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Osvaldo Gervasi · Beniamino Murgante
Sanjay Misra · Elena Stankova
Carmelo M. Torre · Ana Maria A. C. Rocha
David Taniar · Bernady O. Apduhan
Eufemia Tarantino · Yeonseung Ryu (Eds.)

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Editors: Osvaldo Gervasi, Beniamino Murgante, Sanjay Misra, Elena Stankova, Carmelo M. Torre, Ana Maria A.C. Rocha, David Taniar, Bernady O. Apduhan, Eufemia Tarantino, Yeonseung Ryu

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Apart from the general tracks, ICCSA 2018 also includes 34 international workshops in various areas of computational sciences, ranging from computational science technologies, to specific areas of computational sciences, such as computer graphics and virtual reality.
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Editors and Affiliations

University of Perugia, Perugia, Italy

Osvaldo Gervasi

University of Basilicata, Potenza, Italy
Beniamino Murgante

Covenant University, Ota, Nigeria
Sanjay Misra

Saint Petersburg State University, Saint Petersburg, Russia
Elena Stankova

Polytechnic University of Bari, Bari, Italy
Carmelo M. Torre

University of Minho, Braga, Portugal
Ana Maria A.C. Rocha

Monash University, Clayton, Australia
David Taniar

Kyushu Sangyo University, Fukuoka shi, Japan
Bernady O. Apduhan

Politecnico di Bari, Bari, Italy
Eufemia Tarantino

Myongji University, Yongin, Korea (Republic of)
Yeonseung Ryu

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Modelling and Experimental Analysis Two-Wheeled Self Balance Robot Using PID Controller

Aminu Yahaya Zimit[1,2], Hwa Jen Yap[1], Mukhtar Fatihu Hamza[1,2](✉), Indrazno Siradjuddin[3], Billy Hendrik[4], and Tutut Herawan[3,5,6]

[1] Department of Mechanical Engineering, University of Malaya, Kuala Lumpur, Malaysia
emukhtarfah@gmail.com
[2] Department of Mechatronics Engineering, Bayero University, Kano, Nigeria
[3] Politeknik Negeri Malang, Malang, Indonesia
[4] Universitas Putra Indonesia YPTK, Padang, Sumatera Barat, Indonesia
[5] Universitas Negeri Yogyakarta, Yogyakarta, Indonesia
[6] Universitas Teknologi Yogyakarta, Yogyakarta, Indonesia

Abstract. This research is aimed to design and implement Proportional Integral Derivative (PID) controller on Two-wheeled self-balance (TWSB) robot. The PID is used for the purpose of balancing the robot to stand still at upright position and to receive command via Bluetooth to follow the desired trajectory smoothly. The dynamic model of TWSB robot was developed using Lagrangian method. The PID gains were tuned until the optimum values are achieved. The Arduino based PID-controller was implemented on the TWSB robot in real world experiment. The experimental result shows the effectiveness of the proposed controller for stabilization and trajectory tracking control of TWSB robot.

Keywords: PID · Self-balanced robot · Mathematical model
Trajectory tracking control

1 Introduction

Nowadays, robots are more involved in many ways of human life. They are assigned to do many simple and complicated tasks easier, quicker and more precisely. The rationales behind this improvement in industries is to cut labor cost, achieve high productivity, maintain and improve familiarity among products, and eradicate negative human factors such as laziness, tiredness, absenteeism and so on [1, 2]. Over decades, there has been a rapid development in robotics, as a result of technological advancement in industries, military, health sectors and other ways of life [3]. Many types of materials are being used to develop robots so as to be fit and have the capability to tackle things that cannot be solved or are difficult or risky to be solved by human as a result of their limitations in terms of accuracy, speed, size, sense ability and many more [3]. Two wheeled self-balancing (TWSB) mobile robot is a special type of wheeled mobile robot. Signal processing and control techniques are the main factors in which robot performance and stability rely on [4]. In recent years, researchers found two

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wheeled self-balancing robots to be a good area of research due to its characteristics in terms of non-linearity, instability, having multiple variables, and strong coupling [5]. Main focus of this research project is to develop TWSB robot which is to be controlled by microcontroller based PID-controller to improve its robustness in terms of stability and navigation. The TWSB robot is inherently unstable and non-linear in nature, which makes it difficult to attain wheel stability by using its own mass is difficult [5]. Moreover, it is not easy to establish the reference tracking control system. Many different types of controllers have been proposed to solve the mentioned problems. However, to maintain the stability and at the same time achieve tracking control to follow the desired path remained an open research question. This states the driving force that motivates the present research. Self-balancing and navigation systems are the main focus in designing control system of TWSB robots including: (1) Achieving effective stability; (2) improving speed of response; (3) Maintaining steady state error; and (4) Preventing excessive oscillation, fluctuations, and vibration of the robot.

Many researches were conducted to come up with appropriate mathematical model, and to conduct practical work by developing prototype to improve the TWSV robot efficiency. Thus, this research proposed PID-controller for stabilizing and tracking reference control. The optimum gains of PID controller will be determined so as to achieve better performance. This because the excellent performance of PID controller defends on its gains. Two wheeled commercial human vehicles such as SEGWAY [6], NBot [7], JOE [8] are already in existence. However, high-tech and high quality sophisticated components were used to come up with these final products, making them scarce, costly and unaffordable. This research project seeks to develop a prototype from off-the-shelves components in order to cut down cost and make it available and affordable. The scope of this research is focused on the assembling of TWSB robot and its kinematics mathematical modelling. It also includes designing and running of Arduino-based PID controller on the assembled Robot.

The rest of this paper is organized as follow: Sect. 2 presents related works. Section 3 presents mathematical modelling and simulation. Section 4 presents proposed method. Section 5 presents obtained results and following by discussion. Finally, Sect. 6 concludes this work.

2 Related Works

The TWSV robot is an attractive mechanism made up of base which is referred to as cart, and wheels. It is characterized by rotating and translating on a plane surface, in some cases with a swinging member, in which it is center of mass situated just above its pivot axis and also it passes through the center of the wheel. Such kind of robots are employed as vehicle, e.g. Segway [6], telepresence Double, and also for testing techniques of unstable system as a research platform [9]. The basic idea for a TWSB robot is to drive the bikes, in the direction that the upper part of the robot is getting down. While that robot is moving, it can stay under its center of gravity, then the robot remains balanced [10]. The NBot was built by NASA in 2003, by using commercially available inertial sensor (piezo-electric gyroscope and ADXL202 accelerometer), and view information from the motor encoder to balance the system. The two wheels inverted pendulum models have drawn much attention in the area of control theory and engineering, due to been nonlinear and understated with inherent unstable dynamics [11]. Alternative techniques, including controlled Lagrangians [12], adaptive, and passivity-based techniques [13], are among the popular methods for controlling this under actuated mechanical systems.

The state observer based on adaptive fuzzy controller was proposed by [14], with robust techniques which ensure the asymptotic stability of the system. Fang *et al.* [15] presented fuzzy immune PD-controller for attainting stability of TWSB robot, Experimental results prove that it has higher performance in terms of low overshoot and low settling time than the conventional fuzzy PD-controller. Short *et al.* [16] studied the PID control algorithm for controlling two wheeled robot, by taking tilt angle and speed of the motors as the input parameters, in order to achieve stability and navigation. In conventional models of two wheeled self-balancing robot nonlinear terms are usually ignored, nevertheless it has significant effect on the dynamics of robot. The utilization of using accelerometer and gyroscope to measure tilt angle and fed into Kalman filter is investigated in [17]. The proposed controller is PID. The HC-05 Bluetooth module is used to navigate the robot wirelessly. Tsai and Tsai [18] presented a system using a technique of dividing the system into two subsystems, a rotation and inverted pendulum. Two intelligent adaptive fuzzy wavelet neural network (FWNN) controllers were proposed in achieving the stability, and tacking system. Through simulation FWNN proved to be robust and effective, but there is need for real time experiment to validate that. Goher and Tokhi [19] presented a unique system of two-wheel self-balancing robot with additional degree of freedom in vertical direction for the purpose of supporting things at different heights. Lagrangian method was used to derive the special equation of motion. Results from simulation show that stability can be achieved, but there is need for more improvement. Tsai *et al.* [20] also presents the technique of dividing the entire system into two subsystems, comprising of yaw control and inverted-pendulum. Two-intelligent adaptive fuzzy basis-function network controllers to attain asymptotic stability, achieve tracking and yaw motion control. These were achieved as shown by simulated results, but to validate the technique there is need to develop prototype, and conduct real-time experiment. Jamil *et al.* [21] aimed at developing an efficient controller for attaining asymptotic stability of TWSB robot in real time. Dual PID controller was proposed as a result of its simplicity and robustness. Simulink and Matlab were used for simulation to compare its performance and that of LQR controller and both proved to be capable of achieving stability and rejection of disturbance, with LQR controller having higher performance in position control. It is however difficult and cumbersome to conduct real-time experiment. Wasif *et al.* [22] studied and compared different types of PID-controller on a TWSB robot by simulation. Two-level adaptive PD-controller(tuned) was proposed, which proved to have superior performance than those compared with, including P, PD, PI, PID, 2-level adaptive PD (un-tuned). It has higher performance in terms of stability, low overshoot, and capability to resist opposite forces. All of these reviewed researches, have something in common, either in terms of costly materials used or complicated technology utilized. The present research uses affordable and simpler parts. Also an open-source Arduino program is utilized.

3 Mathematical Modelling and Simulation

The TWSB robot is made up of chassis section and wheels section. The chassis (main body) is attached to the motors, the main structure is simplified to modelling. The free-body diagram of TWSB robot is presented in Fig. 1.

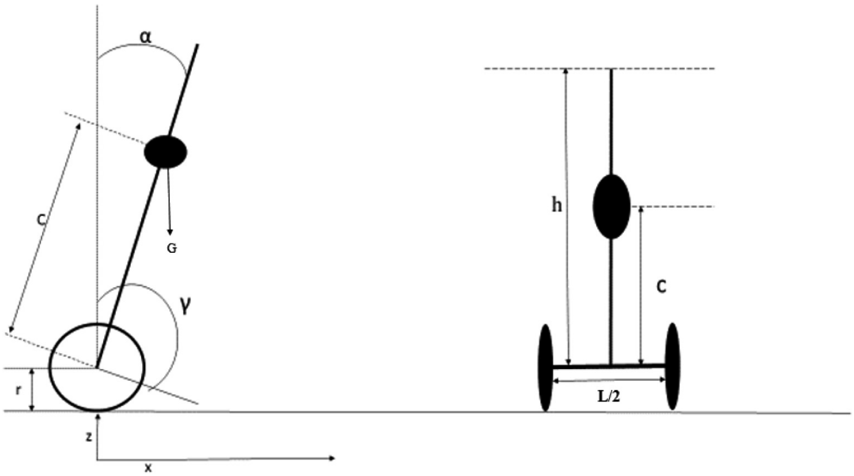

Fig. 1. Free-body diagram of TWSB robot

For ideal modelling of the TWSB robot the following assumptions are considered: (1) The robot chassis and the two wheels are rigid, (2) The left and the right wheels are having the same mass (m) and radius (r), (3) The distance between each wheel to the center of mass are equal ($l_r = l_l = l/2$), (4) There is a true rolling and no slipping during the motion, (5) Internal losses are neglected and (6) Inductance and frictions on the armature are not considered. The TWSB robot is considered to possess three degree of freedom, consisting of yaw angel (γ), tilt angle (α), and transitional motion (x). The two Lagrangian equations are as follows [23]:

$$L = T - V, \tag{1}$$

$$\frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = F, \tag{2}$$

where L is the Lagrangian, T is the kinetic Energy, V is the potential energy, F is the forced function, q_x is the generalized coordinates. This robot has been controlled by two inputs torques applied to the motors produced by voltage.

$$T = T_C^L + T_C^R + T_W^L + T_W^R, \tag{3}$$

where T_C^L is the chassis kinetic energy due to linear displacement, T_C^R is the chassis' kinetic energy due to angular displacement, T_W^L is the wheel kinetic energy due to angular displacement, T_W^R wheel kinetic energy due to linear displacement.

$$T_c^R = \frac{1}{2}\left[I_x\dot{\alpha}^2 + I_y\dot{\gamma}_y^2 \sin\,\alpha^2 + I_z\gamma^2 \cos\,\alpha^2\right] \tag{4}$$

$$T_w^R = \frac{1}{2}Mr^2\left[\dot{\alpha}_r^2 + \dot{\alpha}_l^2\right] + \frac{1}{2}I\left[\dot{\alpha}_r^2 + \dot{\alpha}_l^2\right] \tag{5}$$

and,

$$\alpha_r = x + L\gamma, \alpha_l = x - L\gamma \tag{6}$$

$$\therefore T_w^R = \left(M + \frac{I}{r^2}\right)\left(\dot{x}^2 + L^2\gamma^2\right) \tag{7}$$

$$V = M_c gd\,\cos\,\alpha + M_c gr \tag{8}$$

From Eq. (1), the Lagrangian equation is as follows:

$$L = \left[M + 2M_w + \frac{2I}{r^2}\right]\ddot{x} - \left[Md^2 + \frac{I_x}{r^2}\right]\ddot{\alpha} + \left[\left(M + \frac{I}{r^2}\right)L^2 + \frac{1}{2}(I_z \cos\right.$$
$$\left.\alpha^2 + I_y\,\sin\,\alpha^2 + M_c d\,\sin\,\alpha^2)\right]\dot{\gamma} + M_c d\,\cos\,\alpha\,\dot{x}\dot{\alpha} - [M_c gd\,\cos\,\alpha + M_c gr] \tag{9}$$

For x-coordinate, we have the following equations:

$$\left(\frac{\partial L}{\partial \dot{x}}\right) = \left[M_c + 2M + \frac{2I}{r^2}\right]\dot{x} + M_c d\dot{\alpha}\,\cos\,\alpha \tag{10}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \left[M_c + 2M + \frac{2I}{r^2}\right]\ddot{x} - M_c d\dot{\alpha}^2\,\sin\,\alpha + M_c d\ddot{\alpha}\,\cos\,\alpha \tag{11}$$

$$\frac{\partial L}{\partial x} = 0 \tag{12}$$

$$\therefore \left[M_c + 2M + \frac{2I}{r^2}\right]\ddot{x} - M_c d\dot{\alpha}^2 \sin\,\alpha + M_c d\ddot{\alpha}\,\cos\,\alpha = \frac{\tau_r + \tau_l}{r} \tag{13}$$

$$\ddot{x} = \frac{\left[\frac{\tau_r + \tau_l}{r} - M_c d\ddot{\alpha}\,\cos\,\alpha + M_c d\dot{\alpha}^2 \sin\,\alpha\right]}{\left[M_c + 2M + \frac{2I}{r^2}\right]} \tag{14}$$

For α-coordinate, we have the following equations:

$$\left[M_c d^2 + I_x\right]\ddot{\alpha} + M_c d\ddot{x}\,\cos\,\alpha - \left[M_c d^2 + I_y - I_z\right]\dot{\gamma}^2 - M_c gd\,\sin\,\alpha = -[\tau_r + \tau_l] \tag{15}$$

From Eqs. 11 and 12, for the $\ddot{\alpha}$ can be the subject of the formula as:

$$\begin{aligned}\ddot{\alpha} = &\left[\left(M_c + 2M + \frac{2I}{r^2}\right) + M_c d\,\cos\,\alpha\right][\tau_r + \tau_l]/\{\left[M_c + 2M + \frac{2I}{r^2}\right]\\ &[M_c d^2 + I_x] - M_c^2 d^2\,\cos\,\alpha\} - M_c^2 d^2 \dot{\alpha}^2\,\cos\,\alpha\,\sin\,\alpha/\\ &\{\left[M_c + 2M + \frac{2I}{r^2}\right][M_c d^2 + I_x] - M_c^2 d^2\,\cos\,\alpha\} + [M_c d^2 + I_y - I_z]/\{\left[M_c + 2M + \frac{2I}{r^2}\right]\\ &[M_c d^2 + I_x] - M_c^2 d^2\,\cos\,\alpha\} - M_c gd\,\sin\,\alpha\left(M_c + 2M + \frac{2I}{r^2}\right)/\{\left[M_c + 2M + \frac{2I}{r^2}\right]\\ &[M_c d^2 + I_x] - M_c^2 d^2\,\cos\,\alpha\}\end{aligned} \tag{16}$$

Simplify to get:

$$\begin{aligned}\ddot{\alpha} = &\frac{[M_c d^2 + I_y - I_z][M_c r^2 + 2Mr^2 + 2I]\cos\,\alpha\,\sin\,\alpha}{[M_c rd\,\sin\,\alpha]^2 + ([M_c + 2M]r^2 + 2I)I_x + 2M_c d^2(Mr^2 + I)}\dot{\gamma}^2\\ &- \frac{M_c^2 d^2 r^2\cos\,\alpha\,\sin\,\alpha}{[M_c rd\,\sin\,\alpha]^2 + ([M_c + 2M]r^2 + 2I)I_x + 2M_c d^2(Mr^2 + I)}\dot{\alpha}^2\\ &+ \frac{[M_c r^2 + 2Mr^2 + 2I]M_c gd\,\sin\,\alpha)}{[M_c rd\,\sin\,\alpha]^2 + ([M_c + 2M]r^2 + 2I)I_x + 2M_c d^2(Mr^2 + I)}\\ &- \frac{[M_c r^2 + 2Mr^2 + 2I]M_c dr\,\cos\,\alpha)}{[M_c rd\,\sin\,\alpha]^2 + ([M_c + 2M]r^2 + 2I)I_x + 2M_c d^2(Mr^2 + I)}[\tau_r + \tau_l]\end{aligned} \tag{17}$$

For x coordinate, the Lagrangian from Eq. (9) is as follows:

$$\ddot{\alpha} = \frac{\left[\frac{\tau_r + \tau_l}{r} + M_c d\dot{\alpha}^2\sin\,\alpha - \left[M_c + 2M + \frac{2I}{r^2}\right]\right]\ddot{x}}{M_c d\,\cos\,\alpha} \tag{18}$$

By substituting Eqs. (16) in (12), then it gives Eq. (19) as follow:

$$\begin{aligned}&\left[M_c d^2 + I_x\right]\frac{\left[\frac{\tau_r + \tau_l}{r} + M_c d\dot{\alpha}^2\sin\,\alpha - \left[M_c + 2M + \frac{2I}{r^2}\right]\right]\ddot{x}}{M_c d\,\cos\,\alpha} + M_c d\,\cos\,\alpha\,\ddot{x}\\ &- \left[M_c d^2 + I_y - I_z\right]\cos\,\alpha\,\sin\,\alpha\,\dot{\gamma}^2 - M_c gd\,\sin\,\alpha = -(\tau_r + \tau_l)\end{aligned} \tag{19}$$

Collecting terms with $\ddot{x}$, and making it the subject of the following formula:

$$\ddot{x} = \frac{M_c dr\ \cos\ \alpha[M_c d^2 + l_y - I_z]\cos\ \alpha\ \sin\ \alpha}{[M_c d^2 + I_x][M_c r^2 + 2Mr^2 + 2I] - [M_c dr\ \cos\ \alpha]^2}\dot{\gamma}^2 - \frac{M_c^2 d^2 g r^2 \cos\ \alpha\ \sin\ \alpha}{[M_c d^2 + I_x][M_c r^2 + 2Mr^2 + 2I] - [M_c dr\ \cos\ \alpha]^2} + \frac{r^2[M_c d^2 + I_x]M_c d\ \sin\ \alpha}{[M_c d^2 + I_x][M_c r^2 + 2Mr^2 + 2I] - [M_c dr\ \cos\ \alpha]^2}\dot{\alpha}^2 + \frac{r^2[M_c d^2 + I_x + M_c dr\ \cos\ \alpha]}{[M_c d^2 + I_x][M_c r^2 + 2Mr^2 + 2I] - [M_c dr\ \cos\ \alpha]^2}(\tau_r + \tau_l) \tag{20}$$

For γ-coordinate: The Lagrangian is given in Eq. (21) as follow:

$$\begin{aligned} &\left[2\left(M + \frac{I}{r^2}\right)L^2 + I_y \sin\ \alpha^2 + I_z(\cos\ \alpha)^2 + M_c d^2 \sin\ \alpha\right]\ddot{\gamma} \\ &+ 2\left[\left[M_c d^2 + I_y - I_z\right]\cos\ \alpha\ \sin\ \alpha\right]\dot{\gamma}\dot{\alpha} = \frac{L}{r}(\tau_r + \tau_l) \end{aligned} \tag{21}$$

Simplified further to make $\ddot{\gamma}$ the subject of the following formula:

$$\begin{aligned} \ddot{\gamma} = &\frac{L}{2(r\left[M + \frac{I}{r^2}\right]L^2 + I_y \sin\ \alpha^2 + I_z(\cos\alpha)^2 + M_c d^2 \sin\ \alpha)}(\tau_r + \tau_l) \\ &- \frac{2\left[\left[M_c d^2 + I_y - I_z\right]\cos\ \alpha\ \sin\ \alpha\right]\dot{\gamma}\dot{\alpha}}{2(\left[M + \frac{I}{r^2}\right]L^2 + I_y \sin\ \alpha^2 + I_z(\cos\ \alpha)^2 + M_c d^2 \sin\ \alpha)} \end{aligned} \tag{22}$$

To linearize the non-linear model, it is assumed that the robot conditions are stabilized at the zero tilt angle. For $\alpha = 0$, which implies that $\sin\ \alpha = \alpha, \cos\ \alpha = 1, \dot{\gamma} = 0,$ and $\dot{\alpha} = 0$ [24]. Therefore Eqs. (17), (20), and (22) become:

$$\ddot{x} = \frac{M_c^2 d^2 g r^2}{[M_c d^2 + I_x][M_c r^2 + 2Mr^2 + 2I] - [M_c dr]^2}\alpha + \frac{r(M_c d^2 + I_x + M_c dr)}{[M_c d^2 + I_x][M_c r^2 + 2Mr^2 + 2I] - [M_c dr]^2}(\tau_r + \tau_l) \tag{23}$$

$$\begin{aligned} \ddot{\alpha} = &\frac{[M_c r^2 + 2Mr^2 2I]M_c g d}{[(M_c 2M)r^2 + 2I]I_x + 2M_c d^2(Mr^2 + I)}\alpha \\ &- \frac{[M_c r^2 + 2I] + M_c dr}{[(M_c 2M)r^2 + 2I]I_x + 2M_c d^2(Mr^2 + I)}(\tau_r + \tau_l) \end{aligned} \tag{24}$$

$$\ddot{\gamma} = \frac{L}{r\left(2\left[M + \frac{I}{r^2}\right]L^2 + I_z\right)}(\tau_r - \tau_l) \tag{25}$$

From Eqs. (23), (24), and (25) after substitution of robot parameters, Eqs. (26), (27), and (28) are obtained:

$$\ddot{x} = 0.188\alpha + 3.247(\tau_r + \tau_l) \tag{26}$$

$$\ddot{\alpha} = 5.1\alpha - 70(\tau_r + \tau_l) \tag{27}$$

$$\ddot{\gamma} = 12.85(\tau_r - \tau_l) \tag{28}$$

Where

$$\begin{bmatrix} \dot{x} \\ \dot{\alpha} \\ \dot{\gamma} \\ \ddot{x} \\ \ddot{\alpha} \\ \ddot{\gamma} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0.188 & 0 & 0 & 0 & 0 \\ 0 & 5.1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \alpha \\ \gamma \\ \dot{x} \\ \dot{\alpha} \\ \dot{\gamma} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 3.247 & 3.247 \\ -70 & -70 \\ 12.85 & -12.85 \end{bmatrix} \begin{bmatrix} \tau_r \\ \tau_l \end{bmatrix} \tag{29}$$

These Eqs. (24), (25), and (26) are transformed into state-space form based on the TWSB robot parameters in Table 1.

Table 1. TWSB robot parameters

Parameter	Symbol	Quantity	Unit
Height of the chassis	h	0.08	m
Width of the chassis	w	0.147	m
Distance between wheels	L	0.082	m
Diameter of wheel	d	0.083	m
Mass of the chassis	M_c	0.305	kg
Mass of wheel	M	0.051	kg
Center of mass	C	0.04	m
Acceleration due to gravity	g	9.81	m/s
Moment of inertia of chassis wrt. x-axis	I_x	0.07124 E-3	kgm^2
Moment of inertia of chassis wrt. z-axis	I_z	0.725E-3	kgm^2
Moment of inertia of the wheel	I	0.044E-3	kgm^2

4 Proposed Method

This section presents PID controller methodology for TWSB robot development.

4.1 PID Controller

The main controlling system of the mobile robot adopts PID control. The mobile robot uses sensor feedback data as PID control variable to calculate an output response to do correction and follow the predefined trajectory. The equation of PID controller is as follow [25]:

$$\text{Output} = P + I + D = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t), \tag{30}$$

where P is proportional term which accounts for present error.

$$K_p e(t) = K_p * (\text{setpoint} - \text{input data}) \tag{31}$$

The *I* is an integrate term that accounts the total error history.

$$K_i \int e(t)dt = K_i[(\text{error})_1 + (\text{error})_2 + (\text{error})_3 + \ldots \tag{32}$$

The *D* stands for derivative which accounts for future error through differential/rate changes.

$$\text{Differential error} = K_d * \left[\frac{\partial}{\partial t} error\right], \tag{33}$$

where K_p, K_i and K_d denotes the coefficients of the proportional, integral and derivative terms.

This equation is computed frequently through microcontroller at a very high frequency. Thus several addresses need to be made such as sampling time, derivative error, tuning, reset windup and on/off.

4.2 Methodology for TWSB Robot Development

There are two main electronic systems that were used to conduct this research, first one is the robot itself as an independent unit, sourcing its power from batteries embedded on its chassis, and second unit is an electronic system working also independently for measuring instantaneous coordinates and orientation in terms of degree/second and relative acceleration (g-force), it made up of Arduino Uno, MPU6050 and wiring system, connected directly to the PC. The parts that are procured and assembled to develop the TWSB are as follows: (1) Arduino Leonardo (Microcontroller), (2) MPU6050, (3) HC-60, (4) Arduino Uno, (5) A388, (6) Batteries, (7) Robot chassis, (8) Wheels and (9) Stepper motors. The Arduino Leonardo developed based on ATmega32U4 with hj344 electronic board that has the capabilities to handle routine operations required to achieve controlling and navigation of TWSB robot, processing data, communication between PC, sensors and actuators is used. It contains twenty-three digital Input/output pins for sending and receiving data, a 16 MHz crystal oscillator, a micro USB connection port, a power jack, an ICSP header, and a reset button. It has everything needed for supporting the controller.

The HJ board was used to provide a means for connecting stepper motors, H-bridges, power source, MPU6050, Bluetooth module (HC-06) with the microcontroller. The MPU 6050 used is a special sensor that integrates a MEMS accelerometer and a MEMS gyroscope in a single chip. It has so many advantages like been inexpensive, require low power, and having high efficiency. It incorporates 3-axis accelerometer and a 3-axis gyroscope, together with onboard digital motion processor (DMP), it processes 6-axis motion fusion algorithm. The MPU configuration is described in Fig. 2.

The Accelerometer is used to measure the acceleration relative to the free fall. Gyroscope is used to measure the rate of change of angle around a given axis, with respect to the orientation of world coordinate frame. The orientation of the Gyroscope and Accelerometer is shown in Fig. 3.

Fig. 2. MPU configuration

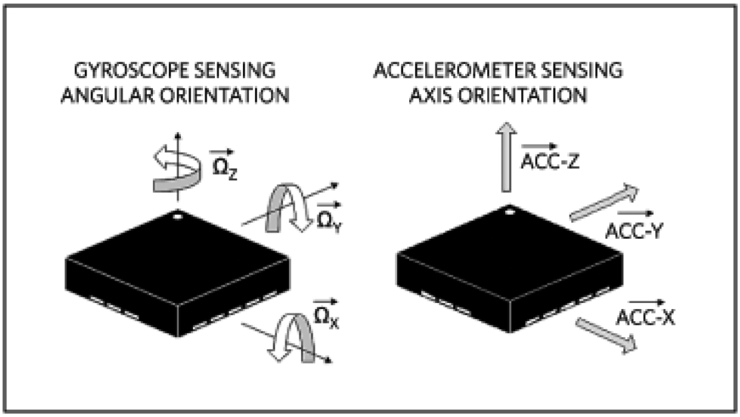

Fig. 3. Gyroscope/Accelerometer orientations

The chassis used is a robot frame made up of metal and plastic, upper part is cuboid in shape, used for mounting all the parts of the robot, consisting of Arduino board, power source (batteries), it also provides support for the mother board on which MPU6050, HC-06, and two H-bridges were mounted. Lower of it serve as a support to left and right stepper motors. The chassis make a robot rigid and one piece. The Nema 17 stepper motor is used to generate the required torque, for achieving stability and navigation, this stepper motor has the characteristics of holding torque of 16Ncm and step angle of 3.75°. The HC-06 is the Bluetooth module used to communicate between android and Arduino Leonardo. It serves as a serial device. Its working independently, but Arduino is the source of power. Pairing take place between Bluetooth module and android only, without Arduino been part of it. Therefore, there may be a scenario where by Bluetooth is connected to the android successful, but may code might not work.

The A0383 is a micro stepper driver is used for controlling the motors in this research project. It has built-in translator which enable motor to be control with just 2 pins from the controller, one pin for controlling the direction and the other for controlling the steps of the motor. The A4988 micro stepping driver gives the following step resolutions, full step, half step, quarter step, eight step, and sixteenth step, it also contains potentiometer for controlling output current, excessive temperature thermal shutdown, and crossover current protection. The picture of the developed TWSB robot is shown in Fig. 4.

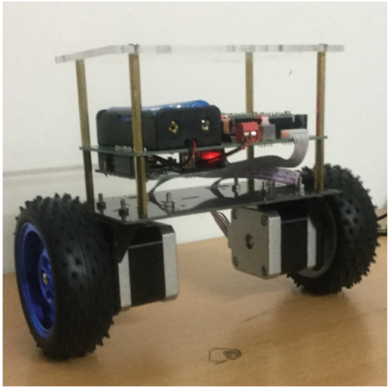

Fig. 4. TWSB robot

5 Results and Discussion

This section presents the experimental results for stabilization and trajectory tracking controls. The experiment is divided into two parts. First part dealt with dynamic stability of the robot, aimed for attaining upright stability. While the second part dealt with navigation at the same time dynamic stability was achieved.

5.1 Stabilization

Optimum set of gains for dynamic stability of TWSB robot were determined here. The K_p and K_d gains play the dominant role in stabilizing the robot [15]. In this contest, at the range of K_d = 20 to 25, and K_p = 0.1 to 0.3, the TWSB robot can dynamically be stabilized with fluctuations, and generating vibration over time.

Both Figs. 5 and 6 show that robot cannot be stabilized with this sets of gains (K_d = 23 and K_p = 0.22, and K_d = 25 and K_p = 0.22 respectively) as there is reciprocating motion on the x-axis, which leads to vibration, and shock on the robot, making it difficult to maintain orientation.

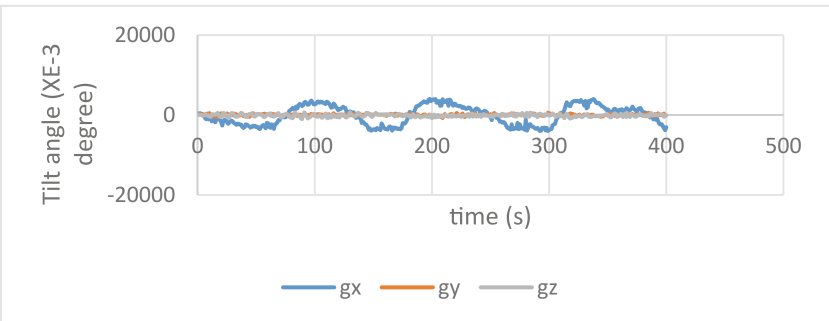

Fig. 5. Gyroscope for K_d = 23 and K_p = 0.22

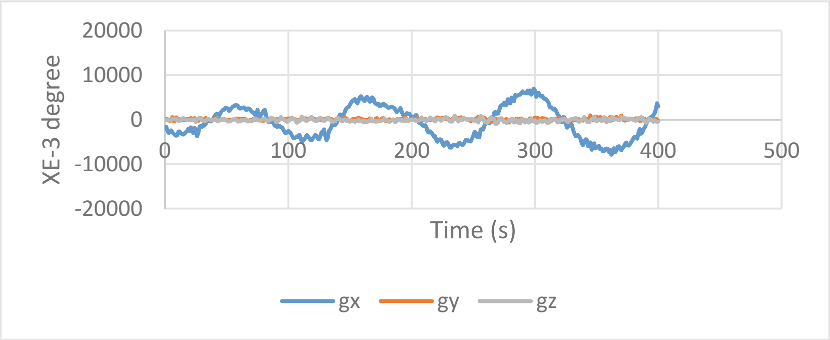

Fig. 6. Gyroscope for K_d = 25 and K_p = 0.22

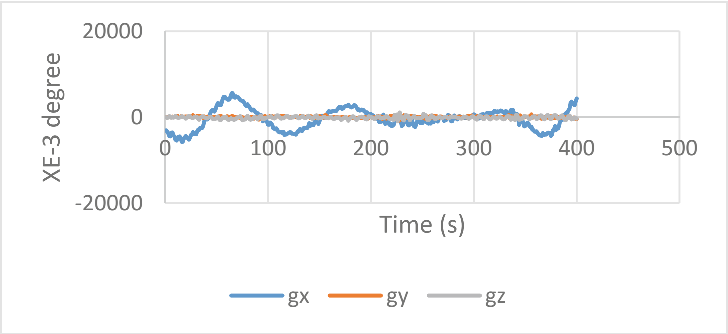

Fig. 7. Gyroscope for K_p= 0.2 and K_d = 24

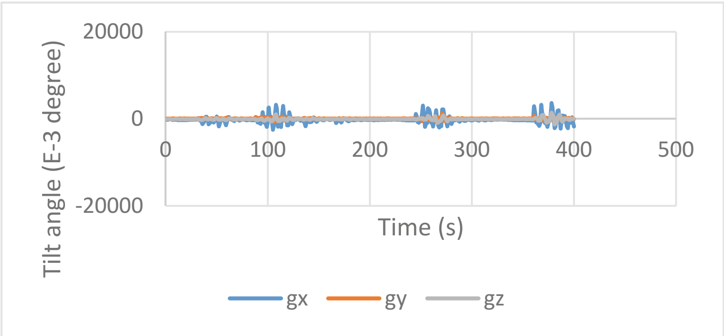

Fig. 8. Gyroscope for K_p= 0.22 and K_d = 24

It had been observed that the TWSB robot is having optimum stabilization behavior at K_d = 24 as shown in Fig. 10. This result has a little vibration, tension, and little oscillation distance to stabilize compared with the results in Figs. 5 and 6. By

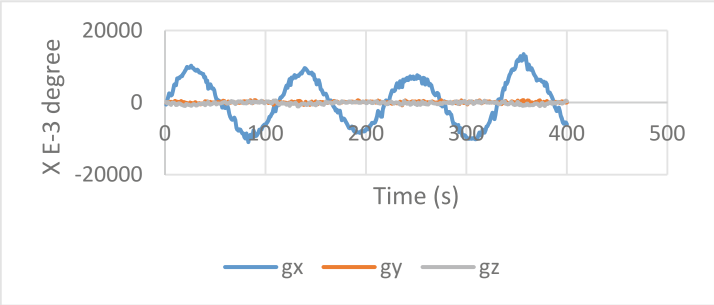

Fig. 9. Gyroscope for K_p= 0.3 and K_d = 24

comparing Figs. 7, 8 and 9 it can be seen that the optimum gains are K_d = 24 and K_p = 0.22, although all the other gains in Figs. 7 and 9 can stabilize the robot with fluctuation in orientation, tension, vibration, and large reciprocating displacement to keep it in upright position. The TWSB robot achieved dynamic stability with smooth navigation and less vibration as shown in Fig. 8. Also it demonstrates some level of robustness by withstanding a small external force (finger tap).

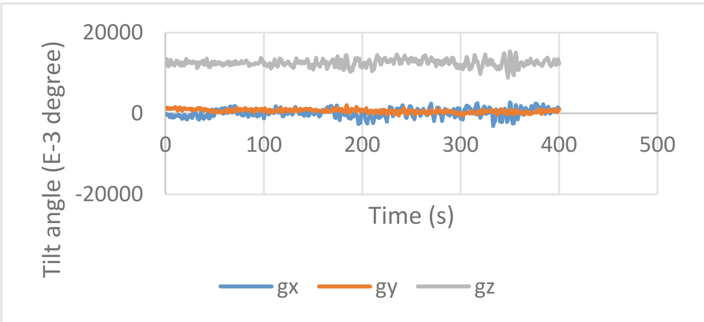

Fig. 10. Gyroscope for turning right

5.2 Navigation

Navigation was successfully run, using the optimum set of gains. The optimum gain values are K_p = 0.22, and K_d = 24 as indicated in Fig. 8. The robot can successfully run without any slipping or skidding of wheels. The three common navigation characteristics that are run are as follows: turning RIGHT, turning LEFT, and running FORWARD.

Figures 10 and 11 show the robot is stable on *z*-axis (at upright position), and *gz* shows the rate at which the robot is turning right and left respectively. Meanwhile there is no change of position along *x* and *y*-axes, which implies there no vibrations and tensions.

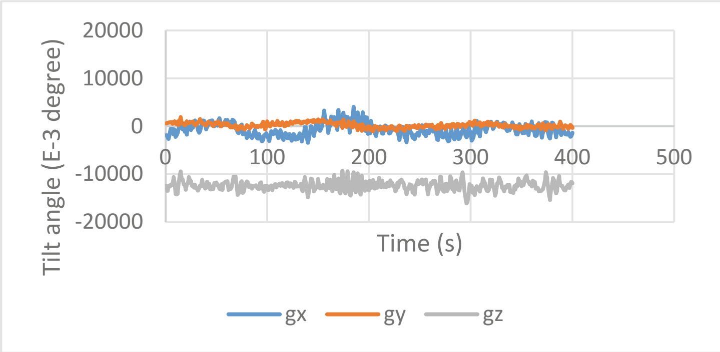

Fig. 11. Gyroscope for turning left

Robot runs forward with reasonable speed, while maintaining upright stability, as shown by Fig. 12. The fluctuation along *x*-axis shows the quantity and nature of its speed. The TWSB robot is speeding up, while balancing the mass on its center, which leads to fluctuation. With these presented results, we believed that developing TWSB robot, using PID-controller, based on Arduino technology is feasible, to cut down cost, and make design flexible.

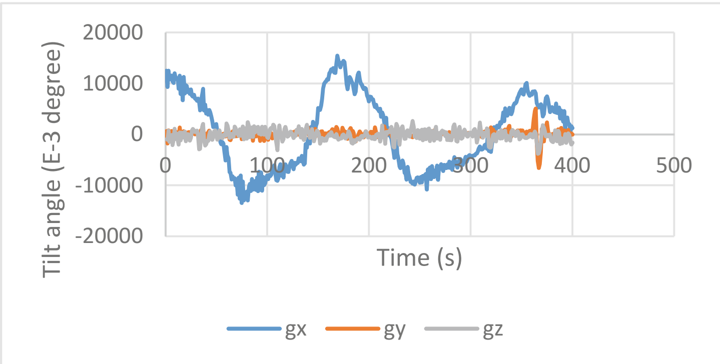

Fig. 12. Gyroscope for forward run

6 Conclusion

This paper has presented a design and implement Proportional Integral Derivative (PID) controller on Two-wheeled self-balance (TWSB) robot. It was illustrated that the TWSB robot that is capable of balancing on its two wheels and can follow desired trajectory is realized. This was done using Arduino, and other off-the-shelves parts to make it affordable, easier for maintenance and improvement. The robot is capable to maintain body's upright stability automatically and follow trajectory tracking path by receiving signal via Bluetooth successfully. The mathematical model was first developed using Lagrangian method. The PID controller was designed and developed in real-time. The importance of manipulating the PID gains to the performance of controller has been shown experimentally.

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