Cooperative Control of Rotating Inverted Pendulum based on Fuzzy Control

Yujue Wang[1], Weining Mao[1], Bin Xin[1], Qing Wang*[1], Jian Wei[1]

[1]School of Automation, Beijing Institute of Technology, Beijing, China

Abstract. The rotating inverted pendulum is a nonlinear, multivariate, strongly coupled unstable system, and its study can effectively reflect many typical problems in control. In this paper, a parameter self-tuning fuzzy controller is proposed to achieve intelligent control of a single rotating inverted pendulum. Particle swarm optimization is used to adjust its structural parameters, and simulation experiments are given to show that the system can achieve stability with the designed parametric self-tuning fuzzy controller, and the control performance is better than that of the conventional fuzzy controller. On the other hand, the leader-follower control strategy is used to realize the cooperative control of multiple rotating inverted pendulums. Two Qube-Servo2 rotating inverted pendulums are used for the cooperative pendulum starting and stabilization experiments, and the effectiveness of the proposed cooperative control strategy is verified.

Keywords: Particle Swarm Optimization, Parameter Self-tuning, Fuzzy Control, Cooperative Control

1. INTRODUCTION

The inverted pendulum system is a common platform in the control field. In the development of control field, the inverted pendulum as a typical control object has the advantages of easy manufacturing, simple structure, low cost and easy adjustment of structural parameters. However, such a seemingly simple and inexpensive inverted pendulum system is an unstable system with nonlinear nature, high order, many variables, rapid changes and high coupling. Because of the simplicity and complexity of inverted pendulum systems, making it an ideal platform for scholars to discover and experimentally validate new control strategies. The self-starting pendulum of inverted pendulum [1], steady pendulum research and control strategies such as PID control, LQR control [2][3], and fuzzy control [4][5] are the hot spots of scholars' attention [6].With the gradual research in the fields of control theory, computer technology, information and digital technology, numerous new control strategies have been proposed in [7], but these control strategies and control algorithms often cannot find a strict proof of them in theory, and then the inverted pendulum system can be used to test the control effect of these control strategies and evaluate the accuracy and use value of these control algorithms.

The cooperative control of multiple inverted pendulums based on the inverted pendulum system belongs to the cooperative control technology of multiple intelligences. The multi-intelligent body technology has been attracting much attention since its birth at the end of the twentieth century and has been developing rapidly, and nowadays the research on multi-intelligent body technology has become a hot topic[8].

The emergence of multi-intelligent systems is a good solution to the problem of modeling complex systems, and its advantages can be used to make the control system can still perform well in front of complex objects [9]. There have been many solutions to the study of multi-intelligent systems on how the whole system achieves stability [10] and the consistency problems therein, and the synchronized actions of individual intelligences. With the development of artificial intelligence technology, collaborative control and emerging technologies have been integrated with each other to achieve fruitful results [11].

In this paper, we propose a parametric self-tuning fuzzy controller for stable control of a single inverted pendulum based on multiple inverted pendulum platforms, and use a leader-follower control strategy to achieve cooperative control of multiple rotating inverted pendulums.

2. INVERTED PENDULUM MODELING

An inverted pendulum system is an unstable nonlinear system with high order, many variables, rapid changes and high coupling. Before designing a control strategy for it, a state-space model needs to be constructed for simulation and verification.

This work was supported in part by the National Natural Science Fund of China under Grant 62003044 and the Basic Science Center Programs of NSFC under Grant 62088101.
*Corresponding author: Qing Wang (wangqing1020@bit.edu.cn).

The physical quantities used in the modeling process and their corresponding symbols are shown in the following table:

Table. 1 Table of physical quantities and their symbols

symbols	Physical Significance	Units
T	Total kinetic energy of the system	J
V	Total potential energy of the system	J
J_r	Rotational inertia of the rotating arm	$Kg \cdot m^2$
J_p	Rotational inertia of the pendulum	$Kg \cdot m^2$
m_p	Mass of the pendulum	Kg
L_p	Length of the pendulum	m
L_r	Length of the rotating arm	m
g	Gravity acceleration	$m \cdot s^{-2}$
θ	Angle of the rotating arm	°
α	Angle of the pendulum	°
τ	Torque of the rotating arm	$N \cdot m$
D_r	Viscous friction torque or viscous damping of the rotating arm	$N \cdot m \cdot s/rad$
D_p	Viscous friction moment or viscous damping of the pendulum	$N \cdot m \cdot s/rad$

A simplified physical model of a rotating inverted pendulum is shown below.

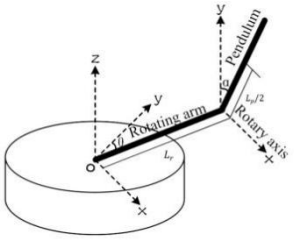


Fig. 1 Simplified model of a rotating inverted pendulum

Choose the upper surface of the base as the zero potential energy surface, then solve state space equations using Euler-Lagrange modeling method.

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du \end{cases} \tag{1}$$

Linearization of the Lagrangian equations near the equilibrium position, which can be neglected in the calculation process due to the small viscous damping, brings in the specific values of the parameters to obtain the state-space model of the rotating inverted pendulum.

$$A = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 149.2751 & -0.0104 & 0 \\ 0 & 261.6091 & -0.0103 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ 49.7275 \\ 49.1493 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \quad D = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

3. THEORETICAL DESIGN

In the following, an intelligent control strategy for the control of a rotating inverted pendulum using a parametric self-tuning fuzzy controller is proposed using the constructed state space model. The design of this control strategy is the key of this paper because the final cooperative control will be achieved based on this intelligent control strategy.

3.1. Design of fuzzy controllers

For fuzzy controllers, changes in structural parameters lead to changes in controller characteristics. Inspired by this, we propose a parametric self-tuning fuzzy controller, and the block diagram of the designed control system is shown below.

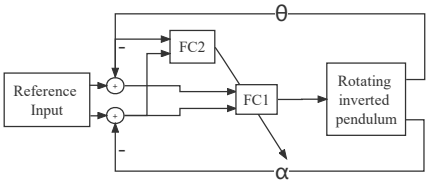


Fig. 2 Block diagram of fuzzy control system for a single rotating inverted pendulum

In this control system, a single rotating inverted pendulum is controlled using two fuzzy controllers. The first fuzzy controller FC1 is used to provide the control amount to the inverted pendulum and the other fuzzy controller FC2 is used to automatically adjust the parameters of the first fuzzy controller.

The internal structure of FC1 and FC2 is shown below.

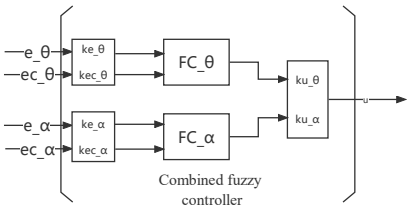


Fig. 3 Internal structure diagram of FC1

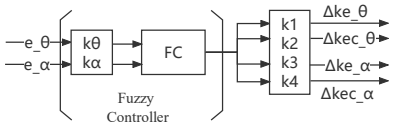


Fig. 4 Internal structure diagram of FC2

For FC1, its membership function uses the triangular membership function. In order to make the control action of the controller more accurate and smooth near the equilibrium position, some adjustments are made to the membership function so that the fuzzy subset around the zero point is finely divided, and the design is shown in the following figure.

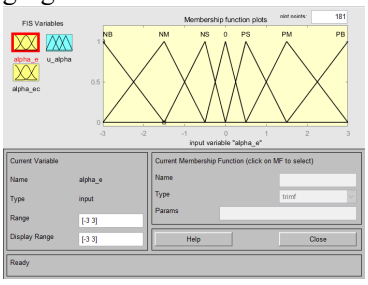


Fig. 5 The membership function of FC1

For FC2, its membership function uses the Gaussian-type membership function.

Combining the automatically generated rules and control experience, the following fuzzy control rule base can be obtained.

Table. 2 Rotary arm angle fuzzy controller rule table

		EC_θ						
		NB	NM	NS	O	PS	PM	PB
E_θ	NB	PB	PB	PM	PS	PS	0	0
	NM	PB	PM	PS	PS	0	0	0
	NS	PM	PS	PS	0	0	0	NS
	O	PS	PS	0	0	0	NS	NS
	PS	PS	0	0	0	NS	NS	NM
	PM	0	0	0	NS	NS	NM	NB
	PB	0	0	NS	NS	NM	NB	NB

Table. 3 Pendulum angle fuzzy controller rule table

		EC_α						
		NB	NM	NS	O	PS	PM	PB
E_α	NB	NB	NB	NM	NS	0	0	PS
	NM	NB	NM	NM	NS	PS	PS	PS
	NS	NM	NM	NS	0	PS	PS	PS
	O	NM	NS	0	0	0	PS	PM
	PS	NS	NS	NS	0	PS	PM	PM
	PM	NS	NS	NS	PS	PM	PM	PB
	PB	NS	0	0	PS	PM	PB	PB

According to the experience, when the error is very large, the fast action of the control system can be achieved by appropriately increasing k_{e_θ} and k_{ec_α}. When the error is small, the anti-interference ability of the control system near the equilibrium position can be enhanced by increasing k_{ec_θ} and k_{e_α} appropriately. Therefore, based on the above experience, the following fuzzy rule table can be obtained.

Table. 4 Fuzzy rule table of FC2

		E_α		
		N	O	P
E_θ	N	FASTB	O	FASTS
	O	STABLES	STABLEB	STABLES
	P	FASTS	O	FASTB

3.2. Design of the optimization algorithm

The particle swarm optimization algorithm (PSO) was chosen to optimize the quantization and scaling factors of the designed fuzzy controller. Particle swarm optimization algorithm is a population-based intelligent iterative algorithm[12]. Compared with the genetic algorithm, the PSO algorithm is simpler and easier to implement, and also converges more quickly[13].PSO has no absolute optimal parameters and needs to be adjusted specifically to the specific problem in order to make the optimization search faster and better[14].

3.3. Design of cooperative control algorithm

The single inverted pendulum controlled with fuzzy control in the above section is considered as one intelligent body, and multiple intelligent bodies are controlled cooperatively. The leader-following model is used to let the state of the slave inverted pendulum follow the state of the master inverted pendulum to achieve the cooperative and consistent control of two inverted pendulums.

3.3.1. Architecture of the system

The whole collaborative control system consists of a computer, two QUBE-Servo 2 rotating inverted pendulums, and it is hoped that the communication service of data distribution will be realized through the computer. Both experimental devices send their respective sensor data to the computer, which analyzes and sends command messages to both experimental devices. The two experimental devices in turn carry out the corresponding control actions according to the command information they receive.

The block diagram of the system architecture is shown below.

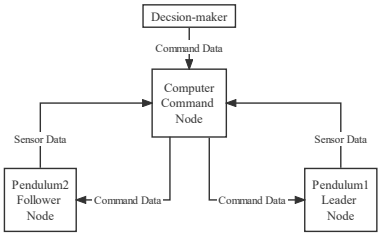


Fig. 6 Block diagram of system architecture for cooperative control of two inverted pendulums

The decision maker sends control commands to the computer, which assigns the control commands to the two inverted pendulum experimental equipment, and receives the state information of the two inverted pendulums, and issues control commands to make the inverted pendulum (follower) from the main inverted pendulum (leader) in the same state to achieve cooperative control.

3.3.2. Communication protocols

When data needs to be sent and received between the nodes, the sending and receiving data format of the system needs to be constructed. There are three data types in the system as follows.

Category 1 - Instruction messages to the computer from the decision maker.

Decision maker ID	Inverted pendulum state	Rotating arm angle

The Decision maker ID represents the decision maker who issued the command, the Inverted pendulum state represents the decision maker's expected state of the inverted pendulum, which is divided into the starting pendulum state and the steady pendulum state, and the Rotating arm angle represents the decision maker's expected angle of the rotating arm.

Category 2 - Command messages from the computer to the experimental equipment.

Command Object ID	Inverted pendulum state	Rotating arm angle	Light information

The Command Object ID represents whether the command is sent to the leader or the follower, the Inverted pendulum state represents the computer's desired state for the command object, the Rotating arm angle represents the computer's desired angle for the command object's rotating arm, and the Light

information represents the computer's command the object's indicator display and kind of color, there are red, green, blue and not light four states.

Category 3 - Command messages transmitted from the experimental equipment to the computer.

Experimental equipment ID	Inverted pendulum state	Rotating arm angle

Experimental equipment ID indicates the number of the current experimental equipment, Inverted pendulum state is the state of this equipment, divided into two states of the starting pendulum, stable pendulum, Rotating arm angle for this equipment at this time the rotation arm angle value.

With the above protocol, it is convenient to design the leader following algorithm.

3.3.3. Cooperative control algorithms

The ultimate goal of cooperative control is to achieve.

1. Both the leader inverted pendulum and the follower inverted pendulum reach the equilibrium state

2.The leader's rotational arm angle returns to the decision maker's set value under various disturbances

3.The rotating arm angle of the follower returns to the current rotating arm angle of the leader under various disturbances

The following situations may occur in the control process.

1.Only one inverted pendulum is connected to the system, i.e. only one inverted pendulum is operated

2.One of the pendulums of the main inverted pendulum or the slave inverted pendulum does not reach the balance state

In order to make correct decisions in various situations and finally achieve the control goal of cooperative control, a computer-based cooperative control strategy needs to be designed, and the overall flow chart of the algorithm is shown below.

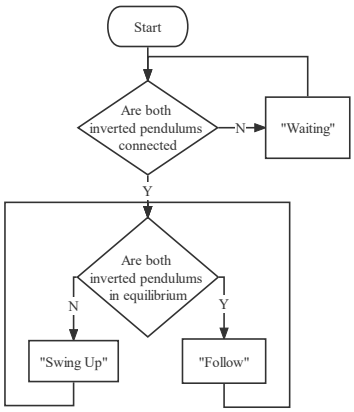


Fig. 7 Collaborative control strategy flow chart

The operations in the algorithm are shown below.

"Waiting" operation: At this time the inverted pendulum is not fully operational. The computer will set the indicator information in the command to light off, at this time, the inverted pendulum that has not joined the system lights up red, and the inverted pendulum that has joined the system lights off, wait until all inverted pendulums have been connected, the indicator information of the master inverted pendulum is set to blue, and the indicator information of the slave inverted pendulum is set to green, and then start the cooperative control.

"Swing Up" operation: When both the master and slave inverted pendulums are in non-equilibrium position, the computer sends the desired information about the stable swing state to both inverted pendulums, and the master and slave inverted pendulums start to swing up to the stable state independently.

"Follow" operation: The computer sends the decision maker's desired information to the master inverted pendulum, which follows the decision maker's wish to make the selection force reach the desired angle. The computer sends the information about the rotation arm of the master pendulum to the slave pendulum, and the slave pendulum follows the rotation arm angle of the master pendulum.

4. EXPERIMENTAL VERIFICATION

The experimental platform on which the experiment is based is the QUBE-Servo2 from Quanser Canada, which is a rotating inverted pendulum experimental platform.

4.1. PSO algorithm optimization for controller

The optimization algorithm is divided into two steps. First, the system is simulated alone without considering FC2, and the parameters to be optimized at this time are those of FC1. Then, for the better FC1, the parameters can be fixed, and only the parameters of FC2 are optimized.

Considering the need to reduce overshoot and rise time while reducing the system error, the following adaptation value function is used.

$$J = \int_0^{+\infty} ((\alpha_1 + m)|e_\theta| + (\alpha_2 + n)|e_\alpha|)dt + \alpha_3 t_c \quad (2)$$

where t_c is the rise time, $\alpha_1, \alpha_2, \alpha_3$,m and n are the weights of each item.

First, the FC1 parameters are optimized, and the optimization results are shown in the following figure.

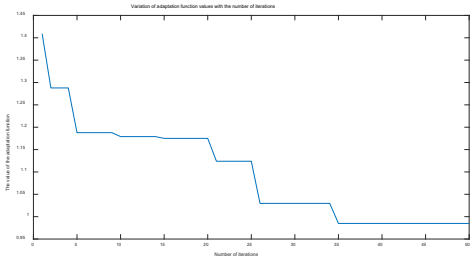


Fig. 8 Plot of the value of the adaptation function of the PSO algorithm with the number of iterations

It can be seen that the algorithm converges at the 35th iteration.

The simulation results are compared with the previous parameters as shown in the following figure.

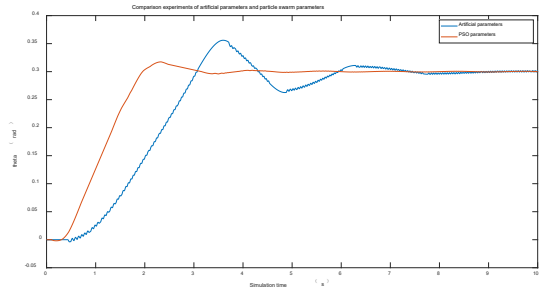


Fig. 9 Graph of experimental results comparing artificial parameters with PSO algorithm parameters

Second, the FC2 parameters are optimized, and the 48th iteration and the optimal value is:

$$\begin{cases} k_\theta = 10.0 \quad k_1 = -1.8 \quad k_3 = 4.5 \\ k_\alpha = 30.9 \quad k_2 = 2.7 \quad k_4 = -0.13 \end{cases}$$

The two controllers before and after the addition of FC2 are compared and the simulation results are shown in the following figure.

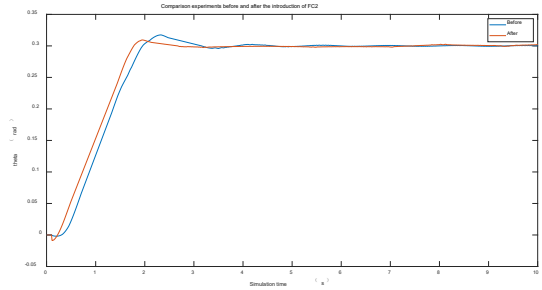


Fig. 10 Comparison of experimental results before and after adding FC2

The introduction of the self-tuning module allows for better controller performance.

4.2. Verification of fuzzy control strategy

In the experiment, it is found that fuzzy control has a certain static error in steady state, and it is hoped that the static error can be eliminated while retaining the advantages of fast and good anti-interference performance of fuzzy control. The LQR control algorithm is considered to be combined with the fuzzy control algorithm to further solve the problem of static error.

The block diagram of the system structure of the control system is as follows.

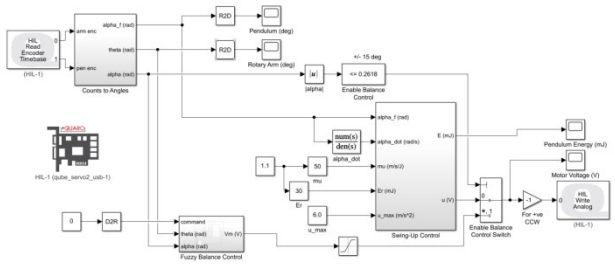


Fig. 11 Control system system structure block diagram

The Swing-Up Control module is a swing control module based on the principle of energy increase, and the Enable Balance Control module is a controller module. When the swing angle error is less than 15deg, the controller starts to control, and when it is greater than 15deg, the swing-up module increases the system energy.The LQR controller and the Enable LQR Control module are added to switch to LQR control only when the error is less than 1deg, which can well eliminate static errors while retaining the advantages of fast and good anti-disturbance performance of fuzzy control in a wider range.

The experimental results of the angle of the rotating arm and the angle of the pendulum of the inverted pendulum using this controller are shown in the following graphs.

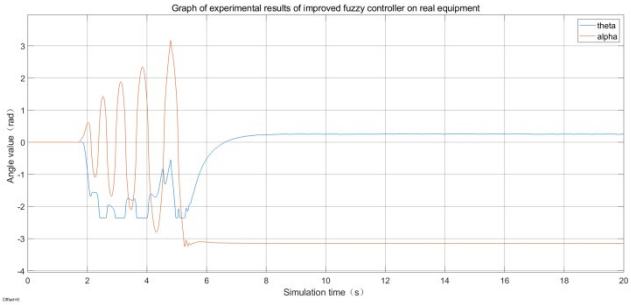


Fig. 12 Graph of experimental results of the proposed fuzzy controller on a real device

Then experiments were conducted without the self-starting pendulum module, and the improved fuzzy control algorithm was experimentally compared with the LQR control algorithm, and the results of the comparison experiments are shown below.

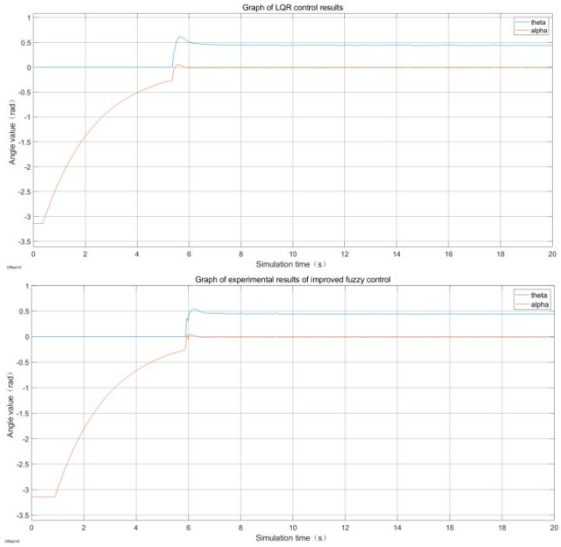


Fig. 13 Experimental results of the improved fuzzy controller compared with the LQR controller on a real device

It is obvious that the improved fuzzy controller performs better than the LQR controller, mainly in terms of shorter time to reach the equilibrium state and smaller overshoot of the rotation arm angle.After calculation, it can be found that the overshoot of the rotating arm angle control using the LQR controller is **15%** in the control of the actual equipment, while the overshoot of the rotating arm angle control is **4%** when the improved fuzzy controller is used for control.

4.3. Verification of cooperative control strategy

The block diagram of the computer node part of the cooperative control is shown below.

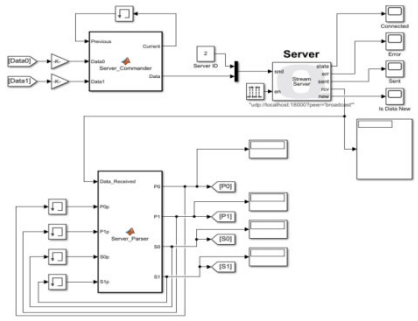


Fig. 14 Block diagram of the system of the computer node

The system block diagram of the inverted pendulum is shown below

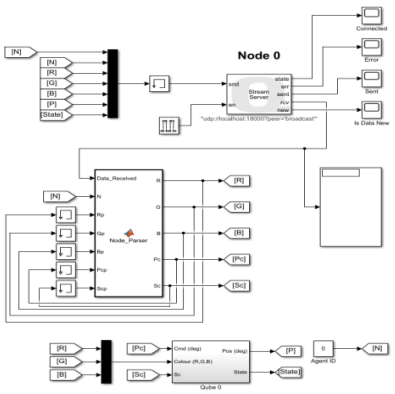


Fig. 15 Block diagram of the system of the inverted pendulum node

The master inverted pendulum is node 0 and the slave inverted pendulum is node 1.And the phenomena during the experiment for the two inverted pendulums controlled in concert are shown below.

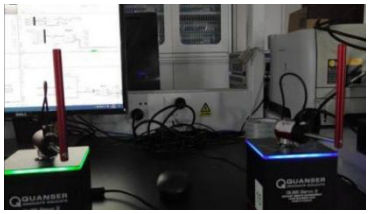


Fig. 16 Experimental phenomenon of cooperative control strategy on real equipment

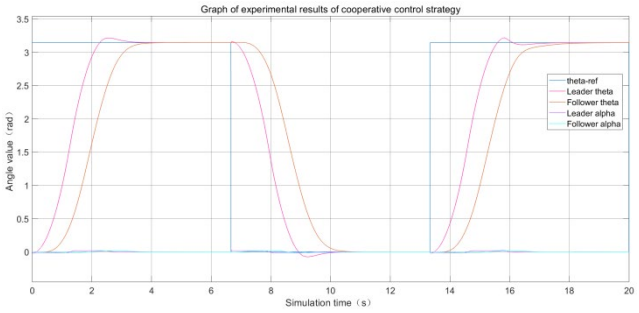


Fig. 17 Experimental result plot of the designed collaborative control strategy

In Figure 16, the inverted pendulum with blue light is the master inverted pendulum, and the inverted pendulum with green light is the follower inverted pendulum, which is currently following the master inverted pendulum. Figure 17 shows that the master inverted pendulum can follow the desired output, and the follower inverted pendulum can follow the master inverted pendulum for motion and can finally reach the same state and ensure the stability of the inverted pendulum. The control effect is good, and the cooperative control of two inverted pendulums is realized by the leader-follower strategy.

5. CONCLUSION

The rotating inverted pendulum is a nonlinear, multivariable, strongly coupled unstable system, and its study can effectively reflect many typical problems in control. In this paper, based on the intelligent control of inverted pendulum, the cooperative control of multiple inverted pendulums is realized and can make multiple inverted pendulums achieve the consistency of control states.

This paper verifies the reliability of the proposed parameter self-adjusting fuzzy controller to achieve stable control of a single inverted pendulum, and verifies that the controller parameters obtained by the particle swarm finding algorithm are significantly better than those set manually. Finally, the effectiveness of the proposed leader-following control strategy is verified by two Qube-Servo2 rotating inverted pendulums for cooperative pendulum starting and stabilization experiments.

6. FUNDATIONS

This work was supported in part by the National Natural Science Fund of China under Grant 62003044 and the Basic Science Center Programs of NSFC under Grant 62088101.

References:

[1] Rubi J, Rubio A, Avello A. Swing-up control problem for a self-erecting double pendulum[J]. Proceedings of Control Theory and Applications, 2002,149(2):169-175.

[2] Watts JW. Control of an inverted pendulum[C]. ASEE Annual Conference, session2527, 1984, 706-710.

[3] H.M L, C.F Z. Stability control and realization of single link rotary inverted pendulum on LQR controller[J]. Zhongnan Daxue Xuebao, 2012, 43(9): 3496-3501.

[4] Tang Y, Zhou D,Jiang W. A new fuzzy-evidential controller for stabilization of the planar inverted pendulum system [J]. Plos One, 2016,11(8): e0160416.

[5] Xiaojie S, Fengqin X, Ligang W, et al. Eventtriggered fuzzy control of nonlinear systems with its application to inverted pendulum systems[J]. Automatica, 2018(94): 236-248.

[6] Knowlton EB, John FA, Leonard DS. Control of Incontinent Urine by Using External Drainage[J]. AJN, American Journal of Nursing, 1949, 49(8): 15-19.

[7] Jialin Y. Research on the Optimization PID Parameters based on Genetic Algorithm[J]. EN,1974,7(11):21-22.

[8] Yongjing H, Wei W, Xuezhi W, et al. An overview of applications of MAS in smart distribution network with DG[C].IEEE 2nd International Future Energy Electronics Conference, Taipei, China, 2015:1-5.

[9] Chen P, Dong Y.Network-Based Optimal Controller Design Based on QoS［J］. Acta Automatica Sinica,2007, 2(33): 214-217.

[10] Zhang W, Branickym S, etc. Stability of networked control system［J］. IEEE Control Systems Magazine, 2001, 21(1):84-99.

[11] Wen G, Hu G, Yu W, et al. Consensus tracking for higher order multi-agent systems with switching directed topologies and occasionally missing control inputs[J]. Systems & Control Letters,2013,62（12）:1151-1158.

[12] Deqing Y. Tuning of PID parameters based on particle swarm optimization[J]. IOP Conference Series: Materials Science and Engineering,2018,452(4).

[13] Dastranj MR, Rouhani M, Hajipoor A. Design of Optimal Fractional Order PID Controller Using PSO Algorithm[J].International Journal of Computer Theory&Engineering,2012:429-432.

[14] John J, Kumar CS. A Comparative Study of Genetic Algorithm and Particle Swarm Optimization based Optimizations of PID Controller Parameters[J]. International Journal of Soft Computing and Engineering (IJSCE),2014,4(5).