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Design and Control of Self-Balancing Electric Motorcycle with Simulink Auto-Tune Pid Controller

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ABSTRACT

This project describes the design and control of a self-balancing electric motorcycle with a Simulink PID controller. In this system, self-balancing refers to the ability to balance by itself without any assistance from external forces. The self-balancing electric motorcycle should also be able to bounce back after being given external force. This project draws on the theoretical principles of the inverted pendulum. The inverted pendulum system, unlike many other control systems, is inherently unstable. Due to this condition, a controller has to be designed so that the system reaches stability in the unstable state. This project presents motorcycle modeling, designing, and implementing a controller using a PID controller. PID controllers are implemented to minimize error to the least possible value and improve the performance of the controller. The ability to successfully perform self-balancing electric motorcycle is greatly reliant on the proportional gain, (K_P), integral gain (K_I), and derivative gain (K_D) values utilized to control the rotation around the front-to-back axis called roll angle and rotation around the vertical axis is called yaw angle. The objective of this research project is to stabilize the motorcycle at speeds less than 10 km/h. The result of the model is compared and analyzed within various K_P, K_I, and K_D values. The response of the system depends on the values of setting time and overshoot percentage. The simulation results show that the controller cannot balance the robot.

1. Introduction

Through the advancement of science and technology, all industries have recently moved toward an intelligent and automated path. The demand for the logistics industry and people's expectations regarding the quality of their day-to-day lives have continued to rise in tandem with improvements in internet finance and living standards. The traditional logistics industry also relies heavily on the distribution of labor. The majority of people in Asia travel by motorcycle as their primary mode of

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transportation. Due to its energy capacity, compact design, contentment and impressive appearance, it has been highly marketable. It is frequently utilized by the populace of this expanding nation as a low-cost vehicle with improved fuel productivity, and many younger people regard it as an elegant vehicle.

However, the motorcycle lacks safety features and carries a high risk. As a result, motorcycle accidents result in death. A fatality is more likely than an injury to occur. Motorcycle accidents can also be caused by the road infrastructure. Nowadays, motorcycle accident is a common issue that happens in all countries, especially in Malaysia. From the statistics of road injuries and fatalities stated by Abdul Manan *et al.,* [1] in Malaysia, motorcycle fatalities are the highest than car fatalities, pedestrian fatalities, and bus passenger fatalities. In 2021, 7 out of 10 road fatalities in Malaysia were motorcycle users. From an article by Free Malaysia Today [2], it is stated that the fatal rate percentage is increasing from 62.7% to 67.3% in just 6 years.

Therefore, this problem can be solved by adjusting the stability of the motorcycle which can help to reduce the number of motorcycle accidents and also users facilitate. In this project, the self-balancing electric motorcycle (SBEM) is designed and controlled by mathematical modeling and the PID controller in MATLAB Simulink software referring to the paper published [3]. Calculating the roll and steering dynamics can lead to the development of an innovation capable of self-balancing the electric motorcycle. An inverted pendulum will be employed at the motorcycle's wheel-ground axis to ensure that the roll dynamics may be utilized as active stabilization referring to the theory from the paper published [3]. This project used two methods to make sure the SBEM can help reduce motorcycle accidents and also increase the safety of an electric motorcycle system [19].

1.1 Self-Balancing System

A system that is analogous to the traditional mechanical system of an inverted pendulum model is the idea of a self-balancing system [4]. Due to its relative simplicity and instability, it is an intriguing system to control [18].

Many academics around the world have adopted this model as a fundamental idea for controlling the system. The self-balancing motorcycle is not the only thing that makes use of these fundamental regulating mechanisms [21]. However, it is also used to construct a variety of self-balancing systems, including two-wheeled self-balancing robots [22]. These robot systems are operated with the help of the digital signal processor. An accelerometer and motor input sensor-based linear mathematical model controller are put into action in this project to stabilize the system [5].

Lagiman *et al.,* [5] demonstrated that a soft actor-critic controller can effectively address complex control problems, while Bakar *et al.,* [6] showed the use of SARSA and Q-learning reinforcement learning controllers for similar challenges. However, due to the simplicity of the self-balancing controller, a PID controller is often preferred as a solution.

Arpit *et al.,* [7] compared the performance of PID and fuzzy logic controllers for DC motor positional control with various defuzzification algorithms in a recent endeavor. The findings demonstrate that a precisely calibrated PID controller results in less overshoot. In addition, the settling time demonstrates that there is no steady-state error. The controller with fuzzy logic and a new defuzzification method has a shorter settling time and zero overshoot compared to the PID controller.

Meena *et al.,* [8] designed a motor driver controller for a discrete-time system to obtain a frequency response from the PID controller design. Simulink and MATLAB were used by the researcher to verify the effectiveness of this novel design strategy. It provides a straightforward and efficient method for creating a speed controller for servo motors [9].

A scale model of a motorcycle with active balance stabilization will be constructed to test the system, using only the trail length and steering angle as control inputs [10]. The motorbike must be balanced by the control algorithm while it is stationary and moving at low speeds in both the forward and reverse directions. In terms of control, the motorcycle could be described as a multi-input, multi-output (MIMO) system, with the voltages supplied to the drive and steering motors serving as the measure inputs and the steering angle, roll angle, and drive motor angular velocity serving as the measure outputs. A fundamental high-level block diagram of the motorcycle stabilization system is depicted in Figure 1 below.

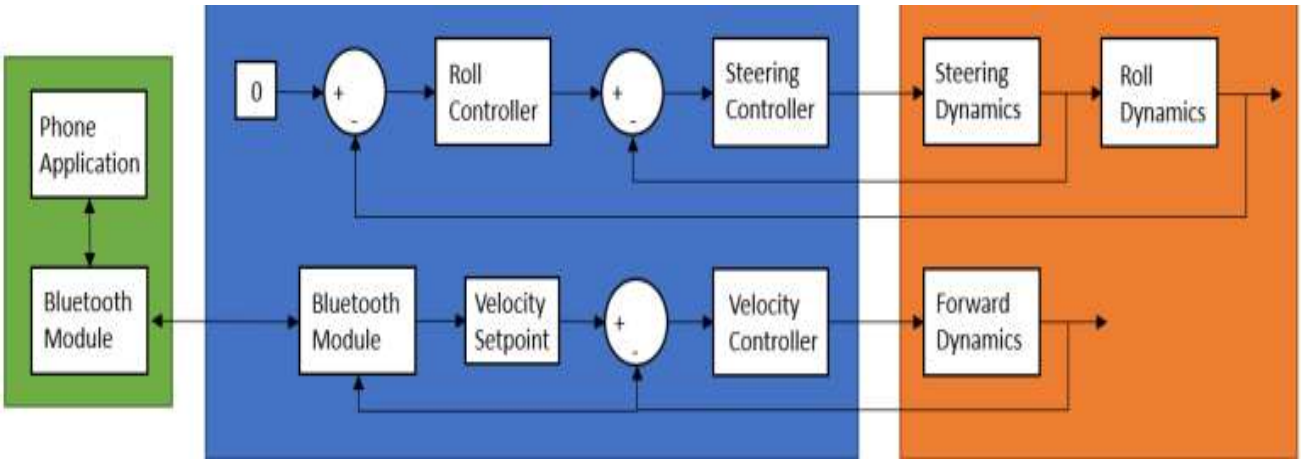

Fig. 1. Motorcycle stabilization system block diagram [3]

1.2 PID Controller

The most common type of feedback is provided by the PID controller. When process control and governors came together in the 1940s, it became the standard instrument. Today, more than 95% of control loops in process control are PID. An essential component of a distributed control system is a PID controller. Additionally, the controllers are incorporated into numerous specialized control systems. To construct the intricate automation systems that are utilized in the production, transportation, and manufacturing of energy, the PID controller is frequently combined with logic, sequential functions, selectors, and simple function blocks [11].

The correct way to adjust the PID value is critical to the self-balancing electric motorcycle's efficiency. The motorcycle will be unbalanced if the PID value is not tuned correctly [12]. According to Nasir *et al.,* [13], the PID controller ought to be improved so that the maximum overshoot for the linear and angular positions does not have a wide range like the design requires.

A PID controller is the control algorithm that is used to keep the self-balancing electric motorcycle running. PID controllers combine proportional, integral, and derivative techniques. These controllers' PI, PD, P or I-only parameters can be used with some control actions. Noise measurement is performed by derivatives, which are never used independently. Due to its drawbacks, it is always used in conjunction with another controller. The self-balancing electric motorcycle will be maintained and stabilized by a feedback controller produced by these combinations. The "error" that is processed by a PID controller is the difference between a measured output and the desired input [14]. The controller will then try to reduce the error as much as possible by adjusting the control parameters. A negative feedback system is another name for the closed-loop control system. demonstrates the fundamental block diagram for the PID controller.

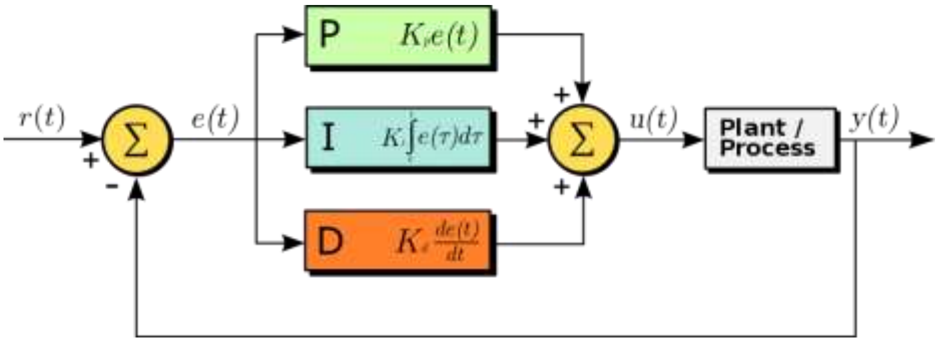

Fig. 2. PID controller block diagram

According to Yuan Chang *et al.,* [15], these days, two-wheel electric motorcycles are very popular in many nations because of their excellent portability and versatility. However, maintaining the bike balance is an important study that hasn't been fully researched in a society that is rapidly getting older. The objectives of the research are to design a self-balancing electric motorcycle using a Simulink PID controller, compare the result of using different K_P, K_I, and $\mathrm{K_D}$ values [16], and propose a controller that can stabilize the motorcycle at 1km/h.

2. Methodology

2.1 Analytical Method

The procedures for obtaining the results of the self-balancing electric motorcycle are broken down into three phases using analytical methods. The three phases are the system-related MATLAB code, the Simulink PID controller block diagram, and an analysis of the electric motorcycle's final state.

Phase I: The Mathematical Modelling Equations

The real motorcycle's mass (m), the wheelbase at zero trail length (b0), the height of the center of mass (h), the trail length (c), and the wheel radius (r) are just a few of the constants used in numerical methods for self-balancing electric motorcycles. In MATLAB Simulink, each of the observed specifications was utilized for mathematical modeling. The self-balancing electric motorcycle's physical parameters, as shown in Table 1 below, are as follows.

Table 1
Specific self-balancing electric motorcycle parameter value [17]

Symbol	Description	Value
m	Mass of the motorcycle	190 kg
a	Horizontal distance from Center of Mass (CoM) to rear axle	0.6 m
		1.1 m
		0.9 m
b0	The wheelbase at zero trail length	0.5236
H	Height of Center of Mass (CoM)	0.5000
λ	Front fork angle	1.5 $\mathrm{kg\ m^2}$
$sin\ \lambda$	Sine of lambda	9.81 $\mathrm{ms^{-2}}$
J_s	Steering mass moment of inertia (kg m^2)	0.3 m
G	Acceleration due to gravity (ms^-2)	0.1 m
R	Radius of wheels (m)	0.75 m^2
c	Trail length (m)	1.2 m
A		

B	Front cross-sectional area	$1.38e^{-4}\ Nms\ rad^{-1}$
B_{md}	Wheelbase	$1.38e^{-4}\ Nms\ rad^{-1}$
B_{ms}	Drive motor viscous friction constant	0.75
C_d	Steering motor viscous friction constant	0.02
C_r	Drag coefficient	76
eta_{gd}	Coefficient of rolling resistance	25
eta_{gs}	Drive motor gearbox efficiency	$0.882\ \mathrm{kg\ m^2}$
J_{md}	Steering motor gearbox efficiency	$0.882\ \mathrm{kg\ m^2}$
J_{ms}	Drive motor moment of inertia	$18.79\ \mathrm{kg\ m^2}$
J_{axle}	Steering motor moment of inertia	$3\ \mathrm{NmA^{-1}}$
K_{md}	Moment of inertia about rear axle	$7.5\ \mathrm{NmA^{-1}}$
K_{ms}	Drive motor machine constant	50 H
L_{ad}	Steering motor machine constant	25 H
L_{as}	Drive motor armature inductance	194
N_{gd}	Steering motor armature inductance	194
N_{gs}	Drive motor gear ratio	1
π_0	Steering motor gear ratio	0
π_1	Integrator in roll angle	60 rad
π_{req}	Integrator in roll angle	8 Ω
R_{ad}	Roll angle setpoint	8 Ω
R_{as}	Drive motor armature resistance	$1.3\ \ \mathrm{kg\ m^{-3}}$
ρ_{air}	Steering motor armature resistance	15 Nm
T_{ld}	Density of air	15 Nm
T_{ls}	Drive motor external load torque	12 Nm
T_{nld}	Steering motor external load torque	12 Nm
T_{nls}	Drive motor external load torque	90 rad
θ	Steering motor external load torque	$80\ \mathrm{ms^{-1}}$
V_{xreq}	The angle of the ground plane	
	Velocity setpoint	

(c) Simulate the parameters involved in a self-balancing electric motorcycle system.

Table 2
Specific value from workspace in MATLAB

Symbol	Description	Value
A_t	$r \times m \times g \times \sin\theta$	499.8961 Nm
		11.1834 Ns
B_t	$r \times C_r \times m \times g$	$0.0065\ (kgm^2)^{-1}$
C_0	$\frac{1}{mh^2}$	$1.6775e^3$ Nm
		42.75 kg m
C_1	$m \times g \times h$	71.25 kg
C_2	m*a*h*(sinλ/b) (kg m)	0.3750
C_3	m*a*c*g*(sinλ/b) (Nm)	$0.1013\ Ns^2\ m^{-1}$
C_4	m*h*(sinλ/b) (kg)	$0.0084\ kg^{-1}\ m^{-1}$
C_5	h*(sinλ/b)	
C_t	$r \times 0.5 \times \rho_{air} \times C_d \times A$	
C_{tv}	$\frac{r}{r^2 \times m + J_{axle}}$	

Phase II: Create the Self-balancing Electric Motorcycle with Simulink PID Controller

(a) Using the mathematical modeling equation, create the self-balancing electric motorcycle's Simulink PID controller block diagram. To design the block diagram, launch the Library Browser.

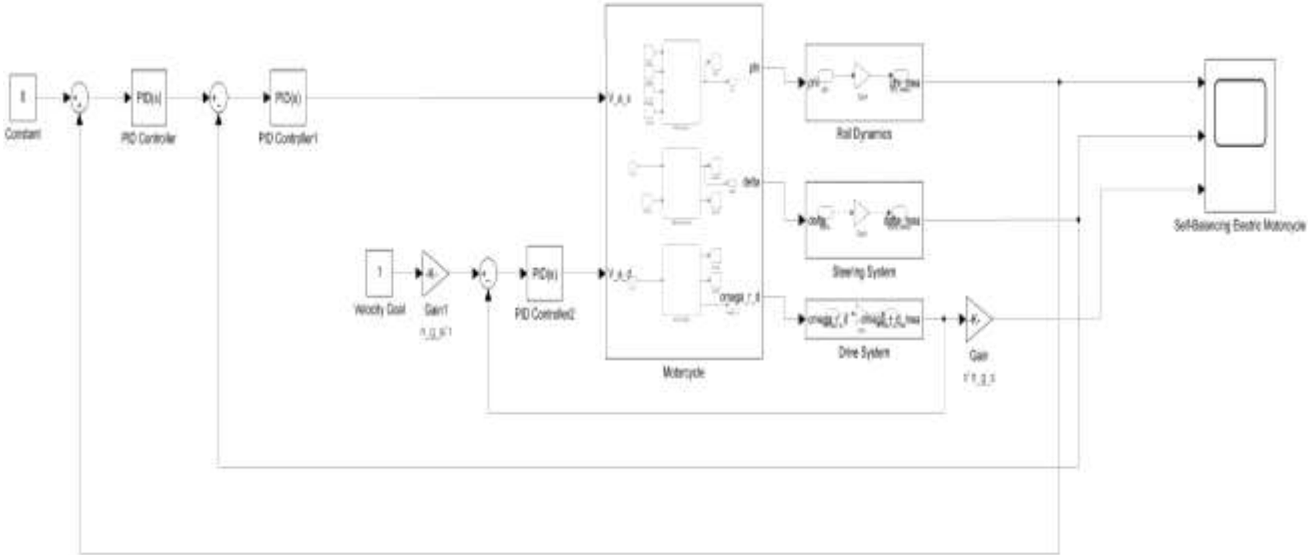

Fig 3. PID controller block diagram for self-balancing electric motorcycle

(b) Insert the parameter value in Table 2 into each block diagram by referring to Table 2.

Phase III: Final State of the Self-Balancing Electric Motorcycle System Analyse

Block diagram simulation and with output dynamic roll system while the input is steering angle and motor velocity from encoder that are shown in Figure 4 below. Auto-tune the PID controllers is used to get the gain value of proportional (P), integral (I), derivative (D) and filter coefficient (N).

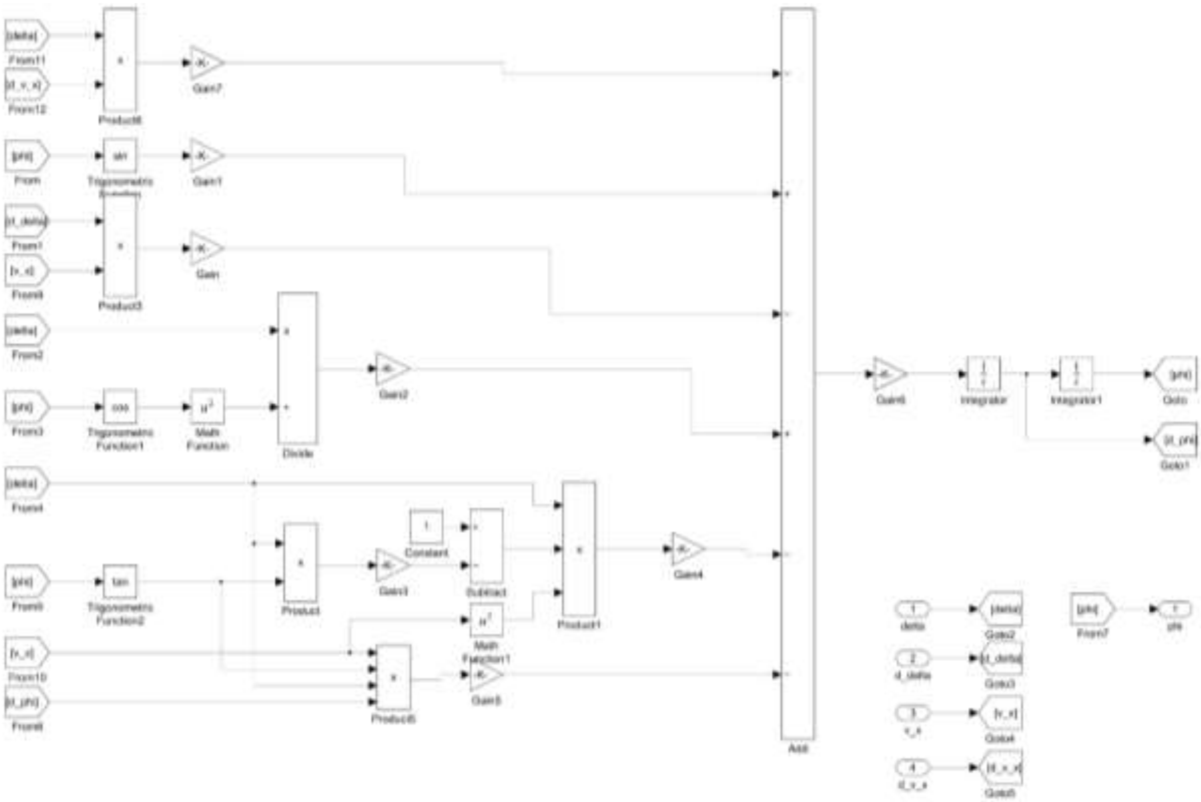

Fig. 4. Roll dynamics block diagram in motorcycle

(c) Analyse the data that is obtained from the PID controller step response and Simulink output result.

3. Results

3.1 Simulation Result

This system was created to control the roll angle and yaw angle of the electric motorcycle. However, the inputs of this system are speed (v), velocity goal (v), roll angle (θ), and steering angle (θ). The velocity goal in this project is 1km/h which means the stabilizing system will activate when the speed is lower than 1km/h. Therefore, the outputs of this system are the velocity goal (v), roll angle (θ) and steering angle (θ). The system output will be considered as the final state after the auto-tune PID controller has generated the K_P, K_I, and $\mathrm{K_D}$ values for each PID controller.

The simulation result for the motorcycle stabilizing and self-balancing electric motorcycle system will be displayed in the scope of the system block diagram. However, the PID controller step response will be displayed when the "tune" button is clicked. All the parameters from the auto-tune PID controller will show. The new parameter will be updated in the block diagram.

3.1.1 Motorcycle Stabilizing System

The motorcycle stabilizing system output results show the roll dynamics, steering dynamics, and drive encoder. Each of the outputs gets a different response by changing the initial condition value of integrators in the roll dynamics block diagram. The 15 times experiments of initial condition value will be compared by the output response and the most stable output response will be the initial condition for this project system.

Table 1 below shows the summaries from all the initial condition experiments. The suitable value for the initial condition of the integrator in the roll dynamics block diagram is "integrator" = -1 and "integrator1" is = -5. It is because the output response becomes most stable that 15 times experiment of different initial conditions with the amplitude at the roll dynamics output response is $4.296e^{173}$, the amplitude at steering dynamics output response is $2.105e^{69}$ and the amplitude at drive encoder output response is $6.479e^{-2}$. Therefore, the value of the initial condition can be used in this system to stabilize the electric motorcycle.

Table 3
Motorcycle stabilizing system summary

No.	Integrator	Integrator1	Roll dynamics	Steering Dynamics	Drive Encoder
1.	0	1	$2.360e^{172}$	$2.792e^{67}$	$6.624e^{-2}$
2.	1	0	$1.676e^{111}$	$8.573e^{37}$	$6.288e^{-2}$
3.	1	1	$6.870e^{125}$	$2.681e^{46}$	$7.024e^{-2}$
4.	1	-1	$3.046e^{121}$	$4.483e^{44}$	$6.374e^{-2}$
5.	0	-1	$2.360e^{172}$	$2.792e^{67}$	$6.591e^{-2}$
6.	-1	1	$3.046e^{121}$	$4.483e^{44}$	$6.411e^{-2}$
7.	-1	0	$1.676e^{111}$	$8.573e^{37}$	$6.502e^{-2}$
8.	-1	-2	$1.783e^{95}$	$5.001e^{32}$	$6.319e^{-2}$
9.	0	-2	$7.307e^{109}$	$4.289e^{37}$	$6.272e^{-2}$
10.	1	-2	$9.812e^{88}$	$1.518e^{30}$	$7.180e^{-2}$
11.	-2	-5	$1.641e^{77}$	$8.870e^{25}$	0
12.	-3	-5	$1.099e^{182}$	$3.345e^{69}$	$2.896e^{-2}$
13.	0	-5	$1.398e^{108}$	$2.708e^{38}$	$7.623e^{-2}$
14.	-1	-5	$4.296e^{173}$	$2.105e^{69}$	$6.479e^{-2}$
15.	-2	-10	$3.175e^{107}$	$8.312e^{37}$	$5.607e^{-2}$

3.1.2 Auto-Tuned PID Controller

Auto-tuned PID controller step response is the automated determined value of K_P, K_I, and K_D. From the step response of the reference track, the transient response of each controller will display when the "Show Parameters" in the "PID TUNER" section clicked. The autotune show different stability result.

(a) First experiment of the auto-tuned PID controller step response

The summary of the transient response that gets from the first experiment is shown in Table 4 below. The first experiment closed-loop for Roll system was not stable while steering system and driver encoder closed-loop control was stable.

Table 4
First experiment PID controller transient response

PID controller 1st auto-tune	Roll system	Steering system	Drive Encoder
$\mathbf{K_P}$	-1184.8606	$3.7547e^{-7}$	41.5613
$\mathbf{K_I}$	-29.2851	$1.2548e^{-12}$	2211.21
$\mathbf{K_D}$	0	0.25732	0.17048
N	100	0.00024469	9139.6149
$\mathbf{t_r}$	648 s	$1.33e^{4}$ s	0.00153 s
$\mathbf{t_s}$	1 s	$1.63e^{5}$ s	0.0318 s
$\mathbf{t_p}$	$1.15e^{3}$ s	1.17 s	1.15 s
$\%\mathbf{M_P}$	0.496%	17%	14.6 %
Closed-loop stability	Unstable	Stable	Stable
Step Response	Critically damped	Underdamped	Underdamped

(b) Second Experiment of the auto-tuned PID controller step response

The summary of the transient response that is obtained from the second experiment is shown in Table 5 below. The second experiment closed-loop for Roll system, steering system and driver encoder closed-loop control was stable.

Table 5
Second experiment PID controller transient response

PID controller 2nd auto-tune	Roll system	Steering system	Drive Encoder
$\mathbf{K_P}$	-206224.31	$1.8085e^{-5}$	41.5613
$\mathbf{K_I}$	-19.1385	$6.8544e^{-10}$	2211.21
$\mathbf{K_D}$	234162795.4681	0.017391	0.17048
N	0.00088069	0.00064807	9139.6149
$\mathbf{t_r}$	$2.44e^{4}$ s	$2.17e^{3}$ s	0.00153 s
ts	$2.05e^{5}$ s	$2.37e^{4}$ s	0.0318 s
$\mathbf{t_p}$	1.13 s	1.17 s	1.15 s
$\%\mathbf{M_P}$	12.9%	17.2%	14.6 %
Closed-loop stability	Stable	Stable	Stable
Step Response	Underdamped	Underdamped	Underdamped

(c) Third Experiment of the auto-tuned PID controller step response

The summary of the transient response that gets from the third experiment is shown in Table 6 below. The third experiment closed-loop for Roll system, steering system and driver encoder closed-loop control was stable.

Table 6
Third experiment PID controller transient response

PID controller 3rd auto-tune	Roll system	Steering system	Drive Encoder
K_P	-119324.9339	$1.4548e^{-5}$	41.5613
K_I	-3.324	$2.9298e^{-10}$	2211.21
K_D	114982074.2	0.0044965	0.17048
N	0.0010378	0.0022301	9139.6149
t_r	$4.56e^3$ s	$6.13e^3$ s	0.00153 s
t_s	$4.37e^4$ s	$5.69e^4$ s	0.0318 s
t_p	1.16 s	1.16 s	1.15 s
$\%M_P$	15.6%	16.4%	14.6 %
Closed-loop stability	Stable	Stable	Stable
Step Response	Underdamped	Underdamped	Underdamped

3.1.3 Self-balancing electric motorcycle system

This section shows the final state of the K_P, K_I, and K_D that can be used in a self-balancing electric motorcycle system referring to article in [19]. Other than that, the transient response and step response from the 3 times experiments are also shown below.

(a) First experiment of the self-balancing electric motorcycle step response

Figure 5 also show the roll angle control, from the result show the motor roll was not stable and continue to swinging while Figure 6 shows steering have no effort to control the roll angle. On the positive side, the motor encoder speed was stable as shown in Figure 7.

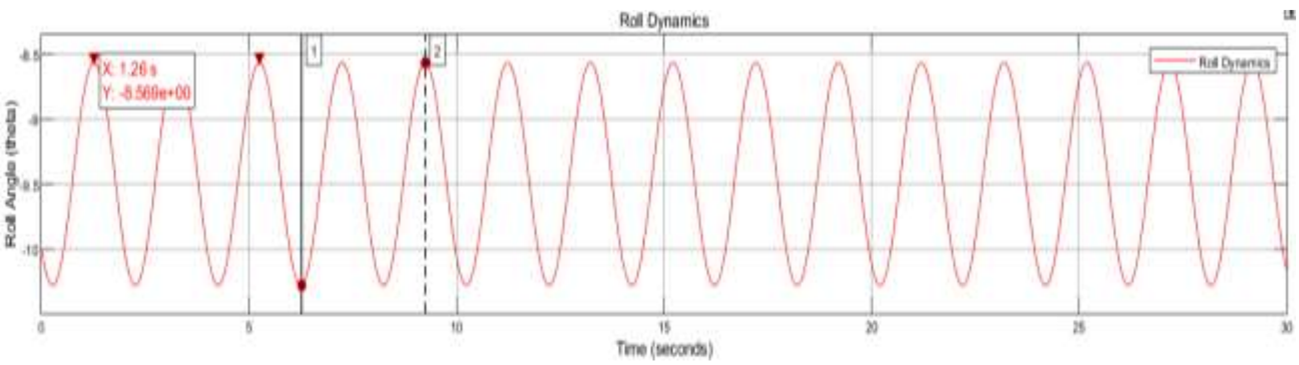

Fig. 5. Roll dynamics final state first experiment for step response

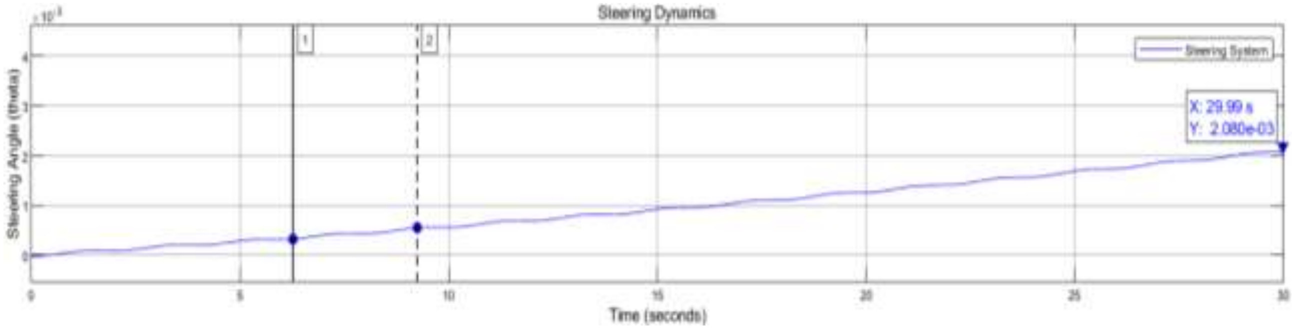

Fig. 6. Steering dynamics final state first experiment for step response

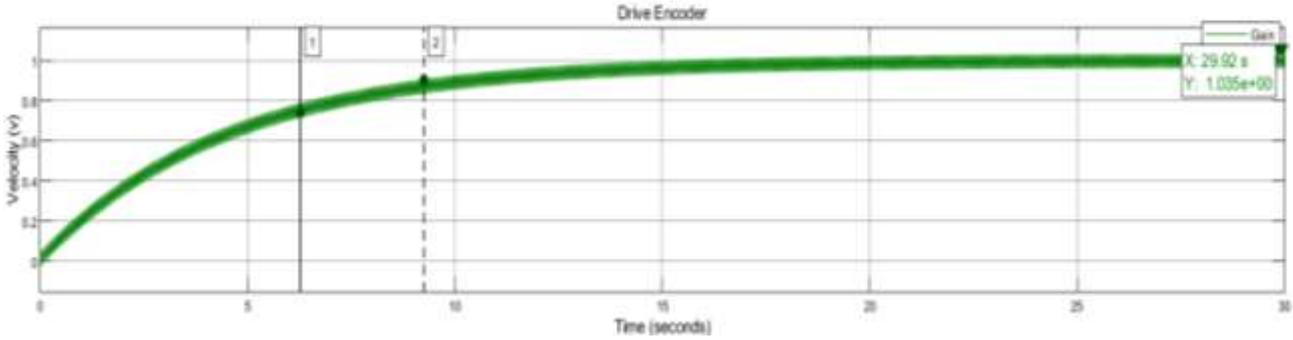

Fig. 7. Drive encoder final state first experiment for step response

(b) Second experiment of the self-balancing electric motorcycle step response

Figure 8 also show the roll angle control, from the result show the motor roll was not stable and continue to swinging while Figure 9 shows steering have no effort to control the roll angle. On the positive side, the motor encoder speed was stable as shown in Figure 10.

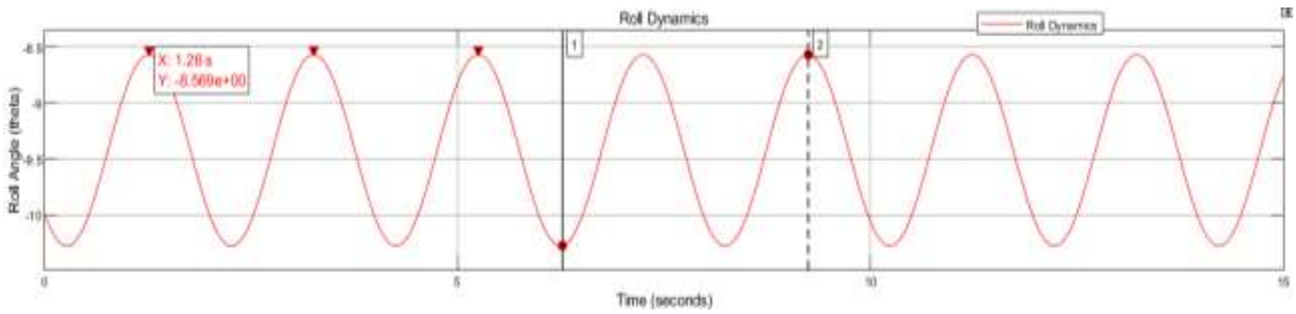

Fig. 8. Roll dynamics final state second experiment for step response

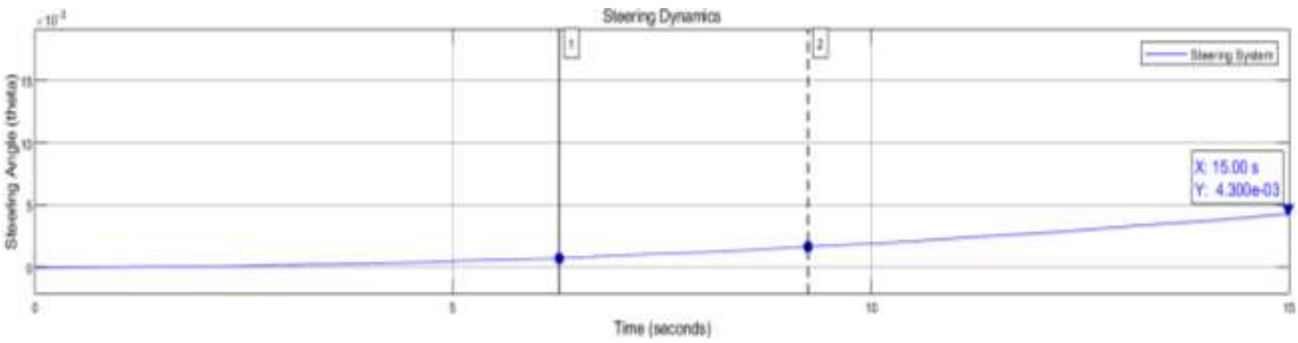

Fig. 9. Roll dynamics final state second experiment for step response

Fig. 10. Drive encoder final state second experiment for step response

(c) Third experiment of the self-balancing electric motorcycle step response

Figure 11 also show the roll angle control, from the result show the motor roll was not stable and continue to swinging while Figure 12 shows steering have no effort to control the roll angle. On the positive side, the motor encoder speed was stable as shown in Figure 13.

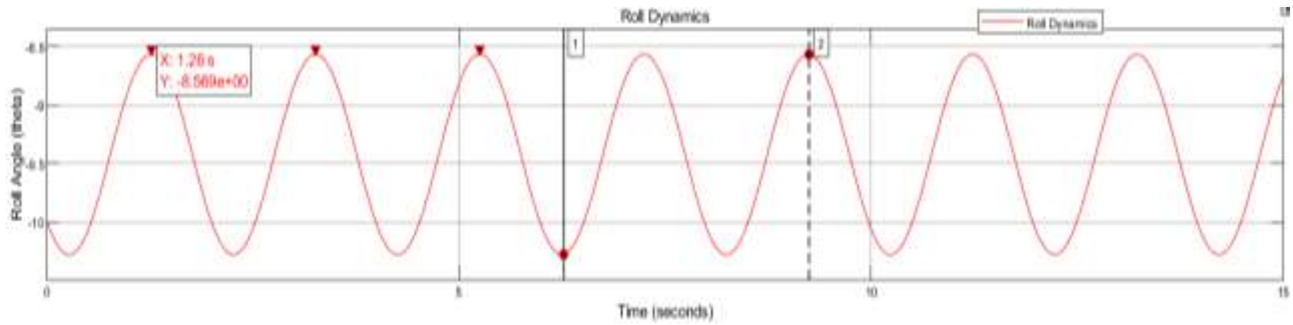

Fig. 11. Roll dynamics final state third experiment for step response

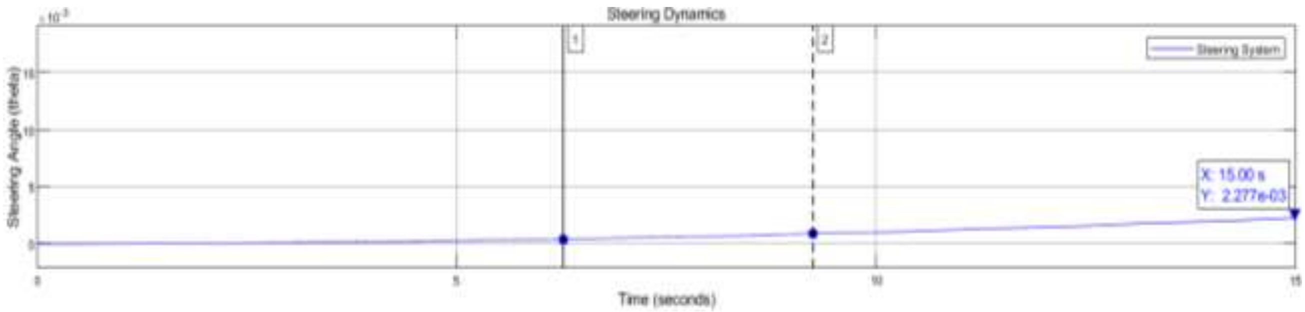

Fig. 12. Steering dynamics final state third experiment for step response

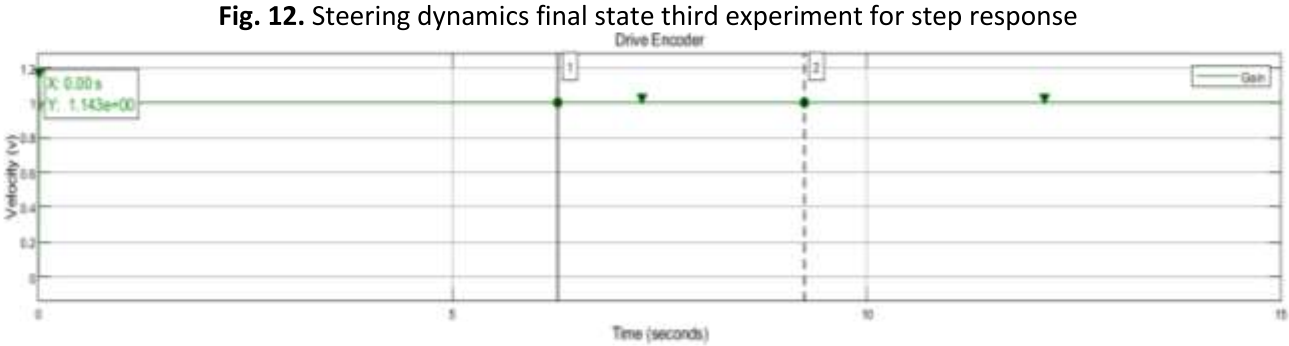

Fig. 13. Drive encoder final state third experiment for step response

Table 7 below shows the summaries from all the auto-tuned PID controller experiments. The output response and transient response of all 3 experiments are almost similar. However, the output response of all 3 times experiments has a similar step response. From all 3 times experiments, the step response of the roll system, steering dynamics, and drive encoder are undamped, overdamped, and critically damped.

Table 7
The final state of transient response for self-balancing electric motorcycle system

Experiment	System	t_r	t_p	$\%M_P$	Step response
1st	Roll	575.221 ms	1.264 s	0.502 %	Undamped
	Steering	0 s	29.993 s	0 %	Overdamped
	Drive	5.749s	29.920 s	14.693 %	Critically damped
2nd	Roll	575.201 ms	1.264 s	0.503 %	Undamped
	Steering	0 s	15.000 s	0 %	Overdamped
	Drive	1.566 ms	0.004 s	14.368 %	Critically damped
3rd	Roll	575.208 ms	1.264 s	0.503 %	Undamped
	Steering	0 s	14.999 s	0 %	Overdamped
	Drive	1.565 ms	0.004 s	14.368 %	Critically damped

4. Conclusions

From the result, the observation was done by doing 3 times experiments by auto-tuning the PID controller. The no suitable value of K_P, K_I, and $\mathrm{K_D}$ was found for the self-balancing system. For the roll system, the K_P, K_I, and $\mathrm{K_D}$ values are -119324.9339, -3.324, and 114982074.1958 with the filter coefficient (N) being 0.0010378. The steering system's K_P, K_I, and $\mathrm{K_D}$ value is $1.4548e^{-5}$, $2.9298e^{-10}$, 0.0044965 with the N being 0.0022301. For the drive encoder, the K_P, K_I, and $\mathrm{K_D}$ values are 41.5613, 2211.21, and 0.17048 with the N being 9139.6149. All the auto-tuned PID controller closed-loop stability was not stable. More sofisticated PID controller is required to stabilize the system successfully.

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