Design of Self-Tuning Fuzzy Logic Controller

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Abstract: During the past several years fuzzy control has emerged as one of the most active and fruitful areas of research in the field of control engineering especially, in the realm of industrial processes. Fuzzy control, based on fuzzy logic is a logical system which incorporates human thinking rather than traditional analytical methods. Therefore, this paper aims to explore the utility of this control strategy by developing a simple self-tuning scheme for a Fuzzy Logic Controller (FLC). Here, the input gains viz. GE (proportional error gain) and GDE (derivative error gain), are adjusted on-line by fuzzy rules according to the current trend of the controlled process. The rule base for tuning the input gains is defined on error (E) and rate of change of error (DE) of the controlled variable. This self-tuning scheme is implemented on a pressure process, and it’s performance is compared with a PID controller and a conventional FLC in terms of time domain measures such as rise time, % overshoot, settling time and % steady state error. The self-tuning scheme shows improved performance in terms of zero percentage overshoot.

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Keywords: Control engineering, Fuzzy control, Self-tuning, Fuzzy logic controller, Pressure process.

1. Introduction

Fuzzy logic has rapidly become one of the most successful of today’s technologies for developing sophisticated control systems. With its aid, complex requirements may be implemented in amazingly simple, easily maintained, and inexpensive controllers. The same fuzzy technology, in the form of approximate reasoning, is also resurfacing in information technology, where it provides decision-support and expert systems with powerful reasoning capabilities bound by a minimum of rules [1].

While modern control theory has made modest in-roads 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 into 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 can be programmed into fuzzy logic language (membership functions, rules, and the rule interpretation) [2].

Fuzzy logic provides an alternative approach which allows one to design a controller using a higher level of abstraction without knowing the plant model. This capability makes the fuzzy logic controller very attractive for ill-defined systems or systems with uncertain parameters. Nowadays, it is very common to say that fuzzy logic controllers rely on a computational structure, which includes the fuzzification of the input variables, the inference or rule firing, the de-fuzzification of the controller output variables [3].

The fuzzy logic controller (FLC) based on fuzzy logic provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy [4]. An FLC may be
regarded as a means of emulating a skilled human operator. More generally, the use of an FLC may be viewed as still another step in the direction of modelling human decision making within the conceptual framework of fuzzy logic and approximate reasoning [5].

Industrial interest in fuzzy logic control as evidenced by the many publications on the subject in control literature has created an awareness of its increasing importance in the academic community [2].

This paper concentrates on fuzzy logic control as an alternative to the PID control strategy which is widely used in industry, and explores the utility of a fuzzy logic control system with a self-tuning scheme. This scheme which tunes process parameters online, has been used to control industrial control processes such as paper machine, heat exchanger etc. [6]. The following papers help to understand this concept in greater detail.

[7] proposes a simple but robust model independent self-tuning scheme for fuzzy logic controllers (FLC’s). Here, the output scaling factor (SF) is adjusted on-line by fuzzy rules according to the current trend of the controlled process. Performances of the proposed self-tuning FLC’s are compared with those of their corresponding conventional FLC’s in terms of several performance measures such as peak overshoot, settling time, rise time, integral absolute error (IAE) and integral-of-time multiplied absolute error (ITAE), in addition to the response due to step set-point change and, in each case, the proposed scheme shows a remarkably improved performance over its conventional counterpart.

In [2], closed-loop control system incorporating 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. The potential of FLC in both software simulation and hardware test in an industrial setting was demonstrated. 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. It is achieved by implementing, in the FLC, a classical control strategy and an adaptation mechanism to compensate for the dynamic changes in the system. The proposed FLC was applied to two different temperature processes and performance and robustness improvements were observed in both cases.

The steam temperature during the extraction process has a great influence on the essential oil quality. Lately, many of the research efforts are seen trying to develop a new control technique to regulate the steam temperature. However, PID is noted to have a simple structure, very straight forward implementation and ease to handle especially when deal with the industrial process. But, the challenges during design the PID is to tune the PID parameters gain that suite to the plant. To overcome this problem, in [8], the online tuning PID using the fuzzy logic controller with self-tuning method is utilized to regulate the steam temperature. From the result, the performance of self-tuning fuzzy PID (STFPID) demonstrated good improvement in terms of process dynamic characteristics which are process rise time, process settling time, percentage overshoot and steady state error. In this work, the proposal control technique has shown the ability to track any parameters changes and have fast recovery the output response during disturbance period.

The temperature control system is increasingly playing an important role in industrial production. Recently, lots of researches have been investigated for the temperature control system based on various control strategies. Hence, in [9], a temperature control system based on fuzzy self-tuning PID is proposed. The new algorithm based on fuzzy self-tuning PID can improve the performance of the system. Also, it's fit for the complicated variable temperature control system. The simulation results show that the validity of the proposed strategy is more effective to control temperature.

[10] presents a fresh air system with solar collectors and LHTS (Latent Heat Thermal Storage). It can not only keep indoor air good quality, but also supply part of heat for rooms. In addition, it has an advantage of energy-efficient and will not cause extra air-conditioning load when the system is used in conjunction with air-conditioning system. For the nonlinearity and hysteresis of the system, it is difficult to find a precise mathematical model. Consequently, fuzzy logic control algorithm can be used to realize the fresh air temperature control in the system. In consideration of the PID controllers’ good performance to minimize the steady state error of the system, a self-tuning-parameter fuzzy PID controller was designed in this paper. Result from experiments shows that the self-tuning-parameter fuzzy PID controller has superior control performance in fresh air temperature control system compared to a conventional PID controller.

The temperature control system has the characteristic of non-linearity, large inertia and time variability. It is difficulty to overcome the effects of these factors and get the satisfactory results with using the normal PID controller. Therefore, a self-adaptive PID controller based on fuzzy is adopted in [11]. By the means of adjusting the adjustable factors on line, it can optimize the control process continuously, so that the fuzzy control system has a strong self-adaptive capacity. The simulation results show that the fuzzy self-adaptive PID controller has good robustness, rapidity and good dynamic performance.

In [12], temperature monitoring of sterilizing equipment system was established with the help of fuzzy and self-tuning fuzzy logic controller designed in LabVIEW software. It combines the advantages of both fuzzy logic and self-tuning fuzzy logic.
controller. The implementation attempts to rectify the errors between the obtained value and the given point which helps to achieve efficient temperature control. With the help of the rules the fuzzy controllers manage the system depend on the obtained values and the difference in the both temperature (errors). The simulation results presented in order to evaluate the proposed method. From the result the self-tuning fuzzy logic controller was forbearing to any kind of interruption and the temperature control is most accurate.

[13] presents a hybrid classical/fuzzy control methodology to integrate low-level machine control and high-level supervision for the steam temperature and water level processes of the power plant boiler. The coupling between two spraying systems can be reduced using hybrid coarse-fine intelligent control with qualitative decoupling strategy. A hierarchical fuzzy system is used for the water level control, instead of the human operator or the proportional integral derivative (PID) control. Industrial applications show the superiority of the proposed intelligent control over the traditional methods.

Self-tuning is being extensively used for industrial research is advantageous since this doesn’t require the modelling of the system. This paper evaluates the self-tuning scheme for a real-time system.

The paper is organized as, Section II highlights the system design. Section III describes the system hardware. Section IV describes the FLC design. Section V presents the results of the implementation. Finally, Section VI, the conclusion provides final remarks about the implementation.

2. System Design

Fig. 1 shows the overall system setup. The pressure process station is interfaced to a computer via USB serial communication.

The pressure of air in the process tank is given as an input to the Data Acquisition Device (DAQ) and the voltage output taken from DAQ is converted to current by using a voltage-to-current (V/I) converter and fed to the actuator i.e. the pneumatic control valve after converting into pressure levels (3-15 psi). NI USB-6221 DAQ plays the role of an interface unit between the pressure process and the computer.

Fig. 2. highlights the process and instrumentation diagram (P&ID) of the pressure process station.

3. System Hardware

3.1. Process Tank

A 3.11 litre with 14.08 cm diameter, closed cylindrical tank is used as a process tank. The tank has two connections for air. The pressure of the tank is maintained by controlling the outlet airflow by pneumatic control valve. Air is entering in the tank through inlet connection. The tank is also provided a drain connection with vent valve.

3.2. Pressure Transmitter

A two-wire pressure sensor transmitter is mounted on the pressure tank. The pressure inside the tank is sensed and transmitted to the interfacing unit for displaying the process value and communicating to the computer for control. This is the device used to transmit data from a sensor over the two-wire current loop. There can be only one Transmitter output in any current loop. It acts like a variable resistor with respect to its input signal and is the key to the 4-20 mA signal transmission system.

The transmitter converts the pressure signal into the control signal necessary to regulate the flow of current in the current loop. The level of loop current is adjusted by the transmitter to be proportional to the actual sensor input signal. An important distinction is that the transmitted signal is not the current in the loop, but rather the sensor signal it represents. The transmitter typically uses 4 mA output to represent the calibrated zero input or 0 %, and 20 mA
output to represent a calibrated full-scale input signal or 100%.

An important distinction of 2-wire transmitters is that they have their power supply and signal sharing the same pair of connection wires. This simplifies installation considerably, and the low DC transmission levels permit the use of small, inexpensive copper wiring [14].

Table 1 summarizes the technical specifications of the pressure transmitter.

### Table 1. Technical specifications of the Pressure transmitter.

<table>
<thead>
<tr>
<th>Operating range</th>
<th>10-30 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>0-6 bar</td>
</tr>
<tr>
<td>Output</td>
<td>4-20 mA</td>
</tr>
</tbody>
</table>

### 3.3. Control Valve

A pneumatic air to close control valve is supported on the support plate controls the outlet air flow from the pressure tank. It is one of the most common final control elements. They are designed such that if the air supply fails, the control valve will be fully open.

Table 2 summarizes the technical specifications of the pressure transmitter.

### Table 2. Technical specifications of the Control valve.

<table>
<thead>
<tr>
<th>Model</th>
<th>MX 101</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>¼” x ¼”</td>
</tr>
<tr>
<td>Actuator</td>
<td>10 sq. inch</td>
</tr>
<tr>
<td>Stroke</td>
<td>10 mm</td>
</tr>
<tr>
<td>Action</td>
<td>air to close</td>
</tr>
</tbody>
</table>

### 3.4. Current to Pressure (I/P) Converter

A WAAREI IPW 400X I/P converter receives signal from the computer through interface unit i.e. NI USB-6221 DAQ. It converts an analog signal (4 to 20 mA) to a proportional linear pneumatic output (3 to 15 psi). Its purpose is to translate the analog output from a control system into a precise, repeatable pressure value to control the pneumatic control valve.

Table 3 summarizes the technical specifications of the I/P converter.

### Table 3. Technical specifications of the I/P converter.

<table>
<thead>
<tr>
<th>Input</th>
<th>4-20 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>3-15 psi</td>
</tr>
<tr>
<td>Supply</td>
<td>18-100 psi</td>
</tr>
</tbody>
</table>

### 3.5. Data Acquisition Device

Thus a DAQ is required to get the real-time data from the pressure sensor. In this paper NI USB-6221 is used as a DAQ.

The NI USB-6221 is a bus-powered USB M Series multifunction data acquisition module optimized for superior accuracy at fast sampling rates. It offers 16 analog inputs; 250 kS/s single-channel sampling rate; two analog outputs; four digital input lines; four digital output lines; four programmable input ranges (±0.2 to ±10 V) per channel; digital triggering; and two counter/timers.

The NI USB-6221 module is designed specifically for mobile or space-constrained applications. Plug-and-play installation minimizes configuration and setup time, while direct screw-terminal connectivity keeps costs down and simplifies signal connections. NI DAQ also supports DMA like bidirectional function [15].

Fig. 3 highlights the data acquisition process.

### 4. Fuzzy Logic Controller Design

#### 4.1. Self-tuning Scheme

An FLC is called adaptive if any one of its parameters viz. scaling factors (SFs), membership functions (MFs), and rules changes when the controller is being used [7]. In this paper, the designed controller is tuned by modifying the input gains viz. GE and GDE.

#### 4.2. Conventional FLC

First a conventional FLC designed and tested in real time. Fig. 4 shows the structure of a conventional FLC without self-tuning, where E (error) and DE (rate of change of error) are the input to the FLC.
Fig. 4. Structure of conventional FLC.

Fig. 5 shows the real-time implementation of the conventional FLC using the DAQ Assistant function block, in order to interface the designed controller in software with the pressure process.

![Control & Simulation Loop](image)

Fig. 5. Real-time implementation of Conventional FLC.

Table 4 shows inference rules for the conventional FLC, where:

- **E** - Error
- **DE** - Rate of change of error
- **U** - Controller output
- **N** - Negative
- **Z** - Zero
- **P** - Positive

**Table 4.** Inference rules for Conventional FLC.

<table>
<thead>
<tr>
<th></th>
<th>E</th>
<th>N</th>
<th>Z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>U</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td></td>
<td>N</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>Z</td>
<td>P</td>
<td>Z</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>N</td>
<td>P</td>
<td>Z</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6 shows the membership functions of E, DE and U in the conventional FLC.

![Membership functions of E in conventional FLC](image)

**Fig. 6a.** Membership functions of E in conventional FLC.

![Membership functions of DE in conventional FLC](image)

**Fig. 6b.** Membership functions of DE in conventional FLC.
4.3. Self-tuning FLC

Fig. 7 shows the structure of a self-tuning FLC. GE and GDE are the proportional and derivative error gains respectively.

Fig. 8 shows the implementation of self-tuning FLC using the DAQ Assistant function block, in order to interface the controller designed in software with the pressure process.

Table 5 shows inference rules for the conventional FLC, where:
E - Error
DE - Rate of change of error
GE - Proportional error gain
GDE - Derivative error gain
U - Controller output
Z - Zero
M - Medium
B - Big

Table 5a. Inference rules for Self-tuning FLC.

<table>
<thead>
<tr>
<th>E</th>
<th>N</th>
<th>Z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>U</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>N</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td>Z</td>
<td>N</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>N</td>
<td>P</td>
<td>N</td>
</tr>
</tbody>
</table>

Table 5b. Inference rules for tuning GE.

<table>
<thead>
<tr>
<th>E</th>
<th>N</th>
<th>Z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>GE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>Z</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>Z</td>
<td>M</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>B</td>
<td>B</td>
<td>Z</td>
</tr>
</tbody>
</table>

Table 5c. Inference rules for tuning GDE.

<table>
<thead>
<tr>
<th>E</th>
<th>N</th>
<th>Z</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>GDE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>B</td>
<td>B</td>
<td>Z</td>
</tr>
<tr>
<td>Z</td>
<td>B</td>
<td>Z</td>
<td>Z</td>
</tr>
<tr>
<td>P</td>
<td>Z</td>
<td>M</td>
<td>Z</td>
</tr>
</tbody>
</table>

Fig. 9 shows the membership functions of E, DE, GE, GDE and U in the self-tuning FLC.
5. Results

This section presents the results of the implementation of the self-tuning FLC and compares it with conventional FLC and PID controllers.

Fig. 10 shows the step response of the pressure process when controlled by a conventional FLC. From the curve, we can see that the rise time is 30.07 seconds. The process settles in 83 seconds with a percentage steady-state error of -1.69%.

Fig. 11 shows the step response of the pressure process when controlled by a self-tuning FLC. From the curve, we can see that the rise time is 57.9 seconds. The process settles in 100 seconds with a percentage steady-state error of 2.63%.

Fig. 12 compares the step responses of the pressure process when controlled by a PID, conventional FLC and self-tuning FLC respectively. Table 6 summarizes the response of the pressure process when controlled by a PID controller, a conventional FLC and a self-tuning FLC. From the data obtained, we infer that though the self-tuning FLC is slower than the PID controller, it completely eliminates peak overshoot as compared to the 6.7% peak overshoot of the PID controller.
7. Conclusions

A smart controller is designed for the real-time pressure process system by adopting the self-tuning fuzzy logic control strategy. First a conventional FLC is designed, tested and evaluated followed by a self-tuning FLC. The performance of the self-tuning control strategy is compared with a PID controller and a conventional FLC in terms of rise time, percentage overshoot, settling time, and percentage steady state error.

The time domain specifications are summarized in table 6. It is evident from the data obtained that, though the self-tuning FLC is slower for this pressure process in terms of, a rise time of 57.9 seconds as compared to that of a PID with a rise time of 14.1 seconds, it completely eliminates overshoot as compared to the 6.7 % peak overshoot of the PID controller; which is an improvement over the PID control strategy.

Table 6. Time domain specifications of the three controllers.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Rise time [s]</th>
<th>% Overshoot</th>
<th>Settling time [s]</th>
<th>% Steady-State error</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>14.1</td>
<td>6.7</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Conventional FLC</td>
<td>38.07</td>
<td>—</td>
<td>83</td>
<td>-1.69</td>
</tr>
<tr>
<td>Self-tuning FLC</td>
<td>57.9</td>
<td>—</td>
<td>100</td>
<td>2.63</td>
</tr>
</tbody>
</table>

References

[14]. White paper: Introduction to the two-wire transmitter and the 4-20 mA current loop, Acromag, Inc.

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