THE RESEARCH FOR DISSOLVED OXYGEN FUZZY PID CONTROL SYSTEM BASED ON ADJUSTMENT FACTORS IN BIOLOGICAL CULTURE

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ABSTRACT
The dissolved oxygen (DO) concentration in the culture solution plays an important role within the process of biological culture. The stable and accurate control of DO can maintain the normal survival and growth of microbes, cells, and tissue. However, the DO system is a typical control system with a large inertia, a longer lag time and a certain degree of uncertain control. The fuzzy PID controller with adjustment factors is presented in this paper. The paper details the structure of the biological culture system and establishes the DO control model based on the material balance formulate. The control rules of the fuzzy PID controller and adjustment factors controller according to the hypothetical process of the DO control are discussed. The idea of variable universe is introduced to design the control algorithm. The anti-interference and dynamic tracking simulations are performed in this paper. Compared with simple PID controller and conventional fuzzy PID controller, the proposed controller has been enhanced in several the performances.

KEY WORDS
Dissolved oxygen, Fuzzy controller with adjustment factor, Biological culture, Variable universe

1. Introduction

Microbes, cells and tissue in the culture solution all need oxygen to maintain growth in the process of biological culture. Also, the concentrations and rates of change of the DO influence the development and survival rate of biological creatures [1]. Thus, the DO concentrations are considered as the most important control parameters for biological cultures. However, the DO concentrations are affected by many factors. Many researchers did a lot of works on the control algorithms for DO. The PID control algorithm was widely used in the control of DO because of its simplicity and practicality. But the PID control cannot well adapt to the large dynamics changes in the process [2]. Although [12] proposed a new type of robust PID controller and simulation result showed a good robustness, the large changes of the DO concentration still could not achieve a better control result. So many researchers had taken several of fuzzy control measures to the DO control. Conventional fuzzy control has many advantages [11] [14]; however, the complicated fuzzy rules are needed to be obtained through a large of experiments. Hence, the new method, which combined the PID with fuzzy algorithms, was introduced into control of DO. Because membership functions and control rules of the conventional fuzzy PID control are not modified after they are set [3], the method had a poor robustness. To solve these problems in the DO control, this paper proposes a new fuzzy PID controller with adjustment factors for the DO control.

The rest of this paper is organized as follows. The system structure of the DO equipment is introduced in Section 2. A model of the DO control is established in Section 3. Section 4 describes the fuzzy PID controller with adjustment factors based on variable universe. The simulation results are reported in Section 5. Finally, the conclusion is given in Section 6.

2. System Structure

The biological culture system is a part of intelligent biological laboratory which is a real-time data acquisition and control system based on CAN bus with the multi-node [4]. The biological culture module includes five biological incubators which are connected to CAN bus as independent CAN nodes. Each node receives control commanders and control parameters of host via the CAN bus. Also each node sends real-time acquisition data of temperature, dissolved oxygen, pressure and PH to host via the CAN bus. A simplified view of biological culture module is shown in the Figure.1. The work in this paper focuses on the design and simulation of the DO control algorithm in the hypothetical biological incubators. As shown in Figure.1, each incubator is equipped with one DO sensor that provides the measurement value of DO. The header pipe beneath the biological incubators carries the supply ambient air to each biological incubator by the flow control valves. Air is supplied by air pumps in opened air valves. The barometer beneath biological incubators real-time monitors air pressure of the header pipe. Three air pumps are designed to maintain air pressure within an acceptable range and ensure the supply of the DO requirements of five incubators at the same time. The culture solution in the incubators comes from solution pipe, and waste solution discharges through waste solution pipe. The outlet and inlet of pipe are
that the control of the DO pipe is equipped with air flow meter. Through the above description, it can be seen that the control of the DO concentration is decided by many parameters in the system.

3. Model of the DO Control

The biological culture system proposed in this paper is a complex dynamic system. Therefore, the mathematical model cannot be accurately described. In order to reduce complexity of model, it is necessary to set up five assumptions for the model [5].

- The aeration process is an ideal plug-flow change and oxygen is completely mixed state in the culture solution.
- The efflux flow of the solution is the same as the influx flow of the solution.
- Variables in the model are continuous change and fully smooth.
- The volume of the incubator in the system is constant. The assumption is that solution evaporation and solution consumption for organisms are ignored.
- The reaction rate of biological organisms is constant.

Five biological incubators involve three kinds of the cultivation: microbe, cell and tissue. According to the design requirements, the three types of incubators have different volumes. The DO formulate is established in reference with material balance formulate:

\[
V_i \frac{dC}{dt} = QC_0 + QC_1 - QC_2 - V_i K_i C
\]  

\(V_i\) — The volume of microbe incubator \((i = 1)\), cell incubator \((i = 2)\) and tissue incubator \((i = 3)\). \((m^3)\)

\(C\) — The concentration of the DO \((mg/m^3)\).

\(C_0\) — The concentration of the oxygen from air input pipe and atmosphere \((mg/m^3)\).

\(C_1\) — The concentration of the oxygen from solution pipe \((mg/m^3)\).

\(C_2\) — The concentration of the oxygen from waste solution pipe \((mg/m^3)\).

\(K_i\) — The constant of reaction rate, \(i = 1\) is microbe, \(i = 2\) is cell, and \(i = 3\) is tissue \((mg/m^3)\).

\(Q\) — The average volume of air flow \((m^3/\text{min})\).

Do LAPLACE transform for Formula (1). The result is shown as:

\[
G(S) = \frac{(C_0 + C_1 - C_2)/V_i}{S + K_i}
\]  

The DO concentration is measured by membrane electrode method in this paper. Therefore, the DO control of biological culture is typical non-linear with hysteresis [6]. Let \((C_0 + C_1 - C_2)/V_i = R\). So the formula (2) can be defined as:

\[
G(S) = \frac{R_i}{S + K_i}e^{-\tau S}
\]  

The above formula is mathematical model of the DO control of the biological incubators.

4. Fuzzy PID Control System with Adjustment Factors

The DO fuzzy control system includes fuzzy PID controller and adjustment factors fuzzy controller. The DO fuzzy PID controller with two-input and three-output uses error \((e)\) and rate of error change \((e^r)\) of the DO concentration as inputs, and the gains \((\Delta K_p, \Delta K_i, \Delta K_d)\) as outputs. Adjustment factors fuzzy controller is consisted
of two types of fuzzy controllers. One is so-called quantized factor fuzzy controller with one-input and one-output. The other one is so-called proportional factor fuzzy controller with two-input and one-output. The quantized factor fuzzy controller 2 uses error of the DO concentration as input, and the quantized factor (Kc) as output. The quantized factor fuzzy controller 1 uses rate of error change of the DO concentration as input, and the quantized factor (Ke) as output. The proportional factor fuzzy controller uses error and rate of error change of the DO concentration as inputs, and the proportional factor (Kp) as output. The fuzzy PID controller based on adjustment factors is proposed in this paper, as shown in Figure 2.

The new controller extends new functions that adjust not only the parameters of the PID controller on-line, but quantized factor and proportional factor on-line with the change of the control process. The DO fuzzy controller comprises fuzzification, rule base and defuzzification. The most important work is the rule base design. Two main core parts of the DO fuzzy controller are PID control rules and adjustment factor fuzzy control rules. The defuzzification adopts the center of gravity method.

4.1 Fuzzy PID Controller

Conventional fuzzy PID control rules are summarized by the experience of multiple operations and theoretical analysis [7][8][9]. In the process of the biological culture, the fuzzy relationships between the value of e, ec and PID three parameters (Kp, Kc, Ke) can be summarized as follow:

- If |e| is larger, set a larger Kp to speed up the response rate of the system. In order to avoid control out of range, set a smaller Kc. In order to avoid a large overshoot, which results in integration saturation effect, remove the integral action, set Ki 0.
- If |e| and |ec| are medium size, set smaller Kp to make system overshoot smaller. In order to maintain the response speed of the system, set Kc appropriately. In this case, increase appropriately Ki.
- If |e| is smaller, set larger Kp and Kc to maintain good performance of the system. In order to avoid shock near the setting value (balance point), set Ki appropriately.
- If |ec| is smaller, set a larger Kc, a larger Kp and a smaller Ki. If |ec| is larger, set a smaller Kc, a smaller Kp and a larger Ki.

Through the above rules, ΔKp control rules table of fuzzy PID can be summarized in Table 1. The linguistic labels of the outputs (ΔKp, ΔKc, ΔKe) are {Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium, Positive Big}, and referred to in the rules bases as {NB, NM, NS ZO, PS, PM, PB}. ΔKc and ΔKe rules also can be summarized by the same rules.

<table>
<thead>
<tr>
<th>Table 1 ΔKp fuzzy rules</th>
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<tbody>
<tr>
<td>e/ec</td>
</tr>
<tr>
<td>NB</td>
</tr>
<tr>
<td>NM</td>
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<td>NS</td>
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<td>ZO</td>
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<td>PS</td>
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<td>PM</td>
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<td>PB</td>
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</table>
4.2 Adjustment Factors Fuzzy Controller

The fuzzy controller has not only a set of good fuzzy control rules, but a group of reasonable gain coefficients of input variables and output variables, which is called adjustment factors (quantized factor and proportional factor). In general, the selections of the quantized factors $K_e$, $K_u$, and proportional factor $K_p$ are subjective and blindness. And they could not be modified after they are selected. However, a great number of experiments and theoretical analysis show that quantized factor and proportional factor have a greater impact on the control performance of the fuzzy controller. This paper applies the idea of the variable universe to the design of adjustment factors fuzzy controller.

In fact, variable universe is the expansion and contraction of the input and output basic universe according to control requirements and guidelines [10] [11]. Specifically, the variable universe is meaning that the basic universe of input and output can be adjusted with the input and output variables change.

The variable universe algorithm can be achieved as follows: $K_e = N_{e_{max}} / E_e$, $K_u = N_{u_{max}} / E_u$, and $K_p = E_p / N_{u_{max}}$, where $N_{e_{max}}, N_{e_{min}},$, and $N_{u_{max}}$ are the biggest discrete values of fuzzy universe, $E_e$, $E_u$, and $E_p$ are new universes of the input and output variables. The new universes can be gotten by the equations: $E_e = \alpha_e \cdot E_{e_{max}}$, $E_u = \alpha_u \cdot E_{u_{max}}$, and $E_p = E_{p_{max}} \cdot \beta$, where $E_{e_{max}}, E_{u_{max}}$, and $E_{p_{max}}$ are basic universes of input and output variables, $\alpha_e$, $\alpha_u$, and $\beta$ are the expansion and contraction factors. The values of $N_k$ for $k = e, u, p$ are unchanged after they are set. According to the above formulas, if the quantized factor and the proportional factor are changed, basic universe of the input and output also will be changed. If the quantized factor $K_e$ becomes larger, basic universe $\left[{-E_{e_{max}}, E_{e_{max}}}\right]$ becomes contraction and the control role of the input $e$ will be enhanced. If $K_u$ becomes smaller, basic universe $\left[{-E_{u_{max}}, E_{u_{max}}}\right]$ becomes expansion and the control role of the input $u$ will be weaken. If the quantized factor $K_p$ becomes larger, basic universe $\left[{-E_{p_{max}}, E_{p_{max}}}\right]$ becomes contraction and the control role of the output $p$ will be enhanced. If $K_u$ becomes smaller, basic universe of the output $\left[{-E_{u_{max}}, E_{u_{max}}}\right]$ becomes expansion and the control role of the output $u$ will be weaken.

As mentioned above, how to determine the expansion and contraction change of basic universe is basic problem of the variable universe. According to [8], the method of expansion and contraction factor based on fuzzy rules is adopted.

The expansion and contraction factor of variables $e$ and $ec$ are set $\alpha_e$ and $\alpha_{ec}$. The fuzzy partition is $\{B, M, S, Z\}$. The expansion and contraction factor fuzzy rules of the input universe can be summarized in Table 2.

<table>
<thead>
<tr>
<th>$e/ec$</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
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<tbody>
<tr>
<td>$\alpha_e$</td>
<td>B</td>
<td>M</td>
<td>S</td>
<td>Z</td>
<td>S</td>
<td>M</td>
<td>B</td>
</tr>
</tbody>
</table>

The expansion and contraction factor of the output universe is decided jointly by the $e$ and $ec$. The expansion and contraction factor of the output universe is set $\beta$.

The fuzzy partition is $\{VB, B, MB, B, SB, ZO\}$. The expansion and contraction factor fuzzy rules of the output universe can be summarized in Table 3.

<table>
<thead>
<tr>
<th>$e/ec$</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
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<tbody>
<tr>
<td>$\beta$</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
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</table>

4.3 Algorithm of the DO Fuzzy Controller

Through the above analysis and design of DO controller, the algorithm of the control can be gotten as follows: $e^*$ and $ec^*$ are assumed as new input variables. $\alpha$ is assumed as output variable. $E_e$, $E_u$, and $E_p$ are assumed as the input and output basic universes. $E_e$, $E_u$, and $E_p$ are assumed as new basic universes. The algorithm can be summed as follows:

1. Calculate the real-time error $e$ and the rate of the error change $ec$.
2. $\alpha_e$, $\alpha_{ec}$, and $\beta$ can be got in the fuzzy rules tables.
3. Adjust the size of input universe and output universe: $E_e = E_{e_{max}} \cdot \alpha_e$, $E_u = E_{u_{max}} \cdot \alpha_{ec}$, and $E_p = E_{p_{max}} \cdot \beta$.
4. Adjust adjustment factors $K_e$, $K_u$, and $K_p$: $K_e = N_{e_{max}} / E_e$, $K_u = N_{u_{max}} / E_u$, $K_p = E_{p_{max}} / N_{u_{max}}$.
5. Calculate the new $e^*$ and $ec^*$: $e^* = K_e \cdot e$, $ec^* = K_u \cdot ec$.
6. Through $e^*$ and $ec^*$, $\Delta K_e$, $\Delta K_u$, and $\Delta K_p$ can be gotten from the fuzzy rule tables.
7. Through $\Delta K_{ij}$, $\Delta R_i$, and $\Delta R$, PID controller outputs the control variable $u$.

8. Calculate the new control variable $u'$: $u' = k_p - u$. And calculate the result of the response of the controlled object.

5. Simulation Results

The objective of the DO fuzzy controller is to provide anti-interference and dynamic tracking control within the process of biological culture. Consequently, each model is simulated by the step signal tracking to test the performance of the DO control algorithm. This paper gives the comparison among simple PID controller, fuzzy PID controller and fuzzy PID controller based on adjustment factors.

The parameters of the DO control model formulate (4) can be assumed in Table 4 and $\tau = 9s$. Also, it is necessary to set up two assumptions:

- The inlet of the solution pipe, the outlet of the waste solution pipe and the inlet of the air pipe are not closed in the process of biological culture.
- The reaction rate of biological organisms $K$ and $R$ are set by assumption.

<table>
<thead>
<tr>
<th>Table 4 DO Control Parameters</th>
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<tbody>
<tr>
<td>Sorts</td>
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<tr>
<td>$R_i$</td>
</tr>
<tr>
<td>$K_i$</td>
</tr>
</tbody>
</table>

5.1 Anti-interference Testing

The input is step signal. Three controllers are adjusted for good characters such as stability, slight shock and slight overshoot. The interference signal is added to the control process. The MATLAB simulations are shown in Figure 3. The results show that the performance of adjustment factors fuzzy PID is better than Fuzzy PID and simple PID. The controller has a quick response and short regulating time.

5.2 Dynamic Tracking Testing

In general, the setting value of the DO is changed in accordance with the culture process. As can be seen in Figure 4, the setting values are changed from 1 to 1.5, and from 1.5 to 0.5. The results show good dynamic tracking performance. Especially, the performance of the fuzzy PID controller based on adjustment factor is obviously better than other controllers when the setting value change from 1.5 to 0.5.

6. Conclusion

This paper details the structure of the biological culture system and establishes the control model with material balance formulate. According to hypothetical DO control process, the fuzzy PID control rules and adjustment factors rules are given in this paper. The control algorithm is created by the idea of variable universe. The simulations with MATLAB show the fuzzy PID controller with adjustment factor has the significantly superior performance than simple PID controller and conventional fuzzy PID controller. Because the biological culture system is still in building, all parameters in the paper are assumed. The results of the DO control algorithm in this paper will provide theoretical support for the establishment of the real biological culture system in the future.

Figure 3 The response to interference with different parameters
Figure 4 Robustness test with different parameters

References


