Control Eng. Practice, Vol. 1, No. 4, pp. 699-714, 1993
Printed in Great Britain.

0967-0661/93 $6.00 + 0.00

AUTOMATIC TUNING AND ADAPTATION FOR PID CONTROLLERS - A SURVEY

K.J. Åström*, T. Hägglund*, C.C. Hang** and W.K. Ho**

**Department of Automatic Control, Lund Institute of Technology, S-221 00 Lund, Sweden*
***Department of Electrical Engineering, National University of Singapore, Singapore*

Abstract. Adaptive techniques such as gain scheduling, automatic tuning and continuous adaptation have been used in industrial single-loop controllers for about ten years. This paper gives a survey of the different adaptive techniques, the underlying process models and control designs. An overview of industrial products is also presented, which includes a fairly detailed investigation of four different adaptive single-loop controllers.

Keywords. Adaptive control, automatic tuning, gain scheduling, PID control.

1. INTRODUCTION

Single-loop controllers have been used in industry for a long time. For example, it was about fifty years ago that derivative action was introduced in pneumatic controllers by Taylor Instruments. Industrial single-loop controllers have gone through an interesting change in technology, from pneumatic via analog electronics to microprocessor implementation. In spite of these changes in technology, the functionality of the controllers has remained the same, namely essentially an implementation of the standard PID algorithm. The controllers are currently going through an interesting phase of development, where features like auto-tuning, gain scheduling and adaptation are added. There is hardly any new product announced that does not incorporate some of these features. The single-loop controller is therefore rapidly becoming a test bench for control theory. Since the controllers are made and used in large numbers, much industrial experience of using sophisticated control is also accumulating. One reason for this development is the advances in microelectronics which give cheap microprocessors whose computational power is continuously increasing. Another reason is the pressure from users and applications, and a third is the growing experience of using advanced control.

It may be asked why a similar development is not taking place in distributed control systems. One reason is that the distributed control systems are quite complicated and that their development cycle is quite long. Therefore it takes a long time for new features to be introduced in such systems. There are, however, indications that the experiences from single-loop controllers are migrating into larger systems.

It is therefore timely to take stock of the development, to assess the current state of the art and to look at the future. To make such an evaluation is the purpose of this paper. The paper is organized as follows. A review of industrial needs is given in Section 2, which also presents some adaptive techniques and matches them to the needs. More details on the techniques are given in Sections 3 and 4 that deal with modeling and control methods. Section 5 gives an overview of some existing industrial products. In Section 6, four products with different adaptive approaches are described in more detail.

2. ADAPTIVE TECHNIQUES

The first general purpose adaptive controller for industrial process control was introduced around 1983. There are now many brands of adaptive controllers for industrial process control and many loops being controlled by such controllers, see (Dumont *et al.*, 1989; Kaya and Titus, 1988; Hess *et al.*, 1987; Hägglund and Åström, 1991). As a result of this there is a growing experience of using adaptive techniques. Unfortunately there is also some confusion in terminology. Therefore we will introduce an appropriate terminology at the same time as we describe some of the adaptive techniques that have been useful.

Automatic Tuning

By automatic tuning (or auto-tuning) we mean a method where a controller is tuned automatically on demand from a user. Typically the user will either push a button or send a command to the controller. Industrial experience has clearly indicated that this is a highly desirable and useful feature. Automatic tuning is sometimes called tuning on demand or one-shot tuning.

Automatic tuning can also be performed using external equipment. These products are connected to the control loop only during the tuning phase. When the tuning experiment is finished, the products suggest controller parameters. Since these products are supposed to work together with controllers from different manufacturers, they must be provided with quite a lot of information about the controller structure in order to give an appropriate parameter suggestion. Such information includes controller structure (series or parallel form), sampling rate, filter time constants, and units of the different controller parameters (gain or proportional band, minutes or seconds, time or repeats/time).

Gain Scheduling

By gain scheduling we mean a system where controller parameters are changed depending on measured operating conditions. The scheduling variable can, for instance, be the measurement signal, controller output or an external signal. For historical reasons the word gain scheduling is used even if other parameters like derivative time or integral time are changed. Gain scheduling is a very effective way of controlling systems whose dynamics change with the operating conditions. Gain scheduling has, however, not been used much because of the effort required to implement it. When combined with auto-tuning, gain scheduling is, however, very easy to use.

Adaptive Control

By adaptive control we mean a controller whose parameters are continuously adjusted to accommodate changes in process dynamics and disturbances. Adaptation can be applied both to feedback and feedforward control parameters. It has proven particularly useful for feedforward control. The reason for this is that feedforward control requires good models. Adaptation is therefore almost a prerequisite for using feedforward control.

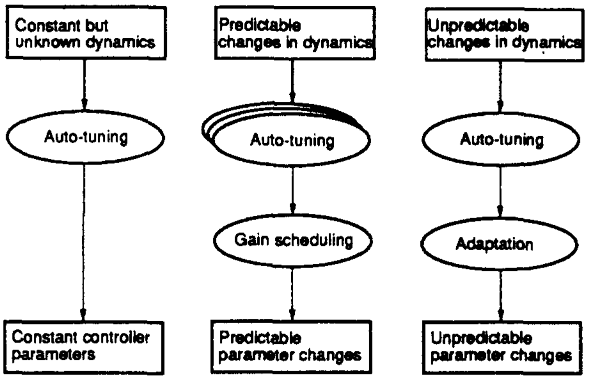

Fig. 1. When to use different adaptive techniques

The notation *adaptive techniques* will be used to cover auto-tuning, gain scheduling and adaptation. Although research on adaptive techniques has almost exclusively focused on adaptation, experience has shown that auto-tuning and gain scheduling have a much wider industrial interest. Figure 1 illustrates when it is appropriate to use the different techniques.

The first issue to consider is controller performance. If the requirements are modest, a controller with constant parameters and conservative tuning can be used. With higher demands on performance other solutions should be considered. If the process dynamics are constant, a controller with constant parameters should be used. The parameters of the controller can be obtained using auto-tuning. If the process dynamics or the nature of the disturbances are changing it is useful to compensate for these changes by changing the controller. If the variations can be predicted from measured signals, gain scheduling should be used as it is simpler and it gives superior and more robust performance than the continuous adaptation. Typical examples are variations caused by nonlinearities in the control loop. Auto-tuning can be used to build up the gain schedules. There are also cases where the variations in process dynamics are not predictable. Typical examples are changes due to unmeasurable variations in raw material, wear, fouling etc. These variations cannot be handled by gain scheduling but must be dealt with by adaptation. An auto-tuning procedure is often used to initialize the adaptive controller. It is then sometimes called pretuning or initial tuning.

Feedforward control deserves special mentioning. It is a very powerful method for dealing with measurable disturbances. Use of feedforward control requires however good models of process dynamics. It is difficult to tune feedforward control loops automatically on demand, since the operator often cannot manipulate the disturbance used for the feedforward control.

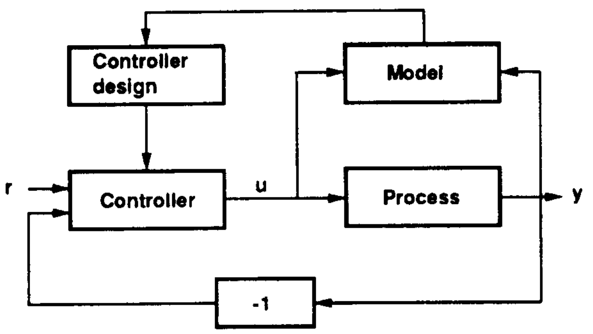

Fig. 2. Block diagram of indirect systems

To tune the feedforward controller it is therefore necessary to wait for an appropriate disturbance. Adaptation is therefore particularly useful for the feedforward controller.

The techniques used for auto-tuning and adaptation are very similar. In broad terms, one can distinguish between direct and indirect methods. In a direct method controller parameters are adjusted directly from data in closed-loop operation. In indirect methods a model of the process is first developed from on-line data. The controller parameters are then determined from this model.

There is a large number of methods available both for direct and indirect methods. They can conveniently be described in terms of the methods used for modeling and control design.

In the direct methods the key issues are to find suitable features that characterize relevant properties of the closed-loop system and appropriate ways of changing the controller parameters so that the desired properties are obtained.

The indirect systems can all be represented by the block diagram in Figure 2. There is a parameter estimator that determines the parameters of the model based on observations of process inputs and outputs. There is also a design block that computes controller parameters from the model parameters. If the system is operated as a tuner the process is excited by an input signal. The parameters can either be estimated recursively or in batch mode. Controller parameters are computed and the controller is commissioned. If the system is operated as an adaptive controller, parameters are computed recursively and controller parameters are updated when new parameter values are obtained.

3. MODELING

A model of a system can be any type of abstract description that captures useful relevant features of a process. Modeling can mean many different things, from the extraction of some simple

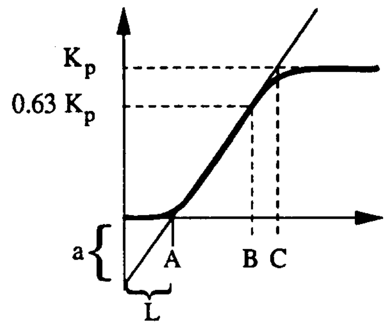

Fig. 3. Determining a first order plus dead-time model from a step response. Time constant T can be obtained either as the distance AB or the distance AC

features of a transient response to the development of a traditional control model in terms of a transfer function or an impulse response. Some models that are used in adaptive PID controllers will now be described.

3.1 Time-Domain Models

Typical time-domain features are static gain, dominant time constant and dominant dead time. They can all be determined from the step response of the process, see Figure 3. Static gain K_p, dominant time constant T and dominant dead time L can be used to obtain a first order plus dead-time model for the process as given in Equation (1).

$$G_p(s) = \frac{K_p}{1 + sT} e^{-sL} \tag{1}$$

The constructions in Figure 3 are sensitive because they are based on a few values of the step response only.

Another method, which is based on determination of areas can be used, see Figure 4. In this method, gain K_p is first determined from the steady-state value of the step response. Area A_0 is then determined. The average residence time of the system is then

$$L + T = \frac{A_0}{K_p} \; . \tag{2}$$

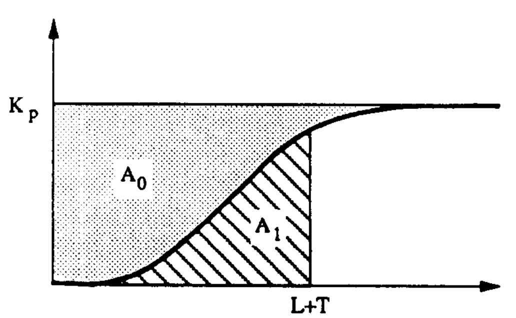

Fig. 4. Determining a first order plus dead-time model from a step response

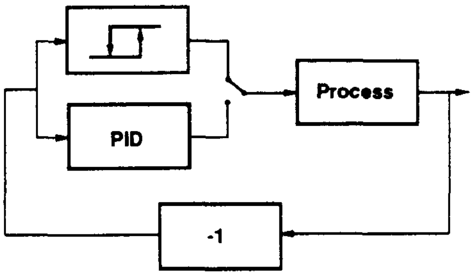

Fig. 5. The relay autotuner. In the tuning mode the process is connected to relay feedback

Area A_1, which is the area under the step response up to time $L + T$, is then determined and T is given by

$$T = \frac{A_1}{K_p} e^1. \tag{3}$$

This method is less sensitive to high-frequency disturbances, because it is based on area determination. More details can be found in (Åström and Hägglund, 1988; Nishikawa *et al.*, 1984).

Higher order models can also be obtained from a step response method, see, for instance, (Seborg *et al.*, 1989).

A discrete time model as given in Equation (4) can also be used to describe the process.

$$G_p(z) = \frac{b_0 + b_1 z + \ldots + b_{n-1} z^{n-1}}{a_0 + a_1 z + \ldots + a_n z^n} \tag{4}$$

There are many methods available to determine the parameters in Equation (4), for instance the recursive least squares method.

3.2 Frequency-Domain Models

Typical frequency-domain characteristics are amplitude margin, phase margin, Mp-value, ultimate gain, and ultimate period. These quantities are all related to simple properties of the Nyquist curves of the open-loop transfer function or of the loop transfer function.

Relay Excitation

Frequency-domain characteristics can be determined from experiments with relay feedback in the following way. When the controller is to be tuned, a relay with hysteresis is introduced in the loop, and the PID controller is temporarily disconnected, see Figure 5. For large classes of processes, relay feedback gives an oscillation with period close to the ultimate frequency ω_{180}. The gain of the transfer function at this frequency is also easy to obtain from amplitude measurements. Details and conditions are given in (Åström and Hägglund, 1984; Åström and Hägglund, 1988; Hang and Åström, 1988). Describing function analysis can be used to determine the process characteristics. The describing function of a relay with hysteresis is

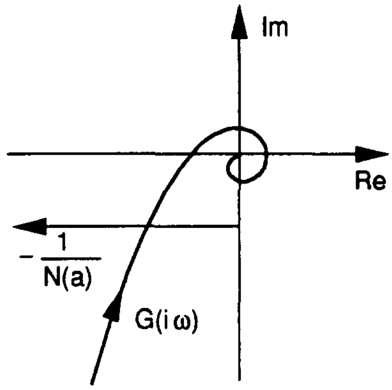

Fig. 6. The negative inverse describing function of a relay with hysteresis $-1/N(a)$ and a Nyquist curve $G(i\omega)$

$$N(a) = \frac{4d}{\pi a}\left(\sqrt{1 - \left(\frac{\varepsilon}{a}\right)^2} - i\frac{\varepsilon}{a}\right)$$

where d is the relay amplitude, ε the relay hysteresis and a is the amplitude of the input signal. The negative inverse of this describing function is a straight line parallel to the real axis, see Figure 6. The oscillation corresponds to the point where the negative inverse describing function crosses the Nyquist curve of the process, i.e. where

$$G(i\omega) = -\frac{1}{N(a)}$$

Since $N(a)$ is known, $G(i\omega)$ can be determined from the amplitude a and the frequency ω of the oscillation.

Correlation Method

In this method, a small pseudo random binary sequence (PRBS) test signal $u(t)$ is injected and the resultant process output $y(t)$ is logged. The cross correlation, $\phi_{uy}(\tau)$, between $u(t)$ and $y(t)$ is then used to compute the impulse response $g(\tau)$ of the process (Hang and Sin, 1991) as follows

$$g(\tau) = \frac{1}{A^2 h}\left(\frac{N}{N+1}\right)\left(\phi_{uy}(\tau) + \sum_{k=0}^{N-1} \phi_{uy}(k)\right) \tag{5}$$

where A is the amplitude of the PRBS signal, h is the sampling interval and Nh is the period of the PRBS signal. The impulse response computed is then numerically transformed into its frequency response from which the ultimate gain, ultimate period, static gain and normalized dead time of the process can be determined.

3.3 Conversion to Time-Domain Models

The estimated frequency-domain model in terms of the full frequency response or at least two points on the Nyquist curve may be used to derive a corresponding time-domain model. This is useful if the controller design is done in the time domain (pole-placement design, Ziegler-Nichols step response design, IMC design, etc. to be discussed in Section 4). The following formulas (Ho *et al.*, 1992), for instance, may be used to derive useful models from knowledge of the ultimate gain (K_u), ultimate period (T_u), and the static gain (K_p):

$$G_p(s) = \frac{K_p}{1 + sT_1} e^{-sL_1}$$

or

$$G_p(s) = \frac{K_p}{(1 + sT_2)^2} e^{-sL_2}$$

where

$$T_1 = \frac{T_u}{2\pi}\sqrt{(K_uK_p)^2 - 1}$$

$$L_1 = \frac{T_u}{2\pi}\left(\pi - \tan^{-1}\frac{2\pi T_1}{T_u}\right)$$

and

$$T_2 = \frac{T_u}{2\pi}\sqrt{K_uK_p - 1}$$

$$L_1 = \frac{T_u}{2\pi}\left(\pi - 2\tan^{-1}\frac{2\pi T_2}{T_u}\right)$$

4. CONTROL DESIGN

The PID control law can be implemented in either the parallel or the series form. The parallel form with derivative action on filtered measurement signal to avoid "derivative kick" is given below.

$$\begin{aligned} u &= K\left(e + \frac{1}{T_i}\int e\,dt - T_d\frac{dy_f}{dt}\right) \\ e &= y_r - y \\ \frac{dy_f}{dt} &= \frac{N}{T_d}(y - y_f). \end{aligned} \tag{6}$$

The controller output, process output and set point are u, y and y_r, respectively. A weighting factor β can be placed on the set point as shown in Equation (7).

$$u = K\left((\beta y_r - y) + \frac{1}{T_i}\int e\,dt - T_d\frac{dy_f}{dt}\right) \tag{7}$$

The factor β when set to less than one can reduce the set-point response overshoot without affecting the load-disturbance response. In a conventional PID controller with $\beta = 1$, tuning to give good load-disturbance responses will often give set-point responses that are too oscillatory. On the other hand, tuning to give good set-point responses often gives sluggish load-disturbances response. The factor β when set to less than one can reduce the set-point response overshoot for tuning that optimizes the load-disturbance response. In some literature, this form of the PID control law is known as a two-degree-of-freedom PID controller (Shigemasa *et al.*, 1987; Takatsu *et al.*, 1991). Several industrial controllers have $\beta = 0$.

The series form of the PID control law, without filter on the derivative term, is given in Equation (8).

$$G_c(s) = K\left(1 + \frac{1}{sT_i}\right)(1 + sT_d) \tag{8}$$

It is not possible to obtain complex zeros from this form of the controller. However, it is sometimes claimed that the series form is easier to tune.

This section describes some methods for determining the parameters of a PID controller. They can be classified broadly into direct and indirect methods. The direct control design techniques are simply prescriptions that tell how the controller parameters should be changed in order to obtain the desired features. The indirect control design methods give controller parameters in terms of model parameters.

4.1 Direct Methods

A vast majority of the PID controllers in the industries are tuned manually by control engineers and operators. The tuning is done based on past experiences and heuristics. By observing the pattern of the closed-loop response to a set-point change, the operators uses heuristics to directly adjust the controller parameters. The heuristics have been captured in tuning charts that show the responses of the system for different parameter values. A considerable insight into controller tuning can be developed by studying such charts and performing simulations. The heuristic rules have also been captured in knowledge bases in the form of rules, both crisp and fuzzy, see (Anderson *et al.*, 1988; Bristol, 1977; Bristol, 1986; Higham, 1985; Klein *et al.*, 1991; Kraus and Myron, 1984; Marsik and Strejc, 1989; Pagano, 1991; Yamamoto, 1991). Rules of this type are used in several commercial tuners. Most products will wait for set-point changes or major load disturbances. When these occur, properties like damping, overshoot, period of oscillations and static gains are estimated. Based on these properties, rules for changing the controller parame-

Table 1. Controller parameters obtained by the Ziegler-Nichols step response method.

Controller	K	T_i	T_d	T_p
P	$1/a$			$4L$
PI	$0.9a$	$3L$		$5.7L$
PID	$1.2/a$	$2L$	$L/2$	$3.4L$

ters to meet desired specifications are executed. An example will be described later in Section 6.

4.2 Indirect Methods

Ziegler-Nichols Step Response Method

This method is based on a registration of the open-loop step response of the system, which is characterized by two parameters. The point where the slope of the step response has its maximum is first determined, and the tangent at this point is drawn. The intersections between this tangent and the coordinate axes give the two parameters a and L, see Figure 3. A simple model of the process which can be derived from these parameters is given by the transfer function

$$G_p(s) = \frac{a}{sL}e^{-sL}. \tag{9}$$

Ziegler and Nichols have given PID parameters directly as functions of a and L, see (Ziegler and Nichols, 1942). These formulas are given in Table 1. An estimate of the period T_p of the dominant dynamics of the closed-loop system is also given in the table. The formulas will roughly give quarter amplitude damping ratio for load-disturbance response for processes that can be modeled by Equation (9). In practice some form of fine tuning has to be done.

There are several design methods which are similar to the Ziegler-Nichols step response method in the sense that they are based on a step response experiment combined with a table that relates the controller parameters to the characteristics of the step response, see (Hang *et al.*, 1979; Hazebroek and van der Waerden, 1950; Miller *et al.*, 1967). The most common method is the Cohen-Coon method (Cohen and Coon, 1953) based on a first order plus dead-time model.

Optimization Techniques

There are other tuning formulas derived to optimize certain criteria such as the integrated absolute error (IAE), the integrated time absolute error (ITAE), the integrated square error (ISE), etc. They are mostly done for the first-order plus dead-time model as given in Equation (1). A word of caution is in order: Formulas derived for the first-order plus dead-time model may not give good results for higher order systems. An example is given in Figure 7. A PI controller for a process with the transfer function

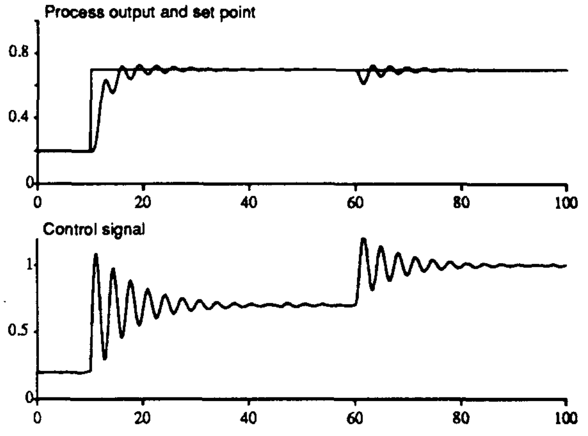

Fig. 7. IAE criteria optimized for first order plus dead-time process applied to a higher order process. $K = 4.3, T_i = 2.0$

$$G_p(s) = \frac{e^{-0.3s}}{(s+1)^2} \tag{10}$$

is determined by first finding parameters L and T by the maximum slope method and then applying Shinskey's closed-loop tuning formula for minimum IAE, see (Shinskey, 1988). It is evident that the tuning performance as shown in Figure 7 is too oscillatory.

Pole Placement

If the process is described by a low-order transfer function, a complete pole-placement design can be performed. Consider the process described by a second-order model in Equation (11).

$$G(s) = \frac{K_p}{(1+sT_1)(1+sT_2)} \tag{11}$$

This model has three parameters. By using a PID controller, which also has three parameters, it is possible to arbitrarily place the three poles of the closed-loop system. The transfer function of the PID controller on parallel form can be written as

$$G_c(s) = \frac{K(1+sT_i+s^2T_iT_d)}{sT_i}. \tag{12}$$

The characteristic equation of the closed-loop system becomes

$$\begin{aligned} &s^3 + s^2\left(\frac{1}{T_1}+\frac{1}{T_2}+\frac{K_pKT_d}{T_1T_2}\right)+ \\ &s\left(\frac{1}{T_1T_2}+\frac{K_pK}{T_1T_2}\right)+\frac{K_pK}{T_iT_1T_2}=0\,. \end{aligned} \tag{13}$$

A suitable closed-loop characteristic equation of a third-order system is

$$(s+\alpha\omega)(s^2+2\zeta\omega s+\omega^2)=0 \tag{14}$$

which contains two dominant poles with relative damping (ζ) and frequency (ω), and a real pole located in $-\alpha\omega$. Identifying the coefficients in these two characteristic equations gives

$$\begin{aligned} \frac{1}{T_1} + \frac{1}{T_2} + \frac{K_pKT_d}{T_1T_2} &= \omega(\alpha + 2\zeta) \\ \frac{1}{T_1T_2} + \frac{K_pK}{T_1T_2} &= \omega^2(1 + 2\zeta\alpha) \qquad (15) \\ \frac{K_pK}{T_iT_1T_2} &= \alpha\omega^3. \end{aligned}$$

These three equations determine the PID parameters K, T_i and T_d. The solution is

$$\begin{aligned} K &= \frac{T_1T_2\omega^2(1 + 2\zeta\alpha) - 1}{K_p} \\ T_i &= \frac{T_1T_2\omega^2(1 + 2\zeta\alpha) - 1}{T_1T_2\alpha\omega^3} \qquad (16) \\ T_d &= \frac{T_1T_2\omega(\alpha + 2\zeta) - T_1 - T_2}{T_1T_2(1 + 2\zeta\alpha)\omega^2 - 1}. \end{aligned}$$

Notice that pure PI control is obtained for

$$\omega_c = \frac{T_1 + T_2}{T_1T_2(\alpha + 2\zeta)}. \qquad (17)$$

Notice also that the choice of ω may be critical. The derivative time is negative for $\omega < \omega_c$. The frequency ω_c thus gives a lower bound to the bandwidth. Also notice that the gain increases rapidly with ω. The upper bound to the bandwidth is given by the validity of the simplified model. Automatic tuning of PID controllers based on pole placement design is discussed in (Gawthrop, 1986).

Cancellation of Process Poles

The PID controller has two zeros. A popular design method is to choose these zeros so that they cancel the two dominant process poles. The method is popular since it is simple and gives good response to set-point changes, see (Haalman, 1965). The method will, however, often give poor response to load disturbances (Åström and Hägglund, 1988). An exception to this is in the case of large dead time, in which case the settling time is already quite long relative to the time constant being cancelled (Ho *et al.*, 1992).

When pole-zero cancellation is safe to apply, the simple IMC (Internal Model Control) based tuning formulas (Morari and Zafiriou, 1989; Seborg *et al.*, 1989) based on a first order plus dead-time model—as shown in Table 2—may be used.

The controller gain may be chosen to be aggressive or conservative by varying the value of λ, which is equivalent to the desired closed-loop time constant.

Table 2. IMC based PID controller tuning formulas.

Controller	K	T_i	T_d	Suggested λ
PI	$\frac{1}{K_p}\frac{2T+L}{2\lambda}$	$T + L/2$		$\lambda \geq 0.2T$ $\lambda \geq 1.7L$
PID	$\frac{1}{K_p}\frac{2T+L}{2\lambda+L}$	$T + L/2$	$\frac{TL}{2T+L}$	$\lambda \geq 0.2T$ $\lambda \geq 0.25L$

Ziegler-Nichols Frequency Response Method

This method is based on a very simple characterization of the process dynamics. The design is based on knowledge of the point on the Nyquist curve of the process transfer function G where the Nyquist curve intersects the negative real axis. For historical reasons this point is characterized by the parameters K_u and T_u, which are called the ultimate gain and the ultimate period. These two quantities can be obtained for many systems by using proportional feedback and choosing sufficiently high gain until continuous cycling occurs. The ultimate gain K_u is then given by the proportional gain and the ultimate period T_u is given by the period of the oscillations. It is, however, more practical to obtain these parameters using the relay feedback experiment or the correlation method presented in Section 3.

The Ziegler-Nichols formulas are given in Table 3. An estimate of the period T_p of the dominant dynamics of the closed-loop system is also given in the table. These formulas were derived to give quarter amplitude damping for load-disturbance response, see (Ziegler and Nichols, 1942). Both T_p and the damping obtained with the Ziegler-Nichols tuning rule can, however, differ significantly from these expected values. Refined Ziegler-Nichols formulas to reduce these discrepancies and to improve the tuning performance are given in (Hang *et al.*, 1991).

Phase and Amplitude Margins

Phase and amplitude margins design methods give a measure of the robustness of the system. It is known from classical control that the damping of the system is related to the phase margin. The phase margin is given by

$$\phi_m = \pi + arg G_p(i\omega_g)G_c(i\omega_g) \qquad (18)$$

Table 3. Controller parameters obtained by the Ziegler-Nichols frequency response method.

Controller	K	T_i	T_d	T_p
P	$0.5K_u$			T_u
PI	$0.4K_u$	$0.8T_u$		$1.4T_u$
PID	$0.6K_u$	$0.5T_u$	$0.12T_u$	$0.85T_u$

where $|G_p(i\omega_g)G_c(i\omega_g)| = 1$ and ω_g is the gain cross-over frequency. The amplitude margin or gain margin is given by

$$A_m = \frac{1}{|G_p(i\omega_u)G_c(i\omega_u)|} \tag{19}$$

where ω_u is the ultimate frequency or the phase cross-over frequency.

If the ultimate gain (K_u) and ultimate period (T_u) are known, the following simple design formula (Åström and Hägglund, 1988) may be used to achieve a pre-specified phase margin ϕ_m:

$$\begin{aligned} K &= K_u \cos\phi_m \\ T_i &= \frac{T_u}{4\pi}\left(\tan\phi_m + \sqrt{1+\tan^2\phi_m}\right) \\ T_d &= T_i/4. \end{aligned} \tag{20}$$

The above design works well for processes with relatively small dead time. Otherwise, especially when the dead time is dominant, the amplitude margin may be poor although the prespecified phase margin is achieved. If a first order plus dead-time process model (Equation 1) is obtained, the following design formula (Ho *et al.*, 1992) may be used to achieve a prespecified amplitude margin A_m:

$$\begin{aligned} K_c &= \frac{\pi T}{2A_m K_p L} \\ T_i &= T. \end{aligned} \tag{21}$$

For this method, the phase margin is consistent with the amplitude margin as given by the following relation (Ho *et al.*, 1992):

$$\phi_m = \frac{\pi}{2}(1 - 1/A_m). \tag{22}$$

The above simplified design is achieved using pole-zero cancellation for a first order plus dead-time model. A corresponding set of formula can also be obtained for a second-order plus dead-time process model. They work well when the process dead time is substantial. For a lag dominant process, pole-zero cancellation is not recommended and hence suitable modifications should be made (Ho *et al.*, 1992).

5. OVERVIEW OF INDUSTRIAL PRODUCTS

Commercial PID controllers with adaptive techniques have been available since the beginning of the eighties. In this section, these products will be classified with respect to their applications and adaptive techniques used. In the next section, some of the products will be described in more detail.

In the following, we will distinguish between *temperature controllers* and *process controllers*. Temperature controllers are primarily designed for temperature control, whereas process controllers are supposed to work in not only temperature control loops, but also in other loops in the process industry such as flow, pressure, level and pH control loops.

Temperature Controllers

A large number of PID controllers are designed specifically for temperature control applications. These controllers are normally cheaper than process controllers. Automatic tuning and adaptation is easier to implement in temperature controllers, since most temperature control loops have several common features. This is the main reason why automatic tuning has been introduced more rapidly in temperature controllers.

In temperature control loops, a serious nonlinearity may result if the heating and cooling dynamics are different. This nonlinearity should be treated by gain scheduling. The temperature controllers have sometimes a facility to shift between different controller parameters when the control action shifts between heating and cooling.

Process Controllers

Since the processes that are controlled with process controllers may have large differences in their dynamics, tuning and adaptation becomes more difficult compared to the pure temperature control loops. One of the first adaptive process controllers was released from Leeds & Northrup Co in 1982, see (Hawk, 1983).

If a temperature controller is applied to, for instance, a pressure loop, the built-in tuning procedure may be very poor, since pressure control loops normally are much faster and more sensitive than temperature control loops. The following presentation will focus on process controllers.

In section 2, different adaptive techniques were discussed. The techniques are: Automatic tuning, gain scheduling and adaptive feedback and feedforward control. In Table 4, a collection of process controllers is presented, together with information about their adaptive techniques.

Automatic tuning is the most common adaptive technique in industrial products. The usefulness of this technique is also obvious from Figure 1. The auto-tuning procedures are necessary to obtain a reasonably comfortable operation of the other adaptive techniques. Most auto-tuning procedures are based on step response analysis.

Table 4. Examples of industrial adaptive process controllers.

Manufacturer	Controller	Automatic tuning	Gain scheduling	Adaptive feedback	Adaptive feedforward
Bailey Controls	CLC04	Step	Yes	Model based	–
Control Techniques	Expert controller	Ramps	–	Model based	–
Fisher Controls	DPR900	Relay	Yes	–	–
	DPR910	Relay	Yes	Model based	Model based
Foxboro	Exact	Step	–	Rule based	–
Fuji	CC-S:PNA 3	Steps	Yes	–	–
Hartmann & Braun	Protronic P	Step	–	–	–
	Digitric P	Step	–	–	–
Honeywell	UDC 6000	Step	Yes	Rule based	–
SattControl	ECA40	Relay	Yes	–	–
	ECA400	Relay	Yes	Model based	Model based
Siemens	SIPART DR22	Step	Yes	–	–
Toshiba	TOSDIC-215D	PRBS	Yes	Model based	–
	EC300	PRBS	Yes	Model based	–
Turnbull Control Systems	TCS 6355	Steps	–	Model based	–
Yokogawa	SLPC-171,271	Step	Yes	Rule based	–
	SLPC-181,281	Step	Yes	Model based	–

Gain scheduling is often not available in the controllers. This is surprising, since gain scheduling is found to be more useful than continuous adaptation in most situations. Furthermore, the technique is much simpler to implement than automatic tuning or adaptation.

It is interesting to see that many industrial adaptive controllers are rule-based instead of model-based. The research on adaptive control at universities has been almost exclusively focused on model-based adaptive control.

Adaptive feedforward control is seldom provided in the industrial controllers. This is surprising, since adaptive feedforward control is known to be of great value. Furthermore, it is easier to develop robust adaptive feedforward control than adaptive feedback control.

6. SOME PID CONTROLLERS WITH ADAPTIVE TECHNIQUES

In this section, some industrial adaptive PID controllers will be presented. The controllers presented are the Foxboro EXACT (760/761), which uses step response analysis for automatic tuning and pattern recognition technique and heuristic rules for its adaptation; the SattControl ECA400 controller, which uses relay autotuning and model based adaptation; the Honeywell UDC 6000 controller, which uses step response analysis for automatic tuning and a rule base for adaptation, and finally the Yokogawa SLPC-181 and 281, which use step response analysis for auto-tuning and a model based adaptation.

6.1 Foxboro EXACT

The single-loop adaptive controller EXACT was announced by Foxboro in October 1984. The reported application experience in using this controller has been favorable, see, for instance, (Callaghan *et al.*, 1986). The adaptive features are now also available in their DCS products.

Process Modeling

The Foxboro system is based on the determination of dynamic characteristics from a transient, which results in a sufficiently large error. If the controller parameters are reasonable, a transient error response of the type shown in Figure 8 is obtained. Heuristic logic is used to detect that a proper disturbance has occurred and to detect peaks e_1, e_2, e_3, and oscillation period T_p.

Control Design

The idea behind the tuning method is pattern recognition as described in (Bristol, 1977). The user specifications are given in terms of maximum overshoot and maximum damping. They are defined as

$$\begin{aligned} \text{damping} &= \frac{e_3 - e_2}{e_1 - e_2} \\ \text{overshoot} &= \left|\frac{e_2}{e_1}\right| \end{aligned} \tag{23}$$

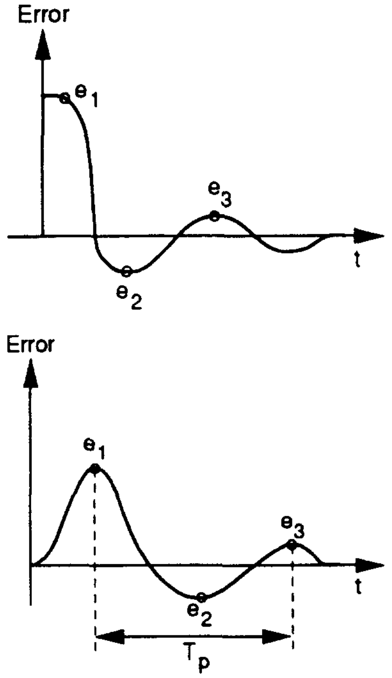

Fig. 8. Response to a step change of set point (upper curve) and load (lower curve)

for set-point changes as well as load disturbances. Note that the definition of damping here is different from the damping factor associated with a standard second-order system.

The controller structure is of the series form. From the response to a set-point change or load disturbance, the actual damping and overshoot pattern of the error signal is recognized and the period of oscillation T_p measured. This information is used by the heuristic rules to directly adjust the controller parameters to give the specified damping and overshoot. It is therefore a direct method. Examples of heuristics are decreasing proportional band PB, integral time T_i and derivative time T_d if distinct peaks are not detected. If distinct peaks have occurred and both damping and overshoot are less than the maximum values, PB is decreased.

Prior Information and Pretuning

The controller has a set of required parameters that have to be set either by the user from prior knowledge of the loop or estimated using the pretune function. (Pretune is Foxboros' notation for auto-tuning). The required parameters are

(i) Initial values of PB, T_i and T_d.

(ii) Noise band (NB). The controller starts adaptation whenever the error signal exceeds two times NB.

(iii) Maximum wait time (W_{max}). The controller waits for a time of W_{max} for the occurrence of the second peak.

If the user is unable to provide the set of required parameters a pretune function can be activated to estimate these quantities. To activate the pretune function, the controller must first be put in manual. When the pretune function is activated, a step input is generated and from a simple analysis of the process reaction curve as shown in Figure 3, values for the PID parameters are calculated using a Ziegler-Nichols-like formula:

$$\begin{aligned} PB &= 120K_pL/T \\ T_i &= 1.5L \\ T_d &= T_i/6. \end{aligned} \tag{24}$$

Maximum wait time, W_{max} is also determined from the step response:

$$W_{max} = 5L$$

The noise band is determined during the last phase of the pretune mode. The control signal is first returned to the level before the step change. With the controller still in manual and the control signal held constant, the output is passed through a high-pass filter with a cut-off frequency higher than the cut-off frequency of the closed-loop system. The noise band is calculated as an estimate of the peak-to-peak amplitude of the output from the high-pass filter.

The estimated noise band (NB) is used to initialize the derivative term. Derivative action should be decreased when the noise level is high to avoid large fluctuations in the control signal. The derivative term is initialized using the following logic:

Calculate a quantity $Z = (3.0 - 2NB)/2.5$;

if $Z > 1$ then set $T_d = T_i/6$;

if $Z < 0$ then set $T_d = 0$;

if $0 < Z < 1$ then set $T_d = Z \cdot T_i/6$.

Apart from the set of required parameters, there is also a set of optional parameters. If these are not supplied by the user then the default values will be used. The optional parameters are as follows (default values in parenthesis):

(i) Maximum allowed damping (0.3)

(ii) Maximum allowed overshoot (0.5)

(iii) Derivative factor (1). The derivative term is multiplied by the derivative factor. This allows the derivative influence to be adjusted by the user. Setting the derivative factor to zero results in PI control.

(iv) Change Limit (10). This factor limits the controller parameters to a certain range. Thus the controller will not set the PB, T_i and T_d values higher or lower than ten times their initial values if the default of 10 is used for the change limit.

6.2 SattControl ECA400

This controller was announced by SattControl in 1988. It has the adaptive functions of automatic tuning, gain scheduling and adaptive control.

Automatic Tuning

The auto-tuning is performed using the relay method in the following way, see (Hägglund and Åström, 1991). The process is brought to a desired operating point, either by the operator in manual mode or by a previously tuned controller in automatic mode. When the loop is stationary, the operator presses a tuning button. After a short period, when the noise level is measured automatically, a relay with hysteresis is introduced in the loop, and the PID controller is temporarily disconnected, see Figure 5. The hysteresis of the relay is determined automatically from the noise level. During the oscillation, the relay amplitude is adjusted so that a desired level of the oscillation amplitude is obtained. When an oscillation with constant amplitude and period is obtained, the relay experiment is interrupted and $G_p(i\omega_0)$, i.e. the value of the transfer function at oscillation frequency ω_0, is calculated using the describing function analysis.

Control Design

The PID algorithm in the ECA400 controller is of series form. The identification procedure provides a process model in terms of one point $G_p(i\omega_0)$ on the Nyquist curve. By introducing the PID controller $G_c(i\omega)$ in the control loop, it is possible to give the Nyquist curve of the compensated system G_pG_c a desired location at the frequency ω_0. For most purposes, the PID parameters are chosen so that $G_p(i\omega_0)$ is moved to the point where

$$G_p(i\omega_0)G_c(i\omega_0) = 0.5e^{-i135\pi/180} \qquad (25)$$

This design method can be viewed as a combination of phase- and amplitude-margin specification. Since there are three adjustable parameters, K, T_i and T_d, and the design criterion (25) can be obtained with only two parameters, it is furthermore required that

$$T_i = 4T_d \qquad (26)$$

For some simple control problems, where the process is approximately a first-order system, the D-part is switched off and only a PI controller is used. This kind of processes is automatically detected. For this PI controller, the following design is used:

$$\begin{aligned} K &= 0.5/|G_p(i\omega_0)| \\ T_i &= 4/\omega_0. \end{aligned} \qquad (27)$$

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 the process has a long dead time, a PI controller with the following design will replace the PID controller.

$$\begin{aligned} K &= 0.25/|G_p(i\omega_0)| \\ T_i &= 1.6/\omega_0. \end{aligned} \qquad (28)$$

Gain Scheduling

The ECA400 controller also has gain scheduling. Three sets of controller parameters can be stored. The parameters are obtained by using the auto-tuner three times, once at every operating condition. The actual value of the scheduling variable, which can be the controller output, the measurement signal or an external signal, determines which parameter set to use.

Adaptive Feedback

The ECA400 controller uses the information from the relay feedback experiment to initialize the adaptive controller. Figure 9 shows the principle of the adaptive controller. The main idea is to track the point on the Nyquist curve obtained by the relay autotuner. It is performed in the following way. The control signal u and the measurement signal y are filtered through narrow band-pass filters at the frequency ω_0, which is the frequency obtained from the relay experiment. These signals are then analyzed in a least-squares estimator which provides an estimate of the point $G(i\omega_0)$. The method is described in more detail in the paper (Hägglund and Åström, 1991).

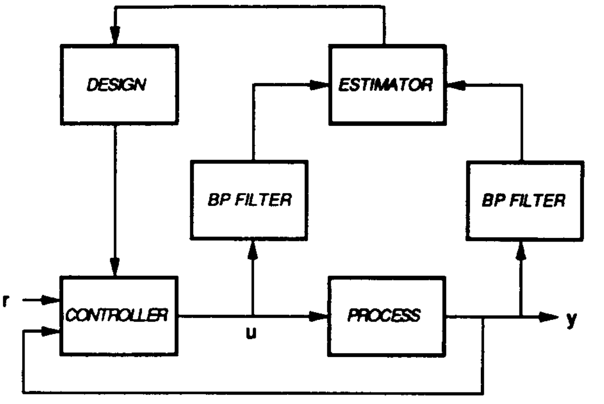

Fig. 9. The adaptive control procedure in ECA400

Adaptive Feedforward Control

Another feature is an adaptive feed-forward algorithm. The adaptive feedforward control procedure is initialized by the relay autotuner. A least squares algorithm is used to identify parameters a and b in the model

$$y(t) = au(t - 4h) + bv(t - 4h) \tag{29}$$

where y is the measurement signal, u is the control signal and v is the disturbance signal that should be fed forward. The sampling interval h is determined from the relay experiment: $h = T_0/8$, where T_0 is the oscillation period. The feedforward compensator has the simple structure

$$\Delta u_{ff}(t) = k_{ff}(t)\Delta v(t) \tag{30}$$

where the feedforward gain k_{ff} is calculated from the estimated process parameters

$$k_{ff}(t) = -0.8\,\frac{\hat{b}(t)}{\hat{a}(t)}. \tag{31}$$

The details are given in (Hägglund and Åström, 1991).

Operator Interface

The initial relay amplitude is given a default value which is suitable for most process control applications. This parameter is not critical since it will be adjusted after the first half period to give an admissible amplitude of the limit cycle oscillation. The operation of the autotuner is then very simple. To use the tuner, the process is simply brought to an equilibrium by setting a constant control signal in manual mode. The tuning is activated by pushing the tuning switch. The regulator is automatically switched to automatic mode when the tuning is complete.

The width of the hysteresis is set automatically, based on measurement of the noise level in the process. The lower the noise level, the lower is the amplitude required from the measured signal. The relay amplitude is controlled so that the oscillation is kept at a minimum level above the noise level.

The following are some optional settings that may be set by the operator:

(1) **Control Design** [normal, PI, dead time]. The default design method [normal] can result in either a PI or a PID controller depending on whether the process is of first order or not (see the discussion about control design above). The operator can force the controller to be PI by selecting [PI]. Finally, the PI design suited for processes with long dead time is used if the option [dead time] is selected. The control design can be changed either before or after a tuning, and during the adaptation.

(2) **Reset** [Yes/No]. A reset of information concerning the autotuner, the gain scheduling or the adaptive controller can be done. Some information from a tuning is saved and used to improve the accuracy of the subsequent tunings, including the noise level, the initial relay amplitude, and the period of the oscillation. If a major change is made in the control loop, for instance if the controller is moved to another loop, the operator can make a reset of the tuning information. A reset of the adaptive controller will reset the controller parameters to those obtained by the relay autotuner.

(3) **Initial relay amplitude**. In some very sensitive loops, the initial input step of the relay experiment may be too large. The initial step can then be decided by the operator.

(4) **Gain scheduling reference.** The switches between the different sets of PID parameters in the gain-scheduling table can be performed with different signals as the gain-scheduling reference. The scheduling can be based on the control signal, the measurement signal, or an external signal. The gain scheduling is active only when a reference signal is configured.

6.3 Honeywell UDC 6000

The Honeywell UDC 6000 controller has an adaptive function called *Accutune*. Accutune uses both model based procedures and rule-based procedures. It can only be used on stable processes. Integrating processes can consequently not be treated.

Initial Tuning

The adaptive procedure is initialized by a step response experiment. The user brings the process value to a point some distance away from the desired set point in manual, and waits for steady state. Switching to automatic mode will initiate a step response experiment, where the size of the step is calculated to be so large that it is supposed to take the process value to the set point.

During the experiment, the process value and its derivative are continuously monitored. The dead time L is calculated as the time interval between the step change and the moment the process value crosses a certain small limit.

If the derivative of the process value continuously decreases from the start, it is concluded that the process is of first order. Static gain K_p and time constant T_1 are then calculated as

$$\begin{aligned} T_1 &= \frac{y_2 - y_1}{dy_1 - dy_2} \\ K_p &= \frac{y_2 + dy_2 T_1}{\Delta u} \end{aligned} \tag{32}$$

where y_1 and y_2 are two measurements of the process value, dy_1 and dy_2 are estimates of the derivatives of the process value at the corresponding instants, and Δu is the step size of the control signal. The values y_i are calculated as distances from the value at the onset of the step. These calculations can be performed before the steady-state is reached. It is claimed that the process is identified in a time less than one third of the time constant. The controller is then switched to automatic mode and controlled to the set point. When this is done, a fine adjustment of the parameters is done by calculating the gain K_p from the steady-state levels.

If the derivative of the process value increases to a maximum and then decreases, the process is identified as a second-order process. The step response of a second-order process with two time constants is

$$y(t) = K_p\left(1 + \frac{T_2 e^{-\frac{t}{T_2}} - T_1 e^{-\frac{t}{T_1}}}{T_1 - T_2}\right) \tag{33}$$

This equation is used to calculate static gain K_p and time constants T_1 and T_2. As for the first order system, the process identification is performed in two steps. A first calculation is done shortly after the time of maximum slope. The controller is then switched to automatic mode and controlled to the set point. When steady state is reached, the parameters are recalculated using the additional information of steady state levels. The equations for calculating the controller parameters are

$$\begin{aligned} K_p &= \frac{y(t_{max}) + dy(t_{max})(T_1 + T_2)}{\Delta u} \\ T_1 + T_2 &= \frac{1 - N^2}{N \ln(\frac{1}{N})} t_{max} \\ N &= \frac{T_1}{T_2} \end{aligned} \tag{34}$$

where t_{max} is the time from the start of the rise to the point of maximum slope. These three equations have four unknowns: K_p, T_1, T_2 and N. At the first time of identification, shortly after the time of maximum slope, it is assumed that $N = 6$, and K_p, T_1 and T_2 are determined from the equations. When steady state is reached, gain K_p is calculated from the steady-state levels. This provides the possibility to calculate the other three unknowns from the three equations above.

Adaptation

The UDC 6000 controller also has the continuous adaptation feature. The adaptation mechanism is activated when the process value changes more than 0.3% from the set point or if the set-point changes more than a prescribed value. (More details are given below.)

The details of the adaptive controller are not published, but it contains a rule base where some of the rules will be presented. The controller monitors the process value. Depending on its nature, the following controller adjustments are made:

(1) The controller detects oscillations in the process value. If oscillation frequency ω_0 is less than $1/T_i$, then the integral time is increased to $T_i = 2/\omega_0$.

(2) If the oscillation frequency ω_0 is greater than $1/T_i$, then the derivative time is chosen to be $T_d = 1/\omega_0$.

(3) If the oscillation remains after adjustment (1) or (2), the controller will cut its gain K in half.

(4) If a load disturbance or a set-point change gives a response with a damped oscillation, the derivative time is chosen to be $T_d = 1/\omega_0$.

(5) If a load disturbance or a set-point change gives a sluggish response, where the time to reach set point is longer than $L + T_1 + T_2$, both integral time T_i and derivative time T_d are divided by a factor of 1.3.

(6) If the static process gain K_p changes, the controller gain K is changed so that the product KK_p remains constant.

Control Design

The UDC 6000 controller is written on series form and has the transfer function

$$G_c(s) = K\frac{(1 + sT_i)(1 + sT_d)}{sT_i(1 + 0.125sT_d)}.$$

The design goal is to cancel the process poles using the two zeros in the controller. If there is no dead time in the process, the controller parameters are chosen in the following way:

$$\text{First order process:}\quad K = 24/K_p,\quad T_i = 0.16T_1,\quad T_d = 0$$

$$\text{Second order process:}\quad K = 6/K_p,\quad T_i = T_1,\quad T_d = T_2.$$

For processes with dead time, the following choice of controller parameters is made:

$$\text{First order process:}\quad K = \frac{3}{K_p\,(1 + 3L/T_i)},\quad T_i = T_1,\quad T_d = 0$$

$$\text{Second order process:}\quad K = \frac{3}{K_p\,(1 + 3L/T_i)},\quad T_i = T_1 + T_2,\quad T_d = \frac{T_1 T_2}{T_1 + T_2}.$$

Operator Interface

The following are some optional parameters that may be set by the operator:

(1) Select whether adaptation should be performed during set-point changes only, or during both set-point changes and load disturbances.

(2) Set the minimum value of set-point change that will activate the adaptation. Range: ±5% to ±15%.

6.4 Yokogawa SLPC-181, 281

The Yokogawa SLPC-181 and 281 both use a first order plus dead-time model of the process for calculating the PID parameters. A nonlinear programming technique is used to obtain the model. With the first-order plus dead-time model, the PID parameters are calculated from equations developed from numerous simulations. The exact equations are not published.

The PID controller can take one of the following structures:

$$\begin{aligned} &1:\quad u = K\left(-y + \frac{1}{T_i}\int e\,dt - T_d\frac{dy_f}{dt}\right) \\ &2:\quad u = K\left(e + \frac{1}{T_i}\int e\,dt - T_d\frac{dy_f}{dt}\right) \end{aligned} \tag{35}$$

where

$$\frac{dy_f}{dt} = \frac{N}{T_d}(y - y_f) \tag{36}$$

Table 5. Set-point response specifications.

Type	Features	Criteria
1	no overshoot	no overshoot
2	5% overshoot	ITAE minimum
3	10% overshoot	IAE minimum
4	15% overshoot	ISE minimum

Structure 1 is recommended if load-disturbance rejection is most important, and structure 2 is set-point responses are most important. The set point can also be passed through two filters in series:

$$\begin{aligned} &\text{Filter 1:}\quad \frac{1 + \alpha_i s T_i}{1 + sT_i} \\ &\text{Filter 2:}\quad \frac{1 - \alpha_d s T_d}{1 + sT_d} \end{aligned} \tag{37}$$

where α_i and α_d are parameters set by the user, mainly to adjust the overshoot of the set-point response. The effects of these two filters are essentially equivalent to set-point weighting. It can be shown that $\alpha_i = \beta$, where β is the set-point weighting factor in Equation 7.

The user specifies the type of set-point response performance according to Table 5. A high overshoot will of course yield a faster response.

The controller has four adaptive modes:

(1) Auto mode. The adaptive control is on. PID parameters are automatically updated.

(2) Monitoring mode. In this mode, the computed model and the PID parameters are displayed only. This mode is useful for validating the adaptive function or checking the plant dynamics variations during operation.

(3) Auto-startup mode. This is used to compute the initial PID parameters. An open-loop step response is used to estimate the model.

(4) On-demand mode. This mode is used when it is desirable to make a set-point change. When the on-demand tuning is requested, a step change is applied to the process input in closed loop. The controller estimates the process model using the subsequent closed-loop response.

The controller constantly monitors the performance of the system by computing the ratio of the process output and model output variances. This ratio is expected to be about 1. If it is greater than 2 or less than 0.5, a warning message for retuning of the controller is given. Dead time and feed-forward compensation are available for the constant gain controller but they are not recommended by the manufacturer to be used in conjunction with adaptation.

7. CONCLUSIONS

Various adaptive techniques have been implemented in single-loop PID controllers during the last decade. In this paper, a summary of these different techniques has been given together with an overview of industrial products.

Almost all controllers that use adaptive techniques have some form of automatic tuning function. The automatic tuning function is not only useful to help the operator in finding suitable controller parameters. It is also useful to build gain schedules and to initialize adaptive controllers.

Gain scheduling effectively compensates for nonlinearities and other predictable variations in the process dynamics. Since it is much easier to implement than other adaptive techniques, it is surprising that many industrial adaptive controllers lack this feature.

The adaptive controllers can be divided into two categories, namely the model based and the rule based. It is interesting to note that there are many successful applications of rule based adaptive controllers, although almost all university research has been focused on model based adaptation.

Adaptive feedforward control is rarely used in single-loop controllers. This is also surprising, since adaptive feedforward control has proven to be very useful in other applications of adaptive control, see, for instance, (Bengtsson and Egardt, 1984). Adaptive feedforward control is also easier to implement than adaptive feedback control.

8. REFERENCES

ANDERSON, K. L., G. L. BLANKENSHIP, and L. G. LEBOW (1988): "A rule-based PID controller." In *Proc. IEEE Conference on Decision and Control*, Austin, Texas.

ÅSTRÖM, K. J. and T. HÄGGLUND (1984): "Automatic tuning of simple regulators with specifications on phase and amplitude margins." *Automatica*, **20**, pp. 645–651.

ÅSTRÖM, K. J. and T. HÄGGLUND (1988): *Automatic Tuning of PID Controllers*. Instrument Society of America, Research Triangle Park, North Carolina.

BENGTSSON, G. and B. EGARDT (1984): "Experiences with self-tuning control in the process industry." In *Preprints 9th IFAC World Congress*, Budapest, Hungary.

BRISTOL, E. H. (1977): "Pattern recognition: An alternative to parameter identification in adaptive control." *Automatica*, **13**, pp. 197–202.

BRISTOL, E. H. (1986): "The EXACT pattern recognition adaptive controller, a user-oriented commercial success." In NARENDRA, Ed., *Adaptive and Learning Systems*, pp. 149–163, New York. Plenum Press.

CALLAGHAN, P. J., P. L. LEE, and R. B. NEWELL (1986): "Evaluation of foxboro controller." *Process Control Engineering*, **May**, pp. 38–40.

COHEN, G. H. and G. A. COON (1953): "Theoretical consideration of retarded control." *Trans. ASME*, **75**, pp. 827–834.

DUMONT, G. A., J. M. MARTIN-S NCHEZ, and C. C. ZERVOS (1989): "Comparison of an auto-tuned PID regulator and an adaptive predictive control system on an industrial bleach plant." *Automatica*, **25**, pp. 33–40.

GAWTHROP, P. J. (1986): "Self-tuning PID controllers: Algorithms and implementation." *IEEE Transactions on Automatic Control*, **31**, pp. 201–209.

HAALMAN, A. (1965): "Adjusting controllers for a deadtime process." *Control Engineering*, **July-65**, pp. 71–73.

HÄGGLUND, T. and K. J. ÅSTRÖM (1991): "Industrial adaptive controllers based on frequency response techniques." *Automatica*, **27**, pp. 599–609.

HANG, C. C. and K. J. ÅSTRÖM (1988): "Practical aspects of PID auto-tuners based on relay feedback." In *Preprints IFAC Int. Symposium on Adaptive Control of Chemical Processes, ADCHEM '88*, Lyngby, Denmark.

HANG, C. C., K. J. ÅSTRÖM, and W. K. HO (1991): "Refinements of the Ziegler-Nichols tuning formula." *IEE Proceedings, Part D*, **138:2**, pp. 111–118.

HANG, C. C. and K. K. SIN (1991): "An on-line auto-tuning method based on cross-correlation." *IEEE Transactions on Industrial Electronics*, **38:6**, pp. 428–437.

HANG, C. C., K. K. TAN, and S. L. ONG (1979): "A comparative study of controller tuning formulae." *I.S.A. Conference*, pp. 467–476.

HAWK, JR., W. M. (1983): "A self-tuning, self-contained PID controller." In *Proc. 1983 American Control Conference*, pp. 838–842, San Francisco, California.

HAZEBROEK, P. and B. L. VAN DER WAERDEN (1950): "Theoretical considerations on the optimum adjustment of regulators." *Trans. ASME*, **72**, pp. 309–322.

HESS, P., F. RADKE, and R. SCHUMANN (1987): "Industrial applications of a PID self-tuner used for system start-up." In *Preprints 10th IFAC World Congress*, volume 3, pp. 21–26, Munich, Germany.

HIGHAM, E. H. (1985): "A self-tuning controller based on expert systems and artificial intelligence." In *Proceedings of Control 85*, pp. 110–115, England.

HO, W. K., C. C. HANG, and L. S. CAO (1992): "Tuning of PI controllers based on gain and phase margin specifications." In *Preprints IEEE Int. Symposium on Industrial Electronics*, P. R. China.

KAYA, A. and S. TITUS (1988): "A critical performance evaluation of four single loop self tuning control products." In *Proceedings of the 1988 American Control Conference*, Atlanta, Georgia.

KLEIN, M., T. MARCZINKOWSKY, and M. PANDIT (1991): "An elementary pattern recognition self-tuning PI-controller." In *Preprints IFAC International Symposium on Intelligent Tuning and Adaptive Control (ITAC 91)*, Singapore.

KRAUS, T. W. and T. J. MYRON (1984): "Self-tuning PID controller uses pattern recognition approach." *Control Engineering*, June, pp. 106–111.

MARSIK, J. and V. STREJC (1989): "Application of identification-free algorithms for adaptive control." *Automatica*, **25**, pp. 273–277.

MILLER, J. A., A. M. LOPEZ, C. L. SMITH, and P. W. MURRILL (1967): "A comparison of controller tuning techniques." *Control Engineering*, December, pp. 72–75.

MORARI, M. and E. ZAFIRIOU (1989): *Robust Process Control*. Prentice-Hall, Englewood Cliffs, New Jersey.

NISHIKAWA, Y., N. SANNOMIYA, T. OHTA, and H. TANAKA (1984): "A method for auto-tuning of PID control parameters." *Automatica*, **20**, pp. 321–332.

PAGANO, D. (1991): "Intelligent tuning of PID controllers based on production rules system." In *Preprints IFAC International Symposium on Intelligent Tuning and Adaptive Control (ITAC 91)*, Singapore.

SEBORG, D. E., T. F. EDGAR, and D. A. MELLICHAMP (1989): *Process Dynamics and Control*. Wiley, New York.

SHIGEMASA, T., Y. IINO, and M. KANDA (1987): "Two degrees of freedom PID auto-tuning controller." In *Proceedings of ISA Annual Conference*, pp. 703–711.

SHINSKEY, F. G. (1988): *Process-Control Systems. Application, Design, and Tuning*. McGraw-Hill, New York, third edition.

TAKATSU, H., T. KAWANO, and K. KITANO (1991): "Intelligent self-tuning PID controller." In *Preprints IFAC International Symposium on Intelligent Tuning and Adaptive Control (ITAC 91)*, Singapore.

YAMAMOTO, S. (1991): "Industrial developments in intelligent and adaptive control." In *Preprints IFAC International Symposium on Intelligent Tuning and Adaptive Control (ITAC 91)*, Singapore.

ZIEGLER, J. G. and N. B. NICHOLS (1942): "Optimum settings for automatic controllers." *Trans. ASME*, **64**, pp. 759–768.