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Abstract

The paper addresses some key problems that arise in applications of adaptive control to industrial processes, prior knowledge, design based on simplified models, initialization and start up. Different ways of solving the problems are discussed. A new technique for automatic tuning of simple control loops is presented. The method has the advantage of automatically generating test signals whose properties are tuned to the process. A novel approach to the adaptive problem is proposed where an expert system orchestrates auto-tuning, conventional adaptive control, on-line diagnosis, and table based gain scheduling.

1. INTRODUCTION

Adaptive control is now slowly but surely finding its way into industrial practice. There are now products like the Electromax V from Leeds and Northrup (Hoopes et al., 1983) and the Novatune from ASEA (Bengtsson and Egardt, 1984), which have been on the market since 1981 and 1982 respectively. A few thousand loops are controlled successfully using these regulators. The following adaptive regulators were announced in 1984 the 6355 from Turnbull Control Systems, the Autotuner from NAF Controls and the Exact from Foxboro. More are in the pipeline. These products are based on different concepts and different regulator structures. The demands on the user are quite different in the systems both in operational terms and in the effort required to understand how the systems really work.

Most schemes currently used can be characterized as local gradient algorithms. This means that given good initial values they will drive the system towards a very good performance. The effort required to obtain the initial values or the prior knowledge may however be quite substantial. Several algorithms therefore have what is called a "pretune mode" which typically uses a pulse test to obtain the required prior knowledge. The autotuner is different because it requires very little prior knowledge. It also generates the test signals automatically. There is also a growing awareness of the need for safeguards to ensure that the adaptive regulators work well under all possible operating conditions.

The purpose of this paper is to look at some of the approaches to adaptive control their strengths and weaknesses. In doing so it is found that systems with very attractive properties can be obtained by combining several different approaches. An autotuner can be used to arrive at a simple control law in a robust way. The information gathered by the autotuner can also be used to derive the prior information required by more sophisticated adaptive schemes. We will thus arrive at a system which contains several different algorithms. To monitor their operation it is then useful to introduce algorithms which supervise the operation of the system and which can initiate switching between algorithms. It is clear that a system of this type will involve a substantial amount of heuristic logic. Expert system methodologies provide a systematic approach for dealing with this logic. The term expert control is therefore coined to describe systems of this type. Once the expert system approach is taken it is also possible to obtain control systems with learning functions.

The paper is organized as follows. The auto-tuner being the simples system which requires the least a priori information is described in Section 2. This system which was designed as a tuner for simple PID regulators can also be used to initialize more sophisticated algorithms. A brief review of the conventional approache to adaptive control based on recursive parameter estimation is given in Section 3. The emphasis is on the prior knowledge required for the different algorithms and on issues which are related to the safe operation of the systems. Some practical problems associated with implementation of adaptive systems are summarized in Section 4. The different ideas are combined in Section 5 to obtain an expert control system. The organization of such a system is described as well as some of its properties.

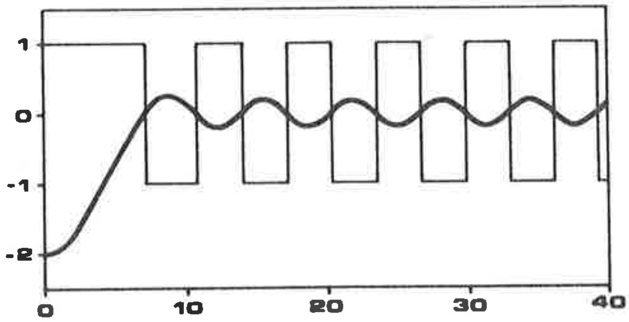

Figure 1. Input and output signals for a system under relay feedback.

2. AUTOTUNING

A novel approach to automatic tuning of PID regulators has recently been proposed by Åström and Hägglund (1984a,b,c). The approach was motivated by a desire to develop a simple robust tuning scheme which requires very little prior information. The approach is based on a special technique for system identification which automatically generates an appropriate test signal and a variation of the the classical Ziegler-Nichols (1943) method for control design.

The Basic Idea. The Ziegler-Nichols method is based on the observation that the regulator parameters can be determined from knowledge of one point on the Nyquist curve of the open loop system. This point is the intersection of the Nyquist curve with the negative real axis. It is traditionally described in terms of the critical gain k_c and the critical period T_c. In the original scheme, described in Ziegler and Nichols (1943), the critical gain and the critical period are determined in the following way: A proportional regulator is connected to the system. The gain is gradually increased until an oscillation is obtained. The gain k_c when this occurs is the critical gain and the oscillation has the critical period. It is difficult to perform this experiment automatically in such a way that the amplitude of the oscillation is kept under control.

The autotuner is based on the idea that the critical gain and the critical frequency can be determined by introducing relay feedback. A periodic oscillation is then obtained. The critical period T_c is simply the period of the oscillation and the critical gain can be determined from the relay amplitude and the amplitude of the oscillation, see Figure 1.

If the process attenuates high frequencies so that the first harmonic component dominates the response it follows that the input and the output are out of phase. Furthermore if the relay amplitude is d it follows from a Fourier series expansion that the first harmonic of the input is $4d/\pi$. If the amplitude of the output is a the process gain is thus $\pi a/4d$ at the critical frequency and the critical gain becomes

$$k_c = \frac{4d}{\pi a} \tag{1}$$

Exact analyses of relay oscillations are also available. See Hamel (1949), Tsypkin (1958) and Åström and Hägglund (1984a). The period of an oscillation can be determined by measuring the times between zero-crossings. The amplitude may be determined from the peak-to-peak values of the output. These estimation methods are easy to implement because they are based on counting and comparison only. Simulations and extensive experiments on industrial processes have shown that the simple estimation method works well in comparison with the more sophisticated estimation methods. The simple methods also have some additional advantages. See Åström (1982).

Control design. When the critical gain k_c and the critical period are known the parameters of a PID regulator can be determined by the Ziegler-Nichols rule which can be expressed as

$$k = \frac{k_c}{2} \quad T_i = \frac{T_c}{2} \quad T_d = \frac{T_c}{8} \tag{2}$$

This rule gives a closed loop system which is sometimes too poorly damped. There are therefore many modifications of the basic Ziegler Nichols rule.

A block diagram of the autotuner is shown in Figure 2. The tuner is very easy to use. The process is simply brought to an equilibrium by setting a constant control signal in manual mode. The tuning is then activated by pushing the tuning switch. The regulator is automatically switched to automatic mode when the tuning is complete. Simplicity is the major advantage of the auto-tuner. It is very easy for the operator to use it. It is also easy to explain the auto-tuner to the instrument engineers. The properties of the autotuner are illustrated in Figure 3 which shows an application to level control in three cascaded tanks. After bringing the system to an equilibrium the auto-tuner is initiated. The relay oscillation then appears. After x half-periods good estimates of the critical gain and the critical period are obtained and the regulator is switched to normal PID control. A set point change is later introduced manually. This shows that the tuning has resulted in a system with good transient behavior.

Prior Information. A major advantage of the autotuner is that it requires little prior information. Only two parameters the relay amplitude and the hysteresis width are required. In the NAF autotuner these parameters are set automatically. The relay amplitude is initially set to fixed proportion of the output range. The amplitude is adjusted after one half period to give an output oscillation of specified amplitude. The modified relay amplitude is stored for the next tuning. The hysteresis width is set automatically based on measurements of the measurement noise.

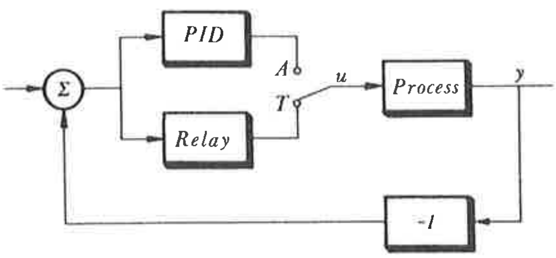

Figure 2. Block diagram of an auto-tuner. The system operates as a relay controller in the tuning mode (T) and as an ordinary PID regulator in the automatic control mode (A).

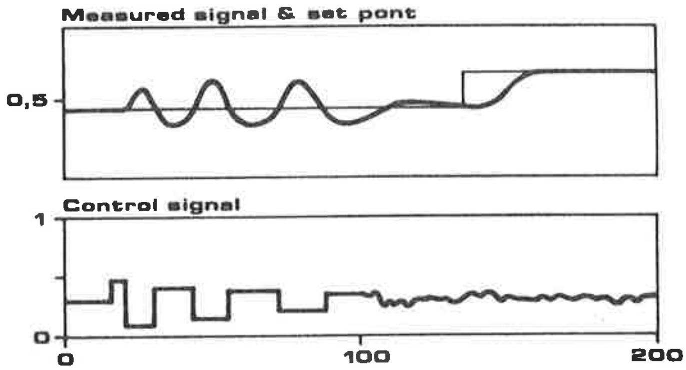

Figure 3. Results obtained applying an auto-tuner to level control of three cascaded tanks.

3. ADAPTIVE CONTROL

A block-diagram of a conventional adaptive regulator is shown in Figure 4. The adaptive regulator can be thought of as composed of two loops. The inner loop consists of the process and an ordinary linear feedback regulator. The parameters of the regulator are adjusted by the outer loop, which performs recursive parameter estimation and control design calculations. To obtain good estimates it may also be necessary to introduce perturbation signals. This function is not shown in Figure 4 in order to keep the figure simple. Notice that the system may be viewed as automated modeling and design.

The block labeled "regulator design" in Figure 4 represents an on-line solution to a design problem for a system with known parameters. This is called the underlying design problem. It is useful to consider this problem because it gives the characteristics of the system under the ideal conditions when the parameters are known exactly.

The adaptive regulator shown in Figure 4 is very flexible. Both model reference adaptive system and self-tuning regulators can be represented by it. Many different design methods and many

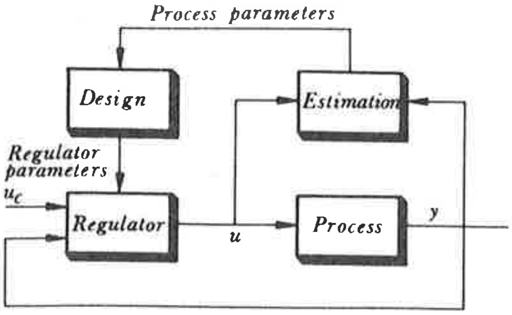

Figure 4. Block diagram of a conventional adaptive regulator.

different parameter estimation schemes can be used. There are adaptive regulators based on phase- and amplitude margin design methods, pole-placement, minimum variance control, linear quadratic gaussian control and optimization methods. Many different parameter estimation schemes have also been used, for example stochastic approximation, least squares, extended and generalized least squares, instrumental variables, extended Kalman filtering and the maximum likelihood method. See Åström (1983a) which gives an overview and many references. An example illustrates a typical case.

Example 1. Estimate the parameters of the second order model

$$y(t) + a_1 y(t-h) + a_2 y(t-2h) = b_1 u(t-h) + b_2 u(t-2h) \quad (3)$$

recursively. Let $\hat{a}_i$ and $\hat{b}_i$ denote the parameter estimates. The control law

$$u(t) = t_0 r(t) - s_0 y(t) - s_1 y(t-h) - r_1 u(t-h)$$

where

$$t_0 = (1+p_1+p_2)/(\hat{b}_1+\hat{b}_2)$$

$$r_1 = [(p_1-\hat{a}_1)\hat{b}_2^2 - (p_2-\hat{a}_2)\hat{b}_1\hat{b}_2]/N$$

$$s_0 = [(p_1-\hat{a}_1)(\hat{a}_2\hat{b}_1-\hat{a}_1\hat{b}_2) + (p_2-\hat{a}_2)\hat{b}_2]/N$$

$$s_1 = -\hat{a}_2 r_1/\hat{b}_2$$

$$N = \hat{b}_2^2 - \hat{a}_1\hat{b}_1\hat{b}_2 + \hat{a}_2\hat{b}_1^2$$

gives a closed loop system whose pulse transfer function from the command signal to the output is given by

$$H_m(z) = \frac{1 + p_1 + p_2}{b_1 + b_2} \cdot \frac{b_1 z + b_2}{z^2 + p_1 z + p_2}$$

where

$$p_1 = -2e^{-\zeta\omega h}\cos \omega h \sqrt{1-\zeta^2} \text{ and } p_2 = e^{-2\zeta\omega h}$$

The closed loop system will thus retain the open loop zero and the closed loop poles correspond to a sampled second order system with bandwidth ω and relative damping ζ. □

Some minor modifications of the control law in the example are needed to handle bias and integral action. A detailed discussion of these factors is given in Åström (1979). The commercial regulators, Electromax V and TCS 6355 are based on estimation of parameters in the model (3). They do however use control design methods which are different from the one used in the example.

The self-tuner shown in Figure 4 is called an explicit STR or an STR based on estimation of an explicit process model. It is sometimes possible to reparameterize the process so that it can be expressed in terms of the regulator parameters. This gives a significant simplification of the algorithm because the design calculations are eliminated. In terms of Figure 4 the block labelled design calculations disappears and the regulator parameters are updated directly. This idea was used in the self-tuning regulator which is based on minimum variance control and least squares parameter estimation given in Åström and Wittenmark (1973). An example illustrates the idea which is also used in the ASEA Novatune.

Example 2. The self-tuner discussed in Åström and Wittenmark (1973) is based on the mathematical model

$$y(k+d) = s_0 y(k) + s_1 y(k-1) + \ldots + s_{n_s} y(k-n_s) + r_0 u(k) + \ldots + r_{n_r} u(k-n_r) + \varepsilon(k+d) \quad (4)$$

where u is the control variable, y the measured output and ε is a disturbance. If ε is independent of the other terms on the right hand side the minimum variance control law for the plant (4) is simply

$$u(k) = -[s_0 y(k) + s_1 y(k-1) + \ldots + s_{n_s} y(k-n_s) + r_1 u(k-1) + \ldots + r_{n_r} u(k-n_r)]/r_0 \quad (5)$$

The basic self-tuning algorithm can be described as follows:

ALGORITHM
Repeat the following steps at each sampling period:

Step 1. Update the estimates of the parameters of the model (4), so that a weighted sum of squares of the errors ε are minimal.

Step 2. Compute the control signal u(k) from past data y(k), y(k-1), ...,u(k-1),... using (5) with the estimates obtained from Step 1. □

Notice that when least squares estimation is used the error $\varepsilon(k+d)$ will be uncorrelated with the other terms in the right hand side of (4). Also notice that no design calculations are required since the parameters of the regulator (5) are obtained directly from the model parameters because of the special model structure used in (4).

Prior knowledge. The parameter estimation step is a crucial part in all adaptive schemes. The sampling period is a critical parameter when discrete time models are fitted to data. The parameter estimation is insensitive to the sampling period if the true system is actually governed by a low order model like (3). The sampling period is however critical when a low order model (3) is fitted to a high order process. A model like (3) can be a very good approximation of a high order system if the sampling period is reasonably long. Results for short sampling periods can, however, be very poor because the parameters b_1 and b_2 will be underestimated, the computed gain becomes too high and the closed loop unstable. Experience indicates that it is not possible to obtain a good model (3) unless the order of magnitude of the sampling period is known. This means that it is not possible to construct a universal regulator for process control based on (3) unless some device for finding the sampling period is devised. For the regulator in Example 1 this can be achieved by relating the sampling period to the desired bandwidth and letting the operator choose it. The adaptive systems Electromax V and TCS 6355 both require prior knowledge of a time scale which among others is used to set the sampling period. A fairly elaborate "pretune" scheme is provided to determine the time scale by experimentation in both systems.

The self-tuning regulator given in Example 2 also requires prior knowledge. The following data is needed:

h	sampling period
d	delay in number of sampling periods
n_r	degree of the polynomial R
n_s	degree of the polynomial S
λ	forgetting factor
θ_o	initial estimate
p_o	initial covariance
uh	high control limits
ul	low control limits

The sampling period is critical as was discussed above. The integer d is also crucial. The closed loop system will become unstable if h and d are underestimated. The parameters are particularly important. Since the self-tuner is based on minimum variance control they will directly determine the closed loop bandwidth. The parameters n_r and n_s are not particularly critical. A calculation of covariances of inputs and outputs will show if they are too small, see Åström (1970). The parameter λ determines the trade-off between the tracking ability and the steady state variance of the recursive parameter estimator. The parameters θ_0 and P_0 determine the initial transient of the estimator but are otherwise unessential.

In control system design it is frequently necessary to make a trade-off between the response time and the size of the control signal. In minimum variance control this trade-off is made indirectly via selection of the sampling period. The regulator gain decreases and the response time increases with increasing sampling period. The minimum variance control law cannot handle nonminimum phase system because the process zeros are canceled by the controller.

By increasing the sampling period and the delay d used in the adaptive control law the problems with nonminimum phase systems will, however, disappear. Sampling of a stable system, with nonzero steady state gain, always gives a minimum phase sampled system provided the sampling period is sufficiently long. See Åström et al. (1984). This is also true for unstable systems provided that the unstability is caused by a single pole. The quality of the approximation by a low order system will also be improved when the sampling period is increased. The drawbacks with a long sampling period are slow responses to disturbances and changes in the set point. Notice that a sampled data system runs open loop between the sampling instants.

4. PRACTICAL ASPECTS

Some practical aspects on the implementation of adaptive regulators will be given in this Section. An ordinary PID-regulator is first discussed to provide some perspective. This regulator is ideally described by:

$$u(t) = \left[e(t) + \frac{1}{T_i}\int^t e(s)ds + T_d\frac{de(t)}{dt}\right]. \qquad (6)$$

The linear behavior of PID-control can be understood very well from this equation. Suitable values of the parameters can be determined. The performance of the closed loop system can be predicted etc. The actual operation of a PID regulator must however take nonlinear behavior into account. It is thus necessary to consider switching between manual and automatic operation and transients due to parameter changes. The actuators will saturate for some period in virtually all applications. This gives rise to problems with windup of the integrator. It is also becoming increasingly more common to connect PID regulators with logic selectors which brings up additional nonlinear problems. An operational industrial PID regulator thus consists of an implementation of the equation (6) and some heuristic logic that takes care of the problems mentioned above. Although these heuristic factors are of extreme importance for good control they have not attracted much interest from theoreticians. They are instead hidden in practical designs and rarely discussed in the control literature. One reason for this is commercial secrecy, another is that most control engineers, being thoroughly indoctrinated by linear system theory, are poorly equipped to understand nonlinear phenomena. We can thus conclude that practical PID control is not solved by linear theory alone, but that nonlinearities plays an important role. They are typically handled by logic that surrounds the linear control law given by equation (6). The logic is often designed heuristically.

Heuristic logic is even more important in adaptive control. The fundamental control law is much more complicated in this case. Windup can occur not only in the integrator but also in the estimator. To obtain a well functioning adaptive control system it is necessary to provide it with a considerable amount of heuristic logic. This goes under many names like safety nets or safety jackets. Experience has shown that it is quite time consuming to design and test this heuristic logic. Some practical issues are discussed in Wittenmark and Åström (1984). It is difficult to get information about what is actually done in practical systems because the manufacturers of adaptive systems are therefore understandably reluctant to disclose their tricks.

The key issues to get a robust controller are good data and an appropriate model structure. It is important that the model is accurate at the cross-over frequency. To obtain a good reduced order model it is essential that the input signal has sufficient energy content around the cross-over frequency and that it is so rich in frequency that it is persistently exciting. To guarantee a good model it is thus necessary to monitor the excitation and the energy of the input signal in the relevant frequency bands. A more detailed discussion is found in Åström (1984).

5. EXPERT CONTROL

The properties of auto-tuners and adaptive regulators are complimentary. The auto-tuner requires little prior information. It is very robust and it can generate good parameters for a simple control law. Adaptive regulators like model reference adaptive controllers or self-tuning regulators can use more complex control laws with potentially better performance. These control laws are local gradient procedures. Starting from reasonably good a priori guesses of system order, sampling period, and parameters, the algorithms can adjust the regulator parameters to give a closed loop system with good performance. The algorithms will however not work if the prior guesses are too far off. With poor prior data they may even give unstable closed loop systems. This has led to the development of the safety jackets mentioned previously. The adaptive algorithms are also capable of tracking a system provided that the parameters do not change too quickly. It thus seems natural to try to combine auto-tuners and adaptive control algorithm. In Åström and Anton (1984) it was proposed to use an expert system to coordinate the algorithms. Moore et al (1984a,b) have proposed another application to process control where the expert system is used as control advisors and alarm advisors.

Expert systems is a popular branch of Artificial Intelligence. See Barr and Feigenbaum (1982) and Hayes-Roth et al. (1983), which describe the ideas and give important examples. A typical expert system has three principal components:

System data base
Knowledge sources
Supervisory strategy

The system data base contains facts, evidences, hypotheses, and goals.

Knowledge representation is a key issue. Rule based expert-systems are common. In these systems knowledge is represented by statements of the type: "if <condition> then <action>" where 'condition' represents facts, evidence, hypotheses, or goals. The 'action' can be physical operations like control actions, estimation, inferences, activation of a new controller, specification of a new goal to be pursued etc. Production rules operate on the data base. They result in new entries in the database and modifications of others. There are also other possibilities to represent knowledge e.g. first order logic, procedural representations, semantic networks, frames etc. See IEEE (1983). Production rules and frame structures have some very desirable features for a process control application.

The supervisory strategy decides which production rule to select next from the current data base. Separation of supervision knowledge (what to do) from the production knowledge (how to do it) gives a significant flexibility for developing and modifying a process control system.

Expert systems have traditionally been applied for off-line problem solving. Criteria for successful applications that are frequently given include a limited domain, availability of experts and complexity. Diagnosis is a typical application where the expert system may be viewed as an interactive check list. The application to control system is different because the expert system interacts in real-time with the process. There are also interesting planning aspects of the problem, which has only been addressed to a limited extent previously. See Sacerdoti (1977) and Stefik (1981a,b).

The idea of expert control is to have a collection of algorithms for control, supervision and adaptation which are all supervised by an expert system. This offers several interesting possibilities. It was mentioned in Section 4 that heuristic logic is important for ordinary PID regulators and even more so for adaptive regulators. The logic shows up as if-then-else or case statements in the regulator code. In many cases the code for the logic is larger than the code for the control algorithm. The debugging, modification, and testing of the control logic can be very time consuming. An expert system is a very convenient way to implement this logic even if it is an overkill for PID control. In Åström (1983b) it is shown that the logic for an auto-tuner is very conveniently implemented using an expert system.

An expert system has the interesting ability to explain its reasoning. This offers interesting possibilities for the control problem. We can thus get answers to questions like. What control law is beeing used? Why was this control law chosen? What is the current knowledge of the process and its environment? Are the fluctuations in the process output normal?

The notion of expert control is illustrated by an example. Consider a simple regulation loop where the goal is to keep the process output close to a set point for a wide range of operating conditions.

A list of the major operations in the system is given below.

- MainMonitor:
  - StabilitySupervisor
  - ComputeMeansAndVariances
- AutoTuning
  - Tune
  - KcTcEstimator
  - DeterminePidStructure
  - EstimateTimeDelay
- BackUpControl:
  - PidControl
  - PidSupervisor
- FixedGainMinimumVarianceControl:
  - MinimumVarianceControl
  - MinimumVarianceSupervisor
    - RingingDetector
    - DegreeSupervisor
- Estimation:
  - ParameterEstimation
  - EstimationSupervisor
    - ExcitationSupervisor
    - PerturbationSignalGenerator
    - JumpDetector
    - DriftDetector
- SelfTuning:
  - SelfTuningRegulation
  - SelfTuningSupervisor
- Learning:
  - GetRegulatorParameters
  - SmoothAndStoreRegulatorParameters
  - TestSchedulingHypothesis

The following discussion explains some of the operators or actions that are used in the system. The "action" MinimumVarianceControl is a primary function of the regulator. The preconditions for this action include knowledge of an appropriate sampling period and models for the process and the disturbances. The process zeros are cancelled in minimum variance control. This may lead to ringing if the cancelled zeros are not sufficiently well damped. To detect ringing and to take the appropriate actions it is useful to include a RingingDetector. Ringing can be avoided by increasing the parameter d or by increasing the sampling period h. See Åström and Wittenmark (1985). There is a convenient way to find out if a process is under minimum variance control simply by calculating the autocorrelation of the process output. See Åström (1970). This can be used in the MinimumVarianceSupervisor.

If the process model required for minimum variance control is not available a self-tuning regulator may be used. This requires certain preconditions as was discussed in Section 3. If the prior information for a self-tuner is not available it can be attempted to use an auto-tuner, which requires less prior information. The data obtained from the auto-tuning experiment can be used to generate initial conditions for the self-tuner. The performance of a self-tuner depends critically on the process being properly excited. An ExcitationSupervisor can check this. If there is not enough excitation there are two options. Either to stop the updating or to introduce perturbation signals. using a PerturbationSignalGenerator. Other functions may also be provided. Assume that it is known that the process dynamics changes with a few parameters like production. Gainscheduling and learning may then be considered. This is done by storing control parameters for different operating conditions in tables.

Process data is stored in lists in the system data base. It is convenient to have event lists associated which each of the knowledge sources listed above. There will thus be a main monitoring table a minimum variance control table an auto-tuning table etc. A typical example of such a table is given in Table 1. An entry is made in this table when there is a major event in the system e.g. a set point change, a tuning, a switching of control modes etc.

Table 1 - Main monitoring table. An entry is made whenever there is a mode switch or a set-point change.

#	Time	u	σ_u	y	σ_y	Stable	Regulator type

It may be useful to add a few entries in the table such as max and min values or percentile values. From the data shown in Table 1 it is possible to make deductions like: What are the relations between the mean values of u and y? Do these relations change with time? Are there any relations between the standard deviations and the mean value of the control signal? What are the patterns of the mode switches? Does the system go to tuning mode after large set point changes? What control modes are used for most of the time? Are these drastic variations in performance with time and modes? The answers to these questions will allow us to make inference about the characteristics of the process.

A system of the type outlined above has been implemented by Årzén. A VAX 11/780 running under VMS is used. The expert system is implemented in Lisp with the algorithms written in Pascal. Parallel processes are implemented using the VMS mail box facility. The expert system framwork OPS4 is used. The design and some experiments are described in Årzén (1985).

6. CONCLUSIONS

Control of systems with unknown parameters has been approached from two points of view automatic tuning and adaptive control. It has been demonstrated that both approaches lead to controllers which contain numerical algorithms as well as heuristic logic. The approaches are also complementary with respect to the prior information needed. It has been suggested to use an expert system to coordinate the different techniques. The approach which clearly can be applied to a wide variety of problems seems to offer interesting possibilities to combine analytical and heuristic approaches. The incorporation of heuristics through AI structures results in systems that are far more flexible and transparent than selector and safety-jacket logic. It also results in a feedback system with many interesting features which includes learning, store of increased process knowledge and explanatory power.

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