Two-wheel self-balanced car based on Kalman filtering and PID algorithm

LIU Kun, BAI Ming, NI Yuhua
College of Information Technology
Beijing Normal University at Zhuhai
Zhuhai, China
sailsmoon@hotmail.com

Abstract—**Self-balanced car is a typical Incomplete control system. Self-balanced car`s body is a natural instability, so it has multivariable, nonlinear, strong coupling and other characteristics. The choice of inertial sensors has become one of the most important issues while designing a self-balanced car. But the sensor module is too expensive that is the reason of the high cost of the self-balanced car. A lower costed acceleration ADXL335 and angular velocity sensor ISZ-650 are chosen to make a sensor module much cheaper and the attitude is measured with Kalman filtering and PID algorithm.Finally a self-balanced car model is made to prove the feasibility of reducing costs.**

Keywords - ***self-balanced; gyroscope; accelerometer; PID control; Kalman filtering***

I. INTRODUCTION

Two wheels for mobile robot from balance inverted pendulum principle model based is transplanted into the mobile robot. Self-balanced robot and inverted pendulum is a different place is not only to realize the balance control but also on the basis of a balance in the forward and backward realization and steering movement. Japanese sanyo motors have developed can rely on to maintain balance, i.e. handstand carts robot "FLATHRU". The robot used for kitchen with user-friendly service robots head using three gyroscope and one 3-axis acceleration sensor.

The sensors in the system of measuring attitude are more expensive,. In this subject a cheaper triaxial acceleration chip ADXL335 and ISZ-650 uniaxial gyro chip is intended to choose with kalman filtering and PID control algorithm to finally achieve low cost two wheel self-balanced car solutions, and the feasibility of the low cost two wheel self-balanced car solutions was proof[1][2].

II. DESIGN OF HARDWARE OF SELF-BALANCED SYSTEM

This system has a master control module, posture, acquisition module, motor driver module, motor and battery module in Fig.1.

The master control module built-in 10 AD digital-to-analog converters is used to the sensor data acquisition and processing, Angle of the conversion, motor PWM control and etc.

The sensor group is used to measure the system

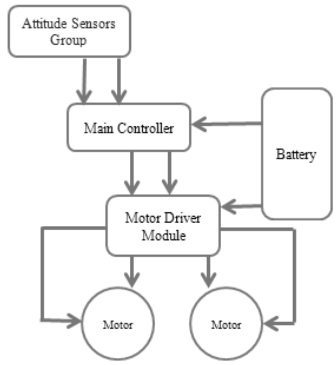

Figure 1. System Structure

acceleration and angular velocity. The motor driver module is used to drive motor . The DC motor drives car to restore balance. The battery part supplies power to the system and motors.

A. Mechanical structure of the system

The system mechanical structure has a certain rigid body in favor of control stably. Upper center of gravity of the car reduces the difficulty of the motor control but the stability worse, at the same time, lower center of gravity of the car adds the control difficulty and improves the motor stringent requirements but the stability becomes better. So the design should take into account the actual various situation.

B. DC motor

The DC motor as one of the most important parts in the self-balanced car affects the control performance of the car to maintain balance and the response speed so that comprehensive consideration of the selection is need when choosing from motor power, motor speed, motor torque etc.

1) Choice of DC motors

The main choice has stepping motor, ordinary toy motors and dc hollow cup decelerating motors considering the low price, performance, linear variety of motor speed and 11.1V power for the car.

The stepping motor is controlled agilely, respond rapidly, strong anti-jamming capability, etc. But the stability of the balance control is more difficult because of the fixed movement step distance horns, inertial load difference, complex circuit and single-step sometimes overshooting.

The ordinary toy motors are very cheap but no gearbox, torque and power small, linear change bad and response speed slow against the car balance control.

The hollow cup decelerating motors due to its special mechanical structure have prominent energy-saving characteristics, sensitive convenient control characteristic and stable operation characteristic since they have lead gearbox, big torque and fast response in the self-balanced car with an irreplaceable advantage compared with other motors.

So this model adopts hollow cup decelerating motors with the system application needs.

2) Hollow cup decelerating motors characteristics

Hollow cup motor on the structure through the traditional motor rotor structure form has no core rotor also called hollow cup type rotor which novel rotor structure eliminated electrical energy loss caused by iron core vortex while its weight and rotational inertia greatly reduced and thereby reducing the rotor own mechanical energy loss.

In tests used eight bits PWM(Pulse width modulation), the encoder of the motor starts to accumulate when output duty cycle is about 5 (2%) that proved the motor began to turn, so the motor hollow cup decelerating motors control performance is more superior .

3) Motor driver circuit

The motor driver circuit is chosed a driver module based on L298N which has several common functions such as the speed and direction indicator light, protect circuit, data extent IO, reset button.

L298N is a kind of high voltage, large current motor drive chip which can reach the highest working voltage 46V, continuous working current 2A and instantaneous peak current 3A. The chip containing two H bridge high voltage large current bridge type drive can directly drive two DC motors.

C. Design of the control circuit

The control circuit mainly adopts AVR microcontroller as the main control panel which is a simple IO board with usb interface including 12-channel digital GPIO(General Purpose Input/Output), 4-channel PWM(Pulse Width Modulation) output and 6/8-channel 10 bit ADC(Analog-to-Digital Converter) input.

Atmega168 or Atmega328 as low price microcontroller is used similar Java/C language IDE integrated development environment and usb to supply power and download programs which the open source and hardware greatly reduce development costs.

D. Sensor Circuit

In order to realize the balance of two rounds of car, information of the robot position and attitude is quickly and accurately acquired which is prerequisite to control the self-balanced car sports and balance. The sensor is not only used for internal feedback control but also used in perception and external environment interaction. When the self-balanced car move, the sensor will send relevant information to the controller to judge and control the balance state of the self-balanced car for keeping dynamic balance.

There are many different kinds of Attitude sensors. The sensors used in this model are a analog output accelerometer and a analog output gyro.

1) Sensor selection

The sensor type and quantity affect the whole stability of the system that the choice of the sensor is crucial in the car performance. This system adopts a tri-axial accelerometer chip ADXL335 of American ADI company and a single axis angle accelerometer chip ISZ-650 of InvenSense company to realize the car stance measurement in order to control the cost after the market research and analysis.

The micro capacitive acceleration sensor ADXL335,300mV/g range, is a low cost single chip tri-axial accelerometer which has been set the low-pass filter,temperature compensation etc.before they leave the factory and peripheral devices very little that are only four capacitance that noise is very small.

ISZ-650 is widely used to measure posture in mobile terminals such as games, remote control, tablet computer, etc. which has 0.5 mV/degree/s and 2.27 mV/degree/s ranges directly connected corresponding output pin.

2) Sensor Circuit Design

This sensor circuit is designed based on the official reference circuit in the sensor manual.

E. Some other detail

The needless interference is prevented when shorter wires are as far as possible on the attachment in PCB design. The sensor group close the wheel axis is put 45 degrees position helpful for accurate detection and reducing unnecessary interference and complex interference processing. The interference is prevented since the motor power supplies, control circuit and the sensor power supplied are separate.

III. SENSOR DATA PROCESSING

Gyro and accelerometer is used to measure the equilibrium position of the self-balanced car off center by Angle, but the gyroscope is more accurate in the measured value of the moment and the measuring accuracy reduced with the extension of time,at the same time, the accelerometer is just opposite that is not accurate in an instant and the measuring accuracy improved with the extension of time, so meanwhile two kinds of the sensor are used for complementary fusion to reach the purpose of accurate measurement.

A. gyroscope's data processing

The PCB of the double-axis gyroscope is made to simultaneously compatible two sensors because the circuit principle diagrams of ISZ–650(single axis) and IDG-650(2 axis) gyro are fully compatible.

Angle accelerometer characteristic is that number changed when the sensor turned a certain angle, or a fixed value. The sensor in position 1 or in position 2 output same value that is 300 though the position is changed but the number no changed when the sensor is turned. In conclusion from the test the value of the gyroscope is comparatively accurate in a short time but has greater error in the long time so the sampling period is tried to minimize so as to achieve precise measurement when the control[3].

So angle is found out by integrating angular velocity to time in (1)。

$$Angle_n = angle_{n-1} + gyro_n \times dt \tag{1}$$

$angle_n$: No. n turned angle value of gyroscope

$angle_{n-1}$: No. n turned angle value of gyroscope

$gyro_n$: angular velocity value sampled with gyroscope

dt: Sampling period

B. accelerometer data processing

The accelerometer peripheral circuit very simple that needs only four 0.1 uF capacitance, 3.3 V power supplied, can output triaxial acceleration value. In this system only biaxial X and Y is used in the triaxial accelerometer to calculate deviation angle.

The accelerometer characteristics is exactly the opposite to the gyro that gravity acceleration always exists with a vertical acceleration to the ground so different values are output with the different locations of the accelerometer if the accelerometer orientation change. The sensor output 300 when the sensor is in the position 1 and 380 in position 2 in the experiment the only one axis accelerometer is measured. This shows accelerometer in a short time due to the influence of inertia measure much error but error down gradually as the measuring time increased.

A formula of anti-trigonometric function method is used to calculate deviation angle and approximate computation used because of the tilt angle often very small[4].

The car inclined angle can be calculated by anti-trigonometric function which can be approximately computed because the angle often is very small in Fig.2[10].

$\theta = \arctan(X/Y)$

$\theta \approx X/Y$

θ: deviation angle

X: lateral acceleration

Y: longitudinal acceleration

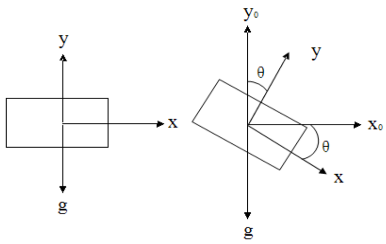

Figure 2. Deviation Angle θ

IV. Design and Realization of software

A. Realize of the equilibrium

Two-wheel self-balanced car is a natural unstable body based on traditional level one handstand pendulum. The processor analyzes and calculates data returned from the sensor which constantly detects the stance and location of the car to control motor torque with the effective arithmetic to achieve balance control.

Make the key steps car balance is one of the effective method is accurate with calculate the current body balance position deviation Angle, namely the two rounds of balanced car now gesture

One of the most important steps for balance is to calculate the current deviation angle with the effective method that is the 2-wheel self balanced car gesture at present get by acceleration and gyro sensor fusion filtering at first ,then reached the final balance with PID algorithm controlling motor torque.

B. Kalman filtering

Kalman filtering is a recursive estimate so the history information does not need to record or estimate as long as the estimated value at the last state and observations of the current state has known. Kalman filter very different from most filters is that it is a kind of pure time-domain filter and does not need to be like a low-pass filter such as frequency domain filter designed in the frequency-domain then converted to the time-domain to realize again[5].

Kalman filter is expressed by the following two variables of the state:

$\hat{X}_{k|k}$: the state estimate in the moment K

$P_{k|k}$:Error correlation matrices to measure the precision degree

Kalman filter operation includes two stages: forecast and update. In predicting stage the filter used the estimation in the last state to make the estimate in the current state. In the update phase the filter optimized the prediction obtained in the forecast stage to get a more precise new estimate[6].

1) Principles of Kalman filtering

The principle of the kalman filter introduces a discrete control process system first can be described by a Linear Stochastic differential equation in (2).

$$X(k) = A\,X(k-1)+B\,U(k)+W(k) \tag{2}$$

The system measurement is added in (3):

$$Z(k) = H\,X(k)+V(k) \tag{3}$$

In the last two formula X (k) is the system state in the moment of K and U (k) is the variable in the the moment of K. A and B is the system parameter but is a matrix for the multi-model systems. Z(k) is measured value in the moment of K. H is the parameter of the measured system but is a matrix for the multi-model systems. W (k) and V (k) is respectively expressed noise in the measurement and the process which has been hypothesized to Gaussian White Gaussian Noise and covariance is Q and R (here they are assumed not to change with the change of the system state).

The optimization output of the system is estimated specific as follows:

First the system of the next state is predicted with the system process model.It is Assumed that the current system state is k and the state at present can be predicted based on the last state of the system according to the system model.

$$X(k|k-1) = A\, X(k-1|k-1)+B\, U(k) \tag{4}$$

In (4) X (k | k - 1) is the result predicted with the last state, X(k-1|k-1) is an optimal result of the last state and U(k) is the control variable at present that can be 0 if not a control variable.

Now this system has been updated but the covariance of X(k|k-1) haven't been updated. If P shows covariance,then:

$$P(k|k-1) = A\, P(k-1|k-1)\, A'+ Q \tag{5}$$

P(k|k-1) is X(k|k-1) corresponding covariance and P(k-1|k-1) is X(k-1|k-1) corresponding covariance in (5). A 'shows A transposed matrix. Q is the systematic process covariance. Equation (1) and (2) are the first two of the kalman filter 5 formulas which are also the prediction of system.

Now there are the predicted results of the state at present and then the measured value of the current state are collected . The optimization X(k|k) of the state of K at present is estimated according to the forecast value and measured values:

$$X(k|k) = X(k|k-1)+Kg(k)(Z(k)-H\, X(k|k-1)) \tag{6}$$

Kg is Kalman Gain in (6).

$$Kg(k) = P(k|k-1)H'|(H\, P(k|k-1)H'+R) \tag{7}$$

The estimated optimization X(k|k) is gotten at the state of K through the above formula, but the covariance of X(k|k) is updated in the state of K in order to let the kalman filter running down constantly until the system process is over.

$$P(k|k) = (I-Kg(k)H)P(k|k-1) \tag{8}$$

I is a 1 matrix in(8) and I = 1 for the single model and single measurement. P (k | k) is P (k - 1 | k - 1) in Formula 2 when the system comes into the state of k + 1. So the algorithm can running down auto-regressively.

Equation (4) to (8) describe the principle of Kalman filtering with which the computer program is easily realized.

2) Results of the Practical measurement

The performance of the kalman filter is tested through programming. The measured curve has great interference and error when the car swings forward and backward from the measured curve of the sensor group so accelerometer greatly influenced by inertia, but fluctuation has effectively filtered away and the curve is much smoothed with kalman filtering for the accelerometer and gyro and data integration so the attitude of the car is more accurate in Fig.3 from the yellow line that is the attitude of the car at present.

It is very adverse for control that is clearer to indicate the sensor effect to inertial while the car running forward, but the measured value is very close to the real one after Kalman filtering and data fusion in Fig.4.

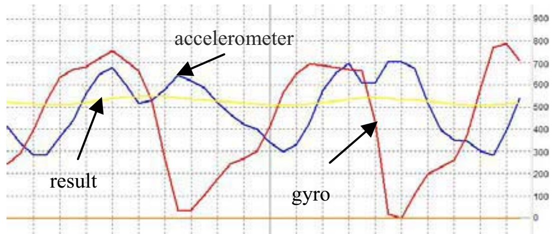

Figure 3. Output value while swinging forward and backward

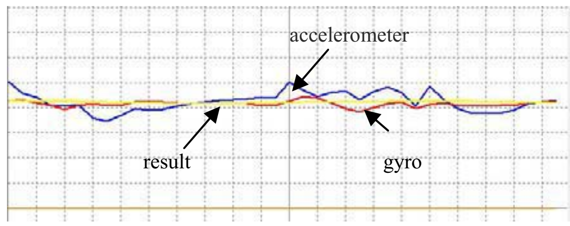

Figure 4. Output value while running forward

C. PID controller

PID controller (proportion-integral-differential controller) is composed by proportion unit P, integral unit I and differential unit D composition. PID controller mainly applies to the system of basic linear and dynamic characteristics no changes with time by setting Kp, Ki and Kd three parameters in Fig.5.

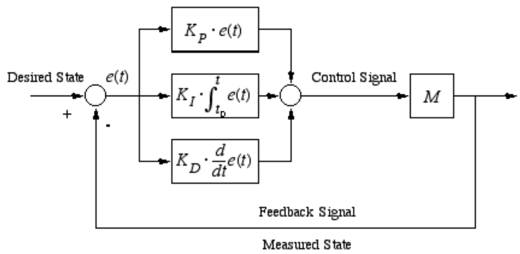

Figure 5. PID structure

PID controller is a common feedback loop component in an industrial control application. This controller put the collected data to compare with a reference which is used to calculate the new input value to let system data keep the reference[7][8]. PID controller is very different from other simple control algorithm that it makes the system more accurate and more stable with adjusting input value according to historical data and differences. Mathematical methods have proved a PID feedback loop can keep system stable when other control methods cause system error or repeated process[9].

After measuring accurately deviation angle the best control coefficient is defined after adjusting the value of K according to the PID formula and then self-balance is realized ultimately in (9).

PD control is just adopted for PWM value of motors to realize balance in this system.

$$PWM = K1 \times angle_n + K2 \times angle\_dot_n \tag{9}$$

PWM: control value of motor PWM. Maximum is 255 and Minimum is 0.

Anglen: No. N angle value.

$angle\_dot_n$: the difference of No.N angle value and

No.N - 1 Angle value, namely the deviation quantity.

K1, K2: both control coefficient.

V. Physical Test

A. Test platform

Test platform is a homemade uniaxial two-wheel self-balanced car model. This model is made of five layers: the bottom is the first layer that is mainly wheels, motors and sensor group installed in the axis where it is more accurate. The second is the battery layer that mainly is placed a 11.1 V lithium battery for motor power. The third layer is the main controller board and drive layer where is placed control model and motor drive control module. The fourth layer is a sensor adjustment layer which adopts two high-precise potentiometers to adjust the PID parameters and another 7.4 V lithium battery that is used to power main controller and sensors. The fifth layer is an expansion layer for the perfecting function.

B. Data analysis

the data Sent from a serial port shows (figure 36) the first column of data, and the second column of data is the parameters of PD control. The third column of the accelerometer data is the value of the X axis AD samples, row 4 is the value of the Y axis AD samples. The fifth column is angle value of accelerometer AD samples. In the last column is system control motor output PWM values. It shows that PWM value remains within 10 and the car can stable stand on the desktop when the car body balance.

The sensor group of ADXL335 and ISZ-650 verified the feasibility of posture detection according to the sensor detect, data processing and data results in Fig.6.

VI. Conclusion

Two-wheel self-balanced car is a complex non-linear system that is broad research significance and the market prospect whether in the theoretical research, science and education and actual transportation especially for low-cost development with study of reducing cost. It's realized that a sense group of accelerometer and gyro, the whole system made of dynamic model, control model and software and the test of self-balance, but some contents will be studied further such as more sports posture, temperature influence, etc.

Acc	Rot	accin_x	accin_y	gyroin	accin_tmp	gyroin_tmp	angle	angle_dot	V
81.00	28.20	512.00	407.00	427.00	−0.03960	0.07434	−0.0003	−0.0003	3.72
81.00	28.10	514.00	407.00	425.00	−0.05941	0.02478	−0.0014	−0.0010	5.82
81.00	28.20	513.00	407.00	426.00	−0.04950	0.04956	−0.0020	−0.0007	6.67
81.00	28.20	512.00	407.00	426.00	−0.03960	0.04956	−0.0026	−0.0005	7.44
81.00	28.20	509.00	407.00	427.00	−0.00990	0.07434	−0.0024	0.0001	6.89
81.10	28.10	512.00	407.00	427.00	−0.03960	0.07434	−0.0027	−0.0003	7.57
80.90	28.10	514.00	407.00	425.00	−0.05941	0.02478	−0.0037	−0.0010	9.63
81.00	28.10	512.00	408.00	426.00	−0.04000	0.04956	−0.0043	−0.0005	10.19
81.00	28.10	510.00	407.00	428.00	−0.01980	0.09912	−0.0040	0.0002	9.37
81.00	28.10	510.00	406.00	429.00	−0.01961	0.12390	−0.0035	0.0005	8.45
81.00	28.20	509.00	407.00	428.00	−0.00990	0.09912	−0.0032	0.0004	7.94
81.00	28.10	509.00	407.00	427.00	−0.00990	0.07434	−0.0031	0.0001	7.90
81.10	28.20	509.00	407.00	426.00	−0.00990	0.04956	−0.0032	−0.0001	8.26
81.00	28.20	508.00	406.00	426.00	0.00000	0.04956	−0.0032	−0.0000	8.19
80.80	28.10	508.00	407.00	425.00	0.00000	0.02478	−0.0035	−0.0002	8.72
80.90	28.20	509.00	408.00	427.00	−0.01000	0.07434	−0.0033	0.0001	8.34
81.00	28.20	508.00	406.00	427.00	0.00000	0.07434	−0.0031	0.0002	7.89

Figure 6. Data sent from serial port

References

[1] Zhang Jichang, Cheng Kai and Zheng Ronger, "The Design of the Self-Balance Two Wheel Vehicle s Attitude Estimation System," Periodical of Ocean University of China, 2009-S1, pp.467-470

[2] QIN Yong, ZANG Xi-zhe,WANG Xiao-yu, ZHAO Jie and CAI He-gao, "Research of Attitude Estimation System Using MEMS Inertial Sensors," Chinese Journal of Sensors and Actuators, Vol. 20,No. 2, pp.298-301, Feb. 2007

[3] Jiang Haitao and Guo Zhanying, "Design of Aircraft Tilt Measurement System Based on MESM Accelerometer Sensor," Computer Measurement & Control, No.1, 2010, pp.107-109

[4] ZHANG San-chuan, PENG Nan and Li Xia, "Design and Analysis of the Two-wheeled Self-balancing Electric Vehicle," Journal of Zhengzhou University(Engineering Science), Vo l.32, No.1, pp.31-33, Jan. 2011

[5] GAO Yuanyuan, Xiaogang, SONG Hongjun and CHEN Jing, "Research on Filtering Problem in Inertial Sensors for a Two-Wheeled Self-Balanced Robot," Chinese Journal of Sensors and Actuators, Vol. 23, No. 5, pp.696-700, May 2010

[6] RUAN Xiao-gang and REN Hong-ge, "Two-wheeled self-balancing mobile robot dynamic model and balancing control," Application Research of Computers, Vol. 26, No. 1, pp.99-101, Jan. 2009

[7] ZHAO Jian-wei; RUAN Xiao-gang, "Modeling and Control of a Flexible Two-wheel Upright Self-balance Humanoid Robot," Robot, Vol.31, No.2, pp.179-186, Mar., 2009

[8] CHEN Wei, YAN Wen-jie, ZHOU Chao-ying and DU Zhi-jiang, "Control system design of two wheels self-balance robot," Transducer and Microsystem Technologies, Vol.27, No.4, pp.117-120, 2008

[9] ZHANG Wei-min，DUAN Xiao-ming and ZHAO Yan-hua, "Research of Trace Control for Two-Wheel Self-Balanced Vehicle Based on FNN," Techniques of Automation and Applications, Vol.30, No. 4, pp.10-13, 2011

[10] ZHANG San-chuan, PENG Nan and Li Xia, "Design and Analysis of the Two-wheeled Self-balancing Electric Vehicle," Journal of Zhengzhou University(Engineering Science), Vol.32, No.1, pp.30-33, Jan., 2011