

Control of suspended low-gravity simulation system based on self-adaptive fuzzy PID

Zhigang Chen*, Jiangan Qu*

*School of Mechanical and Electrical Engineering Harbin Institute of Technology, Harbin 150001, China

Abstract. In this paper, an active suspended low-gravity simulation system is proposed to follow the vertical motion of the spacecraft. Firstly, working principle and mathematical model of the low-gravity simulation system are shown. In order to establish the balance process and suppress the strong position interference of the system, the idea of self-adaptive fuzzy PID control strategy is proposed. It combines the PID controller with a fuzzy control strategy, the control system can be automatically adjusted by changing the proportional parameter, integral parameter and differential parameter of the controller in real-time. At last, we use the Simulink tools to verify the performance of the controller. The results show that the system can reach balanced state quickly without overshoot and oscillation by the method of the self-adaptive fuzzy PID, and follow the speed of 3m/s, while simulation degree of accuracy of system can reach to 95.9% or more.

1 Introduction

Nowadays, aerospace activities is becoming common projects. In order to avoid risks, it is becoming increasingly important to carry out low-gravity simulation experiments on the ground. At present, low-gravity simulation methods are becoming more and more mature^[1], in which the suspended method is widely used because of its simple structure, free test time and high accuracy. The basic principle of suspension is to control the tension of rope constantly to offset part of the gravity of the spacecraft. In this way, system can achieve the simulation of low-gravity.

The control strategy is the key of the suspended low-gravity simulation system. Fujitsu Laboratories Limited in Japan^[2] used the active control method to realize the manipulator experiment under the low-gravity, they made use of PID control strategy and they considered two kinds of interference including impulsive and constant acceleration. Gregory C. White and Yangsheng Xu^[3] developed a system called GC(Gravity Compensation) by the combination of active and passive method. They realized the constant tension control of the system by fuzzy PI control strategy and eliminated influences of the friction torque. NASA had developed an active response gravity compensation system (ARGOS) that could simulated the low-gravity environment of the moon and Mars. It could follow the speed of 3m/s when the load was 136kg in the vertical direction. Naiming Qi^[4] and others observed the friction and some outside disturbances, they used the fuzzy CMAC to compensate for the disturbance and reached high accuracy. Institute of Intelligent Machines, Chinese Academy Of Sciences^[5] developed a low-gravity simulation system by rotating arm, and they used the genetic algorithm based on the PD control to improve the system's response speed and inhibit the overshoot. Zhigang Xu^[6] researched the low-gravity for lunar rover problems, he used the PID strategy and force feedback to reach high accuracy. It can be seen that the studies focused on the rapid follow-up in the horizontal direction and the low speed follow-up in the vertical direction.



Considering that spacecraft will reach a high speed and acceleration in the vertical direction when it separate vertically, so the system should follow up the high speed in a short time. In this paper, spacecraft can reach 3m/s in 10ms in vertical separation, at the same time the low-gravity simulation accuracy should maintain at 95% or more. Firstly, the model is established and the control model is obtained. Then, the balanced state of the system is established by the control strategy of self-adaptive fuzzy PID and the strong position disturbance is suppressed. Finally, we observed the results by Simulink. The results show that this control strategy can reach the balanced state quickly without overshoot and oscillation and it can suppress position interference obviously, at the same time the simulation accuracy meet the requirements.

2 Model of low-gravity simulation system

The simplified schematic diagram of the suspended low-gravity simulation system is shown as Figure 1. The system has four parts including mechanical system, buffer mechanism, measuring system and control system. The mechanical system consists of a torque motor, brake and a wire wheel. The torque motor is the core of the system, which can provide a constant moment for the system. The spring acts as a cushion and can improve response speed. The control system realize the information measurement, data acquisition, information storage, status monitoring, and other functions. The tension sensor detect the tension of the wire so that system can maintain the tension at a constant value.

Firstly, the system should reach to a balanced state, the torque motor works at a stall state. The tension of wire changes when the spacecraft is disturbed suddenly by the strong upward position x_d of the outside. At the same time, the controller send a signal to the torque motor which drive the reel to rotate. The wire will follow up the spacecraft to move upwards until the tension of the it reaches the target value again. According to the above description, we establish the mathematical model. The torque motor works at torque mode, and its control model is shown as equation (1).

$$\frac{\dot{\theta}(s)}{U(s)} = \frac{K_T}{L_m J_m s^2 + (L_m B_m + R_m J_m) s + (R_m B_m + K_T K_e)} \quad (1)$$

Where θ is the rotation of the torque motor, U is the input voltage, K_T is the torque coefficient of the motor, L_m is the inductance, R_m is the resistance, J_m is the rotational inertia, B_m is the damping constant, K_e is the EMF.

When the spacecraft move upwards and form position x_d , and the output torque of motor is M_L . The relationships of them are shown as equation (2) and (3).

$$x_h = r \cdot \theta, \quad x_l = x_d \quad (2)$$

$$M_L = kr \Delta x = kr(x_h - x_d) \quad (3)$$

Where r is the radius of the reel, x_h is the position of the top of the spring, x_l is the position of the lower end of the spring, k is the stiffness coefficient of the spring.

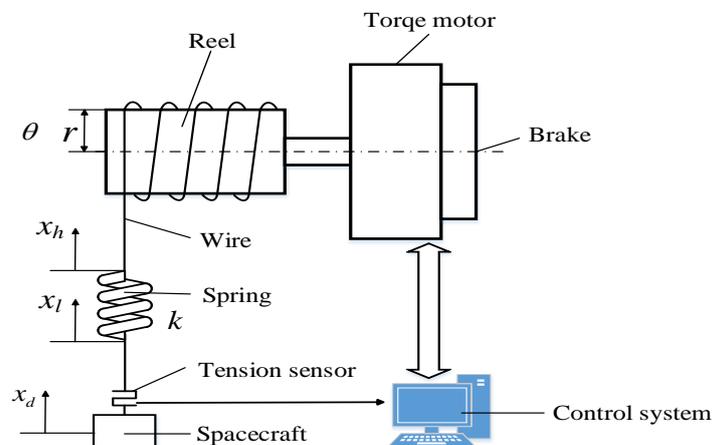


Figure 1: Schematic diagram of system

3 Self-adaptive fuzzy PID control strategy

In fact, some parameters and the structure of the system will change because of load changing or external interference factors, when the system is working. So the self-adaptive control strategy is necessary. Self-adaptive fuzzy PID control strategy can adjust the PID parameters automatically.

3.1 Self-adaptive fuzzy PID control theory

Two-dimensional fuzzy controller is used in this paper, it takes the error e and the error rate of change ec as input variables, and it can adjust the PID parameters in real-time. For the suspended low-gravity simulation system, the whole structure is shown as Figure 2

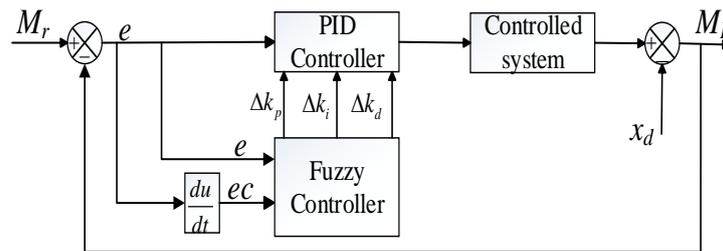


Figure 2: Structure of self-adaptive fuzzy PID controller

The discrete algorithm of PID controller is shown as equation (4).

$$u(k) = k_p e(k) + k_i T \sum_{j=0}^k e(j) + k_d \frac{e(k) - e(k-1)}{T} \quad (4)$$

Where k_p is the proportional gain, k_i is the differential gain, k_d is the derivative gain, k is the sampling number, T is the sampling time.

The fuzzy controller output the adjustable value Δk_p , Δk_i , Δk_d of PID parameters. So the parameters that self-adaptive fuzzy PID controller output finally are shown as equation (5), (6), (7).

$$k_p = k_{p0} + \Delta k_p \quad (5)$$

$$k_i = k_{i0} + \Delta k_i \quad (6)$$

$$k_d = k_{d0} + \Delta k_d \quad (7)$$

Where k_{p0} , k_{i0} , k_{d0} are initial parameters.

3.2 Define the fuzzy variable and membership function

In this paper, we use two-dimensional fuzzy controller, so the input variables are e and ec , the output variables are Δk_p , Δk_i and Δk_d . Their language values are defined as “Negative Big”, “Negative Medium”, “Negative Small”, “Zero”, “Positive Small”, “Positive Medium”, “Positive Big”, and referred to as “NB”, “NM”, “NS”, “ZO”, “PS”, “PM”, “PB”. The interval of e and ec are ranged by $[-900\text{N}\cdot\text{m}, 900\text{N}\cdot\text{m}]$, $[-1800\text{N}\cdot\text{m}/\text{s}, 1800\text{N}\cdot\text{m}/\text{s}]$ by measuring the response curve. The interval of Δk_p , Δk_i , Δk_d are ranged by $[-1.8, 1.8]$, $[0, 28]$ and $[-0.03, 0.09]$ according to the initial parameters which can make the system to achieve a normal state.

The membership function plots of output variables and input variables are shown as Figure 3 and Figure 4. Considering that Δk_p , Δk_i and Δk_d are calculated complicated, so we choose triangular as the membership function. For the input variables, we change the NB and PB to the Z-type membership function.

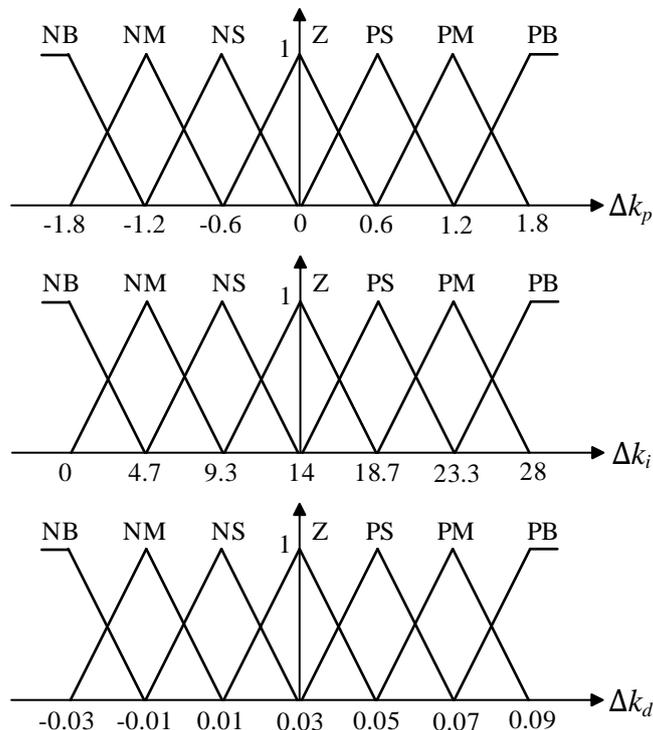


Figure 3: Membership function plots of output variables

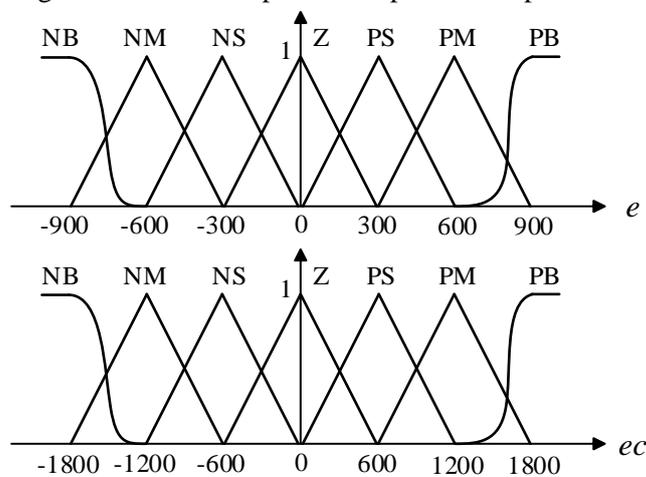


Figure 4: Membership function plots of input variables

3.3 Create fuzzy rules

Fuzzy rules are the key to the whole control system, fuzzy controller carry out the fuzzy reasoning according to the fuzzy rules. For the error e and the error rate of change ec , the setting principles proposed in this paper are as follows.

Firstly, at the beginning of the response, the error e is very big, so k_p should be increased appropriately, at the same time, k_i should take a smaller value or zero and k_d should take a smaller differential coefficient in order to increase the response speed of the system while avoiding overshoot and integral saturation phenomenon, moreover, inhibit the differential supersaturation because ec is too big.

Secondly, at the middle of the response, the error e is smaller than the beginning. So k_p and k_i should maintain at the moderate values, only in this way, controller can take into account the stability of the system and control accuracy, at the same time, ensure the response speed.

Thirdly, at the end of the response, the error e is smaller than before and tends to zero, k_p should be reduced appropriately, k_i should be increased appropriately in order to eliminate the static error of the system, at the same time suppress the overshoot and reduce the oscillation of the system. When the error rate of change is bigger than before, k_d should take a smaller value, on the contrary, when the error rate of change ec is smaller than before, k_d should take a bigger value.

Through the above analysis about the fuzzy rules, we edited nine fuzzy control rules. Fuzzy rules surface of k_p , k_i and k_d are shown as Figure 5, Figure 6 and Figure 7.

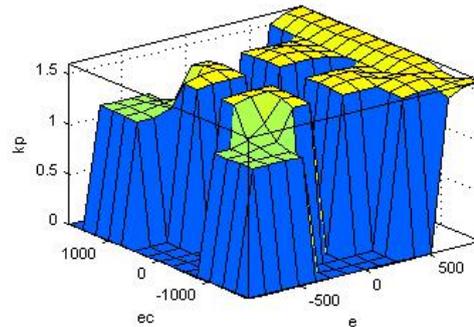


Figure 5: Fuzzy rules surface of k_p

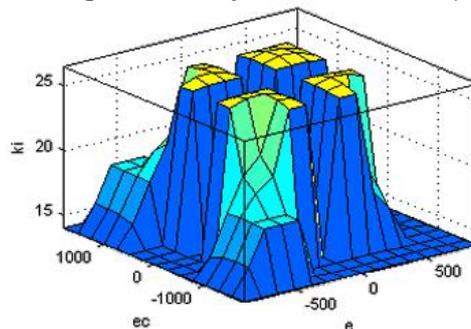


Figure 6: Fuzzy rules surface of k_i

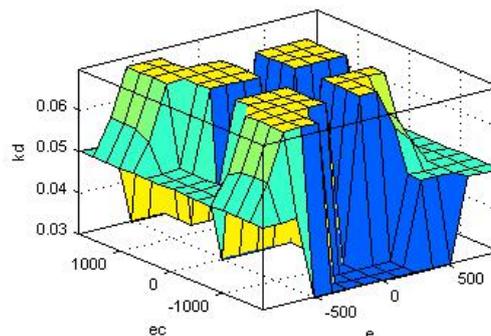


Figure 7: Fuzzy rules surface of k_d

After fuzzy reasoning, we should get a clear value as an output called defuzzification^[7], the method of “center of mass” is used in this paper, which is widely used. Its output formula is shown as equation(8).

$$h = \frac{\sum_{i,j} f_{ij} u_{ij}}{\sum_{i,j} f_{ij}} \quad (8)$$

Where u_{ij} is determined by the fuzzy rules, f_{ij} is the membership value of input.

4 Simulation

In this part, we add the self-adaptive fuzzy controller to the whole control system and get the control block diagram of the system as shown in the Figure 8. Characteristic values of the low-gravity simulation system is shown in Table 1. The system is verified by Simulink.

Symbol	Value	Unit
J_m	1.347	kg·m ²
L_m	6.001754×10^{-3}	H
R_m	0.2865886	Ω
B_m	0.001	N·m·s/rad
K_e	7.795905	V·s/rad
K_T	2.384068	N·m/A
K_i	12	none
k	20000	N/m
r	0.14	m

Table 1: Characteristic values of the low-gravity simulation system

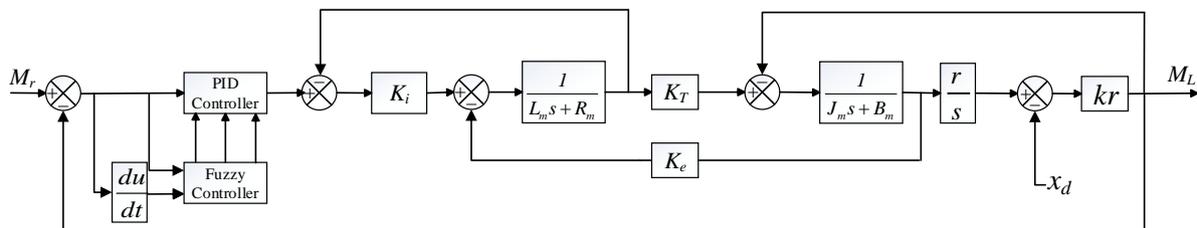


Figure 8: Control diagram of the low-gravity simulation system

The target output torque is 890.6N·m in this paper. The speed of the spacecraft can reach to 3m/s in 10ms when it separate. So we add a pulse signal of \ddot{x}_d to the system in 15th seconds, whose amplitude is 300m/s² and the time of action is 10ms. The system treats it as a strong position interference.

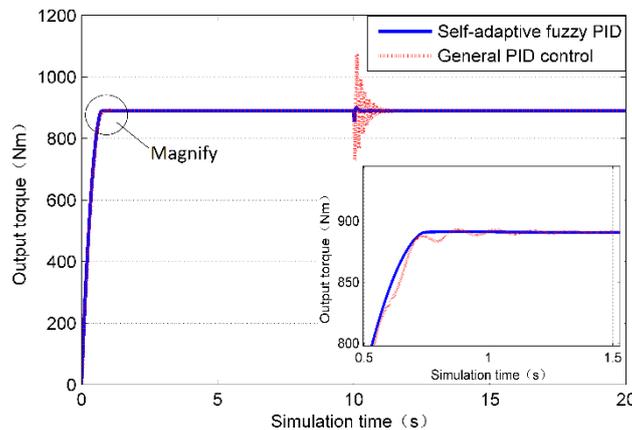


Figure 9: The response curve of system and its partial magnification

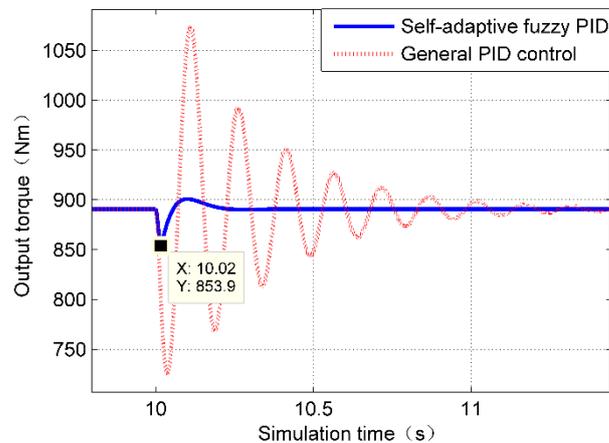


Figure 10: Magnification in position interference

The response curve of the system is obtained by simulation, it is shown as Figure 9 and Figure 10. From the above figures, we can see that the self-adaptive fuzzy controller gets a more smoother response curve than the general PID controller at the beginning of the response. The self-adaptive fuzzy controller can suppress the strong position obviously while the system produces violent oscillation by general PID controller. From the Figure 10, we can see that the maximum error is $36.7\text{N}\cdot\text{m}$, simulation accuracy is 95.9% and the system reverts to the target value quickly because of self-adaptive fuzzy controller. Figure 11 shows the adaptive process of the PID parameters.

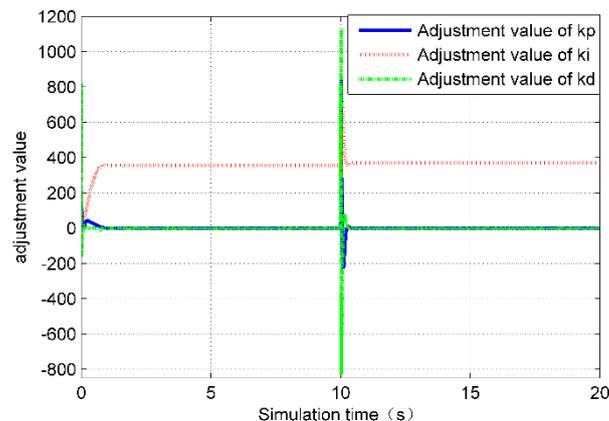


Figure 11: Adaptive adjustment of PID parameters

5 Conclusion

This paper proposes an active suspended low-gravity simulation system to follow the vertical motion of the spacecraft and uses a new method based on the self-adaptive fuzzy PID control strategy to suppress the strong position interference and eliminate the initial oscillation of the system. Simulation results show that the low-gravity simulation system can follow the speed of 3m/s in the vertical direction at the same time simulation accuracy can maintain at 95.9%, meeting the requirements of indicators. Moreover, the low-gravity system can revert to the target value quickly by the self-adaptive fuzzy PID controller whose effects are much better than the general PID controller.

Acknowledgements

This work was supported by Harbin Institute of Technology.

References

- [1] Zou, Meng, et al. "Effect of gravity on the mechanical properties of lunar regolith tested using a low gravity simulation device." *Journal of Terramechanics*, 60, pp. 11-22, (2015).
- [2] Sato, Y., Ejiri, A., Iida, Y., Kanda, S. "Micro-G emulation system using constant-tension suspension for a space manipulator." *IEEE International Conference on Robotics and Automation*, 3, pp. 1893-1900, (1991).
- [3] White, G. C., and Y. Xu. "An active vertical-direction gravity compensation system." *IEEE Transactions on Instrumentation & Measurement*, 43, pp. 786-792, (2002).
- [4] Qi, N., Zhang, W., Gao, J., Ma, J. "Control of spatial microgravity environment ground simulation system based on fcmac." *Spacecraft Environment Engineering*, 28, pp. 31-35, (2011).
- [5] Song, Yan Feng, T. Mei, and X. M. Lin. "The application of field programmable gate array to the controller of a silk microgravity system." *Industrial Instrumentation & Automation*, 4, pp. 48-51, (2006).
- [6] Hao, L. I., Zhi-Gang, X. U., Guo, Y. P., Wang, J. Y. "Design of suspension point tension control system for lunar rover." *Machinery Design & Manufacture*, 4, pp. 50-52, (2012).
- [7] Tang, K. S., Man, K. F., Chen, G., Kwong, S. "An optimal fuzzy pid controller." *IEEE Transactions on Industrial Electronics*, 48, pp. 757-765, (2001).