IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 15, 2021, accepted December 24, 2021, date of publication December 27, 2021,
date of current version January 13, 2022.

Digital Object Identifier 10.1109/ACCESS.2021.3138910

Fuzzy-PID Strategy Based on PSO Optimization for pH Control in Water and Fertilizer Integration

CHANGXIN FU[1], XIAO MA[1], AND LIXIN ZHANG[1,2]
[1]College of Mechanical and Electrical Engineering, Shihezi University, Shihezi 832003, China
[2]Industrial Technology Research Institute, XPCC, Shihezi 832003, China

Corresponding author: Lixin Zhang (zhlx2001329@163.com)

This work was supported in part by the Natural Science Foundation of China under Grant 52065055.

ABSTRACT In the process of crop growth, irrational fertilizer application methods have caused waste of fertilizer resources and water, as well as damaged the soil's structure. To puzzle the above problems out, the research constructs the model of water-fertilizer machine by gathering relevant parameters in the field. Considering the system's plenty of defects and combining it with the MATLAB/simulink system, such as non-linearity, time-varying, large inertia, uncertain mathematical model and severe lag, a fuzzy proportional integral differential control based on particle swarm optimization is proposed in this paper for water and fertilizer integration system. Primarily, the research is done for precision fertilization control of fertilizer integration system and water, and the parameters of fuzzy proportional integral differential gain that schedules controllers are optimized through a particle swarm algorithm. The effectiveness of the suggested controller has been validated by comparing with the control algorithms (proportional integral differential control, fuzzy proportional integral differential control) commonly applied in current fertilizer application systems. Simulation experiments for this research are devised through MATLAB/Simulink simulation platform. Significant improvement in the system's tuning capabilities by incorporating particle swarm algorithm in the hysteretic non-linear system. Eventually, four control algorithms are experimentally validated in this research at different pH values through Experiments čáre designed in the experimental field. The outcomes demonstrate that the control algorithm in this paper possesses better regulation effect, smaller overshoot, excellent stability and more inadequate rising steady state time compared with the previous controls, which can enables precise control of the fertiliser system.

INDEX TERMS Integration of water and fertilizer, hysteretic system, pH value, fuzzy PID control, particle swarm optimization algorithm.

I. INTRODUCTION

Fertiliser's rational application is crucial to crops' growth [1]. The amount of fertilizer applied around the world is increasing but is not proportional to the increase in crop yields. Analysis of the traditional fertiliser application methods demonstrates that the principal reason for this is the low utilisation rate of fertilisers, which leads to an ineffective rise in food production [2]. Excessive fertiliser application can also damage the soil structure, diminish crop survival rates and cause economic costs [3]–[5]. The utilisation and absorption of fertilisers can be enhanced by regulation and rational proportioning of fertiliser concentrations by crops, thus saving increasing yields, decreasing environmental pollution and costs. Therefore, in order to ensure the normal development of the environment and agricultural resources, modern agricultural technology's development should shift from rough to intensive methods. Fertiliser integration technology and water can reasonably proportion the fertiliser concentration and apply fertiliser to crops in a demand-driven manner, which helps preserve water, salvage labour and enhance efficiency [6], [7].

In water fertiliser production, a quantity of crops' roots (e.g. flowers, blueberries, etc.) are suitable to an acidic environment and, as most mono-textured fertilisers are alkaline, the fertiliser solution's pH needs to be regulated throughout the irrigation preparation stage [8]–[10]. The fertiliser's pH is generally described by the pH value. The control of pH is a extremely intrinsically non-linear control and is an acknowledged difficulty in applications in all industries. Apart from

The associate editor coordinating the review of this manuscript and approving it for publication was Wonhee Kim.

the non-linearity of pH control in the fertiliser regulation process and water, the complexity of the fertiliser management procedure and water makes the pH control system also characterised by time variability, hysteresis and uncertainty, increasing control's difficulty. The current research on pH process control is concentrated on two aspects principally: control algorithm research and model research. pH neutral process models can depict the pH process' nature on the one hand, and lay the foundation for model-based control algorithms' design on the other. Model research's principal task is consequently to develop a satisfactory pH model. Mechanistic models, linearisation models, non-linear models, artificial intelligence models, etc. are included by the current modeling research on pH processes mainly [11]–[16].

In terms of control algorithm research, control approaches for non-linear models are focalised on feedback linearisation control, intelligent control, adaptive PID control and several other aspects principally. Considering the non-linearity and the large hysteresis of the fertilizer control system, the limitations of the conventional proportional integral differential control(PID) strategy, an intelligent adaptive control algorithm should to be proposed. To solve this problem. In literature [17], in view of the nonlinear and the time-delay characteristic in acid and alkali neutral process, this article proposed a kind of parameter self-adjusting Fuzzy-PID control method. An approach to it based on self-adjustive fuzzy PID was proposed in literature [18]. It is considered that the fuzzy reasoning doesn't rely on the accurate models, and can solve the affects brought by the nonlinear. In view of the large hysteresis, large inertia and uncertain mathematical model of the water and fertilizer integrated machine to adjust the pH value of water and fertilizer, literature [19] applies fuzzy control to water and fertilizer integrated equipment, and designs a fuzzy control system to adjust the pH value of water and fertilizer. The test proves that the system can meet the control requirements of pH adjustment during precise fertilization, and the system has smaller overshoot and stabilization time, 32% reduction in overshoot, 90 s reduction time, and stronger resistance, 90 s reduction of recovery time. Literature [20] mainly established a grey prediction model of water and focused on use of fertilizer in irrigation and implementation of fuzzy PID control. On a basis of grey prediction, the speed of water and fertilizer pump has been under fuzzy PID control. Considering many shortcomings of the pH control system of Haematococcus pluvialis algae fluid, such as non-linearity, time-varying, severe lag, large inertia and uncertain mathematical model. A method of pH control based on fuzzy PID is proposed in literature [21].

Fuzzy PID's improvement strategy can start from the structure, but also through algorithm optimization to attain the purpose of improving morphological improvements' performance index. In terms, In literature [22], a novel cascade fuzzy-proportional integral derivative incorporating filter (PIDN)-fractional order PIDN (FPIDN-FOPIDN) controller is offered as an expert control strategy to deal effectively with IPS's AGC issue. To deliver a quality power, an intelligent and efficient control algorithm is required by AGC system, Literature [23] proposed a novel fractional order electric power system's AGC fuzzy proportional-integral-derivative (FOFPID) controller. And the proposed approach's robustness is verified. Fuzzy gain that schedules controllers are proposed in literature [24] for interconnected electrical power systems' automatic generation control. Finally, the proposed approach's effectiveness is established for a two-area that is restructured reheat thermal power system.

Additionally, the related researchers concentrated on the fuzzy PID control based on algorithm optimization. Plenty of optimization algorithms have been proposed, such as the genetic algorithm, well-known neural network algorithm and ant colony algorithm [25]–[27]. The optimization of parameter tuning principally includes two aspects to consider: the first is to seek the global minimum point, and the second is to require a excellent convergence speed. Neural network parameter adjustment is currently applied in field of PID control, the advantage is that it can be optimized according to direction of gradient descent to the local minimum, and then obtain more beneficial control, Literature [28] through the neural network prediction control and fuzzy control, the dynamic management control system of time-varying nonlinear models to attain more precise control. But the disadvantage is straightforward to fall into the local minimum; and genetic algorithm needs to carry the process of encoding out and decoding design, in some instances these are extremely difficult, not straightforward to parallel processing, the computation is extremely large. However, particle swarm optimization (PSO) does not possess the complex ideas of coding and decoding crossover, variation and design process of genetic algorithm, no gradient information, faster operation efficiency, convenient implementation, swift convergence, etc.. PID control based on PSO rectification optimization is a more simple-minded and practical new rectification method, which greatly enhances the optimization level of the three parameters of PID, and performance index of the optimized control system is substantially sharpened, with tremendous potential value in the industrial field [29]–[31].

In light of the above, the extant work's significant contributions are as follows.

a) An improved fuzzy PID controller is proposed, which determines the choice of control method based on the range of errors.

b) PSO is brought into practice effectively to optimize the output three scaling parameters of the fuzzy controller.

c) Simulation and verification in MATLAB/Simulink platform, by comparing PID control, fuzzy control, fuzzy PID control and the control proposed in this paper, it is concluded that the performance index of the algorithm proposed in this study is better than other control algorithms.

d) In order to verify the dependability of the proposed algorithm put into production practice, this article devises relevant experimentations, which are implemented by data acquisition, reading to the host computer, passing signals and supplying decision commands. The experimental results illustrate that the proposed control approach has senior performance indicators compared to the other three controls.

The first portion analyzes the pH regulation procedure and establishes the corresponding mathematical model through the equilibrium equation; the second portion constructs the PID control, Fuzzy-PID control and the control proposed in this article respectively, selects the sort of affiliation function, the definition of the thesis domain and the creation of fuzzy rules, and in a similar way supplies implementation operation of the PSO algorithm finally; the third portion calculates selection of the relevant parameters, the comparison analysis of the three ultimately, this research works a validation examination based on the intelligent fertilization system out, and the examination outcomes lead to the conclusion section in following portion of this article.

II. SYSTEM STRUCTURE AND pH VALUE REGULATION PROCESS

A. SYSTEM COMPOSITION

According to the closure and disconnection of the corresponding solenoid valve, the system can realize irrigation, fertilization and irrigation and fertilization at the same time, whose overall structure is shown in Figure 1. The automatic fertilization system mainly consists of pH detection device, upper computer, solenoid valve, controller and fertilizer pump.

During the fertilizer mixing process, use the stirring motor to stir the fertilizer until it is homogeneous. On condition that the pH value that is evaluated by pH sensor does not satisfy the pH value that is called for crop growth, the acid tank solenoid valve will open and be mixed in the mixing tank through negative venturi pressure, and the pH value will be tested to obtain a reasonable pH value. The crop growth requirement will be reached by the pH value of the water and fertilizer in the tank.

B. ANALYSIS OF WATER AND FERTILIZER pH ADJUSTMENT PROCESS

In process of plant growth, soil pH and soil conductivity are significant indicators to evaluate the soil water and fertilizer demanded by plants, whereas the fertilizer concentration ratios of plants at distinct growth stages are varying, and the demands for soil pH and soil conductivity are likewise distinct. Therefore, fertilizing on demand guarantees that plants grow rapid and well. Soil pH and soil conductivity, as the core controlled objects of the fertilizer machine and water, are the control system's significant components. Due to the plant varying plant species, the implementation of fertilization irrigation might be distinct. The fertilization tasks and irrigation of the fertilizer machine therefore are different in different categories and need to be reflected differently in real time according to the environment. The fertiliser liquid for fertilisation and the irrigation water are generally weakly alkaline. The acid tank solenoid valve is opened and the pH in the fertiliser mix tank is made to satisfy the prerequisites needed to suit plant growth by controlling the time of the acid tank solenoid valve. Mathematical models simplify variable and complex systems, are easy to derive and have similarities to real-world prototypes. To facilitate the control of soil pH concentration and soil conductivity, a mathematical model should be therefore analysed. A schematic diagram of pH acid adjustment is shown in the figure 1. The fertiliser that mixes process can be considered an acid-base neutralisation process and can comprise a dynamic equation that describes the a static pH equation and state variables describing the neutralisation titration. Assuming that the volume of liquid ćõ stays constant before and after mixing the mixing tank in and that the water, acid and fertilizer liquid are uniformly mixed, the dynamic model of the fertiliser that mixes process when it reaches equilibrium, based on the principle of conservation of elements, can be deduced as follows [32].

$$V\frac{dN_a}{dt} = q_1N_1 - qN_a \tag{1}$$

$$V\frac{dN_c}{dt} = q_2N_2 + q_3N_3 - qN_c \tag{2}$$

$$q = q_1 + q_2 + q_3 \tag{3}$$

The meaning of the parameters in the formula is listed in Appendix A, the equation for the static pH titration is:

$$10^{-pH} - 10^{pH-14} - N_a + \frac{1}{1 + 10^{-lgK_m+pH-14}}N_c = 0 \tag{4}$$

where pH is the output variable of the process, pH $=$ $-$lg[H+]; K_m is the weak base's ionisation constant, $K_w = 10^{-14}$ for water. Equations(1)-(4)together form the mathematical model for field automatic fertiliser system was irrigated by pH regulation during fertiliser that mixed a drip in.

III. CONSTRUCTION OF THE CONTROL STRATEGIES

A. DESIGN OF THE PID CONTROLLER

In the fertiliser mixing process, when the mixing tank volume is fixed, the fertiliser stock's quality concentration and the flow rate of the pure water are the fundamental factors that affect the system. The fertiliser stock's quality concentration is affected by different fertiliser irrigation ratios; the pure water's quality pH is affected by varying control strategies. The PID controller designed for the drip irrigation field fertiliser application system works when the system is near the equilibrium point, and the proportional, differential and integral coefficients should not be overly large. The PID control system's block diagram is demonstrated in Figure 2. The difference between the output of the control object and the given signal is used as the error *err* of tracking, and the control rate *u* is derived from the proportional (P), integral (I), and differential(D) to regulate the performance index of the control object. Most of the control objects in industrial production are non-linear, with hysteresis links, high order or even time-varying, therefore making it extremely difficult to establish a fine mathematical control model, nevertheless, traditional PID is difficult to track the ideal target and the effect is

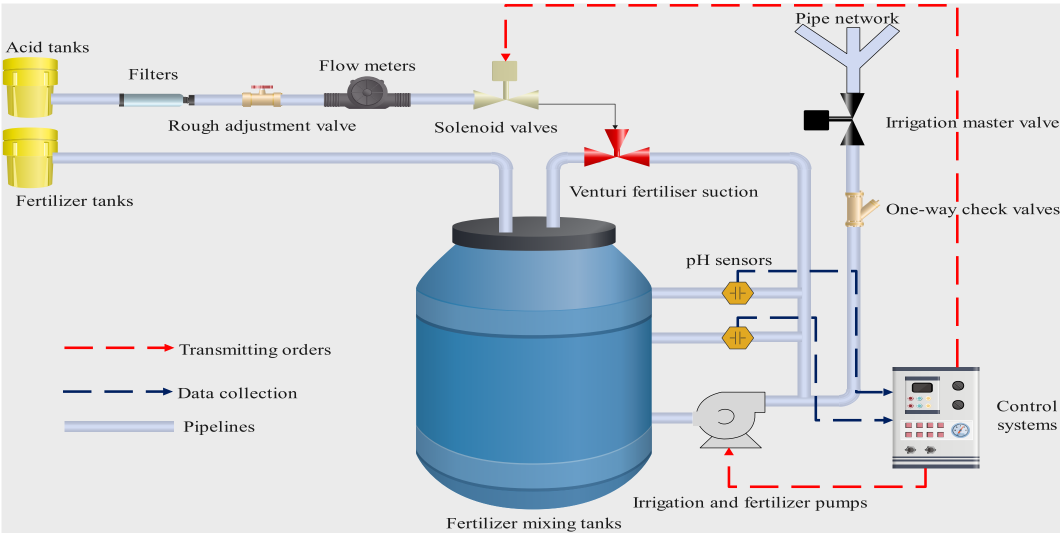

FIGURE 1. Diagram of the pH adjustment process.

inadequate. Besides, in actual production practice, traditional PID controllers' rectification process is often tedious, labour-intensive and time-consuming, and bad PID parameters are prone to, and the control results are badly performed.

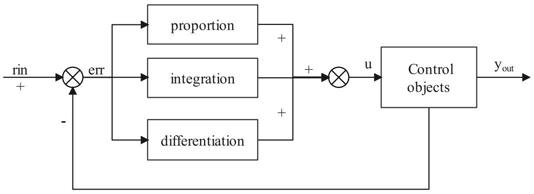

FIGURE 2. PID controller structure.

B. DESIGN OF FUZZY CONTROLLER

The classical Mamdani type two-dimensional fuzzy controller to control the nutrient solution's pH value in the mixing tank is used by the drip irrigation cotton field automatic fertiliser application system's fuzzy controller. The error of pH E and the deviation of change of pH error EC are therefore selected as the two input variables of this system, and the length of time U for the opening of the solenoid valve that controls the acid tank is selected as the output variable. The two-dimensional fuzzy control system's block diagram is shown in Figure 3. The difference between the output of the control object and the given signal is used as the tracked error e. The error e and the reciprocal of the error ec are used as the two inputs of the fuzzy control. The two sets of values are fuzzified by quantization factors, then fuzzy rules are set, fuzzy decisions are made, the read fuzzy information is defuzzified by scaling factors, and finally the transformed information is given to the control object. Where k_{ec} and k_e are the quantization factors for pH deviation change rate and pH deviation respectively; k_u is the scaling factor for the length of time the acid tank solenoid valve is open. The mathematical model of fuzzy control is as follows, where the meaning of the parameters is shown in Appendix A. And the structure of fuzzy control is schematically shown in Figure 3.

$$E_n = b_n - b_a \tag{5}$$

$$E_{n-1} = b_{n-1} - b_a \tag{6}$$

$$EC_n = \frac{E_n - E_{n-1}}{T} = \frac{b_n - b_{n-1}}{T} \tag{7}$$

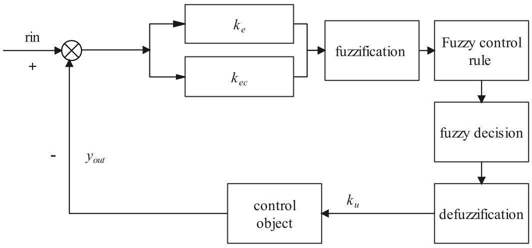

FIGURE 3. Fuzzy controller structure.

The affiliation function of the fuzzy controller's input and output are in the form of a triangle, and the area centre of gravity method is chosen for the clarification method. The affiliation value of two fuzzy subsets' intersection is generally taken as 0.2-0.7, which can make the system more sensitive and more stable.

According to fertilization control's fuzzy experience, the errors, error derivatives, and control rates mentioned in this research possess no special necessities in the affiliation function's selection, and the triangular affiliation function is used as study's object in this article. In order to compare different affiliation functions' influence on the trapezoidal affiliation function, the Gaussian affiliation and the control system function are selected as the research comparison's objects. The comparison consequences are demonstrated in Fig 4.

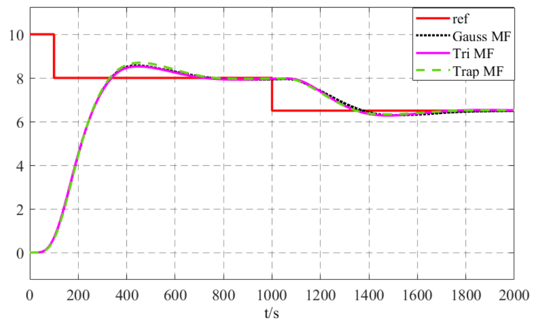

FIGURE 4. Comparative analysis of system control by different affiliation functions.

As is visible from Figure 4, the trapezoidal-type function's performance is pooer, the effect of triangular affiliation and Gaussian-type affiliation function effect nearly no difference. The reason for this is that the triangular affiliation function and the trapezoidal type affiliation function possess a large difference in shape, which will appear to be incompatible with the triangular affiliation function fuzzy rules. On the contrary, the Gaussian type affiliation function is similar in shape to the triangular affiliation function, so the same fuzzy rules are still valid.

To guarantee the designed fuzzy controller possesses a beneficial dynamic response, the linguistic values of pH deviation E and pH deviation rate of change EC are chosen as [NB, NM, NS, O, PS, PM, PB] and the fuzzy domains are $[-3, -2, -1, 0, 1, 2, 3]$. Where NB, NM, NS, denotes negative large, negative medium negative small, respectively, O is 0, It's no coincidence that PS, PM, PB expresses positive small, positive medium and positive large. For instance, when E is NB, it means that the current pH value is much smaller than the optimum pH value for plant growth; when EC is NB, it signifies that the next pH value will be much smaller than the presently measured pH value [33].

The selected linguistic values of the acid tank solenoid valve that opens duration are [NB, NS, O, PS, PB], and the corresponding fuzzy domain is $[-4, -2, 0, 2, 4]$. Where NB indicates the acid tank solenoid valve stays normally closed, NS implies that the acid tank solenoid valve is open for a longer short time, O indicates that the acid tank solenoid valve is open for a average time, PS points out that the acid tank solenoid valve is open for a longer medium time, and PB signifies that the acid tank solenoid valve is open for an extra long time.

The basic domain of pH deviation E is $[-8, 8]$, the elemental domain of pH deviation change EC is $[-1.8, 1.8]$ and the basic domain of the acid tank solenoid valve opening time U is $[-8, 8]$, the quantization factor of the input quantity pH deviation E is $k_e = 3/8 = 0.375$, the quantization factor of pH deviation change EC is $k_{ec} = 3/1.8 = 1.67$, and the output acid tank solenoid valve opening time U possesses a scaling factor of $k_u = 8/4 = 2$.

TABLE 1. Fuzzy rule tables based on fuzzy control.

E / EC	NB	NM	NS	O	PS	PM	PB
NB	NB	NB	NB	NB	NM	NM	NM
NM	NB	NB	NB	NB	NM	NM	NS
NS	NB	NB	NB	NB	NM	NS	O
O	NB	NB	NB	NB	NM	O	PS
PS	NB	NB	NB	NM	NS	PS	PM
PM	NB	NB	NB	NM	NS	PM	PB
PB	NB	NB	NB	NS	O	PB	PB

The fuzzy control statement can be summarised as "if E and EC then U", based on expert experience of the pH value of the appropriate fertiliser for plant growth. For instance, "if E is NB and EC is NB then U is NB", the statement means that when the pH deviation change and the pH deviation value rate are negative, the acid tank solenoid valve will then stay normally closed, the fuzzy control rule is composed of $7 \times 7 = 49$ conditional statements. The fuzzy control rules for controlling the length of time the acid tank solenoid valve is open are shown in Table 1. And the picture of the fuzzy control's affiliation function and the surface plot between them are shown in Figure 5 - Figure 7.

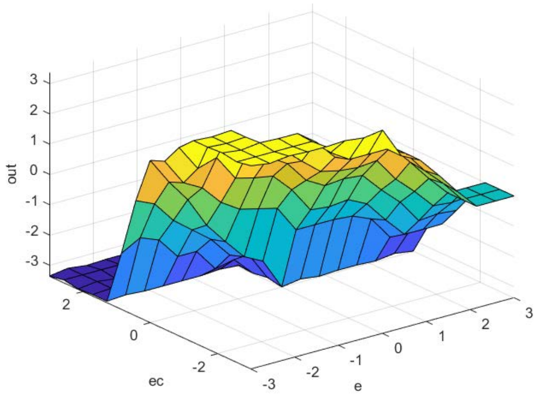

FIGURE 5. Fuzzy control surface diagram.

C. DESIGN OF FUZZY-PID COMPOSITE CONTROLLER

As fuzzy control cannot eliminate the system steady-state error, while the PID controller has the advantage of making the system steady-state error zero, the two are combined to design a fuzzy-PID composite controller, the structure principle of which is demonstrated in [Figure 8]. The difference between the output of the control object and the given signal in Figure 8 is used as the error e of tracking. Where, e_0 is the given error bounds. When $e < e_0$, the system is considered to be in a steady state and PID control is applied; otherwise, the system is considered to be in an obvious dynamic process and fuzzy control would be chosen. This allows the drip irrigation plant field fertiliser system to own both good dynamic performance and the advantage of a low steady-state error, making up for a dead zone's lack near the equilibrium point in the fuzzy control [34]–[38].

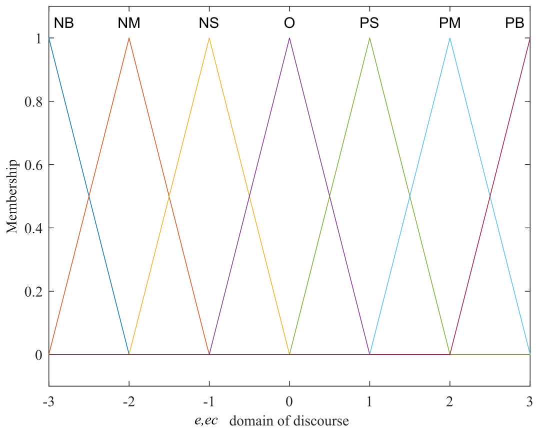

FIGURE 6. Plot of the error and the affiliation function for the rate of change of the error.

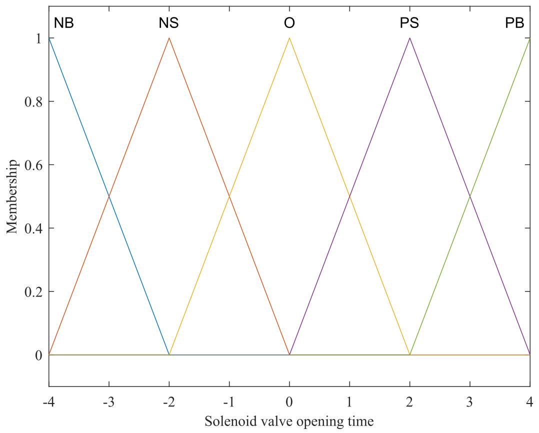

FIGURE 7. Solenoid valve opening subordinate degree function.

D. CONSTRUCTION OF A FUZZY-PID CONTROLLER BASED ON PSO OPTIMIZATION

Fertiliser fusion and sensor detection has a time lag, coupled with the influence of uncertainty factors of control schemes and varying fertiliser ratios in the fertiliser application process, it is difficult to accomplish the fertiliser control effect and desired water using traditional control methods. On the basis of the ordinary fuzzy PID control model, a particle swarm optimised objective function with time weights is added to the target loss function and I, D and the three parameters P are set as the K_i, K_d and three position variables K_p.

There is a certain grouping behaviour of organisms in nature, which is the most central source of the idea of particle swarm algorithm at the beginning. The particle swarm algorithm's core idea is group collaboration and sharing of information sources. It simulates the characteristics of birds' foraging behaviour by comparing them to particles, where multiple particles search for a target on a plane, and as they get closer to the target, they will share their information with other individuals, who will then gradually get closer and find the final optimal solution through this behaviour.

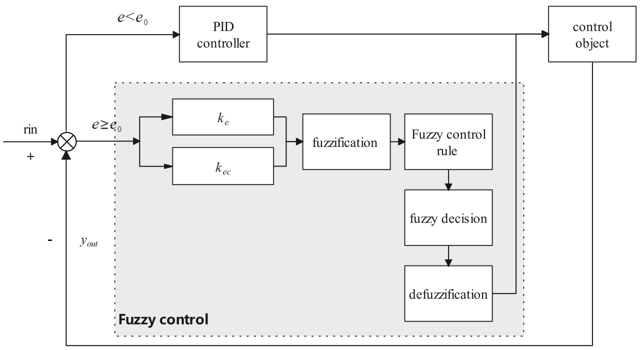

FIGURE 8. Fuzzy-PID controller structure.

In a $K - dimensional$ space, there is a swarm of n massless microparticles, each of which is a K-dimensional vector whose spatial position is denoted as $x_i = (x_{i1}, x_{i2}, \ldots, x_{ik})$, i = 1, 2,. n, and its $K - dimensional$ spatial position is the potential solution in the proposed issue, which is then brought into the objective optimisation function to calculate each particle's corresponding adaptation value, and evaluates the goodness of x_i according to the adaptation value. The i_{th} particle's velocity is also a $K-dimensional$ vector, denoted as $v_i = (v_{i1}, v_{i2}, \ldots, v_{ik})$; the position of the optimal adaptation value in the *ith* particle's iteration cycle is called that particle's historical best position, denoted as $p_i = (p_{i1}, p_{i2}, \ldots, p_{ik})$; the best position that is reached by the whole particle population is called global historical best position, denoted as $pg = (pg_1, pg_2, \ldots, pg_k)$, and the individual update iteration equation can be demonstrated as:

$$\begin{aligned} v_{ij}(t+1) = v_{ij}(t) &+ c_1 r_1(t)(p_{ij}(t) - x_{ij}(t)) \\ &+ c_2 r_2(t)(p_{gj} - x_{ij}(t)) \end{aligned} \tag{8}$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \tag{9}$$

where: the j_{th} dimension is denoted by subscript j, subscript i denotes the i_{th} microparticle, c_2 and c_1 are acceleration constants, usually between 0 and 2, the t_{th} generation is denoted by subscript t, and r_2 and r_1 are two independent random functions uniformly distributed.

Equation (8-9) is the microparticle update formula, which comprises last velocity of the microparticle, the individual's own perceived best vector term, and the population optimal vector term, respectively. This expression embodies particle swarms' idea fully, i.e. including the current state, individual experience, and population experience to determine how to move forwards next time, which is the standard expression and core idea of particle swarm optimisation.

Optimisation demands a corresponding mathematical model, which can comprise three parts: objective function, constraints and component variables.

In parameter optimisation's problem, it is necessary to specify the objective function's performance evaluation metrics, related to as the objective function. The determination of choosing different objective functions is to reflect the different dimensions of the evaluated system's performance indicators, preferably resulting in an evaluation function easy to compute. By choosing different objective functions for the evaluation, the parameters obtained after optimisation may differ for the same control system.

In this research, the absolute value integral type of error is chosen, the expression is listed:

$$J = \int_0^t |e(t)|dt \tag{10}$$

The equation adds the error's absolute value apart from the error's absolute value to eliminate the sign effect, and adds the weight of time t additionally so that errors occurring later in the over process can also be largely eliminated. The expression for the optimisation objective function that is chosen in this paper is taken. The optimisation process' structural diagram is illustrated in Figure 9, The difference between the output of the control object and the given signal in Figure 10 is used as the tracking error e. The error e and the inverse of the error ec are used as the input of the fuzzy control, and the fuzzy output is set to three, which represent the three parameters of the PID. The obtained parameters are optimized by the PSO algorithm and then iterated to the PID control system to complete the parameter adjustment of the whole control process.

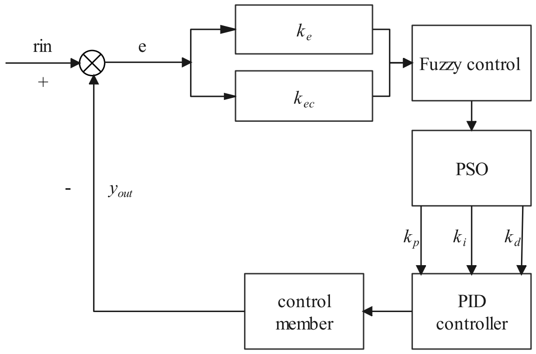

FIGURE 9. The proposed controller structure.

The fuzzy algorithm in this section is designed as follows. The form of the affiliation function applied to both output and input is triangle, and the area centre of gravity approach is chosen for the clarification method. The linguistic values of pH deviation E and the rate of change of pH deviation EC are chosen as [NB, NM, NS, Z, PS, PM, PB], and the fuzzy domains are $[-3, -2, -1, 0, 1, 2, 3]$. The three parameters K_p, K_d and K_i chosen as outputs correspond to linguistic values of [NB, NM, NS, Z, PS, PM, PB] and fuzzy domains of $[-3, -2, -1, 0, 1, 2, 3]$.

By summing the expert experience up on the appropriate fertiliser's pH value for plant growth, the fuzzy control statement was chosen in the form of "if ec and e then K_p, K_i and K_d", comprised $7 \times 7 = 49$ conditional statements. As indicated in the table 2, the fuzzy control rules for controlling the acid tank's three output parameters can be written.

The affiliation functions of both the pH deviation and the rate of change of the deviation for water fertilizer that is composed by Matlab's fuzzy inference system editor are illustrated in Figure 10, the affiliation functions of the output the water fertilizer pH fuzzy controller's variables are demonstrated in Figure 11, and the fuzzy rule 3D surface observation of K_p, K_d and K_i are indicated in Figure 12-14.

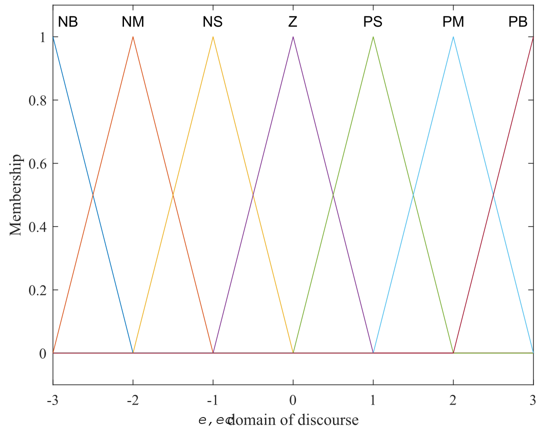

FIGURE 10. The error and the affiliation function for the rate of change of the error.

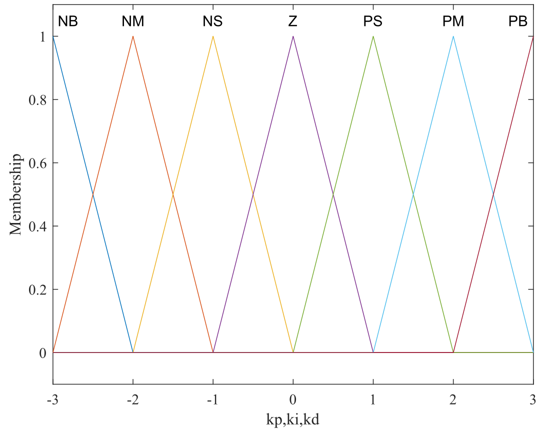

FIGURE 11. Affiliation functions for the three PID parameters.

Algorithm flow:

The basic particle swarm algorithm's flow is as follows.

(1) Particle swarm hyper parameters as well as random solutions are initialised.

(2) Set the PID control parameter values, run the system, and judge whether the system performance index meets the requirements.

(3) The optimal value is updated, if the particle adaptation value at the current time is higher than all previous ones.

(4) Iterate each particle, if the current particle is better than the best position adaptation value in the group, it is then as the group optimum.

(5) Update the position and velocity of the particle that is based on expressions 8 and 9.

TABLE 2. Fuzzy rule tables based on PSO fuzzy control.

E \ EC	NB	NM	NS	Z	PS	PM	PB
				k_p, k_i, k_d			
NB	PB,NB,PB	PB,NB,PB	PM,NM,PM	PM,NM,PM	PM,NM,PM	PB,NB,PB	PB,NB,PB
NM	PB,NB,PB	PB,NB,PM	PM,NM,PS	PM,NM,PS	PM,NM,PS	PB,NB,PM	PB,NB,PB
NS	PM,NM,PM	PS,NM,PS	PS,NS,Z	Z,NS,Z	PS,NS,Z	PM,NM,PS	PB,NB,PB
O	PM,NM,PM	PM,NM.PS	PS,NS,Z	Z,NS,Z	PS,NS,Z	PM,NM,PS	PM,NM,PM
PS	PM,NM,PM	PM,NM,PS	PS,NS,Z	PS,NS,Z	PS,NS,Z	PM,NM,PS	PM,NM,PM
PM	PB,NB,PB	PB,NB,PM	PM,NM,PS	PM,NM,PS	PM,NM,PM	PM,NB,PM	PB,NB,PB
PB	PB,NB,PB	PB,NB,PB	PM,NM,PM	PM,NM,PM	PM,NM,PM	PB,NB,PB	PB,NB,PB

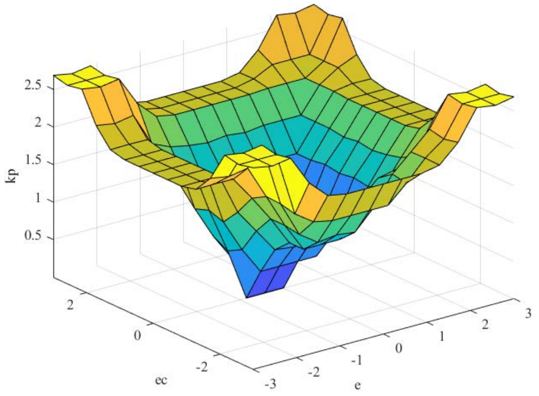

FIGURE 12. Fuzzy surface diagram for k_p.

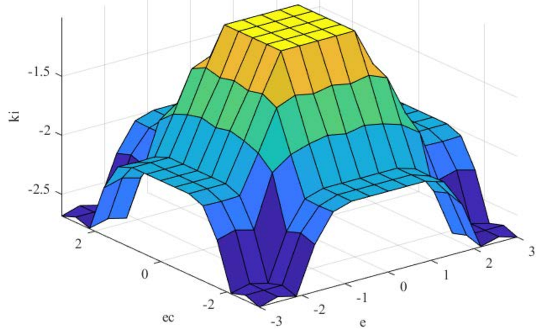

FIGURE 13. Fuzzy surface diagram for k_i.

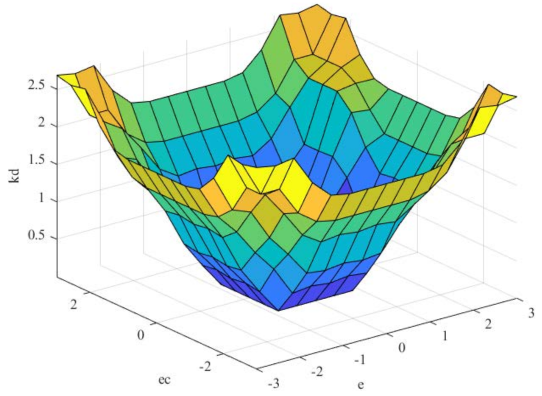

FIGURE 14. Fuzzy surface diagram for k_d.

(6) If the global adaptation value is satisfied to be sufficiently superior or the maximum number of iterations) is reached by the run, it then ends, otherwise it goes to step (1).

The particle swarm optimisation algorithm's flow is demonstrated in Figure 15.

IV. SIMULATION OF WATER AND FERTILIZER pH CONTROL IN FERTILIZER THAT BLENDS PROCESS

In order to verify the performance of the composite control scheme, PID control, fuzzy control, fuzzy-PID composite control and fuzzy-PID based on PSO control system models are established in MATLAB/Simulink respectively. The irrigation water's pH value is 8, the acid that is applied for pH adjustment is dilute hydrochloric acid with a concentration of 0.25 mol/L, the flow rate of the irrigation water into the mixing tank is 1.7 L /s and the system's delay time is 4s. Other relevant parameters for the model runs are shown in Appendix B.

The relevant parameters are brought into the simulation model and the tracking curves for different control algorithms are shown in Figure 16. In general, the performance index parameters of different control methods are extracted by plotting the table and tracking the pH = 8 reference signal as the research object. The control strategy that is designed in this research has a certain degree of decrease in regulation time and rise time, and the overshoot is effectively suppressed compared with the first two algorithms, which makes up for the shortcomings of PID control and fuzzy control and improves the fertiliser application process' accuracy. In theory, the pH regulation of fertiliser and water is optimised by this compound controller. A comparison of performance parameter values is shown in Table 3. In addition, anti-disturbance experiments are conducted for four different controls. $t = 1000$s, set a disturbance signal lasting 10s, it can be seen from Figure 17 that the fuzzy control, and the poor tracking of the composite control, the fluctuation in the regulation process of PID control, the control algorithm proposed in this paper, anti-disturbance ability. In the following stage, algorithms would be brought to experiment for validation.

TABLE 3. Comparison table of performance parameters of different control algorithms.

	PID control	Fuzzy control	Fuzzy-PID control	PSO Fuzzy-PID control
Rise time(s)	334.8	289.5	312.9	274
Peak value	11.38	8.561	8	8
Adjustment time(s)	858	665.9	450.7	384
Overshoot(%)	42.25	7.01	0	0

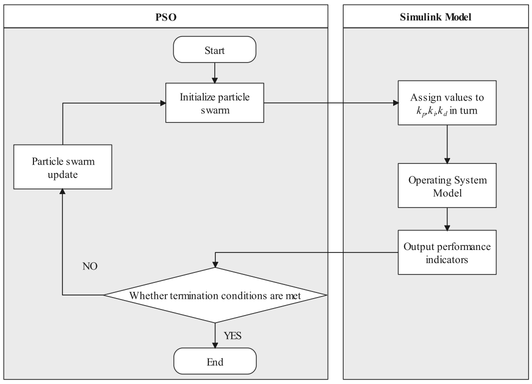

FIGURE 15. The flowchart of proposed controller.

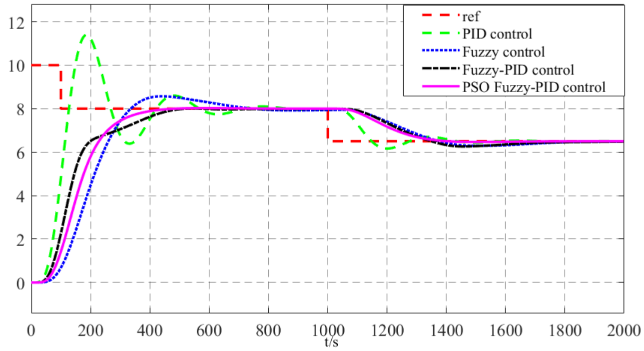

FIGURE 16. Comparative analysis chart for different controls.

V. EXPERIMENTAL VERIFICATION

To confirm the algorithm's stability, intelligent fertiliser application (Figure 18-19) trials are conducted. The schematic diagram of the device's construction is shown in Figure 17. The pH of the water of examination site is measured, and the control algorithm adopts float accuracy and a sampling period is 2s. Two dissimilar sets of pH values, 6 and 5, are set and an electromagnetic flow meter is selected to determine the instantaneous flow rate. The variable control test is read by sensors as well as a data acquisition card to test and compare different control strategies, setting the system flow rate at $6m^3/h$.

The experiment's relevant parameters are listed in Appendix B. The test is carried out to track the accuracy of fertiliser application's pH control by conventional PID control, fuzzy PID control and fuzzy PID based on PSO algorithm respectively. The water replenishment device is responsible for sustaining the mixing tank level at a constant level and replenishing the water for the fertiliser machine and intelligent water. The results of the test comparison are shown in Figures 20-21.

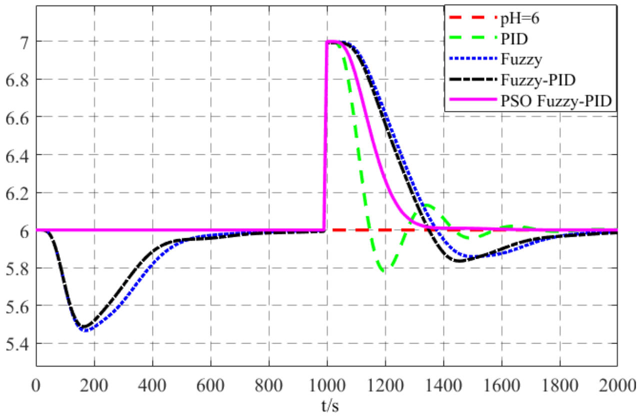

FIGURE 17. Different control algorithms anti-interference comparison picture.

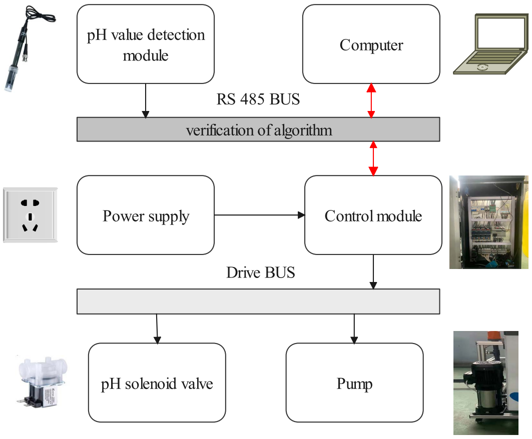

FIGURE 18. Smart fertiliser construction diagram.

As is visible from the graphs: for two different sets of pH tracking, the time to approach steady state for the four algorithms, PID control, fuzzy control, fuzzy PID control fuzzy PID based on PSO control, respectively are 618.6s, 766.8s, 618.9s, 466s when pH = 6. Performance parameters' table is illustrated in the Table 4. The PID control has the largest overshoot, the fuzzy control as well as the fuzzy PID control floats at 6 percentage points, and the control that is proposed in this paper is the smallest, with a reduction of 15.42 percentage points compared to the PID control and methods

FIGURE 19. Smart fertiliser diagram.

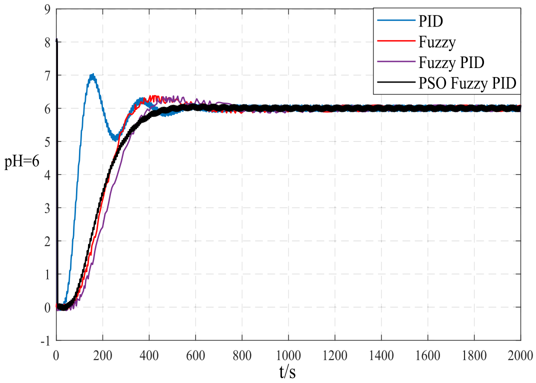

FIGURE 20. Experimental comparison analysis of different control algorithms at pH = 6.

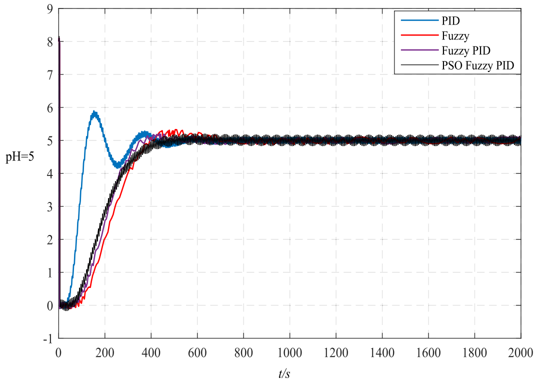

FIGURE 21. Experimental comparison analysis of different control algorithms at pH = 5.

are controlled by approximately 4 percentage points that are compared to the other two. For pH = 5, the approach to steady state times for the four controls similarly respectively are 545.4s, 630.7s, 374s and 538.9s. In comparison with the previous three controls, the overshoot of the proposed control algorithm is reduced by 2.48 percentage points substantially.

TABLE 4. Table of performance parameters at different pH values for different control methods.

	Control method	Rise time(s)	Peak value	Overshot(%)
pH=6	PID	61.05	7.015	16.9
	Fuzzy	221	6.384	6.4
	Fuzzy-PID	180	6.373	6.21
	PSO Fuzzy-PID	234	6.089	1.48
pH=5	PID	61.7	5.856	17.12
	Fuzzy	201.6	5.294	5.88
	Fuzzy-PID	205.5	5.178	3.56
	PSO Fuzzy-PID	216	5.124	2.48

VI. CONCLUSION

In this research, a fuzzy proportional integral differential controller based on particle swarm optimization is proposed to optimise the performance of fertiliser system, which consists of these disadvantages, such as non-linearity and hysteresis. The advantages of the designed controller are verified by comparing it with the control methods commonly applied for intelligent fertiliser systems. The provided controller's excellent dynamic performance has been verified through comparing data on quantities, such as response time, regulation time, rise time and overshoot for the four. The pH tracking experiment is designed by introducing four different control algorithms into the smart fertiliser system. The experimental outcomes demonstrate that the fuzzy PID algorithm based on particle swarm algorithm has better dynamic performance, and the tracking time is reduced by 92s and 152.4s compared to the traditional proportional integral differential control for both pH = 6 and pH = 5, respectively. At different pH values, the proposed control algorithm is effectively optimised compared with the first three algorithms for the performance parameters of response time, regulation time, rise time and overshoot amount, with more excellent steady-state performance. In future work, the studied fertiliser application system should consider other intelligent algorithm optimisation issues to considerably adapt to more complex regulation processes; this work can be extended to process conductivity values' control.

APPENDIX A
NOMENCLATURE

V = Volume of mixed liquid in the mixing tank.
N_a = Acid concentration of the liquid flowing out of the mixing tank.
q_1 = Flow rate of acid into the mixing tank.
N_1 = Acid concentration of the acid flowing into the mixing tank.
q = Total flow rate of liquid out of the mixing tank.
N_c = Alkali concentration of the liquid flowing out of the mixing tank.

q_2 = Flow rate of lye into the mixing tank.
N_2 = Concentration of alkali flowing into the mixing tank fertilizer.
q_3 = Flow rate of irrigation water into the mixing tank.
N_3 = Concentration of irrigation water flowing into the mixing tank.
b_a = The optimum pH of the fertilizer solution set for crop growth.
b_{n-1} = pH value of $n - 1_{th}$ test.
b_n = pH value of n_{th} test.
E_{n-1} = Deviation of the pH value from the set value for the $n - 1_{th}$ test.
E_n = Deviation of the pH value from the set value for the n_{th} test.
EC_n = Rate of change of deviation of the n_{th} test pH value.
T = Sampling time.

APPENDIX B
SYSTEM DATA

pH of irrigation water = 8;
HCL concentration = 0.2 mol/L;
Maximum output flow rate of the fertilizer applicator = $12m^3/h$;
Venturi rated flow = 110L/h;
Solenoid valve frequency = 50Hz;
Solenoid valve flow meter current signal = (4-20)mA;
$w = 0.6$, Inertia factor;
$c_1 = 2$, Acceleration factor;
Acceleration factor $c_2 = 2$, Acceleration factor;
Dim = 3, Dimension;
Swarmsize = 20, Particle swarm size;
MaxIter = 5, Maximum number of iterations;
MinFit = 0.1, Minimum adaptation value;
$k_p = 14.07$, PID control parameters;
$k_i = 0.43$, PID control parameters;
$k_d = 0$, PID control parameters.

REFERENCES

[1] F. Degryse, B. Ajiboye, R. Baird, and R. C. Da Silva, “Availability of fertiliser sulphate and elemental sulphur to canola in two consecutive crops,” *Plant Soil*, vol. 1, p. 420, Mar. 2017.
[2] P. Szulc, P. Barłóg, K. Ambroży-Deręgowska, I. Mejza, J. Kobus-Cisowska, and M. Ligaj, “Effect of phosphorus application technique on effectiveness indices of its use in maize cultivation,” *Plant, Soil Environ.*, vol. 66, no. No. 10, pp. 500–505, Oct. 2020.
[3] X. Hu and X. Chen, “Optimisation of fertiliser dissolution under differential pressure tank during fertigation,” *Biosystems Eng.*, vol. 206, pp. 79–93, Jun. 2021.
[4] Y. Chen, B. Wu, and Z. Jing, “Excessive fertiliser input in farmer-level soybean production: Evidence from the measurements of technical efficiency in Suihua City, China,” *J. Food, Agricult. Environ.*, vol. 9, nos. 3–4, pp. 230–235, 2011.
[5] B. Dubos, D. Snoeck, and A. Flori, “Excessive use of fertilizer can increase leaching processes and modify soil reserves in two ecuadorian oil palm plantations,” *Exp. Agricult.*, vol. 53, no. 2, pp. 255–268, Apr. 2017.
[6] B. Raoa, “Insufficient and excessive N fertilizer input reduces maize root mass across soil types,” *Field Crops Res.*, vol. 10, pp. 611–622, Mar. 2018.
[7] L. Ren, H. Zhang, S. Zhang, G. Fan, Y. Li, and Y. Song, “Experimental research on efficient irrigation system with mixed fertilizer in integration of water and fertilizer,” in *Proc. J. Phys., Conf.*, 2020, pp. 1004–1012.
[8] X. U. Lili, “Effects of integration of water and fertilizer on yield and quality of strawberry,” *J. Changjiang Vegetables*, vol. 6, pp. 24–40, Mar. 2019.
[9] S. Eich-Greatorex, T. A. Sogn, A. F. Øgaard, and I. Aasen, “Plant availability of inorganic and organic selenium fertiliser as influenced by soil organic matter content and pH,” *Nutrient Cycling Agroecosyst.*, vol. 79, no. 3, pp. 221–231, Oct. 2007.
[10] K. Phommasack, “The impact of pH on microbial community structures in a long-term fertiliser experiment Palace Leas plot,” *Carbene Chem.*, vol. 8, pp. 363–380, Apr. 2009.
[11] G. Chen, X. Zhang, and N. Li, “Novel method to simultaneously adjust the size and pH value of individual microdroplets in silicone oil,” *IEEE Access*, vol. 7, pp. 114183–114190, 2019.
[12] Z. K. N. Yin, “Variable universe fuzzy control of water-fertilizer mixing process in fertigation system under rotational irrigation situation,” *Trans. Chin. Soc. Agricult. Machinery*, vol. 7, pp. 73–85, Jun. 2016.
[13] W. Ren, M. Wang, and Q. Zhou, “Effect of soil pH and organic matter on desorption hysteresis of chlorimuron-ethyl in two typical Chinese soils,” *J. Soils Sediments*, vol. 11, no. 4, pp. 552–561, Jun. 2011.
[14] S. I. Hassan, M. M. Alam, U. Illahi, M. A. Al Ghamdi, and S. H. Almotiri, “A systematic review on monitoring and advanced control strategies in smart agriculture,” *IEEE Access*, vol. 1, p. 32517–32548, 2021.
[15] L. Shao, “Design and experiment on PLC control system of variable rate fertilizer,” *Trans. Chin. Soc. Agricult. Machinery*, vol. 11, pp. 84–94, Nov. 2007.
[16] C. Wu, X. Chen, Y. Han, and S. Zhang, “System modeling and control of automatically variable rate fertilizer applicator,” in *Proc. IEEE Int. Conf. Syst., Man Cybern.*, vol. 8, Oct. 2014, pp. 110611–110622.
[17] Z. K. N. Yin, “Variable universe fuzzy control of water-fertilizer mixing process in fertigation system under rotational irrigation situation,” *Trans. Chin. Soc. Agricult. Machinery*, vol. 3, pp. 62–73, Jul. 2016.
[18] L. Xiao-Yan, L. Li-Juan, and Y. Jin-Huan, “Study of self-adjustive fuzzy PID and simulation on pH value’s control,” *Meteorol., Hydrol. Mar. Instrum.*, vol. 4, pp. 56–64, Apr. 2018.
[19] L. Tu, W. Lijuan, H. Yuran, and H. Ran, “Research on pH control strategy of water and fertilizer integration based on fuzzy control,” *J. Chin. Agricult. Mechanization*, vol. 6, pp. 11–17, Aug. 2019.
[20] P. Bi and J. Zheng, “Study on application of grey prediction fuzzy PID control in water and fertilizer precision irrigation,” in *Proc. IEEE Int. Conf. Comput. Inf. Technol.*, Sep. 2014, pp. 789–791.
[21] S. Cui, X. Cai, Y. Zhang, X. Wu, and L. He, “Research on pH value control system of haematococcus pluvialis algae based on fuzzy PID algorithm,” in *Proc. J. Phys., Conf.*, 2020, Art. no. 012051.
[22] Y. Arya, P. Dahiya, E. Çelik, G. Sharma, H. Gözde, and I. Nasiruddin, “AGC performance amelioration in multi-area interconnected thermal and thermal-hydro-gas power systems using a novel controller,” *Eng. Sci. Technol., Int. J.*, vol. 24, no. 2, pp. 384–396, Apr. 2020.
[23] Y. Arya and N. Kumar, “BFOA-scaled fractional order fuzzy PID controller applied to AGC of multi-area multi-source electric power generating systems,” *Swarm Evol. Comput.*, vol. 32, pp. 202–218, Feb. 2017.
[24] Y. Arya and N. Kumar, “Fuzzy gain scheduling controllers for automatic generation control of two-area interconnected electrical power systems,” *Electric Power Compon. Syst.*, vol. 44, no. 7, pp. 737–751, Apr. 2016.
[25] G. A. Rovithakis, M. Maniadakis, and M. Zervakis, “A hybrid neural network/genetic algorithm approach to optimizing feature extraction for signal classification,” *IEEE Trans. Syst., Man, Cybern., B (Cybern.)*, vol. 34, no. 1, pp. 695–703, Feb. 2004.
[26] J. Wang, Y. Zhu, R. Qi, X. Zheng, and W. Li, “Adaptive PID control of multi-DOF industrial robot based on neural network,” *J. Ambient Intell. Humanized Comput.*, vol. 11, no. 6, pp. 95–102, 2020.
[27] K. Vanchinathan and N. Selvaganesan, “Adaptive fractional order PID controller tuning for brushless DC motor using artificial bee colony algorithm,” *Results Control Optim.*, vol. 4, no. 6, pp. 78–91, 2021.
[28] F. Sun, W. Ma, H. Li, and S. Wang, “Research on water-fertilizer integrated technology based on neural network prediction and fuzzy control,” in *Proc. IOP Conf.: Earth Environ. Sci.*, vol. 10, 2018, pp. 24–30.
[29] H. Feng, W. Ma, C. Yin, and D. Cao, “Trajectory control of electro-hydraulic position servo system using improved PSO-PID controller,” *Automat. Construct.*, vol. 127, no. 7, pp. 37–46, 2020.
[30] R. Yang, Y. Liu, Y. Yu, X. He, and H. Li, “Hybrid improved particle swarm optimization-cuckoo search optimized fuzzy PID controller for micro gas turbine,” *Energy Rep.*, vol. 7, pp. 5446–5454, Nov. 2021.

[31] Y. Yu, Y. Xu, F. Wang, W. Li, X. Mai, and H. Wu, "Adsorption control of a pipeline robot based on improved PSO algorithm," *Complex Intell. Syst.*, vol. 4, pp. 964–977, Aug. 2020.
[32] R. A. Wright and C. Kravaris, "Nonlinear control of pH processes using the strong acid equivalent," *Ind. Eng. Chem. Res.*, vol. 30, no. 7, pp. 1561–1572, Jul. 1991.
[33] S. Q. Che, "Simulation and application of automatic irrigation system based on fuzzy control," *Mod. Machinery*, vol. 6, pp. 4–10, May 2016.
[34] M. C. Heredia-Molinero, J. Sánchez-Prieto, J. V. Briongos, and M. C. Palancar, "Feedback PID-like fuzzy controller for pH regulatory control near the equivalence point," *J. Process Control*, vol. 24, no. 7, pp. 1023–1037, Jul. 2014.
[35] Y. Liu, K. Fan, and Q. Ouyang, "Intelligent traction control method based on model predictive fuzzy PID control and online optimization for permanent magnetic maglev trains," *IEEE Access*, vol. 7, pp. 29032–29046, 2021.
[36] Y. Xiao, A. Yu, H. Qi, Y. Jiang, W. Zhou, and N. Gao, "Research on the tension control method of lithium battery electrode mill based on GA optimized Fuzzy PID," *J. Intell. Fuzzy Syst.*, vol. 6, pp. 1–24, Jan. 2021.
[37] M. Aldhaifallah, S. Alsabbah, and M. Al-Jarrah, "Design of multiregional supervisory fuzzy PID control of pH reactors," *J. Control Sci. Eng.*, vol. 2, pp. 156–167, Jan. 2015.
[38] O. Naseer and A. A. Khan, "Hybrid fuzzy logic and PID controller for pH neutralization pilot plant," *Int. J. Fuzzy Logic Syst.*, vol. 10, pp. 17–25, Apr. 2020.

CHANGXIN FU was born in Henan, China, in 1995. He received the B.E. degree in electrical engineering from Henan Normal University, Henan, in 2017. He is currently pursuing the M.E. and Ph.D. degrees in mechanical and electrical engineering from Shihezi University, Xinjiang, China. He joins the National Natural Science of Foundation of China. His research interests include motor control and smart micro-grid.

XIAO MA was born in Henan, China, in 1991. She received the B.E. and M.E. degrees from the School of Mechanical Engineering and Automation, North China University of Water Resources and Electric Power, Henan. She is currently pursuing the Ph.D. degree in mechanical and electrical engineering from Shihezi University, Xinjiang, China. She joins the National Natural Science of Foundation of China. Her research interests include electrical engineering and smart micro-grid.

LIXIN ZHANG was born in Shandong, China, in 1967. He received the Ph.D. degree from Xi'an University of Technology, Mechanical and Electronic Engineering. He is currently a Professor. He is also the Vice President of the School of Mechanical and Electrical Engineering, Shihezi University. He is the Head of the first-level discipline of mechanical engineering at the School of Mechanical and Electrical Engineering, Shihezi University, and the specialty of mechanical design, manufacturing and automation. His research interests include photovoltaic power generation and mechanical engineering. He is an Editorial Board Member of *Journal of Shihezi University* (Natural Science Edition) and a Correspondence Reviewer of the Department of Engineering and Materials Science, National Natural Science Foundation of China.

• • •