Industrial Temperature Control using an AFLC

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Abstract. A closed loop control system incorporating adaptive fuzzy logic has been developed for a class of industrial temperature control problems. A unique fuzzy logic controller (FLC) structure with an efficient realization and a small rule base that can be easily implemented in existing industrial controllers was proposed. It was demonstrated in both software simulation and hardware test in an industrial setting that the fuzzy logic control is much more capable than the current temperature controllers. This includes compensating for thermo mass changes in the system, dealing with unknown and variable delays, operating at very different temperature set points without retuning, etc. Also for auto-tuning the FLC adaptation mechanism is included in one of the input to fuzzy logic controller. It is achieved by implementing, in FLC, a classical control strategy and an adaptation mechanism to compensate for the dynamic changes in the system. The proposed FLC was applied to a temperature process and a significant improvement in the system performance is observed.

Keywords: Adaptive, Fuzzy Control, Temperature Regulation.

1 Introduction

While modern control theory has made modest inroad into practice, fuzzy logic control has been rapidly gaining popularity among practicing engineers. This increased popularity can be attributed to the fact that fuzzy logic provides a powerful vehicle that allows engineers to incorporate human reasoning in the control algorithm. As opposed to the modern control theory, fuzzy logic design is not based on the mathematical model of the process. The controller designed using fuzzy logic implements human reasoning that has been programmed into fuzzy logic language (membership functions, rules and the rule interpretation).

It is interesting to note that the success of fuzzy logic control is largely due to the awareness to its many industrial applications. An industrial interest in fuzzy logic control as evidenced by the many publications on the subject in the control literature has created an awareness of its increasing importance by the academic community. Starting in the early 90s, the Applied Control Research Lab. at Cleveland State University, supported by industry partners, initiated a research program investigating the role of fuzzy logic in industrial control. The primary question at the time was:

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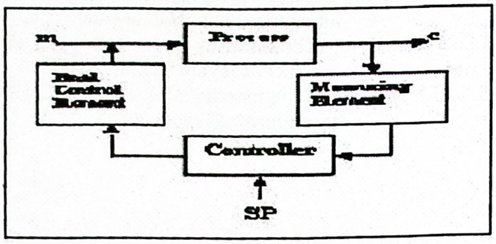
Industrial Informatics
Research in Computing Science 31, 2007, pp. 95-104

"What the fuzzy logic control does that the conventional control can not do?" The research results over the last few years have been reported in [1-5]. In this paper, we concentrate on fuzzy logic control as an alternative control strategy to the current PID method used widely in industry. Consider a generic temperature control application shown in Fig. 1:



m- Manipulated Variable, c- Controlled Variable, SP – Set point

Fig. 1: A typical Industrial Temperature Control problem

The temperature is measured by a suitable sensor such as Thermocouples, RTD, Thermistor, etc. and converted to a signal acceptable to the controller. The controller compares the temperature signal to the desired set point temperature and actuates the control element. The control element alters the manipulated variable to change the quantity of heat being added to or taken from the process. The objective of the controller is to regulate the temperature as close as possible to the set point. To test the new fuzzy logic control algorithms, two temperature regulation processes were used in this research.

One uses hot and cold water as manipulated variable and a valve as the controller element, the other uses electricity as a power source to a heater, actuated by a Solid State Relay (SSR). The new algorithms were tested extensively in both simulation and the hardware tests.

1.1 Motivation

Currently, the classical PID (Proportional, Integral and Derivative) control is widely used with its gains manually tuned based on the thermal mass and the temperature set point. Equipment with large thermal capacities requires different PID gains than equipment with small thermal capacities. In addition, equipment operation over wide ranges of temperatures (140° to 500°), for example, requires different gains at the lower and higher end of the temperature range to avoid overshoots and oscillation. This is necessary since even brief temperature overshoots, for example, can initiate nuisance alarms and costly shut downs to the process being controlled. Generally, tuning the Proportional, Integral, and Derivative constants for a large temperature control process is costly and time consuming. The task is further complicated when incorrect PID constants are sometimes entered due to the lack of understanding of the temperature control process. The difficulty in dealing with such problems is compounded with variable time delays existed in many such systems. Variations in manufacturing, new product development and physical constraints place the RTD temperature sensor at different locations, inducing variable time delays (dead time) in the system.

It is also well known that PID controllers exhibit poor performance when applied to systems containing unknown non-linearity such as dead zones saturation and hysteresis. It is further understood that many temperature control processes are nonlinear. Equal increments of heat input, for example, do not necessarily produce equal increments in temperature rise in many processes, a typical phenomenon of nonlinear systems. The complexity of these problems and the difficulties in implementing conventional controllers to eliminate variations in PID tuning motivate us to investigate intelligent control techniques such as fuzzy logic as a solution to controlling systems in which time delays, non-linearities, and manual tuning procedures need to be addressed.

1.2 The Time Delay Problem and Existing Solutions

To study the temperature control problem using classical control techniques, a simplified block diagram, in Fig. 2, is used, where C(s) represents the controller and $G(s)e^{-st}$ the plant with a pure time delay of τ. It is well known that the time delay makes the temperature loops hard to tune. The time delay problem may be characterized by *large* and *small* delays. A linear time invariant system with finite delay τ can be modeled as $G(s)\,e^{-st}$ where $G(s)$ is a rational transfer function of s. Note that the delay corresponds to a phase shift of $-wt$, where ω denotes the frequency. Small phase shifts at frequencies of interest may be viewed as perturbations and incorporated into a delay free design with sufficient phase margin. A large delay is classified as a delay that significantly affects the stability and phase margins to the point that delay free design methods will not be sufficient.

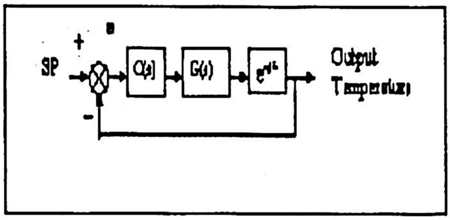


Fig. 2: A Closed Loop Temperature Control System

A number of time delay compensation and prediction schemes have been developed and/or improved with modifications as shown in [7-12]. The performance of Smith Predictor Control (SPC) was studied experimentally in [8]. It shows that the system performs well if the process model is accurate, but that performance degrades rapidly with inaccuracy in the process parameters and time delay. Clearly for an unknown or variable time delay, Smith predictive compensation is no longer a viable technique. Several control design methods for systems with varying time delays have appeared in recent literature including an estimation and self-tuning method proposed by Brone and Harris [10], a variable structure controller by Shu and Yan [11], and a model reference adaptive approach by Liu and Wang [6], to name a few. For systems with large time delays, most design approaches use a prediction mechanism as part of the controller to simulate the process for given system parameters and time delay. In the well known Smith predictor [7], the controller output is fed through models of the process with delay, and the process without delay, respectively. The difference of the output signals is added to the actual plant output and then fed back to the controller, thus allowing the controller to act on the prediction of the plant output.

1.3 Fuzzy Logic Control

Fuzzy control is an appealing alternative to conventional control methods when systems follow some general operating characteristics and a detailed process understanding is unknown or traditional system models become overly complex [6]. The capability to qualitatively capture the attributes of a control system based on observable phenomena is a main feature of fuzzy control. These aspects of fuzzy control have been demonstrated in various research literature, see [13-15, 16,17] and commercial products from vendors like Reliance Electric and Omron. The ability of fuzzy logic to capture system dynamics qualitatively, and execute this qualitative idea in a real time situation is an attractive feature for temperature control systems. The analytical study of fuzzy logic is still trailing its implementation and much work is still ahead, particularly in the area of stability and performance analysis. Furthermore, as solutions to practical problems, fuzzy logic control design is problem dependent and the adaptation of an exiting fuzzy logic controller to a different control problem is not straightforward. The available design tools, such as the Fuzzy Toolbox provided by Mathworks Inc., generally require further improvements before they become acceptable to control engineers. In this paper, the validity of fuzzy logic control as an alternative approach in temperature control applications is investigated.

2 Adaptive Fuzzy Logic Control Design

The FLC developed here is a two-input single-output controller. The two inputs are the deviation from set point *error,* $e(k)$, and *error rate,* $\Delta e(k)$. The FLC is implemented in a discrete-time form using a zero-order-hold as shown in Fig. 3a. The operational structure of the Fuzzy controller is shown in Fig. 3b.

2.1 Fuzzification / Defuzzification

Fuzzification and defuzzification involve mapping the fuzzy variables of interest to "crisp" numbers used by the control system. Fuzzification translates a numeric value for the error, $e(k)$, or error rate, $De(k)$, into a linguistic value such as positive large with a membership grade. Defuzzification takes the fuzzy output of the rules and generates a "crisp" numeric value used as the control input to the plant.

The FLC membership functions are defined over the range of input and output variable values and linguistically describes the variable's universe of discourse as shown in Figure 4. The triangular input membership functions for the linguistic labels zero, small, medium, and large, had their membership tuning center values at 0, 0.2, 0.35, and 0.6, respectively. The universe of discourse for both *e* and *De* is normalized from -1 to 1. The left and right half of the triangle membership functions for each linguistic label was chosen to provide membership overlap with adjacent membership functions. The straight line output membership functions for the labels zero, small, medium, and large are defined as shown in Fig. 4 with end points corresponding to 10, 30, 70, and 100% of the maximum output, respectively. Both the input and output variables membership functions are symmetric with respect to the origin.

Selection of the number of membership functions and their initial values is based on process knowledge and intuition. The main idea is to define partitions over the plant operating regions that will adequately represent the process variables.

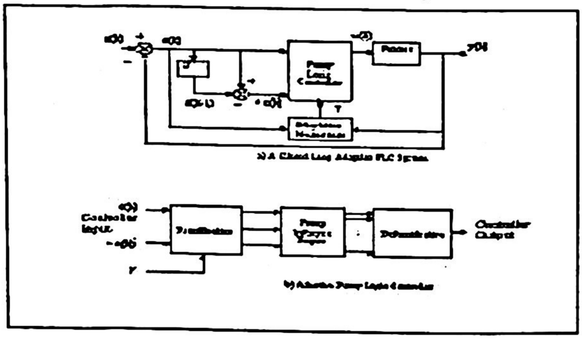


Fig. 3: Adaptive Fuzzy Control System

2.2 Rule Development

Our rule development strategy for systems with time delay is to regulate the overall loop gain to achieve a desired step response. The output of the FLC is based on the current input, *e(k)* and *De(k)*, and adaptation mechanism output γ without any knowledge of the previous input and output data or any form of model predictor. The main idea is that if the FLC is not designed with specific knowledge of mathematical model of the plant, it will not be dependent on it. The rules developed in this paper are able to compensate for varying time delays on-line by tuning the FLC output membership functions based on system performance. The FLC's rules are developed based on the understanding of how a conventional controller works for a system with a fixed time delay. The rules are separated into two layers: the first layer of FLC rules mimics what a simple PID controller would do when the time delay is fixed and known; the second rule layer deals with the problem when the time delay is unknown and varying.

In developing the first layer rules, consider the first order plant, $G(s)e^{-s\tau}$ where $G(s)\frac{a}{s+a}$. In the PID design, the following assumptions are made:

- The time delay τ is known

- The rise time, t_r, or equivalently, the location of the pole is known.
- t_r is significantly smaller than τ
- The sampling interval is T_s

The conventional PI-type controller in incremental form is given by:

$$u(k) = u(k-1) + f(e, \Delta e(k)) \qquad (1)$$

where $f(e,\Delta e)$ is computed by a discrete-time PI algorithm. This control algorithm was applied to a first order plant with delay. Using the Ziegler-Nichols method carried out initial tuning of PI parameters. The step response obtained has about a 20% overshoot for a fixed time delay. Next a fuzzy logic control law was set up where $F(e,\Delta e)$, the output of the FLC for the k_{th} sampling interval, replaces $f(e,\Delta e)$ in the incremental controller described in (1). The rules and membership functions of the FLC were developed using an intuitive understanding of what a PI controller does for a fixed delay on a first order system. They generalized what a PI controller does for each combination of e and Δe in 12 rules as shown in Table 1.

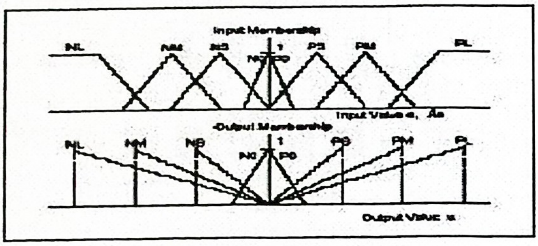


Fig. 4: Fuzzy Membership Functions

Table 1: FLC Control Rules

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="8">Δe</td></tr>
<tr><td>NL</td><td>NM</td><td>NS</td><td>NO</td><td>PO</td><td>PS</td><td>PM</td><td>PL</td></tr>
<tr><td rowspan="8">e</td><td>NL</td><td colspan="8">NL</td></tr>
<tr><td>NM</td><td colspan="5">NM</td><td colspan="3">PS</td></tr>
<tr><td>NS</td><td>X</td><td>X</td><td>X</td><td>NM</td><td>PS</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>NO</td><td colspan="8">NO</td></tr>
<tr><td>PO</td><td colspan="8">PO</td></tr>
<tr><td>PS</td><td>X</td><td>X</td><td>X</td><td>NS</td><td>PM</td><td>X</td><td>X</td><td>X</td></tr>
<tr><td>PM</td><td colspan="3">NS</td><td colspan="5">PM</td></tr>
<tr><td>PL</td><td colspan="8">PL</td></tr>
</table>

X – No Control Action

The output from each rule can be treated as a fuzzy singleton. The FLC control action is the combination of the output of each rule using the weighted average defuzzification method and can be viewed as the center of gravity of the fuzzy set of output singletons.

2.3 Tuning Membership Functions in Design Stage

Since there is little established theoretical guidance, the tuning of rules and membership functions in the design stage is largely an iterative process based on intuition. The number of membership functions can vary to provide the resolution needed. Note that the number of rules can grow exponentially as the number of input membership functions increases. The input membership functions for e and Δe generate 64 combinations, which can be grouped into twelve regions corresponding to each rule in Table 1. The center and slopes of the input membership functions in each region is adjusted so that the corresponding rule provides an appropriate control action. In case when two or more rules are fired at the same time, the dominant rule, that is the rule corresponding to the high membership grade, is tuned first. Modifying the output membership function adjusts the rules contribution relative to the output universe of discourse. Once input membership rule tuning is completed, fine-tuning of the output membership functions is performed to achieve the desired performance. Although this FLC is constructed based on the assumption that the time delay is fixed and known, the only element of the controller that is a function of the delay is the universe of discourse for the output. It is shown below that with some adjustment and extra rules, the FLC can be made to adapt to an unknown nature or change in delay.

2.4 Adaptation Mechanism

The FLC structure presented above can be directly modified to compensate for changes in the plant dynamics and variable time delays by adding a second layer of adaptation mechanism as one of the input to fuzzy inference engine of FLC. More details on adaptive methods can be found in [1,2].
In the case of varying time delay, the FLC gain must be adjusted to offset the effects of the changes in delay. It will be shown in Section IV that the maximum gain or control action is inversely proportional to the time delay. Therefore, if the delay increases, we should decrease the FLC gain to reduce the control action, and vice versa. Based on this relationship, the system performance can be monitored by a second layer of rules that adapts the output membership functions of the first layer of rules to improve the performance of the fuzzy controller.

The design strategy for the second layer of rules is based on two different aspects of tracking performance, i.e., rise time and overshoot calculated from $(e,\Delta e)$. The second layer rules are listed in Table 2. They monitor the plant response and reduce or increase the FLC controller output universe of discourse. The fuzzy membership functions are defined using a membership configuration similar to the control strategy in Figure 3. The adjustment rules perform two actions; they reduce the FLC gain when the plant is significantly overshooting the desired response, and increase the gain when rise time performance is slow.

Fuzzy logic control temperature control scheme is further tested in an industrial application where several components in a machine have to be temperature regulated. These components are of different thermo mass and may be regulated at different temperatures. Currently, a separate PID controller is tuned for each component at each temperature set point, which is quite labor intensive. Furthermore, the PID parameters need frequent adjustments due to the changes in operating conditions. The goal of fuzzy control is to replace this set of PID controllers with one self-tuning fuzzy controller and to eliminate the needs for further tuning, once the machine is in operation.

Table 2 : FLC Output Adaptation

Rise Time Rules If Tracking is L_1 then adjustment is L_2		Overshoot Rules If overshoot is L_3 then adjustment is L_4	
L_1	L_2	L_3	L_4
SS	PS	L	NL
MS	PM	M	NM
VS	PL	S	NS

3 AFLC APPLIED TO INDUSTRIAL PROCESS

3.1 Hardware Setup

A generic diagram of the process that applies to all components of the machine is shown below:

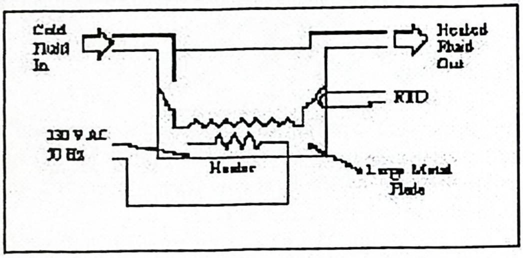


Fig. 5: An Industrial Temperature Control Application

This heating equipment of high temperature liquids has a large thick metal plate on the underside of the tank between the bottom and the inside of the tank, as shown in Fig. 5. It can be shown that this is a second order system with two thermal time constants. The first one correspond the thermal resistance from the heater to the plate and the plate heat capacity [1]. The second one comes from the thermal resistance of the plate to the material and the heat capacity of the material. There are many variations in the dynamics of the system. The thermo capacity is proportional to the size of the tank, which is quite different from one component to another. The time delay in the system is quite sensitive to the placement of the RTD. The heater can be found to be undersized or oversized. The heater on and off is controlled by a 24V pulse width modulated (PWM) signal applied to the SSR, as show in Fig. 6.

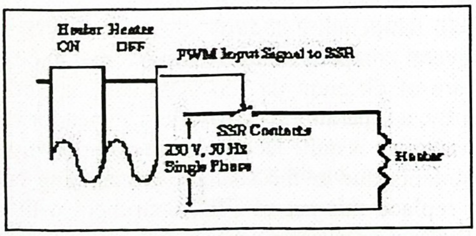


Fig. 6: Heater Excitation

3.2 Hardware Test Results

The proposed Adaptive fuzzy control algorithm was compared experimentally with the existing PID control used in industry. In this application, it is important to prevent over shoots, which seriously affect the quality of the product. It is also desirable to have a smooth control signal that does not require excessive on and off actions in the heater. The results are shown in Figure 7(a)(b)(c)(d). The top portion of each figure is a comparison of the PID vs. Adaptive Fuzzy temperature response, while the bottom portion is their respective heater *on times.* The Temperature Control Node was used to control the process for both controllers under the same conditions (i.e. same ambient temperature, delays, etc.). The results were obtained by actually controlling the process in its industrial setting.
The comparison of the performance of the FLC and PID controllers was performed under different set points, different thermal mass and different time delays. In each case, the FLC was able to successfully meet all design specifications without operator's tuning. On the other hand, it is a standard practice that for each of these different testing conditions, the PID controller needs to be manually tuned. Otherwise, the resulting response produced by PID controller would usually be unsatisfactory, as can be seen in Fig. 7(a)(b)(c)(d).

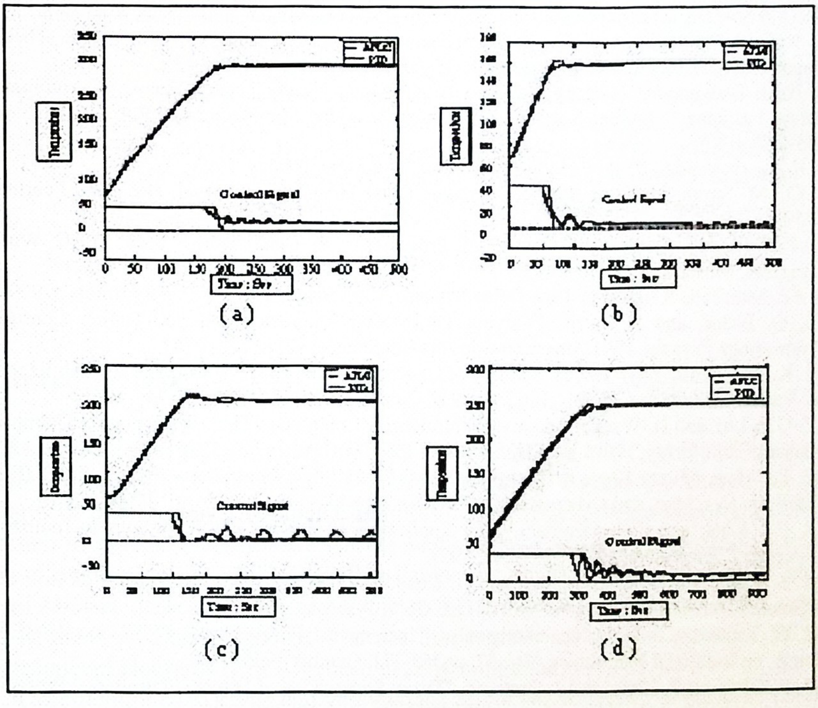


Fig. 7 : PID and Adaptive Fuzzy Control a) at High Temperature b) at Low Temperature c) with Time Delay d) with large Thermal Mass

4 Conclusions

Unlike some fuzzy controllers with hundreds, or even thousands, of rules running on dedicated computer systems, a unique AFLC using a small number of rules and simple scaling adaptation mechanism and straightforward implementation is proposed to solve a class of temperature control problems with unknown dynamics or variable time delays commonly found in industry. Additionally, the FLC can be easily programmed into many currently available industrial process controllers. The FLC was implemented for a tank temperature control problem. The results show significant improvement in maintaining performance. The AFLC also exhibits robust performance for plants with significant variation in dynamics.

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