PID CONTROLLER FOR BALANCING ONE-WHEELED SELF-BALANCING ROBOT

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Abstract: One-wheeled self-balancing robot is a high-order SIMO system. It is developed from bicycle balancing and two-wheeled self-balancing robot by using only one wheel instead of two wheels. In this paper, we consider this model as two combined SIMO systems. Thence, a PID control structure is designed to balance this model not falling on a plane. Simulations are shown to prove again the ability of PID controllers in balancing this robot is two directions. Besides, we present a hardware platform of one-wheel self-balancing robot. Through the real model, PID control algorithm is proved to balance this object well at equilibrium point.
Keywords: one-wheel; self-balance; unicycle; SIMO system; PID control.

1. Introduction

Two-wheeled self-balancing robot, in which two wheels are put horizontally, is a typical model in control system [1]. Bicycle-formed self-balancing, in which two wheels are put vertically, is a similar model but with different structure. This model is also controlled well through researches [3]. By removing a wheel, these models become one-wheeled self-balancing robot (OSR) the challenge of balancing is increased. The purpose of OSR controlling is to keep it not falling down and moving straight forward or backward. This model is different with ball-bot, which operates by a robot on a ball [4]. In [5], dynamic equations of OSR are shown. However, in this study, the balancing is focused on left-right angle of OSR, the robot's body is regarded as being always at the up-right position. Thence, it is not realistic for real model control. In this paper, we present an experimental model of OSR and use reaction wheel to keep balancing for OSR by both sides on the ground. The parameters of system are not measured or identified. Therefore, PID is a suitable algorithm for OSR to be balanced at equilibrium point.

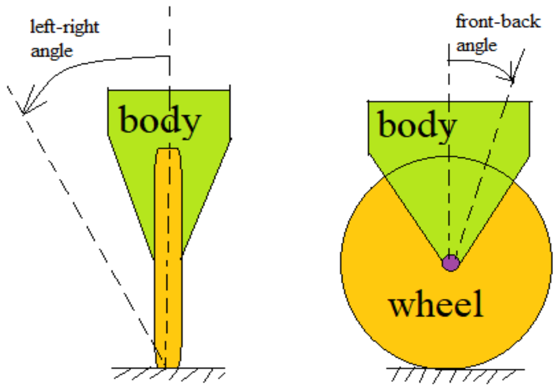
2. Modeling and Controlling

OSR moves on an x-y plane. Thence, front-back direction and left-right direction are considered (Fig. 1). The motion of OSR on each direction is controlled by a PID controller (Fig. 2). The control of each direction is considered as a reaction wheel inverted pendulum (RWIP) (Fig. 3). OSR can be considered as two combined separated RWIP and two-wheeled self-balancing robot (TWSPR). Considering on each side, the motion of each reaction wheel keep the body of OSR balancing through that side (Fig. 2).

In [6], a PID controller for SIMO system is presented for RWIP. Hence, we depend on this study to develop PID to our ORS (Fig. 2 and Fig. 5). Because the angles (in Fig. 1) are controlled to move to zero, error *e* in Fig. 5 is regarded as the same as these angles. Besides, the control signals of PID controllers are signal u in that figure. Also, from side-view, we can also regard OSR as a TWSPR. Thence, we regard OSR to be two equivalent models:

a/ One RWIP (Fig. 3) that one DC motor needs to balance to keep OSR not falling left and right sides.

b/ One TWSPR (Fig. 4) that one DC motor needs to balance to keep OSR not falling toward and backward sides.



(a) (b)

Fig. 1. OSR on x-y plane: (a)-front view; (b)-side view

Now, a MIMO under-actuated system is considered as two combined SIMO systems. Then, each SIMO system is controlled by a separated PID controller.

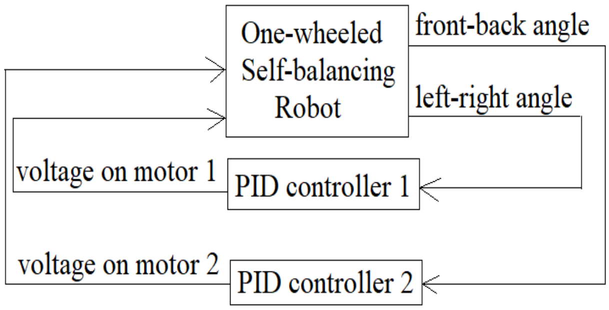


Fig. 2. Block diagram of control schemes for OSR

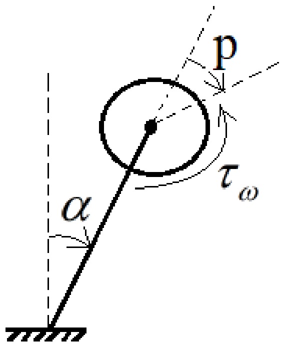


Fig. 3. Mathematical model of RWIP

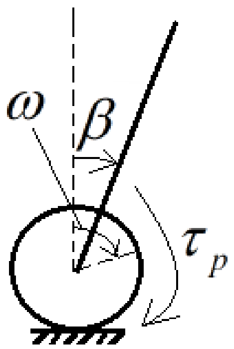


Fig. 4. . Mathematical model of TWSPR

Due to lack of system parameters, we regard the moments of motors to be equivalent to voltages on motor. The calibration of PID controllers will be operated, respectively.

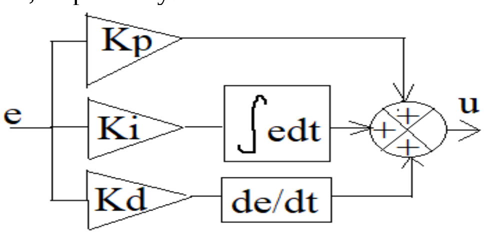


Fig. 5. Structure of each PID controller

In PID controller 1, the angle of left-right angle is considered to be the input, and voltage supplying to motor DC 1 is output.

In PID controller 1, the angle of forward-backward angle is considerred to be the input, and voltage supplying to motor DC 1 is output.

3. Dynamic equations

3.1. Model of RWIP

From [9], if we ignore the angle of wheel, OSR can be regarded as RWIP with this dynamic equation:

$$\ddot{\alpha} = \frac{(m_1 L_1 + m_2 L_2) g}{m_1 L_1^2 + m_2 L_2^2 + I_1} \alpha - \frac{1}{m_1 L_1 + m_2 L_2} \tau_\omega \tag{1}$$

where: m_1 (kg) is mass of wheel; m_2 (kg) is mass of pendulum; L_1(m) is distance from center of pendulum to axis of wheel; L_2(m) is half-length of pendulum; I_2 (kgm^2) is inertial moment of wheel.

Thence, according to (1), we can consider OSR as SISO system.

3.2. Model of TWSPR

According to Fig. 4, side-view of OSR can be considered as a TWSPR model. In [8], dynamic equation of OSR can be regarded as given below:

$$\ddot{\beta} = \frac{\begin{bmatrix} -mL\dot{\beta}\sin\beta\cos\beta + \\ +(M+m)g\sin\beta - \frac{\tau_P}{R}\cos\beta \end{bmatrix}}{L\left(M + m\sin^2\beta\right)} \tag{2}$$

where: β (rad) is angle of body of OSR; m (kg) is mass of body of OSR; M (kg) is mass of wheels; R (m) is radius of wheels; L (m) is length of body of OSR; g (m/s^2) is gravitational acceleration.

In **(2)**, the parameter ω (in Fig. 5), which is rotational angle of wheel, is regarded as not affecting the parameter β. Hence, TWSPR is considered a SISO system if its position is not important.

4. Simulation

4.1. Model of RWIP

From [9], the system parameters are

$m_1=0.87$; $m_2=0.56$; $L_1=0.085$; $L_2=0.13$ (3)

Then, a set of PID parameters are selected as

Kp2= 2; Ki2=0.1; Kd2= 0.3 (4)

If initial values of α and $\dot{\alpha}$ are 0.01 and 0, from (1), (3), (4), we obtain simulation result in Fig. 6.

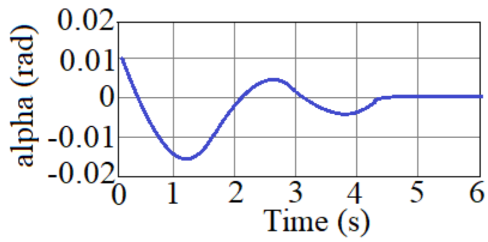


Fig. 6. Left-right angle of OSR under PID control

In Fig. 6, setting time is 4.5 seconds, the angle α oscillates 0.015 rad before being stable at value “zero”. In conclusion, PID controller is proved to work well for balancing OSR in left-right direction.

4.2. Model of TWSPR

If we choose the parameters as:

M=0.1; m=0.01; R=0.01 (5)

Then, it is easy to choose a sample set of PID controller that can balance system in Fig. 4 as

Kp2= 0.3; Ki2=0.01; Kd2= 0.2 (6)

If initial values of β and $\dot{\beta}$ are 0.001 and 0, from **(2**), (5), (6), we obtain simulation result in Fig. 7.

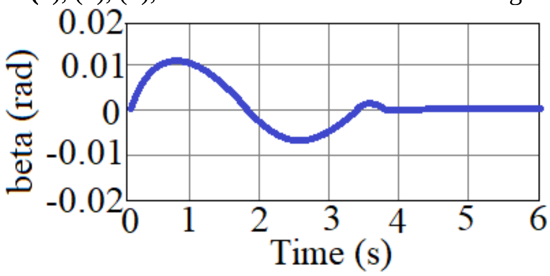


Fig. 7. Forward-backward angle of OSR under PID control

Through Fig. 7, OSR is kept not falling down in forward-backward direction, under PID controller. After 4 seconds and the vibration of 0.01 rad, the angle β is stable at value “zero”.

5. Experiment

5.1. Experimental model

Mechanical structure of OSR is designed by Solid-works program (Fig. 8). Thence, we built an experimental platform for testing in Fig. 9

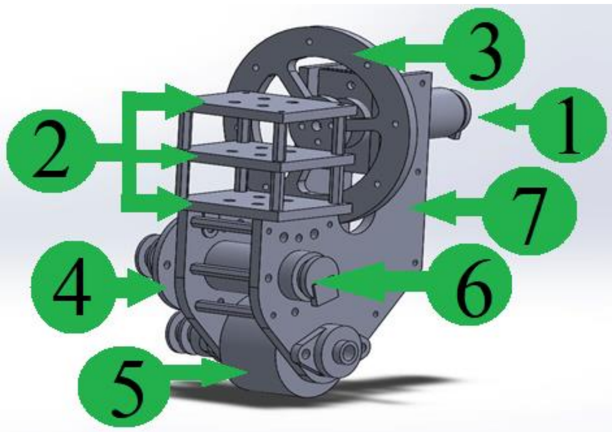


Fig. 8. Solidworks model of OSR

1- Motor 1 that controls the reaction wheel 1
2- Case where circuit boards are put on
3- Reaction wheel 1
4- Reaction wheel 2
5- Wheel
6- Motor 2 that controls the reaction wheel 2
7- Body of OSR

By designing in Fig. 8, a real OSR is created in laboratory of Cao Thang College (CTC) (Ho Chi Minh city, Vietnam) for testing in Fig. 9.

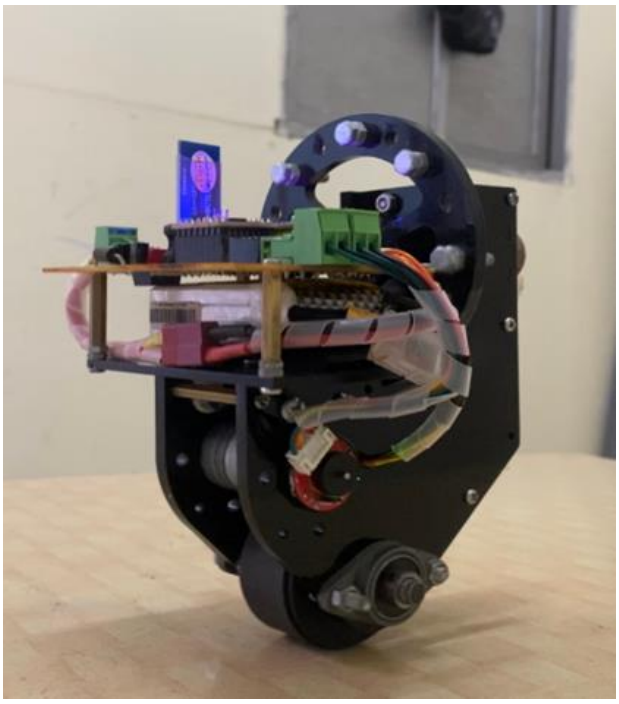


Fig. 9. Experimental OSR in Cao Thang college

The angles of OSR (in Fig. 1) are measured by MPU6050 (Fig. 10).

Fig. 10. MPU6050

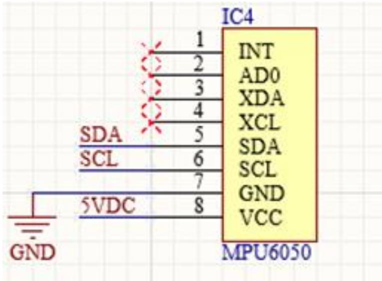


Fig. 11. Structure of electrical structure of MPU6050

The DC motors in Fig. 8 are shown in Fig. 12.

Fig. 12. DC Servo GA25-370

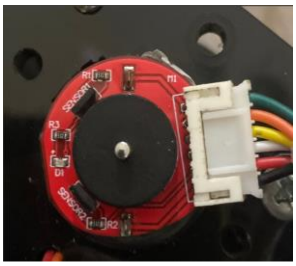


Fig. 13. Encoder in back of DC motor GẠ-370

Control board is showed in Fig. 14. This board is connected with motor by a DC motor driver (Fig. 15). Thence, low-voltage control board can be isolated with the high-voltage DC motor.

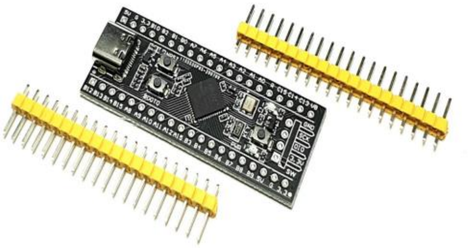


Fig. 14. STM32F401CCUE processor board

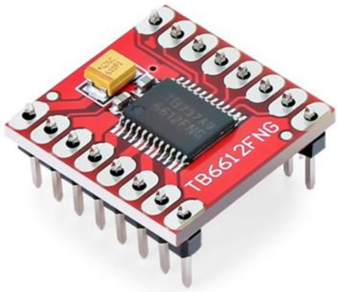


Fig. 15. Motor Driver Circuit TB6612

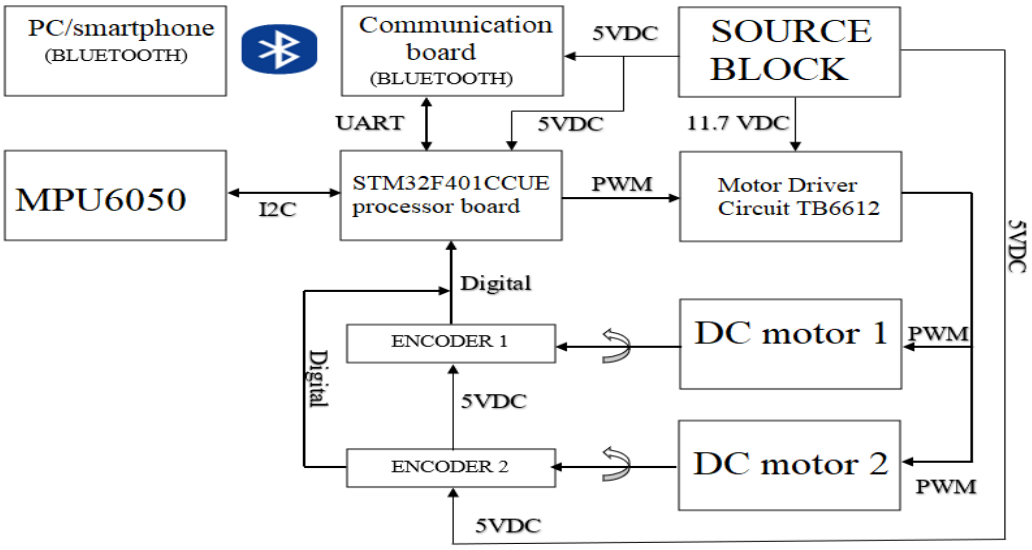


Fig. 16. Electrical connection block diagram of ORS

With components from Fig. 10 to Fig. 15, electrical connection block diagram for OSR are constructed as in Fig. 16.

5.2. Experimental result

With the model in Fig. 9, the angles of OSR in Fig. 1 are listed in Fig. 17 and Fig. 18. The parameters of PID controllers in Fig. 2 are chosen as

Kp1=0.3; Ki1=0.2; Kd1=1.2; Kp2=0.5; Ki2=1.2;Kd2=0.45 (7)

These control parameters are chosen though trial-and-error method. Firstly, PID cotnroller 1 is calibrated to keep OSR not falling in left-right direction. Secondly, under the first controller, the second controller is calibrated until the OSR can be self-balanced. The operation of our OSR is shown in **[**7]. From Fig. 17 and Fig. 18, the left-right angle control is needed to be more focused due to its sensibility of falling down. In Fig. 17, this angle is kept to be around 6 degrees around the vertical axis. In Fig. 18, front-back angle is kept 10 degrees around the vertical axis. The average mean of this angle is more than 0 degree. Thence, this OSR seems to move straight-forward. The vibration of front-back angle can be larger than the left-right angle when OSR operates. PID controllers can keep OSR not falling down but it cannot keep OSR at equilibrium point completely. This model still moves forward slowly uncontrollably. Then, controller should be developed in later researches.

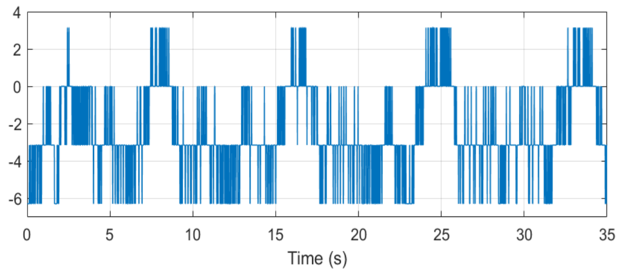


Fig. 17. Left-right angle (degree)

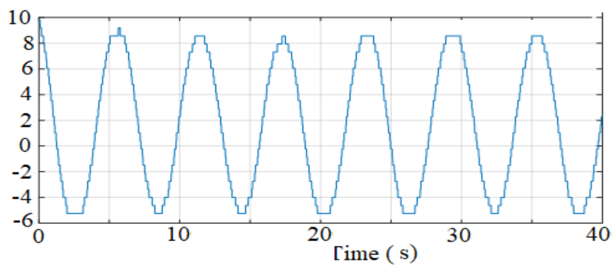


Fig. 18. Front-back angle (degree)

6. Conclusion

In this paper, we suggest a structure of PID controllers to balance OSR on a plane. After some simulation results, we present an experimental OSR. Through this model, a structure of PID controllers is designed to keep it stabilized. The parameters are chosen through trial-and–error method. The OSR is kept not falling down but the motion of straight-forward direction is not guaranteed. Through our experiences by doing this research, there should be an encoder at the axis of wheel to measure the straight-forward motion and a structure of PID should be developed to improve this disadvantage. Besides, other algorithm can be developed, such as fuzzy control. Another method can be considered is LQR or sliding mode control (SMC). However, the system parameters must be identified before using those methods.

7. Acknowledgement

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8. References

[1] Jia Q., Cao X., Sun H., Song J.: “A Novel Design of A Two-Wheeled Robot", 2nd IEEE Conference on Industrial Electronics and Applications, 2007, pp. 1226-1231, 2007.

[2] Astrom K.J., Klein R.E., Lennartsson A.: "Bicycle dynamics and control: adapted bicycles for education and research," in IEEE Control Systems Magazine, vol. 25, no. 4, pp. 26-47, Aug. 2005.

[3] Kim H.-W., An J.-W., Yoo H.D., Lee J.-M.: "Balancing control of bicycle robot using PID control", 2013 13th International Conference on Control, Automation and Systems (ICCAS 2013), pp. 145-147, 2013.

[4] Cai C., Lu J., Li Z.: "Kinematic Analysis and Control Algorithm for the Ballbot," in IEEE Access, vol. 7, pp. 38314-38321, 2019.

[5] Kim H.-W., An J.-W., H.D. Yoo and J. -M. Lee: "Balancing control of bicycle robot using PID control", 2013 13th International Conference on Control, Automation and Systems (ICCAS 2013), pp. 145-147, 2013.

[6] Montoya O.D., Gil-González W.: “Nonlinear analysis and control of a reaction wheel pendulum: Lyapunov-based approach”, International Journal of Engineering Science and Technology, Volume 23, Issue 1, pages 21-29,ISSN 2215-0986, 2020.

[7] ***: www.youtube.com/watch?v=Zc3R1v_vZ5A

[8] Nguyen V.D.H., Ivanescu M., Nitulescu M.: „Observer-based Controller for Balancing Robot with Uncertain Model”, 2016 17th International Carpathian Control Conference (ICCC), pp. 226-231, 2016.

[9] Nguyen B.H., Nguyen M.T., Le T.T.H., Nguyen V.D.H., Tran H.C.: „Controlling a Reaction Wheel Pendulum using LQR Controller: Simulation and Experiment”, Journal of Technical Education Science, No. 50, pp. 1-7, 2018.