Multi-variable Fuzzy Controller for Water Tank Temperature Control System

Liu Xinping, Zhang Xiaodong

Computer and Communication Engineering College, China University of Petroleum, Qingdao Shandong 266555, liuxinp@upc.edu.cn

Abstract

Due to the contradiction between high precision control with complexity of fuzzy controller design, an method for multi-variable fuzzy controller design is presented. A dynamic compensation model for the fuzzy controller is introduced, which simplify the analysis and design of multi-variable fuzzy controller, and improve control performance. The method is applied to high precision water tank temperature control system, and experience show that the multi-variable fuzzy controller with dynamic compensation model has excellent control effects.

Keywords: Multi-Variable Control System, Fuzzy Control, Dynamic Compensation Model

1. Introduction

Temperature control has been widely studied for various thermal systems. It is harder to analytically design a temperature controller based on a physical model, due to heat convection, heat leakage to the environment, variation of environment temperature, and uncertain nonlinear heating dynamics. Conventional PID control strategy can not meet the need of high precision temperature control [1].

In the last few years, Fuzzy control was well known as a method of implementing nonlinear controller. There are numerous successful applications of fuzzy control to solve engineering problems, and many papers addressed the fuzzy control in engineering practice [2-4]. In [5], a fuzzy temperature controller was introduced, where two inputs (error, error change) were employed to infer fixed fuzzy rules and produced an output to actuate the process. In [6], a neuro-fuzzy generalized predictive control was proposed for power plant superheated steam temperature. However, the temperature control systems discussed in [5] and [6] were isolated from environment. In [7], a two-stage fuzzy controller was used to improve the transient response, and a simple fine-tuning adaptive control scheme was proposed to overcome environmental influence and ensure tracking of the temperature setting. In [8], a Takagi–Sugeno–Kang type recurrent fuzzy network (TRFN) designed for temperature control system was proposed, and the TRFN-based direct inverse control configuration was applied to a real water bath temperature control system. In [9], a symmetric system with two inputs and two outputs was divided into two equivalent separated systems, and a multivariable advanced control structure on the basis of fuzzy logic technique was proposed.

Although rule-based fuzzy controller is common in engineering practice, model-based fuzzy controller design is widely studied. We can approximate control model as accurate as possible [10-12], which always lead to the number of control rules increased rapidly, and become a handicap for controller design and application, especially for complex multi-variable high precision control system. In [13] a fuzzy model predictive control strategy was applied to distillation column control system, but it is too complicated to be used in single-chip-microcomputer system.

Furthermore, parameters uncertainty and random disturbances made it more complex to design fuzzy controller.

In this paper, we construct a multi-variable fuzzy controller model. The plant is classified into two parts, one is that the model is difficult to be established, and a fuzzy controller is designed for it; and the other one is that the model can be established based on input and output date, and a controller based on the model is designed. Therefore, the system analysis and design
are simplified, and the fuzzy controller is easily designed and applied to engineering practice. The method of multi-variable fuzzy controller design is applied to a water-tank temperature control system, and the results of experimentation show that the proposed method has excellent control effect.

The paper is organized as follows. Section 2 describes the fuzzy controller design, section 3 describes the dynamic compensation model, section 4 describes the experience results, and conclusion is drawn in section 5.

2. Fuzzy Controller Design

For water-tank temperature control system, the water temperature is controlled by electro-heat device and solenoid valve for heating up and cooling down respectively. Based on characteristics of the water-tank temperature control system, we define two inputs for fuzzy controller, one input $e(k)$ is the difference between the current water temperature and the reference water temperature, and the other one $ce(k)$ is the change of error.

There are many type of membership function for input linguistic variables. We choose the triangular form of membership function, which is the most common, computational efficiency and has been used extensively [14, 15]. Membership functions and fuzzy sets for the controller inputs are as shown in figure 1. Note that to improve the control precision, linguistic variable of the temperature error $E$ and its change $CE$ are defined intensively around zero. Due to the largest overshoot for temperature control system is 1℃, and the quickest changing rate is 3.6℃/min. Let sample time is 1s. We define seven linguistic values for $E$ range from -1 ~ 1℃: {NB: Big Negative, NM: Negative, NS: Small Negative, ZZ: Zero, PS: Small Positive, PM: Positive, PB: Big Positive}, and seven linguistic values for CE: {NB: Quick Descend, NM: Descend, NS: Slow Descend, ZZ: Stop, PS: Slow Ascend, PM: Ascend, PB: Quick Ascend }.

Due to the fuzzy controller outputs of heating up and cooling down are incompatible, we combine them into one unit $U$, where the positive sign of value represents the heating type and the negative sign of value represents the cooling type. Linguistic value for $U$ were described as follows $\{u_1$: full speed cooling, $u_2$: moderate speed cooling, $u_3$: little speed cooling, $u_4$: good, $u_5$: little speed heating, $u_6$: moderate speed heating, $u_7$: full speed heating\}. According to the control experience, we arrive at $7 \times 7 = 49$ fuzzy rules as shown in table 1.

These rules are respectively indicated by $R_i$, and via maximum and minimum fuzzy inference, we can get the total fuzzy relations:

$$ R = \bigcup_{j=1}^{n} R_i = \bigcup_{j=1}^{n} (E_j \cdot CE_j) \times U_i $$

(1)
\[ \mu_R(e, ce, u) = \max_j \{ \mu_R_i(e, ce, u) \} = \max_j \{ \min_i \{ \mu_{E_i} (e), \mu_{CE_i} (ce), \mu_{U_i} (u) \} \} \quad (2) \]

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Table 1. The map of fuzzy controller outputs

For given input variables \((e^*, ce^*)\), we can get fuzzy controller outputs \((3)\).

\[ U = (e^*, ce^*) \circ R \quad (3) \]

Where “\(\circ\)” is fuzzy approximate reasoning.

Based on fuzzy inference, we defuzzificate the outputs by the means of gravity center of area method, and for discrete fuzzy controller, the method of digital integrator is used.

\[ U_0 = \frac{\sum_{i=1}^{n} U_i \mu_U (u_i)}{\sum_{i=1}^{n} \mu_U (u_i)} \quad (4) \]

Temperature control is realized by single-chip-microcomputer real-time control system. Due to single-chip-microcomputer system can not satisfy the calculation on line in time, the output for all the possible input data are calculated by function \((4)\), and we can get the control time output lookup table as shown in figure 2 (units of 10ms).

<table>
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3. Dynamic Compensation Model

During the implementation, temperature control precision is influenced by many factors, such as current water temperature, environment temperature, and water pressure. The control precision cannot be met only via two fuzzy control inputs.

The number of Fuzzy control rules will be increased rapidly, when we take into account external inputs, such as environment temperature and water pressure. Moreover, analysis and design for fuzzy controller will be complicated.

So, we constructed a multi-variable fuzzy controller for temperature control system as shown in figure 2. Where \( y' \) is environment temperature, \( y \) is current water temperature, and \( y^* \) is reference water temperature. Controller is composed of three parts. One is conventional fuzzy controller \( u_0 \) designed for unstructured parts, one is controller \( u \) designed based on dynamic compensation model, and the last one is feedback regulator controller \( u' \); used to reduce the influence of heat power, cooling water pressure, etc. Based on practical situation, we can set \( u' \) from 0 to 1.

\[
\Delta y = y - y^* \\
y = e \\
Fuzzification \rightarrow \text{Fuzzy Rules} \rightarrow \text{Defuzzification} \rightarrow u_0 \rightarrow u \rightarrow u' = u_0 + u + u
\]

**Figure 2.** The fuzzy control with dynamic compensation model

The follow is how to calculate \( u \). Base on human experiences, when water temperature is lower and environment temperature is higher, heat loss is slower; on the contrary, when water temperature is higher and environment temperature is lower, heat loss is faster. To improve control precision, the relationship among water temperature, environment temperature and heat loss should be described carefully. To establish mathematic model and illustrate the relationship, experiments are carried out as follows.

(i) Under a certain environment temperature, we regulate the water temperature according to different reference temperature, and arrive at an input-output response curve based on the date of control input and output.

(ii) Under different environment temperature, we repeat (i), and get a set of curves as shown in figure 3, where x-coordinate is temperature(℃), and y-coordinate is output power percentage of controller.
We can see from figure 3 that the trend of outputs power proportionate is similar under different environment temperature. So fitting segmented curve based on least square method, we can get function (5) and (6).

\[ u = \frac{4}{3} (y - y_n), \; (y - y_n \geq 60^\circ C) \]  \hspace{1cm} (5)

\[ u = 0.068(y - y_n)^{3.6} - 1, (y - y_n < 60^\circ C) \]  \hspace{1cm} (6)

Furthermore, considering the influential factors such as the power of heater, the hydraulic pressure and other influential factors, we introduced a variable \( u' \) which can be designed based on actual condition, in the paper the following function is used to calculate the \( u' \).

\[ u' = -k(y - y^*)u_0 + u \]  \hspace{1cm} (7)

Where \( y \) is current water temperature, and \( y^* \) is reference water temperature, and \( k \) can be designed flexibly based on the control system and its values range from 0 to 1.0, which can improve control system adaptable. The final control output is:

\[ c_u = u_0 + u + u' \]  \hspace{1cm} (8)

In engineering practice, first, we obtained the fuzzy control output \( u_0 \) via querying control table by the information of temperature error \( e \) and calculation error \( ce \). Second, we calculate the compensation value \( u \) by function (5) or (6) using the information of actual measurement water temperature \( y \) and environment temperature \( y' \). And then, calculate the amount of feedback \( u \) according to the differential of measured temperature \( y \) and the ideal temperature \( y^* \). Finally, we can calculate the actual control output \( c_u \). If \( c_u < 0 \) cool down, else heat up.

4. Experiment Results

The conduction time of alternating current can be controlled by solid state relay, which is used to regulate output power. The turn-on or turn-off time of cold water pipe is controlled by solenoid valve, which is used to regulate the cooling rate. The diagram of water tank temperature control system is shown in figure 4.
Let sampling time is 1s, and heating control interval $T_h = 1$s. Electro-heater output power can be regulated continuously in 0~1s, when $T_h = 1$, fully conducting state, the maximum output power; when $T_h = 0$, heating device shut off. Due to solenoid valve can not been turn-on or turn-off frequently, let the cooling interval $T_c = 5$s, which can be adjust between 0~5s. When $T_c = 0$, the cooling device shut off, and $T_c = 5$, fully conducting state.

Experiment results show that, compared with PID control and traditional fuzzy control, the fuzzy control with dynamic compensation model arrive at best control performance, under the influence of environment temperature. Using fuzzy control with dynamic compensation model, we improve dynamic response performance and static control precision. Especially, the method can simplify the analysis and design of temperature control system, and be applied to the engineering practice easily.

5. Conclusions

In the paper, the method of multi-variable fuzzy controller design was proposed, where dynamic compensation and feedback regulation were introduced, which simplified fuzzy controller analysis and design, and dealt with the contradiction between control precision and complexity of fuzzy controller. The method of multi-variable fuzzy controller design was applied to water tank temperature control system. The strategy is realized by single-chip-microcomputer control on line, and experiment results were excellent.

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References


