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An Industrial Adaptive PID Controller

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Abstract
This paper presents a new industrial adaptive PID controller. The controller has the PID structure, with dual rate sampling, which means that the sampling rate for the PID controller is significantly higher than the sampling rate in the parameter estimator. The controller differs from conventional parametric adaptive controllers because it is based on estimation of transfer function properties. For normal industrial process control the adaptive controller can be used without any prior information about the process dynamics, such as sampling period, closed loop pole assignments etc. This is achieved by using a relay auto-tuner to initialize the controller. The auto-tuner determines a point on the Nyquist curve where the phaselag is close to 180°. This point on the Nyquist curve is then tracked by the parameter estimator.

1. Introduction

Adaptive control has been one of the major research areas in automatic control since the early seventies. Two different ways to use adaptive techniques have emerged. The first is auto-tuning, which means that the controller is tuned on operator demand. This is done by estimating the process dynamics and calculating the controller parameters. The second is the true adaptive controller, i.e. a controller which adapt itself to changing process dynamics without operator demand. Autotuners, particularly for tuning of PID controllers, have been accepted and well established among manufacturers of controllers and instrument systems in recent years. Although many successful applications of adaptive control have been presented, see e.g. Åström (1987) and Seborg et al (1986), only few multi-purpose adaptive controllers have appeared on the market. There are several reasons for this: Their proper use requires a certain expertise. They still are too complicated to use for non-experts. Since adaptation is continuous they require a significant safety network to guarantee proper operation in all cases. Adaptation speed is often limited for robustness reasons. An adaptive controller needs some initial parameter settings which are very crucial for the properties of the control, such as sampling period, model order, process dead time. If these parameters are given unsuitable values, the adaptive controller may behave badly. Many adaptive controllers are based on a sampled controller, with a sampling period which is of the same magnitude as the process time constant. These controllers introduce extra dead-time in the control loop because of the sampling. Such a controller is often not suitable for control loops subject to load disturbances. See McMillan (1986). An adaptive controller needs some time to find new parameters when the dynamics change. If a very rapid rate of adaptation is required, a gain-scheduling type of controller is needed. Gain-scheduling means a kind of feedforward. If we know that the process dynamics are different at different operating points (due to nonlinearities) or at different times (due to changes in production rate), the controller can be preprogrammed with different parameter settings for these different situations.

This paper presents a new type of adaptive controller. It can be viewed as a natural extension of the relay auto-tuner in Åström and Hägglund (1984). This auto-tuner was based on estimation of a point on the Nyquist curve where the process has approximately 180° phase shift. In the adaptive controller this point is tracked by a parameter estimator. The regulator is a PID controller with fast sampling which gives close to continuous time behaviour. The approach has several advantages. First of all it is very easy to use. No parameters have to be given by the operator since it is initialized by an autotuner procedure. It can thus be used by normal process operators. Since the process model only has two parameters, identifiability is easy to achieve even under normal operating conditions. It is also possible to get a relatively fast adaptation rate.

The paper is organized as follows. The use of adaptive technique in industrial process control is discussed in Section 2. The relay auto-tuner used in the initialization phase of the adaptive controller is briefly described in Section 3, which also contains a discussion of the use of gain scheduling. The adaptive feedback control based on tracking a point on the Nyquist curve is presented in Section 4. The section contains the principles of the identification as well as a description of the supervisory procedures. The adaptive feedforward compensation is presented in Section 5. Section 6 contains a short description of the industrial process controller ECA400, followed by examples of its use in the process industry. Conclusions are given in Section 7 and references are finally given in Section 8.

2. An Industrial Adaptive Controller

There are many different possibilities to use adaptive techniques for industrial process control. There is a wide range of choices of model structures, identification methods, control design techniques. Operational issues like supervisory techniques, safety networks and user interfaces add to the complexity. In this section we will discuss some of these choices in order to motivate the choices that led to the controller discussed in this paper.

The first adaptive controllers for process control were announced in 1983. There is now about five years of experience of using such devices. Experience has also shown that PID regulators can handle many of the industrial problems. The main exceptions are systems whose dynamics is dead-time dominated, systems with oscillatory dynamics and systems with significant stochastic disturbances. In such cases regulator structures other than the PID may give significant benefits. The PID controller also has the added benefit that users are familiar with it.

The industrial benefits of using feedforward control have also been demonstrated very clearly particularly in applications with the Novatune regulator. Feedforward is very useful but it requires reasonably accurate process models. It has also been demonstrated that automatic tuning which makes it possible

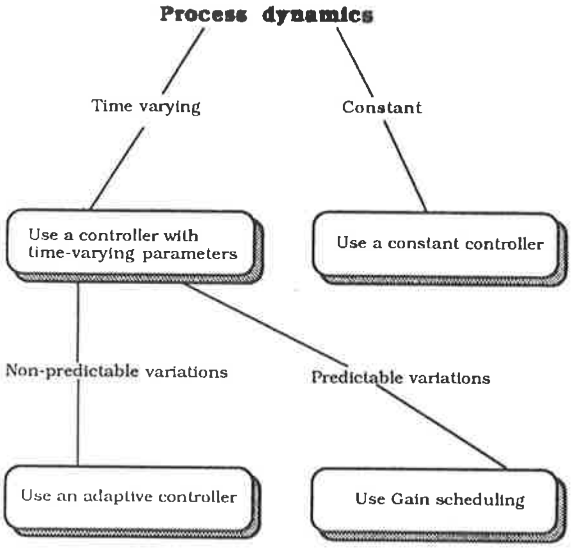

Figure 1. Determination of controller structure

to keep regulators well tuned is a very desirable feature. Often dynamics does not change very much. If it does the changes can often be correlated to measurable signals and thus compensated by gain scheduling. It thus appears that a device capable of realizing PID feedback control and feedforward control could be a useful component for industrial process control. If the regulator is provided with facilities for automatic tuning, gain scheduling and adaptation it will also be very easy to use.

The diagram in Figure 1 gives another view on how the different features can be used. First of all it can be stated, that if the requirements on the control are low, one can often solve the problem using a controller with constant parameters tuned according to the "worst case". With larger demands on the control, the way in which the adaptive technique should be used is determined by the way the process dynamics vary.

If the process dynamics are constant, the controller dynamics should also be constant. An autotuner procedure is then useful to set the controller parameters once and for all. If the process dynamics are varying, the controller should compensate for these variations by varying the controller parameters. We distinguish between two types of variations, predictable variations and nonpredictable variations. The predictable variations are typically caused by nonlinearities in the control loop. These variations are best handled by using a gain schedule. An autotuner procedure is useful to build the schedule by finding the different sets of controller parameters. The second type of process dynamics variations are those which are not predictable. These may be caused by nonmeasurable variations in raw material, wearing, etc. These variations can not be handled by gain scheduling. The true adaptive controller is the only way to make the controller follow the process variations. As will be seen below, an autotuner procedure is useful even in this case to initialize the adaptive controller. The variations of the process dynamics may of course consist of both predictable and nonpredictable parts. A combination of gain scheduling and adaptive control is then suitable.

A diagram analogous to Figure 1 could also be drawn for the feedforward compensation. It is often difficult to tune the parameters in a feedforward compensator manually, since the operator often not has access to manipulate the disturbance from which the feedforward is made. In the feedback case, the control performance can be determined by changing the reference signal. In the feedforward case, the operator often has to wait for suitable transients in the disturbance signal before he can decide if the compensator parameters are suitable. Therefore, an adaptive algorithm is particular useful in the feedforward case, since the adaptive algorithm continuously waits for transients in the disturbance signal, and adjusts the compensator parameters based on the transient response. Adaptation is therefore useful even if the dynamics between the disturbance and the measurement signal are constant.

Initialization or Pre-tuning

Initialization is an important issue for an industrial controller. Some of the early adaptive regulators were very demanding on the user. It was necessary to know parameters like sampling rate, dead-time, model order, desired response time etc. This made use of the controllers very exclusive. It was necessary to have special skills to commission and use the controllers. Many of the early adaptive regulators were therefore provided with a pre-tune feature that was intended to help the operators to derive the required knowledge. The pretune feature was often based on an open loop step response measurement or some other transient response experiment. This will however also require some prior knowledge like the size of the step and how long we have to wait for steady state. In some cases the pre-tune required a closed loop experiment. To make this it is however necessary to know values of the regulator parameters that will give a stable response.

In an industrial adaptive controller, the properties of the initialization phase is of great importance. If the controller is supposed to be operated by personnel not familiar with adaptive control, and perhaps with a limited knowledge about process dynamics, it is not possible to force the operator to make decisions which will determine the performance of the adaptive controller. In the system discussed in this paper this is made using relay feedback which has proven very reliable.

3. Auto-Tuning and Gain Scheduling

The key idea behind the automatic tuning is to use relay feedback. Processes with the dynamics typically encountered in process control will then exhibit limit cycle oscillations. The autotuner identifies one point on the Nyquist curve of the process from a simple relay experiment. The autotuner principle is shown in Figure 2. When the operator decides to tune the controller, he simply presses a button. This switches out the PID algorithm and replaces it with a nonlinear function which can be described as a relay with hysteresis. The relay causes the process to oscillate with a small and controlled amplitude. The process perturbation is very close to the optimum for most of the usual PID design methods. The frequency of the limit cycle is approximately the ultimate frequency where the process has a phase lag of 180°. The ratio of the amplitude of the limit cycle and the the relay amplitude is approximately the process gain at that frequency. A relay feedback experiment thus determines a point on the Nyquist curve associated with the open loop dynamics that is close to the ultimate point. A reasonable PID regulator can be designed based on this point. This idea, which was presented in Åström and Hägglund (1984) and (1988), has been used in commercial auto-tuners since 1984. It has proven to be a convenient tool for fast tuning of PID controllers. One of its main advantages is that it admits one-button-tuning. This means that no prior information has to be given from the operator. Tuning is executed simply by pushing the tuning button.

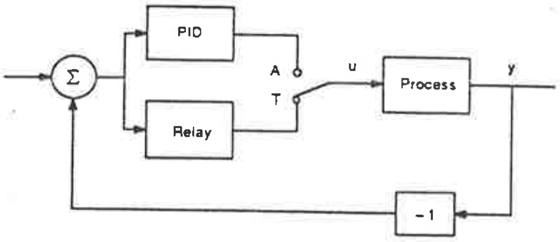

Figure 2. The Autotuner principle

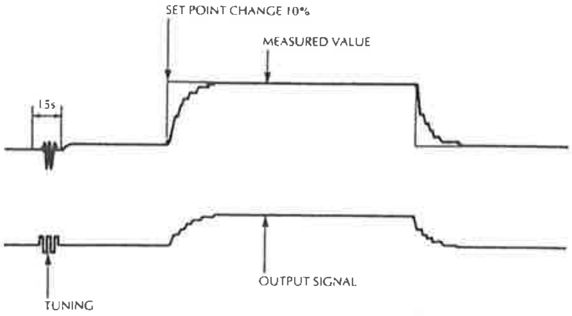

Figure 3. The autotuner used in a flow control loop

Another advantage is that the tuning experiment is executed under tight feedback control and that the experiment generates an input signal that is close to optimal for determining the ultimate point on the Nyquist curve.

In Figure 3, the use of the autotuner in a flow control loop in a chemical plant is presented. The tuning took about 15 seconds in this case. The two set-point changes show that the resulting PID controller is well tuned. (The signals are not smooth because of a sticky valve.)

By using the autotuner, we do not only obtain initial values of the PID parameters which manage to control the process, but as will be seen in the next section, also valuable process information for the initialization of the identification procedure in the adaptive controller.

The design method

Given the information of one point on the Nyquist curve, many design procedures can be used. Unfortunately, there is no design method which will suit all types of processes. By deciding to use a PID controller, we have restricted ourselves to those control problems which are suitable to solve with PID controllers. But even among these problems, it is desirable to have different design procedures for different control problems.

The identification procedure given in the previous section gives us the information of one point $G(i\omega)$ on the Nyquist curve. By introducing the PID controller $G_{PID}(i\omega)$ in the control loop, it is possible to give the Nyquist curve of the compensated system GG_{PID} a desired location at the frequency ω. For most purposes, we have decided to choose the PID parameters so that $G(i\omega)$ is moved to the point

$$G(i\omega)G_{PID}(i\omega) = 0.5e^{-i135\pi/180}$$

This design method can be viewed as a combination of phase- and amplitude-margin specification. Since we have three adjustable parameters, K, T_i and T_d, and the design criterion can be obtained with only two parameters, we furthermore require that

$$T_i = 4T_d$$

Some very simple control problems, where the process is approximately a first order system, can be solved effectively with a PI controller with relatively high gain. For these problems, the D-part of the controller will not be of any help. Furthermore, since we have a high gain the noise will be much amplified through the D-part. Therefore, it is desirable to use only a PI controller in these cases. In our controller, we can automatically detect this kind of processes and thereby switch off the derivative gain in these cases. For this PI controller, we have chosen the following design:

$$K = 0.5/\alpha$$
$$T_i = 4/\omega$$

where $\alpha = |G(i\omega)|$. There is also another situation when it is desirable to switch off the derivative part, namely for processes with long dead-time. If the operator tells the controller that he has a process with long dead-time, a PI controller with the following design will replace the PID controller.

$$K = 0.25/\alpha$$
$$T_i = 1.6/\omega$$

This controller will give a much faster control than the PID design presented above.

Gain Scheduling

Gain scheduling is an effective method to treat processes with predictable variations in the dynamics. A gain schedule is a table with several sets of controller parameters, one set for each operating point. (Parameter schedule would be a more adequate notation than gain schedule!). A reference signal which is related to the nonlinearity determines when to switch from one set of controller parameters to another. If e.g. the nonlinearity is caused by a nonlinear valve, the control signal should form the gain scheduling reference, since it is directly coupled to the valve position. If the nonlinearity is caused by a nonlinear sensor, the measurement signal should be used as a gain scheduling reference.

Most process control plants contains several nonlinear control loops. In spite of this, gain scheduling is seldom used in process control. One reason for this is, that is has been regarded as too time consuming to build this schedule with several different sets of controller parameters. With the use of auto-tuning, this drawback has disappeared. Using the auto-tuner once at every operating point will automatically provide the schedule.

When the process dynamics are predictable, it is better to use a gain schedule than an adaptive controller. The gain schedule will instantaneously provide a suitable set of controller parameters as the operating conditions change, while the adaptive controller needs a fair amount of time before it has adapted itself to the new conditions. Using adaptive control, the operator provides the controller with the information that the process dynamics are varying. Using gain scheduling provides the controller with the additional information about *how* the dynamics are varying.

4. Adaptive Feedback Control

From the auto-tuner experiment described in the previous section, we obtained the frequency ω and the value of the Nyquist curve at this frequency. In this section, we will describe how the point $G(i\omega)$ can be tracked when the dynamics are changing. We will also describe some of the supervisory logic that is included in the controller.

Tracking a point on the Nyquist curve

The identification principle is illustrated in Figure 4. The control signal u and the measurement signal y are filtered through narrow band-pass filters at the frequency ω. These two signals are then analyzed in a least-squares estimator which provides an estimate of the point $G(i\omega)$.

The band-pass filters The two band-pass filters are of the form

$$G_{BP}(s) = \frac{s}{s^2 + 2\zeta\omega s + \omega^2}$$

This filter will give a relatively high gain at the frequency ω, and suppress the signals at other frequencies. We have given the transfer function in continuous form. In the practical implementation, we use the sampled version with fast sampling, i.e. the filters are sampled with the same frequency as the PID controller.

It is well known from practical use of adaptive controllers, that a suitable filtering of the signals must always be used. See e.g. Wittenmark (1986). Low frequencies must be filtered out

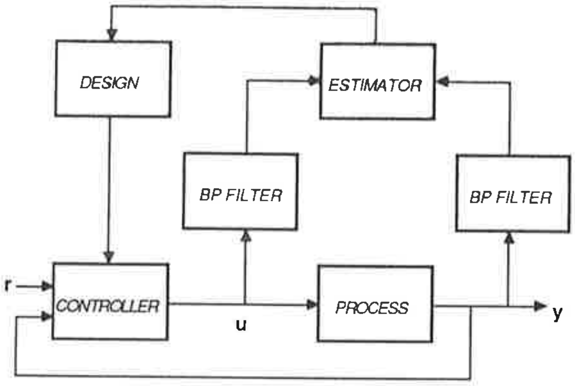

Figure 4. Block diagram describing the identification procedure

to avoid interactions from load disturbances. High frequencies must be filtered out to avoid high frequency noise from disturbing the parameter estimates. Since the process model always is more simple than the process itself, a filtering of the signals must also be made in order to ensure that the interesting part of the dynamics are identified. By using a narrow band-pass filter, we thus not only obtain the goal to track $G(i\omega)$ at the frequency ω. We also solve the traditional filtering problem in a very effective way.

The least-squares estimator The two narrow band-pass filters produce two signals which we can approximate with two sine-waves with different amplitude and phase. The quotient α between the amplitudes and the phase shift φ between the two signals give us $G(i\omega)$.

$$G(i\omega) = \alpha e^{-i\varphi}$$

We have used a least-squares estimator to obtain $G(i\omega)$ from the signals. The parameters of the second-order model

$$y(t) = b_1 u(t-h) + b_2 u(t-2h)$$

are estimated. The sampling period h is determined from the frequency ω. We have found that the choice

$$h = \frac{2\pi}{8\omega}$$

i.e. eight samples per period, gives good identifiability properties. From the parameters b_1 and b_2, $G(i\omega)$ can be determined according to:

$$\varphi = arctan\left(\frac{b_1 sin(\omega h)}{b_1 cos(\omega h) + b_2}\right) - 2\omega h$$

$$\alpha = \frac{b_1 sin(\omega h)}{sin(2\omega h + \varphi)}$$

The least-squares algorithm is of the constant-trace type. Since the signals $u(t-h)$ and $u(t-2h)$ entering the LS-estimator are approximately sine-waves with a constant phase-shift, it is possible to simplify the algorithm. Instead of identifying the parameters b_1 and b_2 directly, the following scaling is performed:

$$\begin{aligned} y(t) =& b_1 u(t-h) + b_2 u(t-2h) \\ =& \frac{b_1 + b_2}{2}\{u(t-h) + u(t-2h)\} \\ &+ \frac{b_1 - b_2}{2} s\{u(t-h) - u(t-2h)\}/s \\ s =& \sqrt{\frac{1 - cos(\omega h)}{1 + cos(\omega h)}} \end{aligned}$$

By estimating the two parameters

$$\theta_1 = \frac{b_1 + b_2}{2} \qquad \theta_2 = \frac{b_1 - b_2}{2} s$$

the expected value of the covariance matrix P becomes diagonal with equal diagonal elements. Hence it is possible to reduce the P-matrix to a scalar.

Supervision

The adaptive controller cannot run continuously without any supervision. E.g. logic to avoid identification when no information is available must always be present. The way this supervision is performed is at least as important as the underlying basic algorithm. However, there are no general rules or guidelines describing how this supervision is to be performed. The different manufactures of adaptive controllers have their own tricks. We will now shortly describe some fundamental procedures at our supervisory level.

First of all, we must ensure that the adaptation mechanism is only active when we have any information in the signals. Under periods of good control, when both the control signal and the measurement signal are straight lines, maybe corrupted with high frequency noise, no identification should be made. We have a procedure that high-pass filters the control signal and the measurement signal. Adaptation is only allowed when both these signals have had a transient recently.

Load disturbances are not covered in our description of the process. Implicitly we assume that changes in the measurement signal are caused by the control actions. To avoid desinformation from high frequency noise and load disturbances, we put band-pass filters on our signals, as described in section 4. Since we found that this is not always enough, we have also included a procedure to detect load disturbances, and thereby avoid adaptation during the first part of a load disturbance transient.

There is a very simple relation between the parameters estimated in the least squares estimator and the physical parameters α and φ. Therefore, it has been possible to check if the estimates have reasonable values. We have bounded the parameters in such a way that φ is always inside a sector in the third quadrant and that α may not vary more than a specified factor from the initial value given by the autotuner.

5. Adaptive Feedforward

Feedforward, constant or adaptive, is a powerful method to compensate for disturbances before they have shown up in the measurement signal. We have included an adaptive feedforward compensator in the controller. The feedforward compensator has the following structure:

$$u_{ff}(t) = k_{ff}(t)v(t)$$

where u_{ff} is the feedforward component of the control signal, k_{ff} is the feedforward gain, and v is the disturbance signal. The feedforward signal is updated with the same frequency as the control signal, i.e. fast compared to the time constants of the process. This simple adaptive feedforward compensator has shown to be very useful. In most cases, it is sufficient to let the feedforward compensation be formed by just a gain times the disturbance signal. Sometimes, it is desirable to delay the signal v, as will be discussed below.

The gain k_{ff} is determined from the model

$$y(t+d) = au(t) + bv(t)$$

where y is the measurement signal. The parameters a and b are determined by an ordinary least-squares estimator. The signals are both high- and low-pass filtered to get rid of noise and bias terms.

The choice of the time delay d in the model is crucial. If d is not chosen suitably, the model will not capture the relations between u and y and between v and y. Let the dead-time plus the dominating time constant of the process be T_{uy} and the dead-time plus the dominating time constant of the transfer function between v and y be T_{vy}. The following cases can then be distinguished:

$T_{vy} >> T_{uy}$ It is desirable to delay the disturbance signal v. Otherwise, the feedforward compensation will influence the signal y before the disturbance. The disturbance signal should ideally be delayed with the time $T_{vy} - T_{uy}$.

$T_{vy} \approx T_{uy}$ In this case, feedforward is often very efficient.

$T_{vy} << T_{uy}$ It is not worth wile to use feedforward. We cannot make any compensation before the disturbance is seen in y. The feedback controller can equally well do the job.

From these considerations, we can conclude that d should ideally be chosen as T_{uy}, i.e. equal to the dead-time plus the dominating time constant of the process.

From the relay experiment in the autotuner, the maximum time delay between u and y is given as half the oscillation period, i.e. $T_u/2$. (If the process consists of only a time delay, the oscillation period is two times the time delay!) We have chosen the parameter $d = T_u/2$. The sampling interval of the least-squares estimator is chosen as in the feedback case, i.e., $h = T_u/8$. This gives the following model equation:

$$y(t) = au(t-4h) + bv(t-4h)$$

We have chosen the gain k_{ff} in the control law as

$$k_{ff}(t) = -0.8\frac{\hat{b}(t)}{\hat{a}(t)}$$

where $\hat{a}$ and $\hat{b}$ are the estimates of a and b. The adaptive algorithm is surrounded with a security net in the same way as the feedback algorithm, e.g., high-pass filtering of the signals tells when the information content in the signals is large enough to allow adaptation.

6. Industrial Experiences

To illustrate the properties of the adaptive controller, some of the experiments from the field tests are presented below. We will first shortly describe how the different uses of the adaptive technique are implemented in the controller.

Implementation

The new industrial adaptive controller, named ECA400, is manufactured by SattControl Instruments AB, Sweden. It is a single station cascade controller. It contains all the adaptive techniques that have been presented in the previous sections, i.e. the relay autotuner, a gain schedule, adaptive feedback and adaptive feedforward. The gain schedule, the adaptive feedback and the adaptive feedforward are independent of each other, and may thus be used separately or together. The autotuner is used to initialize the adaptive controller and the adaptive feedforward. In this way, the operator does not have to provide the controller with any information about the process dynamics. The parameters of the gain schedule are automatically obtained by using the autotuner once at every operating point. The gain schedule may be combined with the adaptive controller. Adaptation will then only be performed with the set of controller parameters that are presently used. The result is the same as if we had several different and independent adaptive controllers.

Temperature control

The first example shows a temperature control loop. Parts of the experiments are presented in Figure 5. Water is heated through a heat exchanger, with steam on the primary side. The water temperature is measured and the controller output determines the steam valve position. The primary disturbances in the loop are changes in the steam pressure and changes in the water flow rate. The drift in the control signal during times of constant temperature are due to the changes in steam pressure.

The setpoint is changed stepwise up and down to activate the adaptation mechanism, and to show the properties of the control. Before the large change in water flow, we had a PI controller with gain 3.2 and integral time 13 s. When the water flow decreased, the gain decreased to 2.6 after the first set point change. After three set point changes the gain had decreased to 2.1. After the fourth set point change, we obtained a PID controller with gain 1.5, integral time 8.2 s and derivative time 2.0 s. These controller parameters were not significantly changed until the next water flow alteration.

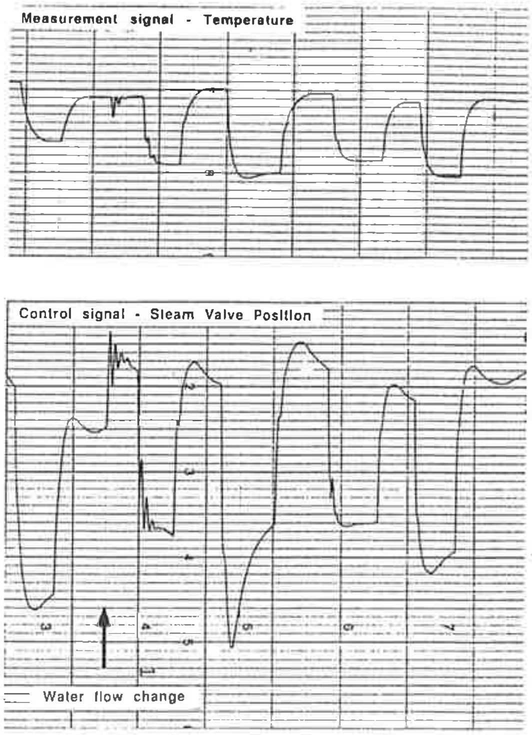

Figure 5. Adaptive control of a temperature control loop

The experiment shows that the adaptation to the new process conditions is rather fast. This is especially the case when the process gain increases, and the controller gain is to be decreased. The reason is that the high loop gain provides good excitation.

Pulp density control

The second example is taken from the paper industry. The pulp is diluted to a desired density by adding water to the incoming pulp. Parts of the experiment are shown in Figure 6. The setpoint of the pulp density was changed stepwise to activate the adaptation. The process gain is changing according to changes in the pulp flow. Figure 6 shows a situation where the pulp flow was increased, resulting in a decreased process gain. Before the flow change, we had a PID controller with a gain of 0.10. As seen in the figure, this low gain gave a very slow control after the pulp flow change. After five set-point changes, the controller gain had increased to 0.30, resulting in a much faster control.

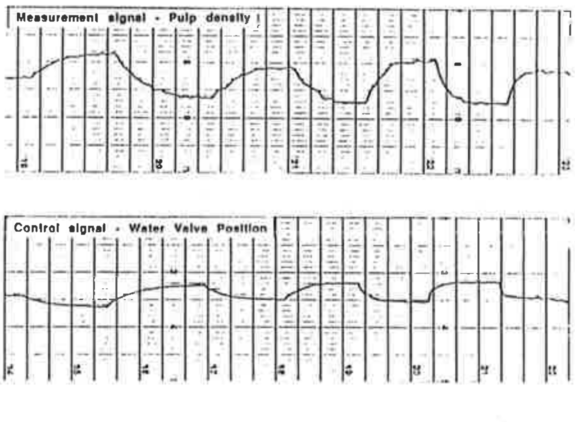

Figure 6. Adaptive control of a pulp density control loop

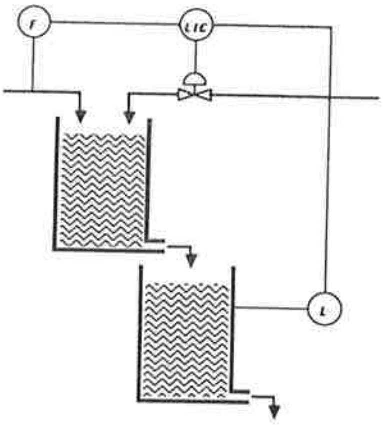

Figure 7. Pilot plant used for adaptive feedforward compensation

Adaptive feedforward in a pilot plant

The last example demonstrates the bahaviour of the adaptive feedforward compensation. A pilot plant consisting of two cascaded tanks was used. Se Figure 7. The level in the lower tank was controlled by the valve on the water inlet tube. A disturbance flow was also connected to the upper tank. This flow was measured and fed into the controller.

Figure 8 shows the results of the experiment. The experiment starts with an auto-tuning to set the PID parameters. The autotuner experiment is followed by two setpoint changes to show the behaviour of the closed loop control. Load disturbances are then introduces by making step changes in the disturbance flow.

When the disturbance signal is connected to the controller and adaptive feedforward compensation is demanded, the controller needs two load disturbances to find a suitable feedforward gain. The two last load disturbances show that the load rejection is significantly better when the feedforward compensation is used.

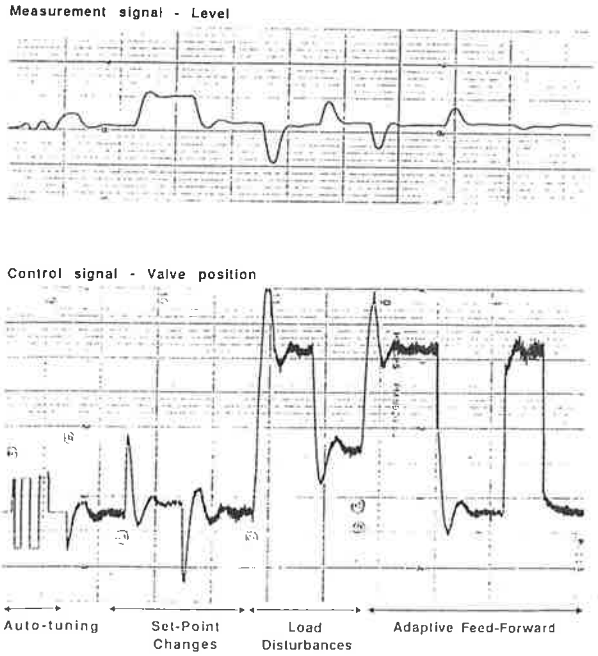

Figure 8. Adaptive feedforward compensation

7. Conclusions

This paper shows that it is possible to combine the ideas of auto-tuning, gain scheduling, feed forward and adaptation in a simple controller that is easy to use. The key idea is to use relay feedback to obtain the time scale of the process. When this is known it is possible to simplify many design issues. The structure and sampling periods of the discrete time models used for adaptive feedback and feedforward can then be determined.

The controller is based on the PID structure. It thus inherits all the advantages and disadvantages of the PID structure. An advantage is that the operators have a well-known structure that they can relate to. They know what the parameters mean. They can compare the parameters with values they know from experience. Since the operators are familiar with the gain, the integral time and the derivative time of a PID controller, they may very well turn the adaptation off for certain periods and make their own adjustments. The PID structure does however also have some disadvantages particularly when dealing with processes with long dead time.

A major advantage of the new controller is that it is easy to operate. No parameters have to be given in advance. The auto-tuner is activated simply by pushing the tuning button. The information required for the adaptation is derived from the auto-tuning experiment. This is important also from the point of view of robustness. Since all parameters are calculated automatically, the behaviour of the controller is predictable. It cannot deteriorate due to e.g. a bad choice of the sampling period.

The controller is based on PID control with fast sampling. This has the advantage that the controller will react very quickly on a disturbance. Adaptive systems based on general linear models often use the same sampling period for control and estimation. It is common practice to use a fairly long sampling period to make the estimator robust. There will then be a delay in responding to disturbances.

Only two parameters are estimated. This is less than in most other adaptive controllers. To be able to describe the process dynamics using only two parameters, these parameters must be chosen properly. This is possible since the initialization with the autotuner makes it possible to choose a good structure. The adaptation rate is rather fast since only two parameters are estimated.

8. References

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