial tuning of the additional feedforward control action. Depending on the amount of information available and the operators choice, the proposal is either a static or a lead-lag compensation, with a delay, if needed.

The process may respond with different speed to disturbances of opposite signs. To handle this, the sign of the disturbance must be monitored and two indices are to be saved. Furthermore, the engineer must be aware of the situation when designing an additional compensator. Logging the number of occurances of the two kinds of disturbances offers a simple aid in the decision making.

Keeping history of the index gives the possibility to monitor the interaction of the process at different operating points and over time. After a revamp or reconstruction of a process section the index history may help in the decision if a change of control structure is needed. A control performance and control structure tool makes it possible to focus the efforts of the maintenance staff on the most needing loops. The intention is that the tool can be used to supervise several loops in combination with signals that are possible disturbances sources. The tool then presents the pairing of loop and signals together with an index indicating which signals that can be used for extra feedforward control actions. Preferably, an assessment report should list the most needing together with proposed changes in tuning and structure of the control loop. Upon these fact the control engineer then can decide upon which items that should get highest priority.

5. Assessment Experiments

In this section an experiment will be presented. It has been carried out on control system consisting of an ABB Control$^{\mathrm{IT}}$ AC800C controller [1] with analogue I/O-module (0-10 V), and two KI-100

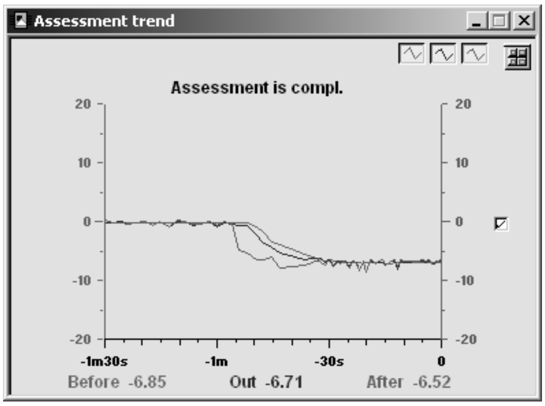


Figure 8 The trend curve during the assessment. The middle curve is the controller response to the detected disturbance, the upper curve is the *before*-reference, and the lower curve is the *after*-reference.

Dual Process Simulators [3]. The control system can also be connected to the laboratory equipment at the department of Automatic Control at Lund Institute of Technology.

The process consists of one main process controlled by a PID controller, and one disturbance which has additive influence on the main process. The process and disturbance transfer functions have one common part, $P_2 = 2e^{-2.5s}/(1+5s)$. The remaining parts of the transfer functions are $P_1 = 0.75e^{-1.0s}/(1+2s)$, and $D_1 = 0.5e^{-0.4s}/(1+s)$, for the process and the disturbance respectively. The total transfer functions are thus:

$$P = P_1 + P_2 = \frac{1.5e^{-3.5s}}{(1+2s)(1+5s)} \tag{2}$$

$$D = D_1 + P_2 = \frac{1.0e^{-2.9s}}{(1+s)(1+5s)} \tag{3}$$

The setpoint was held constant at 30% and a disturbance step of 10% was introduced. The level of the measurement noise was 1%. The T_{ar} of the process is 10.5 s.

The controller response, along with the references, is shown in Figure 8. The index calculated for this disturbance is 0.83, which qualifies the signal to be used for an additional feedforward control action. The proposed lead-lag compensator is

$$C_{\text{FF}} = -0.66\frac{1+5.66s}{1+5.99s} \tag{4}$$

These assessment results can be seen in Figure 7.

6. Conclusions

The presented method enables the control engineer to decide if an additional feedforward control action should be added. The tool presented still needs aid from the operator and the forthcoming work will include automating the methodology. The goal is to automate the assessment as far as possible, and bring other control structures, e.g. cascade control, into the framework.

The implementation allows the use of different detection, monitoring and identification methods. There are implementation issues such as the tradeoff between robustness of methods used against the computational burden it poses on the system the code resides in. The final decision, of which algorithms will be recommended for a possible product, depends not only on the robustness of the different algorithms, but also on where in the control system the tool will be implemented.

Keeping history of indices may help in identifying the root cause of the performance loss, and gain better insight in how future maintenance and reconstructions should be carried out in the plant.

It is clear that improved control can be achieved, by either tuning or changing structure. There is other interesting questions that is to be answered: How much improvement is possible? Can it be achieved by better control, or is it the process that needs to be modified?

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