The Design of a Microcontroller-based Self Balancing Robot Employing PID Control and Kalman Filter

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Abstract

A self-balancing robot is a mobile robot that has two wheels on the right and left sides which will not balance if it is not controlled. This study aims to design a control system that can balance the self-balancing robot. The system used as input is from the MPU6050 sensor, and the output from the sensor in the form of a tilt angle will be processed using a microcontroller. The angle obtained will be compared with the setpoint value which is 0 degrees. The difference between the setpoint and the system output angle is controlled using PID control. For the output from the PID to be more stable, it will be filtered using a Kalman filter. Analysis of calculations using MATLAB software to make it easier to analyze the response of the self-balancing robot that has been given the values of Kp, Ki, and Kd. From the test results, it is obtained that the PID controller parameters that will be used from tunning the Kcr value with the Ziegler-Nichols method are Kp = 5.67, Ki = 85.5 and Kd = 0.0004 can overcome the balance in the self-balancing robot approaching the setpoint value with an angle range between -3° to 3°.

Keywords

Self Balancing Robot, PID Controller, Kalman Filter, Design Microcontroller.

Introduction

A two-wheeled balancing robot is a mobile robot that has two wheels on the right and left sides that cannot be balanced if it is not controlled (B. Zhang & Wu, 2019). This two-wheeled robot is a combination of a wheeled mobile robot and an inverted pendulum system. An inverted pendulum cannot be moved by itself, it uses a gyroscope and accelerometer to sense the tilt of the vertical axis. To overcome the tilt, the controller generates a torque signal to each motor to prevent the system from falling to the ground (An & Li, 2013; Philip & Golluri, 2020). The study of control strategies for such systems remains a topic of interest among researchers such us PID (Philip & Golluri, 2020; Siradjuddin et al., 2018), Linear Quadratic Regulator (LQR) (Imtiaz et al., 2019; Mohammed & Abdulla, 2020; Orostica et al., 2016), Pole Placement (Imtiaz et al., 2019), Fuzzy (Wu et al., 2012; Wu & Zhang, 2011), etc.

This study is implementing PID control and adding a Kalman Filter technique as a filter for the angle value read by the sensor (Patil et al., 2021). Proportional, Integral, and Derivatives (PID) controllers are known as controllers that use 3 conditions, namely $Kp, Ki \; and \; Kd$ which are called proportional, integral, and derivative constants (Sondhia et al., 2017). Any deficiency and strengthen P, I and Dcontrollers can cover each other by combining them in parallel into a PID controller. $Kp, Ki \; and \; Kd$ in the PID control system have a specific purpose. Proportional control makes the system response stable faster, while integral control can reduce steady-state error, derivative control can reduce overshoot (Mudeng et al., 2020). When the three controllers are combined, it is expected that the system has a small error and a fast time to achieve stability.

The way this system works is that the system continuously reads the angle value and will compare it to the angle setpoint, which is 0° when the robot is standing upright. the difference between the sensor and setpoint will be read as an error which will be processed by the controller to move the robot so that the robot can maintain an angle of 0° / stand upright (Xie et al., 2019). Sensor reading is an important part because the angle sensor is the feedback from this system. Therefore, a Kalman filter was added to eliminate interference with sensor readings (Henryranu Prasetio & Kurniawan, 2018; Xie et al., 2019). The addition of the Kalman Filter, hopefully the system has a robot that can adjust its angle with better performance. Kalman Filter is a method that is widely used to estimate a linear state that has a Gaussian distribution (Taylor et al., 2016). The Kalman filter algorithm has two stages, namely prediction and update (Kim & Bang, 2019). The algorithm of the Kalman filter is described in Figure 1 below:

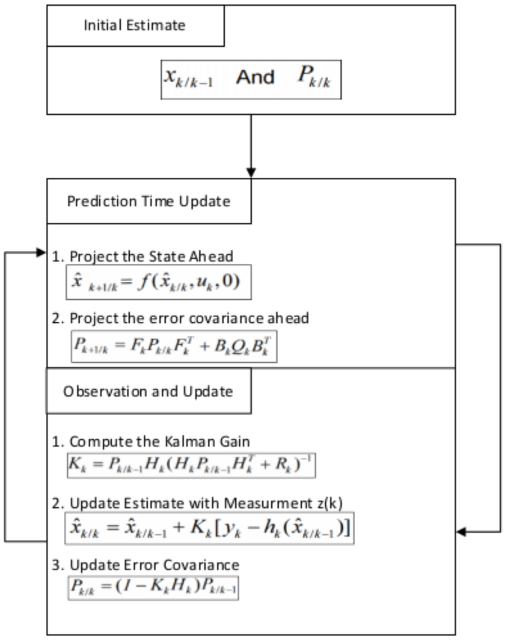


Figure 1 Kalman Filter Algorithm

In addition to sensor readings, another thing to pay attention to is PID tuning to get the appropriate$KP, KI, and\ KD$ values. This study using the Ziegler Nichols tuning method. In this method, experiments are carried out using proportional controllers only. By giving tunning the value of Kp which produces a consistent oscillation graph. This value of the Kp is called the critical gain (Kcr) value. Then from this (Kcr) value, the critical period value (Pcr) is obtained based on consistent oscillations (Jiménez et al., 2020; Paulo Canal et al., 2020). From the values of (Kcr) and (Pcr), it will be used to calculate the PID parameters according to the rules in table 1 below (Sheel & Gupta, 2012):

Table 1 Ziegler Nichols 2 Rules

Controller Type	Kp	Ti	Td
P	$0.5Kcr$		
PI	$0.4Kcr$	$0.8Pcr$	
PID	$0.6Kcr$	$0.5Pcr$	$0.12Pcr$

Research Method

In figure 2 show the phase of this study. The first is planning a system that is made based on several requirements that need to be planned including modeling of robots, robot mechanics, and robot electrical systems. After planning, simulation is carried out to see the response of the system when there is no controller and there is a controller. After seeing the response from the simulation, the next step is to implement a PID controller to the robot and add Kalman to filter from interference with gyro and accelero sensor readings.

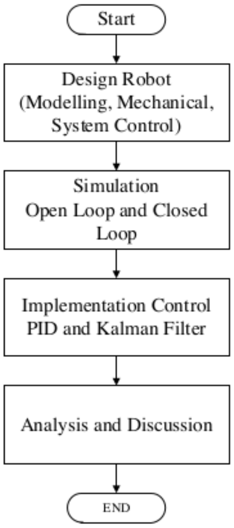


Figure 2 Research Flowchart

The modeling system used in this research is described in the formula below (Jun & Minglun, 2010).

$$\ddot{\theta}_p = \frac{M_p g l(M_p R^2 + 2M_w R^2 + 2I_w)}{(2M_p\, l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2\, l^2 R^2}\theta_p - \frac{M_p I R}{(2M_p\, l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2\, l^2 R^2}(C_R + C_L) \tag{1}$$

$$\ddot{x} = \frac{-2M_p^2\, l^2 R^2 g}{(2M_p\, l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2\, l^2 R^2}\theta_p - \frac{(2M_p\, l^2 R + I_P R)}{(2M_p\, l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2\, l^2 R^2}(C_R + C_L) \tag{2}$$

With the following assumptions

$$X = \begin{bmatrix} x & \dot{x} & \theta_p & \dot{\theta}_p \end{bmatrix}^T$$
$$\dot{X} = \begin{bmatrix} \dot{x} & \ddot{x} & \dot{\theta}_p & \ddot{\theta}_p \end{bmatrix}^T$$

Then the state-space system equation can be expressed as follows

$$\dot{X} = AX + BU$$
$$Y = CX$$

With the following matrix system

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{-2M_p^2 l^2 R^2 g}{(2M_p l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2 l^2 R^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & \frac{M_p g l (M_p R^2 + 2M_w R^2 + 2I_w)}{(2M_p l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2 l^2 R^2} & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ \frac{(2M_p l^2 R + I_P R)}{(2M_p l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2 l^2 R^2} \\ 0 \\ \frac{M_p I R}{(2M_p l^2 + I_P)(M_p R^2 + 2M_w R^2 + 2I_w) - 2M_p^2 l^2 R^2} \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}$$

$$D = [0]$$

In figure 2 shows a block diagram of the system. The MPU6050 sensor reads the gyro meter and accelerometer which will be calculated as angles (R.Q. Zhang et al., 2017). After getting the angle value, the system will eliminate interference when reading the sensor using the Kalman filter. The angle value of the Kalman filter is used as feedback to the microcontroller which will be processed to get the PWM value to drive the motor so that the robot can maintain angle and stand upright (Philip & Golluri, 2020).

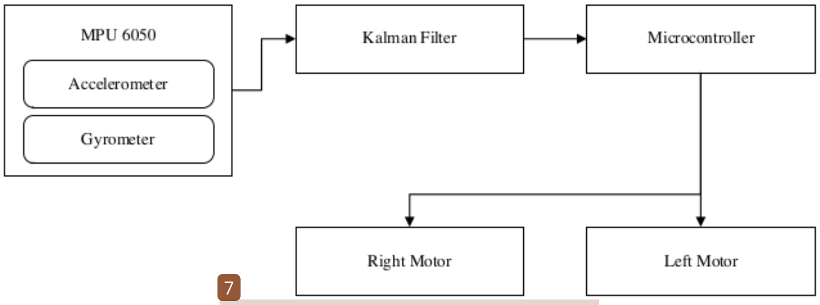
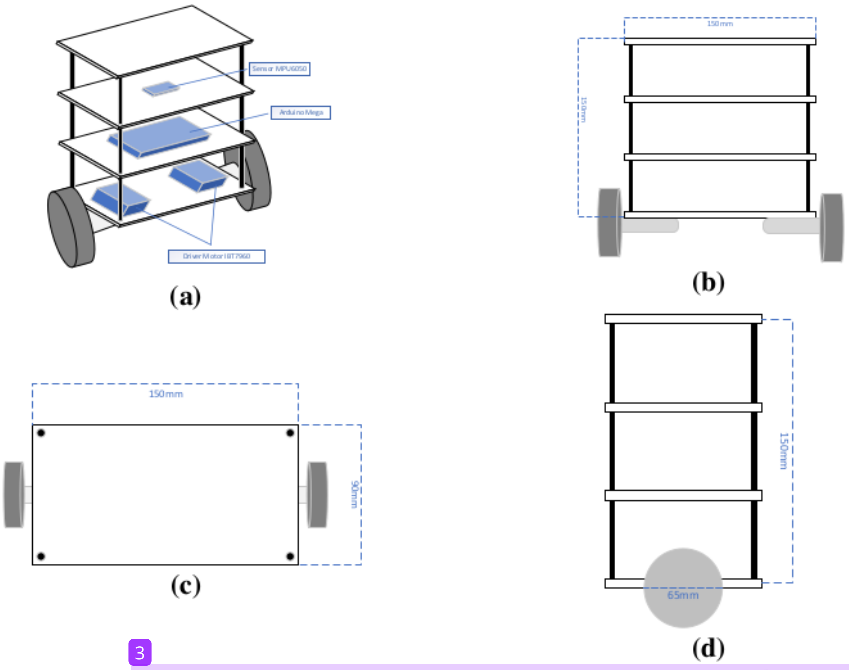


Figure 3 Block Diagram System

Figure 3 shows the mechanical design of the robot. The robot has a size of 15cm x 15cm and 9 cm and a wheel diameter of 6.5 cm. Figure 3(a) shows the isometric design of the robot, Figure 3(b) shows the design of the robot from the front, Figure 3(c) shows the design of the robot from above, and Figure 3(d) shows the design of the robot from the side.



(a) (b) (c) (d)

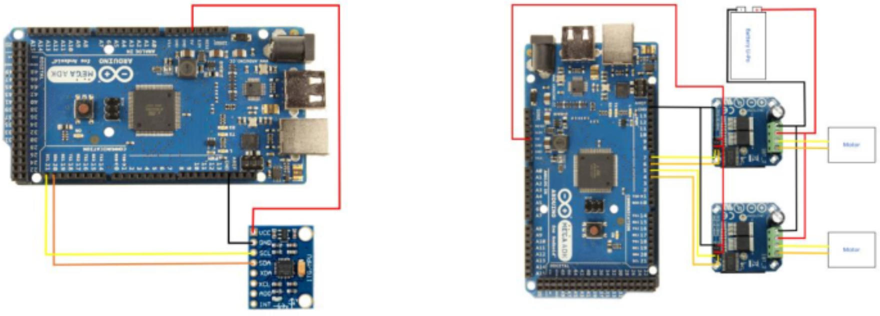
Figure 4(a) Isometric View, (b) Front View, (c) Top View, (d) Side View

From the mechanical design of the robot above, the parameters of the robot are obtained as follows:

Table 2 Robot Parameter

Parameter	Value	Unit	Explanation
g	9.81	m/s	Gravitational acceleration
Mp	0.8	kg	Mass of body
Mw	0.05	kg	Mass of wheel
R	0.065	m	Radius of wheel
l	0.05	m	Distance of wheel to the center of mass
W	0.015	m	Width body
H	0.0145	m	Height body
D	0.09	m	Depth body
Jb	0.013	kgm2	Inertia of body
Jw	0.00015	kgm2	Inertia of wheel

Figure 4(a) shows the MPU6050 sensor wiring. The MPU6050 sensor uses Serial I2C communication. Figure 4(b) shows the wiring between the IBT7960 motor driver to the Arduino. The IBT7960 module has 8 pins. In this system, 6 pins are used, namely Vcc (Power), Gnd (Ground), R_PWM, L_PWM, R_EN, and L_EN. Vcc and Gnd are used to power the module, R_EN and L_EN are connected to Vcc (+5V) from Arduino which is used to activate the IBT7960 module. R_PWM is connected to D6 and L_PWM is connected to D7 which is used for setting PWM as a motor speed controller.



(a) **(b)**

Figure 5 (a) MPU6050 Wiring (b) Driver Motor Wiring

To make the robot can be balanced, a control system is needed. This research using a PID control system and added a Kalman filter to filter out noise that is on the readable angle sensor. As explained in figure 5 below:

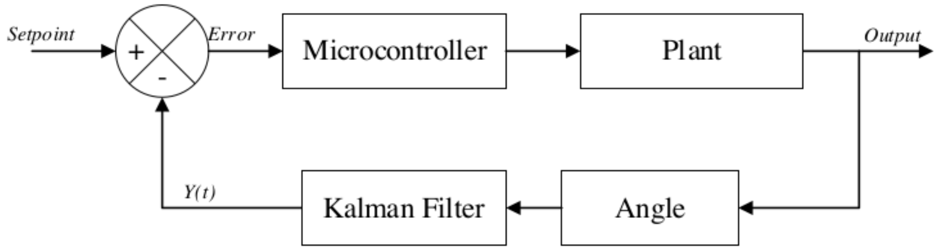


Figure 6 System Control Block Diagram

Results and Discussion

1. Simulation

The simulation was carried out using MATLAB software. Simulations are carried out in an open-loop system and a closed-loop system. From the simulation of the open-loop system, the following results are obtained which indicate that the system is unstable.

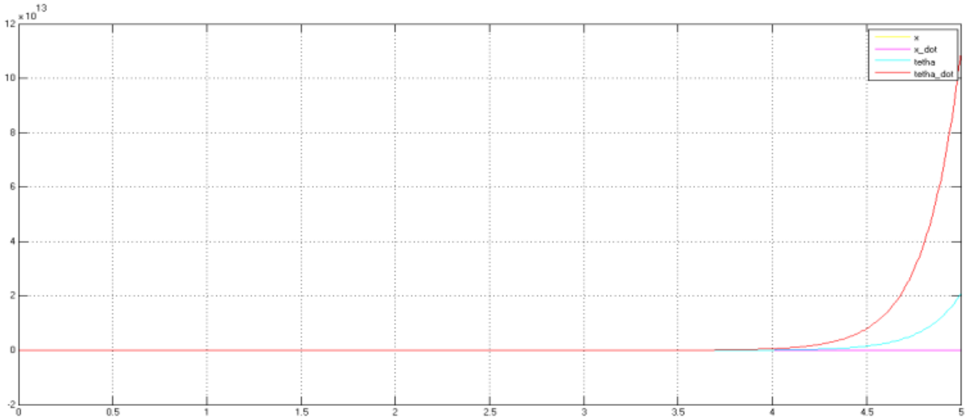


Figure 7 Open-Loop Simulation Result

After simulating an open-loop system, a closed-loop system simulation is performed to see the response of the system when using the controller. To determine the controller parameters (Kp, Ki, Kd) using the Ziegler Nichols method 2. By doing 4 experiments with Kcr values of 20,30,40 and 50 with a simulation circuit as shown in figure 6 below:

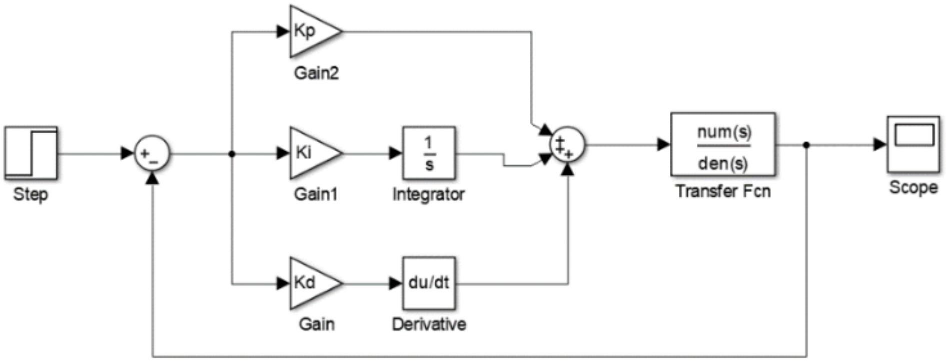


Figure 8 PID Simulation

From the Kcr value above, the PID parameter value will be simulated in the table below:

Table 3 PID parameter value

Kcr	Kp	Ki	Kd
20	12	160	0.225
30	18	276.9	0..292
40	24	400	0.36
50	30	666	0.3375

From the PID parameters obtained, the simulation results are shown below. All parameters can stabilize the robot but isolation occurs when it is run.

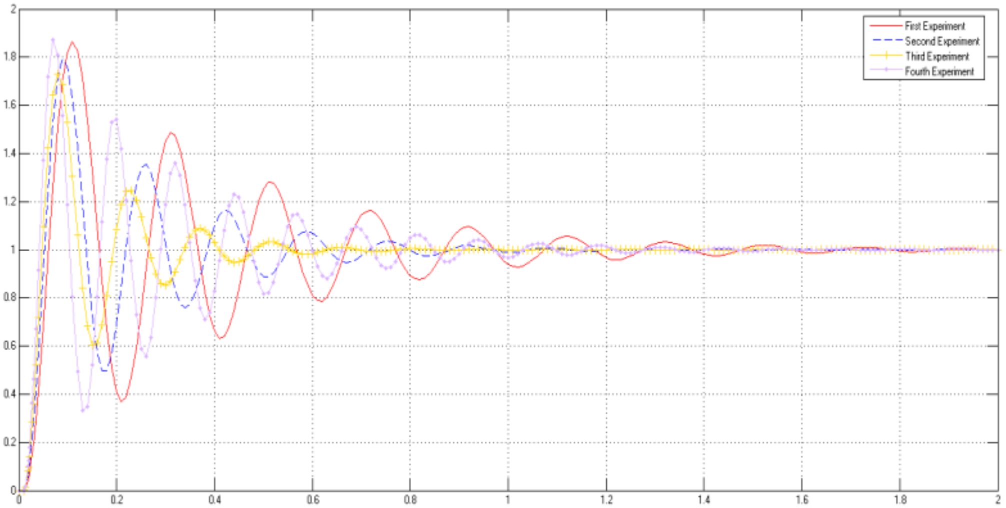
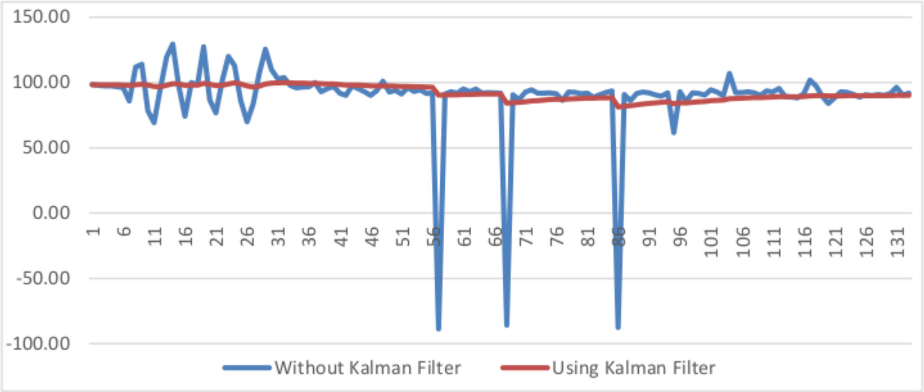


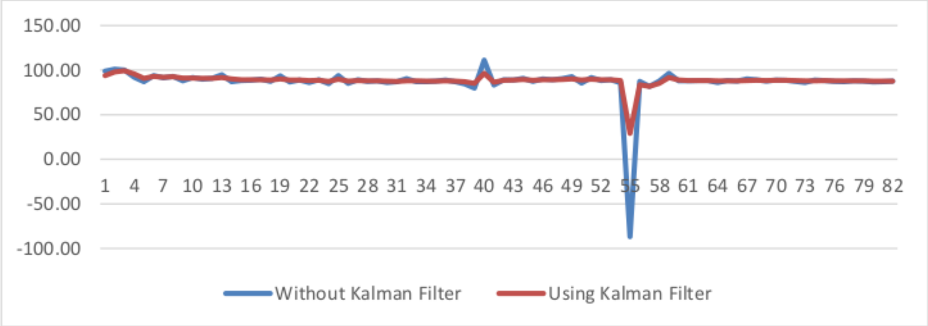
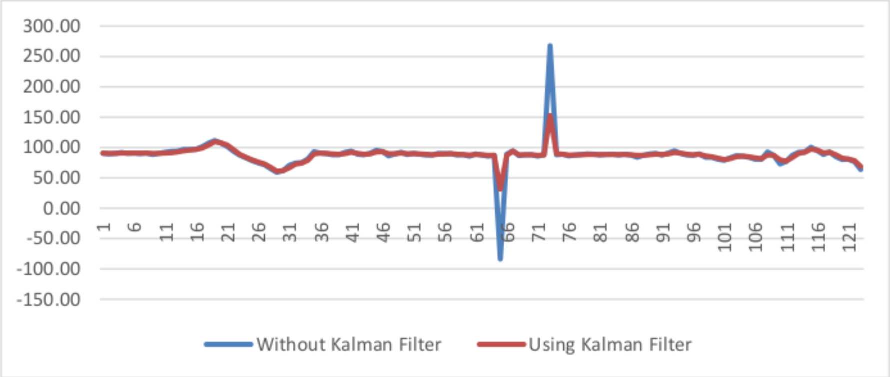
Figure 9 PID Simulation Result

2. Kalman Filter Experiment

This experiment was conducted to see the performance of the Kalman filter in estimating the angle which will be used for feedback to the controller. The experiment was carried out by changing the Q value. Q is process noise covariance. Q value used there were 3 variations, namely 0.01, 0.5, and 1. The results obtained are described in the table below:

Table 4 Result for each Q value in experimental using Kalman Filter

Q	Result
0.01	

0.5	
1	

From the three experiments above, the best filter is obtained using a Q value of 0.01 because the system can reduce noise from angle readings when disturbance/vibration occurs.

3. PID Experiment

The experiment was carried out 4 times with PID parameters in the table below:

Table 5 Experimental with PID parameters

Experimental	Kp	Ki	Kd
First Experiment	8.4	0	0
Second Experiment	8	0	0.0003
Third Experiment	7.7	0	0.001
Fourth Experiment	5.67	85.5	0.0004

From the four experiments, the results are shown in the figure below.

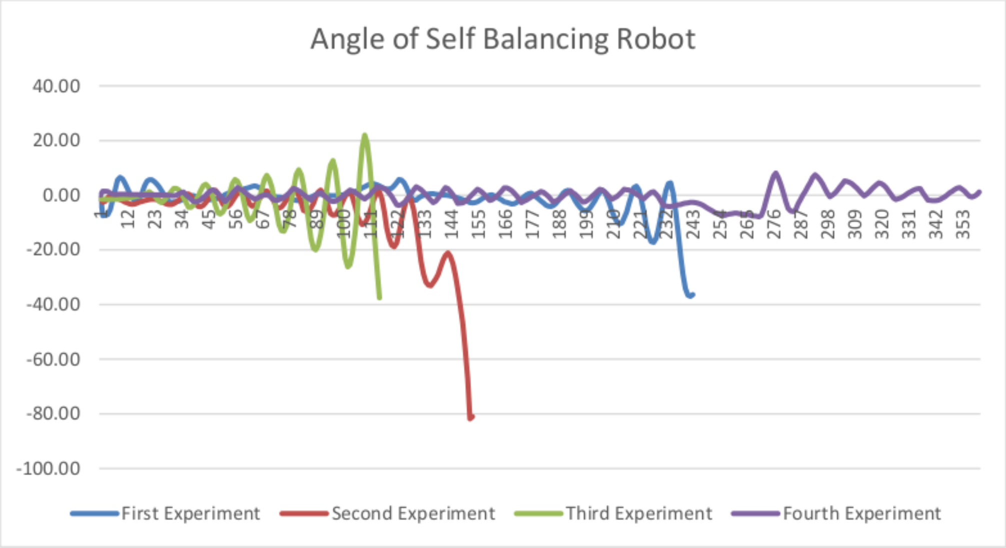


Figure 10 Comparison Result of 4 Experimental using PID parameters

Experiments 1-3 found that the robot was unable to maintain its angle and fell. Due to the incorrect PID parameter value. In the fourth experiment, the robot was able to maintain an angle so that the robot did not fall.

Conclusion

Based on this research, several conclusions can be drawn: 1) the position of the sensor affects the reading of the Y-axis data, then the sensor is placed on the top of a robot that is accurate in reading and easy to do calibration without having to remove the sensor from the robot; 2) the condition of the battery must be fully charged (12V) if the battery is in a weak condition, the voltage entering the motor will decrease which results in slow motor rotation, so that the robot will experience oscillation; 3) based on the tests that have been done, the robot can only survive in the angular range between -3° to 3° with a tolerance of 0.5°, provided that the rotation speed of the robot does not increase. The smallest oscillations with constant movement occur at the values of $Kp = 5.67$, $Ki = 85.5$ and $Kd = 0.0004$. Based on the findings of this research, several suggestions are offered: 1) in this study the simulation of the balancing robot system was carried out by using the Ziegler-Nichols second tuning method so that further PID tuning methods could be used, for example, the Cohen-Coon method or Direct Synthesis; 2) for further development the self-balancing robot can be used for line follower or wall follower applications; 3) the design of the self-balancing robot trainer can be made with a larger size so that it can carry an item on it, but the DC motor used must also have a large torque to maintain its balance.

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References

An, W., & Li, Y. (2013). Simulation and Control of a Two-wheeled Self-balancing Robot. *In IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 456-461. https://doi.org/10.1109/ROBIO.2013.6739501

Prasetio, B.H., & Kurniawan, W. (2018). Disturbance rejection using feed-forward control system on self balancing robot. *In MATEC Web of Conferences*, 154. https://doi.org/10.1051/matecconf/201815403002

Imtiaz, M.A., Naveed, M., Bibi, N., Aziz, S., & Naqvi, S.Z.H. (2019). Control System Design, Analysis Implementation of Two Wheeled Self Balancing Robot (TWSBR). *IEEE 9th Annual Information Technology, Electronics and Mobile Communication Conference, IEMCON 2018*, 431–437.

Jiménez, A., Jiménez, F., & Ruge, I. (2020). Modeling and Control of a Two Wheeled Self-Balancing Robot: a didactic platform for control engineering education. *Proceedings of the 18th LACCEI International Multi-Conference for Engineering, Education, and Technology: Engineering, Integration, And Alliances for A Sustainable Development" "Hemispheric Cooperation for Competitiveness and Prosperity on A Knowledge-Bas*, 1–12. https://doi.org/10.18687/LACCEI2020.1.1.556

Kim, Y., & Bang, H. (2019). Introduction to Kalman Filter and Its Applications. *In Introduction and Implementations of the Kalman Filter*, IntechOpen, 1–16. https://doi.org/10.5772/intechopen.80600

Mohammed, I.K., & Abdulla, A.I. (2020). Balancing a Segway robot using LQR controller based on genetic and bacteria foraging optimization algorithms. *Telkomnika (Telecommunication Computing Electronics and Control)*, *18*(5), 2642–2653. https://doi.org/10.12928/TELKOMNIKA.v18i5.14717

Mudeng, V., Hassanah, B., Priyanto, Y.T.K., & Saputra, O. (2020). Design and Simulation of Two-Wheeled Balancing Mobile Robot with PID Controller. *International Journal of Sustainable Transportation Technology*, *3*(1), 12–19. https://doi.org/10.31427/IJSTT.2020.3.1.3

Oróstica, R., Duarte-Mermoud, M.A., & Jáuregui, C. (2016). Stabilization of inverted pendulum using LQR, PID and fractional order PID controllers: A simulated study. *In IEEE International Conference on Automatica (ICA-ACCA)*, 1-7. https://doi.org/10.1109/ICA-ACCA.2016.7778434

Patil, S., Mantri, S., Bhavsar, D., & Gosavi, S. (2021). Self Balancing Robot. *International Journal of Engineering Research & Technology (IJERT)*, *9*(3), 249–252.

Paulo Canal, I., Reimbold, M.M.P., & Campos, M. De. (2020). Ziegler–Nichols Customization for Quadrotor Attitude Control under Empty and Full Loading Conditions. *Computer Modeling in Engineering & Sciences*, *125*(1), 65–75. https://doi.org/10.32604/cmes.2020.010741

Philip, E., & Golluri, S. (2020). Implementation of an Autonomous Self-Balancing Robot Using Cascaded PID Strategy. *2020 6th International Conference on Control, Automation and Robotics, ICCAR 2020*, 74–79. https://doi.org/10.1109/ICCAR49639.2020.9108049

Sheel, S., & Gupta, O. (2012). New techniques of PID controller tuning of a DC motor—development of a toolbox. *MIT International Journal of Electrical and Instrumentation Engineering*, *2*(2), 65-69.

Siradjuddin, I., Amalia, Z., Setiawan, B., Ronilaya, F., Rohadi, E., Setiawan, A., Rahmad, C., & Adhisuwignjo, S. (2018). Stabilising a cart inverted pendulum with an augmented PID control scheme. *MATEC Web of Conferences*, *197*. https://doi.org/10.1051/matecconf/201819711013

Hegde, S.S., Chakole, S., & Vora, V. (2017). Development of Self Balancing Robot with PID Control. *International Journal of Robotics Research and Development (IJRRD)*, *7*(1), 1-6.

Taylor, L.E., Mirdanies, M., & Saputra, R.P. (2016). Optimized object tracking technique using Kalman filter. *Journal of Mechatronics, Electrical Power, and Vehicular Technology*, *7*(1), 57–66. https://doi.org/10.14203/j.mev.2016.v7.57-66

Wu, J., & Zhang, W. (2011). Design of fuzzy logic controller for two-wheeled self-balancing robot. *Proceedings of the 6th International Forum on Strategic Technology, IFOST 2011*, *2*, 1266–1270. https://doi.org/10.1109/IFOST.2011.6021250

Wu, J., Zhang, W., & Wang, S. (2012). A two-wheeled self-balancing robot with the fuzzy PD control method. *Mathematical Problems in Engineering*, *2012*. https://doi.org/10.1155/2012/469491

Xie, Y.G., Wang, H., Su, H.R., & Lan, J.Y. (2019). Noise Reduction Based on Kalman Filter of Low Precision Gyroscope. *Journal of Computers*, *30*(5), 313-327.

Zhang, B., & Wu, G. (2019). Design of two-wheel self-balancing vehicle based on visual identification. *Eurasip Journal on Image and Video Processing*, *2019*(1). https://doi.org/10.1186/s13640-019-0434-7

Zhang, R.Q., Zhang, L., & Sun, Sh. L. (2017). Stability Analysis and Verification of self-balancing control system. *Proceedings of the 2017 2nd International Conference on Automation, Mechanical Control and Computational Engineering (AMCCE 2017)*, *118*(Amcce), 399–406. https://doi.org/10.2991/amcce-17.2017.70

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