A MULTILEVEL PAPER MACHINE CONTROL SYSTEM

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SUMMARY

A multilevel approach to design of a paper machine control system has been presented. The system described includes not only regulating and coordinating control, but also on-line optimizing algorithms. In addition to being a convenient means for organizing the control activity, the multilevel approach provides a framework for organizing the computer software. In actual operating systems, the frequently executed first level programs are core memory resident, while the remaining levels of control reside in a rapid access drum mass storage. The core-drum memory combination is an economical way to implement multilevel control structures.

INTRODUCTION

It is apparent that computer control of the paper making process cannot be economically justified on the basis of replacing analog controllers with digitally-implemented equivalent control algorithms. The computer control system, to be justified, must provide capabilities beyond simple regulatory direct digital control (DDC).

The purpose of this paper is to present an approach to computer control of a paper machine in which significant areas of economic justification have been automated through on-line optimizing control algorithms (1). The paper has been divided into two parts; the first discusses the structure of the control system in general terms, and the second discusses selected examples of the control algorithms in more detail.

REVIEW OF MULTILEVEL CONTROL DESIGN PHILOSOPHY

Optimal control

One approach to optimization of a process is to develop an optimal control policy from the minimization of an appropriate objective function, or economic criterion. Such an approach requires the development of a detailed process model and a meaningful economic performance index. Since the paper making process is a non-linear, time-dependent, distributed parameter process, detailed modeling of the complex physio-chemical relationships is a major obstacle to the synthesis of "the" optimal controller.

HIERARCHIAL CONTROL

The multilevel approach to control system design represents a practical approach to complex control problems. One of the basic assumptions of the multilevel approach is that the system is too complex to be effectively controlled as an entity. In addition to the unrealizability of a single controller, it may be undesirable from the view point of computing requirements and reliability. The multilevel approach subdivides the single complex problem into a hierarchy of simpler control design problems. With this approach, the controller on a given "level of control" is less complex due to the existence of lower level controllers which remove higher frequency disturbances. It is possible to generalize that at each succeeding level in the hierarchy, the complexity of the control algorithms increases, but that the required execution frequency decreases.

LEVELS IN THE HIERARCHY

The multilevel control approach is a means of ordering the control activity into a convenient structure. The number and functions of the levels in a hierarchial system has been the subject of much research and many arbitrary definitions (1). For the purpose of this discussion, the structure defined in fig. 1, will be used. The proposed hierarchy consists of four levels, the process level, the coordination level, the optimization level, and the management strategy level.

On the first level of control, selected process variables, such as flows and speeds, are regulated to specific set points. Since many of the process loops cannot be mani-

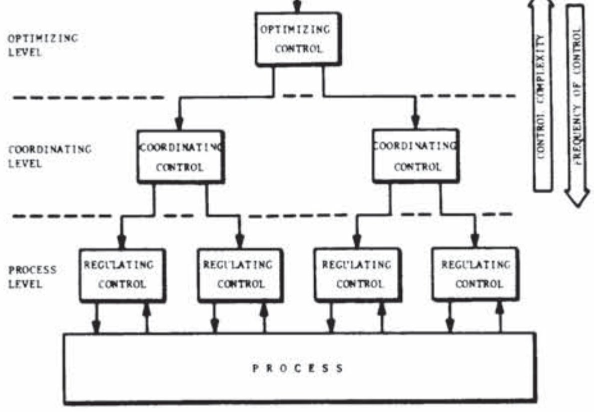

Fig. 1. Multilevel Control System Structure

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(1) The system described herein is the control system being marketed as a part of the AccuRay ® Process Management (APM) systems of Industrial Nucleonics Corporation, Colombus, Ohio, USA.

pulated independently without exhibiting strong interactions, first level control does not guarantee that product control objectives will be met.

The purpose of the second level control is to provide the necessary coordination of the process level controllers to insure the realization of product control objectives. An alternate name for the coordination level might be "product level" since the coordination function involves interpreting product set points and providing process level set points required to satisfy product specifications.

The third level of control has been defined as the process optimization level. The function of the optimizing algorithms is to determine the optimum set points for the product and process level loops. This level may include both steady state and dynamic optimization.

The fourth level of control can be referred to as the management strategy level. Combined in this level are the control activities which involve human decision making, often based on complex or unquantifiable variables. It is on this level of control that the mill management implements the production strategy, for example, selecting operating set points based on customer acceptance of the products. While this level is not treated explicitly in this paper, its importance is not to be underestimated. Good system design for this level requires efficient information transfer to the operators and supervisors, in terms of management information reports and data presentation on operator consoles. The key to an economically successful installation is this fourth level of control.

MULTILEVEL PAPER MACHINE CONTROL SYSTEM

Process loop selection

The control system described in the following paragraphs and shown in block diagram form in fig. 2 was designed for general applicability to many different paper machines. Since the system was to operate in a medium-scale computing environment, an effort was made to limit the scope of the system to those control loops which have demonstrated the most potential for a return on investment. Published results indicate that basis weight control, moisture control, and automatic grade change control each have major economic potential (2,3). With these economic objectives, six process level loops were selected. These six loops, along with the controlled variables associated with each manipulated variable, are tabulated in Table 1. While there are many possible combinations of manipulated and controlled variables, the assignment was made on a basis which would comply with conventional mill practice.

TABLE 1

PROCESS LEVEL CONTROL LOOPS

MANIPULATED VARIABLES		CONTROLLED VARIABLES
THICK STOCK FLOW	→	BASIS WEIGHT
DRYER STEAM PRESSURE	→	MOISTURE
TOTAL HEADBOX FLOW	→	DRY LINE POSITION
HEADBOX AIR PAD	→	HEADBOX LEVEL
SLICE POSITION	→	JET-TO-WIRE RATIO
MACHINE SPEED	→	PRODUCTION RATE

COORDINATION METHODS

Since many of the variables listed in Table 1 have strong interactions, one of the primary design criteria for the coordination level loops was to provide a non-interacting control system.

The coordination requirements were grouped into three second level control programs, basis weight and moisture control, coordinated headbox control, and coordinated grade change control (speed, basis weight, and moisture changes). The basis weight and moisture program provides control during on grade operation.

The coordinated headbox program, while stabilizing the wet end during on grade operation, provides required control during dynamic process changes. Grade change control provides the essential coordination during dynamic machine changes.

ON-LINE OPTIMIZATION

The automation of the optimizing functions is achieved on the third level of control. Two areas of economic interest are concerned. The first is the selection of optimal set points for on grade basis weight and moisture control. The objective is to optimize the fiber and moisture content of the sheet, subject to constraints on product weight and moisture. An algorithm for the on-line optimization of the set points is included under the name of Target Optimization Control (2).

Another area of economic interest is the optimization of production throughput. Using a peak-seeking technique, the algorithm called Speed Optimizing Control gradually increases the production rate until some well defined, measureable process limit is reached. The constraint on production may come from a dryer limitation, a mechanical limitation, or a furnish limit. In certain applications, these limits are easily definable in terms of process actuators being in a limit condition. In the case of a dryer limited machine, the ramping of the speed stops when a steam flow or steam pressure limit is reached. In this dryer limited condition, the second level moisture control algorithm reverts to an alternate mode, controlling moisture with the machine speed and thick stock flow.

SYSTEM DETAILS

As a vehicle for describing the multilevel system, representative control algorithms are discussed. The intention is not only to demonstrate the program interactions and software implementation, but also to present specific applications of techniques to compensate for control problems in the paper making process.

Process loops

The six process loops depicted in fig. 2 are either DDC

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(2) U.S. Patent 3,515,860 and patents pending

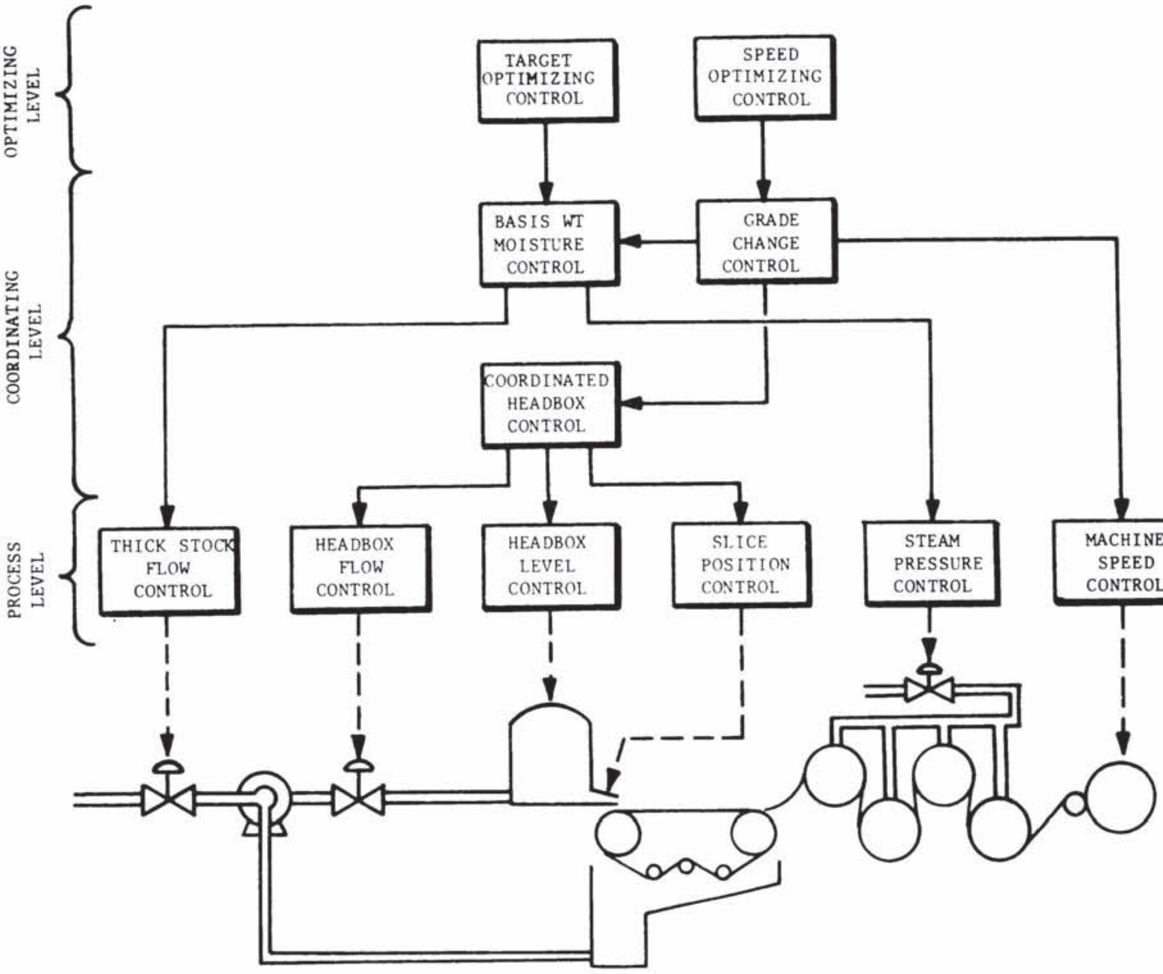


Fig. 2. Multilevel Paper Machine Control System

or supervisory set point control, depending on the analog control backup requirements. The decision to provide backup control is based on the amount of residual control capability judged necessary when the coordinating controller is inoperative.

Steam pressure and headbox air pad control usually require backup regulation when the computer is off line. Thick stock flow, headbox flow, slice position, and machine speed supervision are generally not required, so the latter loops have been implemented as DDC.

Since the first level loops are intended to stabilize the process and to eliminate higher frequency disturbances, they are executed frequently, typically once per five seconds.

The first level algorithms are generally representative of the state of the art techniques in DDC design, therefore the details of these algorithms have been eliminated. One feature of the DDC approach which is important to note, however, is that the process level loops must have the ability to track moderately slow ramp changes in set point. This requirement stems from the ramped set point commands generated by the grade change and Speed Optimizing controllers. Consequently, the deadband in the algorithm applies only to the feedback error and not to the feedforward set point changes.

Coordination loops

As an example of a second level algorithm, consider the control of basis weight and moisture. Most documented approaches to this type of control incorporate thick flow and steam pressure as the manipulated variables (4). The two primary control problems are the interactions between basis weight and moisture and the long transport delays inherent to the paper making process.

Since non-interacting basis weight and moisture control was a design objective, one approach would have been to use classical multivariable non-interacting design techniques. An understanding of the process and its instrumentation provides a simple alternative: bone dry basis weight control. The elimination of the interaction between moisture and basis weight is straight forward and easily implemented in the computer. The approach taken in this system, therefore, is to provide bone dry control, leaving the stock flow-moisture interaction to be eliminated by design.

Dahlin reports that a moisture control system developed from the classical non-interacting approach may provide sluggish response to moisture upsets (5).

This is due to the inclusion of a delay term to coordinate the moisture and basis weight responses. Consequently, for this system, a completely non-interacting controller was sacrified for improved moisture response. Stock flow to moisture decoupling is achieved by feeding forward the stock flow corrections computed in basis weight control to an empirical model of the interaction. The computed effects of stock flow changes are used to bias the observed moisture error, resulting in the following control algorithm:

$$\Delta P_{set} = K_m \times \frac{1}{\left.\frac{\partial M}{\partial P}\right|_{(M,P)}} \times \left\{ \underbrace{M_{set} - M_{ave}}_{\text{Feedback Error}} \underbrace{- \Delta Q_{stk} \times \frac{\partial M}{\partial Q}}_{\text{Feedforward Decoupling}} (M,P) \right\}$$

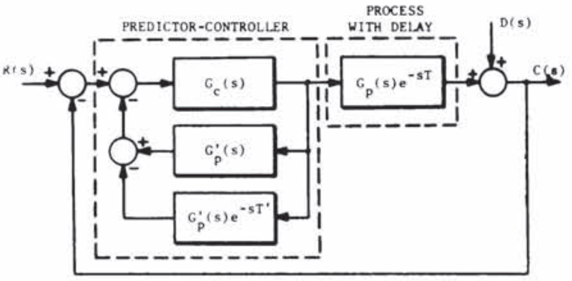
where:

ΔP_{set}	-	change in steam pressure set point
M_{set}	-	moisture set point
M_{ave}	-	moisture average
Δ ΔQ_{stk}	-	stock flow change from basis weight control
K_m	-	adjustable gain
$\frac{\partial M}{\partial P}, \frac{\partial M}{\partial Q}$	-	partial derivatives describing process response

While the approach to non-interacting control is frequently encountered in the paper industry, methods of compensation for transport delays have been diverse (4). Long term variations in basis weight are controlled using an average of the observed basis weight during one scan of the measuring system. Typical delays from the stock valve to the measurement vary from approximately one minute to several minutes, meaning that several scan averages may be computed within a process delay. If simple integral control is applied, using the scan average bone dry basis weight as the process feedback, the controller must be detuned to prevent delay-excited instabilities.

In the late fifties, Smith proposed a technique for achieving better transient response from controllers operating in the presence of process delays (6). This technique, known as a Smith Linear Predictor, adds a minor feedback loop around the controller, as shown in fig. 3. The minor loop includes a negative feedback of the simulated process dynamics and a positive feedback of the simulated response plus the estimated time delay. During the delay between control action and measurement, the negative feedback appears to the controller as the process response without the delay, inhibiting controller response to a previously measured error. When the process delay has passed, the positive feedback loop cancels the negative minor loop, removing the compensation of the measured feedback. The net result of Smith's technique is the ability to tune the controller to a higher loop gain.

The basis weight and moisture control programs developed for this system (3) by Rice of Industrial Nucleonics include an extension of the Smith Linear Predictor to a sampled data system. The intention was to provide the capability to control within a transport lag, without appreciably detuning the controller. Furthermore, it was intended to use this model reference approach during grade changes which could occur within a process delay. A conceptual block diagram of this approach is presented in fig. 4. The significant departure from the Smith approach is the use of a steady state model in the negative minor feedback loop, in place of a dynamic model without the delay term. In unpublished results, Rice reports this improves controller response during the transport delay.



$$\frac{C(s)}{R(s)} = \frac{G_p(s)G_c(s)e^{-sT}}{1 + G_p(s)G_c(s)}$$

Assuming $G'_p(s) = G_p(s)$ and $T' = T$

Fig. 3. A Smith Linear Predictor

The application of the model reference approach requires a steady state and dynamic model of the process. Since many wet end controls are varied in a predetermined manner during a grade change, it was desired to develop a model which would reflect these dynamic changes. A first principles approach was adopted. This technique results in a fixed model structure which is determined by the physical characteristics of the paper machine. The parameters of the model may be continuously adapted using measured wet end variables, such as flows and levels. Variables which are not measureable on-line, but which change from grade to grade and can be predicted by off-line analysis, are stored in a productcoded data file. These characteristics of the model may be loosely termed "open loop adaptive". Operating experience on several different types of paper machines indicates that this approach is an economically attractive tradeoff between model accuracy and computing requirements.

To put the basis weight and moisture control system in the classical perspective, a block diagram is presented in fig. 5.

OPTIMAL CONTROL METHODS

As an example of a third level controller, consider the problem of determining optimal set points for basis weight and moisture.

Grant has pointed out that criteria for saleable paper are usually derived from limit conditions, such as minimum fiber content or maximum moisture content (7).

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(3) Patent Pending

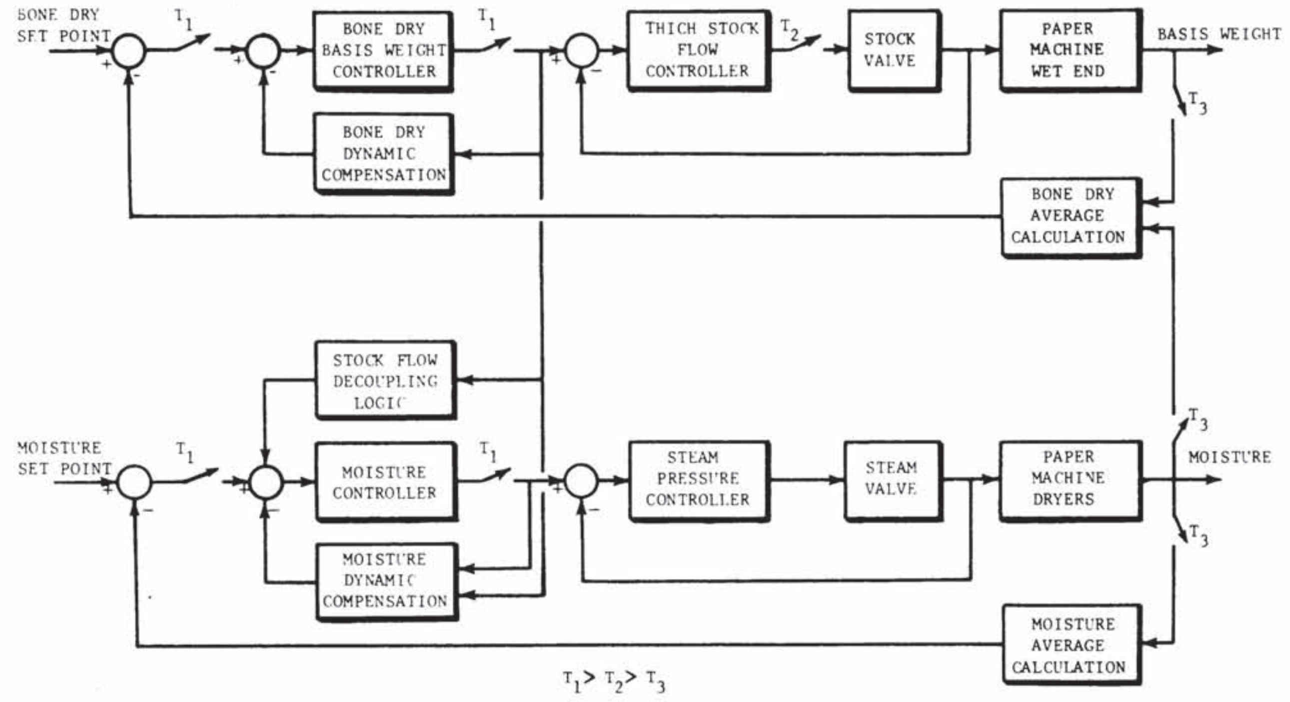

Fig. 4. A Model Reference Approach to Process Delay Compensation

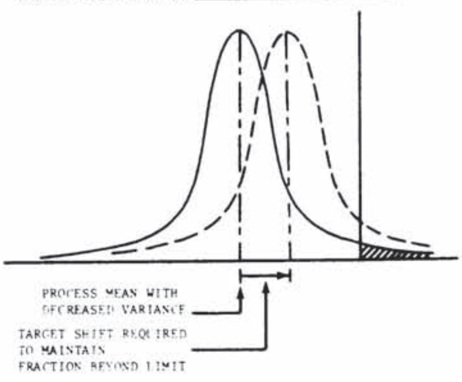

Fig. 5. The Basis Weight and Moisture Control System

Since basis weight and moisture are statistically distributed about their mean values, the set points are usually manually selected to insure that the majority of the product does not exceed the limiting factor. For a given mean, a process distribution, and a limiting factor, it is possible a small fraction of the product exceeds the limit, as shown in fig. 6. In a practical situation, the variance of the product variable may be a slowly changing function of time. Since the mean value is under control, and relatively stationary, the amount of product beyond the limit also will be time varying.

It is apparent that as the product variance changes, the efficiency of material utilization changes, since the process is not operated as close to the limit factor as possible. The motivation for Target Optimization Control is to take advantage of the changes in process variance to shift the mean in relation to the limit. To optimize the useage of raw materials, it is desirable to dynamically determine the product set points as a function of the limit factor, the estimated process variance, and the desired fraction of production beyond the limit. This problem can be conveniently formulated as a steady state optimal control problem.

In the optimal control formulation, the control objective is to choose a mean value (set point) such that the amount of product exceeding the limit is maintained in the presence of a changing process variance. To formalize this, the objective function

$$Q = \frac{1}{T} \int_0^T [\, q(t) - q_{sp} \,]^2 \, dt$$

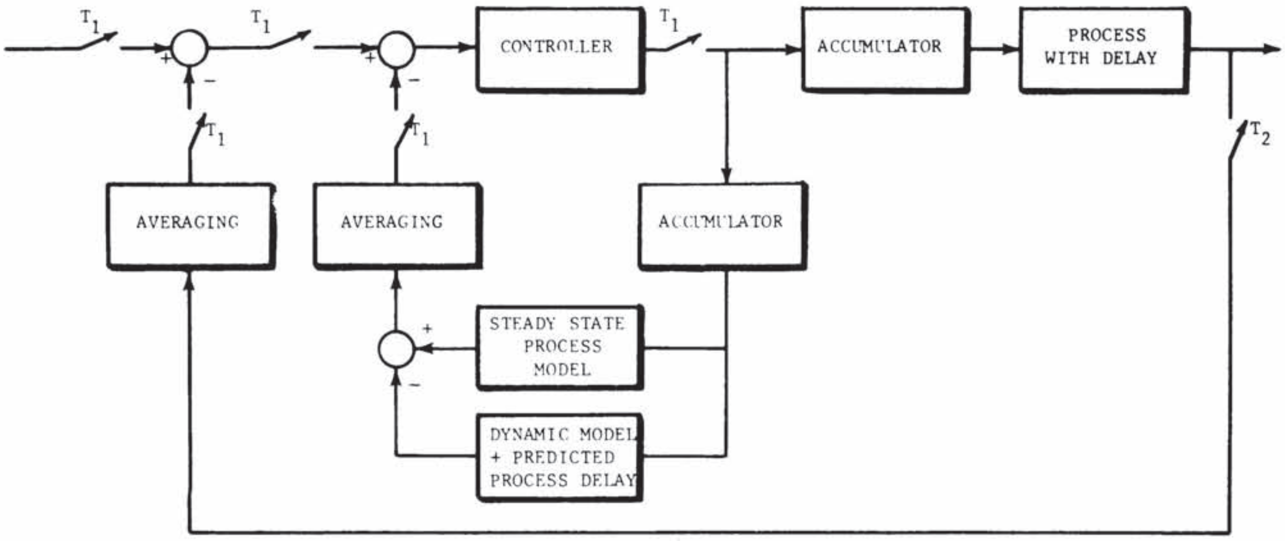

Fig. 6. Concepts Basic to Target Optimization Control

where:

$q(t)$ - fraction exceeding process limit
q_{sp} - desired fraction exceeding limit
T - a suitably long period of time, relative to the basis weight and moisture control dynamics

is defined and minimized. One approach is to assume a distribution function, such as a normal distribution and to relate the fraction exceeding the limit, q(t), to the limit, the mean, and the variance. Appropriate mathematical manipulation produces an algorithm relating the mean of the process to changes in process variance. The resulting algorithm is difficult to implement in practice since it requires storing tables of the distribution function.

Spitz of Industrial Nucleonics has developed an approximate version of the algorithm using a fit to a normal distribution function in the region of the tails. The approximate optimal control algorithm is attractive since it is a simple linear relationship between the process mean and the estimated variance. The approximate algorithm is

$$SP_{new} = L + \left[\frac{A_2 + A_3 q_{sp}}{A_1 + q_{sp}}\right] \times \left[\frac{A_1 + q_e}{A_2 + A_3 q_{sp}}\right] \times \left[SP_{old} - L\right]$$

where:

SP - process mean set point
q_{sp} - desired fraction exceeding limit
q_e - measured fraction exceeding limit
L - process limit
A_1, A_2, A_3 - parameters of the fit to the distribution

To implement the approximate algorithm, an initial estimate of the variance is made, and subsequent values are computed from on line observations. Analysis indicates that approximately 1000 samples, which would normally require 10 scans of the measurement system at 100 discrete samples per scan, is a reasonable number from which to compute a new set point. Consequently, the period between set point changes is on the order of 10 to 20 minutes.

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REFERENCES

1. Lefkowitz, I. "Multilevel Approach Applied to Control System Design". Proceedings of the 1965 Joint Automatic Control Conference. Troy, New York, 1965.
2. "Where North American Mills are Using Process Computers and With What Benefits". Paper Trade Journal. Vol. 154, August 31, 1970, pp. 25-31.
3. "Us Control Experts Voice Thier Views". Pulp & Paper International. Vol. 11, No. 12, Nov. 1969, p.63.
4. Brewster, D. B. and Bjerring, A. K. "Computer Control in Pulp and Paper 1961-1969". Proceedings of IEEE. Vol. 58, No. 1, January 1970, pp. 49-69.
5. Dahlin, E. B., et al. "Designing and Tuning Digital Controllers". DDC Tuning Reference Book. Rimbach Publications, Philadelphia, Pennsylvania, 1969.
6. Smith, O. J. M. "A Controller to Overcome Deadtime". ISA Journal. Vol.6, No.2, p.28, Febr. 1959.
7. Grant, M.P. "Target Optimization Control for Automatic Maintenance of Product Factors at Limits". To be presented at 1970 TAPPI Engineering Conference, Denver, Colorado, USA.