Research on edge controller based on industrial furnace

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Abstract—Traditional control instruments and DCS control systems are limited by shortcomings such as single control function, independent controlled elements, inability to close-loop control on site, and ineffective communication. Aiming at these problems, this paper proposes a kind of industrial furnace edge controller which has the functions of acquisition, calculation, control, storage, output and communication in one. The edge controller structure, edge computing and the control method applied to edge computing are designed. The fuzzy PID control method is compared with the conventional PID control method by taking the temperature control of resistance furnace as an example. The simulation shows that the control effect of fuzzy PID on resistance furnace temperature is obviously better than that of conventional PID. The test results also show that the performance indices for the fuzzy PID control are better, which again proves that the fuzzy PID control outperforms. The research results of this paper are of reference value for engineering applications.

1. Introduction

With the continuous progress and development of science and technology, automatic control methods are constantly changing due to the complexity and uncertainty of the controlled objects. The backward traditional controller software and hardware has led to the instability of the process control system of industrial kilns, resulting in unstable product quality \cite{1-2}. In the production process of industrial kiln, the control of temperature is to formulate a reasonable firing curve according to the process requirements such as the nature, shape and size of raw materials and the moisture process into the kiln. When firing each product, it is necessary for a temperature curve to be formulated in strict accordance with its own product characteristics to ensure a certain heating, insulation and cooling system. If the automation level of traditional kilns is not high, nor the hardware and software of temperature data acquisition, condition monitoring and other instruments in kilns are sufficient, this will result in large deviation of temperature curve, leading to scrapping of products and burning of kilns in serious cases.

Industrial furnaces are thermal equipment used for smelting, heating, drying, sintering and distillation of workpieces or materials. The process control parameters of industrial furnaces include temperature, flow, pressure, composition, etc \cite{3-4}. At present, the process control of industrial furnace mainly consists of traditional control instruments and DCS control systems.

Although traditional control instruments have the advantages of high measurement accuracy, simple operation, and good stability, they have disadvantages such as poor automation, poor
adaptability, and insufficient communication functions. Moreover, they fail to automate the whole process of instrument placement, fixation, disconnection and range adjustment. They are incapable of remote monitoring and real-time communicating due to single function and poor real-time performance. Furthermore, traditional instruments are prone to errors after running for a long time due to their complex process of maintenance and data reading, recording and maintenance [5-6].

The DCS control system has the advantages of diversified functions, high reliability, and easy maintenance. However, it can only achieve point-to-point detection, not on-site control, and belongs to information islands. DCS control system is limited by its high costs (spare parts and maintenance), a long time required for installation and debugging, demanding requirements for PC programming and Ethernet knowledge, and monopolized prices by DCS manufactures [7-8].

Aiming at the abovementioned shortcomings of traditional control instruments and DCS control systems, this paper proposes an edge controller based on industrial furnaces. The edge controller can collect real-time process parameters of industrial furnaces, and collect, calculate, control, and store data at the source, realizing on-site closed-loop control and remote communication.

2. Structure of edge controller and edge computing

2.1 Structure of edge controller

Figure 1 shows the structure of the edge controller of industrial furnace’s process parameters.

![Figure 1 Structure of the edge controller of industrial furnace’s process parameters](image)

In the production process of industrial furnaces, indicators such as temperature, pressure, flow and composition determine whether their working state meets the requirements of production. It is therefore particularly important to monitor and control these indicators. The traditional control instrument can only collect and control a certain parameter, and the data cannot interact with each other; the DCS control system has such shortcomings as incapability of on-site closed-loop control and information islands, which weaken the correlation between data.

The industrial furnace edge controller studied in this paper collects temperature, flow, pressure, composition and other parameters simultaneously, and at the same time performs linearization, cold junction compensation, edge calculation, closed-loop control, data output and communication.

2.2 Edge computing of process parameters

Edge computing is data analysis and processing at the edge node of the network. The edge node here is defined as any node with computing and network resources between the cloud center and the field layer. Edge computing refers to the calculation, analysis, and processing of data at its source [9].

Edge computing and cloud computing complement each other. Computing tasks with high real-time requirements and small data sizes are immediately processed at the edge application layer; while those low real-time requirements and large data sizes are uploaded to cloud computing for further processing [10]. The edge controller of industrial furnace studied in this paper processes the data generated during the production of the industrial furnace on-site, which can realize the analysis, processing and storage of the data on the network edge. In this way, it not only reduces the dependence
on the cloud, but also improves the security of data. Whether it is out of cloud computing itself, network transmission limitations, or concerns about data security, industrial furnace edge controllers are one of the priorities that must be considered while building intelligent factories.

The edge layer controller designed in this paper constructs an edge computing environment to reduce the dependence on the cloud data center. The edge layer undertakes downlink cloud services and uplink terminal computing, which can significantly reduce data interaction delay and network transmission overhead.

In the heating control of industrial furnaces, the stability and precision of temperature, pressure, flow, composition and other parameters are quite important. These process parameters determine the qualified rate of products, and a small mistake will cause the product to be scrapped. As more and more devices are connected to the cloud platform, the massive amount of data generated during device operation will cause the cloud platform to have the following problems: insufficient computing power, high data transmission delay, poor real-time data forwarding between the cloud and devices, and poor data security and privacy [11-12]. Because of these problems of the cloud platform, the controller of the industrial furnace cannot be directly connected to the cloud, and the edge controller is required to analyze, process and control the data on site before data output.

3. Control method of edge controller
This paper illustrates the application of conventional PID and fuzzy PID control algorithms in edge controllers by an example of the temperature control of resistance furnace.

3.1 Construction of temperature control model of resistance furnace
The resistance furnace temperature control system model based on edge controller includes: given temperature, controller, actuator, controlled object (resistance furnace), feedback element, etc. The diagram of the resistance furnace temperature control system is shown in Figure 2.

![Figure 2 Diagram of the resistance furnace temperature control system](image)

Let the transfer function of the controller be \( G_0(s) \), and the resistance furnace itself is a controlled object with self-balancing ability and hysteresis, then its mathematical model can be approximated as a series of large inertia and hysteresis:

\[
G_1(s) = \frac{K_1 e^{-\tau}}{T_1 s + 1}
\]  

In the above formula: 
- K — proportionality coefficient;
- T — time constant;
- \( \tau \) — latency time.

The actuator is a voltage regulator circuit composed of thyristors, and its transfer function is \( G_2(s) = \frac{K_2}{T_2 s + 1} \). The transfer function of the feedback element is \( H(s) = K_0 \). The steady-state error of the system is \( e(t) = \tau(t) - y(t)K_0 \). Converting \( e(t) \) into \( E(s) \) by Laplace transform, then the closed-loop transfer function between the output temperature and the given temperature in the s domain can be obtained from the Mason formula:

\[
G(s) = \frac{G_0(s)G_1(s)G_2(s)}{1 + G_0(s)G_1(s)G_2(s)H(s)}
\]

The steady-state error transfer function of the system is:

\[
E(s) = \frac{G_0(s)G_1(s)G_2(s)H(s)}{1 + G_0(s)G_1(s)G_2(s)H(s)}
\]
3.2 Control algorithm of resistance furnace

For conventional PID control, the difference e(t) between the given temperature and the actual output temperature is first calculated, and then e(t) is used as the input to change the parameters of the proportional, integral and differential links of the PID controller. The expression of the conventional PID control algorithm is as follows:

$$u(t)=K_p e(t)+\frac{1}{\tau} \int e(t) dt + K_D \frac{de(t)}{dt}$$  \hspace{1cm} (4)

In formula (4):
- $K_p$ — proportionality coefficient;
- $K_I$ — integral time;
- $K_D$ — differential time;
- $e(t)$ — system deviation;
- $u(t)$ — system output.

The biggest limitation is that when $K_p$, $K_I$ and $K_D$ are determined, if the previously set temperature is changed, they need to be changed accordingly. Due to the harsh working environment of the resistance furnace and various interference factors, the actual output temperature will deviate from the expected temperature. Under these conditions, the conventional PID control method will make the output temperature slower and less responsive. Figure 3 shows the diagram of the conventional PID control system.

Fuzzy control can simplify the system design, and is especially suitable for situations where the controlled object model is uncertain. The mathematical models of the resistance furnace and the thyristor in the proposed resistance furnace temperature control system are approximated. Fuzzy control also has the advantages of good robustness and excellent dynamics [13-14]. This paper proposes a fuzzy PID control system, which has the merits of both fuzzy control and PID control, to adjust PID parameters online through fuzzy rules [15-16]. The fuzzy PID control system is shown in Figure 4.

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The fuzzy PID control system is mainly composed of an adjustable PID and a fuzzy controller. With the error e between the given temperature and the actual output temperature and the error change rate ec as input, this system adjusts the parameters $K_p$, $K_I$ and $K_D$ online through fuzzy rules.

Fuzzy rules are the core of fuzzy control. The fuzzy rule is to output the values of $\Delta K_p$, $\Delta K_I$ and $\Delta K_D$ according to the changes in actual e and ec, and modify $K_p$, $K_I$ and $K_D$ through $\Delta K_p$, $\Delta K_I$ and $\Delta K_D$, which makes the control more precise, reduces the steady-state error, and reaches the set temperature [17].
The setting rules are as follows:

1) When the resistance furnace just starts to work or at the beginning of heating, the difference between the artificially set temperature and the current temperature of the resistance furnace is large. To ensure the temperature of resistance furnace can rise rapidly, $K_p$ (the larger the $K_p$, the faster the response speed of the system) should be large, and $K_D$ (a large $K_D$ may lead to early braking [18]) be small. The larger the $K_I$, the smaller the steady-state error of the system, but an excessively large $K_I$ will cause a large overshoot in the system. Given that $K_p$ is relatively large at the initial stage of resistance furnace respond, in order to avoid a large overshoot, $K_I$ is set to 0.

2) When the resistance furnace is in the middle of the temperature rise, $|e|$ and $|ec|$ are of medium size, so $K_p$ is set to a small value, and $K_D$ and $K_I$ to moderate values. (Since the temperature of the resistance furnace is rising rapidly at this time, the key is to avoid overshoot of the system, so the value of $K_p$ cannot be large, and the values of $K_I$ and $K_D$ should be moderate).

3) When the temperature of the resistance furnace is close to the set value, $|e|$ is small. It is therefore necessary to increase the values of $K_p$ and $K_I$ to avoid the repeated oscillations of resistance furnace temperature around the set value. In this case, if $|ec|$ is large, $K_D$ is small; if $|ec|$ is small, $K_D$ is moderate.

It can be known that fuzzy PID continuously outputs the values of $\Delta K_p$, $\Delta K_I$ and $\Delta K_D$ through the system error and error change rate, so as to adjust the $K_p$, $K_I$ and $K_D$ of PID controller. The modified $K_p$, $K_I$ and $K_D$ are denoted as $K_p'$, $K_I'$ and $K_D'$. Their expressions are

\[
K_p' = K_p + \Delta K_p; \quad (5)
\]

\[
K_I' = K_I + \Delta K_I; \quad (6)
\]

\[
K_D' = K_D + \Delta K_D; \quad (7)
\]

Before formulating the fuzzy rules, the variables (input: $e$ and $ec$; output: $\Delta K_p$, $\Delta K_I$ and $\Delta K_D$) are fuzzified to determine the fuzzy domain and the basic domain.

The fuzzy domains and basic domains of variables are shown in Table 1.

Table 1 Domains of fuzzy PID

| Variable | $e$ | $ec$ | $\Delta K_p$ | $\Delta K_I$ | $\Delta K_D$ |
|----------|-----|------|--------------|--------------|--------------|
| Basic domain | [-100,400] | [-10,400] | [-0.9,0.9] | [-0.0003,0.0003] | [-3,3] |
| Fuzzy domain | [-40,40] | [-40,40] | [-3,3] | [-3,3] | [-3,3] |

The fuzzy subsets of the variables are [Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, and Positive Big]. The functions of input $e$ and $ec$, and output $\Delta K_p$, $\Delta K_I$ and $\Delta K_D$ are triangular membership functions. The fuzzy rules are formulated as follows:

Fuzzy Rule 1: if ($e$ is NB) and ($ec$ is NB), then ($\Delta K_p$ is PB) ($\Delta K_I$ is NB)($\Delta K_D$ is PB)

\vdots

Fuzzy Rule 49: if ($e$ is PB) and ($ec$ is PB), then ($\Delta K_p$ is NB) ($\Delta K_I$ is PB)($\Delta K_D$ is PB). Some of the fuzzy rules are shown in Figure 5.

Figure 5 Some of the fuzzy rules
3.3 Modeling and simulation of resistance furnace

In this paper, MATLAB R2020b/ Simulink is used for simulation. According to reference [19], the mathematical model of resistance furnace can be given by

\[ G_1(s) = \frac{0.5e^{-8.3s}}{100s+1} \]  

(8)

The fuzzy PID simulation model is shown in Figure 6.

![Figure 6 The fuzzy PID simulation model](image)

In Figure 7, the PID parameters for manual adjustment are: \( K_p = 2 \); \( K_i = 0.014 \); \( K_D = 18 \).

The internal structure of fuzzy-PID is illustrated in Figure 7.

![Figure 7 Internal structure of fuzzy-PID](image)

Figure 8 presents the simulation curve of resistance furnace temperature control. In order to verify the advantages of using fuzzy PID to control resistance furnace temperature, the dynamic characteristics of the fuzzy PID temperature control system are compared with that of the conventional PID temperature control system. The dynamic characteristics mainly include: rise time, overshoot, number of oscillations, etc.
In the simulation, P, I and D of PID control are determined by manual adjustment. Specifically, P ranges within [1.5, 3], I ranges within [0.01, 0.02], and D is within in [1,30].

From the simulink simulation curve, it can be seen that the overshoot (σ%) of the conventional PID temperature control curve is obviously larger than that of the fuzzy PID temperature control curve, and the overshoot of the latter is approximately zero. The rise time of fuzzy PID control system is obviously longer than that of PID controller. In terms of the number of oscillations and the stabilization time, the conventional PID control system has only one oscillation, and it stabilizes at around 600s. By contrast, the fuzzy PID control system basically does not oscillate after reaching the set value at about 300s, and is completely stable.

From the above analyses of several performance indicators, it can be concluded that system, the fuzzy PID control system outperforms the conventional PID control system in the resistance furnace temperature control.

4. Application case test of edge controller

4.1 Construction of edge controller test platform
Characterized by stable output temperature and small size, the constant temperature platform (resistance furnace) plays an important role in the welding process of electronic components. In this paper, a constant temperature platform is used as the controlled object to construct an edge controller test platform. The constant temperature platform is shown in Figure 9, and the edge controller is shown in Figure 10.
Figure 10 Picture of the edge controller

The edge controller first collects the real-time temperature of the constant temperature platform through a thermocouple, and then amplifies, reshapes, converts, and processes the collected temperature signals, and controls the temperature of the constant temperature platform by setting the temperature manually. The edge controller stores the historical temperature and displays the current and historical temperatures on the display screen.

4.2 Human-machine interface and test curve

Figure 11 shows the human-machine interface.

![Parameter Setting](image)

The edge controller parameter setting interface includes: set temperature, real-time temperature, PID parameters, and fuzzy parameters. Various parameters such as temperature, flow, pressure, and liquid level can be modified through the interface.

The temperature control curve of the case is shown in Figure 12.
The edge controller display screen can display historical temperature curves and real-time temperature curves.

It can be seen from Figure 12 that the temperature control of resistance furnace curve obtained by actual test differs slightly from that obtained by simulation. This is because the simulation is the result obtained in an ideal environment, but in practice, the temperature control of the resistance furnace is affected by various factors.

Table 2 lists the simulation and test results.

| Verification mode | Overshoot | Rise time (s) | Setting time (s) | Number of oscillations | Method     |
|-------------------|-----------|---------------|------------------|------------------------|------------|
| Simulation        | 3.8%      | 117           | 517              | 1                      | PID        |
|                   | 0         | 97            | 217              | 0                      | Fuzzy PID  |
| Test              | 17.5%     | 150           | 700              | 1.2                    | PID        |
|                   | 5%        | 106           | 500              | 1                      | Fuzzy PID  |

It can be seen from Table 2 that the performance indices of fuzzy PID control are obviously better than those of PID control in both simulation and test.

5. Conclusion

Aiming at the deficiency of the current control instruments and systems of industrial furnace (traditional control instrument and DCS control system), this paper proposes an edge controller based on industrial furnace. The edge controller overcomes the shortcomings of traditional control instruments and DCS control systems by directly collecting, calculating, controlling, storing, outputting, and uploading important data in the production process of industrial furnaces. In this paper, a case study is carried out on the temperature control of resistance furnace. The fuzzy PID control and the conventional PID control are respectively used to simulate the resistance furnace temperature under the ideal environment. It is concluded that the performance indices (overshoot, rise time, the number of oscillations, and the setting time) of the fuzzy PID control are better than those of the conventional PID control. With the constant temperature platform as the controlled object, a similar conclusion is also drawn. Simulation and test results demonstrate that the method proposed in this paper is feasible.
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