Fuzzy Control to Non-Minimal Phase Processes

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Abstract: This paper presents a fuzzy control methodology to control non-minimal phase industrial processes. The integration between a simple fuzzy controller and Smith predictor gives a superior performance rather than using fuzzy logic controller only. The proposed fuzzy control methodology has been applied to control a fan and plate process in real-time environment. The process under consideration contains a rich dynamics: time constant, transportation lag, resonant poles, non-linear characteristics and air turbulence. The obtained results showed that the proposed control methodology gives a superior performance rather than the use of fuzzy control only without dead time compensation. This paper is organized as follows: section 1 presents the motivation to use a simple fuzzy controller with a dead-time compensation in order to improve the control loop performance. Section 2 is devoted to the development of a fuzzy control with dead time compensation. In section 3, the real-time application to control fan and plate process is demonstrated and the obtained results are presented. Some concluding remarks given in section 4 end the paper.

ملخص البحث: يقدّم البحث تصميم متحكم المنطقي المتباين للعمليات الصناعية ذات الطور الغير متناوب. التزايد بين متحكم المنطقي المتباين البسيط ومتوافق سيؤدي لنتائج أفضل من استخدام متحكم المنطقي المتباين وحده. تم تطبيق المتحكم المقترح عمليا على نموذج عملية صناعية للتحكم في زاوية ريشة معدنية من خلال تغير الجهد الداخلي لدرجة كهربائية. هذه العملية الصناعية غنية بمعالجات متعددة مثل الزمن الثابت والطور الغير متناوب. خصائص عبارة عن تلقائية التحكم. النتائج التي تم الحصول عليها أوضحت أن المتحكم المقترح الذي تم تطبيقه عمليا أعطى نتائج أفضل من تطبيق متحكم المنطقي المتباين وحده دون معالجة تأثير الطور الغير متناوب.

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1. Introduction

Dead time or transportation lag is a common part of many industrial processes. Dead time element adds phase lag to a feedback loop and could lead to unstable response. If a standard PID controller is used, significant de-tuning is required to preserve stability and system performance will be degraded. In many cases, particularly quality loops with long dead time, it may not even be possible to use PID control at all. Dead-time compensator is now available as a standard block in many commercial digital controllers. Smith predictor is developed in 1957 and is widely used in many industrial applications. Dahlin has developed the simplest one and independently by Higham in 1968. Vogel and Edgar also developed their algorithm in 1980. Garcia and Morari developed internal model control in 1982 [1]. All algorithms require the mathematical model of industrial processes, which may be inaccurate or unavailable for complex ones. Figure 1 shows the principle of smith predictor. Smith proposed the idea of dead-time compensation before process control computers were available to carry it out. The process model excludes the dead time of N samples. The output of the block is fed back to the controller, which then would be controlling the process without dead time. To correct for model error and unmeasured disturbances, the output of the model is delayed by N samples and subtracted from the actual controlled variable. The difference is added to the output of the model. In the absence of model error and disturbances, the difference will be zero [1].

![Diagram](image)

**Fig. 1. Feedback control with Smith predictor**

In last decade, fuzzy logic has increased attention for controlling equipment and systems to make them respond more intelligently to imprecise knowledge. Fuzzy control is a non-model base technique, it gives a good performance especially for controlling ill-defined or complex industrial processes. Fuzzy logic is developed by Loffi Zadeh to deal with uncertainty in system representation [2]. This logic has found a variety of applications in various fields ranging from sensors, motors, steam turbines, intelligent controllers, to medical diagnosis and decision making.
Mamdani and his research group developed the first attempts to control industrial processes using fuzzy logic [3] where ill-defined processes can be satisfactorily controlled using IF-THEN fuzzy rules. Fuzzy logic controller bases its decision on inputs such: (error, variation of error, ..., etc) in the form of linguistic variables derived from membership functions which are used to determine the fuzzy set to which a value belongs and its degree in that set. The variables are then matched with the IF-THEN rules, and the response of each rule is obtained through fuzzy inference. The response of each rule is weighted according to the confidence or degree of membership function of its inputs, and the centroid of responses is calculated to generate the appropriate controller output [4]. Figure 2 shows a simple fuzzy controller structure. It consists of four main blocks: Fuzzification, Knowledge base, Fuzzy inference and defuzzification. Fuzzification block converts crisp measurements into linguistic variables (fuzzy labels) into the universe of discourse. Knowledge base includes input/output membership functions and If-Then fuzzy rules. Fuzzy inference computes the corresponding fuzzy decision (action). Defuzzification block converts the fuzzy action into crisp value applied to the process [5].

![Fuzzy controller structure](image)

1.1 Fuzzification interface

The fuzzification interface consists of the following operations:

- Compute the input variables (crisp values of error and change of error).
- Perform a scale mapping that transfers the input variable ranges into a corresponding universe of discourse (Quantization/Normalizaion).
- Perform the fuzzification strategy that converts input crisp data into suitable linguistic variables that may be viewed as fuzzy labels.
The fuzzification strategy converts the crisp input data into fuzzy sets (linguistic variables) such as:

- PB: Positive Big
- PM: Positive Medium
- PS: Positive Small
- ZE: Zero
- NS: Negative Small
- NB: Negative Big
- NM: Negative Medium

The fuzzification action consists of a set of analog membership functions, describing the input linguistic terms. The membership function is assigned to give the semantics of a fuzzy variable. The membership function can be triangle-shaped, trapezoidal-shaped, etc.

1.2 Knowledge base

This block includes the input/output membership functions and the control rules. The dynamic behavior of a fuzzy system is characterized by a set of imprecise (If-Then) conditional statements that form a set of decision rules. The system model can be expressed linguistically as a set of linguistic decision rules.

There are four methods to derive fuzzy control rules:

- Referring to human operator's experience and/or control engineer's knowledge.
- Modeling the human operator's control actions.
- Using fuzzy model of the system.
- By learning which is so-called a self-organizing fuzzy controller [6-7].

Most fuzzy controllers have been designed by the first and second methods, mainly when an operator plays an important role in the control task. For the first method, fuzzy control rules provide a convenient way to express the human expertise. It is also possible for the control engineer to list his knowledge about the system to be controlled and his control engineering sense. This method cannot be used mainly when the operator cannot explain linguistically his knowledge. Also, it is difficult to derive the control rules from a control engineer's sense when the system is too complex.

1.3 Inference engine

The inference mechanism involves the following two functions:

- Determine for any fuzzy controller inputs (error and change of error) which rules are applicable.
- Determine the fuzzy control action by using fuzzy reasoning such as Mamdani's minimum operation, Larson's product operation, Tsukamoto and Takagi [8].
1.4 Defuzzification interface

The defuzzification interface consists of the following operations:

- Defuzzification strategy that converts the fuzzy control action into a crisp control action.
- Perform a scale mapping that converts the crisp control action from normalized universe of discourse into suitable ranges to be applied to the system (Dequantization).

The output of inference engine is a fuzzy set. As the system (or industrial process) usually requires a crisp control action, a defuzzification strategy is needed. However, there are three main methods to tackle this problem [9]. These methods are: maximum criterion method, mean of maximum method and the center of gravity method.

The simple fuzzy controller as shown in Figure 2 has a limited performance and cannot respond perfectly for processes with dead time. Therefore, this paper is motivated to introduce a fuzzy control methodology for controlling industrial processes that contain a significant dead time.

2. Fuzzy control with a dead-time compensation

The proposed fuzzy control methodology consists of two main parts: the former is a simple fuzzy controller structure as shown in figure 2 and the latter is a Smith predictor to compensate the effect of transportation lag. Figure 3. Presents the integration of fuzzy logic controller with smith predictor.

![Diagram of fuzzy control with dead time compensation](image)

Fig. 3. Fuzzy control with dead time compensation

Smith proposed the idea of dead time compensation before process control computers were available to carry it out. The output of the process model block is fed back to the controller, which then would be controlling the process.
without dead time. To correct for model error and unmeasured disturbances, the output of the model is delayed by \( N \) samples and subtracted from the actual controlled variable, and the difference is added to the model output [1]. In the absence of model error and disturbances, this difference will be zero. Usually, fuzzy controller do not use a mathematical model, while the Smith predictor requires it. In the proposed methodology, the required process model by Smith predictor is an approximate model, it obtained by taking the average of process parameters around different operating points. A set of reduced order models can be obtained by identification around different operating points to cover the region of process operation. The approximate process model can be constructed as the average values of process parameters in the form of first order or second order transfer function. The approximate dead time is \( N \) samples representing the average dead time for the obtained models around different operating points. A pre-filter can be used to exclude the high frequency noise measurements. The exponential filter is the standard filter used in digital control systems to attenuate a noisy signal [1]. It is an emulation of the original “R-C” low pass filter. The filter is a first order lag with unity gain. The digital filter is given by:

\[
y_n = a y_{n-1} + (1-a)x_n \quad ; \quad a = \frac{\tau_f}{T + \tau_f}
\]  

(1)

Where \( y_n \) is the filtered output at sampling instant \( n \), \( x_n \) is the noisy input at sampling instant \( n \), \( \tau_f \) is the filter time constant and \( T \) is the sampling period. Parameter \( a \) should be in the range \( 0 \leq a < 1 \). The reason why it is important that parameter \( a \) be positive and less than unity is that to preserve its stability and convergence to real data. In general, the filter dynamics should be faster than process dynamics under control. Process model can be approximated by the following first order system

\[
G(s) = \frac{k e^{-\tau_d s}}{1 + \tau s}
\]  

(2)

Where \( k \) is the steady state gain
\( \tau_d \) is the dead time
\( \tau \) is the process time constant

Therefore, the parameter \( a \) should be selected in order to \( \tau_f \ll \tau \). This makes the closed loop system dynamics will be dominated by process dynamics itself.
3. Application

3.1 Fan & Plate Process

The process consists of a hinged rectangular plate and a variable speed electrical fan as illustrated by the given block diagram in Figure 4. The process is fabricated in our department using cheap components in the market. Blowing an air stream at the plate with a variable speed fan controls the plate orientation angle. A. dc motor drives the fan and the plate rotation angle is measured with a low friction potentiometer. The fan and its motor are mounted on a slide. This process has a rich dynamics: fan motor constant, air transportation lag, resonant poles, and air turbulence. It is also easy to change the dominant parameters (time constant and dead time). By varying the position of the fan relative to plate, the dead time then will be changed. The dead time is proportional with the distance between the electrical fan and the plate stand. Small magnetic weights can be placed on the hinged plate before or during a control experiment. These weights change the dominant time constant and also act as load disturbance. The air turbulence around the plate naturally provides the stochastic disturbance. Therefore, this process is a versatile pilot plant for studying the effects of parameter changes. Similar dynamics are also accounted in aerospace vehicles and chemical reactors.

Fig. 4. Fan & Plate process

3.2 Control environment

The process can be controlled manually or by a digital controller implemented on a PC microcomputer through an interface ADDA card. Figure 5 shows the digital control environment.

Fig. 5. Digital control environment

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The microcomputer is used to implement the digital control algorithms using C++. The interface is implemented by using ADDA card. The signal conditioning box uses a voltage regulator to protect the ADDA card from the maximum measured output voltage by the potentiometer. It also used to modify the analog output signal from the ADDA card (0-10 volt) into (0-24 Volt) to be applied to the motor of the fan. The manual box has a switch to toggle between manual and computer control experiment.

3.3 Experimental results

First, we have applied fuzzy control without any numerical identification to process parameters. That means a simple fuzzy controller is used in feedback as in Figure 2. The control objective is to track the desired set point of plate angle. Seven fuzzy sets are used to fuzzify the error and five fuzzy sets are used for error variation. Five fuzzy sets are used to defuzzify the control action. Triangular membership functions are used for all fuzzy sets. The obtained result is given in figure 6. We observe that the tracking objective is achieved. It is clear that the response is delayed due to the dead time involved in the process behavior. An external disturbance is emulated by adding a weight on the plate at the instant (54 sec). The disturbance signal is unstructured and can be considered as an small duration energy type signal (pulse) just to excite the system dynamics. It is shown that the objective is achieved well. A steady state error is obtained because the process is type zero and the fuzzy controller is equivalent to a nonlinear PD controller. However, adjusting the controller gain can reduce the steady state error.

Second, we identify the process model around different operating points using reaction curves (step response). The identification results are given in the table below.

<table>
<thead>
<tr>
<th>$K$ (volt/volt)</th>
<th>$\tau_d$ (sec.)</th>
<th>$\tau$ (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.17</td>
<td>3.78</td>
<td>0.84</td>
</tr>
<tr>
<td>0.2</td>
<td>6.72</td>
<td>1</td>
</tr>
<tr>
<td>0.19</td>
<td>8.4</td>
<td>5.04</td>
</tr>
<tr>
<td>0.136</td>
<td>10.92</td>
<td>6.72</td>
</tr>
</tbody>
</table>

These results indicate that the process is a nonlinear and includes a significant dead time. The average model for smith predictor can be obtained by tacking the average value for each parameter. This gives the following model ($K = 0.174$, $\tau_d = 7.455$ and $\tau = 3.4$). The pre-filter is designed by selecting $a = 0.9$. The sampling time is 0.1 second. Using equation (1), $\tau_r$ is equal to $0.9 < \tau$. The following figure represents the obtained results. We observe that the response is faster than
the previous case due to compensation of the dead time. Tracking and regulation objectives are achieved.

Fig. 6. Simple fuzzy control results

Fig. 7. Fuzzy control with dead time compensation

4. Conclusions

In this paper, a fuzzy control methodology is proposed to control non-minimal phase processes. The idea is based on the use of a Smith predictor to compensate the dead time with a simple fuzzy controller structure. This method is applied to a fan and plate process in a real time environment. The process is nonlinear with a significant dead time parameter. The obtained results affirmed that the proposed control methodology has the potential to achieve well the tracking and regulation objectives. It also speeds up the output response and decreases the effect of dead time parameter.
References


