IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received April 30, 2020, accepted May 5, 2020, date of publication May 20, 2020, date of current version June 1, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2994105

Design and Implementation of Novel Fractional-Order Controllers for Stabilized Platforms

JIE ZHANG[1,2], ZHAOPENG JIN[3], YANZHI ZHAO[3], YINGGAN TANG[2], FUCAI LIU[2], YAO LU[1,2], AND PENGCHENG LIU[4], (Member, IEEE)

[1]Liren College, Yanshan University, Qinhuangdao 066004, China
[2]Institute of Electrical Engineering, Yanshan University, Qinhuangdao 066004, China
[3]Key Laboratory of Parallel Robot and Mechatronic System, Yanshan University, Qinhuangdao 066004, China
[4]Department of Computer Science, University of York, York YO10 5GH, U.K.

Corresponding authors: Zhaopeng Jin (zhaopengjin@stumail.ysu.edu.cn), Yanzhi Zhao (yzzhao@ysu.edu.cn), and Yinggan Tang (ygtang@ysu.edu.cn)

This work was supported in part by the National Key Research and Development Program under Grant 2017YFE0112200, in part by the Natural Science Foundation of Hebei Province under Grant E2018203436, in part by the Science Technology Research of Higher Education of Hebei Province under Grant ZD2018024, and in part by Guangdong Province Jihua Laboratory under Grant Y80311W180.

ABSTRACT As a position servo system to isolate disturbance from its carrier, stabilized platform requires high-precision and high-adaptability control. However, conventional integer-order PID (IOPID) control fails to meet that requirement. In this paper, a new controller design scheme is proposed for stabilized platform based on fractional calculus. The designed controller is called fractional-order PID (FOPID) controller, which has two extra parameters compared to conventional PID controller. On one hand, it provides more degrees of freedom to design FOPID controller. On the other hand, its differential order and integral order provides more flexibility to tune the controller performance. Therefore, a design method of FOPID controller based on dynamic software modeling is presented. To obtain the ideal controller's parameters, the particle swarm optimization (PSO) bionic algorithm is used to optimize an objective function. In addition, software simulation platform and hardware experiment system are built to design and test the FOPID controller. Finally, the results of simulation and experiment are included to show the effectiveness of the new control method.

INDEX TERMS Stabilized platform, fractional-order PID, tuning method, particle swarm optimization.

I. INTRODUCTION

Capable of isolating instruments and equipment from external interference in harsh environments, the stabilized platforms have been applied in many fields ranging from national defense and military to rescue operations [1]–[3]. In national defense and military fields, stabilized platforms are used to achieve a dynamic and stabilized strike of fire control systems in complex combat environments for many countries. In industry, stabilized platforms are the top priority for dynamic rotation guidance of mining tools. In offshore oil extraction operations, stabilized platforms not only isolate the interference of the waves, but also assist the tools to complete the desired trajectory of drilling. Furthermore, in the course of rescue operation, stabilized platforms isolate the complex road conditions such as bumps, accelerations, decelerations and sharp turns during the ambulance driving process. The on-board self-balancing ambulance platform can actively achieve dynamic stability in space and provide relatively stabilized rescue transportation for the injured surroundings.

The high-performance of the stabilized platforms in the above applications is mainly determined by their control methods which have become one of the recent research hotspots. Abdo *et al.* [4] proposed a fuzzy PID controller for a two-axis gimbal system of two axes gimbal system, which can isolate the interference of the sensor and the working environment. Mao *et al.* [5] proposed a continuous finite time sliding mode control method with cascade control structure in order to improve the dynamic response and anti-interference ability of the inertial stabilization platform. Bai and Zhang [6] demonstrated an active disturbance rejection control based on

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

least mean square for aerial remote sensing stabilized imaging. Fang *et al.* [7] proposed an adaptive decoupling control system based on neural network to improve the tracking and stability performance of stabilized platforms.

Seen from the above researches, the conventional PID control method is widely used in the current industrial process control because of its simplicity and applicability. On this basis, more modern control theories and intelligent control theories have also been applied to stabilized platforms, such as fuzzy control [4], synovial film control [5], auto-disturbance control [6], and neural network control [7], etc [8]. However, characterized by non-linearity, time-varying and parameter uncertainty under the disturbance of multiple sources from outside, the stabilized platform requires a control method with high accuracy and high stability in a complex environment. Zhou *et al.* [9] added a non-linear state error feedback to active disturbance rejection control scheme and obtained good anti-interference ability. Wu and Dong [10] proposed an adaptive controller for the high-precision photoelectric gyroscope stabilization platform based on a new continuous differentiable nonlinear friction model. Although corresponding solutions are proposed to solve the problems of model nonlinearity and time variability, the above methods still have disadvantage on insufficient applicability and difficult application in practical engineering.

Compared with integer-order, the differential operators of the fractional-order calculation are an extension of integer-order calculation, which are global and infinitely-dimensional. Fractional-order differential can reflect not only the system information at the current time, but also the system at a certain time in history information. When describing many non-linear physical systems such as the data flow in network communication and the properties of non-linear materials such as rubber isolators, the description of fractional-order models is more accurate. Therefore, fractional-order calculations have attracted more attention with the development of computer technology. The controller designed according to fractional-order calculations has more tuning freedom, a wider parameter range and a significant improvement in robustness.

In view of this, the research on the application of fractional-order operations in the field of machinery has also gradually increased [11]. Compared with traditional integer-order controllers, fractional-order controllers have wider applications and better performance. It is also shown that the fractional-order control has indeed robust compensation effect on pole assignment caused by space relative acceleration. Muresan *et al.* [12] proposed the Non Rational Transfer Function (NRTF) approximation, which is successfully in implementing fractional order systems. It can offer better results compared to the two of the most widely used approximation methods. Mujumdar *et al.* [13] studied the application of a fractional-order theory in the control and state estimation of a class of unsteady systems and selected a single-link flexible manipulator as an experimental object. The study found that the fractional-order model can better describe system, and this kind of fractional sliding mode observer can provide robust noiseless estimation for the controller. Sun and Ma [14] proposed an adaptive fractional-order terminal sliding mode control strategy to solve the tracking control problem of linear motors. Under the uncertain situation of the controlled system, the control with high tracking accuracy and fast response speed was obtained. Chen *et al.* [15] researched an adaptive fuzzy fractional-order sliding mode control for a permanent magnet synchronous motor system, which improved the anti-interference ability of the system and suppressed the phenomenon. The experiments proved that the proposed control method has good performance and robustness when driving a permanent magnet synchronous motor system. It can be seen that the fractional-order controller has better tracking and system stability in the case of controlling complex non-linear objects and has great prospects for application in the mechanical field because of its inherent advantages.

Although fractional-order theory has many applications in the mechanical field [16], [17], there is still a lot of research gap for its application in stabilized platforms. Since fractional-order controllers have more parameters, parameter tuning is a common difficulty in controller design. In the case of a large number of parameters, the traditional trial and error method not only takes a long time, but also may not be able to find the optimal parameters. A lot of research have been done in this area in order to get a better tuning method [18]. Birs *et al.* [19] focus on general tuning procedures, especially for the fractional order proportional integral derivative controller. Juchem *et al.* [20] proposed a tuning methodology of fractional-order PI controller based on the Kissing Circle(KC) method for those systems which are highly-coupled and Multiple-Input Multiple-Output(MIMO). Bingul and Karahan [21] studied the performance of FOPID controller and evolutionary algorithm in robot trajectory control. The PSO and GA algorithm was used in the FOPID tuning process. Copot *et al.* [22] adopted genetic algorithm and automatic tuning algorithm to solve the parameter tuning problem for stabilized platform. However, applying FOPID controllers to engineering practice still faces many challenges. Due to the unknown external environment and the uncertainties in the motion of the controlled object, many researches are still stuck in the software simulation and fail to achieve good control effect in the actual engineering requirements. Aiming at the above problems, this paper intends to use a particle swarm optimization bionic algorithm to find the optimal controller parameters through successive iterations. A fractional order controller for stabilized platform with fast stability and strong adaptability is designed and applied to the practical experiment.

The rest of this paper is organized as follows: Section II introduces the configuration of stabilized platform and its three-dimensional dynamic model is constructed. Section III introduces the mathematical definition of fractional-order theory and the transfer function form of fractional-order

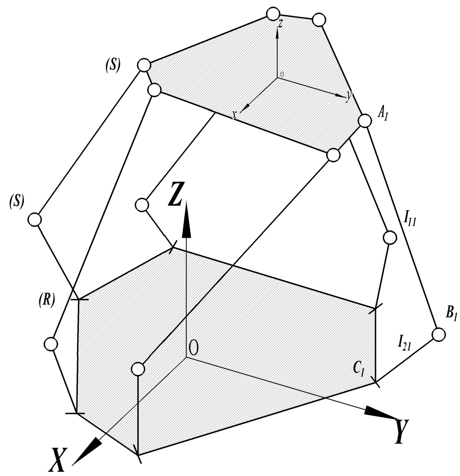


FIGURE 1. **Mechanism sketch.**

controllers. The simulation model about the controller was built by Simulink software and the parameters of the controller were calculated iteratively by particle swarm optimization. Section IV conducts three groups of experiment about the novel fractional controller: A comparison experiment between fractional-order and integer-order PID controller and a stability effect experiment under external disturbance was performed. Finally, a hardware model of a stabilized platform was built and the feasibility in practical application was tested through the practicality experiment. Section V draws conclusions.

II. STEWART STABILIZED PLATFORMS

Stabilized platforms are generally divided into parallel platforms and series platforms according to their configurations. Parallel stabilized platform has the advantages of high rigidity and strong bearing capacity. Occupying a small space, each drive is load-balanced and is easy to achieve fast response. Compared with other parallel mechanisms, the Stewart platform has the advantages of simple, compact structure, good symmetry and easy control.

A. STRUCTURAL PRINCIPLE

In order to establish the relationship between the six servo drives and the collected posture information of the upper platform, the inverse solution of the mechanism needs to be obtained. Simplify the kinematics mechanism of the parallel stabilized platform. A dynamic coordinate system o-xyz and a fixed coordinate system O-XYZ is established at the center points of the upper and lower platforms respectively. As shown in Figure 1.

In this paper, the closed-loop vector method is used to obtain the inverse solution of the mechanism. The specific solution process is not repeated and the concise expression of the inverse solution is as follows:

$$\theta_i = 2\arctan\frac{p_z \pm \sqrt{p_z^2 + W^2 - V^2}}{V + W} \tag{1}$$

FIGURE 2. **Six degree of freedom stabilized platform ADMAS model.**

where,

$$\begin{aligned} W &= M\cos\phi_{1i} + N\sin\phi_{2i} \\ V &= \frac{l_2^2 + M^2 + N^2 + p_x^2 - l_1^2}{2l_2} \\ M &= -(p_x + r_o\cos\phi_{2i} - R_o\cos(\phi_{1i})) \\ N &= p_y + r_o\sin\phi_{2i} - R_o\sin phi_{1i} \end{aligned}$$

In the formula, p_x, p_y and p_z are the position of the upper platform reference point relative to the lower platform; r_o and R_o are the radius of the circumscribed circle of the upper and lower platforms; ϕ_{1i} and θ_i are the rotation input angles of the branch drive lever; l_1 and l_2 are the lengths of the two vectors in the closed-loop vector method.

Through the establishment of the inverse solution formula for the kinematics of the mechanism, the steering angle parameters of the steering gear leveling on the driving platform can be calculated in real time. Obviously, using the inverse solution formula alone cannot obtain better stability effects. It is necessary to choose a suitable control method to decide how to maintain balance.

B. DYNAMIC MODEL

The ADMAS software [23] is used to build a three-dimensional model of the experimental platform, as shown in Figure 2. By adding kinematic pairs and corresponding drives, a dynamic model is constructed, which cannot only co-simulate with Simulink and lay the foundation for subsequent work, but also can add various types of external disturbances directly into the model.

Through the control plug-in in ADMAS, the three-dimensional model can be converted into an m-file format and the corresponding mathematical model can be imported into the main workspace and Simulink of Matlab. After this, the dynamic model of the stabilized platform can be called by simulation experiments.

III. DESIGN OF FRACTIONAL-ORDER PID CONTROLLER

The parallel mechanism is a multi-dimensional input, multi-dimensional output, strong coupling and highly nonlinear complex control system. In order to improve the performance

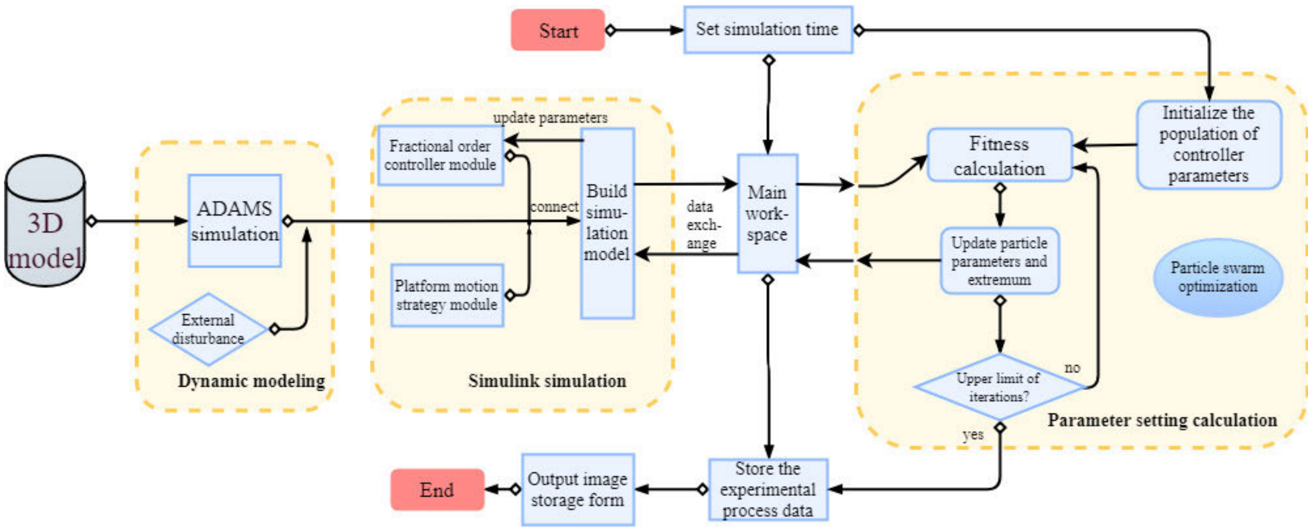


FIGURE 3. Simulation flowchart.

of the stabilized platform, this article designs the FOPID controller by simulation. The simulation process is shown in Figure 3. The main work includes dynamic modeling based on ADMAS, simulation model based on Simulink, controller parameter tuning based on an improved particle swarm optimization algorithm and simulation experiment.

A. MATHMATICAL BACKGROUND

1) DEFINITION OF FRACTIONAL CALCULUS

The definition of fractional calculus has already been given at the end of the nineteenth century. There are many definitions of it, the two most commonly used [24], [25] including the Riemann-Liouville definition and Grunwald-Letnikov definition are introduced in this article:

First form, the Riemann-Liouville definition is given as:

$$ {}_aD_t^{\alpha} f(t) = \frac{1}{\Gamma(m-\alpha)} (\frac{d}{dt})^m \int_a^t \frac{f(\tau)}{(t-\tau)^{1-(m-\alpha)}} d\tau \quad (2) $$

Second form, the Grünwald-Letnikov definition is given as:

$$ {}_aD_t^{\alpha} f(t) = \lim_{h\to 0} \frac{1}{\Gamma(\alpha)h^{\alpha}} \sum_{k=0}^{(t-a)/h} \frac{\Gamma(\alpha+k)}{(k+1)} f(t-kh) \quad (3) $$

where,

$$ \binom{n}{r} = \frac{\Gamma(\alpha+k)}{\Gamma(k+1)} \quad (4) $$

The operator used in the above two formulas ${}_aD_t^{\alpha}$, where a and t represent the upper and lower limits of calculus respectively, α is the order of calculus. A positive number indicates the differential link and a negative number indicates the integral link.

Since the theory of fractional calculus was introduced into engineering applications, its ability to accurately describe certain physical phenomena has attracted widespread attention from many researchers. In the field of engineering, many related studies have proved that fractional-order has better stability and superiority than traditional integer solutions.

2) TRANSFER FUNCTION OF THE CONTROLLER

In the design process of the controller, the relevant operator can be used to describe the model of the controller. For IOPID and FOPID controllers, the transfer function forms are as follows:

$$ G_i(s) = K_p + K_i s + K_d \quad (5) $$
$$ G_f(s) = K'_p + K'_i s^{-\lambda} + K'_d s^{\mu} \quad (6) $$

where, λ and μ are fractional orders of integrals and derivatives.

B. SIMULATION MODEL BASED ON SIMULINK SOFTWARE

Simulink is a simulation tool in Matlab [26], which is widely used in the process of modeling, simulation and analysis of dynamic systems such as digital signal processing and control theory. The platform dynamics model established in the previous section is called in Simulink. The simulation diagram is shown in Figure 4.

Where, the strategy1 module is implemented by Simulink programming based on the inverse mechanism formula obtained in Section II-A. It can calculate the steering angle required to level the upper platform.

The controller module designed in this article is encapsulated in the controller module. The type of controller can be modified by replacing the module and the parameters of the controller can be changed by modifying the parameters in the module. The corresponding parameters of fractional-order control are defined as Kp, Ki, Kd, λ and μ, then the data communication with the main working area of Matlab is achieved by declaring global variables, which lays the foundation for the next parameter tuning work.

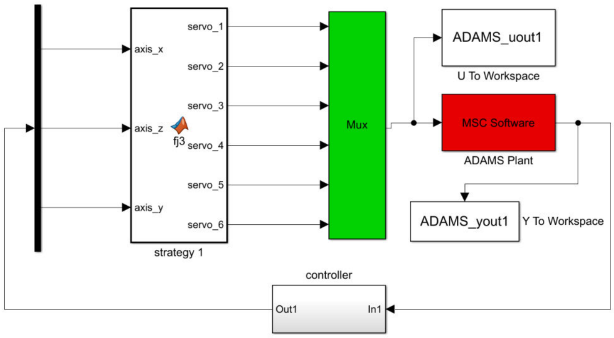


FIGURE 4. Simulation diagram in Simulink software.

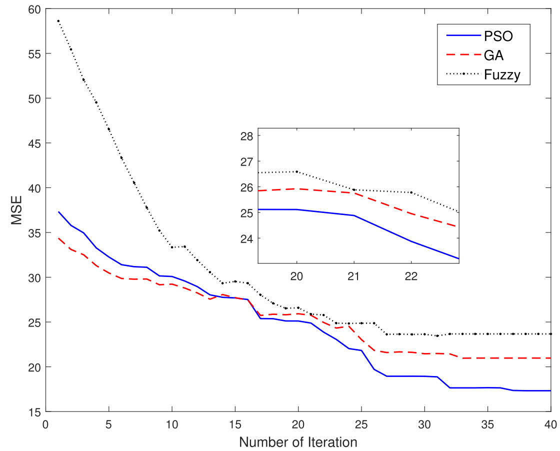


FIGURE 5. Comparison of three algorithms.

C. PARAMETER TUNING OF FRACTIONAL-ORDER CONTROLLER

Different from the IOPID controller, the time complexity of parameter tuning is obviously greater because of the increase of parameters. Fractional differential equations are also difficult to express during simulation. In engineering applications, the trial-and-error method and empirical method commonly used for IOPID are difficult to use for parameter tuning of FOPID when two unknown dimensions are added. In this section, three intelligent algorithms are selected to tune the fractional-order controller.

1) ALGORITHM SELECTION

The fractional simulation platform based on the dynamic model has been built in Section III-B. Since each parameter adjustment of the controller performs model simulation which requires a lot of time. It means that even if the time complexity of the tuning process is only linear function of the running time of the model, the whole tuning time will still be very long. This requires the selected algorithm to have fewer number of populations, iterations, adjustable parameters, etc. The comparative experiment with MSE function as performance index is analyzed based on PSO, GA and fuzzy algorithms. The PSO algorithm has the better convergence ability as evident in Figure 5. It requires fewer parameters to adjust, which means it is relatively easy to implement and is suitable for solving engineering problems [27].

Particle swarm optimization algorithm [28] is an algorithm established to simulate the predation behavior of bird swarms. For other bionic algorithms, the particle swarm algorithm does not have crossover and mutation operations, however, it can pass the optimal particles in the iteration and the search speed is fast. The algorithm needs to initialize a group of random particles and updates its own speed and position by tracking two extreme points respectively during each iteration. The related formula is as follows:

$$V_{id}(t+1) = \omega V_{id}(t) + c_1 r_1(0,1) \times (P_{id} - x_{id}) + c_2 r_2(0,1)(P_{gd} - x_{id}) \quad (7)$$

$$X_{id}(t+1) = X_{id}(t) + V(t+1) \quad (8)$$

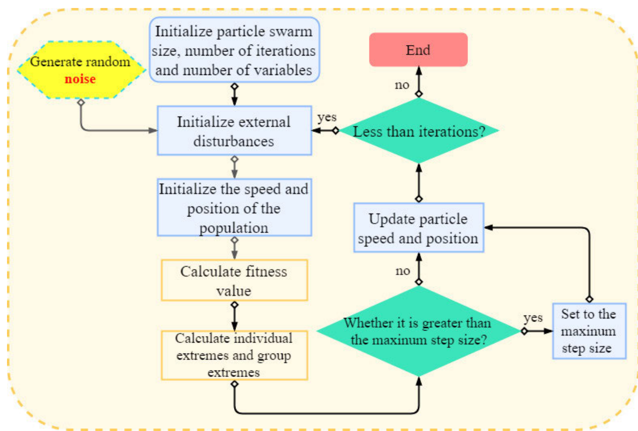


FIGURE 6. Particle swarm algorithm flowchart.

where, ω is inertia factor. C_1 and C_2 are acceleration constant, the former is the individual learning factor for each particle and the latter is the social learning factor for each particle. It is shown in experimental research that a better solution can be obtained when C_1 and C_2 are constant. Generally take $C_1 = C_2 \in [0, 4]$. r_1 and r_2 means take a random number on the interval [0,1]. P_{id} represents the d-th dimension of the individual extremes of the i-th variable. P_{gd} represents the d-th dimension of the global optimal solution. V represents the velocity of the particles and X represents the position of the particles.

In addition, this paper adds a set of random noise to the simulation of external disturbances during the tuning algorithm to simulate the environment of uncertainty in consideration of the stability and applicability of the controller. The PSO algorithm flowchart is shown in Figure 6:

The initial parameters of the PSO algorithm are shown in Table 1:

After determining the initial parameters, the next step is to determine the fitness function of the algorithm. The fitness function is an indicator used to judge the performance of the results during the iteration of the particles. For different

TABLE 1. Initial parameters of PSO algorithm.

Parameter	Meaning	Value
ω	Inertia factor	0.6
C_1, C_2	Acceleration constant	1
V_{i1}	Initial particle velocity	[0,0.05][0,1][0,0.05]
X_{i1}	Initial particle position	[0.1,1.2][2,18][0,1]
$maxinum$	Maximum number of iterations	10
$part$	Particle swarm size	20
$narvs$	Number of independent variables	5

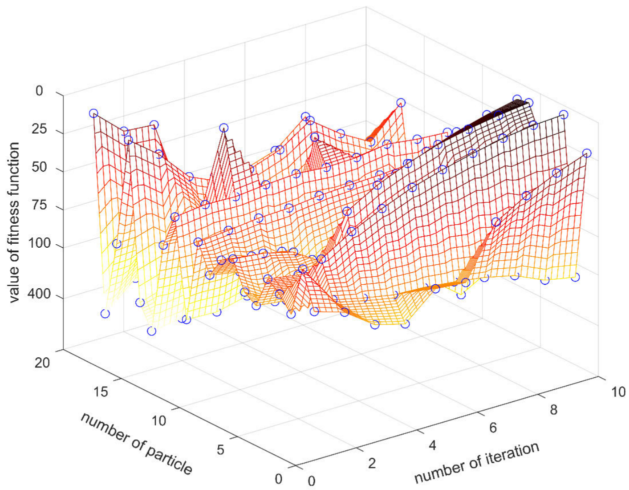


FIGURE 7. Particle swarm algorithm iterative tuning results graph.

problems, flexibly specifying the corresponding fitness function becomes the key to the algorithm result. This paper sets the fitness function as follows:

$$fitness = \begin{cases} 0.1 \times \sum_t^i |e(t)|, & i \leq 1 \\ \sum_t^i |e(t)|, & i > 1 \end{cases} \tag{9}$$

In Equation 9, e(t) is the deflection angle between the platform and the horizontal plane after simulation. Within $0 \sim 1$ second, this period is at the beginning of leveling. The rotation error of the platform is relatively large at this stage, so the weight occupied by this stage is reduced. The weight is restored after 1 second in order to consider the performance during the leveling process. The tuning algorithm uses the fitness function as a criterion for stability performance and iteratively searches for suitable controller parameters. Obviously, the fitness value is a positive number and the smaller value represent the better stability effect of the platform.

With the above algorithm programmed through Matlab and after each particle position update, the ADMAS-Simulink joint simulation model established in the previous section is called. The simulation time is set to 20 seconds, the result of each iteration is saved and the image is output after the algorithm is finished.

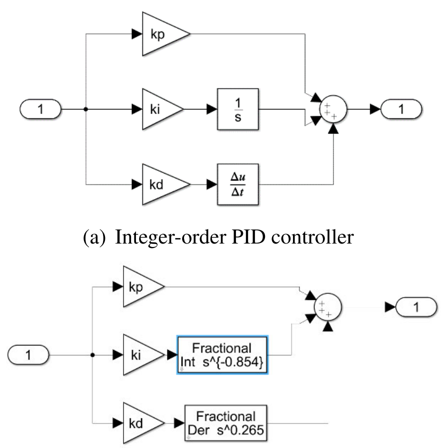
2) RESULTS OF ITERATIVE CALCULATION

By selecting 20 random particles and performing ten iterative calculations, the fitness value of each group of examples during the iteration is shown in Figure 7. It can be seen that the change trend of each group is different and three of them have lower final fitness values. The fitness values are monotonically decreasing and the fitness value gradually converges as the number of iterations increases.

The third set of data with the lowest fitness value is selected as the optimal solution for the parameter tuning of the controller. The following simulation and experiment will further verify the performance of the tuned FOPID controller.

TABLE 2. Two kinds of controller parameter setting results.

Controller type	Parameter	Value
Fractional-order controller	K_p	0.982
	K_i	11.352
	K_d	-0.040
	λ	1.065
	μ	0.923
Integer-order controller	K_p	0.6
	K_i	6.0
	K_d	0.1



(a) Integer-order PID controller

(b) Fractional-order PID controller

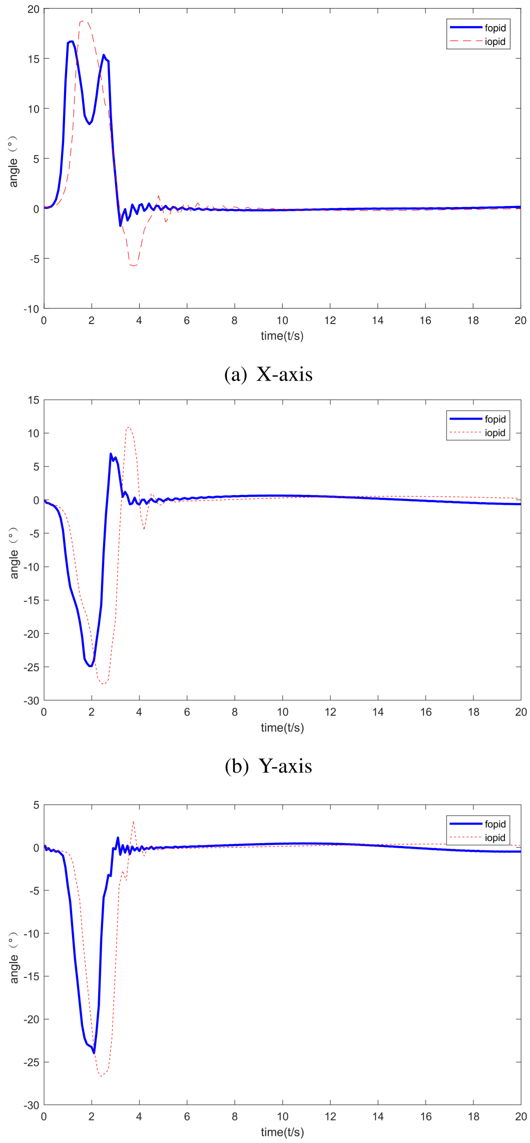
FIGURE 8. Two controller schematics.

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. SIMULATED PERFORMANCE COMPARISON OF FOPID CONTROLLER AND IOPID CONTROLLER

In order to verify the performance of the FOPID controller, the PID tuning tool was used in Matlab to tune the controller's proportional, integral and derivative parameters based on the phase angle margin and amplitude margin. A set of relatively better parameters is selected. The parameters of the IOPID controller are shown in Table 2. The parameter selection process is not described in detail here.

In the experimental stage, a set of sine waves to the external disturbance of the stabilized platform is added in the dynamic model. The IOPID and FOPID controllers were used for simulation in this experiment by changing the controller module in the software simulation model built in Section III-B. The internal structure of the controller is shown in Figure 8.

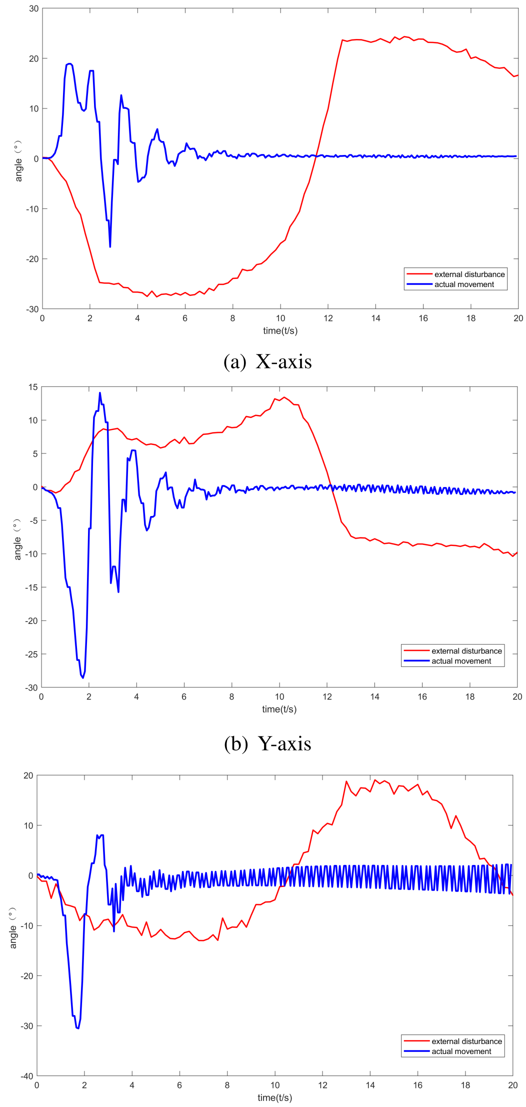


(a) X-axis

(b) Y-axis

(c) Z-axis

FIGURE 9. **Comparison of stability effects of integer and fractional PID controllers.**



(a) X-axis

(b) Y-axis

(c) Z-axis

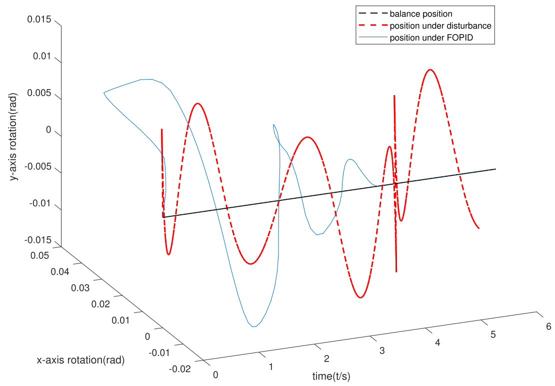
FIGURE 10. **External disturbance and stability effect curve of fractional-order controller.**

Shown as Figure 9, the stability effect of IOPID controller and FOPID controller under the same sine wave disturbance. From the figure, it can be seen intuitively that fractional-order controller has smaller overshoot, faster response speed and shorter stability time compared with the integer-order controller. The equilibrium position can be found after a single oscillation, which has a better stability effect.

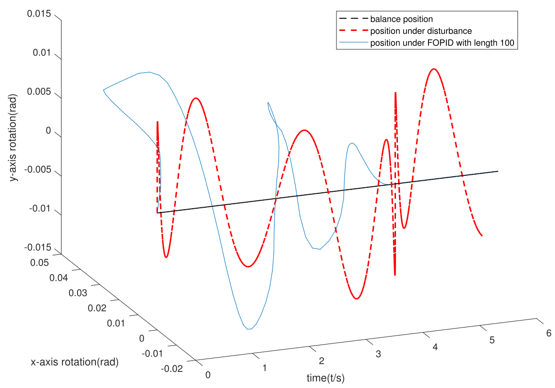
In order to further verify the performance of the FOPID controller, especially to prove that the designed controller can be applied in engineering practice. The following experiments will increase the complexity of external disturbances. They are added in the X-axis, Y-axis and Z-axis directions. Meanwhile, in order to simulate the uncertain factors of the actual process, a Gaussian white noise with an average value of 0 and a standard deviation of 5° is added to the above disturbances. In the current external disturbance situation, the IOPID cannot achieve a stabilized platform. A FOPID controller is used in simulation experiments and the results are shown in Figure 10.

As can be seen from the figure, the FOPID controller can still achieve the effect of self-stabilized control under the condition of complex external disturbances. The final stabilization effect in the X-axis and Y-axis directions is good and the static stability error is very small. Although there is a certain static stability error in the Z axis, the stabilization speed in this direction is relatively fast. The above experiments have fully proved that the FOPID controller has better stability in the face of complex external disturbances when controlling nonlinear systems.

As mentioned above, fractional calculus operators have some interesting properties. One of them is that it can reduce



(a) Unlimited



(b) Limit L = 100

FIGURE 11. FOPID controller two-axis rotation angle change.

the number of calculation data sets by reducing the memory duration, although this can increase the errors. This method of calculation is called short-memory effect:

$$ {}_aD_t^\alpha f(t) \approx {}_{t-L}D_t^\alpha f(t) \tag{10} $$

where, L means the memory duration. In this way, the GL definition in Section III-A can be approximated as:

$$ {}_aD_t^\alpha f(t) \approx \frac{1}{h^\alpha} \sum_{k=0}^{N(t)} \omega_k f(t-kh) \tag{11} $$

where,

$$ N(t) = min\{[\frac{t-t_0}{h}], \frac{L}{h}\} \tag{12} $$

Using this feature to reasonably reduce the calculation step size can effectively reduce the amount of calculation and storage space. It has certain research significance for improving the response speed of actual engineering equipment. There may be certain laws of external disturbance during the work of the stabilized platforms. This paper explores the impact of short-memory effect on stabilized platform systems by limiting the input and output data involved in calculations during the simulation. The change of the two-axis rotation angle of the FOPID controller under unlimited and certain limits is shown in the Figure 11.

Since the total number of points in the simulation process is less than four hundred, selecting a large number of limits will result in no difference from the control group and a small number of limits will result in excessive errors. Under this

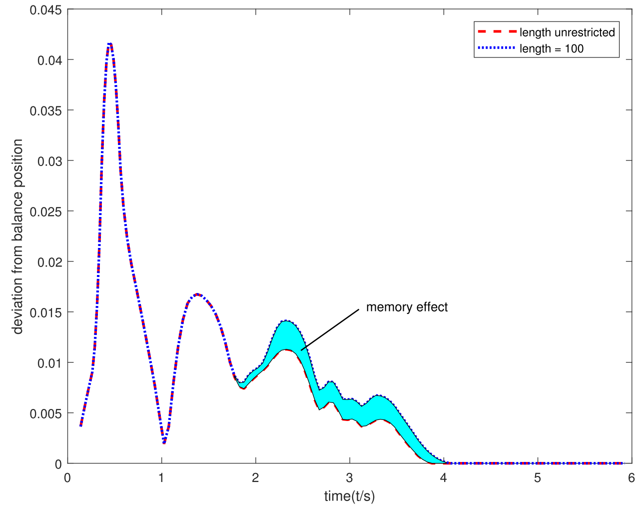


FIGURE 12. Memory effect of stabilized platform FOPID controller.

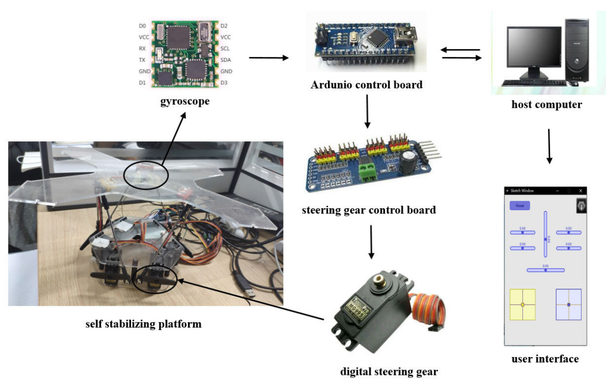


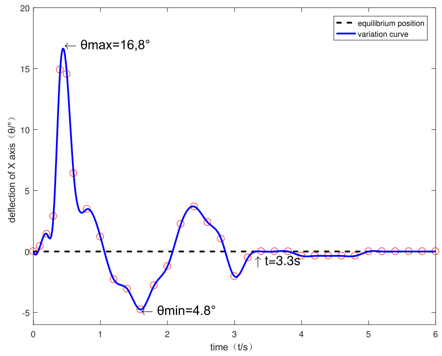
FIGURE 13. Hardware schematic diagram of the prototype experimental stage.

TABLE 3. Table of experimental platform parameters.

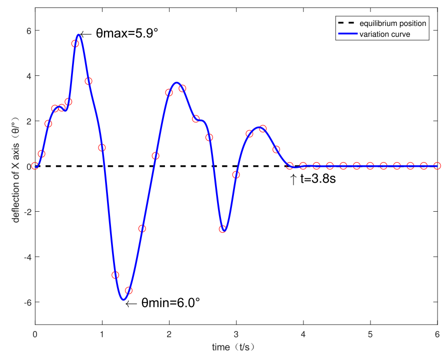
Platform parameters	Value
Hinge point circle radius of upper platform	70mm
Hinge point circle radius of lower platform	85mm
Initial height of upper and lower platform	120mm
Steering arm	25mm
Center distance of connecting rod	130mm

TABLE 4. Prototype parameters for experiments.

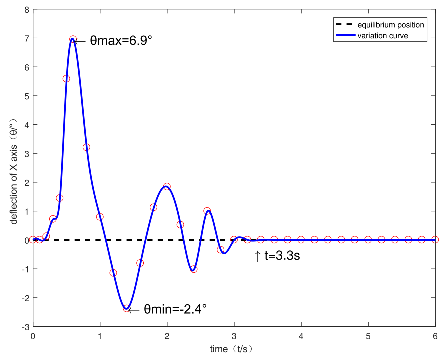
Group number	Amplitude	Period
1	20°	2s
2	20°	1s
3	10°	2s
4	10°	1s



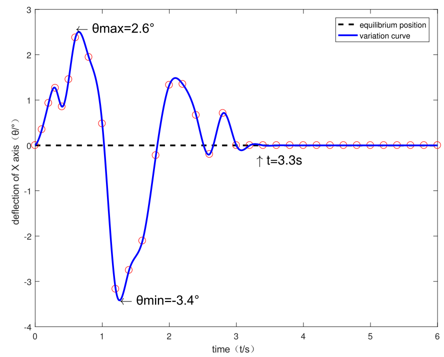
(a) First group around the X axis



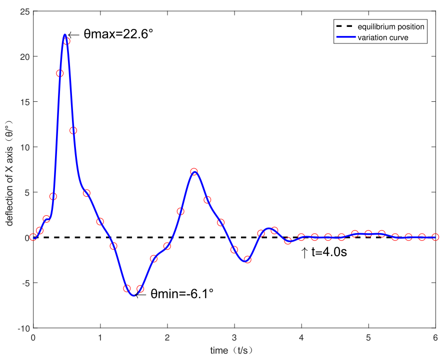
(b) First group around the Y axis



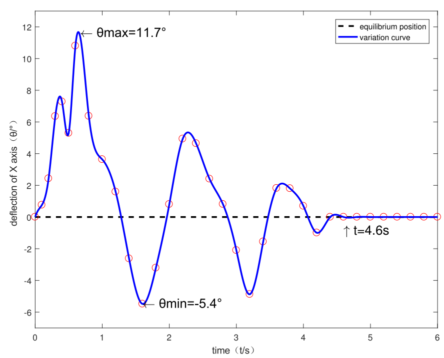
(c) Second group around the X axis



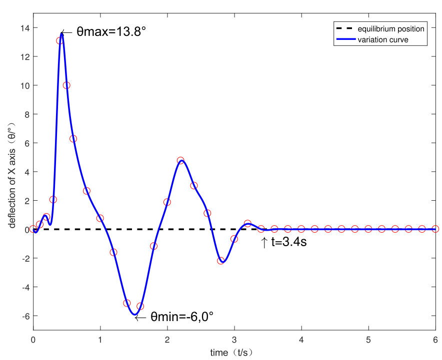
(d) Second group around the Y axis



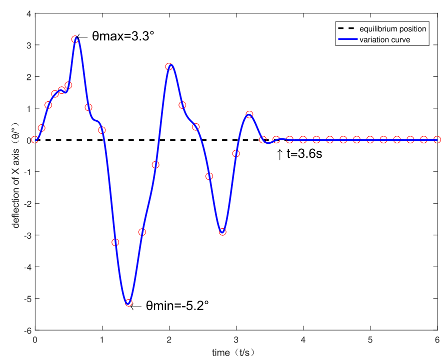
(e) Third group around the X axis



(f) Third group around the Y axis



(g) Fourth Group around the X axis



(h) Fourth group around the Y axis

FIGURE 14. **Experimental curve.**

condition, $L = 100$ is an appropriate choice. The difference between the two sets of experimental results and the balanced position is plotted in order to display the experimental results intuitively. As shown in Figure 12.

In fact, the memory effect has a little effect on the stability performance of the parallel stabilized platform in this paper, but it is not significant. The stability effect after limiting a certain memory duration is still within the acceptable range, which may make contribution to reading less serial port information in practical applications.

B. PRACTICALITY EXPERIMENT

It is difficult to get good results when the parameters of FOPID controller in software simulation are applied in practice because the hardware equipment and the external environment cannot reach the ideal condition in the actual engineering. It is also one of the difficulties for the controller to be widely used. In order to verify the feasibility of the controller design method, the tuning parameters in the third section are directly used in the real machine experiment.

1) HARDWARE SYSTEM COMPOSITION

An experimental system of stabilized platform was developed, as shown in Figure 13. The Ardunio control board is selected and connected to the 16-way servo drive board and the JY-901 gyroscope by IIC communication. Six MG995 analog servos are connected to the 16-way servo drive board sockets in sequence and the 16-way servo drive board is connected to the external power. The inertial navigation module installed at the center of the upper platform is used as an attitude acquisition system to measure the three-dimensional rotational attitude angle of the upper platform.

The upper platform is composed of acrylic plates and 3D printed parts connected by bolts, while the lower platform is composed of acrylic plates and six steering gears, as well as bolted rubber columns for fixing in the middle. The related size parameters of the platform are shown in Table 3.

In order to realize the feedback control and the output signals of the acquisition system, it is necessary to collect the position information of the platform in real time. The data collected by the JY901 gyroscope is sent to the lower computer in hexadecimal form. The machine transfers it to the upper computer to obtain the position information of the upper platform. The received data needs to be calculated using the following formula:

Tumble angle (deflect around X axis):

$$Roll = ((RollH \ll 8)|RollL)/32768 * 180^\circ$$

Pitch angle (deflect around Y axis):

$$Pitch = ((PitchH \ll 8)|PitchL)/32768 * 180^\circ$$

2) EXPERIMENTAL RESULT

In this paper, four groups of sine waves with the same direction but different amplitude and period are selected as external disturbances, as shown in Table 4.

During the movement of the upper platform, the value returned by the gyroscope cannot accurately return the position information of each moment. For the original gyroscope data of the four experimental results, the redundant data was cleaned up and the spherical interpolation method is used to fit the curve for the discrete data in the stabilization process. The result is shown in Figure 14.

The peaks and valleys in the above curve and the time it takes for the platform to stabilize are marked in the figure. It can be seen that after a period of leveling, the platform can remain stabilized under different external disturbances, which not only proves the effectiveness of the fractional-order controller applied to the stabilized platform, but also verifies the performance of the PSO algorithm to adjust the parameters of the random disturbance.

V. CONCLUSION

In order to improve the performance of stabilized platforms, a FOPID controller, mainly divided into simulation experiments and physical verification, is designed. There are three steps in the simulation experiment phase: 1) Construction of dynamics-based software simulation platform. 2) The parameter of the fractional-order controller was tuned by using the PSO algorithm and the Gaussian white noise was added to the external disturbance signal during the iteration process to enhance the adaptability of the parameter tuning results. 3) The performance and applicability of the fractional-order controller were verified through two sets of experiments: The first group is the fractional-order control comparison experiments between the controller and the integer-order controller. The second group is the experiments on the stability superiority of the fractional-order controller over the integer-order controller, but also the effectiveness of the fractional-order controller. After that, physical experiments were performed on the designed controller. The stabilized platform and the main structure of the controller were established by setting up the hardware platform and computer programming. The external signals were collected through the gyroscope and several groups of experiments were performed. Experimental proof: 1) Fractional-order controllers still have good stability effects when applied to practical stabilized platforms. 2) In the process of parameter tuning using the PSO algorithm, the introduction of appropriate random disturbances can increase the adaptability of the controller system to a certain extent provides new ideas for the promotion of fractional-order controllers to practical applications.

REFERENCES

[1] Z. Zhang, Z. Li, Q. Zhou, L. Zhang, and D. Fan, "Application in prestiction friction compensation for angular velocity loop of inertially stabilized platforms," *Chin. J. Aeronaut.*, vol. 27, no. 3, pp. 655–662, Jun. 2014.

[2] F. Königseder, W. Kemmetmüller, and A. Kugi, "Attitude control strategy for a camera stabilization platform," *Mechatronics*, vol. 46, pp. 60–69, Oct. 2017.

[3] B. Rohani, Y. Yazicioglu, M. Mutlu, O. Ogucu, E. Akgul, and A. Saranli, "Lagrangian based mathematical modeling and experimental validation of a planar stabilized platform for mobile systems," *J. Comput. Appl. Math.*, vol. 259, pp. 955–964, Mar. 2014.

[4] M. M. Abdo, A. R. Vali, A. R. Toloei, and M. R. Arvan, "Stabilization loop of a two axes gimbal system using self-tuning PID type fuzzy controller," *ISA Trans.*, vol. 53, no. 2, pp. 591–602, Mar. 2014.

[5] J. Mao, S. Li, Q. Li, and J. Yang, "Design and implementation of continuous finite-time sliding mode control for 2-DOF inertially stabilized platform subject to multiple disturbances," *ISA Trans.*, vol. 84, pp. 214–224, Jan. 2019.

[6] C. Bai and Z. Zhang, "A least mean square based active disturbance rejection control for an inertially stabilized platform," *Optik*, vol. 174, pp. 609–622, Dec. 2018.

[7] J. Fang, R. Yin, and X. Lei, "An adaptive decoupling control for three-axis gyro stabilized platform based on neural networks," *Mechatronics*, vol. 27, pp. 38–46, Apr. 2015.

[8] L. Zhuchong, L. Kun, and Z. Wei, "Inertially stabilized platform for airborne remote sensing using magnetic bearings," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 1, pp. 288–301, Feb. 2016.

[9] X. Zhou, C. Yang, B. Zhao, L. Zhao, and Z. Zhu, "A high-precision control scheme based on active disturbance rejection control for a three-axis inertially stabilized platform for aerial remote sensing applications," *J. Sensors*, vol. 2018, pp. 1–9, Jul. 2018.

[10] Y. Wu and D. Yue, "Desired compensation adaptive robust control of electrical-optical gyro-stabilized platform with continuous friction compensation using modified LuGre model," *Int. J. Control, Autom. Syst.*, vol. 16, no. 5, pp. 2264–2272, Oct. 2018.

[11] R. Cajo, T. T. Mac, D. Plaza, C. Copot, R. De Keyser, and C. Ionescu, "A survey on fractional order control techniques for unmanned aerial and ground vehicles," *IEEE Access*, vol. 7, pp. 66864–66878, 2019.

[12] C. I. Muresan, I. R. Birs, C. Darab, O. Prodan, and R. De Keyser, "Alternative approximation method for time delays in an IMC scheme," in *Proc. Int. Aegean Conf. Electr. Mach. Power Electron. (ACEMP) Int. Conf. Optim. Electr. Electron. Equip. (OPTIM)*, Istanbul, Turkey, Aug. 2019, pp. 532–539.

[13] A. Mujumdar, B. Tamhane, and S. Kurode, "Observer-based sliding mode control for a class of noncommensurate fractional-order systems," *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 5, pp. 2504–2512, Oct. 2015.

[14] G. Sun and Z. Ma, "Practical tracking control of linear motor with adaptive fractional order terminal sliding mode control," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 6, pp. 2643–2653, Dec. 2017.

[15] S.-Y. Chen, H.-H. Chiang, T.-S. Liu, and C.-H. Chang, "Precision motion control of permanent magnet linear synchronous motors using adaptive fuzzy fractional-order sliding-mode control," *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 2, pp. 741–752, Apr. 2019.

[16] H. Malek and Y. Chen, "Fractional order extremum seeking control: Performance and stability analysis," *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 3, pp. 1620–1628, Jun. 2016.

[17] A. Maddahi, N. Sepehri, and W. Kinsner, "Fractional-order control of hydraulically powered actuators: Controller design and experimental validation," *IEEE/ASME Trans. Mechatronics*, vol. 24, no. 2, pp. 796–807, Apr. 2019.

[18] C. Copot, C. Muresan, T. MacThi, and C. Ionescu, "An application to robot manipulator joint control by using constrained PID based PSO," in *Proc. IEEE 12th Int. Symp. Appl. Comput. Intell. Informat. (SACI)*, May 2018, pp. 279–284.

[19] I. Birs, C. Muresan, I. Nascu, and C. Ionescu, "A survey of recent advances in fractional order control for time delay systems," *IEEE Access*, vol. 7, pp. 30951–30965, 2019.

[20] J. Juchem, C. Muresan, R. De Keyser, and C.-M. Ionescu, "Robust fractional-order auto-tuning for highly-coupled MIMO systems," *Heliyon*, vol. 5, no. 7, Jul. 2019, Art. no. e02154.

[21] Z. Bingül and O. Karahan, "Fractional PID controllers tuned by evolutionary algorithms for robot trajectory control," *Turkish J. Elect. Eng. Comput. Sci.*, vol. 20, pp. 1123–1136, Feb. 2012.

[22] C. Copot, Y. Zhong, C. Ionescu, and R. De Keyser, "Tuning fractional PID controllers for a Steward platform based on frequency domain and artificial intelligence methods," *Central Eur. J. Phys.*, vol. 11, no. 6, pp. 702–713, Apr. 2013.

[23] L. Yu, Y. Xue, and S. Mei, "The application of ADAMS in the mechanical system simulation course," in *Proc. Int. Seminar Bus. Inf. Manage.*, Dec. 2008, pp. 244–247.

[24] X. Ma, M. Xie, W. Wu, B. Zeng, Y. Wang, and X. Wu, "The novel fractional discrete multivariate grey system model and its applications," *Appl. Math. Model.*, vol. 70, pp. 402–424, Jun. 2019.

[25] S. Urooj and B. Singh, "Fractional-order PID control for postoperative mean arterial blood pressure control scheme," *Procedia Comput. Sci.*, vol. 152, pp. 380–389, 2019.

[26] V. Moroz and T. Borovets, "Using of FOTF toolbox and Z-transform for fractional control systems," in *Proc. IEEE Int. Young Scientists Forum Appl. Phys. Eng. (YSF)*, Oct. 2017, pp. 50–53.

[27] S. Kizir and Z. Bingül, "Fuzzy impedance and force control of a stewart platform," *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 22, pp. 924–939, 2014.

[28] Z. Bingul and O. Karahan, "Comparison of PID and FOPID controllers tuned by PSO and ABC algorithms for unstable and integrating systems with time delay," *Optim. Control Appl. Methods*, vol. 39, no. 4, pp. 1431–1450, Jul. 2018.

JIE ZHANG received the B.S. degree in statistics specialty from the College of Science, Yanshan University, China, in 2003. She is currently pursuing the Ph.D. degree in control science and engineering with Yanshan University. She is also a Lecturer with the Liren College, Yanshan University. Her current research interests include system identification of fractional order systems and robot control theory.

ZHAOPENG JIN received the B.S. degree in mechanical and electronic engineering from Yanshan University, Qinhuangdao, Hebei, China, in 2017, where he is currently pursuing the M.S. degree in mechatronics engineering. His research interests include fractional order controller and intelligent algorithm research.

YANZHI ZHAO received the B.S. degree in mechanical engineering and the Ph.D. degree in mechatronics engineering from Yanshan University, Qinhuangdao, Hebei, China, in 2003 and 2009, respectively. He is currently a Professor with the Department of Mechatronics Engineering, Yanshan University. His current research interests include parallel multi-dimensional force sensors, theory, and application of parallel manipulators.

YINGGAN TANG received the B.Sc. degree in instrument science and the M.Sc. and Ph.D. degrees in control science and engineering from Yanshan University, China, in 1999, 2002, and 2006, respectively. He is currently a Professor with the Department of Automation, Yanshan University. His main research interests include image processing, system modeling, and computational intelligence.

FUCAI LIU received the B.S. and M.S. degrees from the Department of Automation, Northeast Heavy Mechanism Academe, in 1989 and 1994, respectively, and the Ph.D. degree from the Department of Control Science and Engineering, Harbin Institute of Technology, in 2003. He is currently a Professor of Yanshan University, and the Head of Automation Department, Electric Engineering Institute, Yanshan University. He has authored/coauthored more than 200 articles in mathematical, technical journals, and conferences. He is the author of the book *Fuzzy Model Identification for Nonlinear Systems and Its Applications*. His current research interests include fuzzy identification, predict control, and space robot control.

YAO LU received the B.S. degree in applied mathematics from Tangshan Normal University, China, in 2005. She is currently pursuing the Ph.D. degree in control science and engineering with Yanshan University, China. She is also a Lecturer with the Liren College, Yanshan University. Her current research interest includes system identification of fractional order systems.

PENGCHENG LIU (Member, IEEE) received the B.Eng. degree in measurement and control and the M.Sc. degree in control theory and control engineering from the Zhongyuan University of Technology, China, in 2007 and 2012, respectively, and the Ph.D. degree in robotics and control from Bournemouth University, U.K., in 2017. He is currently an Assistant Professor with the Department of Computer Science, University of York, U.K., where he is supervising several Ph.D. students. Before joining York, he has held several academic positions at Cardiff, Lincoln, Bournemouth and China. He held academic positions as a Visiting Fellow at the Institute of Automation, Chinese Academy of Sciences, China, and Shanghai Jiao Tong University, China. He has published over 60 articles on flagship journals and conferences. He was nominated as a regular Funding/Grants reviewer for EPSRC, NIHR, and NSFC. He has been leading and involving in several research projects and grants, including EPSRC, Newton Fund, Innovate U.K., Horizon 2020, Erasmus Mundus, FP7-PEOPLE, NSFC, and so on. He serves as a reviewer for over 30 flagship journals and conferences in robotics, AI and control, e.g., NEUNET, AURO, NODY, JINT, ICRA, IROS, RA-L, NCAA, and so on. His research interests include robotics, machine learning, and dynamical systems control and optimization. Dr Liu is a member of the IEEE Robotics and Automation Society (RAS), IEEE Control Systems Society (CSS), and International Federation of Automatic Control (IFAC). He is also a member of the IEEE Technical Committee on Bio Robotics, Soft Robotics, Robot Learning, and Safety, Security and Rescue Robotics. He received the Global Peer Review Awards from Web of Science, in 2019, and the Outstanding Contribution Awards from Elsevier, in 2017. He is an Associate Editor of IEEE Access.