Intelligent PID controller based on ant system algorithm and fuzzy inference and its application to bionic artificial leg

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Abstract: A designing method of intelligent proportional-integral-derivative (PID) controllers was proposed based on the ant system algorithm and fuzzy inference. This kind of controller is called Fuzzy-ant system PID controller. It consists of an off-line part and an on-line part. In the off-line part, for a given control system with a PID controller, by taking the overshoot, setting time and steady-state error of the system unit step response as the performance indexes and by using the ant system algorithm, a group of optimal PID parameters $K_p$, $T_i$, and $T_d$ can be obtained, which are used as the initial values for the on-line tuning of PID parameters. In the on-line part, based on $K_p$, $T_i$, and $T_d$, and according to the current system error $e$ and its time derivative, a specific program is written, which is used to optimize and adjust the PID parameters on-line through a fuzzy inference mechanism to ensure that the system response has optimal transient and steady-state performance. This kind of intelligent PID controller can be used to control the motor of the intelligent bionic artificial leg designed by the authors. The result of computer simulation experiment shows that the controller has less overshoot and shorter setting time.

Key words: ant system algorithm; fuzzy inference; PID controller; Fuzzy-ant system PID controller; intelligent bionic artificial leg

1 INTRODUCTION

Up to now, proportional-integral-derivative (PID) controllers have been used to control many industrial processes because of their simple structure and acceptable performance. The performance of a PID controller, however, fully depends on tuning of its parameters. Many researchers studied this problem. Fuzzy inference is an intelligent control method. Its advantage is that the control input can be determined by imitating a human operator experience without knowing the accurate model of the controlled object. Integrating fuzzy inference with PID control theory enables a control system to have not only the intelligent behavior of fuzzy inference but also the simpler structure and robust performance of PID controllers. Many researchers studied fuzzy PID controllers.

Ant system (AS) algorithm was proposed by Dorigo et al. which is a new kind of general-purpose heuristic algorithms and can be used to solve different combinatorial optimization problems. The main characteristics of an ant system algorithm are positive feedback search mechanism, distributed computation and the use of a constructive greedy heuristic. So far, ant system algorithms have been used successfully to solve many practical problems, such as traveling salesman problem (TSP), quadratic assignment problem, discrete optimization problem, and so on. In this paper, a new designing method for intelligent PID controllers is proposed based on the ant system algorithm developed by the authors and fuzzy inference and used to control the motor of the intelligent bionic artificial leg designed by the authors. The result of computer simulation experiment shows that this kind of intelligent PID controller has better control performance.

2 OFF-LINE OPTIMIZATION OF INITIAL VALUES OF PID PARAMETERS

2.1 PID control law

The PID control law of a continuous system is expressed as follows:

$$u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int_0^t e(\tau) d\tau + T_d \frac{de(t)}{dt} \right]$$  (1)

where $e(t)$ is the system error, $u(t)$ is the control variable, $K_p$ is the proportional gain, $T_i$ is the integral time constant, and $T_d$ is the derivative time constant. In the discrete-time domain, the PID control law can be expressed as follows:
\[ u(k) = K_p e(k) + K_i \sum_{j=0}^{k} e(j) + K_d [e(k) - e(k-1)] \]

where \( K_i = K_p T_i / T \), \( K_d = K_p T_d / T \), and \( T \) is the sampling period.

2.2 Generation of knots and paths

Take PID parameters \( K_p \), \( T_i \) and \( T_d \) as the optimized variables, and assume that the value of each of them has 5 valid digits. According to the ranges of their values in many practical applications, we assume that in the 5 digits of \( K_p \) value there are 2 digits before decimal point and 3 digits after decimal point; in the 5 digits of \( T_i \) and \( T_d \) there is 1 digit before decimal point and 4 digits after decimal point. In order to use the ant system algorithm conveniently, figure \( K_p \), \( T_i \) and \( T_d \) abstractly on plane \( OXY \), as shown in Fig. 1.

In Fig. 1, \( L_1 \) - \( L_5 \), \( L_6 \) - \( L_{10} \) and \( L_{11} \) - \( L_{15} \) represent the first digit to the 15th digit of \( K_p \), \( T_i \) and \( T_d \), respectively. The positions of these lines on axis \( X \) are represented by numbers 1 - 15, respectively. Then, divide equally each of these lines into 9 segments and thus 10 knots are generated on each line, as shown in Fig. 1. The 10 knots of each line represent respectively 10 numbers 0 - 9, which are 10 possible values of the digit corresponding to the line.

On plane \( OXY \) there are \( 15 \times 10 \) knots in total. \( M(x_i, y_{ij}) \) is used to denote a knot, in which \( x_i \) is the horizontal coordinate of line \( L_i (i = 1 - 15, x_i = 1 - 15) \) and \( y_{ij} \) is the vertical coordinate of knot \( j \) on line \( L_i (j = 0 - 9) \). Each knot represents a value that is equal to the vertical coordinate of the knot. For example, \( M(5, 8) \) indicates that the value of the 5th digit of \( K_p \), i.e., the value of the third digit of \( K_p \) after decimal point, is equal to 8.

Let an ant depart from the origin of plane \( OXY \). When it moves to any knot on line \( L_{15} \), it completes one tour. Its moving path is expressed by \( \text{Path} = \{0, M(x_1, y_{1j}), M(x_2, y_{2j}), \ldots, M(x_{15}, y_{15j})\} \), where \( M(x_i, y_{ij}) \) is on line \( L_i \). Obviously, the values of \( K_p \), \( T_i \) and \( T_d \) represented by the path can be computed by the following formulas:

\[
\begin{align*}
K_p &= y_{11,1} \times 10^0 + y_{12,1} \times 10^1 + y_{13,1} \times 10^{-1} + y_{14,1} \times 10^{-2} + y_{15,1} \times 10^{-3} \\
T_i &= y_{11,1} \times 10^0 + y_{12,1} \times 10^{-1} + y_{13,1} \times 10^{-2} + y_{14,1} \times 10^{-3} + y_{15,1} \times 10^{-4} \\
T_d &= y_{11,1} \times 10^0 + y_{12,1} \times 10^{-1} + y_{13,1} \times 10^{-2} + y_{14,1} \times 10^{-3} + y_{15,1} \times 10^{-4}
\end{align*}
\]

For example, a moving path of an ant is shown in Fig. 1, the values of \( K_p \), \( T_i \) and \( T_d \) represented by the path are \( K_p = 64.378 \), \( T_i = 5.4267 \) and \( T_d = 3.4254 \).

2.3 Development of objective function

In order to make a control system have good performance, developing the objective function should be based on the performance indexes of the system. Here we mainly consider the overshoot \( \sigma \), setting time \( t_s \), and steady-state error \( e_{ss} \) of the system unit step response. First 3 functions \( f_1, f_2 \) and \( f_3 \) are constructed by use of \( \sigma , t_s \) and \( e_{ss} \), which are given as: \( f_1 = \sigma / \sigma_0 \), \( f_2 = t_s / t_s \) and \( f_3 = e_{ss} / e_{ss0} \) (if \( e_{ss0} \neq 0 \)) or \( f_3 = 0 \) (if \( e_{ss0} = 0 \)), where \( \sigma_0 \), \( t_s \) and \( e_{ss0} \) are the values of performance indexes of the system unit step response obtained by using the Ziegler-Nichols (Z-N) tuning formula\(^{[1]} \).

\[ Y \]

\[ X \]

\[ L_1 \, L_2 \, L_3 \, L_4 \, L_5 \, L_6 \, L_7 \, L_8 \, L_9 \, L_{10} \, L_{11} \, L_{12} \, L_{13} \, L_{14} \, L_{15} \]

\[ \text{Fig. 1} \quad \text{Diagram for generating knots and paths} \]