Fractional-order internal model control algorithm based on the force/position control structure of redundant actuation parallel robot

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Abstract
This article proposes a new control structure for the complex redundant actuation parallel robot based on force/position hybrid control structure. The traditional proportional–integral–derivative control method, integer-order internal model control method and fractional-filter internal model control–proportional–derivative control method are used in the position structure of force/position hybrid control. The fractional-filter internal model control–proportional–derivative control method is used in the position loop of the permanent magnet synchronous motor to reduce the position error. A fractional-order theory with the internal model control method is used in redundant actuation force control structure, which can improve the control precision of the driving force of the parallel robot. The Admas/Matlab simulation results show that the proposed method outperforms other methods and can obtain good robustness and tracking performance.

Keywords
Parallel robot, force/position hybrid control, fractional order, internal model control

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Introduction
The mechanism of parallel robot¹,² is parallel structure, which is different from the traditional serial robot. It consists of moving platform connecting with fixed platform by multiple kinematic chains. It has multiple degrees of freedom (DOF) and is driven by many branched chains. Parallel robot has large stiffness and load capacity and has better practical application than conventional serial robots on industrial assembling, space docking and precision processing. Because the number of input of redundant driven parallel robot is more than the number of degree of freedom, the error caused by the parallel robot in machining, assembling or moving can result in deformation of the
machine if all inputs are in position control mode. The strong internal force of this non-linear system can make the gap of branch joint become large, the loss of end precision and even destroy the original mechanism, which will result in motion commands of parallel robot not executed properly. The characteristic of parallel robot has limited its development and applications.

In this article, the plant of control is 6PUS-UPU 5-DOF redundant actuation parallel robot. The dynamics expression of 6PUS-UPU is very complicated. A high computational demand is thus required, which is difficult to realize real-time control. So force/position hybrid control strategy is used for complex redundancy actuation parallel robot, that is, redundant actuators uses force control mode, and other branches use position control mode. For 6PUS-UPU redundant actuated parallel robot, the same control structure is used. Position control ensures accuracy of the position and attitude of the moving platform, while the force control of redundant actuators is used to adjust the distribution of the driving torque of all actuators.

For redundant parallel robot, the precision requirements of mechanism in manufacturing process is very high. The control problem of redundant actuated parallel robot has been the key technology and difficulty problem of parallel robot. In recent years, the research on the control theory of parallel robot includes: (1) The kinematics control method, which avoids the complex dynamics calculation, but the speed and the precision are not high. (2) The dynamic control method has high control precision and performance, but it needs an accurate dynamic model of parallel robot. (3) Nonlinear position control solves the problem of the strong coupling of each joint of the redundant actuation parallel robot and the motion synchronization of the actuator. (4) Force/position hybrid control structure: redundant branch uses the force control method, the other branches of movement use the position control movement precision of mechanism. The traditional three-loop control method is applied to the servo system, but the control effect is not ideal and the control precision is not high.

Permanent magnet synchronous motor (PMSM) is widely used in high precision AC servo system because of its good starting performance, mechanical characteristics and reliable operation. With the emergence of vector control, AC servo system has developed rapidly, and the control of AC servo system is developing towards high precision and intelligence. Three-loop control structure is used in the general AC servo system, which is the current loop, the speed and the position loop. Under parameter variations, torque ripple and load disturbance of uncertain factors, the traditional proportional–integral–derivative (PID) controller is difficult to satisfy the control precision and anti-interference performance requirements. In order to better solve the control precision of the system, some advanced control methods were used. The internal model control (IMC) is a new control strategy based on the mathematical model of the process. Because its design is simple and has strong anti-interference performance, it has drawn many researchers’ attention.

In recent years, some results of IMC have been obtained. The work in Zheng and Wang, an IMC-PID control method with 2-DOF is applied to the position control of the 6PUS-UPU redundant actuated parallel manipulator, and the controller has only two adjustable parameters. However, this method does not have a good solution to the tracking performance of the system. In the work of Wang et al., an improved internal model controller is proposed, which further improves the servo accuracy of the electro-hydraulic servo actuator of the hydraulic four legged robot. Yet this method requires off-line identification parameters. In Liu et al., the authors proposed a new control strategy based on IMC method. It is applied to the PMSM, which has good dynamic and anti-interference performance. The work in Bachir and Duvaud, the authors designed a nonlinear internal model controller in nonlinear high power amplifiers and effectively solved effective solution to the system nonlinearity and hysteresis phenomenon. However, the computation of this method is complex, and it needs to solve the inverse of the whole model. In Jin and Liu, the authors designed an internal model PID controller based on linear quadratic Gaussian adjustment parameters, which effectively avoided the experimental adjustment of parameters. Whereas the method requires the maximum sensitivity function, and the calculation method is complicated.

Conventional IMC method has only one filter time constant to be adjustable. The parameter directly determines the closed-loop performance of the system. The adjustable parameter needs to compromise between tracking performance and robustness. So in this article, a fractional-order internal model controller is designed for integer-order model of AC servo system. It is an integer PID structure cascaded with a fractional filter. There are two adjustable parameters, the filter time constant and the non-integer order of the filter. The tracking performance and anti-interference performance of the system are improved effectively.

The combination of IMC method and fractional-order control (FOC) method can not only effectively prevent the deterioration of control quality when the model mismatch seriously but also solve the problem of steady state error. In the aspect of control, more and more researchers focus on theory of fractional calculus and its application in the field of automatic control. Fractional-order controller can achieve the purpose of improving system control performance. In the work of Bettayeb and Mansouri, the fractional-order internal model PID controller is designed for the non-integer order system. It uses the structure of the fractional-order filter, which has good tracking and disturbance rejection. However, this method can not be applied to complex structures. In Vinopraba et al., the authors proposed a kind of internal model controller based on the
2-DOF fractional order. The robustness of the system is improved when the order of the integral term is reduced. In Maamar and Rachid,\textsuperscript{31} an integer PID structure cascaded with a fractional filter is designed. This method can easily be implemented on the modern control hardware. However, it cannot apply to the proposed controller in large-scale systems and complex structures.

In our previous research work, we analyzed and improved the redundant force branch of the parallel robot. The work in Wen et al.,\textsuperscript{32} we studied an anti-interference controller, which can improve the performance of the driving force of the parallel robot. But the position branches of the parallel robot adopted PID controller, the control precision of robot is not good. In Wen et al.\textsuperscript{33} and Shuhuan et al.\textsuperscript{34}, the fuzzy T-S model of 6PUS-UPU parallel robot dynamic model is obtained by fuzzy identification method. In order to solve the force delay problem of redundant driving force branch, the authors designed the Smith predictor compensator to solve the delay problem. The simulation results show that the proposed method can obtain the ideal fuzzy T-S model and eliminate the delay problem of the force branch. However, the position branches of the parallel robot used PID control method, which cannot guarantee the accuracy of the movement of the parallel robot. The PID control method is used in the force branch, and the controller design is simple, however it cannot improve the anti-interference performance of the robot. Because parallel robot is widely used in high-performance and high-precision applications, we need not only to improve the position precision of the robot but also to reduce the internal forces to improve the overall performance of the robot.

In this article, the hybrid force/position control strategy is applied to 6PUS-UPU redundant actuation parallel robot.\textsuperscript{32} Two different low-pass filters are proposed for the speed servo system and the torque servo system, respectively. The position branch controller combines the fractional-order filter with the integer-order PD controller, which has the advantage of both. The force control in fractional form greatly increased the range of adjustable parameters, making the control more stable. Fractional-filter internal model control–proportional–derivative (FFIMC-PD) control strategy is used in the position branches of parallel robot, and fractional-order internal model control (FOIMC) method is used in the force branch. In the position branches of parallel robot, the performance of FFIMC-PD controller, PID controller and integer-order internal model control method (IOIMC) controller are compared. The results of simulation demonstrate that FFIMC-PD controller has the better tracking performance than PID controller and IOIMC controller. In FOIMC algorithm of redundant force branch, fractional-order theory combining with IMC can describe the dynamic change process of the complex system more precisely, which realizes the generalization of integral PID controller and improves the design flexibility. Compared with the traditional PI controller and IMC controller, the simulation results demonstrate that the FOIMC controller has better force tracking ability and anti-interference ability than that of traditional PI and IMC.

The structure of this article is as follows: in the second section, we study the dynamics modelling and driving force optimization of the 6PUS-UPU redundant actuation parallel robot. The control method of position branches of parallel robot and the force branch are presented. Simulation results of the proposed controller are in the third section. Finally, conclusions are given in the fourth section.

### Dynamics modelling and control design

Control strategy based on PID control in joint space\textsuperscript{35} is the most typical kinematics. The PID controller has the advantages of simple model and small computational capacity, while the dynamic solution is not accurate, but it is difficult to coordinate fast and stability, and its robustness is poor. So it is difficult to apply PID control scheme to the complex 6PUS-UPU parallel robot in real situation.

Because the input number of the redundant actuated parallel robot is more than that of freedom, dynamic control method is mostly used for redundant actuated parallel robot. If all branches adopt force control mode, it is necessary to build an accurate dynamic model, but it is difficult to get the precise dynamic parameters of robot, such as friction coefficient in practice. Especially for the complex multi-DOF robot, such as the 6PUS-UPU parallel robot, the dynamics expression is very complex, the computational amount is very large, and it is difficult to realize real-time control. Considering the complex structure of 6PUS-UPU redundant actuation parallel robot, we use hybrid force/position control strategy.\textsuperscript{33} The 6PUS-UPU redundant actuation parallel robot model is shown as in Figure 1.

In Figure 2, the first five branches use the position control mode to ensure the position precision of the moving platform; the sixth branch adopts force control mode. This hybrid structure can adjust all actuator torque distribution to achieve the position control and force control of decoupling.\textsuperscript{32}

### Dynamics modelling

The dynamics modelling process of the 6PUS-UPU parallel robot by using KANE method is explained in our previous works.\textsuperscript{32,33} In our previous research work,\textsuperscript{32,33} the model of the mechanism is described in detailed, the dynamics model of the parallel robot is established, and the driving force is optimized. We also consider the uncertain interference for the 6PUS-UPU parallel robot, such as friction or backlash, and the uncertain interference is white Gaussian noise added in the sixth force branch. The study by Wen et al.\textsuperscript{32,33} also analysed the velocity and acceleration of the
6PUS-UPU parallel robot, and the driving force of every branch can be calculated. The optimal solution of the driving force can be obtained by making the driving force minimum

\[ \tau = G^T(GG^T)^{-1}F^T = G^+F^T \]  

where \( G \) is a non-invertible matrix, \( G^+ \) is the pseudo-inverse matrix of \( G \), \( \tau \) is the driving force vector, \( F^T \) is the rest part of the KANE equation.

**Internal model control**

The AC servo system generally uses three-loop control structure, that is, current loop, speed loop and position loop. The control structure of the position branches of the 6PUS-UPU redundant actuation parallel robot is shown in Figure 3. Position loop, speed loop and current loop controllers are P, PI and PI controllers, respectively.

\[ \frac{KV_s}{s+1} \]  

\[ \frac{1}{Ls+R} \]  

\[ K_s \]  

\[ J \]  

\[ Ke \]  

In the AC servo system of industrial robot, however, there exist some problems such as time-varying parameter and time-varying parameters, load disturb, uncertainty and so on. It is difficult to meet the requirement of high precision and stability if conventional PID controller is used. The parameters are difficult to be adjusted and the anti-interference ability is weak in this case. We also consider the uncertain interference for the 6PUS-UPU parallel robot, such as friction or backlash, and the uncertain interference is white Gaussian noise added in the sixth force branch. IMC has the advantage of simple structure, good tracking performance and strong robustness, but it requires mathematical model of the object, that is the internal model. When the model mismatch is serious, the control effect will degrade and even lead to system instability. Under the condition of model mismatch, the parameter tuning in the conventional IMC needs to be compromised between the system dynamic performance and robustness. In this article, a new control structure is proposed. The IMC and fractional Calculus are combined, which improves the position tracking precision.

The IMC diagram is shown in Figure 4.

\[ Q(s), P(s) \text{ and } M(s) \text{ are internal model controller, the 6PUS-UPU parallel robot and the internal model,} \]

**Figure 1.** 6PUS-UPU parallel robot model.

**Figure 2.** The force/position hybrid control structure diagram of 6PUS-UPU redundant actuation parallel robot.

**Figure 3.** The control structure of the position branches of the 6PUS-UPU redundant actuation parallel robot.

**Figure 4.** The IMC diagram.
respectively. \( R(s) \), \( Y(s) \) and \( D(s) \) are represent the input, output and the interference signal, respectively.

From Figure 4, we can get the following equation
\[
Y(s) = \frac{Q(s)P(s)}{1 + Q(s)[P(s) - M(s)]} R(s)
\]
\[
Y(s) = \frac{1 - Q(s)M(s)}{1 + Q(s)[P(s) - M(s)]} D(s)
\]

So we can get the closed-loop response.
\[
Y(s) = \frac{Q(s)P(s)}{1 + Q(s)[P(s) - M(s)]} R(s) + \frac{1 - Q(s)M(s)}{1 + Q(s)[P(s) - M(s)]} D(s)
\]

When the model has no error, namely \( P(s) = M(s) \), as long as the \( Q(s) \) and \( M(s) \) are stable, then the IMC system is closed-loop stable. In this case, when the inverse of minimum phase \( M(s) \) of system model is existence, and the internal model controller \( Q(s) = M^{-1}(s) \), the system can achieve the desired control, that is \( Y(s) = R(s) \). In the practical application, the low-pass filter \( f(s) \) needs to be added in the internal controller. This can ensure the realization of the \( Q(s) \) and adjust the performance of the system. The internal model controller has the following form
\[
Q(s) = f(s)M^{-1}(s)
\]

where \( f(s) \) is the low-pass filter. The reason we design \( f(s) \) is to keep the \( Q(s) \) rational, so \( f(s) \) is chosen to be the following form
\[
f(s) = \frac{1}{1 + \lambda s} \quad \text{(6)}
\]

where \( r \) is big enough to ensure \( Q(s) \) rational. \( \lambda \) is the parameter of the filter, and it is the only parameter of the IMC control method. Figure 4 can be converted into a conventional feedback control system as shown in Figure 5.

\[
C(s) = \frac{Q(s)}{1 - M(s)Q(s)} \quad \text{(7)}
\]
\[
Q(s) = \frac{C(s)}{1 + M(s)C(s)} \quad \text{(8)}
\]

**FFIMC-PD controller design**

PMMS position servo system is based on the double closed loop speed regulation system, which is attached to the position loop in Figure 3. The speed loop can be simplified as an inertial link under the condition of ensuring the stability of the system. Then the whole position servo system is a typical system (type 1), and it can be written as the following equation
\[
M(s) = \frac{K}{s(Ts + 1)} \quad \text{(9)}
\]

where \( T \) is the inertial time constant of the system, \( K \) is the open-loop gain.

In this article, \( f(s) \) could be designed as the following equation
\[ f(s) = \frac{2\lambda s^\alpha + 1}{(\lambda s^\alpha + 1)^2} \]  

Then the equivalent feedback controller \( C(s) \) is then given by

\[ C(s) = \frac{(2\lambda s^\alpha + 1)(Ts + 1)}{K\lambda^2 s^{2\alpha-1}} \]

which can be written as

\[
C(s) = \underbrace{\left(\frac{2}{K\lambda^2} + \frac{2T}{K\lambda^2} s^\alpha\right)}_{\text{fractional filter}} + \underbrace{\left(\frac{1}{K\lambda^2} + \frac{T}{K\lambda^2} s^{2\alpha-1}\right)}_{\text{PD controller}}
\]

\[ C(s) \] is a usual PD controller cascaded with the fractional filter. Obviously, there is only two parameters \( \lambda \) and \( \alpha \) which need to be adjusted, \( \lambda \) is the time constant of the filter, \( \alpha \) is the non-integer order of the filter. The order \( \alpha \) and the time constant \( \lambda \) determine the overshoot (dependent on \( \alpha \)) and the settling time (dependent on \( \lambda \)), respectively. The larger of the parameter \( \alpha \) is, the larger the system overshoot and the longer the system adjustment time are. When \( \lambda \) increases, the adjustment time of the system will become longer, and the stability of the system will become slower. Therefore, a reasonable value is chosen to achieve the optimal compromising of dynamic characteristics and robustness of the system.

**The result of FFIMC-PD position control design**

In order to testify the validity of the proposed method, we compare FFIMC-PD position scheme with three-loop and IOIMC position scheme. Three kinds of controller at the same time to track the sine curve, tracking effect and tracking error are shown in Figures 6 and 7.

Figure 6 shows that the tracking performance of FFIMC-PD method is better than the three-loop and IOIMC control method. Figure 7 shows that the FFIMC-PD method has smaller tracking error than the three-loop and IOIMC control method. Motor parameters and position control parameters can be displayed in the study by Wen et al.\(^{32}\)

**Force branch control design**

Because of the redundant branch, the parallel mechanism becomes a variable degree of freedom mechanism. The dynamics model of the redundant branch not only associates with the motion state of moving platform, also the forces acted on a moving platform, which is difficult to obtain desired effect by conventional controller.

Current loop control which is the basis of torque control mode is used in the redundant force branch of AC servo control system of 6PUS-UPU parallel robot. Considering the system stability and simplicity, the current closed loop should be regarded as a first-order inertial system\(^{32}\) written as the following form\(^{43}\)

\[ N(s) = \frac{K}{Ts + 1} \]  

where \( T \) is the time constant, \( K \) is the open-loop gain.

Because of the complexity of 6PUS-UPU redundant actuation parallel robot in the control process, it is difficult to obtain a good control performance under the environment with disturbances. In this article, a fractional-order internal model controller is designed based on the simplified model. Based on the principle of IMC design, the FOIMC is designed as follow

\[ T(s) = g(s)N^{-1}(s) \]
where $g(s)$ is the low-pass filter. The order of the low-pass filter is extended to the fractional order, so fractional low-pass filter is chosen

$$g(s) = \frac{1}{1 + s^{\mu}}$$  \hspace{1cm} (15)

where $\mu$ is the filter parameter, $v$ is the filter order.

According to the IMC theory, we can get the following expression

$$R(s) = \frac{T}{K\mu}s^{1-v} + \frac{1}{K\mu}s^{-v}$$  \hspace{1cm} (16)

When the filter order $v = 1$, equation (16) is equivalent to the PI controller. When $0 < v < 1$, equation (16) is equivalent to the fractional order integral and derivative (FOID) controller. When $1 < v < 2$, equation (16) is equivalent to the fractional order integral and integral (FOII) controller.

### Digital realization of fractional calculus

Fractional differential operator $s^\alpha$ is an irrational operator and has infinite dimensions. In order to achieve a fractional-order controller, it needs to be rationalized approximation. Higher-order transfer function of integer order is used to approximate the fractional-order transfer function. There are some common fractional-order continuous-time transfer function rational approximation methods, such as Carlson method, Chareff method and so on. Although these algorithms have good approximation in the amplitude-frequency characteristics, the accuracy of the approximate frequency characteristics of the phase is not high.

Modified oustaloup filter algorithm (MOFA) in the frequency response amplitude frequency characteristics and phase frequency characteristic aspects have a better approximation.

Its transfer function can be expressed as follows

$$s^\alpha \approx K \cdot H(s) \frac{M}{\prod_{m=1}^{N} \frac{s + w_k^m}{s + w_k}}$$  \hspace{1cm} (18)

where $\alpha$ is the order of the differential, $M$ is the order of the filter, and it can be an even number. $\gamma$ is the band gain. $\gamma > 1$ indicates that the frequency band becomes wider, $0 < \gamma < 1$ indicates that the frequency band is narrowed, and the band is unchanged when $\gamma = 1$.

Now we still suppose that the order of the differential is 0.5, and the frequency band is (0.01, 100), namely $\alpha = 0.5$, $w_b = 0.01$ and $w_h = 100$. The band gain $\gamma$ is 35, and the order of the filter $M$ is 11. The Bode diagram of these two filters is shown in Figure 8.

In Figure 8, whether the amplitude frequency characteristic or the phase frequency characteristic of the fractional differential operator, the optimal approximation in the endpoint frequency approximation effect outperforms the modified oustaloup algorithm.

### Simulations

In this section, we use MATLAB/Simulink and ADAMS joint simulation to testify the control effect of the controller based on the 6PUS-UPU simulation platform. The output of the Simulink (the control of the six branches) can be used as the input of the ADAMS, and the output of the ADAMS (the first five branches of the displacement, the sixth branch of the force) can be used as the input of Simulink, which is shown in Figure 9(a). The desired trajectory of the moving platform is shown in Figure 9(b), the desired trajectory of the platform is designed to move from (0, 0, 928) to (−100, −100, 928), and then move from (−100, −100, 928) to (100, 100, 928), and the unit is mm. In this article, the trajectory of z-axis is not considered because we have to perform the complex computations resulting from singular
point, end-effector pose and large internal force. The virtual model of 6PUS-UPU redundant actuation parallel robot was demonstrated in the study by Wen et al.\textsuperscript{32} Figure 9(c) is the virtual model of the 6PUS-UPU in ADAMS. The parameters of the PMSM and the parameters of position controller were in the study by Wen et al.\textsuperscript{33}

The simulation results of first five branches

In order to verify the validness of the proposed method, the branches from first to the fifth use FFIMC-PD method. The simulation result of FFIMC-PD method proposed in this article is compared with three-loop and IOIMC control method.
**Figure 10.** Theoretical displacement of the slider of the first five branch.

**Figure 11.** The position errors of the first five branches with three-loop control method.

**Figure 12.** The position errors of the first five branches with IOIMC control method. IOIMC: integer-order internal model control.

**Figure 13.** The position errors of the first five branches with FFIMC-PD control method. FFIMC-PD: fractional-filter internal model control–proportional–derivative.

**Figure 14.** The driving forces of six branches with PI control method. PI: proportional–integral.

The simulation results of redundant force branch

FOIMC method is used in the sixth branch, that is, redundant branch. The filter parameter $\mu$ is 30, the filter order $\nu$ is 0.17. We also compared the redundant force branches of FOIMC method with traditional PI controller and IMC method. The simulation results are shown in the Figures 14 to 19.

Figures 14 to 19 show that FOIMC method outperforms the traditional PI controller and the IMC controller. The error of each branch using FOIMC method obviously reduces. In order to test the anti-interference performance of the fractional-order internal model controller, the white noise is added to the redundant branch. Figures 20 to 22...
demonstrated the results of different anti-interference performance under different controllers.

Our planning trajectory is (0, 0, 928)→(−100, −100, 928)→(0, 0, 928)→(100, 100, 928). The robot moves to the inflection point of the trajectory at 2 s, so there will be fluctuations. Under the same interference, Figure 20 shows that each branch actual driving force curve has violent fluctuation using PI control method. Figure 21 has certain fluctuation using IMC method. Figure 22 shows that the force curve is smooth and has good anti-interference performance using FOIMC. FOIMC method used in the parallel robot redundant branch not only can effectively improve the control accuracy of the driving force of each branch, but also improve the robustness of the robot control system, enhance the ability of the robot to overcome the uncertain interference.

In order to further analyse the advantages of the FOIMC method, IMC and the traditional PI controller, the average value of the driving force error of each branch is presented.

\[
\begin{align*}
I_{pf} & = \frac{|E_{foimc} - E_{pi}|}{|E_{pi}|} \\
I_{pi} & = \frac{|E_{imc} - E_{pi}|}{|E_{pi}|} \\
I_{fi} & = \frac{|E_{foimc} - E_{imc}|}{|E_{imc}|}
\end{align*}
\]  

(20)

where \(I_{pf}\), \(I_{pi}\) and \(I_{fi}\) respectively describe the improvement of FOIMC method compared with traditional PI controller, IMC method compared with traditional PI controller and FOIMC method compared with IMC controller. \(E_{foimc}\) represents the average value of the 1-norm of
the driving force error of each redundant branch using FOIMC method, \( E_{\text{foimc}} \) represents the average value of the 1-norm of the driving force error of each redundant branch using IMC method, \( E_{\text{pi}} \) represents the average value of the 1-norm of the driving force error of each redundant branch using the traditional PI method. The results are shown in Tables 1 and 2.

Tables 1 and 2 show that the control performance using FOIMC method is obviously improved than using PI method and IMC method. The force error of each branch using FOIMC method is less than that of the traditional PI method and the IMC method, which means the performance of the driving force of each branch. In Tables 1
Table 2. The improvement of FOIMC method over IMC control method.

| Force | $E_{\text{fimc}}(N)$ | $E_{\text{imc}}(N)$ | $I_{p}$(%) |
|-------|-------------------|-------------------|-----------|
| 1     | 30.55             | 49.00             | 37.66     |
| 2     | 13.53             | 14.07             | 3.86      |
| 3     | 32.63             | 51.53             | 36.67     |
| 4     | 10.10             | 14.01             | 27.95     |
| 5     | 31.20             | 49.95             | 37.54     |
| 6     | 8.00              | 13.07             | 38.74     |

FOIMC: fractional-order internal model control; IMC: internal model control.

Conclusions

FFIMC-PD controller of the first to fifth branches and FOIMC controller of the sixth branch of 6PUS-UPU redundant actuation parallel robot are proposed in this article. The FFIMC-PD method can reduce the position error, while FOIMC can improve the control performance. The proposed method can not only ensure the tracking precision of the parallel robot but also reduce the internal force of the system, which can avoid damaging the permanent motor. The control method proposed in this article is compared with other control methods, and the simulation results show that the proposed control method has the ability of anti-interference and tracking performance. Future study is to design 2-DOF internal model controller, making the following performance and anti-interference performance can be adjusted separately. Future work is to consider doing the experiment on the platform of 6PUS-UPU parallel robot in the proposed framework.

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