

ADAPTIVE CONTROL APPLICATIONS IN PULP AND PAPER

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ABSTRACT

Adaptive control is a general term that has been applied to control schemes that automatically adjust their control characteristics under various operating conditions to maintain control of a process. The adaptive mechanism used and the degree to which the control scheme adapts to the process result in a wide variety of adaptive process controllers.

This is a general introduction to adaptive control and an overview of some of Process Automation Systems's field application results with a new, adaptive controller called the Universal Adaptive Controller (UAC). Its unique automatic model development and continuous on-line adaptation to process dynamics have resulted in significant improvements in process control.

PROPORTIONAL-INTEGRAL-DERIVATIVE CONTROL

Proportional-Integral-Derivative or PID control has been the major control scheme to date in industry. The controller works by examining the instantaneous error between the process value and the set point. The Proportional term causes a larger control action to be taken for a larger error. The Integral term adds to the control action if the error has persisted for some time and the Derivative term supplements the control action if the error is changing rapidly with time.

The values of the P-I-D terms depend on characteristics of the process and must be tuned accordingly to yield satisfactory results. Properly tuned and maintained PID controllers provide adequate control for a large portion of industrial applications.

However, there are many processes with time-variant or non-linear characteristics that are difficult to control with fixed parameter PID controllers. Often it is these processes that are the most critical to the operation of the plant. To cope with these problems, PID controllers have evolved to include adaptive features such as gain scheduling and self-tuning.

Gain scheduling involves experimentation to determine optimal PID parameter values under a variety of operating conditions. The PID parameter values are stored and later recalled for use in the controller according to prevailing ambient factors via a custom scheduling scheme.

Self-tuning PID controllers use a variety of techniques to automatically determine the optimal values for the PID tuning parameters such as the Ultimate Sensitivity method developed by Ziegler and Nichols, the Reaction Curve method, or model fitting algorithms. These techniques typically require the introduction of a disturbance and subsequent analysis of the process reaction. Often the disturbance cannot be tolerated while in production or difficulty arises trying to identify the process response due to other load disturbances. Some self-tuning PID controllers are capable of continuous self-tuning on-line while others only perform the self-tuning function on demand.

In addition to processes that have time varying or non-linear characteristics, processes that have a significant dead time also pose a problem for PID controllers. The Smith Linear Predictor scheme has been applied to the PID controller to compensate for dead time. This scheme relies on a predetermined process model that is difficult to accurately obtain and automatically update on-line as operating conditions change. Modeling errors inhibit the success of this approach. When significant dead times are present, PID controllers are typically tuned with smaller proportional gain and longer integral action than is actually required. This attempt to prevent process cycling results in poor response to load disturbances.

While these adaptive features offer some improvements for PID control of difficult processes, often the process still cannot be controlled within desired tolerances. The underlying problem with PID based control schemes is that the control action is based on instantaneous error between the process variable and the set point without anticipation of the long term effects of the present control action or of the effects of previous control actions to which the process has not yet responded.

ADAPTIVE CONTROL

As mentioned in the introduction, many types of control schemes can be classified as adaptive. However, adaptive control schemes developed to date can be divided into two general categories:

Compensator-based Designs

These designs are based on the automatic tuning of a controller that compensates for the gain and frequency response characteristics of the process. Self-tuning and gain scheduling PID controllers are examples of compensator-based designs. These designs regulate an error signal (typically set point minus process value) to generate a control input to the plant which is compensated for the plant dynamics so that the process remains stable and can respond to load and set point changes quickly and with minimal overshoot.

Process Model-based Designs

These controller designs are based on the automatic adjustment of a mathematical model of the process that is used to predict future process response and calculate the actual control action required to obtain a set point. Commercially produced controllers of this type have commonly been called "true" adaptive controllers or "predictive" adaptive controllers to emphasize the differences in control philosophy compared to the common Compensator-type controllers.

For simplicity, Process Model-based predictive adaptive controllers will be referred to as "Adaptive Controllers" and the Compensator-based adaptive controllers will be referred to as "Self-Tuning PID Controllers" in this document.

Adaptive control schemes provide the opportunity to achieve improved control performance by basing the control action on a mathematical model of the process, including dead time, so that the control actions made are done in consideration of the effects of past control actions that have not yet appeared in the measurable process variable and the long-term consequences of the action about to be taken.

The mathematical model is adjusted automatically to compensate for changes in the process characteristics so that the controller can maintain control under various operating conditions.

Adaptive controllers are of particular interest for use on complex processes with significant dead times that typically cause difficulty for PID-based controllers.

HISTORY OF ADAPTIVE CONTROL

Adaptive controllers were developed in the early 1950's for the avionics industry when difficulties were encountered applying PID controllers to the task of auto-piloting aircraft.

The ability of adaptive control to "adapt" to variations in flight characteristics caused by such factors as air speed, altitude and aircraft load, and the ability to incorporate all these factors into a single mathematical control strategy, made adaptive control the ideal candidate for this task.

To incorporate these factors requires the development of a mathematical model that can be used to represent the responses of the aircraft. This mathematical development, along with the requirement of a fast computer to execute the algorithm, is the major reason that the potential of adaptive control has taken

so long to be realized in conventional industrial applications. Adaptive control has been limited primarily to specialized applications in aerospace and naval auto-pilots.

The cost of computers has dropped dramatically over the past few years and research into adaptive control algorithms has increased. The control improvements possible with adaptive controllers have also become more significant due to increasing economic pressures and environmental concern as better process control can often save money and reduce pollution.

These factors have caused new interest in adaptive control applications for industry.

BASIC STEPS IN ADAPTIVE CONTROL

Numerous adaptive control schemes have been developed to date but they all perform essentially the same basic steps as shown in Figure 1.

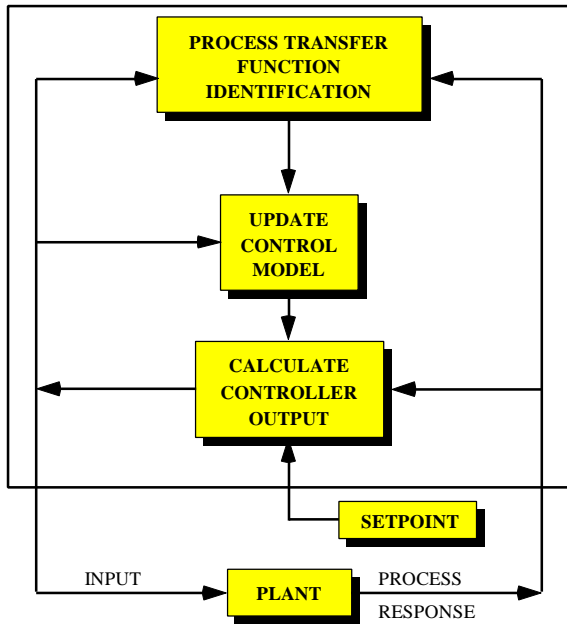


Figure 1. Basic Steps in an Adaptive Controller

1. **Process Transfer Function Identification:** The process model is adjusted to correct for model errors and to respond to changes in process characteristics by fitting observed process responses to the process model.
2. **Control Update:** The previous control action and observed process response are incorporated into the model.
3. **Control Output:** The plant model is used to predict process response and calculate the required controller output to bring the process variable to the desired set point.

The most important step is the model update (identification of the model parameters). The model structure chosen, and the method of fitting the observed process responses to that model, account for a significant portion of the variations found among the different adaptive control schemes. The degree to which the model is able to represent the process and automatically adjust to the process changes

determines the accuracy of the calculated control actions and the resulting control performance.

Model Reference Adaptive Systems (MRAS) are one popular adaptive control scheme currently used. These schemes rely on the creation of an exact mathematical model of the process for each application of the controller. It requires a detailed knowledge of the transfer function (plant order, time constants, dead time), usually determined experimentally, before it is possible to make an accurate process model. This requirement limits the ability to transfer a single controller design from process to process.

Until now, commercially available industrial adaptive controllers have been based on general process models that do not always adequately represent the individual process characteristics; they are usually difficult to apply and have had varying degrees of success.

UAC CONTROLLER

The Universal Adaptive Controller (UAC) is a breakthrough in adaptive control based on new theory developed by Dr. Guy Dumont and Dr. C. Zervos at the University of British Columbia.^[1] Process Automation Systems has been working on the UAC for almost nine man-years and it consists of over 25,000 lines of 'C' code. The advantage of the UAC is that it does not require a predetermined model of the process to be controlled. Only a minimum amount of prior knowledge of the process dynamics is required to apply the controller. The UAC's unique feature is its ability to learn the process transfer function while it is controlling the process. The UAC adapts its control action to changing process dynamics and dead times by building and continuously updating a mathematical model of the process being controlled. The UAC is also able to learn the effects of measured process disturbances (feedforward signals), resulting in further improvements.

APPLICATION EXAMPLES

CHLORINE PLANT APPLICATION

The UAC controller was tested on the pH loop of a Chlor-Alkali plant. The purpose of the test was to compare the performance of the UAC controller with that of the existing, automatic self-tuning, PID controller.

The loop controls the pH of the combined waste water of the Chlor-Alkali and adjacent Pulp and Paper plant. The waste water enters a neutralizing tank at a high pH (11 to 12) and is buffered down to a pH of about 4 before exiting to a settling pond. A sulfuric acid source with a pH of 2 is used to buffer the waste water.

This loop is difficult to control for a variety of reasons:

- typical gain non-linearities associated with an acid-base reaction.
- pH sensor located at the bottom of the tank while effluent discharge and acid addition occur at the top,
- the acid addition control valve is oversized and normally operates in the non-linear 0 to 10% range,
- an undersized tank and agitator.

As the objective of the test was to evaluate the relative performance of the two controllers, these process deficiencies were not corrected. Hence both controllers had to contend with the same physical problems.

The reason for trying to control pH accurately is to minimize chemical costs and optimize plant operation.

Under normal operation, sodium sulfide is added to the sewer water to settle out the mercury in the form of mercury sulfide, an insoluble compound. If the pH is too low, the amount of sodium sulfide added increases, resulting in higher operating costs. If the pH is above 7 a soluble compound, mercury polysulfide, and insoluble forms of polysulfide are created. This allows the mercury to escape the reclaiming process while the insoluble polysulfides plug up the filters designed to reclaim the mercury sulfide. The target pH of the loop is 4, however the optimum pH is between 5 and 6. The target pH is lower than the optimum because the existing self-tuning PID controller cannot control rapid fluctuations in the process. The set point of 4 represents a compromise between the cost of the sodium sulfide and ensuring that the pH does not exceed 7. A block diagram of the test loop is shown in Figure 2.

Steady State Results

The test was conducted over a 22-hour period with control switched between the UAC and the PID controller. The relative performance is shown in Figure 3. The rms error of the PID controller was 31.9% versus 15.9% for the UAC controller which represents a 50% reduction in process error compared to set point. The UAC output was clamped to a final output range of 0 - 30% during the tests to prevent large output swings. The 30% valve limit was reached during the three major upsets from 15 hours to 16.5 hours, which prevented the UAC from reducing the transient.

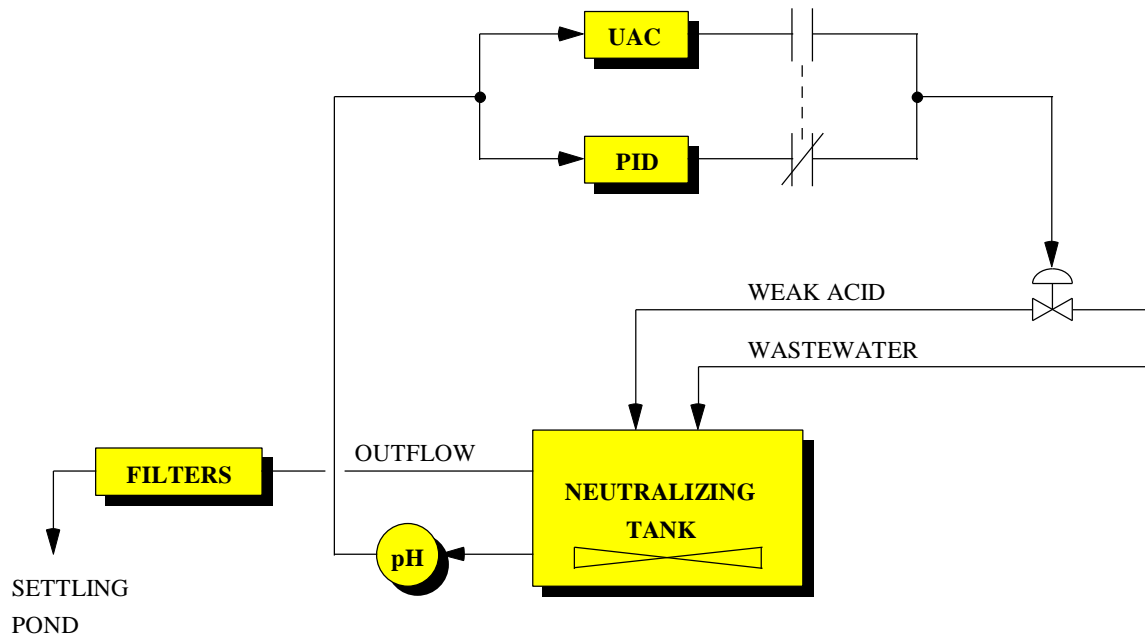


Figure 2. Chlor-Alkali Plant - pH Test Loop

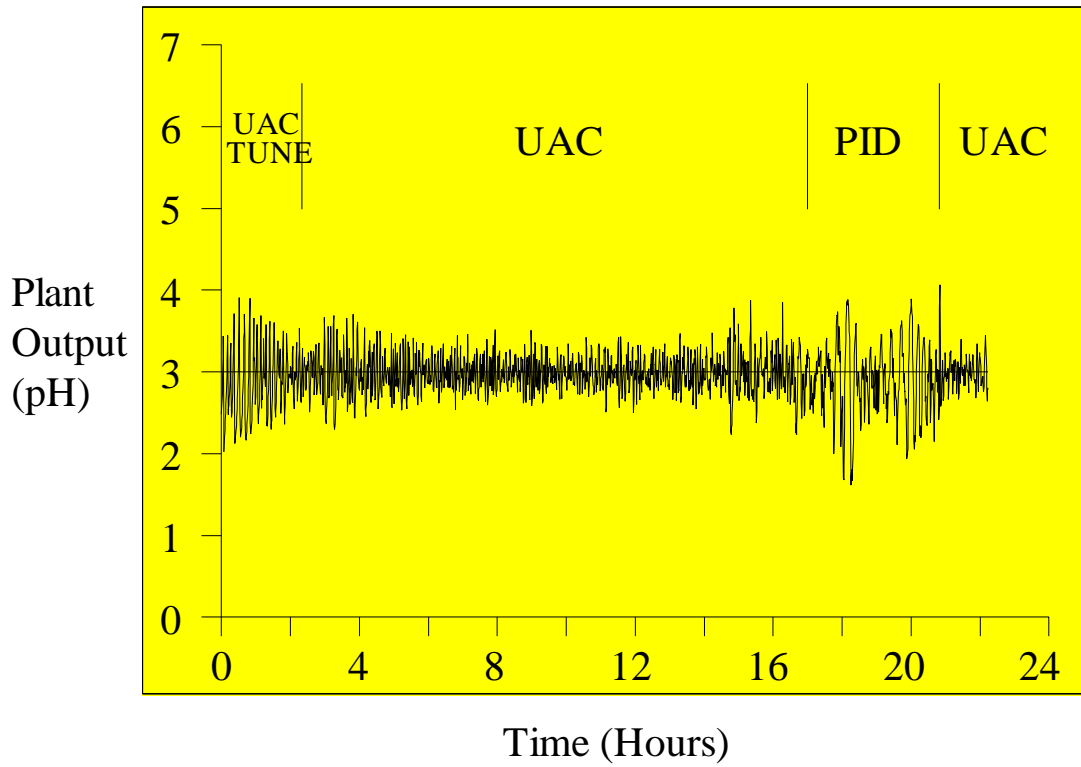


Figure 3. Chlor-Alkali Plant AC - Steady State Comparison

Transient Results

Figure 4 shows the response of the UAC and PID controllers to set point changes. The process was initially under manual control until a pH of approximately 8.5 was reached after 30 minutes. The UAC controller was then inserted and cycled through two set point changes. At about 150 minutes a bumpless transfer to the PID controller showed its inability to cope with the changes in gain due to the prevailing pH. This difficulty was also evident at about 250 minutes when the set point was changed to 3.0 pH. Control was switched back to the UAC controller at about 290 minutes with a set point of 5.5 pH.

The Self-Tuning PID controller had a difficult time adapting to different process conditions while the UAC controller had only an initial overshoot before settling down about set point.

INDUSTRIAL IMPLEMENTATION AT A ROTARY LIME KILN

The UAC is presently installed at a rotary lime kiln as part of an expert system that controls kiln operation. The UAC is an important factor in the success of the expert system because the UAC is able to follow set points generated by the expert system accurately despite long process dead times, non-linear characteristics and changing process gains.

An overview of the lime kiln is shown in Figure 5. Limestone passes through the preheater before entering the kiln where most of the calcination occurs. The calcination is completed in the cooler where heat is recuperated from the lime for combustion before the lime is discharged.

It is important to have stable level and temperature conditions in the cooler to ensure product consistency. In addition, stable temperatures in the cooler tend to stabilize temperatures in the firing hood and in the kiln.

Four vibratory feeders located at the bottom of the cooler are adjusted to control the level and temperature distribution of the lime in the cooler. A control schematic for one of the four feeders is given in Figure 6.

This cooler is difficult to control because:

- the process dead time between changes in feeder rate and discharge temperature at the feeder varies from 45 minutes to 90 minutes;
- final control element (feeder) is a vibrating trough with non-linear characteristics;
- interaction of all four feeders with each other.

Prior to installation of the UAC, cooler level was controlled using a single PID controller to regulate all four feeders. Temperature control in each feeder was performed manually using a trim signal added to the output of the cooler level controller as PID control of the trim signal had been unsuccessful. Level control was satisfactory, but the lime discharge temperature control was poor.

The UAC controller was installed to control cooler level and four additional UAC controllers were installed to automatically provide a trim signal to stabilize the temperatures in the four feeders.

Results

A comparison between cooler feeder temperatures under manual control and under UAC control is given in Figure 7. The UAC reduced cooler feeder temperature deviations from 200°F to about 30°F. (Note that there is an intentional 40° offset in temperature between the north and south pairs of feeders.)

The UAC was able to successfully automate the level and temperature control in the cooler. Stabilized cooler conditions have improved product quality and enabled the kiln to produce lime with a more consistent slaking rate.

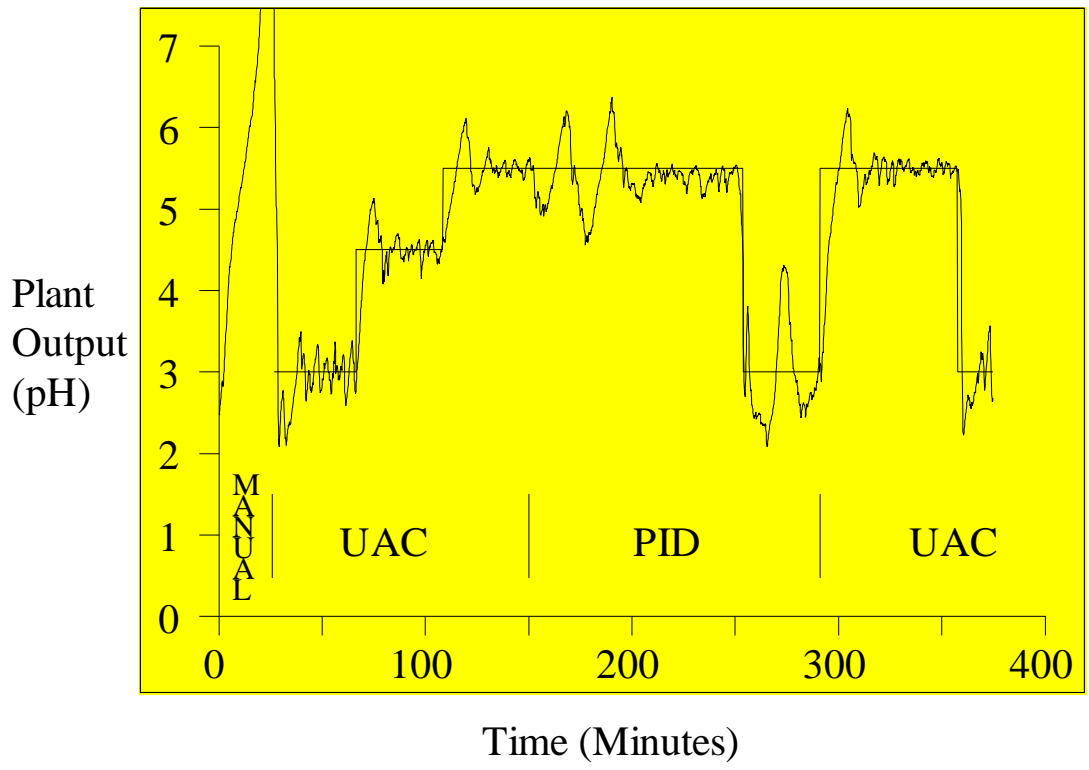


Figure 4. Chlor-Alkali Plant - Step Change Comparison

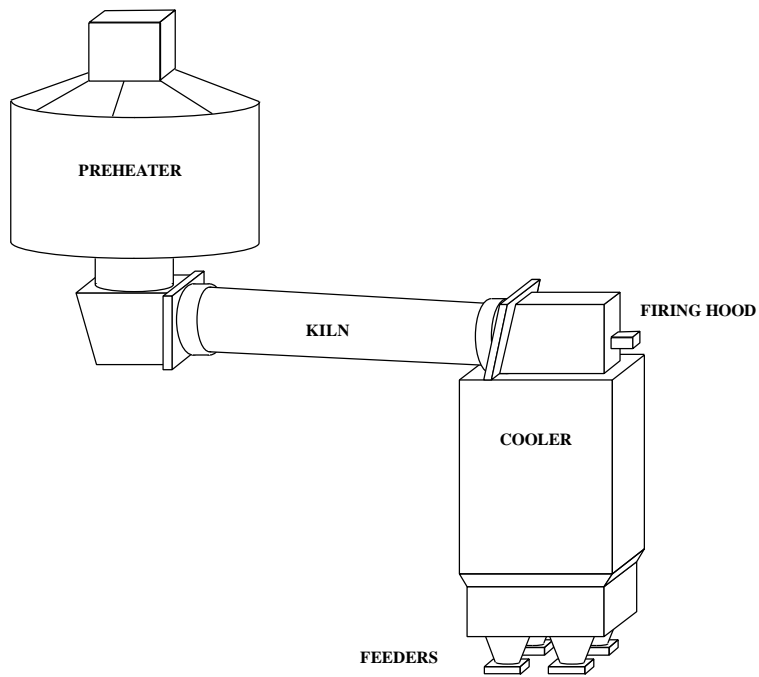


Figure 5. Lime Kiln Overview

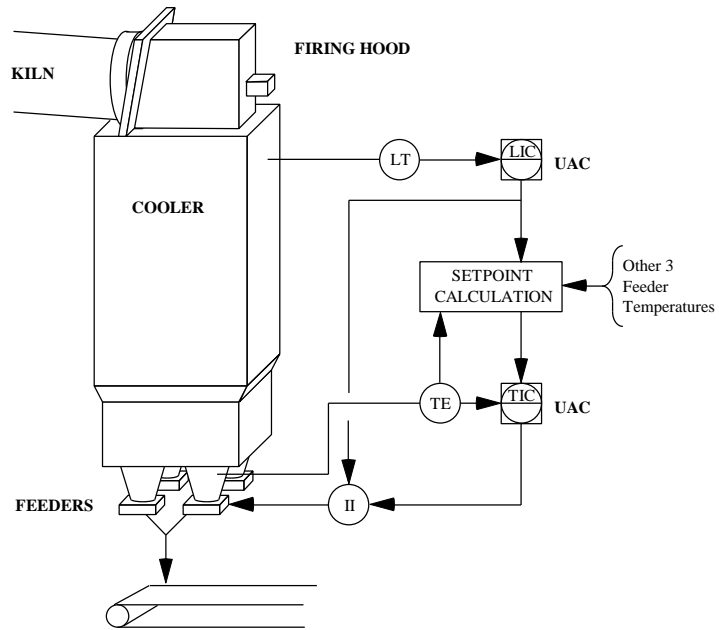


Figure 6. Lime Kiln Cooler - Single Feeder Control Schematic

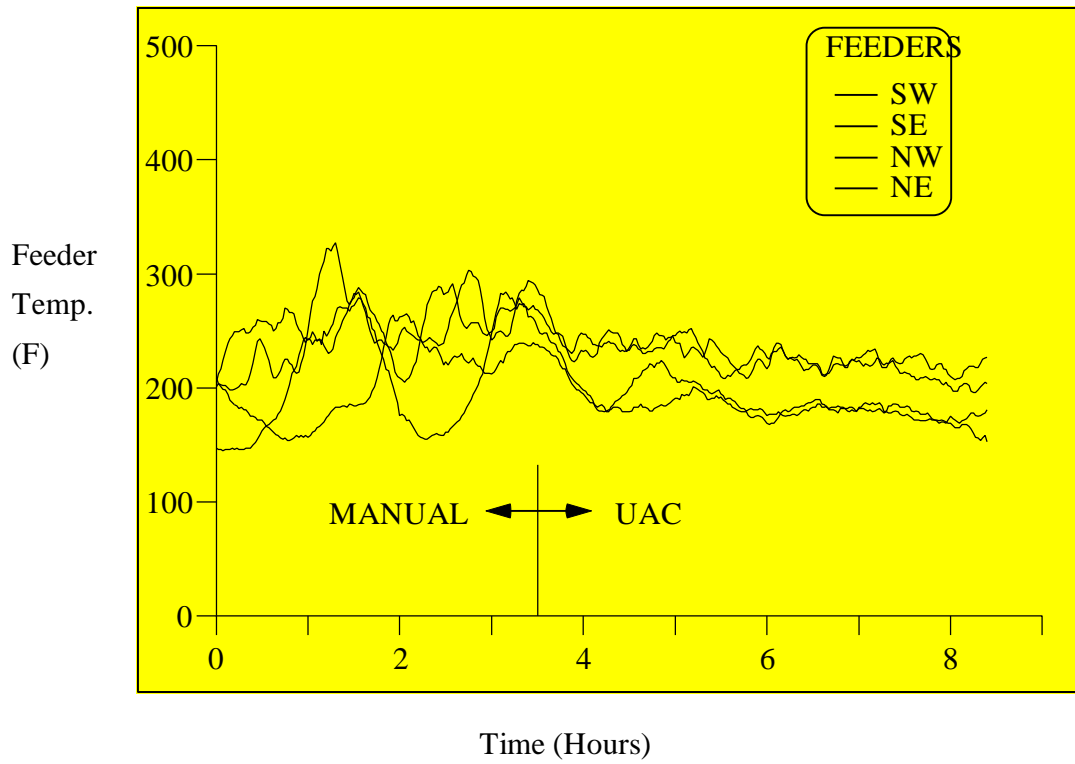


Figure 7. Lime Kiln Cooler Feeder Temperatures

PULP AND PAPER - BLEACH PLANT BRIGHTNESS CONTROL

The UAC was installed in the bleach plant of Weyerhaeuser Canada's Kamloops mill to control the compensated brightness and after tower brightness of the pulp in the first bleaching stage.

The objective of the compensated brightness control is to regulate the dosage of chlorine dioxide (ClO_2) in order to achieve a given pulp brightness after a brief reaction time (about 1 minute) with some residual ClO_2 remaining to complete the bleaching reaction in the 30-minute retention tower. A measurement of pulp brightness after the tower is used to determine the set point for the compensated brightness controller. A control schematic is given in Figure 8.

COMPENSATED BRIGHTNESS CONTROL

The compensated brightness signal is created from a measurement of the optical brightness of the pulp and the level of residual ClO_2 before the pulp enters the retention tower.

The existing controller was a distributed control system (DCS) based PID controller.

The control problems on this loop are:

- 1 minute dead time between ClO_2 dosage change and change in compensated brightness,
- process gain changes due to sensitivity changes of the residual ClO_2 sensor at different levels of ClO_2 substitution for chlorine (Cl_2) (60% ClO_2 or 100% ClO_2),
- process gain changes due to different wood species and variations in lignin content (K-number) of the pulp from the digester.

Figure 9 is a comparison of PID versus UAC performance over a period of 16 hours. Figure 10 shows the distribution of data compared to the set point for the PID control, and Figure 11 gives the distribution for the UAC. The PID had a standard deviation of 0.84, while the standard deviation of the UAC was 48.8% lower at 0.43.

AFTER TOWER BRIGHTNESS CONTROL

A brightness sensor installed immediately following the first bleaching tower provides an indication of the success of delignification in that tower. This signal is used to adjust the set point of the compensated brightness controller in order to reduce deviations in after tower brightness and kappa number.

The idea of using the after tower brightness sensor for feedback control is quite simple. Because of the long and varying dead times, setting this control loop up properly using PID algorithms is difficult and time-consuming. Dead times in this loop vary with production rate between 25 and 40 minutes. Care must be taken to ensure that the loop is stable at all production rates. The loop must be tuned to be very sluggish at high production rates, which tend to be the operating production rates 80% of the time.

A tool available to most DCS users to help speed up the control loop is the Smith Predictor as shown in Figure 12. A properly tuned Smith Predictor can be used to significantly speed up loops with long dead times.

One of the parameters of the Smith Predictor is dead time. If the dead time parameter is not accurate, the Smith Predictor will not work. When a process has varying dead times, it becomes much more difficult to enter accurate dead time values into the Smith Predictor. Process bumps must be done at two to three different production rates in order to determine an accurate formula for the varying dead time. In practice, it is very difficult to enter an accurate varying dead time into the Smith Predictor. In order to get stable control, the action of the Smith Predictor must be held back or slowed down somewhat. This, of course, leads to less than optimum control of the after tower brightness deviations.

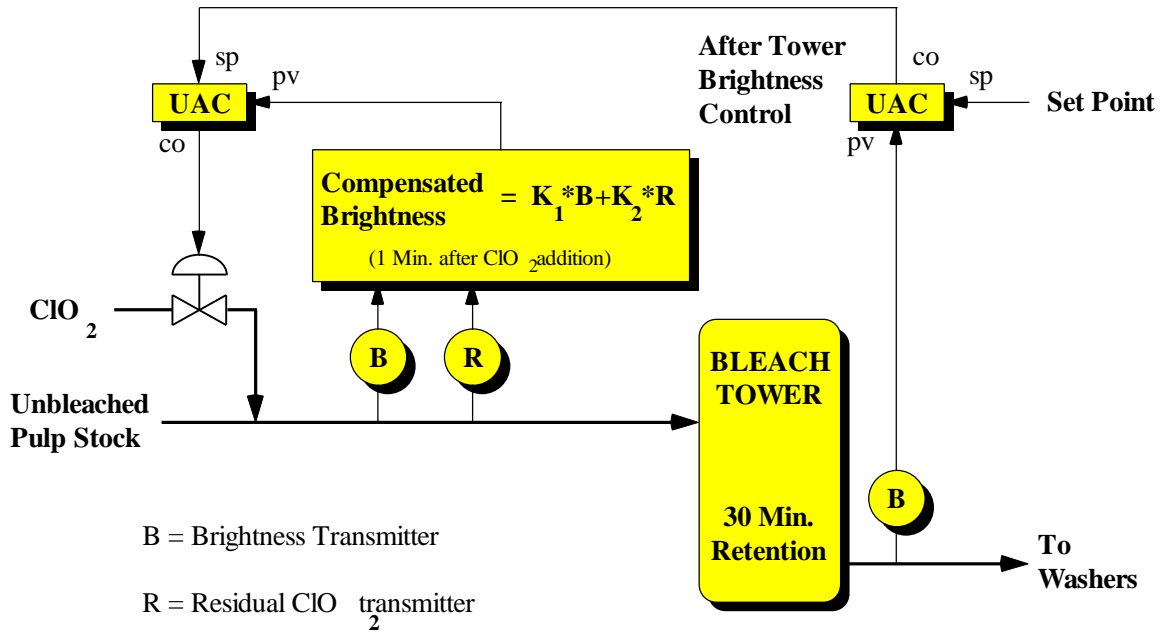


Figure 8. First Stage Pulp Brightness Control Schematic

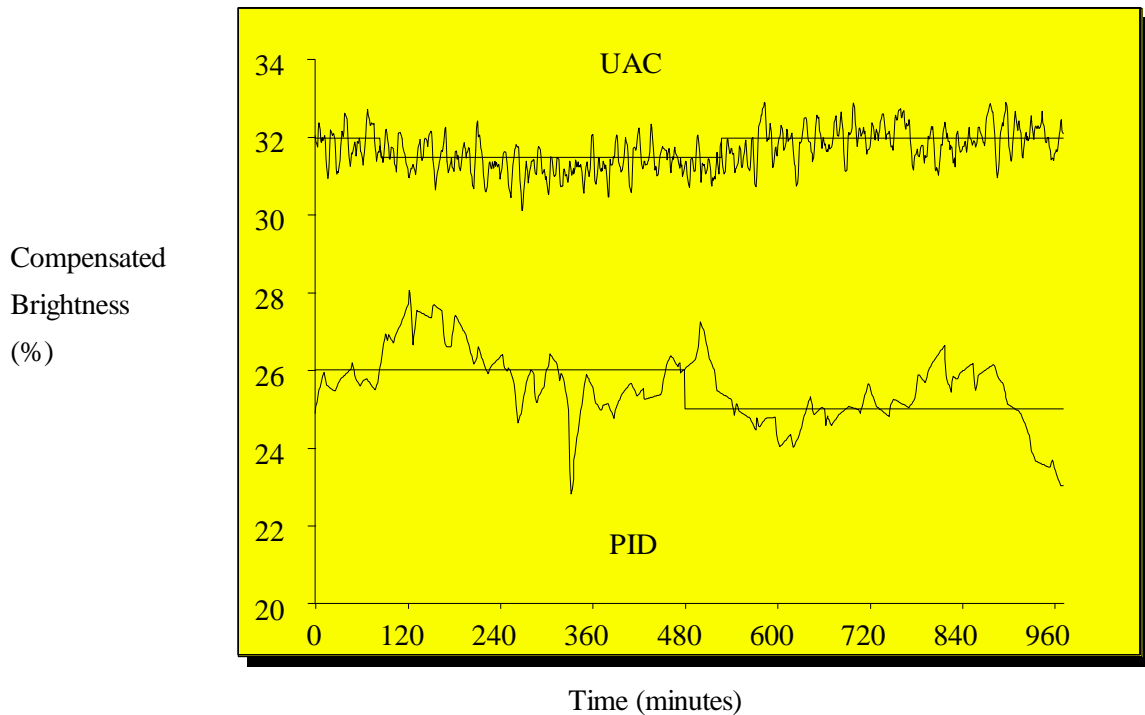


Figure 9. UAC versus PID Compensated Brightness Control (100% ClO_2)

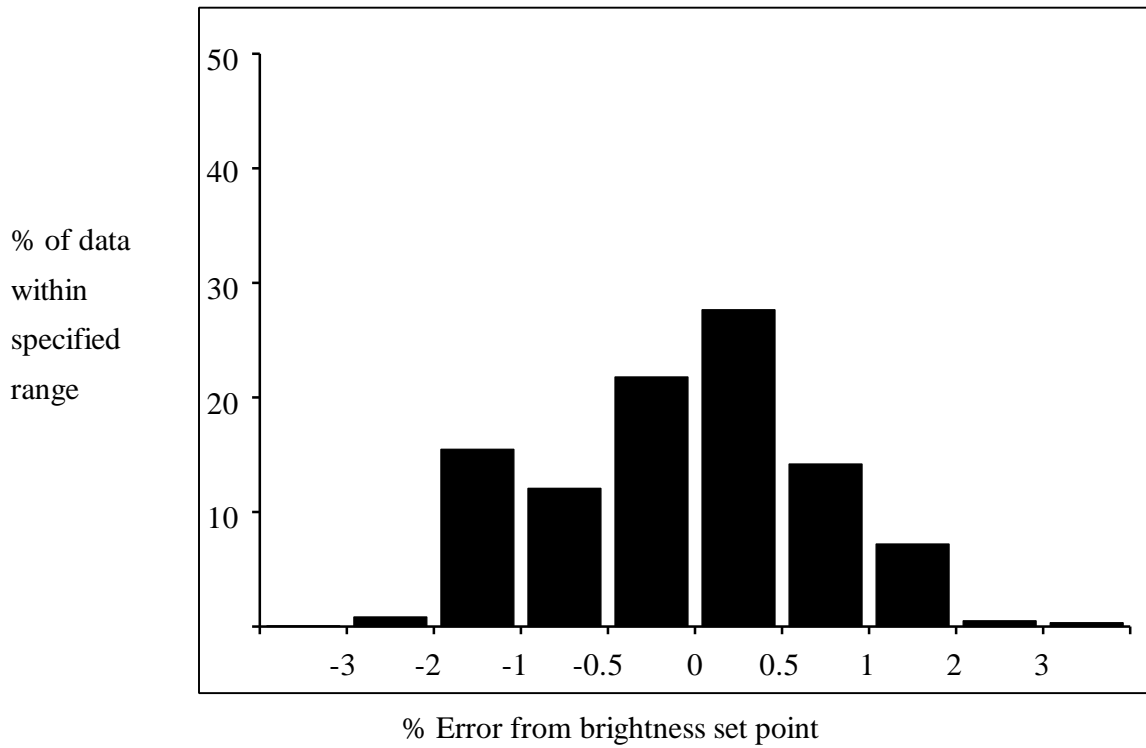


Figure 10. PID Distribution of Compensated Brightness Error from Set Point (100% ClO₂)

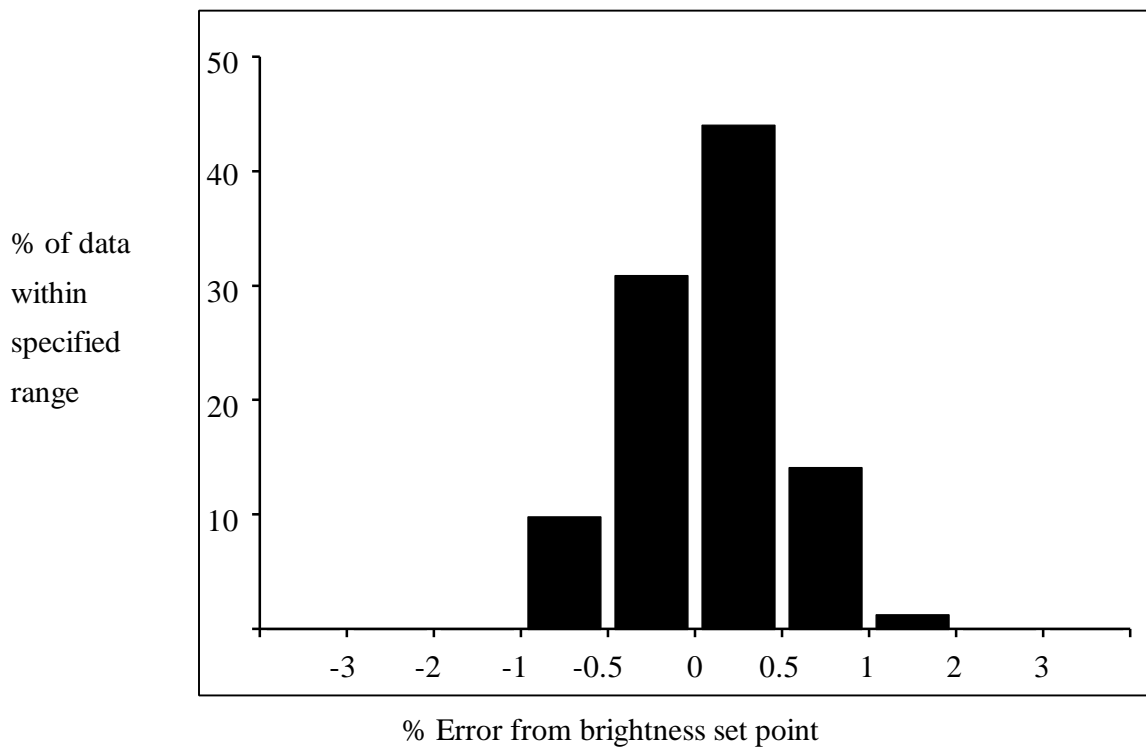


Figure 11. UAC Distribution of Compensated Brightness Error from Set Point (100% ClO₂)

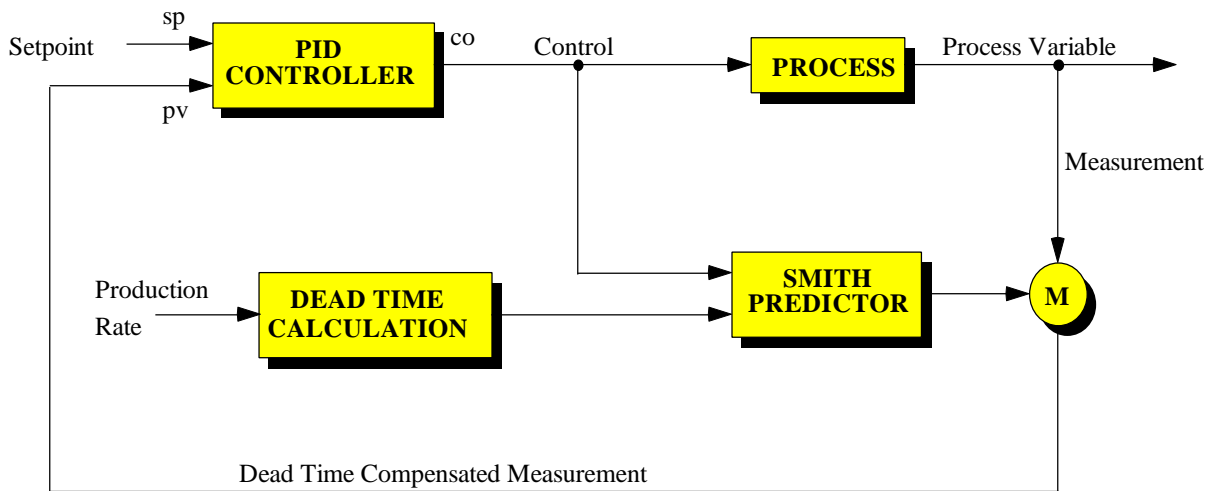


Figure 12. Smith Predictor Block Diagram

The after tower brightness control performance for the Smith Predictor PID controller and the UAC is shown in Figure 13.

The Smith Predictor PID had a standard deviation of 1.57 while the standard deviation of the UAC was 48.1% to lower at 0.81.

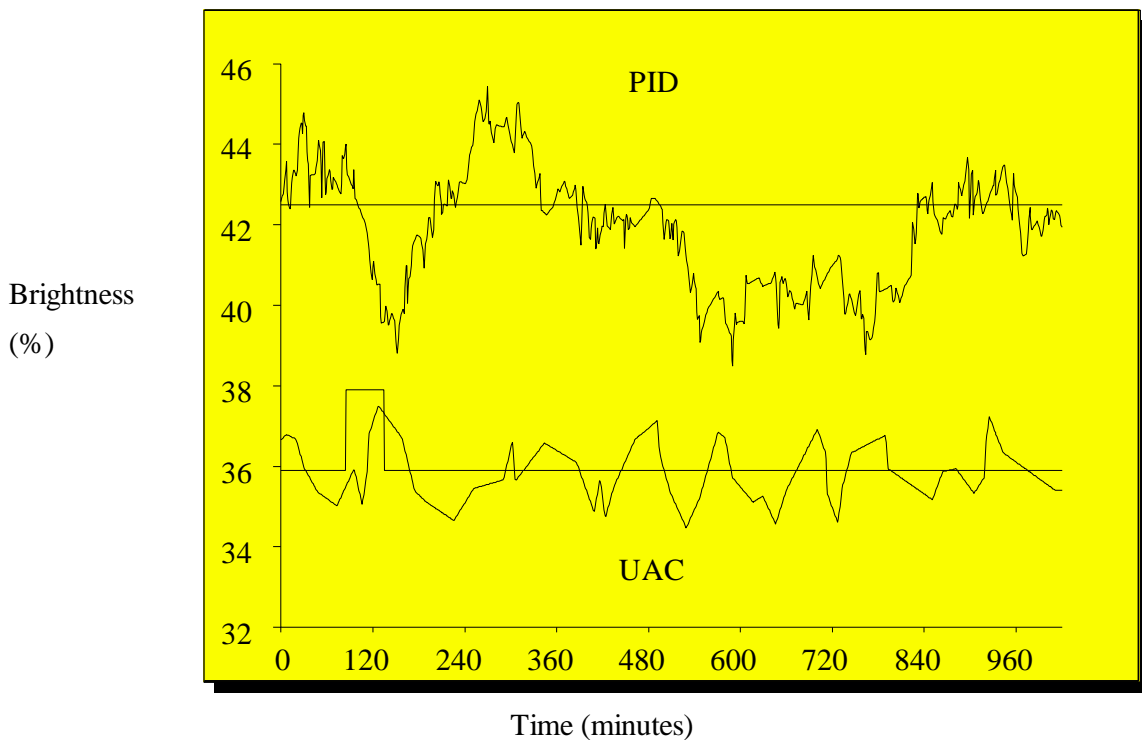


Figure 13. After Tower Brightness Performance

CONCLUSIONS

The Universal Adaptive Controller solves difficult control problems such as those caused by:

- long process time delays,
- non-linear process characteristics,
- changes in process gains and time constants.

The unique ability of the UAC to learn the process behaviour automatically and continuously ensures optimum process performance all the time. There is no need to re-tune the controller after it is started up. The problems of long development time, long set up time, repeated tuning and poor reliability associated with controllers such as Smith-Predictor PID and model-based controller designs are solved with the UAC.

The superior control performance of the UAC reduces product variability and enables the potential quality improvement benefits of supervisory and statistical process control systems to be realized.

The UAC is a new tool available for the control engineer to implement the continuous improvement concepts advocated by Deming ^[2] and Juran ^[3] in their Total Quality philosophies.

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