A Posture Control System Design for a Two-wheeled and Self-balancing Robot

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Abstract

This paper establishes a self-developed mathematical model for the two-wheeled and self-balancing mobile robot pose. For the model nonlinear and unstable characteristics, we use a fuzzy method to achieve the optimal parameters of the PID controller in order to make the PID parameters self-tuning. The gyroscopes and accelerometers fusion algorithm are used to solve the sensor inaccurate angle measurement problem. Also a self-balance control system is designed based on the K60 microprocessor. The results show the superiority and good robustness of the control method, and good control effects have been achieved.

1. Introduction

This robot has a self-balancing system, and its wheels are arranged in parallel sides. Compared with other types of robots, its main feature is to solve the problem of self-balancing. The balance of the robot is increasingly important because of the increasing interest from controlling scholars. In literature [1] they used LQR controller to solve stability problems during the two self-balancing robot control, but it relied on an accurate mathematical model of the controlled object. In literature [2] the PID and PI-PD were applied to a two-wheeled self-balancing robot system to achieve a better self-balance, but without interference analysis. In literature [3] they used a fuzzy control theory on an inverted pendulum control problem, achieving a balance and robot motion control, but it's not combined with other control methods .In literature [4] they used fuzzy and PID compound control, and simulation results showed that the system dynamic performance is much better; however, there is no physical experiment for verification. In literature [5] they used the Kalman filter method for robot angle measurements.

This paper presents a two-wheeled and self-balancing robot, using gyroscopes and accelerometers as a pose measurement sensor to measure the robot's posture information. Solved are problems associated with the impact of a single sensor body swing and integral saturation, and the control strategy takes fuzzy PID. Not only inheriting the traditional fuzzy control which is independent on the object model, simple control structure, high reliability, easy engineering implementation, etc., this method also overcomes the traditional PID controller's shortcomings like poor following while adjusting under the strong interference, which shows highly nonlinear and uncertain feature. Microprocessor driven by a motor circuit uses PWM control signal to drive the DC motor, achieving the purpose of regulating body posture; then the self-balancing robot control is done, greatly improving the performance of the controller.

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This paper is structured as follows: Section 2 describes the robot system architecture; Section 3 describes the mathematical model; Section 4 describes the control strategy; Section 5 describes the gyroscopes and accelerometers fusion algorithm; Section 4 describes the physical experimental analysis, and finally Section 5 is the conclusion.

2. Two-wheeled Self-balancing Robot's System Architecture

A self-balancing robot control system has four main parts. The first part is the core controller unit, K60, which uses the Motorola 32-bit processor. It's used to analyze and process the data obtained from posture through the corresponding control algorithm; in order to make control decisions, it will send a control signal to the driving unit to control the drive motor. The second part is the robot sensor unit, including gyroscopes, accelerometers and velocity sensors [6] for measuring the posture information in real time. The third part is the driving unit of the robot, which is used to adjust the motion state of the two motors with the corresponding signal. The fourth part is the robot's communication unit, which enables PC to modify the parameter. The lower machine controller stores the received parameters in the EEPROM, while the lower computer sends the robot's posture information in real time to the PC monitor screen. The control system hardware structure is shown in Fig.1.

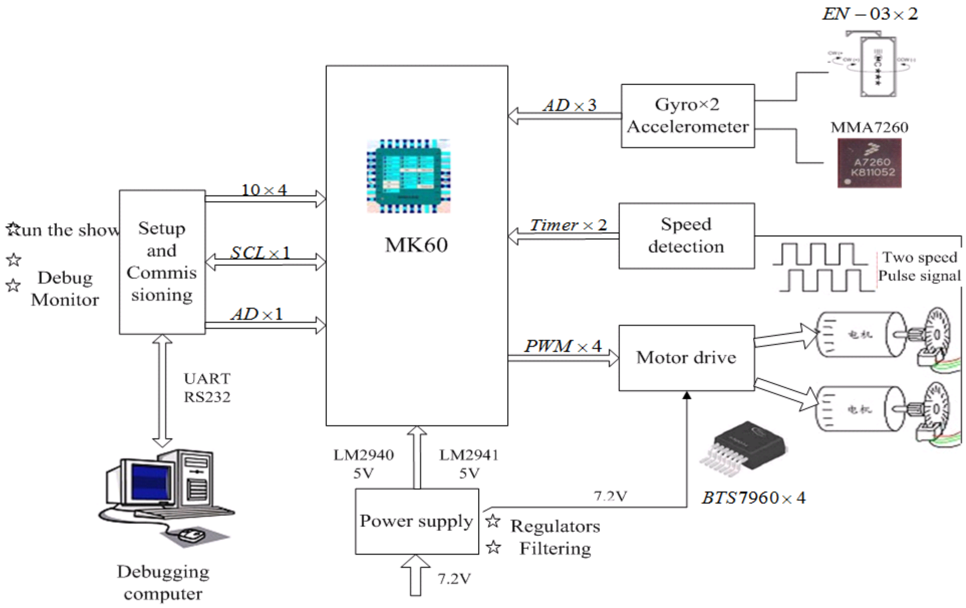


Figure 1：The two-wheeled self-balancing robot system block diagram

3. Two-wheeled Self-balancing Robot's Mathematical Model

A two-wheels self-balancing robot is composed of the main body and two wheels which are coaxial and driven respectively by motors, and we take the two wheels' mass, moment of inertia and radius as the same. The body's center of gravity is upside down on top of the wheel shaft, which maintains the balance through the movement. In this paper's modeling process, the wheel and swing analysis are separated, Then through the two simultaneous parts, this robot's dynamics equation of state is derived. This robot's left wheels and body stress analysis are shown in Fig. 2 and 3[7].

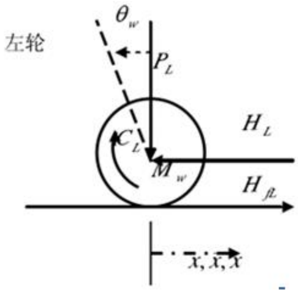


Figure 2: Left wheel's stress analysis

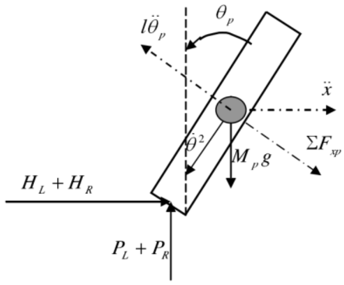


Figure 3: Body stress analysis

Based on Newton's law applied on stress analysis, considering the DC servo motor voltage and torque relationships, and in the small angle range linear process, you can get the two-wheeled and self-balancing robot state's equation [8]:

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{\theta}_p\\ \ddot{\theta}_p\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\\ 0 & \frac{2k_m k_e(M_p lr - I_p - M_p l^2)}{Rr^2 A} & \frac{M_p^2 g l^2}{A} & 0\\ 0 & 0 & 0 & 1\\ 0 & \frac{2k_m k_e(rB - M_p l)}{Rr^2 A} & \frac{M_p g l B}{A} & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \theta_p\\ \dot{\theta}_p\end{bmatrix} + \begin{bmatrix}0\\ \frac{2k_m(I_p + M_p l^2 - M_p lr)}{RrA}\\ 0\\ \frac{2k_m(M_p l - rB)}{RrA}\end{bmatrix}U_a$$

In which： $A = \left[I_p B + 2M_p l^2 (M_w + \frac{I_w}{r^2})\right]$; $B = (2M_w + \frac{2I_w}{r^2} + M_p)$

Then we get this result: $y = \begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}X\\ \dot{X}\\ \theta_p\\ \dot{\theta}_p\end{bmatrix}$

4. Two-wheeled Self-balancing Robot's Control Strategy

Through the mathematical model, we can see this robot is a typical multi-variable, nonlinear system, and the actual mathematical model is difficult to be accurate. Based on fuzzy control design idea [9], and combining traditional PID controller design method, this paper uses the state feedback matrix to set proportionally differential coefficients initially. Then through the fuzzy inference to make the appropriate control decisions, and tuning PID control parameters online with the characteristics of the system response's curve, satisfactory control effect is ultimately achieved. Among them, the input parameters are body with a given angle deviation E, and error change rate EC; and left and right wheel motor's voltages U are the output. Fuzzy PID controller structure is shown in Fig.4.

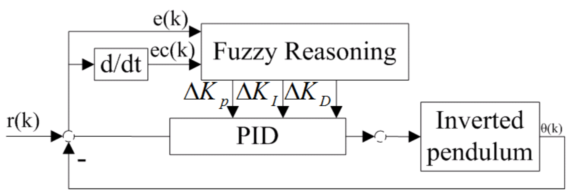


Figure 4: Two-wheeled self-balancing robot fuzzy PID controller design

4.1 Definition of Fuzzy Variables and Membership Functions

In this paper, we choose $E, EC, \Delta K_p, \Delta K_i, \Delta K_d$ as fuzzy variables, and the number of corresponding fuzzy subset is designed to 7 defined fuzzy subsets: {NB, NM, NS, ZO, PS, PM, PB}; the elements of the subset represent negative large, negative middle, negative small, zero, positive small, middle, and positive large, respectively.

Fuzzy subsets of each membership function use a trigonometric form. Error e and error rate of change of the membership functions are shown in Fig. 5. Error e and erroneous rate of change of the membership functions e_c are shown in Fig. 5:

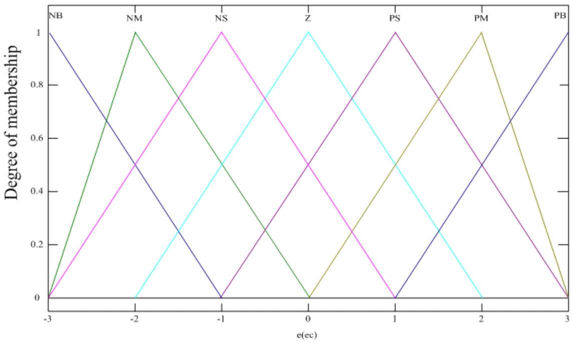


Figure 5: E (EC) membership function

4.2 Design of Fuzzy Control Rules

Theory and Practice show that the proportion of the control system can be faster, but the proportion part's coefficient is too large, which will increase the number of shocks, making the system unstable. Integration can reduce steady-state errors, but it easily leads to overshoot; while differential can enhance the damping to reduce overshoot, this will cause the system to have a bad dynamic performance. Therefore, through a set of ideal PID parameters based on the self-balancing experimenter on the actual operation of the robot, PID controller's parameters ΔK_p, ΔK_i, ΔK_d, and Tuning fuzzy rules are shown in Table1 [10]:

Table1: Fuzzy rules of ΔK_p

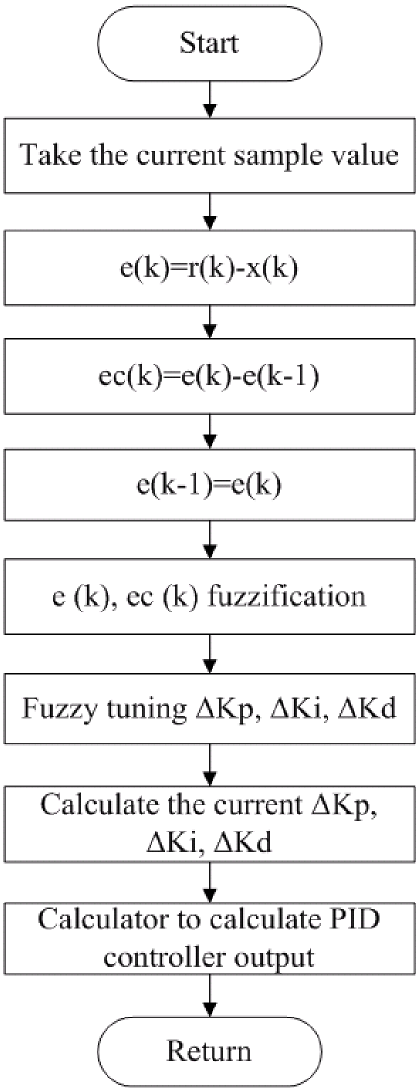
ΔK_p		ec						
		NB	NM	NS	ZO	PS	PM	PB
	NB	PB	PM	PS	NS	NM	NM	NB
	NM	PM	PS	PS	PS	PM	PM	PM
	NS	ZO	NS	NS	ZO	PS	PS	PM
e	ZO	PS	PS	ZO	ZO	ZO	PS	PS
	PS	PM	PS	PS	ZO	NS	NS	ZO
	PM	PM	PM	PS	PS	PS	PS	PM
	PB	NB	NM	NM	NS	PS	PM	PB

4.3 Defuzzification

In this paper, we use the center of gravity defuzzification method. Gravity method is to take the membership function curve and the abscissa of the center of gravity as the area enclosed by the final outcome of the fuzzy inference, having a smooth, real-time output results. For a series of m quantized discrete domain scenario, the fuzzy output equation is [11]:

$$u = \frac{\sum_{k=1}^{m} x_k \mu_v(x_k)}{\sum_{k=1}^{m} \mu_v(x_k)}$$

4.4 Fuzzy PID algorithm[12]



5. Two-wheeled Robot Angle and Angular Velocity Measurements

Two-wheeled robot inclination angle and its velocity measurements are the key to control two-wheeled robot upright. This paper takes the angle from the acceleration sensors as a correction method to adjust the angle from the gyro. By comparing the integration of the angle and the angle obtained by the acceleration of gravity, we use the deviation between them to change the output of the gyro, so we can get the angle of the acceleration sensor from the integration view. It's shown in Fig. 7:

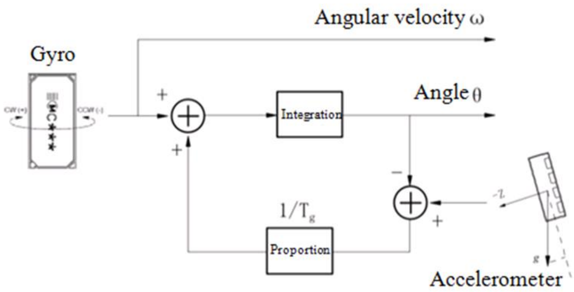


Figure 7: Gyroscopes and accelerometers fusion algorithm

As mentioned above, we compare the accelerometer angle θ_g and θ obtained by the gyro angle and after Integration, and then integrate their amplified (the rate is $1/T_g$) deviation signal superimposed and the gyro output signal. After proportion, integral part the output angle θ would ultimately equal θ_g.

6. Tow Self-balancing Robot Physics Experiments

While the self-balancing robot is moving, we use JZ863 module for wireless communication[13] with the host computer to send data information one time. Through the self-developed LABVIEW monitoring platform [14], we can always read the data from wireless transmission, observing the robot's moving at runtime.

System testing includes the gyro and accelerometer integration test, upright at balance point test and anti-interference balance test.

Fig. 8 shows acceleration, synthetic angle and gyroscope curves at vertical equilibrium point. It can be seen from Fig. 8 that when the hour increasing, the gyro angle values obtained by integration gradually move away from the true value, especially more obvious at large angle, which is caused by the drift of gyro Integration. The angle value from accelerometer has rapid small fluctuations in some places, which increases the instability of posture detecting. Using simple filtering [15] to get the two complementary sensor data fusion, the two issues have been well solved. The estimation value of a filtered angle is very close to the angle measured by the protractor, and the curve is smooth.

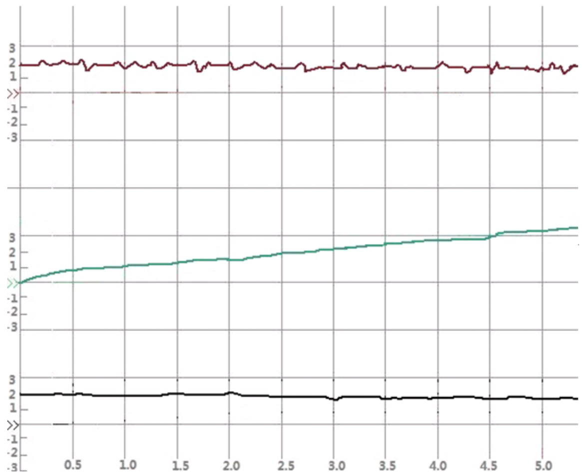


Figure 8: Gyroscopes, accelerometers, and angle and curve

Fig. 9 is a point self-balanced posture test curve near the equilibrium, Fig. 11 is a real picture at equilibrium point. From the analysis of measured data, the robot can be stabilized near the center position.

Figure 9: Self-balancing test curve near the equilibrium point

Fig. 10 shows a test curve near the equilibrium point after disturbance. Fig. 12 is a real posture picture around equilibrium point with interfering. From the measured data analysis, after a certain disturbance being applied with a few minor oscillation, 2.5 seconds later, the system is able to adjust itself to a steady state.

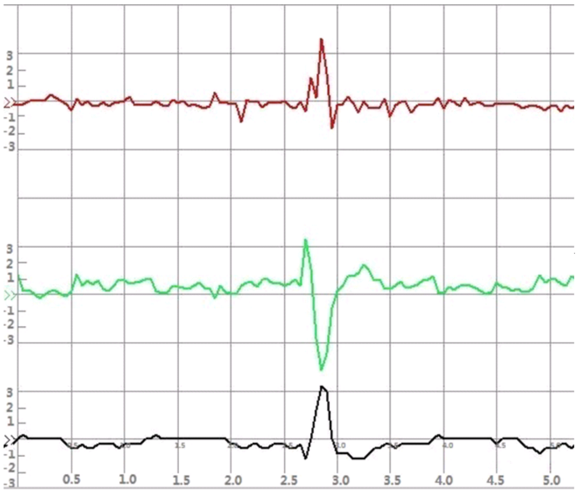


Figure 10: Test curve after interference is applied near the equilibrium point

Figure 11: Real picture at equilibrium point

Figure 12: Posture picture around equilibrium point with interfering

7. Conclusion

Experimental results show that the hardware system design of a two-wheeled and self-balancing robot platform is reliable, and gyroscopes and accelerometers fusion algorithm can achieve accurate measurement of the angle. A fuzzy PID control algorithm can be applied to achieve a stable upright control after disturbance, which solves the problem of a robot self-balancing control system. Meanwhile, the two-wheeled and self-balancing robot hardware design and mathematical model built provides a good platform for the subsequent works, if anyone wants to look for a more accurate, stable and robust control method.

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