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Autonomous Process Control

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Abstract — Different approaches to intelligent control are reviewed. This includes knowledge-based control, fuzzy control, neural networks and qualitative reasoning. The key ideas behind these approaches are outlined and it is indicated how they may be used to make control systems with significantly improved capabilities.

1. Introduction

During the development of automatic control there have been strong efforts to design systems with higher and higher levels of automation. Methods and tools for design of highly automated systems have increased significantly over the last ten years. Ideas are coming from many diverse directions, automatic control, artificial intelligence, computer science, computer engineering, neural networks, learning theory, fuzzy systems etc. The application areas are equally diverse, from consumer products like VCRs, camcorders and copiers, via process control to highly sophisticated aerospace systems.

To provide a perspective it is useful to look back at some developments that have taken place. Automation in the process industries originated when manual control was replaced by automatic controllers. This relieved the operators from tedious supervision tasks. The first controllers only had proportional action, it was thus necessary for the operators to reset the controllers to make sure that the variables were kept at the desired levels. Adjustment of the reset was a less demanding task than the primary control function, since the adjustments were less frequent. This task was also automated when controllers with automatic reset or integral action appeared. With such controllers it was, however, still necessary to provide manual tuning. Since the need for tuning occurred quite infrequently, the demands for manual interaction decreased further. Tuning is, however, a more demanding task than the primary control function and more skill is needed to perform it. This became the task of the instrument engineers rather than the operators. The relatively recent development of methods for automatic tuning have again decreased the need for manual interaction. With the automatic tuning tools it is also possible to let the operator perform the tuning.

Plant operations have undergone a similar development. Operations like startup, shutdown, sequencing and batch control were originally performed manually. This is a demanding task, because operations have to be done in the right sequence and certain conditions must be satisfied before a next step is taken. This task has also been automated. Relay-based interlock systems made sure that the operational constraints are obeyed and sequences of operations were automated using sequential logic. Current systems for batch control can handle sophisticated manufacturing procedures automatically.

There are many driving forces that stimulate the development of autonomous systems. Good tools are required to handle systems with thousands of feedback loops. Requirements on product quality in terms of standards like ISO 9000 give strong incentive to improve performance of the individual control loops. Development in areas like automatic tuning, adaptation, and diagnosis has given many ideas for improving controllers. The configuration of future process control systems will also change drastically because of the introduction of the field bus. Development of microelectronics has given the computing power required to implement the systems. In this paper we will discuss natural next steps in the development of automation. The discussion will be focused on process control systems although there is a much wider application area.

2. Primary System Tasks

In this section we will describe some of the primary tasks of an autonomous controller.

Control

The ordinary control functions are of course a primary task of the system. This includes steady-state control as well as startup, shutdown, set-point changes and recipes. Techniques for design of good primary loops are

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well known. For a system with thousands of loops it may however be difficult to apply this knowledge. A recent report indicate that in a large paper mill as many as 80 % of the loops may have substandard performance. In an autonomous controller it is therefore important to have support for good control practice built into the system.

To obtain good performance of a control system it is of prime importance that the measured signal is filtered properly. Anti-aliasing filters should be matched to the characteristics of each individual loop. To do this it is necessary to have facilities for choosing sampling rates and filter characteristics for each individual loop. Although this is straightforward in principle it is rarely found in systems. In many cases there is a significant advantage in using a predictive first-order hold, which gives a piece-wise linear control signal instead of a piece-wise constant control signal, see [10]. These features can be implemented in a cost effective manner using dual rate sampling. For systems with high sampling rates it may be necessary to use digital signal processors. Examples are given in [7], which describes systems with sampling rates of several kHz.

Control functions include steady state control as well as set-point changes. Many different algorithms can be used for steady state control. Controllers like PI, PID, and Smith Predictors should be included because they are so well known, even if they are special cases of a general linear controller. There are interesting possibilities to provide fast and accurate changes of operating conditions subject to constraints on control and process variables by using optimization techniques.

Tuning, Gain Scheduling and Adaptation

Automatic tuning is a necessity to achieve good control in a large system. Tuning should of course provide good control parameters but it should also give data like bandwidth that can be used for selection of sampling rates and filters and for data logging. The tuning operation should also provide models that can be used for set-point changes, diagnostics and loop assessment. There are many ways to perform tuning and adaptation, see e.g. [5] and [8].

There has been an increased interest in methods of tuning PID controllers because of the importance of automatic tuning. This has led to a reevaluation of many of the classical tuning schemes. This has revealed that traditional tuning rules give systems that are too sensitive. For example, Ziegler-Nichols methods typically give closed-loop systems with sensitivities around $M_s = 4$ or higher, see [14] and [6]. A good tuning procedure should also make it possible to make an assessment of the trade-offs between performance and controller complexity. Analysis of the PID control problem has given new design methods, which have this capability. One method is described in [19] and [20]. An example illustrates what can be achieved.

EXAMPLE 1—Control Design and Assessment
Consider a process with the transfer function

$$G(s) = \frac{1}{(s+1)^8}$$

The design criterion was to maximize integrated error subject to the sensitivity being no higher than 1.6. The design method gives PI and PID controllers with parameters given in the table below.

	IAE	k_{hf}	ω_s	A_m	ω_a	ϕ_m	ω_ϕ
PI	11.05	0.28	0.22	3.1	0.30	61.3	0.10
PID	7.91	5.69	0.30	3.1	0.40	62.3	0.13

The table also gives parameters that characterize the performance obtained with the different controllers. The integrated absolute error due to load disturbances is denoted by IAE, the high frequency gain of the controller is k_{hf}, the frequency ω_s where the sensitivity is largest, amplitude and phase margins a_m and ϕ_m, and corresponding frequencies ω_a and ω_ϕ.

The essential difference between the controllers is that the PID controller has better rejection of load disturbances and that it gives a closed-loop system with faster response. It is however much more sensitive to measurement noise. Properties of the different controllers are illustrated in the simulation in Fig. 1, which shows the responses to unit step changes in set point and input load disturbance. A measurement error in the form of a cosine pulse of magnitude 1 and duration 0.5 is also introduced at time 150. The figure illustrates the differences in the closed-loop responses obtained by the controllers. The reduction of the sensitivity to load disturbances for the PID controller is obtained at the cost of a higher sensitivity to measurement noise. Based on information of this type it is possible for an instrument engineer or a knowledge-based system to make trade-offs. □

If a good tuning procedure is available it is straightforward to use it to build gain schedules as is discussed in [13]. Adaptation may also be viewed as an extension of tuning. Many techniques for this are also available, see [8]. An interesting issue is whether adaptation should be performed automatically or on demand.

Fault Detection and Diagnosis FDD

Fault detection and diagnosis is often considered separately from control. In conventional systems alarms

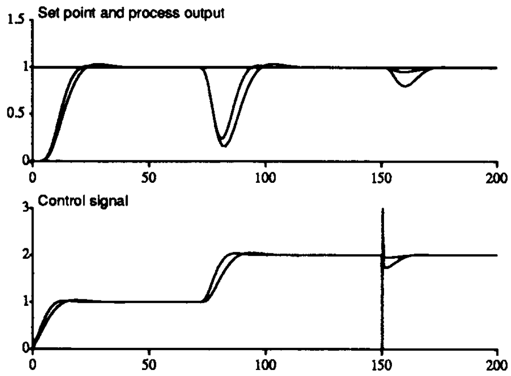

Figure 1. Responses step changes in set point and load of closed-loop system under PI and PID control.

are generated when the error signal exceeds certain trip levels. This simple way of generating alarms has the drawback that many nuisance alarms are generated, for example during startup. It has been attempted to reduce the number of nuisance alarms by adding an expert system, which attempts to eliminate nuisance alarms at a higher level of the system. There are several advantages by considering control and diagnosis together. The signals in the feedback loop tells much about all components involved, the process, the sensors, the actuators, and the control equipment. While FDD is traditionally based on the error signal only there are many other signals in the control loop that can be used. The diagnosis will be more precise and there will be less spurious alarms. Tuning and design of the control loop give data that is very useful for FDD. Information about the closed-loop bandwidth is useful for filtering of the signals. Information about noise levels is also obtained during tuning.

It is also possible to use other signals in the control loop that are very useful for FDD. All controllers can be interpreted as a combination of a state feedback and an observer. The observer error is also useful for diagnosis because the signals $\hat{y}(t|t-h)$ and $R(t|t-h)$, which correspond to the mean and covariance of the prediction of the measured signal, are available in an observer. The controller error may be large during changes in command signals that occur during startup and shutdown. The observer error will, however, be small in these cases, provided that the system operation is normal. Some of the spurious alarms can thus be eliminated by also considering the observer error. An observer is also useful for sensor fusion. With redundant signals it is possible to have graceful degradation.

Diagnosis based on a Kalman filter can also be augmented with diagnosis based on qualitative models, see [11]. Notice that there are also important issues in diagnosis that require a global view of the system where the interaction of many loops is considered.

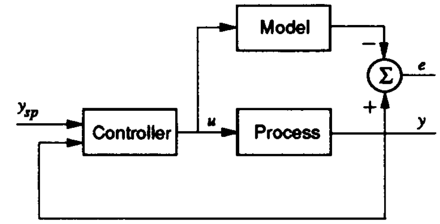

Figure 2. Using a parallel model for diagnosis.

Another approach to diagnosis is illustrated in Figure 2. The system is provided with a model that is connected in parallel with the process. The error e is small if process disturbances are small and if the model matches the plant well for the control signal u in normal operation. If the model is accurate the error represents the disturbances reduced to the process output. The system is thus also useful for classification of process disturbances.

There are also diagnostics functions not normally found in conventional systems that are needed in an autonomous controller. Since stability is a prime requirement of a control system, it is necessary to detect instabilities. To have advanced warning it is also desirable to have facilities to measure stability margins.

Valves are common sources of performance degradation and failures. Because of their special nature it is useful to have dedicated diagnosis methods for these components. Valves typically have nonlinear characteristics with dead-zones and hysteresis. By monitoring these it is possible to obtain useful insight into the state of the valves. Some valves have valve positioners that measure the position of the valve stem. In this case it is possible to estimate the static relation between the command signal and the valve stem. Both the dead-zone and the hysteresis can be determined from these characteristics. In cases where there is no valve positioner it is possible to perform valve diagnosis based on the signals in the control loop. An example of such a system is described in [12].

Control Loop Assessment

There are several functions, which are not normally found in control systems, that are useful. One of them is control-loop assessment. This facility should give a classification of the key features of the control problem. In [3] it is shown that it is possible to automatically determine if a controller is performing a servo task or a regulation task. It is also useful to have possibilities to determine if the controller is performing according to its design specifications. It is also highly desirable to automatically determine the performance that can be achieved and what the key limiting factors are. To do this it is necessary to automatically determine the nonlinear static input-output relation of the process, to classify process dynamics and disturbances. This information is useful both for the operation of the process and for process improvement.

Performance Assessment

The purpose of performance assessment is to answer the question: How well is the control loop doing? This requires a reference in the form of a data base. Traditionally this was done by recording the measured variable and the set point using a strip recorder. With the advent of distributed control systems various types of data historians were introduced. Sampling and filtering are key issues, which will influence the results significantly. To obtain reliable results it is essential to perform these functions consistently. It is also useful to relate control quality to the presence of disturbances.

When the disturbance are well modeled as random processes stochastic control theory gives a nice way to characterize control performance. A good assessment of achievable performance can be made by computing the variance of the error in predicting the output over different time horizons and relating this to restrictions in plant dynamics caused by time delays, right half-plane poles and zeros, see [2].

3. Tools and Techniques

There are a large number of different tools that can be used for the tasks discussed in the previous section. The techniques include the standard tools of modeling and control design from control engineering together with techniques from computer science such as neural networks and knowledge-based systems.

Models

One of the most fundamental results of control theory is the internal model principle which tells that a controller should contain a model of the system that is controlled. Many methods for control system design will also automatically give such a controller. The model will typically be a linear dynamical system. This is in strong contrast to controllers of the PID type that do not contain an explicit process model. Many other models are needed in an autonomous controller. In such a controller it is necessary to describe the static process characteristics, process dynamics, and disturbances at different levels of precision. It is also necessary to have tools to determine the different models from experiments. In particular we need techniques to make preliminary assessments of the problems.

The static input-output characteristics is useful to make a preliminary assessment of the nonlinearity of the process. This can easily be done from static input-output data.

There are many ways to obtain linear process dynamics. Linear transfer functions or state models can be obtained using system identification techniques. These methods do, however, require prior information. In many cases it is also useful to have a crude qualitative assessment of dynamics. For example, we would like to know if the system is stable or unstable, if it has right half-plane zeros or time delays, if the step response is monotonous or oscillatory etc. It is also useful to have some quantities that give a gross assessment of dynamics. Some useful parameters for stable systems are the average residence time, the frequency ω_θ (i.e. the frequency where the phase lag is θ), and the gain k_θ at this frequency. Parameter k_0 is the static gain and k_{180} is the gain where the phase lag is 180°. The dimensionless quantity $\kappa = k_0/k_{180}$ is, for example, useful to determine the performance limitations imposed by process dynamics, see [6]. In [17] it is shown how this idea is used to automatically select suitable controller specifications. These parameters can be derived from the transfer function. It is, however, of interest to have methods for determining the parameters directly.

It is also of interest to have an assessment of the disturbances, e.g. to know if they are regular or irregular, deterministic or stochastic. Both qualitative and quantitative characterizations are also needed.

Relay Feedback

Relay feedback is a powerful method of exciting a dynamical system and to estimate useful system characteristics. The key idea is that many systems will exhibit stable limit cycles when subject to relay feedback. The frequency and the amplitude of the limit cycle are determined by system features and give useful insight into system properties. The idea of using the excitation provided by relay feedback to tune simple controllers has been applied very successfully in several industrial products [13]. There are also many interesting variations of the method, see [22]. There are several interesting questions related to existence and stability of the limit cycles obtained. In this paper we will not discuss these problems. For simplicity the discussion will be based on describing function analysis [9]. There are, however, also exact methods, see [25] and [4]. In [23] it is suggested to use relay experiments to estimate uncertainty bounds for unmodeled dynamics.

Phase Crossover Characteristics

The behavior of the plant transfer function at the phase crossover frequency, i.e. the frequency ω_{180}, where the phase lag is 180°, is of particular interest for design of PID controllers. It gives an estimate of the achievable closed-loop bandwidth and it is also the basis for the Ziegler-Nichols tuning procedure. The frequency ω_{180} can be determined automatically from an experiment with relay feedback as is shown in Figure 3. By making the observation that the describing function of a relay is the negative real axis it follows that the system oscillates with a frequency that is close to ω_{180}, see [9]. The frequency can be determined from zero crossings of the limit cycle. The magnitude of the transfer function can be determined by a simple harmonic analysis. In practice it is useful to introduce hysteresis in the relay. The describing function is then a line parallel to the negative real axis. Such a measurement will give the value of the transfer function at a frequency close to ω_{180}.

A slight modification of the experiment shown in Figure 3 gives other frequencies of interest. Figure 4 shows an experiment that gives the frequency ω_{90}, i.e. the frequency where the plant has a phase lag of 90°. The frequency ω_{270} can be obtained in a similar way by introducing a lead network instead of an integrator. Notice that there are two different versions of the experiment depending on the order of the integrator and the relay.

Closed-Loop Experiments

Relay feedback can also be applied to closed-loop systems as is shown in Figure 5. Let L be the loop transfer function, i.e. the combined transfer function of the controller and the plant. The closed-loop transfer function is then

$$G_{cl}(s) = \frac{L(s)}{1 + L(s)} \tag{1}$$

The experiment with relay feedback then gives an oscillation with the frequency such that the phase lag of $G_{cl}(i\omega)$ is 180°. It then follows from (1) that this is also the frequency where $L(i\omega)$ has a phase lag of 180°, i.e. the phase crossover frequency. If the relay has hysteresis, then a conformal mapping argument shows that the

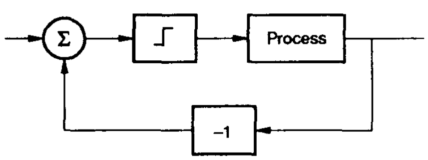

Figure 3. Determine the phase crossover frequency ω_{180} from an experiment with relay feedback.

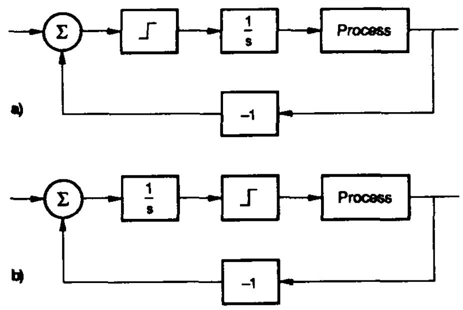

Figure 4. Two ways to determine the frequency ω_{90} by using relay feedback.

experiment gives the frequency, where the loop transfer function intersects part of the circle

$$\left| L(i\omega) - 1 + i\,\frac{1}{2a} \right| = \frac{1}{2a}$$

which is shown as curve A in Figure 6. By introducing an integrator in series with the relay, the frequency where $G_{cl}(i\omega)$ has a phase lag of 90° is obtained. This occurs where the Nyquist curve of the loop transfer functions intersects the circle

$$\left| L(i\omega) + \frac{1}{2} \right| = \frac{1}{2}$$

which is shown as curve B in Figure 6.

4. Examples

An autonomous controller will consist of a collection of many different algorithms. It will also contain information about procedures like how to tune a controller and how to design a controller. Algorithms and procedures can be used in many different ways. We illustrate this by a few examples.

EXAMPLE 2—Relay Tuning

A primitive relay tuning can be done as follows. The process is brought close to the desired steady state by manual control. The process output is then observed

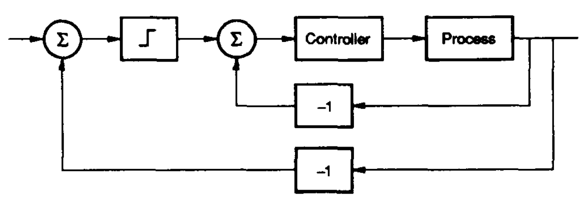

Figure 5. Applying relay feedback to a closed-loop system.

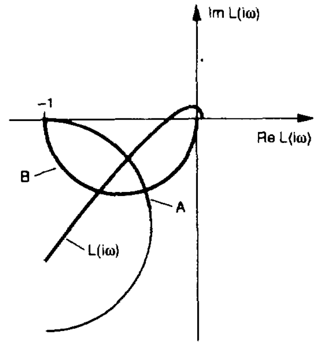

Figure 6. Frequencies obtained by different experiments with relay feedback.

for a few periods to determine the noise level. An appropriate hysteresis level is then determined and the process is connected with relay feedback. The amplitude and the period are determined when a steady state is achieved. Parameters of a PID controller are computed and the system is automatically switched to PID control. A specified amplitude of the limit cycle can be obtained by adjusting the relay amplitude. Assymetric oscillations can be avoided by a bias compensation as was discussed in [15]. It is also possible to obtain useful information about the system by a more detailed analysis of the limit cycle.

A system that performs this task can be built from the following algorithms: a signal analyser, relay feedback, a PID algorithm, a design computation. The procedure can be controlled by a finite state machine. Alternatively the operation can also be described using a script or a plan. A useful system should also take care of exceptions for example that no limit cycle is obtained or that the limit cycle will not be stable. □

The algorithms used in Example 2 can also be used in many other ways. Assume for example that we are interested in determining the stability margins for a control loop. This can be done as follows.

EXAMPLE 3—Determination of Stability Margins
The amplitude margin can be determined from an experiment with feedback on the closed-loop system as shown in Figure 4. Using a describing function argument it follows from Equation (1) that the amplitude margin is given by

$$A_m = \frac{a + d}{a}$$

where a is the amplitude of the first harmonic of the limit cycle oscillation and d is the relay amplitude. If the relay experiment is repeated with an integrator in series we get the intersection with the circle B in Figure 5. This will give an approximation of the sensitivity. □

When a preliminary tuning has been done it may be useful to change sampling intervals and to introduce proper prefiltering. The tuning procedure should then be repeated. It may also be useful to obtain further information about the system by more process experiments.

EXAMPLE 4—Improved Tuning
An improved tuning can be obtained by determining the steady state process gain from a closed-loop step experiment. More information about the transfer function of the process can be obtained by frequency analysis. Since the crossover frequency is known, a proper frequency range can be chosen. A multifrequency signal is a good choice of the input signal. To perform this experiment it is necessary to have a signal generator that can produce steps and multifrequency sinusoids and a frequency analyser. □

To investigate if the system is operating properly it is also useful to have direct measurements of system performance. The following example illustrates how this could be done.

EXAMPLE 5—Direct Measurement of IAE
The response to load disturbances is often of prime importance in process control. This property can be characterized by the integrated absolute error due to a load disturbance. This can be measured simply by injecting a step at the process input and integrating the absolute value of the control error obtained. The size of the step must be chosen judiciously with respect to the process disturbance and process nonlinearities. Information about the noise level is, however, available after the initial tuning. The results can also be compared with the value of $1/k_i$. The values should be close. If not, the closed-loop system is oscillatory. □

EXAMPLE 6—Filtering and Logging Rates
Information about a suitable bandwidth of the closed loop is obtained after the first tuning experiment and can be refined in further experiments. This information can be used to determine sampling rates and prefiltering. To capture information about the system it is reasonable that control signal, set point and process variable are logged at each sampling interval. This data can, e.g., be stored in a ring buffer in the controller. Quantities like mean value, standard deviation, max and mean, can also be computed based on these intervals. Values that represent extreme deviations and mean values over the dominant closed-loop period can then be sent to a supervising system. Data from each sampling period can be sent to instability detectors. □

5. System Structure

Several of the examples described in the previous section have been implemented in industrial systems in an *ad hoc* manner. These systems contain a mixture of procedures and logic. It is useful to implement the system hierarchically with algorithms at the lower levels and symbol manipulation at the higher levels. The expert control paradigm [1], illustrated in Figure 7, is a convenient way to combine algorithmic and symbolic manipulation. Several autonomous controllers have also been implemented using this approach. This system is useful because it give a clear separation of algorithms and procedures, which are implemented in the expert system.

The structuring of the system is an interesting problem. In a broad sense it can be described as automating what a control engineer does in designing a good system. Although much symbolic manipulation can be described using an expert system, it does not necessarily lead to a well-structured system. A black-board system is useful, because it gives a way to group the rules into natural tasks. The grouping of rules still has to be done manually. Planning, [24, 18], is another way to provide some structure. The algorithms are then provided with pre- and post conditions and the structure is indirectly obtained via the planning system. Scripts [21] is another way to obtain a structure of the problem. This has been used, e.g., for control system design, see [16].

One possibility is to consider system structuring as a high-level control problem. A number of-low level functions is first grouped in to primary tasks. Each task should perform a given function but it should also generate signals that can be used for higher level decision making and it should also be able to receive symbolic commands to modify its behavior. This is illustrated in

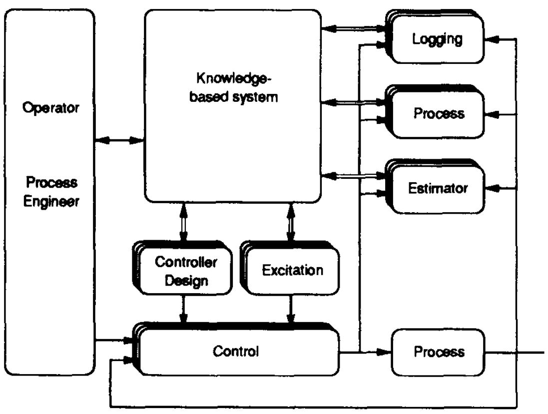

Figure 7. An expert control system.

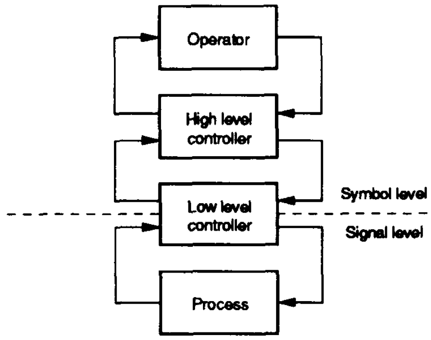

Figure 8. A structuring mechanism.

Figure 8. This figure only shows two levels, but the approach can be extended to an arbitrary number of levels.

To illustrate the idea let us consider a basic control task. The box denoted controller could thus contain a PID algorithms and various diagnostic algorithms. The control task provides the basic low level control but it also delivers the following symbolic signals:

- Normal
- Emergency
- Uncertain

The control task should also be able to receive symbolic commands such as:

- Resume normal operation
- Determine stability margins
- Retune immediately
- Determine plant transfer function
- Investigate disturbance characteristics

From the high-level controller the system below the dotted line in Figure 8 can thus be viewed as a discrete control system. A learning control algorithm for such a system can be approached as a control problem for a discrete Markov process.

6. Conclusions

In this paper we have outlined some properties of an autonomous controller. This controller is composed of a number of different algorithms for control, fault detection and diagnosis. It has been argued that there are several advantages in combining control and diagnostics. Many of the algorithms are known. A significant research problem is to find suitable ways to structure the system so that it can be designed in a systematic way. There are many potential applications of systems of this type in process control because of the large number of loops that have to be attended with a small staff. The demands for such systems are increasing because of the increased requirements on product quality.

Acknowledgement

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