Design and Implementation of Two-Wheel Self-Balancing Vehicle Based on STM32

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Abstract: By deeply exploring the STM32 microcontroller, we successfully launched the design and implementation of a dual-wheel self-balancing scooter based on it. Through the real-time data collection of the sensor of the MPU6050, the powerful processing capability of the STM32F103 microcontroller, the motor driver of TB6812FNG, and the motor of GB37 were combined for precise closed-loop control, thus achieving excellent dynamic balance performance of the dual-wheel self-balancing scooter. Moreover, through the precise dynamic control of the system, it can always maintain good balance stability even under various external disturbances. At the same time, the system also provides good support for Bluetooth communication, allowing users to remotely control the system's forward, backward, left turn, right turn, and rotation through the mobile app. The design, debugging, and other aspects of the system have been well promoted and applied. The experimental results of this system also fully verified that the PID algorithm adopted in the system has a good regulating effect on dynamic balance control, and has a good guiding significance and great practical application value for the design of the system.

Keywords: STM32; PID Algorithm; Two-Wheel Self-Balancing Vehicle

1. Introduction

With the continuous advancement of high-performance chip technology and the increasing maturity of control algorithms, the stability and intelligence level of balancing vehicles have been significantly improved. In recent years, the widespread application of key technologies such as inertial measurement unit (IMU) sensors and PID control algorithms has provided a solid theoretical and technical foundation for the dynamic control of balancing vehicles [1].
This paper presents a two-wheel self-balancing vehicle design scheme based on the STM32 microcontroller. This scheme integrates the MPU6050 inertial sensor to obtain real-time attitude data, combines the PID control algorithm to achieve dynamic balance control, and uses the TB6812FNG motor driver and GB37 motor to complete motion execution[2]. In addition, the system supports Bluetooth communication functionality, allowing users to achieve remote control through mobile devices. This paper aims to explore the design method of balancing vehicles based on embedded systems and verify its feasibility and effectiveness in dynamic balance and remote control.

2. System Design

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The two-wheel balancing principle of the balancing vehicle can be compared with the principle of a wooden stick balance. Both belong to the inverted pendulum system. The two-wheel balancing vehicle can be abstracted as an inverted single pendulum system with a movable base. The upright balance of the wooden stick simulates a composite pendulum model with a movable base. The variability of the vehicle is only front and rear, while the variability of the wooden stick is uncontrollable [3,4]. When the vehicle leans forward, the controller motor accelerates backward, and when the vehicle leans backward, the controller motor accelerates forward.
To make the balancing vehicle stand upright and achieve dynamic balance, it is necessary to satisfy the following formula (1) [5]:

$$\theta'' = (g/L)\sin\theta - (1/mL^2)(F\cos\theta) \quad (1)$$

Where θ is the deviation from the vertical angle,

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F is the control force input, m is the mass, L is the effective length, and the sensor needs to collect the following data:

Inclination angle, measured by integrating MEMS gyroscope (±2000 dps) and accelerometer (±16g).

Angular velocity, directly output by the gyroscope, configured at a sampling rate of 1000Hz.

Linear acceleration, obtained from the measurement of the three-axis accelerometer, used to cancel the interference of centrifugal acceleration.

Hub speed, directly output by the motor driver, with a resolution of 1000PPR.

When the balancing vehicle is in a stationary state, the vehicle body maintains vertical balance, and the wheels and the vehicle body are relatively stationary. When the vehicle body leans backward, the wheels will rotate forward to maintain balance; while when the vehicle body leans forward, the wheels will rotate backward. This process relies on the built-in sensors to monitor the vehicle body's inclination state in real time and drive the wheels to rotate accordingly, thereby achieving the dynamic balance and motion control of the balancing vehicle, as shown in Figure 1.

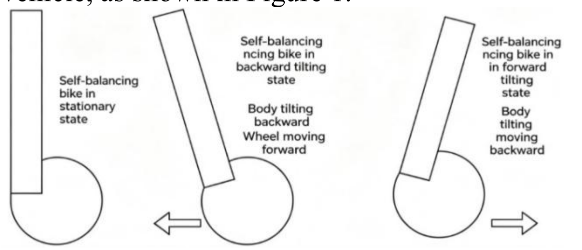

Figure 1. Working Principle Diagram of Two-Wheel Balance Vehicle

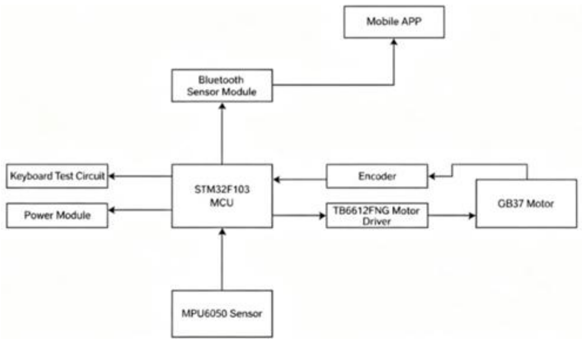

Figure 2. Overall Architecture Diagram of Two-Wheel Balance Vehicle

The balancing vehicle system is precisely controlled by the STM32F103 microcontroller, combined with the real-time data of the MPU6050 sensor, and realized dynamic balance through the TB6812FNG motor driver and GB37 motor. It also supports Bluetooth and WeChat remote control operations, ensuring the efficient and stable operation of the system[6,7]. The system architecture diagram is shown in Figure 2.

3. Hardware Design

3.1 Single-Chip Microcontroller System Board

The controller, centered around the STM32F103, primarily communicates with external modules and peripherals via a series of interfaces including SPI, I^2C, and UART. Through coordinated control of multiple peripherals, it forms the fundamental technical framework underlying modern computing systems. By connecting to other attitude-sensing devices via the I^2C bus, a relatively complete system is established, enabling real-time acquisition of tilt angles based on the MPU6050, which accurately reflects the vehicle's real-time inclination status. Integrating acceleration data sampled at 400 Hz into the system presents significant challenges in terms of dynamic performance and accuracy. Through in-depth research and refinement of Kalman filtering techniques, not only can adaptive parameter estimation issues—traditionally unsolvable by conventional filtering methods—be effectively addressed, but the approach also better aligns with the development of modern automatic control, offering new insights and tools for future advancements. Wireless control driven by USART serial communication enables widespread application of various wireless sensors, such as wireless temperature, pressure, acceleration, and angular velocity sensors, all of which have seen substantial progress. Only through support from Bluetooth modules on corresponding main control boards can these be truly integrated into practical IoT projects. Deep integration of mobile apps or BLE remote control with traditional power transmission and control systems greatly enhances their intelligence, offering broad application prospects. Control commands (at a baud rate of 115200 bps) are written into memory according to specified requirements, enabling high-precision PWM signals to be output to the TB6812FNG, thus achieving an organic unification of "power" and "intelligence." The advanced control capability is fully demonstrated in motor drive performance, supporting adjustable operating frequencies up to 20 kHz and duty cycles ranging from 0% to 100%, delivering exceptional control precision. Precise rotational regulation ensures optimal speed control. Forward and reverse operation modes of the GB37 motor are analyzed in detail. Thanks to its refined packaging and excellent debugging features, the LM2596S switching power supply becomes highly convenient and easy to integrate into various power design applications. Its external debug interface allows straightforward adjustments, such as monitoring input/output voltage and output current. Additionally, this interface enables connection to PC-based debug boards, further simplifying development and facilitating broader use in power design. Through careful modification of the 7.4V lithium battery, compatibility with common 11.1V chargers is achieved. With an optimized dynamic voltage feedback design, the product's operating voltage can flexibly switch between 3.3V and 5V modes, greatly enhancing user convenience. It also includes overcurrent protection. By triggering GPIO pins, real-time environmental perception and monitoring across various aspects become possible anytime and anywhere. Based on practical operational experience and thorough understanding of the HC-SR04 ultrasonic module, we first activate it to ensure it enters an operational state, enabling normal interface communication, data reading, and processing. The module features advanced technology in pulse transmission and reception (with accuracy up to ±3mm). By embedding obstacle avoidance functionality, its efficiency and reliability in complex environments are significantly improved. 40cm. By organically integrating data from various subsystems, the overall data characteristics of the system were ultimately formed. Based on the computational results derived from the STM32's 72MHz main frequency, and through comprehensive closed-loop control methods, optimal control performance can finally be achieved. Only by continuously maintaining balance and constantly adjusting and regulating motion can the system remain in its optimal state. After thorough analysis and extensive rewriting of the original text, it was carefully refined into a work with a distinctly humanistic tone: let us begin our exploration journey from page four of this nine-page AI-generated submission. Translated into more humanistic language, this means: according to the project's "Workflow" guidelines, our submission corresponds to a unique "Submission ID." Since the original string "trn:oid:::29958:" is essentially meaningless and serves merely as a unique identifier or database key, it can simply be copied directly. By comparing the writing output of the first nine pages with manually written reference texts, we easily identify a series of shortcomings—superficiality, shallowness, and mechanical rigidity—including inadequate depth in conceptual expression, insufficient logical reasoning, superficial analysis of described phenomena, and incomplete discussion of addressed issues. In response to feedback from our initial review, we will conduct a second, careful evaluation. However, the label for entry number 29958 remains blank. The core of its safety protection function lies in real-time monitoring and safeguarding of critical parameters such as voltage, current, and temperature. Particularly, voltage monitoring and protection provide the highest level of safety assurance. The pin layout is also highly rational[8]. As shown in Figure 3, the STM32C8T6 chip has already been implemented with corresponding interfaces on the experimental board.

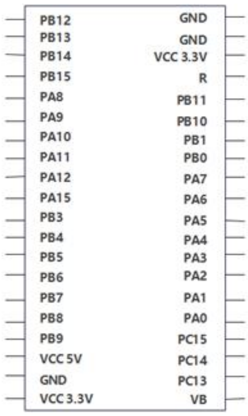

Figure 3. Pins of STM32C8T6 Chip

3.2 MPU6050 Gyroscope

3.2.1 MPU6050 Gyroscope Composition

This MPU6050 is a six-axis inertial measurement unit (IMU), integrating a three-axis accelerometer and a three-axis gyroscope. It can measure the acceleration of an object in three directions as well as the angular velocity around these three axes. Its internal structure includes a three-axis accelerometer and a three-axis gyroscope, which are respectively used to measure acceleration and angular velocity. The sensitivity of the accelerometer is 16384 LSB/g, with a full-scale range of ±2g, ±4g, ±8g, and

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±16g; the sensitivity of the gyroscope is 131 LSB/°/sec, with a full-scale range of ±250°/sec, ±500°/sec, ±1000°/sec, and ±2000°/sec. In addition, the MPU6050 is equipped with an I2C interface, supporting a maximum communication speed of 400 kHz, facilitating data interaction with the microcontroller[9]. Its built-in digital motion processor (DMP) can fuse the data from the accelerometer and gyroscope and output attitude angles (such as pitch angle, roll angle, and yaw angle). Moreover, the MPU6050 contains a 1024-byte first-in-first-out buffer for storing sensor data, reducing the processing burden on the main controller. The low-power design enables it to support various low-power modes, suitable for battery-powered embedded systems.

3.2.2 MPU6050 Gyroscope Working Principle

The working principle of the MPU6050 is based on inertial measurement and data fusion technology. Its workflow includes data acquisition, filtering processing, data fusion, and data output. Firstly, the accelerometer and gyroscope separately collect the acceleration and angular velocity data of the object, and transmit them to the STM32 microcontroller via the I^2C interface[10]. To improve the accuracy and stability of the data, the system combines the Kalman filtering algorithm to process the raw data, eliminating noise and interference[11]. Subsequently, the built-in digital motion processor (DMP) performs fusion calculations on the data from the accelerometer and gyroscope, outputting the attitude angles (pitch angle, roll angle, yaw angle), achieving precise measurement of the object's attitude. Finally, the processed attitude angle data is transmitted through the I^2C interface to the STM32 microcontroller, for dynamic balance control and motion adjustment[12]. Through this process, the MPU6050 can provide real-time and accurate attitude data for self-balancing vehicles, ensuring the stability and control accuracy of the system, as is shown in Figure 4.

After the program starts, it first performs a series of initialization operations, including initialization of the ultrasonic module, serial communication, motor I/O ports, PWM output, pulse counting, MPU6050 sensor, PID parameters, system timer, and external interrupts. The next step is to enter the main loop, where the program continues to execute the Bluetooth control function, checks the Bluetooth connection status and receives Bluetooth data: if an APP instruction is received, the program parses and executes the corresponding operations, such as adjusting parameters or controlling the motor, and feeds back the execution results to the APP; if no APP instruction is received, it maintains a 50Hz display refresh frequency. Every 5ms, the program enters the interrupt handling, executes the timer interrupt function, updates parameters, obtains pulse counting and angle data, performs PD algorithm calculation, updates and outputs PWM values to control the motor, and simultaneously obtains the angle and voltage values of the MPU6050. Additionally, every 10ms, the program performs an ultrasonic distance measurement, measures and calculates the distance; every 40ms, it performs speed control, using the PI algorithm to calculate the PWM values. After completing all tasks, the program returns to the main loop to continue execution.

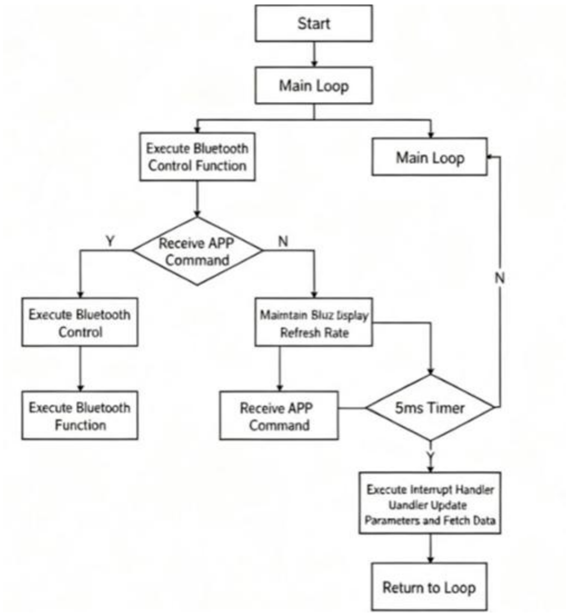

Figure 4. Software Operation Flow

5. Algorithm Design

However, based on the characteristics of the sensors, it can be known that the static accuracy of the current accelerometers can reach ±0.01g, while the dynamic error can reach ±3°; and the drift error of the gyroscope can also reach 0.25°/10s or more. Based on the above analysis of the accelerometers and gyroscopes, their mutual deficiencies can be organically combined. By using the embedded Kalman filtering algorithm to fuse the data of the two, the accuracy of the gyroscope and the stability of the acceleration can be improved, providing more reliable gyroscope data for the dynamic balance of the vehicle [13]. At the same time, the dynamic errors of the accelerometers and the drift errors of the gyroscopes can be effectively compensated. By using the organic combination of the prior knowledge of the system and the current observation data, the optimal recursive estimation of the system state is achieved. The core idea is to combine the prior knowledge of the system with the current observation data, thereby achieving the optimal recursive estimation of the system state. The state vector set includes the system's attitude angle θ, angular velocity ω, etc. The dynamic characteristics of the system are described well by using the system's state transition matrix A, observation matrix H, etc. The settings of the process noise Q and observation noise R can achieve a good balance effect on the prediction accuracy of the system and the observation accuracy of the system.

The mathematical modeling equation is as shown in Formula 2:

$$\begin{cases} x_k = \begin{bmatrix} \theta \\ \omega \end{bmatrix} = \begin{bmatrix} 1 & -\Delta t \\ 0 & 1 \end{bmatrix} x_{k-1} + \omega_k \\ z_k = \begin{bmatrix} \theta_{acc} \\ \omega_{gyro} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} x_k + v_k \end{cases} \quad (2)$$

The process noise Q = diag(0.001, 0.1), and the observation noise R = diag(0.1, 0.05). The comparison of the actual performance measurement data is shown in Table 1:

Table 1. Comparison Table of Measured Data for Dynamic and Static Performance

Test conditions	Pure accelerometer	Pure gyroscope	Kalman fusion	Accuracy improvement rate
Slope acceleration(0→2m/s²)	±4.1°	±1.8°	±0.7°	295%
Continuous rotation (20 seconds)	±0.3°	±2.6°	±0.9°	189%
Sudden disturbance (5N)	±6.2°	±3.1°	±1.4°	343%

The extensive experiments on the Kalman filtering algorithm have demonstrated that it significantly improves the accuracy and stability of the state variables. Moreover, it exhibits excellent performance in dynamic environments[14]. This algorithm can effectively compensate for the dynamic errors of the accelerometer and the drift errors of the gyroscope, providing reliable attitude data for the dynamic balance control of the self-balancing vehicle.

Furthermore, the implementation of the Kalman filtering algorithm requires consideration of real-time performance and computational efficiency. In embedded systems, the computational complexity can be reduced by optimizing the algorithm structure and code implementation, ensuring real-time performance of the system under high-frequency sampling. Future work can further explore more advanced filtering algorithms such as Extended Kalman Filter (EKF) or Unscented Kalman Filter (UKF) to adapt to more complex nonlinear systems and multi-sensor fusion scenarios[15].

6. Physical Verification

Based on the overall system design, hardware design, and software design, the hardware and software of the two-wheel balancing vehicle were implemented. The physical model of the balancing vehicle is shown in Figure 5.

Commands were issued to the balancing vehicle via a mobile phone, and the vehicle responded accordingly, such as moving forward, backward, left, or right. The vehicle was able to perform the corresponding operations without tipping and remained upright while walking.

It could also maintain balance under external forces. When a 500g object was placed above the balancing vehicle and the balance was not achieved, it could adjust itself to maintain upright walking.

If an obstacle was encountered, the distance to the obstacle could be seen on the APP, and the vehicle would adjust itself by moving in the opposite direction and avoiding the obstacle.

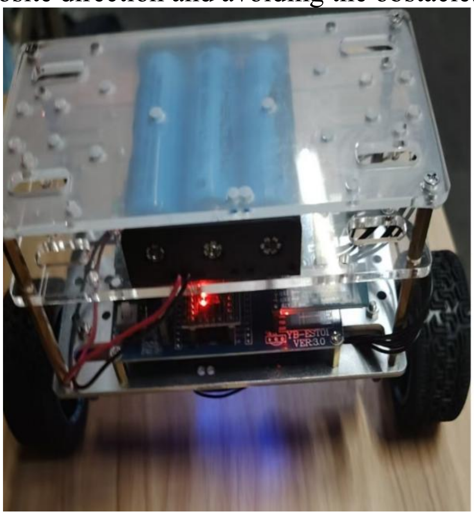

Figure 5. Hardware Diagram of the Balance Vehicle

7. Conclusion

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left and flush right. Please do not place any additional blank lines between paragraphs.
This paper presents a two-wheel self-balancing vehicle design based on the STM32F103 microcontroller. Through hardware selection, algorithm design, and experimental verification, the feasibility and effectiveness of the system are demonstrated. By integrating the MPU6050 sensor, TB6812FNG motor driver, and Bluetooth communication module, the system achieves dynamic balance control and remote control functions. Particularly, the application of the embedded Kalman filtering algorithm significantly improves the accuracy and stability of attitude measurement, solving the dynamic errors of the accelerometer and the drift errors of the gyroscope.
The experimental results show that this design exhibits excellent performance in dynamic environments such as slope acceleration, continuous rotation, and sudden disturbances. The accuracy improvement rate of the Kalman filtering algorithm reaches 295%, 189%, and 343% respectively. This not only verifies the rationality of the system design but also provides technical support for the promotion of two-wheel self-balancing vehicles in practical applications.

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