# Self-Balancing Cycle bot by reaction wheel using PID controller

Aniket Nayak
*Dept. of Mechanical Engg (Mechatronics Engg)*
*Chitkara University(Rajpura campus)*
Punjab, India
aniket2404.mt18@chitkara.edu.in

Prit Varmora
*Dept.of Electronics and Commu. Engg*
*Dharmsinh Desai University*
Nadiad, India
pritjvarmora14044@gmail.com

Hruthwik K
*Dept.of Information Science and Engg*
*BMS college of engineering*
Bangalore, India
hruthwik.is17@bmsce.ac.in

Avinash Kr Dubey
*Dept.of Computer Science and Engg*
*IIT Bombay*
Powai, India
dubeyavi.ec@gmail.com

Avijit Pandey
*Dept.of Computer Science and Engg*
*IIT Bombay*
Powai, India
avijit@e-yantra.org

***Abstract*—This paper discusses on the balance control of cycle bot.[1] A self-balancing cycle bot based on the concept of an inverted pendulum is an unstable and nonlinear system. To stabilize the system in this work, the following three main components are essential, i. e., an IMU sensor that detects the tilt angle of the cycle bot, a controller that is used to control motion of a reaction wheel, and a reaction wheel that is employed to produce reactionary torque to balance the cycle bot.[2] The PID controller is implemented to control the reaction wheel. The performance of the cycle bot is confirmed by the experiments.**

***Index Terms*—self-balancing, PID controller, cycle bot, bicycle robot, reaction wheel**

## I. Introduction

The development of technology for the convenience of humans has been evolving day by day. The leading sector in this development of technology is the robotics. This field is applied to many applications, including the industrial robots and unmanned robot. Among them, the research of unmanned robot is actively in progress. Most of unmanned robot was developed based on the four-wheel and six-wheel. The robot based on the four-wheel or six-wheel is hard to drive in the special environmental factor, such as the confined space. To solve the matter, a lot of research on the two-wheeled robot is in progress. The two-wheeled robot called the cycle bot/bicycle robot can freely drive in the narrow and the confined space, however, the robot has the characteristics of unstable structure. Many control methods have been proposed in order to improve the stability of the robot which has the unstable characteristics. This paper will also cover the control method for improving the stability of the robot. However, proving the dynamic model of robot is too complex to implement in real time. Therefore, the PID controller which don't requires mathematical modeling of system to implement is proposed to control the robot. To control the balance of robot, we assume that the robot's body and the reaction wheel as an inverted pendulum. The basic idea of working is when cycle bot starts falling in either direction the reaction wheel gets accelerated by PID controller to generate counter torque opposing the torque applied on cycle by gravity about pivot (contact point of wheel with ground). Due to the inertia of reaction wheel, reaction torque overcomes the gravity torque and cycle gets back to stable position vertically.

As mentioned above, cycle bot will behave like a inverted pendulum and,[3] there are many ways to balance an inverted pendulum. The most common way is to use a moving cart to move the pivot point to create counter moment. Another uncommon way of balancing is by rotating clockwise and anticlockwise to generate moment. Out of the many variations out there, the focus here is to balance an inverted pendulum by using reaction wheel. Unlike other type of inverted pendulum such as rotary or cart they require a runway or platform to balance itself because it is balanced by motion of the whole pendulum. However, reaction wheel inverted pendulum is balance by torque generated by the reaction wheel mounted on it self, this don't requires any platform or runway. To balance the cycle bot, The PID controller is used to not relying much on the dynamics of the cycle bot. And wireless communication is used to control the basic parameters of the cycle bot for speed controlling and left-right motion, for navigation process manually.

Reaction wheel is also mainly used in the satellite to provide precise rotation. To rotate the satellite in space, satellite rotated by spinning the reaction in the opposite direction. This allows the satellite to have rotational motion through its rotational axis according to newton's 3rd law.

The rest of the paper is organized as follows. The dynamics of the cycle bot is discussed in the sec. 2. Hardware and Electronic design is presented in sec. 3. Controller design for the cycle bot is described in sec. 4. In sec. 5, the performance of the system and experiment's results is presented. Then, the conclusion of the research is described in the 6 sec.

## II. Dynamics And Force Analysis

### A. Dynamic of cycle bot with reaction wheel

Since our system is based on the principle of an inverted pendulum with a reaction wheel as seen in Figure 1, by disregarding forces generated from moving forward and steering, a simplified dynamic model of the bicycle robot can be derived using a Lagrange method. Let $m_1$, $O_1$, $I_1$, $\theta$ and $L_1$ be the bicycle mass, its center of mass, its moment of inertia about its center of mass, the angle between the bicycle and the vertical upright direction and the distance from the origin O to the center of mass of the bicycle, respectively and let $m_2$, $O_2$, $I_2$, $\phi$ and $L_2$ be the reaction wheel mass, its center of mass, its moment of inertia about the center of mass of the reaction wheel, the rotation angle of the reaction wheel, and the distance from its center of mass to the origin O, respectively, then a Lagrange equation of the dynamic model can be derived by using:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right) - \frac{\partial L}{\partial q_i} = \tau_i \tag{1}$$

where $\tau_i$, i = 1, 2, 3, . . . , n, denotes the external force corresponding to generalized coordinates qi, and

$$L(q, \dot{q}) = K.E(q, \dot{q}) - P.E(q, \dot{q}) \tag{2}$$

where L, KE, PE, and q are the Lagrangian operator, the kinetic energy of the system, the potential energy of the system, and the generalized coordinates of the system, respectively. In this paper, $\theta$ and $\phi$ are considered as system generalized coordinates.

The total kinetic energy of the system can be written as

$$K.E = \frac{1}{2}(m_1{L_1}^2 + m_2{L_2}^2 + I_1 + I_2)\dot{\theta}^2 + I_2\dot{\theta}\dot{\phi} + \frac{1}{2}I_2\dot{\theta}^2 \tag{3}$$

The potential energy of the bicycle body and of the reaction wheel are obtained as follows

$$P.E = (m_1L_1 + m_2L_2)gcos\theta \tag{4}$$

After that,the Lagrangian operator can be obtained as follows:

$$L = K.E - P.E$$

$$= \frac{1}{2}(m_1{L_1}^2 + m_2{L_2}^2 + I_1 + I_2)\dot{\theta}^2 + I_2\dot{\theta}\dot{\phi} + \frac{1}{2}I_2\dot{\theta}^2$$

$$-(m_1L_1 + m_2L_2)gcos\theta \tag{5}$$

Using the Lagrange equation defined in (1),the following two equations are derived

$$(m_1{L_1}^2 + m_2{L_2}^2 + I_1 + I_2)\ddot{\theta} + I_2\ddot{\phi} + -(m_1L_1 + m_2L_2)gsin\theta = 0$$

$$I_2(\ddot{\theta} + \ddot{\phi}) = T_r \tag{6}$$

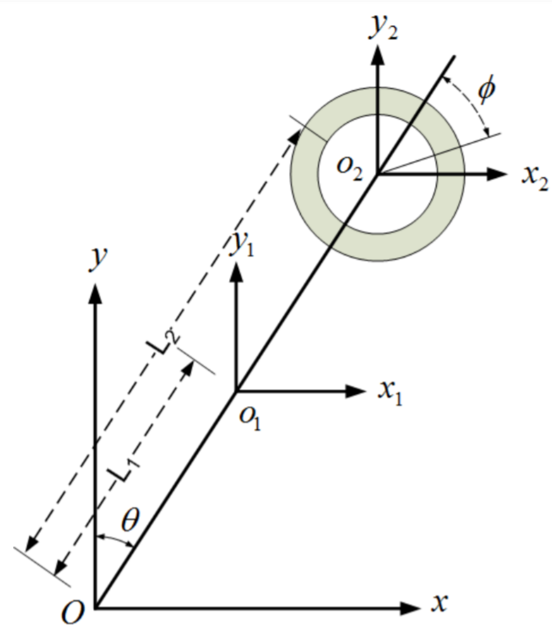


Fig. 1. A model of a bicycle robot with a reaction wheel system based on the principle of an inverted pendulum system.

TABLE I
Parameters of physical cycle bot

| Parameters | Values |
|---|---|
| Cycle c.g. upright height($L_1$) | 0.07 $m$ |
| Reaction wheel c.g. upright height($L_2$) | 0.102 $m$ |
| Mass of the cycle | 0.725 $kg$ |
| Mass of the reaction wheel | 0.306 $kg$ |
| Cycle Moment of inertia about c.g.($I_1$) | 9.66 x $10^-5$ $kgm^2$ |
| Reaction wheel moment of inertia about c.g.($I_2$) | 5.36 x $10^-4$ $kgm^2$ |

### B. System Parameters

## III. Hardware and Electronic design

### A. Electronic components in the system

Electrical components are the vital part of the cycle bot. Table 1 shows the description of each component.

Direct current (DC) motor is used due to the ability to provide high RPM and easy to control ability. The importance of reaction wheel is to create counter torque, and this is proportional to the acceleration of the wheel. High acceleration can be obtained by changing the velocity in a short time. This can be achieved by DC motor; hence DC motor is used.Since the location of the reaction wheel affects the performance, if we keep reaction wheel at much height it requires less maximum torque to be generated on reaction wheel in order to balance cycle but it requires more RPM ratings and visa-versa if we keeps reaction wheel at less height we need more maximum torque but less RPM ratting of motor. So according to this tread off between motor torque and RPM ratings we have chose reaction wheel motor with 8.5 kg-cm stall torque and with 300 no load RPM as we are keeping our reaction wheel at height of 10.2 cm.

Another DC motor is used for navigation speed control. To measure the accurate tilt angle of the cycle bot, measurement of accelerometer and gyroscope sensors are fused together using kalman filter because accelerometer gives better results for long time interval but highly sensitive to noises and gyroscope can give better results in noisy environment but as we need to integrate data it generates problem of drifting over time it gives better result for small time span and . For navigation process i.e left/right motion DC servo motor is used. We are using Xbee's for wireless communication. Arduino Mega is used as a microcontroller due to its reliability and low cost.

TABLE II
ELECTRONIC COMPONENTS IN THE SYSTEM

| components | Description of the components |
|---|---|
| Actuators | 6V DC Motors and Servo Motor |
| Microcontroller | Arduino Mega |
| Sensor | IMU MPU-6050 up to 6 DOF Accelerometer and Gyroscope |
| Motor Driver | L298N |
| Transmitter and Receiver | Xbee |
| Remote control | Joystick |

### *B. Block diagram of electronic system*

In our closed-loop control system, the output of the cycle bot is the tilt angle, which is the instantaneous angle of the cycle body with respect to the vertical upright position. Sensor data from the IMU sensor are transmitted to the microcontroller via I2C communicaton. The received data gets fused through a complementary filter algorithm in order to obtain a precise tilt angle. We determine the error, which is the difference between the desired tilt angle and the actual tilt angle. It is fed into our proposed controller so that the controller will process, calculate, and generate the corresponding motor PWM values to control the DC motor (that, in turn, controls the reaction wheel) via the motor controller, in order to achieve balancing at the upright position.

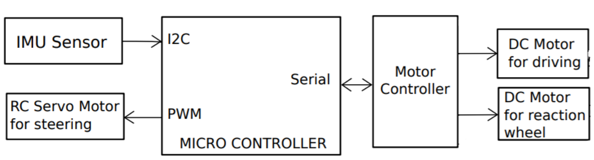


Fig. 2. Block diagram of electronic system.

Figure 2 and 3 shows the mechanical structure of the self-balancing cycle bot. It consists of three motors: a gear DC motor connected to the rear wheel, providing propulsion; a gear DC motor connected to the reaction wheel, providing balance; and an RC servo motor connected to the steer, providing directional steering.

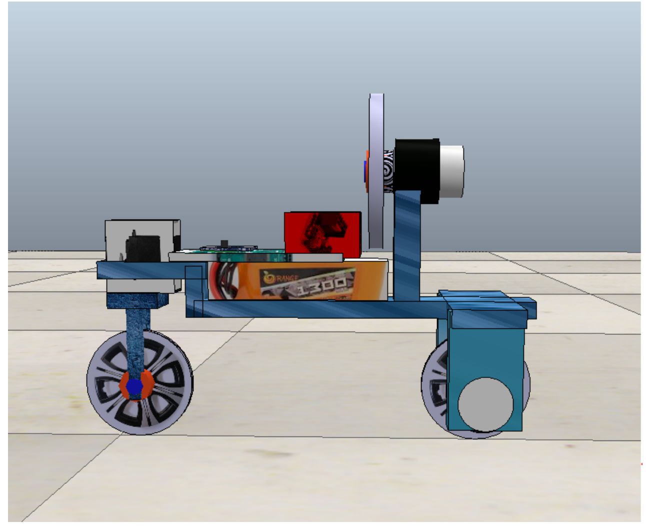

Fig. 3. Cycle bot design in V-Rep simulation software.

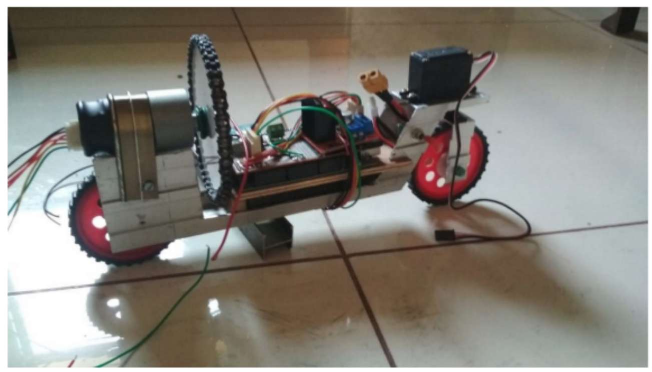

Fig. 4. Photo of real world cycle bot.

## IV. CONTROLLER DESIGNING

Controller designing is one of the most essential part for any system to be control to achieve desired performance. A common control system consists of the controller, sensor and an actuator. Actuator is the component where it converts electrical signal to mechanical energy to change the physical environment. Sensor reads the change in physical environment and sends the electrical signal to the controller. Controller acts as the processor, which calculates the difference of the environmental value and target value, which also known as response error. This value is then processed by the controller and the correct signal is sent to the actuator. A target value is the value which the user desire to achieve. In fig. 5 block diagram of a basic example of a control system is shown.

Where, r=reference value
e=error
u=controlled input signal
y=output
ym=sensed value

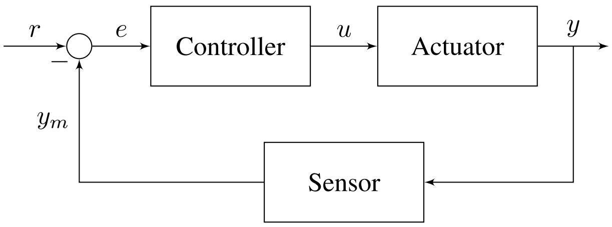


Fig. 5. Block diagram of control system.

### A. PID controller

PID is a very well-known feedback controller, due to its efficiency and reliability. PID consists of three parameters, proportional gain, integrated and derivative. Like most of the controller, it calculates the differences between the measured and the desired output value as shown in Fig. 5. One of the examples of PID in daily life is air conditioning. First air conditioning is set to a desire temperature by using the remote. Most of the air conditioning has a built-in temperature sensor to feedback the ambient temperature. The purpose of the PID is to constantly receive feedback from the ambient temperature and send the suitable control signals to the system to lower down the temperature. Once the desire temperature is achieved, the PID controller will then try to maintain the temperature within a range. This range is known as the steady state error. A good controller has a low range of steady state error, also achieve the desire value in a shorter time with low overshooting. The proportional gain acts as multiplier which multiplies the error response. It is also one the factor to make the response quicker, however too much will result in oscillation and eventually unstable. The function of an integral gain is sum up all the errors produce to reduce the steady state error, whereas the derivative gain is product of rate of change of the error. The function is to increase the reaction magnitude when there is a quick change in error. However, it is sensitive to noises such as disturbance in the electrical signal. fig. 6 shows the block diagram for control structure of cycle

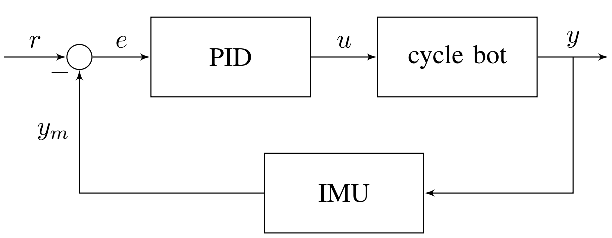


Fig. 6. Flow process of Cycle bot with PID.

This research paper based on auto-stabilizing the cycle bot, based on the PID controller and plot its simulation and physical implementation results. Balancing is done by controlling acceleration of reaction wheel to generate reaction torque to maintain upward vertical position of cycle.

### B. Tuning the PID parameters

For tuning process, we used the famous Ziegler-Nichols tuning method to tune the PID parameters. [4]The basic tuning steps are:

1) Set all gains to zero.
2) Increase the $K_p$ until the response to is steady oscillation starts diverging. This is called the ‘ultimate’ gain $K_u$.
3) Measure the ‘ultimate’ oscillation period $T_u$ at this state.

$K_u$ and $T_u$ can then be used to calculate values for $K_p$, $K_i$ and $K_d$, depending on the type of control algorithm implemented, according to the table below.

TABLE III
TABLE TO CALCULATE THE PID GAIN

| Control Type | $K_p$ | $T_i$ | $T_d$ | $K_i$ | $K_d$ |
|---|---|---|---|---|---|
| P | $0.5K_u$ | – | – | - | - |
| PI | $0.45K_u$ | $T_u$/1.2 | – | $0.54K_u/T_u$ | - |
| PD | $0.8K_u$ | – | $T_u$/8 | - | $K_u$ $T_u$/10 |
| Classic PID | $0.6K_u$ | $T_u$/2 | $T_u$/8 | $1.2K_u/T_u$ | $3K_u$ $T_u$ /40 |
| Pessen Integral Rule | $0.7K_u$ | $T_u$/2.5 | $3T_u$/20 | $1.75K_u/T_u$ | $21K_u$ $T_u$ /200 |
| Some overshoot | $0.33K_u$ | $T_u$/2 | $T_u$/3 | $0.66K_u/T_u$ | $K_u$ $T_u$/9 |
| No overshoot | $0.2K_u$ | $T_u$/2 | $T_u$/3 | (2/5)$K_u/T_u$ | $K_u$ $T_u$/15 |

### C. Navigation control

[5]To control the direction of the bicycle robot, a servomotor is used, which is directly connected to the front wheel and changes the directional angle. A 5V DC power supply is used to drive the servomotor to control the angle using the PWM duty cycle.

## V. Experiments

### A. Simulation Results

In this part we modelled and simulated the cycle bot in Coppeliasim (formerly V-rep) implementing PID controller. The result of simulation is shown in figure 7 and figure 8 below.

Where fig. 7 shows the inclination angle of cycle bot, the graph shows that at starting the bot is tries to fall but the reaction wheel balances it, bot has some oscillation at starting and tries to self-balance itself, after some time, the cycle bot successfully balances itself and as shown in the fig.7.

Fig.8 shows the variation of the torque of reaction wheel motor with respect to the inclination angle variation in figure 7, to balance the cycle bot.

### B. Physical Implementation Results

This part of the paper shows the behaviour of physical cycle bot in real environment which balances itself by the help of reaction wheel using PID controller.

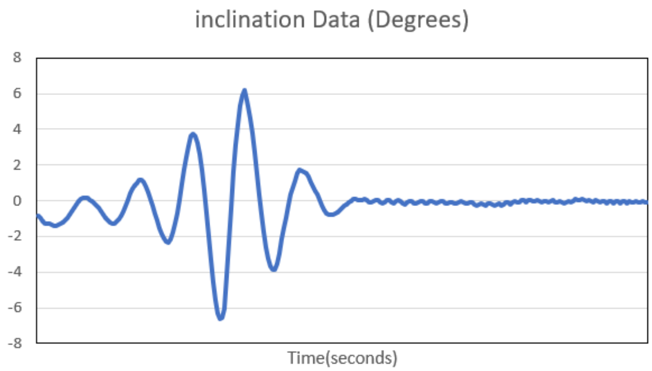


Fig. 7. Inclination

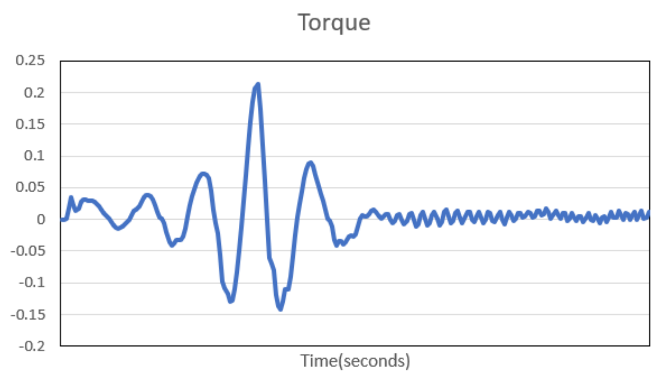


Fig. 8. Torque

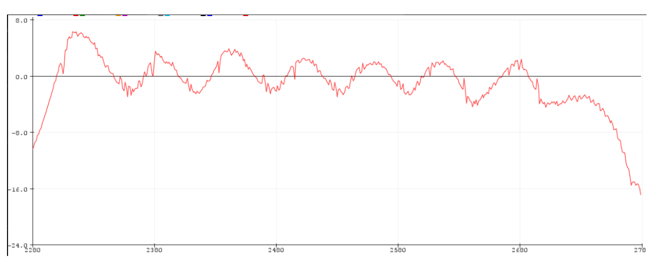

Fig. 9. Red line shows the inclination angle of the physical cycle bot

The above graph shows the inclination angle of the physical cycle bot. If we compare with the simulation results in figure.7, we can see that the physical implementation is not as smooth as the simulation because in simulation we have all ideal conditions possible and tuning in physical implementation is much harder. We used famous Ziegler-Nichols Method to tune the PID gains. With Ziegler-Nichols tuning method, even if the mathematical modelling unknown it is possible to balance it by evaluating the response of the system and tune each gain until a positive result is achieved.

If we notice in the graph of figure.9, after some time the angle of the cycle bot is oscillating for some time and trying to balance and and then falling. This is because of recovery angle. Recovery angle is the maximum angle from which the cycle bot can recover its upright position. If the bot exceeds the recovery angle than it is very hard for the cycle to recover from that position.

From experiments, we estimated that our cycle bot has approximately +/- 3 degrees of recovery angle.

## VI. Conclusion and Future works

In this paper, we studied stabilization of a self-balancing cycle bot with a reaction wheel under voltage input constraints, where the objective is to balance the cycle bot at the upright position. Simulation results showed that the cycle bot has been successfully stabilized by using PID controllers. In PID, proportional gain is responsible for amplifying the error; integral gain is to reduce the steady state error; derivative is sensitive in change in error. The results also shows that the cycle bot has very little recovery angle because of lower torque and RPM ratings of reaction motor, if the cycle bot body angle exceeds that even because of environmental noise or disturbance, it will not be able to stabilize or recover to the upright position. The controller performance is verified in both the virtual and real environment and the above results shows concrete proof that an cycle bot can be balanced using PID controller.

In future, we try to add some extra element into it like sensors for perception to make the cycle bot to make partial or fully autonomous to make decision on its own or with some little help of users to make the ride smooth.

## Acknowledgment

This work is supported by Ministry of Human Research and Development(MHRD), INDIA. And done under E-yantra summer internship program(EYSIP-2020), Eyantra IIT Bombay.

## References

[1] Kiattisin Kanjanawanishkul, “LQR and MPC controller design and comparison for a stationary self-balancing bicycle robot with a reaction wheel” Kybernetika, Vol. 51 (2015), No. 1, 173–191.

[2] Hyun-Woo KIm , Jae-Won An ,Han ong Yoo ,an Jang-Myung Lee, “Balancing Control of Bicycle Robot Using PID Control,” 2013 13th International Conference on Control, Automation and Systems (ICCAS 2013) Oct. 20-23, 2013 in Kimdaejung Convention Center, Gwangju, Korea.

[3] Yon Yaw Lim1, Choon Lih Hoo2, and Yen Myan Felicia Wong1 ”Stabilising an Inverted Pendulum with PID Controller,” MATEC Web of Conferences 152, 02009 (2018) Eureca 2017.

[4] ”https://arduinoplusplus.wordpress.com/2017/06/21/pid-control-experiment-tuning-the-controller/”.

[5] Yunki Kim, Hyunwoo Kim and Jangmyung Lee1, ”Stable control of the bicycle robot on a curved path by using a reaction wheel”, Journal of Mechanical Science and Technology 29 (5) (2015) 2219 2226.

[6] Jepsen, F., Søborg, A., Pedersen, A. R., & Yang, Z. (2009). ”Development and Control of an Inverted Pendulum Driven by a Reaction Wheel”, In The 2009 IEEE International Conference on Mechatronics and Automation (pp. 2829-2834). IEEE. https://doi.org/10.1109/ICMA.2009.5246460.

[7] Pratik Raut, Shabbir Karjatwala, Shishir Kadam, ”Dynamic Modelling, Simulation & Control Design of Drive & Reaction Wheel Balancing Bot”, DOI:10.15680/IJIRSET.2016.0505112.

[8] Olfa Boubaker, ”The inverted Pendulum: A fundamental Benchmark in Control Theory and Robotics”, National Institute of Applied Sciences and Technology INSAT, Centre Urbain Nord BP. 676 – 1080 Tunis Cedex, Tunisia.