Control System Design for Two-Wheel Self-Balanced Robot Based on the Stepper Motor

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***Abstract*— A general control system of two-wheel self-balanced robot usually has a complex structure due to plenty of sensors, whose price is very expensive. According to this condition, a control system with the stepper motor driver is proposed, eliminating the expensive components, like optical encoder and brushless DC motor. At the same time, the low-power and high-performance STM32, 32-bit microprocessor, is selected as a controller. Outputted pulse frequency is adjusted through the adjustment of STM32 timer prescaler value, which regulates the step motor speed. With inclination angle formed by the Kalman filter of the output signal of the accelerometer and gyroscope as feedback, self-balanced closed loop control of two-wheeled robot is realized.**

Key Words*—*Two-wheel robot; Self-balanced; STM32; Kalman Filter; PID control; Prescaler value

I. INTRODUCTION

A two-wheel self-balanced robot, one of special wheel-driven robots, whose control model is similar to inverted pendulum model which symbolizes a nonlinear, strong coupling, multi-variables and intrinsic unstable system. In fact, a two-wheel self-balanced robot is an inherent unstable mobile robot [1].

A manned two-wheel self-balanced electric vehicle of the United States has been the successful listing, and one of the most famous is "Segway" [2]. In recent years, the craze of the two-wheel self-balanced robot is increasingly high. The two-wheel self-balanced robot become an ideal platform used for researching all kinds of filter algorithm and the control strategy, led to the concern of more and more experts and scholars.

But so far, applications of the two-wheel self-balanced robot, in addition to theoretical studies, is only limited to traffic, and is very expensive. The goal of this paper is to develop a high performance and low cost control system of a two-wheel self-balanced robot by employing novel filtering algorithms and control strategies to reduce cost. The paper chooses a low cost stepper as drive units to build mobile car for realizing self-balanced control of the car by means of appropriate control strategy which can eliminate high disturbance of steppers. The experiment shows that control strategy in this paper achieves satisfactory results.

II. BALANCE PRINCIPLE

The balance principle of two-wheel self-balanced robot is similar to an inverted pendulum, also relies on the movement of the motor to ensure that the vertical balance of the body, this movement is achieved by controlling the motor rotation speed and direction.

Therefore, the control principle of self-balanced robot is as following. When the sensors detect the robot intermediate tilting towards one direction, controller will produce a corresponding torque, drives two wheels to the direction which the intermediate will tilt to, so the wheel will move the same displacement as center of gravity, in order to maintain the dynamic balance of the robot [3].

As a result, we can get the balance principle of two-wheel self-balanced robot, as shown in Figure 1 below. When the robot goes forward, the robot intermediate tilts towards back because of inertia, then the wheel should be back to correct the intermediate inclination angle error. Similarly, when the robot goes back, the robot intermediate tilts towards front due to inertia, then the wheel should go forward to correct the inclination angle error.

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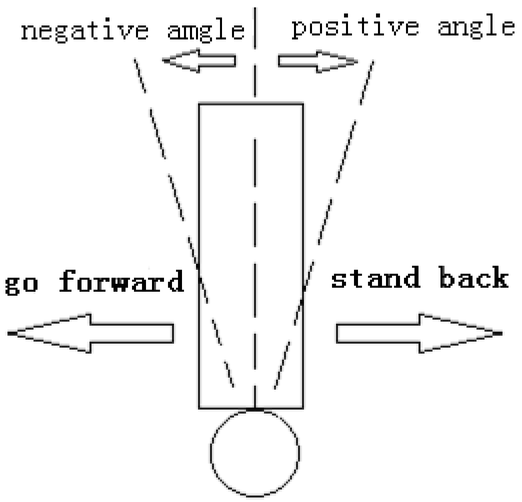

Fig.1. Balance principle of the two-wheel self-balanced robot

III. CONTROL SYSTEM DESIGN

The two-wheel self-balanced robot uses digital output attitude sensors, including gyroscope MPU-3050 and accelerometer ADXL345, using the second I2C interface of MPU-3050 connected with ADXL345 to form a six-axis attitude sensor. A simple self-balanced closed loop control of the two-wheel robot is realized, with the low-power and high-performance 32-bit microprocessor STM32F103C8T6 as a controller, inclination angle formed by the Kalman filter of the output signal of the accelerometer and gyroscope as feedback, step motor as executive agencies, and LV8731 as motor drive.

Outputted pulse frequency is adjusted through the adjustment of STM32 timer prescaler value, which regulates the step motor speed. With inclination angle formed by the Kalman filter of the output signal of the accelerometer and gyroscope as feedback, self-balanced closed loop control of two-wheel robot is realized. System principle block diagram is shown in Figure 2.

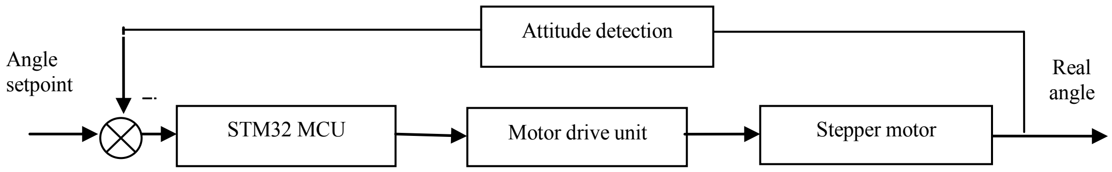

Fig.2. System principle block diagram

The system regulates the speed of step motor according to the inclination angle of the robot intermediate to correct the inclination angle error, so that the robot can maintain the dynamic balance. The output signal of the gyroscope is angular velocity, while the output signal of accelerometer is acceleration, which can be converted to dip angle through approximate linear operation in small angle range. Each sensitive axis test results are stored in two registers, fill of high eight and low eight binary code complement data. Therefore, 32 bit microprocessor needs to read the fusion of two registers when receiving data, and does the positive and negative judgment.

IV. HARDWARE STRUCTURE OF THE SYSTEM

Since the system with stepper motor drive, we only need to adjust control pulse frequency to control motor speed, which has a higher precision. The overall system block diagram is shown in Figure 3.

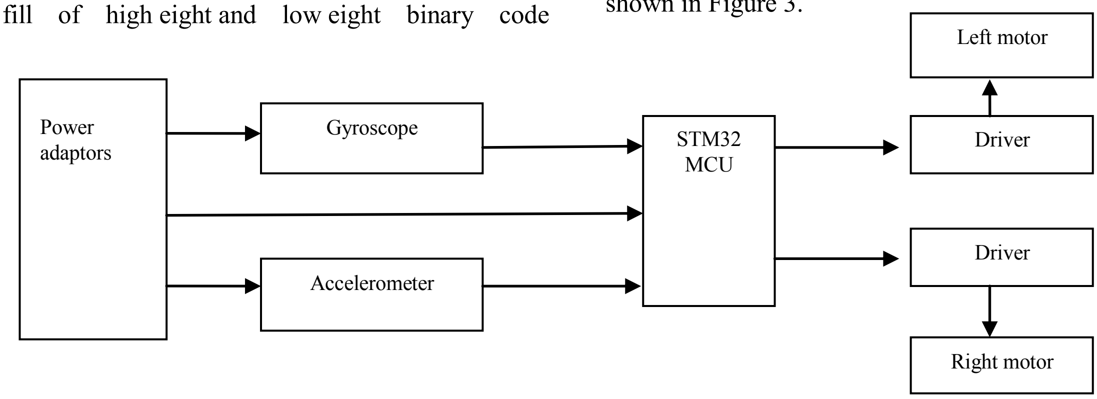

Fig.3. The system structure diagram of the two-wheel self-balanced robot

The speed of stepper motor is adjusted by the output pulse frequency of STM32 MCU. With testing and computing the output signal of attitude sensors as feedback information, the system realizes the dynamic balance of the robot.

V. SYSTEM SOFTWARE DESIGN

The software system selects Keil ARM-MDK as the integrated development environment. As the latest version of ARM microcontroller embedded development, Keil uVision4 supports the development of the Cortex-M3 processor, and contains the Firmware Library of STM32F10x series processor periphery connection and very complete data handbook.

The software function module, in addition to main function, contains sub-functions as initializations of sensors and motor, receiving sensors signal by I2C, the positive and negative judgment of 16-bit binary number, Kalman filter, PD control PWM output, direction control and motor-driven sub-function. The main function - initialization and the main loop module-flow chart is shown in figure 4.

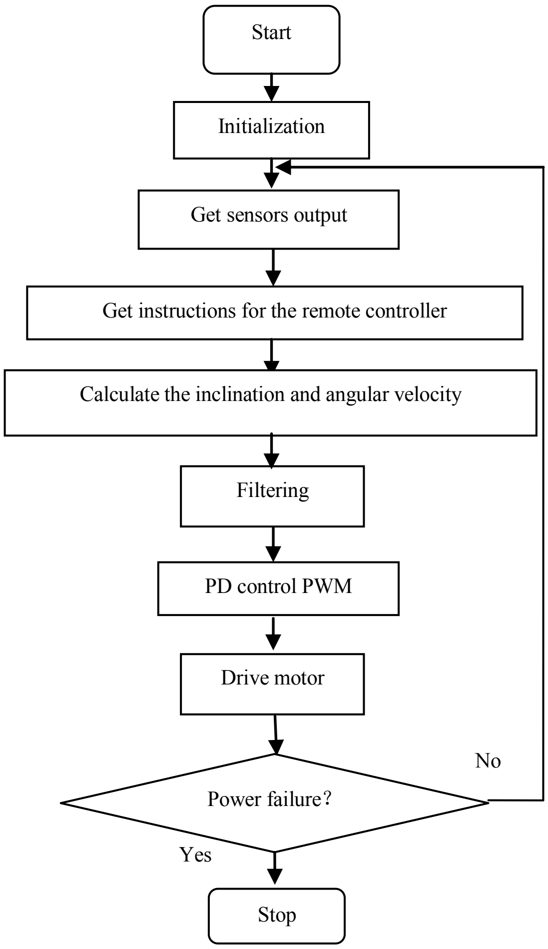

Fig.4. Main circulation program flow chart

In consideration that the robot is driven by a stepper motor, the duty cycle of the pulse sequence is fixed at 15%, and count period T is set to 99, so we only need to adjust the frequency of the pulse train to maintain the dynamic balance of the robot, according to the characteristics of the stepper motor. This paper chooses the timer 1 of STM32, whose default clock frequency is 72 MHz, to undertake clock prescaler operation.

First of all, under STM32 control, the speed V calculation formula of stepper motor is:

$$V=\frac{f}{(fre+1)(T+1)} \quad (1)$$

Among them, fre means prescaler value, which is set by TIM_Prescaler; T means count cycle, which is set by TIM_Period; f means the default timer clock frequency.

It is equivalent to set the default output frequency of timer 1at 720 KHz when the count cycle T is fixed at 99. Then we can take clock prescaler operation to adjust the real output frequency of the timer 1. So just changing TIM_Prescaler (fre) value can change TIM1 actual output frequency, which regulates the step motor moving velocity. This system considers the angle and angular velocity respectively as a proportion link and differential link, and the proportion coefficients and differential coefficient are determined by modeling and practice.

fre=1000-Kp*(u8)angle-(u8)(angle_dot*Kd);

When gradually approaching the optimal value of the differential link parameter Kd, we should adjust it from small to large. In view that the angular velocity is commonly big, the differential link parameter should be small. Finally taking Kd as 0.15, ideal dynamic self-balance state is achieved.

However, we need to judge whether the Kd is positive or negative, due to the influence of the sensor installation direction. The direction of the sensor sensitive axis is shown as figure 5.

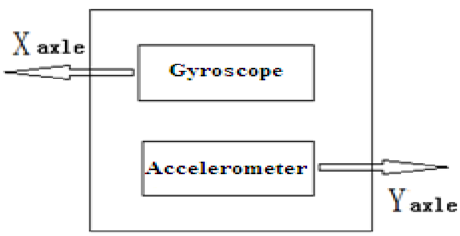

Fig.5. The direction of sensor sensitive axis

As is known from the graph, if inclination angle and angular velocity are positive, which means the angle is positive and it is becoming smaller and smaller, the prescaler value fre should become bigger, so that the stepper motor can become more slowly. In this case, the differential link parameter Kd should take a negative value, while it should take a positive value at other cases. So,

if(angle>0&&angle_dot>0) Kd=-0.15;

fre=1000-Kp*(u8)angle-(u8)(angle_dot*Kd)

In this way, the system adjusts the step motor speed by adjusting the prescaler value of timer through PD regulation. When the robot inclination angle is from -3° to 3°, the motor stops moving; When the robot inclination angle is smaller than -3°, the robot goes forward; When the robot inclination angle is bigger than 3°, the robot goes back.

Combined with speed control and direction control, the dynamic self-balance control of the robot can be realized.

VI. EXPERIMENT

After adjusting PD regulation parameters, the dynamic balance of the robot has been very sensitive. The robot can quickly attain to stable, and keeps the stability for a long time. However, the stepper motor can't really stop moving due to low frequency oscillation while power-on. So after realizing the balance, the motor will still has a tiny shock. Figure 6 is a screenshot of the data gotten from the system serial debug imported into MATLAB. After the robot reaching a dynamic equilibrium, a huge disturb is added to the system, then we can see the robot can restore balance.

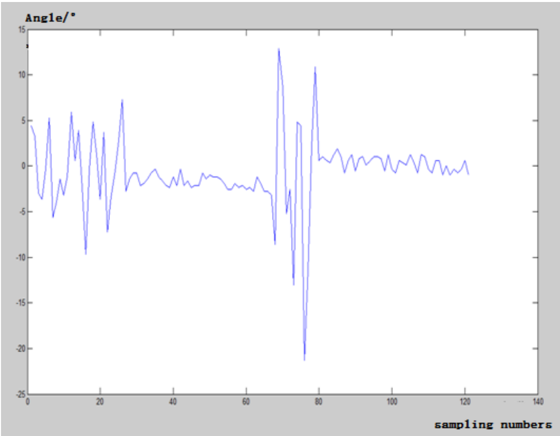

Fig.6. Angle control effect diagram of the two-wheel self-balanced robot

VII. CONCLUSION

The main characteristic of the two-wheel self-balanced robot is to solve the balance problem, which means to maintain balance in a variety of states. Therefore, the robot belongs to typical balance control system. The static state of robot is unstable, because the center of gravity of the system is higher than the fulcrum. Dynamic system takes angle in the vertical direction for the control object, and makes the angle be controlled in a small scope near the balance. In fact, this system can be understood as under the control of STM32 microcontroller, through analyzing on the system inclination angle and angular velocity in real time, controlling the offset angle in the vertical direction in allowing range, so that the robot can keep balance automatically.

From the perspective of the sensor, digital output sensors dispense with AD transform program, but put forward higher request for data processing. From the point of the motor selection, stepper motor is not suit for stability due to large disturbance. From the view of design for frequency conversion control, PD control can meet the requirements of the system. But because the robot body can tilt to front or back, we need to judge whether the differential coefficient should be positive or negative.

As the system chooses stepper motor as a driver, photoelectric encoder can be eliminated. With PD control adjusting the output pulse frequency, the dynamic balance control of the two-wheel robot can be realized. So that the development cost can be limited to a minimum. This paper takes PD inverter frequency control method by means of setting prescaler value of STM32 timer 1 for producing PWM signal to regulate speed of steppers considering the features and property of steppers. It is very obvious that this is a simple and efficient control method.

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