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Robust Navigational Control of a Two-Wheeled Self-Balancing Robot in a Sensed Environment

CELESTINE IWENDI [1], (Senior Member, IEEE), MOHAMMED A. ALQARNI [2], JOSEPH HENRY ANAJEMBA [3], AHMED S. ALFAKEEH [4], ZHIYONG ZHANG [1], (Member, IEEE), ALI KASHIF BASHIR [5], (Senior Member, IEEE)

[1]Department of Electronics, BCC of Central South University of Forestry and Technology, Changsha 410004, China
[2]College of Computer Science and Engineering, University of Jeddah, Jeddah 21959, Saudi Arabia
[3]Department of Communication Engineering, College of Internet of Things, Hohai University, Changzhou Campus, Changzhou 213000, China
[4]Faculty of Computing and Information Technology, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[5]Department of Computing and Mathematics, Manchester Metropolitan University, Manchester M13 9PL, U.K.

Corresponding author: Joseph Henry Anajemba (herinopallazo@ieee.org)

ABSTRACT This research presents an improved mobile inverted pendulum robot called Two-wheeled Self-balancing robot (TWSBR) using a Proportional-Derivative Proportional-Integral (PD-PI) robust control design based on 32-bit microcontroller in a sensed environment (SE). The robot keeps itself balance with two wheels and a PD-PI controller based on the Kalman filter algorithm during the navigation process and is able to stabilize while avoiding acute and dynamic obstacles in the sensed environment. The Proportional (P) control is used to implement turn control for obstacle avoidance in SE with ultrasonic waves. Finally, in a SE, the robot can communicate with any of the Internet of Things (IoT) devices (mobile phone or Personal Computer) which have a Java-based transmission application installed and through Bluetooth technology connectivity for wireless control. The simulation results prove the efficiency of the proposed PD-PI controller in path planning, and balancing challenges of the TWSBR under several environmental disturbances. This shows an improved control system as compared to the existing improved Adaptive Fuzzy Controller.

INDEX TERMS TWSBR, 32-bit Microcontroller, robust control, PD-PI, sensed environment, IoT.

I. INTRODUCTION

In recent years, robots which are an integration technology of multi-disciplinary theory and technology have been widely used in various fields as a new type of production tool. This is because robots show great superiority in reducing labor intensity, improving labor productivity and reducing the dangers of operation. According to [1], robots can be divided into two categories: the first is the operating robot which can manipulate its mechanical arms for the movement of objects and the other is the mobile robot; a walking robot with mechanical legs or wheels. However, the mobile robot has become an important branch in the field of robotics due to its wide prospect of application. Today, amongst different kinds of mobile robots, the robot with wheels is most popular and has become a part of robot research because of its simple structure, low cost and high energy efficiency. Wheeled mobile robots, are a focal point undergoing intense study in research such as how they can be implemented to not only adapt to specific environments and requirements of missions, but also reflect the highly flexible adaptability in the dynamic change of complicated unknown environments. Based on this context, self-balancing two-wheeled robots have emerged [2].

As a new research, the self-balancing two-wheeled robot combines the characteristics of wheeled and autonomous mobile robots, and has advantages that compare with traditional robot technology [3].

Firstly, its turning radius is zero because it can rotate around the center of its body, which can make it flexible in a narrow place. Secondly, the CPU automatically gives positive and negative torque to achieve fast and stable braking, which means its control is extremely convenient. Thirdly, with the continuous development of microelectronics, computer technology, control technology, power technology, drive technology and sensor technology in a SE, the self-balancing two-wheeled robot has been provided a solid theoretical foundation and greatly decreases its development cost.

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Internet of Things (IoT) is considered a communication between the physical and digital spheres. The digital sphere communicates with the physical through a collection of several sensors and actuators. These functionalities are applied to either possibly change the state of an object or query its state. Technically, IoT can be considered as a new kind of phase where virtually all the devices and gadgets that we use are interconnect and controlled, this includes Robots [4].

The IoT devices considered in this paper communicates and are controlled through a Java-based program configured to and interconnects the IoT devices for an efficient Robotic-IoT transmission and control.

Although the PID controller can be well-designed, it still has a low robust ability compared with the robust controller when the system encounters multiple obstacles such as temperature, weather, power surge, and so on in the sensed environment. The major drawback of a PID controller is in the feedback path. Notwithstanding the robustness of the controller, it does not perform efficiently in case of optimal control. Some other drawbacks associated with the controller's linear system and derivative part is noise sensitivity. The PID is highly noise sensitive that any amount of noise in the operating sensed environment can cause great alteration in the navigation output. However, in this paper, balancing of the TWSBR is optimal. We established the dynamic model, through Lagrangian Equation and considering Newton's Second Law in three-dimensional coordinate system. By analyzing the relationship between forces and motors' voltage through a series of mathematical derivations in X-O-Y and X-O-Z coordinate system as shown in Figures 1 and 2. Practical experiments as to show the speed, angular and turn controls is performed and the result prove that with the PD-PI controller, the robot can navigate a sensed environment, with maximum noise resistance, and retained balance for a given period.

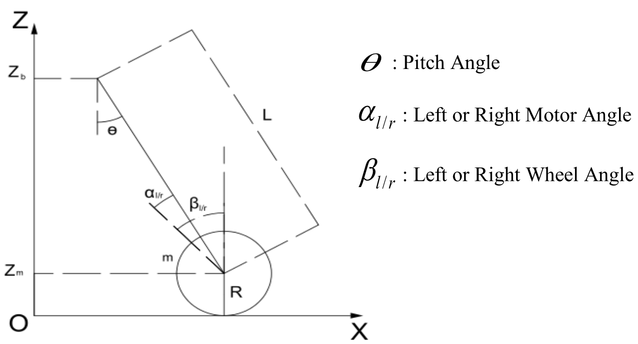

FIGURE 1. XOZ modeling.

The result of the experiment on the avoidance mechanism shows the efficiency of the PD-PI controlled TWSBR with Kalman Filter Algorithm with minimal Integral Square Error (ISE) as against the compared Improved Adaptive Fussy Control (AFC) and other existing algorithms.

This paper is organized as follows: the first part I is the introduction and is the section where Robotic Technology,

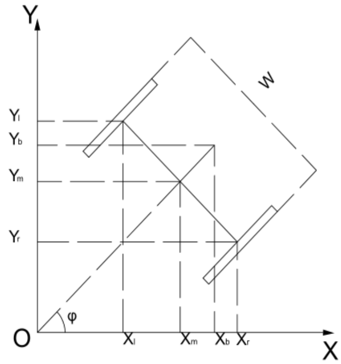

FIGURE 2. XOY modeling.

Self-balancing, Sensed Environment and IoT were briefly discussed; the section II makes a quick description of the related works with respect to self-balancing and robotic control, section III describes the method and evaluation of derived mathematical operations and models. Simulations showing the experimental implementations of the method, and a Java code responsible for Robotic-IoT controls and communications were analyzed in section IV. The performance evaluation of the proposed technique compared with a selected algorithm (Adaptive Fussy Control Algorithm) is analyzed in section V. Conclusions and proposals for future works are presented VI and VII sections respectively.

II. RELATED WORKS

It is critical for this project that several related researches as conducted on undertaking control and design of the robot before be reviewed because some information regarding the technologies and methodologies available were provided by many researchers around the world. Therefore, this section presents a condensed summary of related works which link with the self-balancing two-wheeled robot. An intelligent system uses an adaptation fuzzy controller using Mamdani algorithm modified by relation models for a two wheeled self-balancing robot was developed by Mai et al [5]. The proposed system that is considered differs, [6] uses the adaptive fuzzy controller for stability of the robot and allows a more control to be implemented. Their proposed adaptation fuzzy controller was not optimized based on the analysis of dynamic characteristics as shown in [7] to improve the performance of the robot. Karam et al in [8] modified the Integral Sliding mode controller based on Neural Network and Optimization. The work designed an intelligent non-linear Modified Integral Sliding Mode Controller (MISMC) based on simple Adaline neural network for balancing a two-wheeled self-balancing mobile robot and tried to improve the performance of their robot in tracking the desired trajectory. They used their simulation results to show the efficiency of the proposed controller (MISMC with MCS) in handling the tracking and balancing problems under uncertainties which gave a high response speed. The authors in [9] proposed a heuristic function algorithm to improve the efficiency of the path-planning of two-wheeled self-balancing vehicle and a dynamic weighting method for the evaluation function.

The path planning algorithm has many advantages according to the author, such as short time-consuming, higher search efficiency, better smoothness and shorter path. A two-wheeled robot is an unstable system such that a control system is required to stabilize it [10]. Therefore, the authors in [11] presented a control design for two-wheeled robot (TWR) stabilization using linear quadratic regulator (LQR) method and states estimation. The authors in [12] shows that wheeled inverted pendulum robots have advantages over the common automated guided vehicles; they have high maneuverability on flat surfaces, and they have a self-balancing system such that height and weight of the payload do not have effect on the base size.

The author in [13] investigates the trajectory tracking control problem of wheeled mobile robots by firstly using analytic B-spline function commonly used to generate a smooth feasible trajectory between the initial and the desired configurations. The reason is to allow the motion path to pass through the desired intermediate points and satisfies the kinematic constraints and curvature restrictions. The author was able to enhance the robot tracking performance with an assurance that the error convergence, the robust adaptation laws for the FCMAC and compensated controller were derived from the stability analysis. The research in [14] is slightly different from ours, however, it reveals the development of radio-frequency identification system and voice broadcast system on a wheeled mobile robot. The main research purpose was to establish a wheeled mobile robot on a working platform of the blind guide system and to assimilate the progressively sophisticated radio frequency identification (RFID) system and voice broadcast mechanism to read the concealed messages in the guide bricks or the Braille in public places. In the system, a CMOS image sensor is used to detect two markings on the guide brick and to achieve the goal design of the guide blind robots.

The goal of [15] was to develop a controlled robot that can move with only two wheels. They elaborately discussed the design and evaluation of a robotic chassis through the application of Lego Mindstorm NXT [16], and to be controlled by the AVR ATMega16 microcontroller. Their experiment shows that a robot chassis must address stability and mechanical issues. [17] invented a famous balancing robot called Segway, which can keep its balance with someone's standing on its platform. It uses brushless DC electric motors in the wheels powered by lithium-ion batteries with encoders and gyroscopic sensors to check the pitch in order to be upright. JOE is a self-balancing robot based on the inverted pendulum which was designed by the Industrial Electronics Laboratory at the Swiss Federal Institute of Technology. It was controlled by a Digital Signal Processor (DSP) IC and used the feedback of a controller. When running, the maximum of speeds reaches 1.5m/s. The paper called 'Two-wheel self-balanced car based on Kalman filtering and PID algorithm' presented by [18] and [19] shows that a low-cost acceleration ADXL335 and angular velocity sensor ISZ-650 were used as sensors and Kalman filtering and PID algorithm were used as algorithms to implement the balance of the car with two wheels. This research provided some theories of algorithms for the two-wheel self-balanced technique. Some experimental Data was provided for the two-wheel self-balanced robot from a paper named Two Wheel Self-Balanced Mobile Robot Identification based on Experimental Data. Also, in [19], two phases of system identification process were applied to implement dynamic equilibrium of the robot. [20] presented details on how to overcome the limitations of 'Weiner-Hopf' Filter in solving problems of statistical nature which seriously curtailed practical usefulness. The process is named as Kalman Filtering, which is powerful because it can estimate the past, present and future states. Several researchers have studied the application of Kalman Filtering in solving related robotic balancing problems, around the world. The authors in [1], and [21] provide research on how to use the Kalman Filtering to solve the problems of the self-balancing two-wheeled robot control.

III. METHOD AND EVALUATION

A. MODELING

In this section, the mathematical modeling according to [22] and [23], is established before analyzing the relationship between forces and motors' voltage through a series of mathematical derivations in X-O-Y and X-O-Z coordinate system.

1) MATHEMATICAL MODELING

The Figure 1 and Figure 2 present the mathematical modeling in different coordinate system.

2) MATHEMATICAL DERIVATION

The main idea of mathematical derivations [24] is based on the Lagrangian Equation and Newton's Second Law in three-dimensional coordinate system. Meanwhile, assume $t = 0$ as a precondition. The mathematical derivations are shown as following. At first, we used cylindrical coordinate to establish mathematical relationship since wheels are cylindrical.

$$(X_m, Y_m, Z_m) = (R\beta \cos\varphi, R\beta \sin\varphi, R) \tag{1}$$

where

$$(\beta, \varphi) = \left(\frac{1}{2}(\beta_l + \beta_r), -\frac{R}{W}(\beta_l - \beta_r)\right) \tag{2}$$

$$(X_l, Y_l, Z_l) = (X_m - \frac{W}{2}\sin\varphi, Y_m + \frac{W}{2}\cos\varphi, Z_m) \tag{3}$$

$$(X_r, Y_r, Z_r) = (X_m + \frac{W}{2}\sin\varphi, Y_m - \frac{W}{2}\cos\varphi, Z_m) \tag{4}$$

$(X_b, Y_b, Z_b) = (X_m + L\sin\theta\cos\varphi, Y_m + L\sin\theta\sin\varphi, Z_m + L\cos\theta)$ The translational kinetic energy T_1, rotational energy T_2, and the potential energy U are derived as:

$$T_1 = \frac{1}{2}(\dot{X}_l^2 + \dot{Y}_l^2 + \dot{Z}_l^2) + \frac{1}{2}m(\dot{X}_r^2, \dot{Y}_r^2, \dot{Z}_r^2) + \frac{1}{2}M(\dot{X}_b^2 + \dot{Y}_b^2 + \dot{Z}_b^2) \tag{5}$$

$$T_2 = \frac{1}{2}J_w\dot{\beta}_l^2 + \frac{1}{2}J_w\dot{\beta}_r^2 + \frac{1}{2}J_\varphi\dot{\theta}^2 + \frac{1}{2}J_\varphi\dot{\theta}^2 + \frac{1}{2}J_m n^2(\dot{\alpha})_l - \dot{\theta}\,2 + \frac{1}{2}J_m n^2(\dot{\alpha})_r - \dot{\theta}\,2 \quad (6)$$

$$U = mgZ_l + mgZ_r + mgZ_b \quad (7)$$

Considering the combination of kinetic and potential energy, $L = T - V$ is considered the Lagrangian Equation. The equation is given through the following the Lagrangian equation.

$$L = T_1 + T_2 - U \quad (8)$$

According to the Newton's Second Law, $F = ma$. Combining the Lagrangian equation and Newton's Second Law, the equation of motion is derived as:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial x}\right) - \left(\frac{\partial L}{\partial x}\right) = F_x \quad (9)$$

The motion equations about this modeling can then be deduced as:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \beta}\right) - \left(\frac{\partial L}{\partial \beta}\right) = F_\beta \quad (10)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \theta}\right) - \left(\frac{\partial L}{\partial \theta}\right) = F_\theta \quad (11)$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \varphi}\right) - \left(\frac{\partial L}{\partial \varphi}\right) = F_\varphi \quad (12)$$

$$(F_\beta, F_\theta, F_\varphi) = \left(\frac{1}{2}(F_l + F_r), F_\theta, -\frac{R}{W}(F_l - F_r)\right) \quad (13)$$

$$F_l = nK_tI_l + f_m(\dot{\theta} - \dot{\beta}_l) - f_w\beta_l \quad (14)$$

$$F_r = nK_tI_l + f_m(\dot{\theta} - \dot{\beta}_r) - f_w\beta_r \quad (15)$$

$$F_\theta = (nK_tI_l + nK_tI_r + f_m(\dot{\theta} - \dot{\beta}_l) + f_m(\dot{\theta} - \dot{\beta}_r)) \quad (16)$$

where $I_{t/r}$ is the current of left or right DC motor. Hence the voltage of DC motor is based on PWM, which means current cannot be used to deduce the voltage. Therefore, the DC motor equation shown as (17) is evaluated to build up the relationship between current and voltage.

$$L_m\dot{I}_{l/r} = V_{l/r} + K_b\dot{\theta} - \alpha_{l/r} - R_mI_{l/r} \quad (17)$$

where is L_m the motor inductance, assume that it is approximately as zero. The current $I_{t/r}$is given as

$$I_{t/r} = \frac{V_{l/r} + K_b(\dot{\theta}) - \dot{\alpha}_{l/r}}{R_m} \quad (18)$$

In conclusion, the relationship between forces and DC motor voltage can be calculated as:

$$\lambda = \frac{nK_t}{R_m} \quad (19)$$

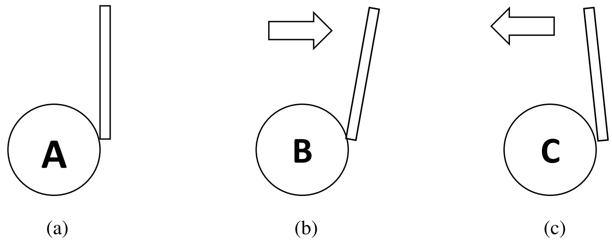

FIGURE 3. (a)Describes the stable state for the two-wheeled self-balancing robot. (b) Indicates the robot leans to the right. (c) Demonstrates the robot leans to the left.

$$\mu = \frac{nK_tK_b}{R_m} + f_m \quad (20)$$

$$F_\beta = \frac{\lambda}{2}(V_l + V_r) - (\mu + f_m)\dot{\beta} + \dot{\mu}\,\theta \quad (21)$$

$$F_\theta = -\lambda(V_l + V_r) + 2\mu(\dot{\beta} - \theta) \quad (22)$$

$$F_\beta = -\frac{R}{W}\lambda(V_l - V_r) - (\mu + \frac{W}{R}f_w)\dot{\varphi} \quad (23)$$

B. ROBOTIC CONTROLS

1) CONTROL ALGORITHM

The control algorithm of the self-balancing –two-wheeled robot can be based on PID control according to [25]–[27]. However, some problems are shown in these papers. Therefore, the control algorithms of this project are improved to be PD-PI control. Adopting adaptive and internal model control (IMC) system, [28] focused their study on practically implementing of remote control. Hence, the adaptive auto-adjustable controller is dependent on the pole's placement control technique and the hierarchical identification strategy.

[29] developed and implemented a neural network integrated modfied DAYANI technique for path and navigational control of a TWSBR in a cluttered environment. The authors instigated a five-layered back-propagation neural network to find out the intensity of various weight factors considering seven navigational parameters as obtained from the modfied DAYANI method.

2) UPRIGHT CONTROL (PD CONTROL)

Upright Control of self-balancing two-wheeled robot makes two wheels balancing on the ground with the body of the robot using negative feedback. Having two wheels, the body of the robot does nothing but fall down in a direction that the wheels are running.

3) PITCH ANGLE CONTROL

Using the mathematical modeling to analyze the pitch angle control as described in the Figure 4 below:

$a(t)$: Acceleration of Running Wheel

$x(t)$: Angular Velocity Caused by External Force

Deriving from the modeling, a motion equation of the robot is written as:

$$L\frac{d^2\theta(t)}{dt^2} = g\sin\theta(t) - a(t)\cos\theta(t) + Lx(t) \quad (24)$$

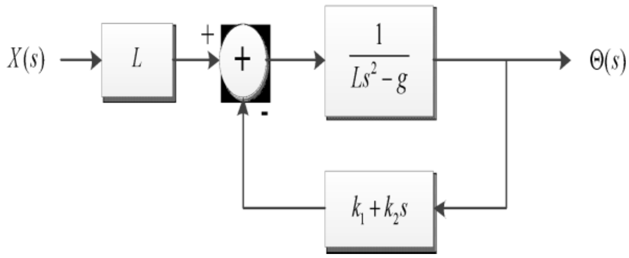

FIGURE 4. Pitch angle control modellin.

When the Angle θ is approaching to 0, the motion equation is rewritten as:

$$L\frac{d^2\theta(t)}{dt^2} = g\theta(t) - a(t) + Lx(t) \quad (25)$$

Considering the static condition $a(t) = 0$, simplify the foregoing second-order differential equation:

$$L\frac{d^2\theta(t)}{dt^2} = g\theta(t) + Lx(t) \quad (26)$$

Converting the differential equation from time-domain to s-domain through Laplace Transform (LT), and then calculate its transform function;

$$H(S) = \frac{\Theta(s)}{X(s)} = \frac{1}{s^2 - \frac{g}{L}} \quad (27)$$

Assume $s^{2-}\frac{g}{L} = 0$ the poles of the transform function $H(S)$ are given as $S_p = \pm\sqrt{\frac{g}{L}}$. Because of the positive pole, the system of this robot is unstable.

Rewriting the transform function, we obtained;

$$H(s) = \frac{\Theta(s)}{X(S)} = \frac{1}{s^2 + \frac{k_2}{L}s + \frac{k_1 - g}{L}} \quad (28)$$

The poles of this system are given as:

$$S_p = \frac{-k_2 \pm \sqrt{k_2^2 - 4L(k_1 - g)}}{2L} \quad (29)$$

The system is stable in the condition that all poles are negative. Therefore, the roots in (29) should satisfy $k_1 > g$, $k_2 > 0$.

In the angle control, k_1 and k_2 are respectively referred to as the proportional and differential parameters. Moreover, the differential parameter is equivalent to damping force, which can restrain effectively the vibration of body of this robot.

4) ANGULAR VELOCITY CONTROL

Angular velocity is measured by gyro of MPU6050. In addition, since motion of the robot has no influence on the angular velocity, the noise in the signal of angular velocity is too tiny to ignore at the time of designing circuits of the robot. Furthermore, the integral of angular velocity signal is to calculate the pitch angle of the robot, which can make the angle signal more stable.

C. SPEED CONTROL (PI CONTROL)

Because of the angle bias on angular control, the robot is accelerating in the direction of pitch to keep it balancing on horizon, which leads to the problem of speed control. The speed control is complex because it cannot adjust directly the revolving speed of DC motors to implement the balance [30], [31].

1) SPEED CONTROL

To give a suitable velocity from motors, a method which is the speed control is drawn as Figure 5 below.

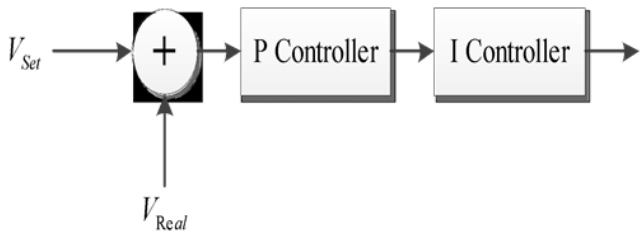

FIGURE 5. Block diagram of speed control.

The biases of speed control are directly adding into the controlled real velocity variables of DC motors through PI controller.

In order to test the PI Control, it will combine with PD control as the control system to run the robot on a straight line by (33).

$$V = K_p \times \theta + K_d \times \theta - K_p \times e(k) + K_i \sum e(k) \quad (30)$$

2) TURN CONTROL (P CONTROL)

When the upright and speed controls are done, the robot can keep balance with direction. However, the robot needs to implement the object avoidance mechanism so that it needs turn control to change different directions.

The turn control focuses on the different voltages in the left and right motor because different voltages will generate the speed differences that can used to control the robot's turn. P Controller is used in order to implement these differences in voltage. The block diagram for the robot's turn control is shown in Figure 6.

D. KALMAN FILTER ALGORITHM

The gyroscope and accelerometer of MPU6050 provide measures of instantaneous angular and accelerated velocity change but they also generate drifts when MPU6050 is running. Besides, the output of signals from MPU6050 is often corrupted with noise. It is a fact that the drifts and noise have an influence on control of the robot. Therefore, the robot needs a signal-level fusion technique to filter drifts and noise in signals. In the robot, the Kalman Filtering [32], [33] as the filter algorithm is implemented to overcome these problems.

Kalman Filtering is described by a Linear Stochastic Differential Equation like the (31).

$$X(k) = AX(k-1) + BU(k) + W(k) \quad (31)$$

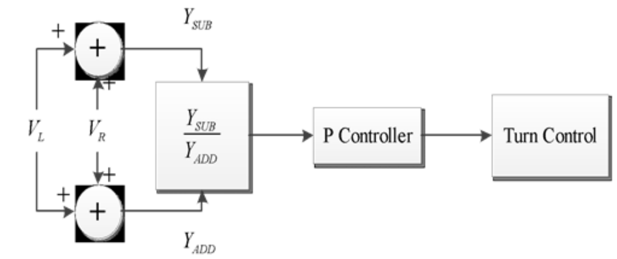

FIGURE 6. Block diagram of turn control.

The system measurement is added by:

$$Z(k) = HX(k) + V(k) \tag{32}$$

Assume that the robot's acceleration $a(t) = 0$, and then define the vector of the state $\vec{x}$ and covariance P_k as follow

$$\vec{x}\begin{pmatrix} position \\ velocity \end{pmatrix}$$

$$P_k = \begin{pmatrix} \sum pp \sum pv \\ \sum vp \sum vv \end{pmatrix} \tag{33}$$

Suppose that $\vec{x}_{k-1}$ and $\vec{x}_k$ as the last and current state, the updating state equation can be given according to equations of Kalman Filtering,

$$\begin{aligned} p_k &= p_{k-1} + \sigma t v_{k-1} \\ v_k &= v_{k-1} \end{aligned} \tag{34}$$

Rewrite the vector of the state $\vec{x}$

$$\vec{x_k} = \begin{pmatrix} 1 & \sigma t \\ 0 & 1 \end{pmatrix} \vec{x}_{k-1} = F_k \vec{x}_{k-1} \tag{35}$$

By establishing the covariance matrix to update dependency between different states we derived:

$$Cov(x) = \sum Cov(Ax) = A \sum A^T \tag{36}$$

Combining the vector matrix with covariance matrix

$$\begin{aligned} \vec{x}_k &= F_k \vec{x}_{k-1} \\ P_k &= F_k P_{k-1} F_k^T \end{aligned} \tag{37}$$

Assuming the robot has acceleration $a(t)$, it gives

$$\begin{aligned} P_k &= P_{k-1} + \sigma t v_{k-1} + \frac{1}{2} a(t) \sigma t^2 \sqrt{a^2 + b^2} \\ v_k &= v_{k-1} + a(t) \sigma t \end{aligned} \tag{38}$$

Finally, Use a matrix to stand for updating (39)

$$\vec{x}_k = F_k \vec{x}_{k-1} + \begin{pmatrix} \frac{\sigma t^2}{2} \\ \sigma t \end{pmatrix} a(t) = F_k \vec{x}_{k-1} + B_k \vec{\mu_k} \tag{39}$$

E. AVOIDANCE MECHANISM

The avoidance mechanism according to [34], [a] is implemented for this robot due to its dynamic working environment. The introduction of Ultrasonography makes this mechanism possible in this robot because of 'Ultrasonic Waves' character that an ultrasonic wave is transmitted before meeting an objective, and then it will be reflected in the same path.

TABLE 1. Physical parameters of mathematical model.

Parameter	Unit	Definition
$g = 9.8$	m/s^2	Acceleration of Gravity
$m = 0.06$	kg	Weight of Wheels
$R = 0.033$	m	Radius of Wheels
$J_w = \frac{m \times R}{2}$	kgm^2	Moment of Inertia of Wheels
$M = 0.867$	kg	Weight of Body
$W = 0.19$	m	Width of Body
$H = 0.135$	m	Height of Body
$D = 0.066$	m	Depth of Body
$L = \frac{H}{2}$	m	Distance of the Center of Mass from the Wheel Axle
$J_\psi = \frac{ML^2}{3}$	kgm^2	Moment of Inertia of Body's Pitch
$J_\phi = \frac{M(W^2+D^2)}{12}$	kgm^2	Moment of Inertia of Body's Yaw
$J_m = 1\times10^{-5}$	kgm^2	Moment of Inertia of DC Motor
$R_m = 6.8$	Ω	Resistance of DC Motor
$K_b = 0.47$	$V \cdot s / rad$	EMF Constant of DC Motor
$K_t = 0.32$	Nm / A	Torque Constant of DC Motor
$n = 1$		Gear Ratio
$f_m = 0.0022$		Friction Coefficient between Body and DC Motor
$f_w = 0$		Friction Coefficient between Wheels and Ground

In Figure 7, the TWSBR with ultrasonic equipment is transmitting blue ultrasonic waves to detect roadblocks. And the red waves are reflected by a roadblock. The robot is turning to avoid the objective in this simulation of MATLAB Robot Toolbox.

A Genetic algorithm (GA) based on Dynamic path planning algorithm (DPPA) proposed in [32] is analyzed and implemented in the path planning and obstacle avoidance of the TWSBR. The algorithm confirms the flexibility of the robot in reaching its targeted destination from any arbitrary starting position. The implementation shows an improvement in the TWSBR feasible path generation, acute and dynamic obstacles avoidance, and shortest path selection from starting point to the desired destination.

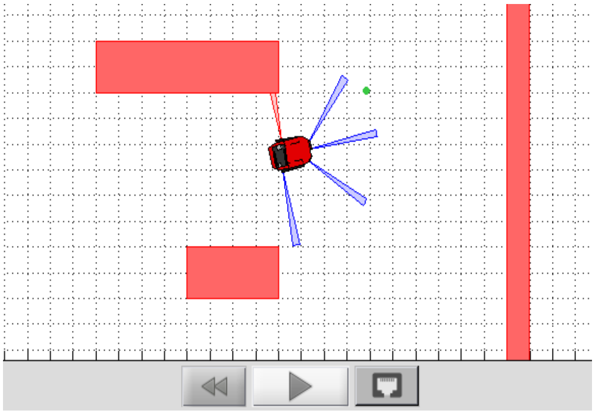

FIGURE 7. Simulation of avoiding mechanism.

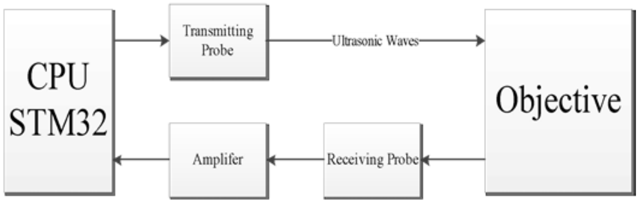

FIGURE 8. Avoidance system.

F. WORKING PRINCIPLE

Based on this character, a system for the avoidance mechanism is designed like Figure 8, which includes transmitting probe, receiving probe and amplifier.

In order to decrease the cost and size of this robot, a simple ultrasonic product having two probes is used as the avoiding sensor. Meanwhile, ADC of STM32 microcontroller is adopted to confirm the Transit Time.

IV. SYSTEM DESIGN AND PERFORMANC

A. MECHANICAL STRUCTURE

Figure 9 show the mechanical structure of the top layer designed TWSBR. The sub-layer of the circuit is to place DC motors as the drive module for this robot. In order to decrease the size and space of this robot, a plastic baseboard and two metallic racks in are employed to immobilize the left and right DC motor as two-wheeled system. When they are combined, the sub-layer design will be done. The aim of the middle-layer design is to lay the 12V battery over the plastic baseboard as a place of the power supply. Because the robot has a top-layer to put the main PCB, copper cylinders are used to support the plastic baseboard of top-layer. The goal of the top-layer design is to install the main PCB with all sub-modules and circuits of this robot. In addition, a transparent plastic board over main PCB plays a defending role for this robot.

B. SYSTEM PERFORMANCE

Analyzing the system of the TWSBR, the main flowchart in Figure 10 is established in order to present the main idea for programming the robot, and it can be provided by visualized theoretical basis for what main functions should be included in the software of this robot.

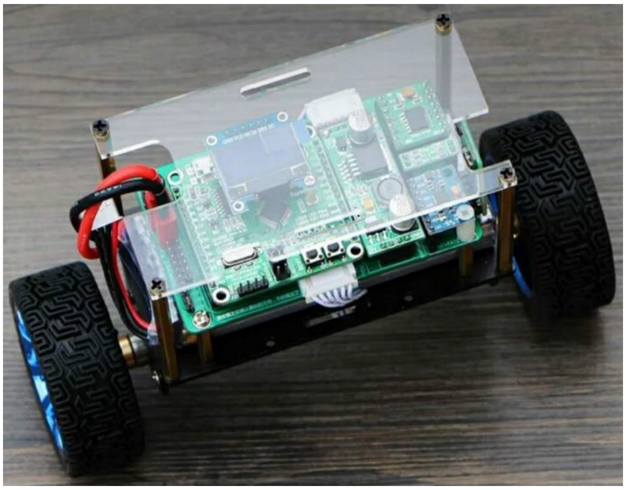

FIGURE 9. Top-layer design.

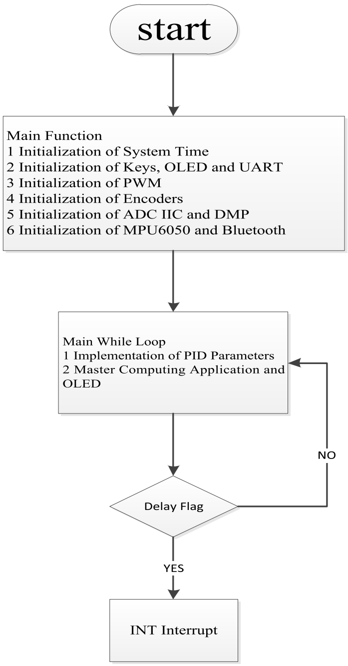

FIGURE 10. Software main flow char.

The most important task in the system is the settings of Baud Rate which can be define as 12800 Baud per second in this situation. Additionally, the length of frame which is a constant while the microcontroller is communicating with the application. Furthermore, the delay time in the communication between the two frames need to be less than 1ms. Otherwise, forward frame will be missing.

Finally, there is no limit for refreshing the User Interface (UI) on the application, which means that the refreshing rate of UI depends directly on the Graphics Processing Unit (GPU) and Central Processing Unit (CPU) of the computer and the reliability of the communication chain. While the PC application is running to communicate between the robot and the PC, the window of this application will show the communicating signals like Figure 11.

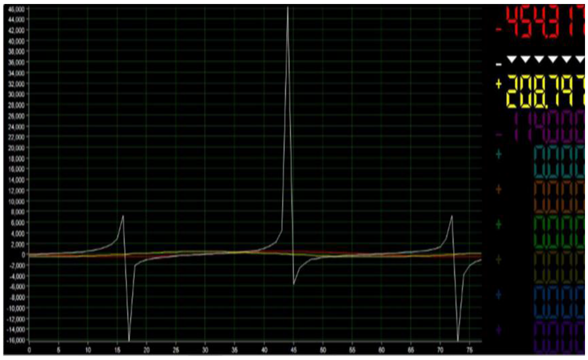

FIGURE 11. Running PC application.

In Figure 10, the numbers with different colors presents peaks of signals. In order to observe the communicating data, they are amplified to be 100 times as much as initial values.

C. PERFORMANCE OF BALANCING MEDIAN

The balancing median is significant because it has an influence on the selection of parameters of PI-PD-P controller. To obtain the median, the self-balancing two-wheeled robot need be laid on the horizontal ground and then given an initializing speed for recording the angle which can make this robot balancing. While the robot was debugging on ground, the balancing median was showing on the window of the application, which was around 0 degree. Therefore, the median is defined as 0, hence Bias = Angle-0.

D. PERFORMANCE OF POLARITY OF PROPORTIONAL PARAMETER

To confirm the polarity of proportional parameter, the probable theoretical range of proportional parameter is evaluated at first. In this project, standing for the 100 percent Duty Ratio, the setting of PWM's parameter is 7200. Therefore, the maximum theoretical proportional parameter can be assumed as 720, which leads to the full turn of the robot at positive and negative 10 degree. According to the physical situation, it is too small to control the robot accurately. However, the theoretical absolute range of proportional parameter is seemingly confirmed between 0 and 720. Based on the range of proportional parameter, the polarity of proportional parameter can be confirmed via assuming positive or negative proportional parameter into codes to check out the operating situation of the robot. On the one hand, choose the negative proportional parameter into codes of the project before turning on the robot, and then operating circumstance of the robot is that it is falling with the acceleration of DC motors, which is an undesirable situation because it illustrates the result of positive feedback. On the other hand, refresh the proportional parameter to be positive, which lead to the upright state of the robot. The upright circumstance means there is a negative feedback between DC motor and the body of the robot, which is an expecting result. According two different situations, the polarity of the proportional parameter can be confirmed as positive one.

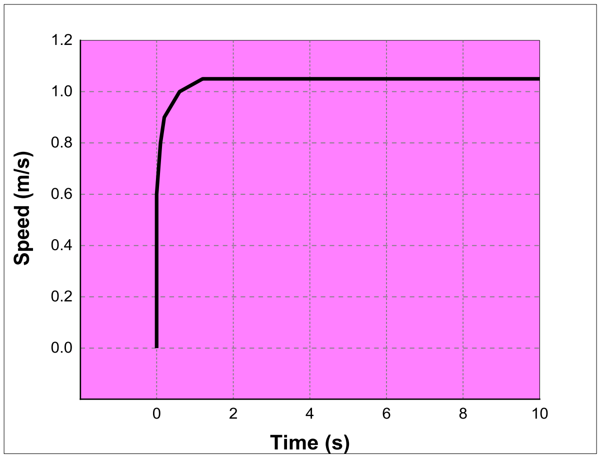

FIGURE 12. PD control SIMULINK result.

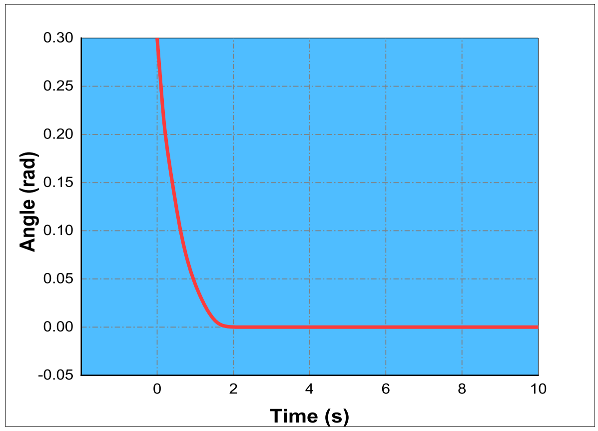

FIGURE 13. PD-PI control SIMULINK result.

E. CONFIRMING AMPLITUDE OF PROPORTIONAL PARAMETER

Based on the theoretical range of proportional parameter between 0 and 720, different proportional parameters can be tested into codes to discover the suitable parameter, with increasing of proportional parameters until the robot vibrates dramatically in low frequency.

Some proportional parameters as following are checked into codes:

1) When $K_p = 200$, the robot has the state trend of upright with slow response.
2) When $K_p = 350$, the robot upright with faster response than first situation, the state of response is so slow that the robot cannot reach a balancing state at a moment not keep balanced on a whole time.
3) When $K_p = 500$, the response is significantly fast with dramatically vibration in low frequency, which means the proportional parameter is suitable and the D controller need be added into the control system to restrain the vibration in low frequency.

F. CONFIRMING POLARITY OF DIFFERENTIAL PARAMETER

The initialization of data from output of MPU6050 an assemblage whose maximum is under 10000 and the 100 percent

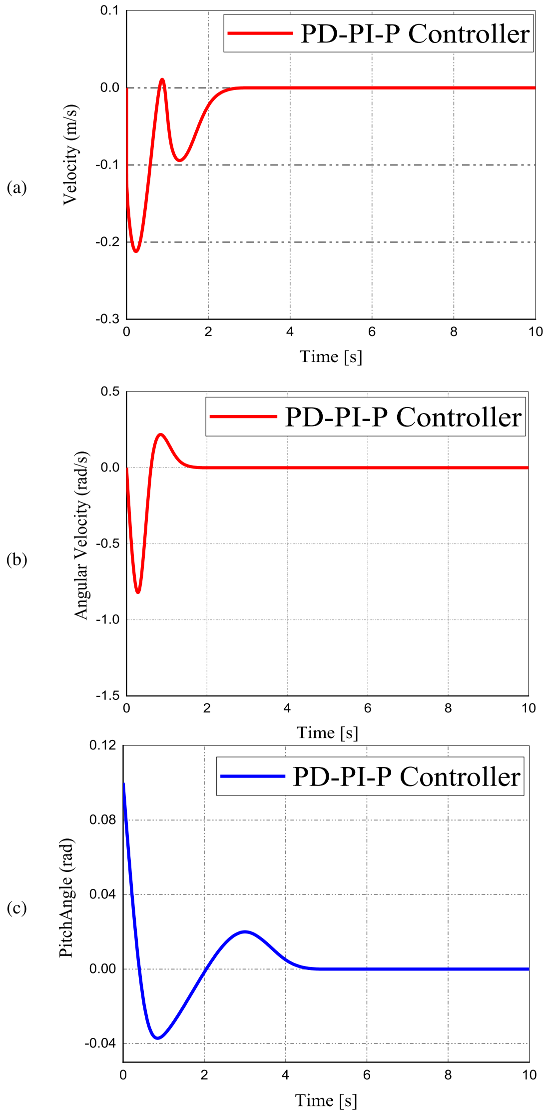

FIGURE 14. **Response of the TWSBR using the PD-PI controller (a. for the pitch angle, b. for the angular velocity, and c. for velocity).**

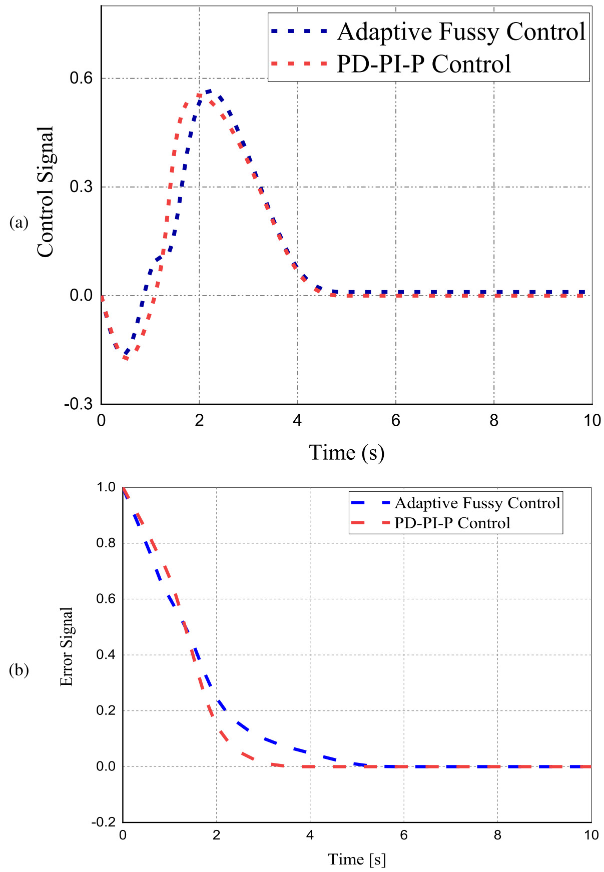

FIGURE 15. **(a) PD-PI controlled TWSBR robot w/ Kalman filter algorithm against the adaptive fussy control – (Control Signal). (b) PD-PI controlled TWSBR robot w/ Kalman filter algorithm against the adaptive fussy control – (Error Signal).**

Duty Ratio 7200, the theoretical absolute range of the differential parameter can be computed from 0 to 2.

Compared with the range of the differential parameter, the positive and negative parameters are selecting into codes. Foremost, the differential parameter is supposed to a negative one, which causes the rotating body of robot with the opposite turning DC motors, which leads to the unbalancing robot. Secondly, turn the differential parameter to the positive one, which implement the effect of following that the body of the robot is rotating with synchronous DC motors. This result means that the close-loop of angular velocity is implementing into the control system and is conclude that the polarity of the differential parameter is positive.

G. CONFIRMING AMPLITUDE OF DIFFERENTIAL PARAMETER

According to the theoretical absolute range of the differential parameter from 0 to 2, some parameters in this range are debugged into codes. With adding of the differential parameter, the robot is vibrating at high frequency, which can decrease the influence of vibration of low frequency to make the robot balancing in static.

Some differential parameters as following are checked into codes:

1) When $K_d = 0.5$, the vibration of low frequency is canceling.
2) When $K_d = 1$, the vibration of low frequency is gone, and the robot is balancing on the ground.
3) When $K_d = 1.7$, the robot is vibrating on high frequency.

V. EXPERIMENTS AND RESULTS

The theory of the PD Control is verified by SIMULINK of MATLAB to make sure it is correct. The result shown in Figure 12 indicates that the robot can be balanced with two wheels as time goes because the dip angles are going to be 0°.

When a disturbance is simulated for the robot on SIMULINK's window, the line chart in Figure 6 presents that the robot will expedite in the direction of the disturbance to reach the saturation. To confirm the working principle is correct, a simulation of Robotic toolbox is done as shown in Figure 13.

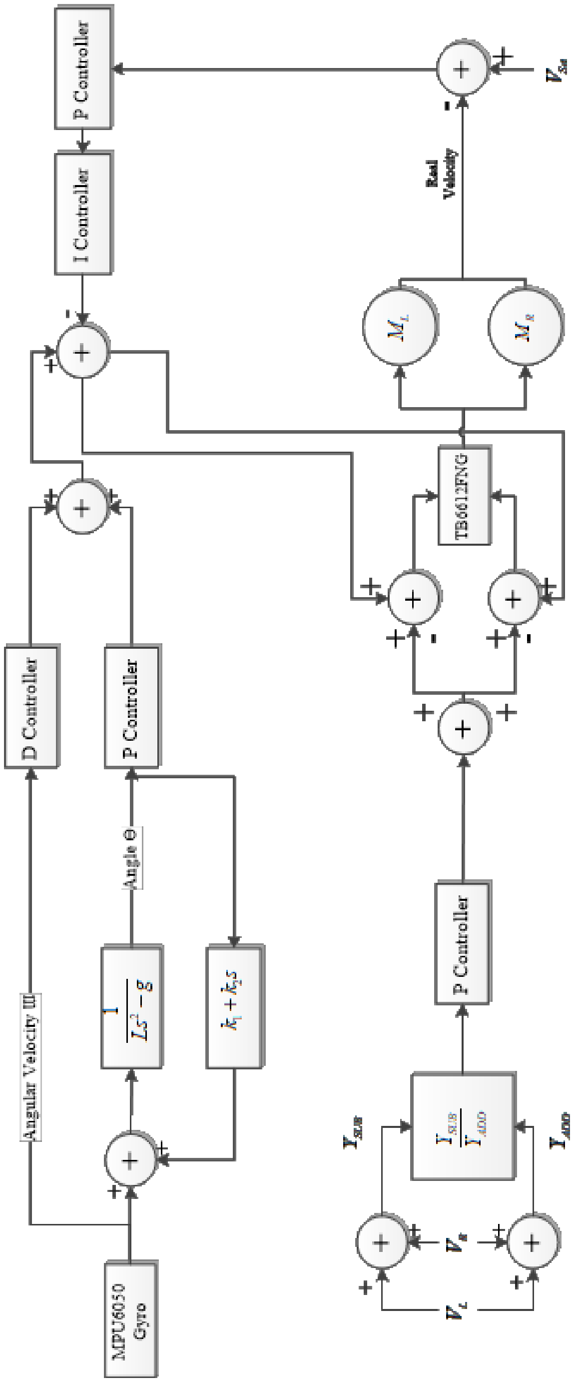

FIGURE 16. **PD-PI controller block diagram.**

VI. PERFORMANCE EVALUATION

Using MATLAB simulations, we conduct several experiments to evaluate the performance of the proposed PD-PI controller. The point of balance is set at 0 [rad], as we simulate the mathematical model of two-wheeled self-balancing robot using the Kalman Filter Algorithm. The response curves of the controller in the balance point applied is shown in Figures 14 (**a., b., and c.**). These simulation results with PD-PI control as shown in Figure 14 represents the pitch angle, angular velocity, and the velocity of the tested TWSBR respectively. Analyzing the simulation, it is observed that both the pitch angle, the angular velocity, and the velocity of the TWSBR can be controlled as close as to 0 [rad], the robot position attains equilibrium point and remains constant after 4.3 [s] for the pitch angle, at 1.5 [s] the angular velocity attained equilibrium and remain constant, while the velocity reached equilibrium at 2.4 [s] and remained stable.

The simulation results in Figures 15a and 15b show that the TWSBR stabilized at the set 0^{o} even under pressure and external force disturbance and follows the intended input signal very fast with zero error. The experiments show error signal indicating the performance of the TWSBR in the sensed environment. The avoidance mechanism of obstacles, uncertainties, and noise signal control. The proposed PD-PI controller based on Kalman filter algorithm is compared against the improved Adaptive fuzzy controller (AFC) in [5]. The results show that the performance of PD-PI controlled TWSB robot with Kalman Filter Algorithm is more efficient with minimal Integral Square Error (ISE) as against the compared improved AFC. It is also observed that the TWSB robot with PD-PI control follow the planned path in the sensed environment with an optimal obstacle avoidance, and more accurately with minimal overshoot and zero steady state error. A block diagram explaining for the PD-PI controller is represented in Figure 16.

VII. CONCLUSION

The research experimented a PD-PI navigational control for a TWSBR. Kalman filter algorithm is considered to determine the stability of the robot in a sensed environment. This research is successful since the objects of self-balancing two-wheeled robots were implemented, and a maximum obstacle avoidance achieved. The robot can make itself balancing with wheels through PD-PI control and turned by P control. In addition, the Kalman Filtering is used to eliminate the drift of MPU6050's gyro allowing for an accurate estimate of the tilt angle. Avoidance mechanism is implemented by using the ultrasonic waves to detect obstacles around the robot. Communication between the robot and the IoT devices in the environment is established through a JAVA code embedded in the controller and manipulated through Bluetooth connection.

Finally, the proposed PD-PI control technique introduces theoretically the relationship of different controls including upright control (PD Control), speed control (PI Control) and turn control (P Control) to make the robot self-balanced with two wheels. In the built Kalman algorithm, parameters of PD-PI Control need to pay attention to the polarity and amplitude which have an influence on the balance of the robot. However, the maximum proportional and differential parameters are 500 and 1.7 respectively. Although the performance of the robot in maximum is vibrating slightly. Therefore, to decrease the slight vibration, the maximum proportional and differential parameters multiply an influencing constant whose value is 0.6. In addition, the suitable proportional and differential parameters become 300 and 1 respectively without any vibration in the robot. These parameters are programmed into the codes and the robot keeps upright during navigation.

VIII. FUTURE RESEARCH

More research should be conducted to exploit more complex algorithm for avoidance mechanism based on ultrasonic waves and extend the connectivity for Bluetooth to Wireless-Fidelity.

The parameters of PD-PI control is not perfect because the robot shakes a little when the velocity is increased. Therefore, future research is recommended for improving the control algorithm to implement more self-balancing with two wheels as an inverted pendulum robot.

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CELESTINE IWENDI (M'01–SM'17) received the second master's degree in communication hardware and microsystem engineering from Uppsala University, Sweden, 2008, ranked under 100 in the world University ranking and the Ph.D. degree in electronics from the University of Aberdeen, U.K., in 2013. He is an Associate Professor from Sweden. He is highly motivated researcher with a wireless sensor network security book, and over 100 publications. He is currently a Senior Lecturer with the BCC of Central South University of Forestry and Technology, Changsha, China, and has strong teaching emphasis on communication, hands-on experience, willing-to-learn, and 18 years technical expertise and currently teaches engineering team project, circuit theory, data networks and distributed systems, and control systems. He has developed operational, maintenance, and testing procedures for electronic products, components, equipment, and systems; provided technical support and instruction to staff and customers.

He is a wireless sensor network Chief Evangelist, researcher, and designer. A Board Member of IEEE Sweden Section (2017 to date) and a Fellow of The Higher Education Academy, U.K. to add to his teaching and professional experiences. He is the Editor, *International Journal of Engineering and Allied Disciplines 2015*, Newsletter Editor, IEEE Sweden section-2016–2018, Editor-in-Chief, *Wireless Sensor Network Magazine, 2009*, Committee Member, International Advisory Panel, International Conference on Marine, Ocean, and Environmental Sciences and Technologies (MAROCENET) 2014–2016, Editor-in-Chief, *Journal of Wireless Sensor Network, 2009*, Advisory Board, *International Journal of Innovative Computer Science and Engineering (IJICSE) 2013*. He is the Co-Chair of the special session on "Wireless Sensor Networks: Hardware/Software Design aspects for Industry" at the Prestigious International Conference of Industrial Technology ICIT. His research focuses on wireless sensor networks, Security of Things (SoT), communication controls, the Internet of Things (IoT), electromagnetic machines, 5G networks and low power communication protocols.

MOHAMMED A. ALQARNI received the bachelor's degree in computer science from King Khalid University, Saudi Arabia, in 2008, and the M.Sc. degree in computational sciences from Laurentian University, Sudbury, Canada, in 2012, the Ph.D. degree in computer science from McMaster University, Hamilton, Canada, in 2016. He is currently an Assistant Professor and the Dean with the College of Computer Science and Engineering, the University of Jeddah, Saudi Arabia. He enjoys research in a wide variety of topics including the IoT.

JOSEPH HENRY ANAJEMBA received the bachelor's degree in computer science from the Federal Polytechnic Oko, Nigeria, the M.Sc. degree in information communication technology from the National Open University of Nigeria, in 2016. He is currently pursuing the Ph.D. degree in information and communication engineering with the College of Internet of Things, Department of Communication engineering, Hohai University, China. He has credited several articles and conference papers. His current research interests include cellular wireless communications, antenna and V2V technology, and 5G cellular networks and security, and several other IoT related areas.

AHMED S. ALFAKEEH received the bachelor's degree in computer science and education, in 2005, from King Abdulaziz University, and the M.Sc. degree in IT from De Montfort University, in 2010, the Ph.D. degree from Software Technology Research Laboratory, a research institute established within De Montfort University, Leicester, UK, in 2015. He is an Assistant Professor with Information System Department, Faculty of Computing and Information Technology, King Abdulaziz University, Jeddah, Saudi Arabia. He is currently a Vice-Dean with the Research and Consultation Institute for Development. His research projects involve feature interactions detection and resolution in context-aware systems, smart homes systems, software engineering, the IoT, and data science.

ZHIYONG ZHANG (M'17) received the B.Sc. degree in electronic engineering from Bangor University and Central South University of Forestry and Technology. He is an enthusiastic learner and believer of the benefits of WSNs and control systems. He has presented and published papers in IEEE conferences. He has a project of a drawing robot which was accepted by Hunan (China) Government and got the scholarship to finish it.

ALI KASHIF BASHIR (SM'16) received the B.S. degree from the University of Management and Technology, Pakistan, the M.S. degree from Ajou University, South Korea, and the Ph.D. degree in computer science and engineering from Korea University, South Korea. He is a Senior Lecturer with the School of Computing, Mathematics, and Digital Technology, Manchester Metropolitan University, U.K. He is a Distinguished Speaker of ACM. His past assignments include: Associate Professor of Information and Communication Technologies, Faculty of Science and Technology, University of the Faroe Islands, Denmark; Osaka University, Japan; Nara National College of Technology, Japan; the National Fusion Research Institute, South Korea; Southern Power Company Ltd., South Korea, and the Seoul Metropolitan Government, South Korea.

He is author of over 80 peer-reviewed articles. He is supervising/co-supervising several graduate (M.S. and Ph.D.) students. His research interests include the Internet of Things, wireless networks, distributed systems, network/cyber security, cloud/network function virtualization, etc. He is serving as the Editor-in-Chief of the IEEE Future Directions Newsletter.

He is the Editor of several journals and also has served/serving as Guest Editor on several special issues in journals of IEEE, Elsevier, and Springer. He has served as the Chair (program, publicity, and track) and the Chair on several conferences and workshops. He has delivered several invited and keynote talks, and reviewed the technology leading articles for journals like IEEE Transactions on Industrial Informatics, the IEEE *Communication Magazine*, the IEEE Communication Letters, IEEE *Internet of Things*, and the IEICE journals, and conferences, such as the IEEE Infocom, the IEEE ICC, the IEEE Globecom, and the IEEE *Cloud of Things*.