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Researches and Development of an Efficient Electric Personal Mover for City Commuters

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Abstract

In order to reduce the carbon emission, saving fuel energy and for the convenience of personal transportation in urban area, a two-wheel-driven self-balancing vehicle was developed, which utilize the well-known inverted pendulum control technique, can carry one person and travels at a maximum speed of 20km/h. The vehicle which is called "Tiny", consists up of two brushless DC motors, the motors are placed coaxially. A gravity sensor and a gyro are mounted on the vehicle, signals from the two sensors are combined with Kalman Filter to indicate the tilt angle of the vehicle. By controlling the tilt angle to be 0 degree (which means the vehicle body is perpendicular to ground), the vehicle can perform travelling forward and backward. In this paper, the implementation of the Kalman filter is discussed by using Matlab simulations, and the mathematical model of the vehicle is also presented, then the controlling diagram is presented. In the end of this paper, some experimental parameter is presented.

Keywords: Self-balancing vehicle, EV Development, Kalman filter

1. Introduction

In recent years, researching in self-balancing vehicles, which typically consist up of two wheels in coaxial and a standing platform, works as an inverted pendulum, are drawing more and more attention from both researchers and public. Among this kind of vehicles, the most famous is Segway, which is a kind of standing-driving selfbalancing vehicle, with a maximum speed of 10km/h. Later EN-V was development by GM and SAIC, which is expected to be commercially available in 2030. This kind of vehicle provides us a completely new way in solving traffic and pollution issues: Driving by electric makes them environmental-friendly, small size and flexible running style(including zero-radius turning) enable them to travel smoothly in city streets. In order to provide drivers with a more comfortable driving environment, longer driving distance and in this paper, an efficient and flexible selfbalancing vehicle—"Tiny"--was developed, which allows people sit and driving, with a maximum speed of 20km/h and maximum driving distance of 20km within once charge. Firstly, its mechanical structure and the

mathematical model was developed. Then the electronic control system was introduced and the control system was discussed, including Kalman Filter and inverted pendulum control algorithm. Finally some experiments were performed to verify its performance.

2. System Overview

2.1 System State Space Model

Tiny consists up of aluminum alloy chassis and two co-axially placed wheels; each of them is driven by two geared BLDC motors. Two wheels and a seat chair are mounted on the chassis. There is a mechanism to enable drivers manipulate the seat back and forth, hence to change the center of gravity of the vehicle. This will make the vehicle lean forward or backward, the inclination angle is sensed by on board microcontroller through gravity sensor and gyroscope. Then the microcontroller will make wheels to generate torque to keep the vehicle vertical, just like the inverted pendulum.



Figure 1: Simplified Model of the Vehicle

Figure 1 is a simplified model of Tiny, it shows the basic configurations of wheel and chassis. From this figure the mathematical model of the vehicle can be derived. The variable definitions are as follows:

- θ : Inclination angle;
- *l*: Distance from COG to wheel axis;

M: Total mass of driver and chassis;

- ν : Speed of vehicle;
- *u*: Forces applied to wheel axis;
- x: Position of the vehicle
- m: Mass of wheels
- *I* : Inertia of chassis and driver;

For the wheels, the kinetic equation is:

$$m\ddot{x} = u - b\dot{x} - N \tag{1}$$

$$N = M \frac{d^2 (x + l\sin\theta)}{dt^2}$$
(2)

Where N represents the lateral reaction force applied to the wheel axis by the chassis and driver. Substituting equation (2) into equation (1) and we assume θ is near 0, take the approximation of $\sin \theta = \theta$, $\cos \theta = 1$, $\dot{\theta}^2 = 0$ we get:

$$(M+m)\ddot{x} = u - b\dot{x} - Ml\ddot{\theta} \qquad (3)$$

Consider the vertical forces on chassis and driver:

$$P - Mg + M \frac{d^2 (l\cos\theta)}{dt^2} = 0 \quad (4)$$

And the torque equation is:

$$P/\sin\theta - N/\cos\theta = I\ddot{\theta}$$
(5)

Combine equation (4) and (5) we get the second state equation, after approximation it is:

$$\left(I + Ml^2\right)\dot{\theta} + Ml\dot{x} - Mgl\theta = 0 \quad (6)$$

We take θ , $\dot{\theta}$, x, \dot{x} as state variables, since M >> m, we can neglect the wheel weight, the state space model is:

$$\frac{d}{dt}\begin{bmatrix} \theta \\ \dot{\theta} \\ x \\ \dot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\frac{g}{I} & \frac{I+M\hat{I}}{M\hat{I}} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ g & -\frac{I+M\hat{I}}{MI} & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \dot{\theta} \\ x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ \frac{M}{M} \\ 0 \\ 0 \end{bmatrix} (7)$$

If we only consider the first two state variables, we can find that the system is fully controllable.

2.2 Sense of Inclination Angle

In Tiny's control system, we only incorporate θ and $\dot{\theta}$ as feedback state variables. There are two sensors, one is acceleration sensor, and the other is gyroscope. The acceleration sensor is to get the inclination angle θ , and the gyroscope is to measure the inclination rate of chassis $\dot{\theta}$.

Both of the two sensors have drawbacks. Accelerometer has good accuracy and stability, but the response time is relatively long. Meanwhile gyroscope has a rapid response but poor in accuracy and has bias problem. To overcome the drawbacks, we use Kalman filter to combine the two variables.

The Kalman filter is a tool that can estimate the variables of a wide range of processes. In order to use a Kalman filter to remove noise from a signal, the process that we are measuring must be able to be described by a linear system [1].

The Kalman filter addresses the general problem of trying to estimate the state x of a discrete-time controlled process that is governed by the linear stochastic difference equation [2]:

$$\dot{x} = Ax + Bu + w \tag{8}$$

$$y = Hx + z \tag{9}$$

State variable matrix x is the quantity to be measured, w is process noise and z is measurement noise. They are assumed to be independent (of each other), white, and with normal probability distributions:

$$p(w) \sim N(0, R)$$
 (10)
 $p(z) \sim N(0, Q)$ (11)

There are two steps in Kalman filter: Predict and Correct, in Predict step, we use equation (8) to predict the current value of x, here we use discrete time equations:

$$\hat{x}_{k}^{-} = A\hat{x}_{k-1} + Bu_{k-1}$$
(12)
$$P_{k}^{-} = AP_{k-1}A^{T} + Q$$
(13)

P in equation (13) is called estimate error covariance matrix. \hat{x} denotes the estimated value of x.

Then the Correct step is performed:

$$K_{k} = P_{k}^{-} H^{T} (HP_{k}^{-} H^{T} + R)^{-1} \quad (14)$$
$$\hat{x}_{i} = \hat{x}_{i}^{-} + K_{i} (v_{i} - H\hat{x}_{i}^{-}) \quad (15)$$

$$P_{k} = (I - K_{k}H)P_{k}^{-}$$
(16)

After the Correct step, the filtered value \hat{x}_k is obtained. Then the next Predict step can be performed. Equation (12) to (16) form the whole Kalman filter algorithm.

Here we take the output of accelerometer and gyroscope bias as state variables. Then we have the following equations:

$$\theta = \omega - b \tag{17}$$

$$b = 0 \tag{18}$$

$$x = \begin{bmatrix} \theta \\ b \end{bmatrix} \tag{19}$$

Where ω is the output of gyroscope, \dot{b} is the gyro bias. We use the Jacobian of \dot{x} with respect to its states as the matrix A:

$$A = \begin{bmatrix} \partial \dot{\theta} / & \partial \dot{\theta} \\ \partial \partial \theta & \partial b \\ \partial \dot{b} / \partial \theta & \partial b \\ \partial \dot{b} / \partial \theta & \dot{b} / \partial b \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} (20)$$

And we set the initial value of P to be:

$$P = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$
(21)

We use the output of accelerometer as variable y in equation (9) and (15). *H* is set to be:

$$H = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{22}$$

Figure 2 is a Matlab simulation of Kalman filter of inclination angle; here we set the sampling time to be 2ms.



Figure 2: Matlab Simulation of Kalman Filter

The upper plot is the output of accelerometer with white noise, the value of which is set to match the AD's result. The lower plot is the filtered accelerometer output, take the arcsine of which will get the inclination angle. The red line in lower plot represents the gyroscope bias. We can see that gyroscope bias is automatically tracked by Kalman filter.

In Kalman filter, it is important to determine matrices Q and R. The two matrices reflect how the controller trusts in the two sensors.

Figure 3 is the control diagram of Tiny:



Figure 3: Control Diagram

There are two control loops in the diagram— Inclination loop and steering loop. The inclination loop uses a PD controller, in which we simply use the filtered and unbiased gyroscope signal as the derivation component. The steering loop is used to amend the difference between two motors.

3. Hardware and Software Implementation

3.1Hardware Design

We use a 48V 10Ah LiFePO₄ battery as the power source. The battery has built-in power management system and over current protection. The maximum current is limited at 30A.

The central controller is based on Freescale MC56F8037, a 16-bit microcontroller with PWM output and on-chip ADC. Main control algorithm and sensor signal sampling are performed by the controller. Two ADI's MEMS sensors are used to get the inclination angle of the vehicle.

The BLCD commutation is accomplished by an Altera EPM7128 CPLD. It receives two pairs of complementary PWM signals and hall signals from the two motors. Then send 6PMW output signals to the motors respectively.

Each of the motor driving circuit is built on 6 power MOSFETs, is capable of driving motor with power up to 500Watts. In Tiny, two 440W BLDC motor is equipped.

Figure 4 is the hardware configuration of Tiny:



Figure 4: Hardware Configuration of Tiny

We utilize 20 kHz bi-polar PWM modulation in controlling BLDC motors. According to our experiment, bi-polar modulation has a better torch output than uni-polar modulation.

3.2 Software Design

In Tiny's software implementation, the main routine is the system running state control. A state machine is used to control each of the states and the transfer between them. The state machine flow diagram is shown in figure 5.



Figure 5: State Machine Flow

There are three buttons in Tiny-Power, Start and Brake. For safety considerations user should switch the Power on while the Start keeps in off state, then push the Start on. In the Init state, this power on sequence is checked, if user doesn't follow that sequence, Tiny will remain in Init state. In Init state, software will examine the state of Start switch and the filtered outputs of two sensors, in a 200ms self test. Then it will display messages on LCD to indicate driver whether to start the vehicle. When driver see "Ready to start" on LCD, he or she may switch the Start button on, which will change the state machine to Run state. The vehicle needs a large torch applied to the wheel axis to lift to a balanced position ($\theta = 0$). However, this large torch may bring shock to the driver. In order to make the vehicle lift smoothly, a "soft start" procedure is executed when changing state to Run. This procedure controls the torque increasing rate at a moderate level. With the "soft start" feature Tiny takes 2 seconds to lift balance.

In Run state, when driver steps on the brake pedal, an auxiliary braking wheel will expand and hydraulic braking system will take effect. Meanwhile the torch generated by the motor gradually decrease to zero. This will make the vehicle stop. When user releases brake pedal, it will turn back to Run state again.

Figure 6 is a full view of "Tiny" at exhibition:



Figure 6: Tiny at Exhibition

4. Conclusion

In this paper, a self-balancing vehicle-Tiny is introduced. The control algorithm and implementation (both hardware and software) is discussed. A Matlab simulation is performed to verify the Kalman filter in processing the sensor signals.

A few experiments were performed on city road to verify the usefulness of Tiny. Table 1 shows the basic performances:

Max Speed	25km/h
Max Distance (48V 10Ah)	20km
Braking Distance (20km/h)	5m
Max Load	80kg
Balancing $ heta$	$\pm 1.5 \deg$

From the above table we can see "Tiny" is capable of serving as a personal mover, replacing motorcycles and even cars for short distance travelling.

However, there are still some drawbacks in "Tiny". The max load is limited due to the motor power and battery capacity. The center of gravity of "Tiny" is relatively high with respect to its width, which makes it dangerous in traveling above 20km/h.

In our future work, the safety issues will be focused. New braking algorithm will be developed to shorten the braking distance and shock to drivers will be eliminated.





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