DESIGN AND CONTROL AUTO-BALANCED ROBOTIC BICYCLE

Vu Ngoc Kien*
College of Technology - TNU

ABSTRACT

Autonomous vehicles has attracted many researchers in the recent years. In this paper, the author has built a auto-balance robotic bicycle (ABRB) by using flywheel based on inverted pendulum principle. The ABRB has only two in-line wheels, it reduces both weight and widths. The ABRB could be used both as a teaching tool, and as a device to test balanced control algorithms. At the same time, to maintain the stable balance of ABRB the author designs a balance control system based PD control law. The experimental results showed that the correctness of robot models of and balance control system.

Keywords: *auto-balance robotic bicycle (ABRB), inverted pendulum principle, flywheel, balance control system*

PROBLEM STATEMENT

Autonomous vehicles have has attracted many researchers in the recent years. However, one major limitation of automated vehicles is in the area of stability. Most robots require a wide wheel base and a minimum of three points in contact with the ground to maintain stability. Increasing the number of wheels of a robot reduces the efficiency of the drive system by adding weight, increasing friction or drag, and increasing power draining components. The Auto-Balanced Robotic Bicycle (ABRB) offers a new way to circumvent these limitations. By using only two in-line wheels, the ABRB reduces both weights and widths without sacrificing stability.

DESIGN ABRB

There are many methods used to control balancing of ABRB such as flywheel balancing [1, 2, 5], mass balancing [3], and steering balancing [4]. Among these methods, flywheel balancing method which uses a reaction wheel (flywheel) is a good choice because the response time is shorter and the system can be stable even at stationary position. There are two principles used flywheel in the flywheel balancing method. The first principle uses a spinning wheel as a gyroscopic stabilizer [1]. Its advantages includes low mass and produce large amounts of torque. Its disadvantages are that it consumes more energy. The second principle uses a spinning wheel based on the inverted pendulum principle [2, 5]. Its advantages are low cost, simplicity and consumes low energy consumption. Its disadvantages are that it cannot produce large amounts of torque.

In this study, we will design ABRB based on the inverted pendulum principle. ABRB could be used both as a teaching tool, and as a device to test control algorithms.

The law of conservation of momentum states that if no extenal torque effects on an object or system (or total torque impact to the object is zero), total angular momentum of that object will be preserved. Based on the law of conservation of momentum states, my robotic bicycle contains a reaction wheel and which using to maintain its balance. When it is deflected from the equilibrium position (corresponding to a vertical angle) the gravity of the bicycle will create a torque leading it to pour down. This reaction wheel will revolve around the axis (with the angular acceleration is α) and generate a torque which is balanced with the torque caused by the gravity the bicycle creates. A DC motor is used to control the acceleration of the reaction wheel. A

* *Email: kienvn@tnu.edu.vn*

control system receives the robot's tilt angle as the feedback and outputs a torque on the reaction wheel to drive the entire system to a vertical orientation.

Mechanical Design

The design of the ABRB closely resembles a low riding scooter. The goal is to optimize space for electronics, while maintaining rigidity in the entire frame as shown in Figure 1.

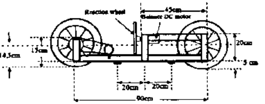

Figure 1. *ABRB's mechanical frame design*

The front wheel is intentionally fixed so the robot could drive through only a straight line, and rely only on a control mechanism to balance itself. The wheels of the vehicle are 30-cm bicycle wheels and the drive train is implemented with two sprockets and a chain. The reaction wheel (flywheel) is the most important component of the mechanical design. A careful balance of mass vs. moment of inertia is also very critical. In order to attain a high moment of inertia while minimizing the overall mass, the wheel needs contain the majority of its mass concentrated at the outer edge. The final reaction wheel which selected is custom machined of steel with a diameter of 26-cm and mounted perpendicularly in the middle of the bicycle. A detailed description of ABRB constitute is in Figure 2 as follows:

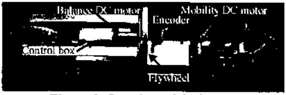

Figure 2. *Details model of ABRB*

Control Design

The control system of ABRB is shown in Figure 3.

The central element of the control system is used the Arduino board. Arduino board is a microcontroller board based on the ATmega328P (datasheet). It has 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button.

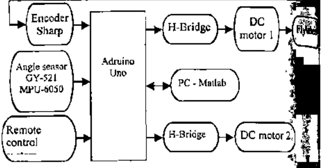

Figure 3. *The control system of ABRB*

The control system of ABRB consist of two primary subsystems. The first subsystem is responsible for maintaining the balance of the vehicle, whereas the second subsystem control the mobility.

The first subsystem elements of the control system is built up with the following components: to spinning the flywheel using DC motor 100w-15v-3400 rev/min + H-bridge; measuring speed of flywheel using Encoder Sharp 100 pulses, measuring tilt using angle sensor GY-521 MPU-6050.

The second subsystem elements of the control system is built up with the following components: a DC motor, H-bridge and the remote control.

Modeling and balance control system design

Modeling ABRB

The balance control system of the ABRB is modeled as an inverted pendulum model in the Figure 4.

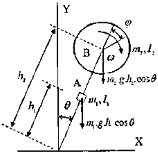

Figure 4. *Inverted pendulum model of ABRB*

m_1 is the weight of the ABRB (including the DC motor), m_2 is the weight of the flywheel, ı$_1$ is the height of the center of the gravity of he ABRB (excluding the flywheel), h_2 is the ıeight of the center of the gravity of the lywheel, I_1 is the moment of inertia of the ABRB, I_2 is the moment of inertia of the lywheel, θ is the tilt angle of the ABRB ;ompared to the vertical, φ is the angle of otation of the flywheel

To build the dynamic models of system, the ıuthor [2] using the Lagrange equations.

$$\frac{d}{dt}\left\{\frac{\partial T}{\partial \dot{q}_i}\right\}-\frac{\partial T}{\partial q_i}+\frac{\partial V}{\partial q_i}=Q_i. \quad (1)$$

T is total kinetic energy of system, V is total potential energy of system, Q_i is external forces, q_i is generality coordinates.

Total the kinetic energy of the system is defined as:

$$T=\frac{1}{2}\ m_1h_1^2+m_2h_2^2+I_1+I_2\ \dot{\theta}^2 + \frac{1}{2}I_2\dot{\varphi}^2+I_2\dot{\varphi}\dot{\theta}. \quad (2)$$

Total potential energy of system is:

$$V=g.\cos\theta.\ m_1h_1+m_2h_2 \quad (3)$$

Using the Euler-Lagrangian equations, the following two equations are derived:

$$m_1h_1^2+m_2h_2^2+I_1+I_2\ \ddot{\theta}+I_2\ddot{\varphi} - g.\sin\theta.\ m_1h_1+m_2h_2\ =0. \quad (4)$$

$$I_2\ddot{\varphi}+I_2\ddot{\theta}=T_m. \quad (5)$$

With T_m is torque if the motor shaft.

Consider a DC motor with a transmission ratio is a:1, the (torsion) torque of DC motor drives for the flywheel as the follows:

$$T_m=aK_m\left[\frac{U-K_e\dot{\varphi}}{R}\right], \quad (6)$$

where K_m is the torque constant of the motor; K_e is the electromotive force constant of the motor; R is the resistance of the motor.

Replace (6) into (5) we get the following equation:

$$I_2\ddot{\varphi}+I_2\ddot{\theta}=T_m=aK_m\left[\frac{U-K_e\dot{\varphi}}{R}\right]. \quad (7)$$

Equation (4) and (7) are the kinematic equations of the system. Obviously with the above aerodynamics equations, the system is nonlinear system.

Linearizing model: Assuming that when the bicycle is operating, its angle is very small ($\theta<10^\circ$), we linearized equation (4) around the equilibrium ($\theta=\varphi\approx 0$, $\sin\theta=\theta$) then obtained the following equations:

$$m_1h_1^2+m_2h_2^2+I_1+I_2\ \ddot{\theta}+I_2\ddot{\varphi} -g.\theta.\ m_1h_1+m_2h_2\ =0, \quad (8)$$

$$I_2\ddot{\varphi}+I_2\ddot{\theta}=T_m=aK_m\left[\frac{U-K_e\dot{\varphi}}{R}\right]. \quad (9)$$

Let $A=m_1h_1^2+m_2h_2^2+I_1+I_2; B=m_1h_1+m_2h_2$

Performing equation (8) and (9) in the following plant model

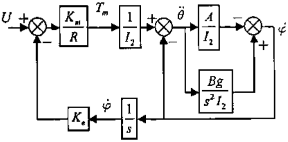

Figure 5. *ABRB model*

Control balance system design

Let $G=\frac{Bg}{s^2I_2}-\frac{A}{I_2}; C=\frac{K_m}{I_2R\ 1+G}; D=\frac{GK_e}{s}$

and $E=\frac{C}{1+CD}$

Simplifying the ABRB model in Fig.5, w obtained ABRB model in Fig. 6 as follows:

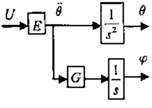

Figure 6. *Compact ABRB model*

With the plant model, combining PD lav controller and the system of ABRB a depicted in Figure 7.

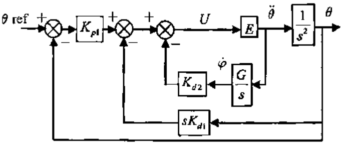

Figure 7. *Balance control system of ABRB*

To determine the parameters (K_{p1}, K_{d1}, K_{d2}) of the controller in Figure 7, the author follows these steps:

Step 1: Writing the C^{++} code and loading that code into the Arduino board in order that Arduino board can send and receive data from the Matlab software through the PC.

Step 2: Building the input – output signal processing unit in Matlab – Simulink.

The function of the input signal processing unit is receives and processes the tilt angle signal and the rotational speed signal of the flywheel from the Adruino board.

Accurately obtaining the feedback signals of the control system is the key to successfully balancing the ABRB. Because of the importance of detecting the tilt angle of the balancing control algorithm, an accurate and precise method used to measure the angle. The MPU6050 contains both a 3-Axis Gyroscope and a 3-Axis accelerometer allowing measurements of both independently. A gyroscope offers a very fast angular velocity reading, however, the round-off errors from digital integration may cause the position output to "drift" over time. To compensate for this drift, the error between the raw tilt angle form the gyroscope and the absolute tilt angle from the accelerometer was used.

The compensated tilt angle output is shown in Figure 8.

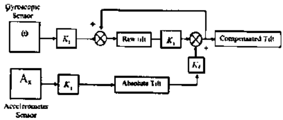

Figure 8. *Gyroscopic drift compensation*

The inputs signal processing unit is shown in Figure 10.

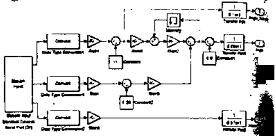

Figure 9. *The input signal processing unit in Matlab – Simulink*

The function of blocks in Fig. 9 as follow:

Stream Input Block: receiving sensor signals posted from Arduino board.

Data Type Conversion Block: Converting measured signal of gyroscopic Sensor.

Data Type Conversion 1 Block: Converting measured signal of accelerometer Sensor.

Data Type Conversion 2 Block: Converting measured signal of encoder.

The function of the output signal processing unit is sends the signal control of controller to H-bridge which controls the DC motor. The output signal processing unit is shown in Figure 10 as follows:

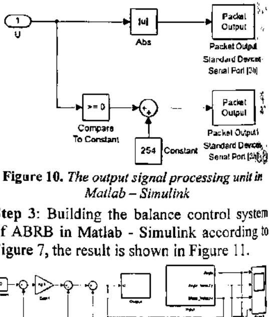

Figure 10. *The output signal processing unit in Matlab – Simulink*

Step 3: Building the balance control system of ABRB in Matlab - Simulink according to Figure 7, the result is shown in Figure 11.

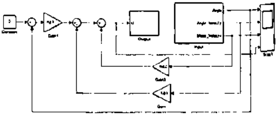

Figure 11. *Balance control system of ABRB in Matlab - Simulink*

Through experiments, the author chooses the parameters of the controller are $K_{p1} = -30$; $K_{d1} = -13$; $K_{d2} = 9$.

The experiment results of balance control system of ABRB

The experiment results of balance control system of ABRB is shown in Figure 12.

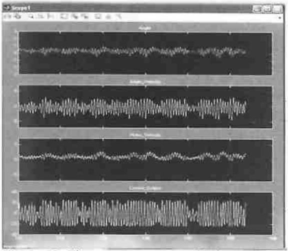

Figure 12. *The output response of balance control system of ABRB*

The results in Fig. 12 show that: the tilt angle of ABRB changes from -0,8 ÷ 1 degree; the rotational speed of the DC motor changes from 2,5 rad/s ÷ -0,5 rad/s; the voltage U which applied to the DC motor changes from – 24V ÷ 24 V.

Comment: The balance control system keeps the tilt angle of ABRB balance around the angle 0 degree.

CONCLUSION

This paper was introduced in detail the desigr process auto – balance robotic bicycle usec flywheel balancing method. At the same time to maintain the balance of the ABRB the author designed a balance control systerr based PD control law. Using the Matlat software, the author identified the parameter of the balance controller of the ABRB. The experimental results showed that ABRB car stable equilibrium with controller designed ir this paper.

REFERENCES

1. Gallaspy J.M., *Gyroscopic stabilization of ai unmanned bicycle*, M.S. Thesis, Auburr University, 1999.
2. Lee Suk-In; Lee In-Wook, Kim Min-Sung; He He, Lee Jang-Myung, "Balancing and Driving Control of a Bicycle Robot", Journal of Institute of Control, Robotics and Systems, Volume 18 Issue 6, 2012, pp.532-539.
3. Lee S., Ham W. (2002), "Self-stabilizing strategy in tracking control of unmanned electric bicycle with mass balance", In: *Proceedigns of the IEEE International Conference on Intelligent Robot and Systems*, pp. 2200 – 2205.
4. Tanaka Y., Murakami T., "Self sustaining bicycle robot with steering controller", *In Proceedings of international workshop or advanced motion control 2004*, pp. 193-197, 2004.
5. Yunki Kim, Hyunwoo Kim, Jang myung Lee "Stable control of the bicycle robot on a curvec path by using a reaction wheel", Journal o Mechanical Science and Technology, May 2015 Volume 29, Issue 5, pp 2219–2226.

TÓM TẮT

THIẾT KẾ VÀ ĐIỀU KHIỂN ROBOT XE ĐẠP TỰ CÂN BẰNG

Vũ Ngọc Kiên*
Trường Đại học Kỹ thuật Công nghiệp – ĐH Thái Nguyên

Hiện nay, nghiên cứu robot tự hành là một lĩnh vực thu hút sự quan tâm của nhiều nhà nghiên cứu. Trong bài báo này, tác giả đã xây dựng được một một robot xe đạp tự cân bằng (ABRB) nhờ việc sử dụng bánh đà dựa trên nguyên lý con lắc ngược. ABRB chỉ có hai bánh nên sẽ giảm được cả trọng lượng và chiều rộng. ABRB có thể được sử dụng như một công cụ giảng dạy và một thiết bị để thử nghiệm thuật toán điều khiển. Đồng thời, để duy trì ABRB cân bằng ổn định, tác giả đã xây dựng được một hệ thống điều khiển dựa trên luật điều khiển PD. Các kết quả thực nghiệm điều khiển robot cho thấy tính đúng đắn của mô hình robot và hệ thống điều khiển cân bằng.

Từ khóa: *ABRB, nguyên lý con lắc ngược, bánh đà, hệ thống điều khiển cân bằng*

Email. kienvn@tnu.edu.vn