Design of Control System Based on Electromagnetic Balance Vehicle

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Abstract. This paper introduces the design of control system of electromagnetic balance vehicle based on kea128. From two aspects of hardware and software, the control system is designed. The hardware layer includes micro controller, vehicle model attitude measurement and road information recognition module. According to the collected information, combined with filtering algorithm and closed-loop control of upright, speed, direction, etc., through repeated practice verification, the balance car can achieve independent tracking, and can maintain upright state under different track elements, fast and stable operation.

Keywords: Kea128; electromagnetic balance vehicle; Tsinghua filter; closed loop control.

1. Introduction
The vertical balance car is widely used in many fields, such as industrial production and life travel. The design of a high-performance balance car system needs the complementary of hardware circuit and software programming.

Based on the hardware circuit design and software control algorithm, the electromagnetic balance vehicle can achieve independent tracking and keep the vertical state stable and fast operation.

2. Hardware system design

2.1. Microcontroller module
Kea128 single chip microcomputer is selected as the control core of the control system of the electromagnetic balance vehicle. The controller is based on the high efficiency of arm Cortex-M0 + core, with the working frequency of 48Hz, 128KB of embedded memory and 5V power supply. It has excellent EMC/ESD compatibility, can adapt to high temperature environment, and has low radiation emissions.

2.2. Angle measurement module
The measurement of the inclination angle and the velocity of inclination angle is the key to control the vertical balance of the vehicle model. Using mma7361cl acceleration sensor module, the acceleration value of the vehicle model on the z-axis can be obtained in real time, which has the characteristics of low power consumption and high sensitivity. Using enc-03mb + lpr550 type gyroscope sensor, it can
measure the angular velocity value on x-axis and Z-axis in real time, with the characteristics of zero temperature drift, no overshoot and stable performance.

2.3. Road recognition module
The electromagnetic induction coil is made of I-shaped inductance, and the capacitors at both ends are connected to form a detection amplifier circuit to realize the detection of the electromagnetic line at the center of the track.

2.4. Speed sensor module
The measurement module of the vehicle speed uses two 500-line biphase Omron encoders. The two-way output two sets of pulses with A/B phase difference of 90 degrees, through these two sets of pulses, not only can measure the wheel speed, but also determine the direction of rotation. It has the characteristics of light weight and small size, which can meet the requirements of speed measurement.

3. Algorithm analysis

3.1. Posture angle fusion based on filtering algorithm
The key to realizing the upright walking control of the car model is to accurately collect the current attitude information of the car model. The acceleration sensor installed on the car model can measure the inclination of the car model, and the signal can be differentiated to obtain the inclination speed. However, in actual operation, the acceleration generated by the swing of the car model will cause a large interference signal. Because it is superimposed on the measurement signal, the output signal cannot accurately reflect the inclination of the car model.

The gyroscope can measure the inclination angular velocity of the car model, and the inclination angle of the car model can be obtained by integrating the angular velocity signal without interference from the movement of the car body. If there is a slight error and drift in the angular velocity signal, after the integration operation, the change forms a cumulative error, and gradually increases with time, eventually resulting in circuit saturation, and the correct angle signal cannot be obtained.

In summary, when the acceleration sensor and the gyroscope are working independently, they will produce a large tilt error, so they need to work together. After the measured car model inclination angle and inclination speed are processed by the angle fusion filtering algorithm, a more accurate angle can be obtained, which can reflect the current actual change of the pitch angle. After many tests and experiments, the filtering algorithm is used to fuse angle and angular velocity to achieve better results:

\[ g = \frac{(a - b)}{c} \]

\[ m = (t + n) * d \]

In the formula, \( a \) and \( T \) are the normalized angle and angular velocity respectively; \( c \) is the gravity compensation coefficient; \( d \) is the integral time coefficient; \( b \) is the final fusion angle; \( g \) is the angle deviation corrected by the time coefficient; \( m \) is the last fusion angle.

In the filtering process of angle fusion, the gravity compensation coefficient \( c \) and integral time coefficient \( d \) are mainly modified to optimize the fusion effect. When debugging, first determine a certain value for \( c \) and \( d \), and then set it to different parameters when it is upright. With the help of anonymous four-axis host computer, combined with the angle curve before and after fusion, the effect of the parameters was observed. The final optimal parameters were \( c = 2 \), \( d = 0.0031 \).

3.2. Upright control algorithm
The upright balance control of the car model is based on the inverted pendulum model and is realized by negative feedback. First, the angular velocity and acceleration collected by the gyroscope and
accelerometer are normalized, and the fused angle is obtained by the Tsinghua filter algorithm. The pd controller is used to obtain the angle deviation of the car model in the vertical direction, which is sent to the motor to correct the posture of the car model in real time, and a better upright control effect can be achieved:

\[ p = ((b + \text{speed}) \times \text{pid.p}) + t \times \text{pid.d} \]  

(3)

In the formula, \( p \) is the pwm output of the upright loop; \( \text{speed} \) is the pwm output of the speed loop after frequency division; \( \text{pid.p} \) and \( \text{pid.d} \) are the upright loop proportional and integral parameters, respectively.

The \( \text{pid.p} \) in the PD control algorithm is a proportional parameter, which is directly multiplied by the fused angle, that is, the deviation. Therefore, it is dominant in the pd controller and plays a role in increasing the reaction rate. When this parameter is too large, it will cause shock. \( \text{pid.d} \) is an integral parameter, which cooperates with \( \text{pid.p} \) to suppress the shock. When this parameter is too large, it will reduce the reaction rate and suppress the \( \text{pid.p} \) parameter to a certain extent.

When adjusting the parameters, first set the \( \text{pid.p} \) and \( \text{pid.d} \) parameters to zero, and gradually increase the \( \text{pid.p} \) parameters. When there is a slight shock, adjust the \( \text{pid.p} \) parameters until the shock disappears. Then fine-tune the two parameters to make the car model achieve better upright control effect. The setting parameters are \( \text{pid.p} = -28, \text{pid.d} = -20.09 \).

![Fig 1. Schematic diagram of the car model staying upright](image)

### 3.3. Speed control algorithm

Speed control will interfere with the upright state, so it is necessary to maintain the balance of the car model at all times, and you cannot directly change the motor speed for speed control. The speed control algorithm is used for positive feedback control to control the inclination of the car model, so as to realize the speed regulation of the car model.

The pulse signal collected by the encoder is orthogonally decoded to obtain two rounds of rotation speed and direction of advance. After the average filter, the speed deviation can be obtained by making a difference from the set speed. The function of the integral parameter \( I \) in the PID controller is to reduce the static error. When the parameter is small, it does not work. When the parameter is large, it causes overshoot. After repeated experiments and demonstrations, the speed loop adopts pure proportional control, and the PD controller connected to the vertical loop can also achieve better results:

\[ \text{speed_error} = \text{set_speed} - (\text{valr} + \text{vall})/2 \]  

(4)

\[ \text{speed_pwm} = \text{speed_error} \times \text{pid.p} \]  

(5)
In the formula, speed_error is the speed deviation; set_speed is the set speed; valr and vall are the filtered values of the left and right encoders; speed_pwm is the output of the speed loop pwm; pid.p is the speed loop proportional parameter.

When adjusting the parameters, first set the pid.p parameter to zero, gradually increase the pid.p value, and stop increasing when the vehicle model slightly shakes. On this basis, fine-tuning is carried out until the car model can stand still at a speed of zero value. The adjusted parameter is pid.p=0.1.

3.4. Direction control algorithm
Realizing the direction control is the key to ensure that the car model can drive along the track. Because an enameled wire with an alternating current of 20kHZ passing 100mA is laid in the middle of the track of the electromagnetic upright group, an alternating magnetic field is generated around the center of the road. Through the detection of the deviation of the electromagnetic center line of the road and the differential control of the motor, the direction control of the car model is then realized.

(1) Road detection can be achieved by 5 electromagnetic induction coils installed in front of the car model, the coil adopts 10mH I-shaped inductance. The inductance is arranged in a double T-shape plus an intermediate level inductance:

![Fig 2. Diagram of the inductance distribution](image)

When the electromagnetic balance car is driving on different track elements, there is a certain angle between the inductance and the center line of the track. The magnitude of the induced electromotive force is not equivalent to the induced electromotive force in the vertical direction of the center line of the track. An error occurs when calculating the deviation of the car model position from the center line. The double T-shaped inductor arrangement can effectively solve this problem. The two horizontal inductances are parallel to the x-axis, and the magnitude of the induced electromotive force is only related to the y-axis wire; the two vertical inductances are parallel to the y-axis, and the magnitude of the induced electromotive force is only related to the x-axis wire. The combination of the induced electromotive forces generated in both directions can increase the predictive ability of the car model, avoid the occurrence of blind spots on the track, and enable it to calculate the correct direction deviation in time on different track elements to ensure that the car model can quickly and smoothly Run on the track.

(2) The motor differential control uses the electromagnetic signal to add and subtract the car model speed control signal to form the left and right wheel differential control voltages, so that the left and right wheels of the car model have different angular speeds, thereby controlling the wheels to rotate in different directions.

During the direction control process, the values of the five inductors are first obtained, and the collected values are firstly low-pass filtered and then high-pass filtered, and then normalized. At the same time, in order to better adapt to the track, collection and calibration should be performed on the runway site.

According to the distance from the enameled wire, three or three horizontal inductances are given a certain weight. The closer the inductance obtains a greater weight, the farther the inductance obtains a smaller weight, so that the weighted average deviation can more reflect the actual distance from the center line Distance, in any case can be stable corners.

When calculating the direction deviation, the two sets of symmetrical inductors use the ratio method.
Deviation =
\[
\frac{(E_1 + s_{\text{ratio}}E_0 - E_3 - s_{\text{ratio}}E_4)}{(E_0^2 + E_1^2 + E_3^2 + E_4^2)}
\]

In the formula, deviation is the direction deviation; \(E_0\) and \(E_4\) are the induced electromotive forces generated by the left and right vertical inductors \(E_1\) and \(E_3\) are the induced electromotive forces generated by the left and right horizontal inductors; \(s_{\text{ratio}}\) is the vertical inductance proportional coefficient.

According to Biot-Savart theorem, the induced electromotive force detected by the inductor will decrease as the cart moves away from the current-carrying wire. In the previous electromagnetic tracking scheme, there is a common drawback: after the car deviates from the centerline by a certain distance, as the deviation distance increases, the deviation of the voltage detected by the left and right inductors after calculation will gradually decrease. Misjudgment is caused and the driving speed is limited. The advantage of the ratio method is that when the car gradually deviates from the center of the track, the amount of deviation calculated by this algorithm increases as the distance from the car to the centerline increases. The decrease caused misjudgment and significantly increased the running speed of the car.

After field verification on the track, the stability and rapidity of the electromagnetic balance car system have been improved after adopting the ratio method, and it can smoothly pass most curves at a faster speed.

The direction ring adopts PD control, which can achieve better tracking effect.

In order to eliminate the overshoot in the direction control of the car model, differential control is added here. Differential control is a control method that corrects the motor differential control according to the change rate of the direction of the car model, and uses a gyro sensor to detect the rotation rate of the car model to optimize the direction control.

When adjusting the direction parameters, first set the two parameters to zero, and gradually increase the \(\text{pid.p}\) parameter. When the car model oscillates slightly at the center line, slowly increase the parameter \(\text{pid.d}\) until the swing stops, the car model can achieve a good patrol forward.

**Fig 3. Diagram of the track tracking**

4. Conclusions
This paper explores and implements the electromagnetic balance vehicle control system with KEA128 as the control core. The system includes hardware circuit and software programming. Among them the hardware circuit involves the microcontroller, the car model attitude measurement and the road recognition and other modules. The software control is based on the information collected by the sensor, and realizes Tsinghua filtering angle fusion and three closed-loop algorithm control of upright, speed and direction. After multiple rounds of testing in the track environment, the balance car can well complete autonomous road tracking and run quickly and steadily in an upright state.
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