IMPLEMENTATION OF AN INNOVATIVE SELF-TUNING ADAPTIVE CONTROLLER FOR COMPLEX INDUSTRIAL PROCESSES

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ABSTRACT:

This paper describes the implementation of an adaptive controller based on a new control method developed at the University of British Columbia. The unique feature of this scheme is the use of an orthogonal function space to represent the plant transfer function as opposed to the model based approaches employed by previous adaptive control designs. The use of orthogonal filters permits rapid transfer function identification with a minimum of prior process information while maintaining robust control under a wide range of operating conditions. The mathematical model, the development of a computer algorithm and the results of testing at two industrial sites are presented.

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INTRODUCTION

Proportional-Integral-Derivative (PID) control has been the mainstay of process control for the past forty years. Today, the PID loop has advanced to include automatic self-tuning techniques and discrete computer control. However, there are many time-variant or non-linear processes with significant dead-times which PID controllers cannot control adequately.

Adaptive controllers offer a partial solution to these problems. Adaptive controllers approximate the plant transfer function by fitting observed process responses to a pre-determined mathematical model of the plant using an identification method such as Recursive Least Squares (RLS). The model is continuously updated to account for changes in process characteristics and can be designed to include the effects of process dead-time. However, these types of controllers require some exact knowledge of the plant transfer function. In most cases the plant time delay, phase characteristics and the number of poles and zeros must be determined before controller implementation.

A new adaptive control method developed at the University of British Columbia [1] uses an orthonormal series to represent the process transfer function. The main advantage of this approach compared to other adaptive control schemes is that it is not based on a pre-determined mathematical model and hence requires a minimum prior knowledge about the true plant dynamics. The controller is able to operate with only four initial parameters: an estimate of the plant time delay; an initial controller direction; a minimum number of filters required for plant identification; and a controller output clamping range.

UAC CONTROLLER ALGORITHM

The Universal Adaptive Controller (UAC) uses a Laguerre function series to model plant dynamics. The orthonormality of the function space provides rapid de-coupling of the filters which facilitates identification of the plant dynamics using data fitting techniques such as RLS. Laguerre functions are ideal for this application due to their simplicity and ability to represent transient signals.

There are three major steps in UAC control:

The State Update: The state update maps the controller output (u(t)) into Laguerre space so that the effects of past control actions can be taken into account.

$$\bar{l}(t+1)=A\bar{l}(t) + \bar{b}u(t)$$

where:

$\bar{l}(t)$ = state vector
A = Laguerre function matrix
$\bar{b}$ = Laguerre function vector
$u(t)$ = Controller output

The Parameter Estimation: This step uses a Kalman filter and Recursive Least Squares to estimate the coefficients (c(t)) of the state vector (l(t)).

$$\bar{K}(t) = \frac{P(t-1)\,\bar{l}(t)}{1 + \bar{l}^T(t)\,P(t-1)\,\bar{l}(t)}$$

$$\bar{c}(t) = \bar{c}(t-1) + \bar{K}(t) * \left(y(t) - \bar{c}^T(t-1) * \bar{l}(t) \right)$$

$$P(t) = P(t-1) - \bar{K}(t) * \bar{l}^T(t) * P(t-1)$$

where:
$\bar{K}(t)$ = Kalman Gain
$P(t)$ = Co-variance matrix
$\bar{c}(t)$ = Parameter estimation
$y(t)$ = Plant Output

The Control Update: This step uses the parameter estimation to determine controller output based on a prediction of future plant response.

$$u(t) = \left[Ysp - y(t) - \bar{K}^T * \bar{l}(t)\right] / B$$

where:

Ysp = Desired set point
y(t) = actual plant output
d = Prediction Horizon
$\bar{K}^T = \bar{c}^T(t) * (A^d - I)$,
$B = \bar{c}^T * (A^{d-1} + A^{d-2} + \ldots + I) * \bar{b}$

The following additional features were incorporated into the algorithm for application in an industrial environment:

RLS Exponential Forgetting and Resetting Algorithm (EFRA): There are many variations of the RLS Algorithm which exhibit different properties when used on-line (as in process control) for extended periods of time. The upper diagonal (UD) factorization algorithm [2] with an error-trace based forgetting factor [3] was used in the UAC during field trials at the Chlor-Alkali plant and initially at the Precipitated Calcium Carbonate (PCC) plant as it was recognized as one of the better RLS algorithms available at the time.

EFRA is a recently developed RLS method [4] which places upper and lower bounds on the trace of the co-variance matrix while maintaining a robustly valued forgetting factor. EFRA was implemented during subsequent trials at the PCC plant and demonstrated improved process transfer function identification compared to the UD algorithm. The EFRA algorithm is presently incorporated in the UAC as we consider it to be the best RLS algorithm (for this application) developed to date.

Feed Forward and Stochastic Filters: Feed forward compensation is designed to enhance the response of the controller to measured process disturbances in order to minimize the impact of the disturbance on the process. The UAC can accommodate up to three independent feed forward variables. Stochastic compensation accounts for the effects of unmeasured plant disturbances and inaccuracies in the process transfer function representation used in the UAC. Stochastic filters result in improved process identification. The feed forward and stochastic filters are implemented using the Laguerre series technique and extended RLS.

Controller Direction: It was determined experimentally that the initial UAC process transfer function identification could be substantially accelerated and that the magnitude of the controller output swings reduced by seeding the controller with an artificial set of control actions and process responses representative of the known process control direction. This technique is only applied during UAC initialization when the UAC is connected to the process for the first time. It should be noted that the UAC process transfer function identification will converge even if the seeded control direction is incorrect or unspecified.

Once the plant transfer function has been identified, the parameter estimates are stored at regular intervals. If there is a power failure, or if the controller is re-started, the stored estimates can be recalled to ensure a smooth start-up.

Controller Output Clamping: The control actions taken by the UAC during initial convergence of the process transfer function identification tend to swing resulting in undue process disturbance. A controller output limiting scheme was implemented in the UAC which imposes output range restrictions during both initial process identification and during subsequent long-term operation (if desired). This scheme was found to reduce process disturbances during initial convergence of the UAC without interfering with the identification of the process transfer function.

Parameter Estimation Bypass: In order to perform on-line identification, it is necessary that the UAC identification algorithm be provided with a continuous stream of data from the plant, relating changes in the process variable to changes in the control variable. To avoid using data which provides no useful information about the plant and to conserve computer processing time, the parameter estimation routine is suspended when any of the following conditions occur:

A. Controller Output or Process Variable Constrained: The identification algorithm would attempt to identify the process transfer function based on a control output which does not adequately excite the process (control output constrained) or on an inaccurate measurement of the actual process response (process variable constrained).

B. Process Shutdown: If the process is shut down, the control output may not be related to the observed changes in the process variable. The corresponding process transfer function identified would not be representative of the actual process under normal operating conditions.

C. Process Identification Accurate: If the controller is able to accurately predict process responses and the process variable is arbitrarily close to the set point then no benefit can be obtained from executing the parameter estimation routine.

The following information is required to implement the UAC on a particular process:

Number of Laguerre Filters: The number of Laguerre filters required to accurately represent the process transfer function depends on the plant complexity. Typically, five to eight filters are used for first and second order plants, while twelve to fifteen filters may be required for complex second (or higher) order plants.

Process Dead-Time Estimate: An estimate of the process dead-time is required to determine the control update interval and to ensure that the UAC will predict process response far enough into the future so that the effects of present control actions can be accurately anticipated. The process dead-time estimate must be longer than the actual dead-time but not longer than two to three times actual dead-time.

Controller Direction: The controller direction (direct or reverse acting) is easily determined for a given process. The controller direction information improves initial identification of the process transfer function.

UAC Output Clamping Range: This is an optional feature of the UAC which limits controller output swings during initial operation to minimize process disturbance.

INDUSTRIAL IMPLEMENTATION AT A CHLORINE PLANT

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, 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 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.

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.

The UAC controller was implemented on an XT compatible computer using analog I/O modules to interface with the existing pH sensor and acid addition control valve. A block diagram of the test loop is shown in Figure 1.

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 2. 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. 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.

Transient Results

Figure 3 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 PCC PLANT

The UAC controller is presently installed in a PCC plant. The batch process, indicated in Figure 4., involves the cooling of slaked lime slurry by passing it through a heat exchanger. The cooled lime slurry is finally passed into a carbonation tank where it is mixed with carbon dioxide resulting in the precipitation of the product, calcium carbonate (CaCO3), and the formation of water. A deviation of more than 0.2 degrees Fahrenheit from the desired temperature in the carbonation tank causes large deviations in the physical characteristics of the resulting precipitate. Therefore the slaked lime is cooled in two passes: the first cooling pass is used to step the temperature down closer to the final set point to facilitate greater control on the second pass; the second pass is used to bring the slurry temperature down to set point.

The main reasons this loop is difficult to control are:

- large gain changes between set points,
- slurry flow is controlled by tank head,
- cooling water head varies,
- cooling water temperature varies from 32oF to 80oF.

Prior to the installation of the UAC, the loop was controlled with a PLC PID card. Due to the differences in gain between high and low set points different sets of PID tuning parameters were used for the second pass. During the second pass the temperature of the cooling water is close to the lime slurry temperature, producing a long process dead-time which causes difficulty for the PID controller, resulting in oscillatory behavior at the lower set point as shown in Figure 5.

The UAC controller was implemented using a XT compatible computer communicating with the PLC. The UAC initialization parameters in this application were exactly the same as they were for the Chlor-Alkali plant except for the update period and initial estimate of the plant time delay.

UD Algorithm

At first, the UAC algorithm using the UD RLS was implemented at the plant. The improvement in performance over the existing PID controller is illustrated in Figure 6. The UAC controller was able to adapt to the gain changes between set points with little difficulty. It was found, however, that the offset seen at the end of the second pass deteriorated to as much as 3 degrees as more batches were processed. A measurement of the trace of the UD RLS co-variance matrix found that the value of the forgetting factor was causing the controller to gradually lose its ability to adapt to rapid gain changes. The new EFRA algorithm was implemented to see if any improvement could be realized in controller performance for gain changes after repetitive batches.

EFRA Algorithm

The results following the implementation of the EFRA algorithm are indicated in Figure 7. The increased robustness of the UAC resulted in a minimal temperature offset at the end of the second pass which was repeatable after several batches. The UD algorithm was permanently replaced by the EFRA algorithm in the UAC based on this field trial.

NEW APPLICATIONS

The UAC has been recently installed as part of a rotary lime kiln automation package which includes process set point optimization for reduced fuel consumption and improved lime quality. A total of seven UAC's are implemented in a single 386 personal computer together with an operator interface program which generates graphic controller faceplates for each UAC under the multi-tasking OS/2 operating system. The UAC is installed on the following process control loops: firing hood pressure, cooler fan, cooler level, and four cooler feeders. Initial results at the time of writing are good.

Installation of the UAC at a pulp mill to control power boiler drum level is planned for this Fall.

CONCLUSIONS

The UAC offers an effective alternative to self-tuning PID controllers in difficult process control applications. The Universal Adaptive Controller enables the control benefits possible with adaptive control to be realized using a single control algorithm without having to perform a complex analysis of process characteristics as required by previous adaptive controllers.

GLOSSARY

Adaptive control	- Control which can modify its behavior in response to changes in the dynamics of the process and the disturbances.
Forgetting factor	- Factor used in the parameter estimation to determine the weight assigned to the current plant measurements compared to the past measurements. A conservative forgetting factor assigns less weight to the current plant measurement than a robust forgetting factor.
Recursive Least Squares	- A method of performing ordinary least squares on a continuous discrete basis.
Orthogonal functions	- A series of functions which have the properties that when integrated by a multiple of itself the result is one, but if integrated by another function in the series the result is zero. This is in effect stating that the functions each have length one and are perpendicular to each other.
Prediction Horizon	- This is the period over which the adaptive controller bases its actions. The length must always be longer than the loop time delay.
Stochastic Control	- This type of control takes the error in the predicted model into account.

ACKNOWLEDGMENT

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BIOGRAPHY

David Lyon Graduated 1988 from the University of British Columbia with a B.A.Sc. in Engineering Physics. Worked with Trans Mountain Pipe Line Company in project management for one year before joining Universal Dynamics Limited in special projects.

Bill Gough   Graduated 1986 from the University of British Columbia with a B.A.Sc. in Electrical Engineering. Worked as a consulting engineer with Spectrum Engineering in Ontario for two years on various control and automation projects for the DND and the plastics industry, and performed reliability analyses of special safety systems at the Point Lepreau CANDU NGS. Joined Universal Dynamics Limited in 1988 as a staff engineer and has since completed several process control projects, primarily in the pulp and paper industry. Registered professional engineer in the Province of British Columbia.

Malcolm Cameron   Received B.A.Sc. in electrical engineering in 1976 and M.B.A. in 1988, both from the University of British Columbia. Employed by B.C. Hydro between 1976 and 1980 in Production and Substation Commissioning departments. Joined Universal Dynamics Limited in 1980 as a staff engineer. Became Manager of Computer Applications in 1987 and Vice-President in 1989. Responsible for design of power and control systems in electrochemical and grain handling industries. Member of Canadian Institute of Mining and Treasurer of Vancouver Section of IEEE.

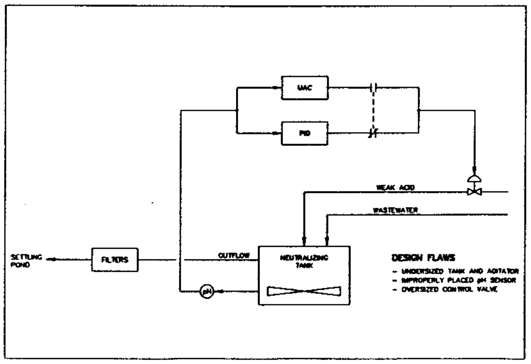

Figure 1. Chlor-Alkali Plant
pH Test Loop

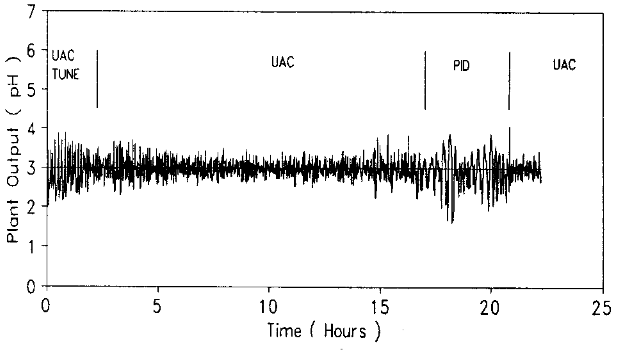

Figure 2. Chlor-Alkali Plant UAC Trials
Steady State Comparison

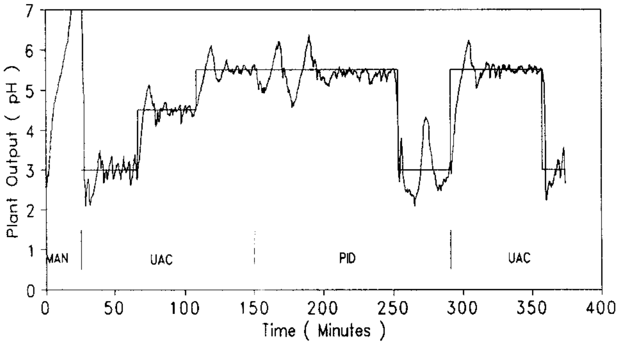

Figure 3. Chlor-Alkali Plant UAC Trials
Step Change Comparison

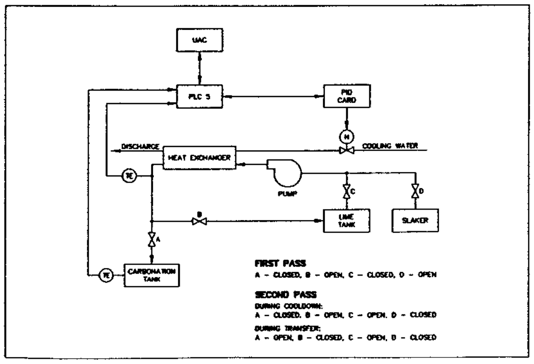

Figure 4. PCC Plant
Lime Slurry Test Loop

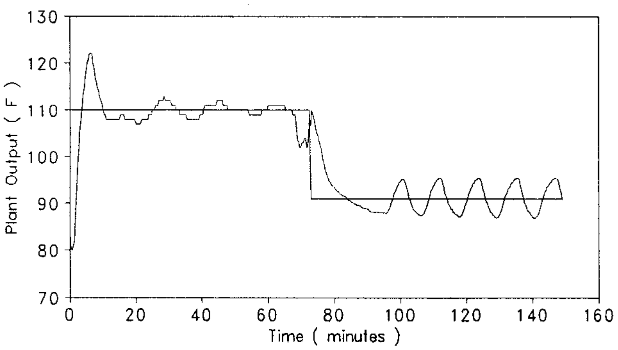

Figure 5. PCC Plant UAC Trials
Lime Slurry Cooling (PID)

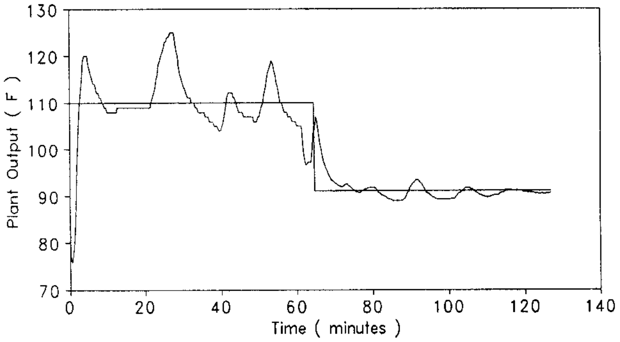

Figure 6. PCC Plant UAC Trials
Lime Slurry Cooling (UAC UD)

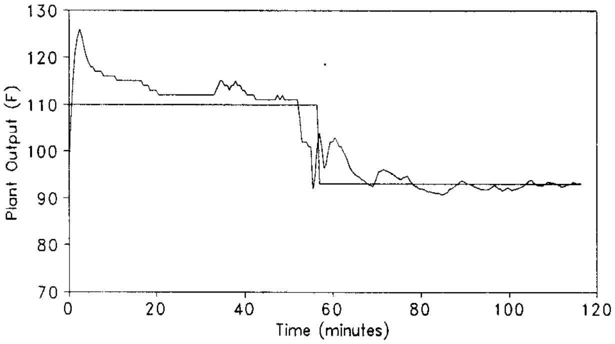

Figure 7. PCC Plant UAC Trials
Lime Slurry Cooling (UAC EFRA)