The Design of Fuzzy Adaptive PID Controller of Two-Wheeled Self-Balancing Robot

Congying Qiu and Yibin Huang

***Abstract*—A two-wheeled self-balancing robot system is developed and the hardware system mainly consists of a controller of TMS320LF2407 DSP, a main sensor of Mio-x AHRS module, and other bargain components. The traditional linear controllers have a number of crucial flaws in controlling of two-wheeled self-balancing robot, such as long settling time and large overshoot. Therefore, we conducted further research on the fuzzy control method, designed a fuzzy adaptive PID controller with an improved structure, and simplified its algorithm process. Simulation results demonstrate that the fuzzy adaptive PID controller has a shorter settling time and smaller overshoot than the traditional linear controller and it is more suitable for large time delay, multi-parameter, high-order, strong coupling, and nonlinear two wheel self-balancing robot system control.**

***Index Terms*—Intelligent robot, two-wheeled self-balancing robot, fuzzy logic, fuzzy PID, adaptive, MATLAB simulation.**

I. Introduction

With the advance of technology in two-wheeled self-balancing robots, many researchers have sought to focus on this area. While the majority of commercial applications of two-wheeled self-balancing robots in the China's market, we use special components from foreign countries, which are advanced but experience, resulting an unacceptable high cost [1], [2]. Therefore, many efforts have been made to design a robot with cheap materials and then universalize it. To exploit the running gear of AROBOT teaching robot, which belongs to Institute of Automation, Chinese Academy of Sciences, a two-wheeled self-balancing robot is presented in this paper. This research aims to reduce the cost of two-wheeled self-balanced robots, especially for the researchers who have been devoted to the application development of robots. The key of two-wheeled robots' stability is to choose an appropriate control algorithm. In this paper, the deficiency of linear PID control, the selection of fuzzy adaptive PID controller and the modification of control algorithm based on actual demand are determined, which are based on a complete analysis. Finally, simulation is performed to evaluate the method's feasibility to control the two-wheeled self-balancing robots. The results show that the method has improved the robustness.

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II. Robotic Dynamic Model

The two-wheeled self-balancing robot is shown as Fig. 1 and its dynamics analysis is referred to [3]. Its state-space model is expressed as (1) shows. Meanwhile, the transfer function can be obtained from (3).

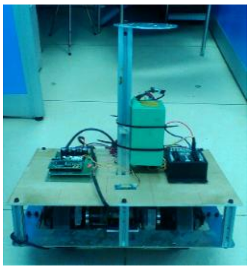

Fig. 1. The model of two-wheeled self-balancing robot.

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\alpha} \\ \ddot{\alpha} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2.7507 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 29.4590 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \alpha \\ \dot{\alpha} \end{bmatrix} + \begin{bmatrix} 0 \\ 0.0800 \\ 0 \\ 0.1879 \end{bmatrix} u \tag{1}$$

$$y = \begin{bmatrix} x \\ \alpha \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \alpha \\ \dot{\alpha} \end{bmatrix} \tag{2}$$

$$G(s) = \frac{A(s)}{U(s)} = \frac{0.1879}{s^2 - 29.4590} \tag{3}$$

x, $\dot{x}$, α, $\dot{\alpha}$, and u stand for robot's location, velocity, angle, angular velocity and controlling force, respectively [3].

According to the actual sampling time T=0.005s, we discretized the robotic transfer function model and then the robotic discrete transfer function was obtained as follow.

$$G(z) = 10^{-6} \frac{1.175z^2 + 2.349z + 1.175}{z^2 - 2.001z + 1} \tag{4}$$

By conducting the Z inverse transformation for discrete transfer function, the difference equation of output angle and input control of controlled object are obtained.

$$\begin{aligned} y(k) &= 2.001y(k-1) - y(k-2) + 10^{-6} \times \\ &[1.175u(k) + 2.349u(k-1) + 1.175u(k-2)] \end{aligned} \tag{5}$$

In order to verify the feasibility of the control algorithm, we performed a number of simulations in the MATLAB environment to the system, which was developed based on equations mentioned above.

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III. Deficiency of Linear Controller

Reference [3] has introduced LQR, PID and etc. methods to control the robotic balance. The core algorithm of controlling the balance of robot, in essential, is PID algorithm or the improved PID control algorithm. Firstly, we conducted the experiment of discrete simulation with PID controller. Fig. 2 shows the results obtained with the PID parameters K_P=497.69, K_I=180, K_D=94.31. With such PID parameters, the settling time of PID algorithm is too long. Therefore, it doesn't meet the requirement of effectiveness of real-time control of robotic balancing and it is demanded to shorten settling time by adjusting PID parameters. As shown in Fig. 3, after adjusting PID parameters to K_P=497, K_I=380, K_D=40, settling time T_s=2.135s, overshoot MP=86.7%. Large overshoot and integral oscillation after overshooting must lead poor control effect of robotic system. Therefore it is crucial to decrease the system's overshoot. The common method of PID controller to decrease overshoot usually includes the means to reduce the scale factor, integral separation, and windup processing or increase the differential parameters etc [4].

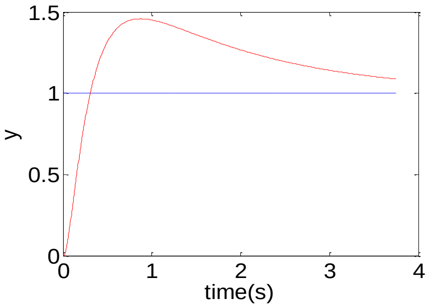

Fig. 2. Robot's PID control step response.

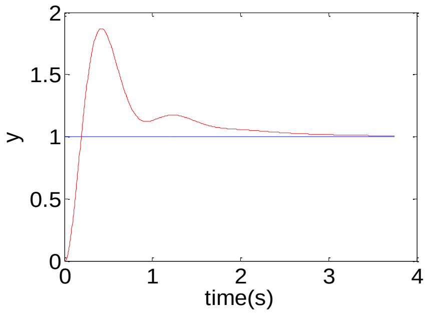

Fig. 3. Step response of increased PID integral control.

If decreasing the proportionality coefficient to reduce overshoot, system response will be slower. Furthermore, it may not be able to achieve the reduction in overshoot, because when robot keeps in balance, its tilt angle generally doesn't exceed ±3°. Integral separation algorithm isn't applicable. Although integral windup can reduce overshoot, it weakens the capacity of integral departure tracking. Enlarging differential parameters can reduce overshoot, but the parameters are likely triggered to be oversized; and consequently the system friction will be too large to bring a faster response to the system. In addition, exaggerated differential parameters will introduce extra speed noise to the system. In Fig. 4, the effect of controlling robot is disappointing, because it restricts integral amplitude, decreases proportionality coefficient, and increases differential coefficient etc. Therefore, it is urgent to adjust the parameters of linear PID controller to guarantee that the response has a small overshoot.

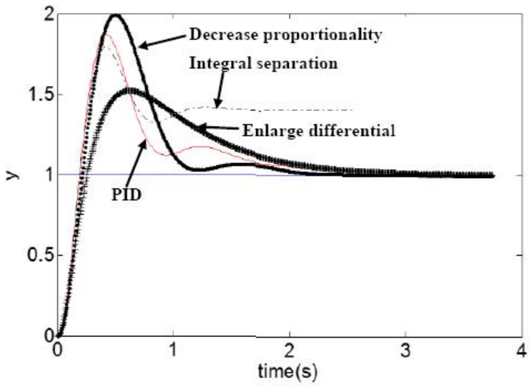

Fig. 4. Effect of reducing the overshoot by conventional methods.

IV. Design of Fuzzy Self-Adaptive PID Controller

Referred to fuzzy logic control, it is a computer-based digital control technology based on fuzzy set theory, fuzzy linguistic variables and fuzzy logic [5], [6]. A PID controller is likely to cause some problems, such as large overshoot, depth integral saturated and points oscillation near the equilibrium point. The deficiency of PID controller can be fixed by applying fuzzy control. Fuzzy PID algorithm, combined PID theory with fuzzy control theory, can easily control the balance of two-wheeled robot according to the expertise. Thus, in comparison to the traditional algorithms, smaller oscillation, faster response and better stability can be realized by the fuzzy control due to the fact that the fuzzy rules are rather similar to human cognitive level. Fuzzy adaptive PID control is adaptive [7], [8]. In general, this method uses fuzzy control algorithm to adjust PID parameters by means of fuzzy reasoning to the current values of controlling departure and error rate. And, the algorithm finally meets the requirements of parameters of different e and *ec* ranges [9].

Mamdani fuzzy controller shown in Fig. 5 is referred to the actual needs in MATLAB structure. There are two inputs and three outputs. The Mamdani fuzzy reasoning method adopted has 49 fuzzy rules in total. Among them, the fuzzy approach is fuzzy single value, the defuzzification method is average gravity. The output surface of fuzzy controller is shown as Fig. 6 to Fig. 8. Compared to the initial algorithms, it has smoother fuzzy surface; and the effect of fuzzy controller is better. PID parameter group is K_P=500, K_I=50, K_D=40. According to controlling the surface shape, or system step response curve (Fig. 9), we adjust the quantization factor, the scaling factor, fuzzy space partition or fuzzy rules of fuzzy controller in the simulation process.

In Fig. 9, we set the fuzzy PID system with parameters Ts=1.715s, overshoot MP=38.7%. And, the simulation results show that this settling time has faster step response speed and smaller overshoot. Moreover, it is shorter than the one of classic PID control system, whose T_s=2.135s. Meanwhile, its overshoot is much less than the latter one, which is 86.7%. It proves that dynamic performance of fuzzy control system is better than the classic PID control system. However, due to the integral hysteresis, the hysteresis of system overshoot is also too large.

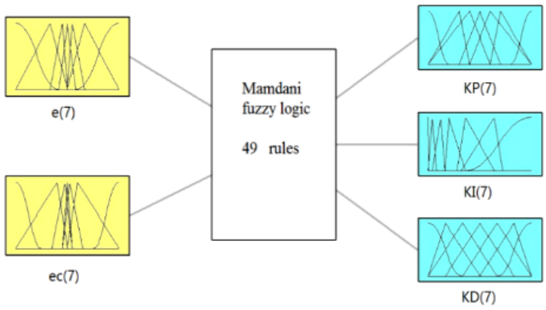

Fig. 5. Fuzzy controller structure.

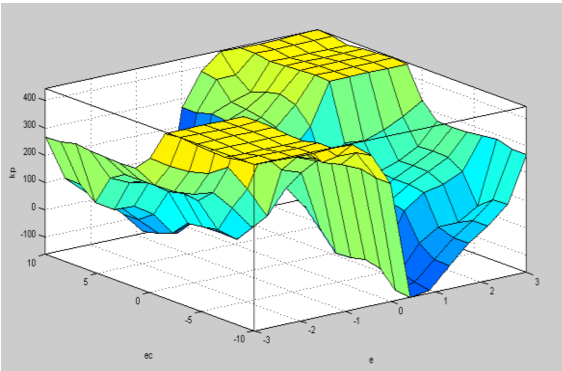

Fig. 6. The output ΔKP surfaces of fuzzy controller.

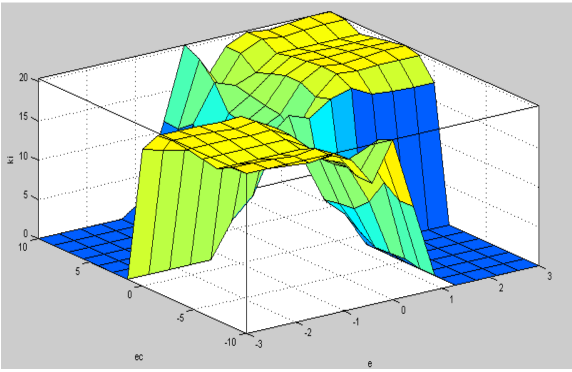

Fig. 7. The output ΔKI surfaces of fuzzy controller.

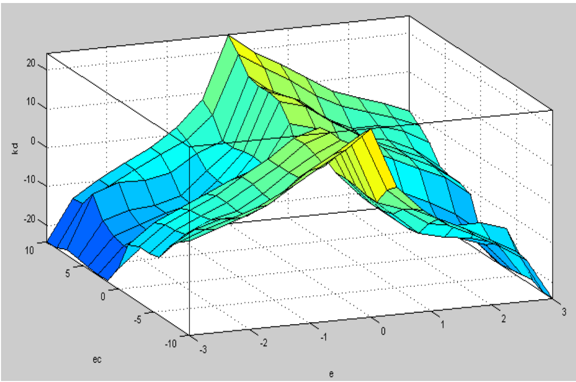

Fig. 8. The output ΔKD surfaces of fuzzy controller.

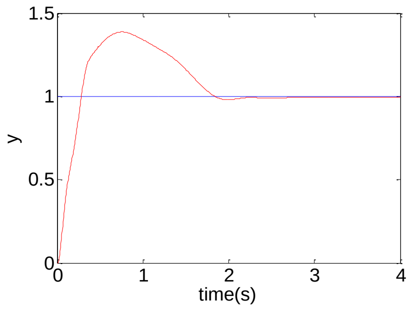

Fig. 9. Step response curve of fuzzy control system.

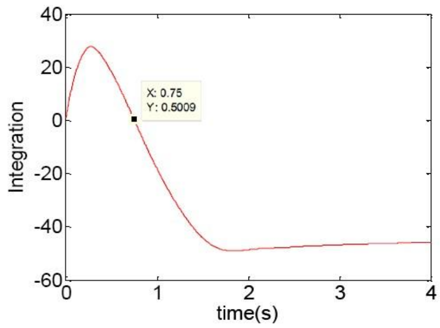

Fig. 10. Integral-time curve of fuzzy control system.

V. Improvement of Fuzzy Self-Adaptive PID Controller

The output of fuzzy PID controller is

$$u(k)=(K_P+\Delta K_P)e(k)+\Delta K_I\sum_{j=1}^{k}e(j) +(K_D+\Delta K_D)[e(k)-e(k-1)] \quad (6)$$

Its integral term $I=\sum_{j=1}^{k}e(j)$ must have hysteresis. The rise time of fuzzy PID control system is T_r=0.28s, and systemic error passes through the equilibrium point again. The scope-time curve of integral term is shown in Fig. 10. When t_0=0.75s, integral term passes through zero point to become negative. The hysteresis time is $\tau=t_0-Tr$=0.47s. Integral term hysteresis leads to large overshoot. Thus it is necessary to improve integral structure to ensure that the integral approach is more flexible and the hysteresis is weaker. The improved input of the system is

$$u(k)=(K_P+\Delta K_P)e(k)+\sum_{j=1}^{k}\Delta K_I e(j) +(K_D+\Delta K_D)[e(k)-e(k-1)] \quad (7)$$

Its integral term $I=\sum_{j=1}^{k}\Delta K_I e(j)$ is flexible. Fuzzy logic controller adjusts the value of ΔK_I to what can meet the requirement. Meanwhile, the changed integral speed decreases its integral hysteresis and plays a similar role such as integral separation when the integration is not required. As shown in Fig. 11, the time of fuzzy control system after being improved is T_r=0.29s, settling time T_s=1.485s, overshoot value MP=33.8%. The improved integral-time curve is shown in Fig. 12. Integral term gets a zero crossing when t_0=0.59, and hysteresis time $\tau=t_0-T_r$=0.30s.

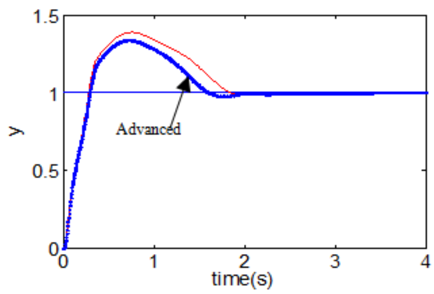

Fig. 11. Step response of improved structure before and after.

Hysteresis time is shorter and the maximum value ahead to

t_0 is smaller than before. They not only help reduce system overshoot, but also shorten the convergence time. And it leads settling time of the improved system to be shorter, and overshoot to be smaller. The result proves that the method of an improved control system is better than the one of a fuzzy PID system.

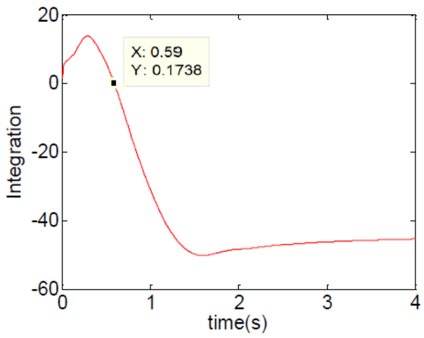

Fig. 12. Integral-time curve of improved structure before and after.

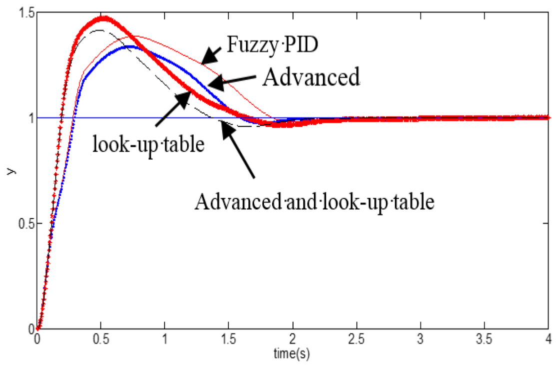

Fig. 13. Step response of fuzzy PID system by look-up table method.

Fuzzy logic controller algorithm is complex. It is hard to code the algorithm if directly by the program of C language, because there are too many parameters in fuzzy controller and flexible structure. In addition, calculation and memory space of such method is too large to be available for low-frequency, small-capacity controller. The fuzzy controller uses fuzzy logic in reasoning process, but each certain input only corresponds to one certain output in the same fuzzy system. Thus, we used the Matlab platform to program an appropriate controller. By replacing the fuzzy reasoning process by approximation, the look-up table method, reasoning process can be shortened in terms of processing time. Furthermore, this method has good portability in engineering. We make approximate simplification to above improved control system structure before and after. The input e is approximate to 60 equidistant points and input *ec* to 50 equidistant points, and thus a two-dimensional table of 60×50 can be generated. Each element in the table contains the value of ΔK_P, ΔK_I and ΔK_D, which are corresponding to the respective input. The result in Fig. 13 shows an example of simulated look-up table. The overshoot and settling time of fuzzy PID control system, which are obtained by look-up table, are respectively that MP=47.2% and T_s=1.445s. After structural improvement, MP=41.5% and T_s=1.22s. Table method, to some extent, lows the system ambiguity and larges the overshoot. After the system's structural improvement, settling time is significantly shorter and overshoot is smaller to a certain extent than before. It proves the feasibility of replacing fuzzy reasoning process with a look-up table and that the improved integration system structure is better than linear integral system.

VI. Conclusion

This research work takes advantage of cheap components to design a two-wheeled self-balancing robot system. Considering the deficiency of the LQR and PID controller, this paper mainly studies the fuzzy adaptive PID controller to further improve the controlling performance of the robot. Aiming at the shortage of long settling time and large overshoot of the linear PID control method, a fuzzy adaptive PID controller is designed, which is suitable for controlling a two-wheeled self-balancing robot based on the simulation results. By means of analyzing the hysteresis of integral term, we improved the integral structure of fuzzy PID controller. On the basis of concrete analyses of robot system, we replaced the fuzzy inference process method with the look-up table one. The MATLAB simulation results show that, the improved control system integration structure can be further shortened the robot settling time and reduces the system overshoot, and that self-balancing control is more suitable for the robot. Moreover, the feasibility of look-up table method is verified. Calculation amount of the control method in this paper is small, and the design process is simple, which is able to improve the oscillation phenomenon of a two wheeled robot. This technology is promising in wide application prospect.

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