Design and application of fuzzy immune PID control based on genetic optimization

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***Abstract* - The PID controller is the most used controller in the industry thanks to its simplicity and satisfactory performances, unfortunately there is a class of systems that can't achieve satisfactory performances with a simple PID controller as the nonlinear and the delayed systems. These last years, it appeared a lot of innovative control techniques as the bio-inspired methods, one of the most promising of them is the immune PID controller, it is inspired by the immune system regulating mechanism known by its robustness and self-adaptability. In this paper, the immune feedback mechanism and fuzzy inference were applied to design a fuzzy immune PID controller and the genetic algorithm was used to optimize its parameters. The simulation results verify that the strategy has strong adaptability to the transformation of the system parameters and has advantages of a good time performances and robustness of the control system.**

Index Terms - immune PID control; fuzzy control; genetic algorithm

I. Introduction

PID control is the most widely used control strategy in industrial process control, its algorithm control structure is very simple and can be tuned very easily, but for the time-varying, uncertain and nonlinear characteristics, it can't achieve satisfied control performances. Artificial immune system as an intelligent information processing system is an emerging field of researches on control, optimization, pattern recognition, classification and other fields. According to [1, 2] the immune cells role in promoting and inhibiting the immune response in the adjustment process, it can guarantee to obtain fast response and adequate stability. Although this response mechanism needs further exploration, but as a mechanism for biological information processing engineering, the immune regulatory mechanisms can be used to effectively improve the performance of the control system.

Consider the biological immune system has strong robustness and self-adaptability in the environment with mass disturbance and uncertainty. Some control systems based on the immune feedback mechanism are recently proposed to improve the control effect [3, 4]. Reference [5] proposed a PID-P cascade controller based on the immune feedback mechanism, which has better control performances than traditional PID controller and strong anti-interference ability.

In this paper, a brief outline of the feedback regulation mechanism in the immune system is introduced and used to determine an immune feedback law. The mechanism of artificial immune system is incorporated with traditional PID to design the immune controller whose nonlinear function is achieved by fuzzy inference while the genetic algorithm is used to deal with parameters optimization of the designed controller. Simulation results using a nonlinear delayed system as the controlled process show that this control strategy is superior to conventional PID control and has advantages of good robustness, fast response and satisfactory overshoot.

II. Immune Feedback Mechanism

Recent studies on immunology have shown that the immune system plays important roles to maintain its own system against hostile dynamically changing environment through mutual interaction among lymphocytes and antibodies. The dynamic balance of the immune system can be disturbed by the antigen.

Due to the key role of *T* cells in immune response, the immune feedback algorithm is mainly based on *T* cells feedback regulating principle of biology immune system. The basic cells that are involved in the process are antigens Ag, antibodies *Ab*, *B* cells, helper *T* cells (T_H) and suppressor *T* cells (T_S).

According to Fig. 1, when the antigens invade the body, the antigen information is passed to the *T* cells. After receiving the message, *B* cells will be stimulated by *T* cells and creates antibodies immediately to eliminate the antigen. When the number of antigens is increasing, the number of T_H cells will increase and the human body can create more *B* cells to protect itself. Along with the decrease of antigens, the amount of T_S cells in the body would increase and the number of *B* cells would reduce accordingly. After a period of time, the immune system inclines to balance.

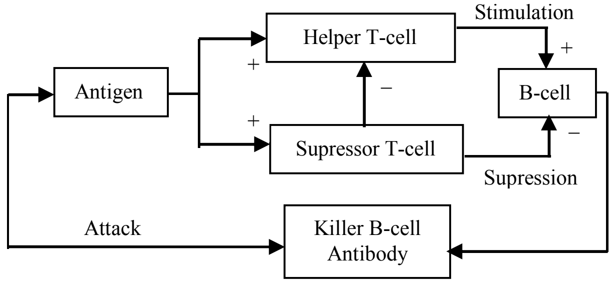

Figure 1. Scheme of the immune regulating system

Table 1 summarizes the regulation actions of T cells in the process of the above immune response.

TABLE 1. T CELLS IMMUNE ACTIONS

Immune response	Antigen concentration	Antibody concentration	Function of *T* cell
Antigen invasion	High	Very Low	——
Preliminary invasion	High	Low	Activation
Later stage	Low	High	Suppression
Final stage	Very Low	Low	——

This cooperation between the inhibitive mechanism and the main feedback mechanism enables the immune feedback system to rapidly respond to foreign materials and to quickly stabilize the immune system.

To be more simply, suppose the activation and inhabitation are all imposed on the B cells, so the immune feedback theory can be described as that the activation effect on the B cells equal the difference between the activation of T_H cells and the inhabitation of T_S cells:

$$B(k) = T_H(k) - T_S(k) \tag{1}$$

$$T_H(k) = k_1\, \varepsilon(k) \tag{2}$$

$$T_S(k) = k_2 \{ f[\Delta B(k-d)]\}\, \varepsilon(k) \tag{3}$$

Where $\varepsilon(k)$ is the consistency of antigen at the k^{th} generation, k_1 is the stimulation factor, and K_2 is a suppression factor. $\Delta B(k-d)$ is the change of B cell's consistency and d is the delay-time of immune response.

$f(x)$ is a nonlinear function that represents the interaction between antibody which emerge from B cells and antigen. It is showed as followed:

$$f(x) = 1 - \exp(-x^2/a) \tag{4}$$

a: A parameter to change the functional form, $a < 0$. For a different value of a, the input output relationship of $f(x)$ is shown in Fig. 2.

From (2) and (3), we can obtain the relationship formula about the consistency of B cells and antigen. It is shown as follows:

$$B(k) = k_1\, \varepsilon(k) - k_2 \{ f[\Delta B(k-d)]\}\, \varepsilon(k)$$
$$= k\{1 - \eta f[\Delta B(k-d)]\, \varepsilon(k) \tag{5}$$

Where $k = k_1$ and $\eta = k_2 / k_1$. The parameter k is used to control the response speed, and the parameter η is used to control the stabilization effect. Therefore, the performance of the immune feedback law greatly depends on how these factors are selected.

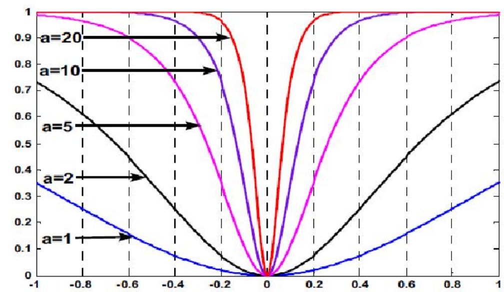

Figure 2. The effect of parameter a on f(x)

III. DESIGN OF FUZZY IMMUNE PID CONTROLLER

In this section, a controller inspired by the feedback mechanism of the immune system is proposed and called IMF controller. The table below shows the transformation between the immune system and the control system.

TABLE 2. COMPARISON BETWEEN ARTIFICIAL IMMUNE SYSTEM AND CONTROL SYSTEM

Immune system	Control system
The k^{th} generation reproduction of antigens and antibodies.	The k^{th} sampling time of discrete system.
$Ag(k)$ is the antigen concentration of k^{th} generation.	$e(k)$ is the deviation of the desired value and output value at the k^{th} sampling time.
$B(k)$ is the B cell concentration of the k^{th} generation.	$u(k)$ is the output value of controller at the k^{th} sampling instant.

Equation (5) can be considered a discrete-time feedback control law. When we directly apply this analogy to design a feedback controller, the obtained IMF controller is similar to a proportional controller whose gains are tuned by using its own output. Hence, the P-type IMF control law is as follows: [6]

$$u(k) = k\{1 - nf[\Delta u(k-d)]\}\, e(k)$$
$$= k_{pI}\, e(k) \tag{6}$$

Where $k\{1 - nf[\Delta u(k-d)]\} = k_{pI}$ is the nonlinear proportional gain of the IMF controller.

The Immune feedback controller is a nonlinear P-type controller like it is shown in (6). It cannot compensate for errors caused by noise or nonlinear interference so that it is not used alone, while the conventional PID control considers the past, present and future information of deviation comprehensively, therefore, it can further improve control performance of the system by connecting the immune feedback controller with the conventional PID controller.

Regular raising PID controller algorithm is as follows:

$$U_{PID} = u_{PID}(k-1) + k_p((e(k) - e(k-1)) + \frac{k_i}{k_p} e(k) + \frac{k_d}{k_p}(e(k) - 2e(k-1) + e(k-2)) \quad (7)$$

Where: k_p, k_i and k_d are coefficients of proportionality, integral and derivation respectively.

So the immune PID control algorithm is as follows:

$$u(k) = k_{pI}((e(k) - e(k-1)) + \frac{k_i}{k_p} e(k) + \frac{k_d}{k_p}(e(k) - 2e(k-1) + e(k-2))$$

For simplification [7], the final immune PID control algorithm can be written as:

$$u(k) = k_{pI}((e(k) - e(k-1)) + k_i' e(k) + k_d'(e(k) - 2e(k-1) + e(k-2)) \quad (8)$$

Considering the difficulties in the design of the nonlinear function of the immune controller in the inhibitive term, and taking advantage of the good approximation of fuzzy logic, a fuzzy controller is used to achieve the nonlinear function *f (x)*.

In this fuzzy controller design, there are two inputs and one output. The two input variables are the output of IMF controller $u(k)$ and its variation $\Delta u(k)$, while the output variable is the suppressing-quantity of *TS* cell $f(u(k), \Delta u(k))$.

Justifications of each input variable are five fuzzy sets which separately are: *NB, NS, ZE, PS* and *PB*; Justifications of the output variable are of seven fuzzy sets, which separately are: *NB, NM NS, ZE, PS, PM* and *PB*. The above membership functions are all defined in (-6,+6) range. According to the principle that the greater stimulation cells accept, the smaller inhibition ability cells have; the smaller stimulation cells accept, the greater inhibition ability cells have, fuzzy rules can as follows in table 3:

TABLE 3. FUZZY CONTROL RULE TABLE FOR ***f(x)***

$u(k)$	$\Delta u(k)$				
	NB	*NS*	*ZE*	*PS*	*PB*
NB	*PB*	*PB*	*PM*	*PS*	*ZE*
NS	*PB*	*PM*	*PS*	*ZE*	*NS*
ZE	*PM*	*PS*	*ZE*	*NS*	*NM*
PS	*PS*	*ZE*	*NS*	*NM*	*NB*
PB	*ZE*	*NS*	*NM*	*NB*	*NB*

The membership functions of input and output are as shown in figure 3 and 4.

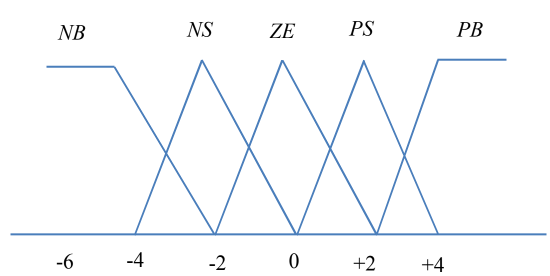

Figure 3. The two inputs membership functions

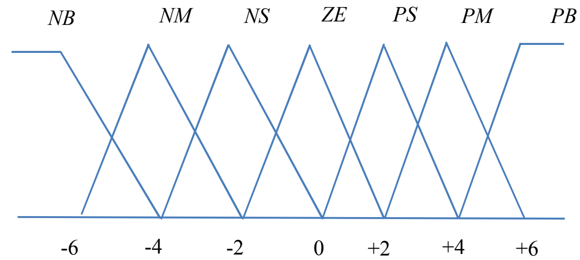

Figure 4. Output membership functions

As a result of the above designed rules and algorithms, the fuzzy immune PID block diagram shows in Fig. 5.

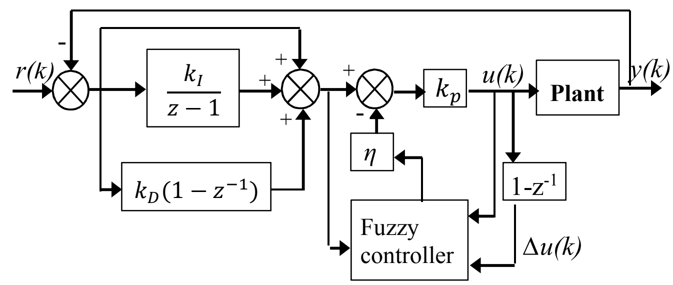

Figure 5. Block diagram of the fuzzy immune PID controller

IV. PARAMETER OPTIMIZATION BASED ON GENETIC ALGORITHM

As a result of the introduction of nonlinear parameter of K_{pI} in immune controller, the controller parameters of *k, n,* k_i and k_d are difficult to be determined with traditional analysis method. At present, there are many optimization methods, for example, simplex method as well as expert tuning method and so on. Although these methods have good optimization ability but they are mostly sensitive to initial values and easy to fall into local optimal solutions which result in optimization failure. Genetic algorithm [8, 9] is a global optimization method with parallel random search which simulates the genetic mechanisms and biological evolution in nature. It does not require any initial information and can obtain the global optimal solution through genetic evolution based only on the fitness function. Therefore, it is feasible to apply genetic algorithm into parameters optimization of the immune PID controller.

Steps to optimize the designed controller parameters according to genetic algorithm are as follows:

- Step1: Encode parameters and determine the approximate range of each parameter and the code length.
- Step2: Generate initial population.
- Step3: Design the fitness function. If binary encoding is used, it is need to decode. Individual is decode into the corresponding

parameter of immune controller and determine the optimal index function *J* with the parameter based on the specific performance requirements. The fitness function can be *F = 1/J*.

- Step4: selection operator, crossover operator and mutation operator are used for genetic operation to produce the next generation of population.
- Step5: determine whether the end conditions have been reached. If the end conditions have been reached, then end the genetic evolution; otherwise, return to step 4.

The objective function selected for the genetic optimization in this paper depends on the integration of error signal *e(t),* the control signal *u(t)* and the rise time t_u, which is described as:

$$J = \int w_1|e(t)| + w_2.u^2(t)dt + w_3.t_u \qquad (9)$$

Fig. 6 shows the fuzzy immune PID feedback system construction based on GA optimization, which is realized on Matlab.

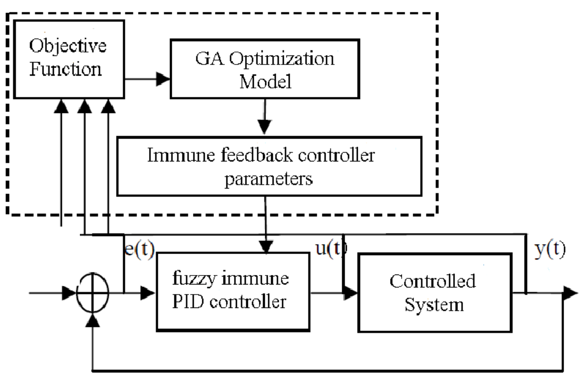

Figure 6. Construction of Fuzzy immune PID controller based on GA optimization

Some particularly important parameters of GA are the population size (number of individuals) and number of generations. If the number of chromosomes is too small, GA has fewer possibilities to perform crossover and only a small part of search space is explored. Small populations cause premature convergence. Large population size takes longer time to run but converges faster than smaller populations. A number of 100 individuals are used as a trade-off. The higher crossover rates lead to better relative fitness function values. A crossover rate of 0.90 was used. Zero mutation probability causes premature convergence to a suboptimal value. Higher mutation probabilities, on the other hand, cause fluctuations and disturb convergence. Generally, the mutation probability should be high enough to expand the search space, but low enough to bring about convergence. A mutation probability of 10% was used as a trade-off. The chosen GA operators and parameters are summarized in Table 4.

TABLE 4. GENETIC ALGORITHM OPERATORS AND PARAMETERS

Operator	Type	Parameter	Value
encoding	binary	Encoding precision	40
Crossover	Double point	Crossover rate	0.90
mutation	Bit inversion	Mutation rate	0.10
Fitness function	Linear ranking	Number of generation	50

IV. SIMULATION AND RESULTS

In order to illustrate the efficiency of the control strategy, a complex system which has characteristics of time variation and nonlinearity is chosen in this paper. The mathematical model of the controlled plant is described via a second-order plus time delay structure, given by:

$$G(s) = \frac{2(0.5s + 1)e^{-0.1s}}{(s + 1)(4s + 1)} \qquad (10)$$

The controlled system simulation modules are set up with MATLAB/Simulink to compare the PID controller with the developed fuzzy immune PID controller.

A step signal is used as the reference signal of the system. Both, the PID controller and the fuzzy immune PID controller parameters are obtained using the GA optimization and shown as below:

- PID controller coefficients:

  $k_p = 1.4233 \quad k_i = 0.4501 \quad k_d = 0.1952$

- Fuzzy immune PID controller coefficients:

  $k = 3.9908 \qquad \eta = 1.3862$

  $k_i^{'} = 7.7389 \quad k_d^{'} = 0.6002$

Simulation results are shown in fig. (7) to (10).

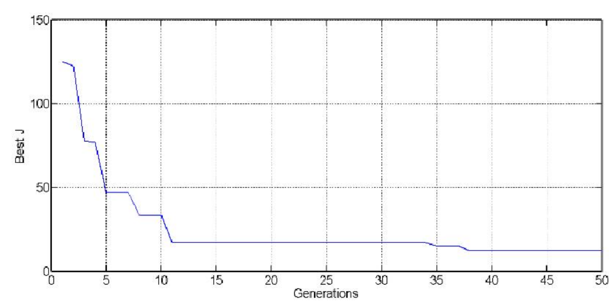

Figure 7. Parameter optimization process based on GA

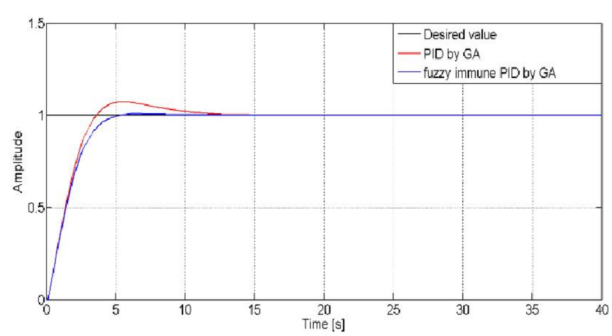

Figure 8. Step responses of the fuzzy immune PID controller and the conventional PID controller

Simulation curves in fig. 8 clearly show us that the overshoot of traditional PID feedback control system is large and the transition-time is long. When the fuzzy immune PID controller based on GA designed in this paper is applied to the control system, it can achieve a small acceptable overshoot with faster response speed and short transition-time.

In order to test the robustness and adaptability of the controller proposed in this paper, a step disturbance is added into the system and the response curves of anti-disturb capability are shown in fig. 9; in addition, the parameters of the model and delay time are changed by 15%, and the simulation result of output is as shown in fig. 10.

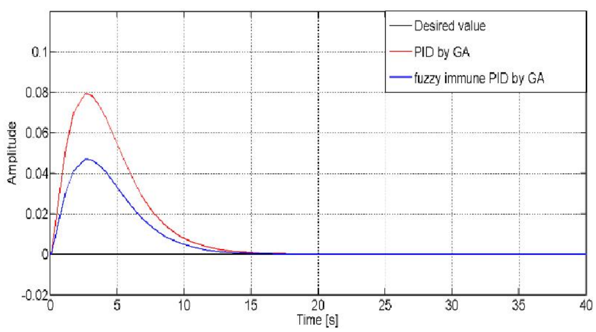

Figure 9. Simulation curves of anti-disturb capability

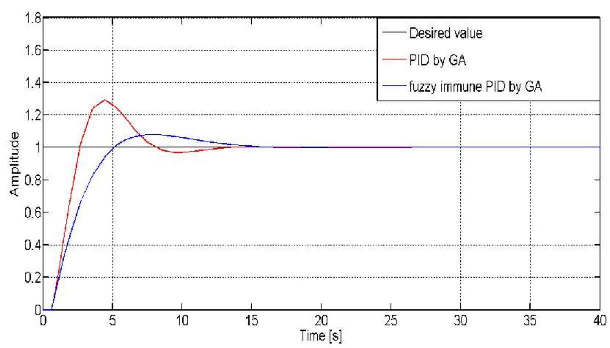

Figure 10. Step responses of the two control strategies when the parameters of model and delay time changed by 15%

As can be seen from the simulation curves in fig. 9, when the developed fuzzy immune PID controller is adopted and the system is impacted by external interference, it can restore to a stable status quickly, that is, robustness and stability are both better and anti-interference ability is improved. It is also well obvious in fig. 10 that when the parameters of the system and delay time changes, the fuzzy immune PID feedback control system can adapt better than the conventional PID controller to the new model which proves the good adaptability and strength of the designed control system.

V. Conclusion

According to the simulation results, we can conclude that the proposed fuzzy immune PID controller based on genetic optimization has better performances than the PID controller when it is applied on complex systems such as a nonlinear inertial system. When the controlled object is exposed to external factors or some disturbances, it is also able to overcome these effects and return to steady state quickly. The response of the system is fast and the control performance is superior to the traditional PID control. Hence, the proposed controller may be well applied on other complex systems.

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