

## Design and prototype model for smart autonomous self-balancing bicycle

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### Article Info

#### Article history:

Received Dec 11, 2025

Revised Jul 25, 2026

Accepted Aug 28, 2026

#### Keywords:

Autonomous vehicle

BLDC motor

Dynamic system simulation

Gyroscope and flywheel  
mechanism

MATLAB analysis

Self-balancing

### ABSTRACT

There are still a huge demand for safe and sustainable modes of transport which has led to the creation of autonomous self-balancing bicycles. The design and analysis of the self-balancing bicycle with flywheel mechanism assisted by gyroscope is presented in this study. A Lagrangian approach was used to model the tilt dynamics; it includes kinetic energy, potential energy, damping and actuator torque generated by the BLDC motors. The nonlinear system was linearized around the upright equilibrium for control implementation and simulated in MATLAB. Results indicate that an initial lean disturbance is stabilized within about 1 s, and that the motor current also reaches steady state values, thus signifying efficient use of energy. The gyroscopic response trends corroborate the realistic tilt sensing and the effectiveness of the proposed stabilization framework is confirmed for autonomous operation on straight and curved paths.

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## 1. INTRODUCTION

The bicycle is a common means of transport, recreation and fitness, but it is still a challenge to keep the bicycle stable, especially in autonomous system. To make bikes more balanced, safe and easy to handle, it is crucial to understand their dynamics. Gyroscopic stabilization has proven to be an effective method to improve the stability while reducing the effects of external disturbances. The proposed smart autonomous self-balancing bicycle is comprised of a mobile application, Wi-Fi enabled microcontroller, sensors, gyroscope, BLDC motor and computer vision modules. The microcontroller serves as the central processing unit, handling the sensor data and implementing balancing and navigation algorithms. This integrated architecture allows for seamless communication, control and autonomous operations, guaranteeing safe and intuitive riding performance. The general scheme and flow of the system is shown in Figures 1 and 2.

Gyroscopic stabilization has been shown to work in the self-balancing vehicles. Using inertia-wheel pendulums on self-balancing electric motorcycles demonstrated strong stabilization results but led to a more complex control system [1], [2]. Implementation problems were also pointed out by practical gyroscope-based prototypes and the need for accurate control of gyroscopic forces for stability was highlighted [3], [4]. There is also been a lot of focus on autonomous navigation capabilities. Wavelet transforms and moving edge detection for automatic video object segmentation showed improved object recognition for autonomous systems [5], [6]. Prototype validation tests of self-stabilizing two-wheelers highlighted the need for precise nonlinear dynamic modeling and effective control approaches [7]. The studies of gyroscopic stabilization

configurations and control mechanisms also provided basic knowledge to enhance the balance and maneuverability of self-balancing bicycles [8]-[10].

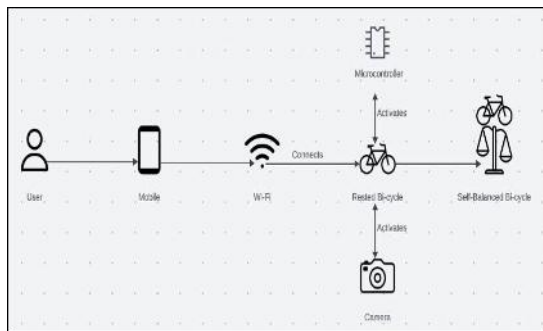


Figure 1. Overall framework

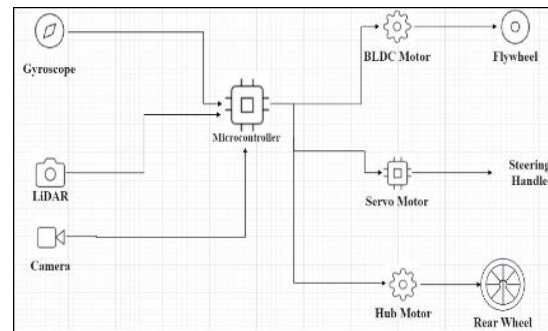


Figure 2. Design components and system flow

The fusing of visual and inertial sensing has greatly enhanced the ability to achieve environmental awareness and autonomous navigation performance. Integration of vision systems and inertial measurements showed improvements in perception and navigation accuracy, however, sensor fusion and system complexity were challenges [11], [12]. With the advent of deep-learning based computer vision, autonomous vehicles have been able to further develop their capability to detect objects, understand scenes and navigate their way around [13], [14]. Implementation studies have been conducted in the fields of motor control, processing with microcontroller, IoT aspects and adaptive navigation strategies. The studies on autonomous vehicle motor control and embedded processing highlighted the need for efficient real-time computation [15], [16]. Other more sophisticated traffic-sign detection algorithms have also demonstrated great promise for urban autonomous navigation, facing difficulties due to changing environmental conditions [17]. In addition, mechanical gyro-wheel stabilization approaches [18] and adaptive fuzzy-guidance approaches [19] have been investigated, which have furthered the development of autonomous balancing technologies. As a whole, these studies provide a solid basis for the design of a gyroscopically stabilized and autonomously steered bicycle [20].

Advanced control techniques have become a recent focus of research. Sliding mode controllers based on a neural network have been found as an effective tool in stabilizing nonlinear robotic systems [21], [22], state space modelling approaches have been found as an effective way of representing and controlling robotic systems [23]. But most of the current research is focused on designing controllers and on the controller's stabilization performance, neglecting the energy-saving and efficiency aspects at the actuator level. In the fast-evolving world of electric mobility, energy-efficient control architectures are increasingly gaining significance, especially for battery powered autonomous bicycles [24]. At the same time, multi-sensor fusion systems that combine vision systems and LiDAR have made substantial strides in perception and navigation precision [25], [26].

There is a lack of investigations that focus on a comprehensive framework that includes dynamic modeling, performance evaluation using simulation and energy-efficiency analysis. In order to overcome this drawback, the present work is a blend of Lagrangian-based dynamic modeling, simulation analysis using MATLAB and experimental validation in one single platform. Besides stability, other actuator-level properties like torque-speed curve and current-response dynamics are also examined to assess the efficiency and controllability of the system. The proposed framework adds the system level modelling along with the actuator characterization and is a complete methodology which helps to evaluate the effectiveness of the stabilization methods, the energy usage and the real-time control performance of autonomous self-balancing bicycles.

## 2. PROPOSED DESIGN OF BICYCLE

The proposed methodology is based on the combination of several subsystems to create a smart autonomous self-balancing bicycle like the one shown in Figure 3. To ensure the safe and efficient operation of the system, autonomous navigation, propulsion, control and gyroscopic stabilization are all combined.

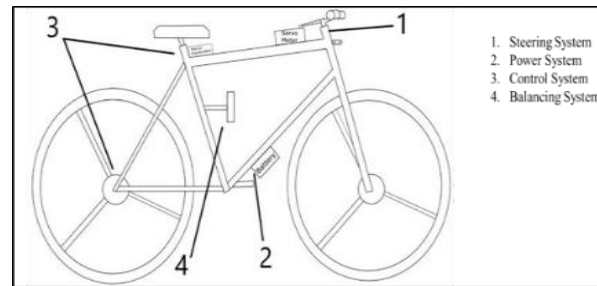


Figure 3. Proposed system design for autonomous and self-balancing driving

The subsystem of autonomous driving is responsible for the control of the direction of movement and perception of the environment. It combines a camera, LiDAR sensor, servo motor and computer vision algorithms. The microcontroller processes the visual and depth data that is received from the camera and LiDAR, then outputs commands for steering. These commands are used to control a servo motor attached to the handlebar for real time path corrections, obstacle avoidance, traffic detection and mapping of the environment. A steering mechanism based on perception thereby enables accurate autonomous navigation in dynamic environment. The power subsystem includes a rechargeable battery system with a battery management system (BMS) to control and manage voltage, current, and temperature, and to maximize the use of the energy stored in the battery. Energy recovery is also possible on deceleration with regenerative braking to increase the range of operation and enhance the overall efficiency of the system. Propulsion and control subsystem is the decision-making core of the bicycle which is described in Figure 4. As shown in Figure 4(a), the control system integrates the microcontroller with the hub motor which will be mounted on the rear wheel and communication peripherals which include LiDAR and Camera inputs, while Figure 4(b) illustrates the hub motor which will be mounted at the rear wheel. The microcontroller receives navigational input and sends control signals to the hub motor, continuously provides feedback to adjust the speed, acceleration, and braking based on environmental conditions and obstacle information, ensuring smooth and reliable operation.

The balancing of bicycle is achieved by integrating microcontroller, gyroscope sensor, BLDC Motor and flywheel as shown in Figure 5. The gyroscope senses any tilt changes which are fed to the microcontroller and corrective torque commands are generated. The BLDC motor spins the flywheel at a very high rate, creating gyroscopic and inertial forces which oppose lean disturbances and keep the flywheel upright – especially when the motor is operating at low speed. The perception-based steering in combination with the energy-saving power management, feedback-controlled propulsion and reaction torque balancing, form an overall framework for autonomous mobility.

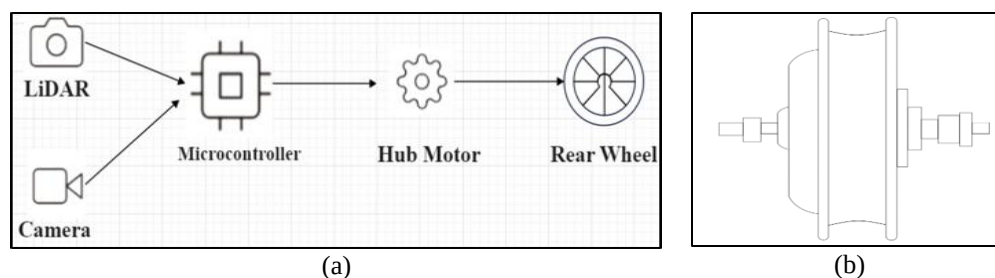


Figure 4. Propulsion and control system: (a) components of control system and (b) front view of the hub motor

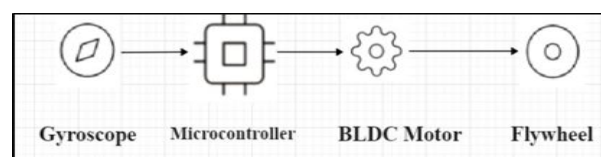


Figure 5. Components of balancing system

The MPU6050 Gyroscope Accelerometer module is used in tilt sensing. A continuous measurement of the angular motion and acceleration of the sensor enables the bicycle's inclination to be detected accurately. The bicycle is nominally upright ( $90^\circ$ ) when in operation. The control unit receives information about whether the tilt is within or outside of the set range. The MPU6050 delivers high-quality motion-sensing, and is ideal for self-balancing use and the central processing unit of the system is the ESP32 microcontroller. Figure 6 presents the main electronic sensing and control components used in the bicycle, Figure 6(a) shows the MPU6050 gyroscope sensor, while Figure 6(b) shows the ESP-32 microcontroller. The MPU6050 is interfaced with the ESP32 using the designated I2C pins for data communication. It offers a considerable processing power, low energy usage and communication through Wi-Fi and Bluetooth, which helps in the real-time processing of data and wireless communication. A special printed circuit board (PCB) is responsible for the sensor data transmission ensuring reliable communication, power distribution and coordinated operation of all electronics. A BLDC motor is used to produce the stabilizing torque needed for balancing by connecting it with a flywheel. The motor's brushless technology ensures it operates smoothly and efficiently, has low maintenance, and a longer service life. The flywheel has a high moment of inertia and therefore has the ability to store rotational energy and to resist the sudden change of orientation of the bicycle. When external disturbances such as uneven terrain or abrupt motion occur, the flywheel's rotational inertia opposes these disturbances, enhancing stability and ride comfort.

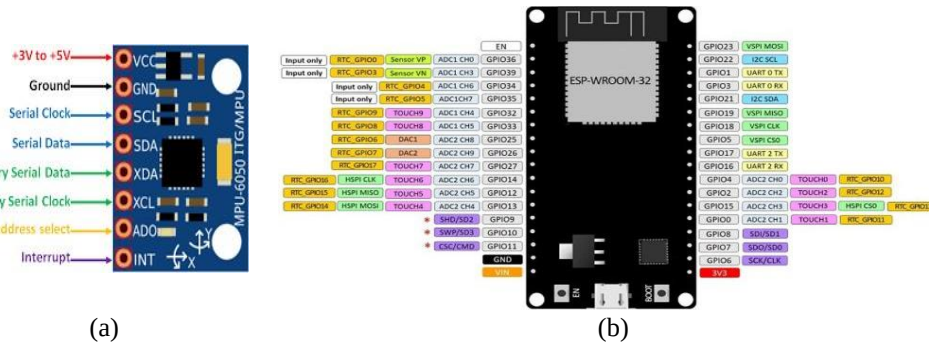


Figure 6. Circuit configuration: (a) MPU6050 (Gyroscope sensor) and (b) Microcontroller ESP-32

### 3. MATHEMATICAL MODELLING OF BALANCING MECHANISM

To give the system analytical tractability and the ability to implement it in real time, it is modeled with a number of assumptions. It is estimated that the bicycle is an inverted pendulum with a reaction-wheel (flywheel) stabilizing system. It is assumed that the motion is planar (no dynamics in the yaw direction), and the small-angle approximation ( $\sin\theta \approx \theta$ ) is used around the upright equilibrium. The flywheel is assumed to be a rigid body, having constant moment of inertia and the losses due to friction are modeled by linear damping coefficients. Stability and response requirements influence the system parameter choices. The flywheel inertia has been selected to give enough angular momentum to quickly correct the tilt, and the BLDC motor torque constant has been selected to generate enough torque ( $\sim 6$  Nm) during initial disturbance. The damping coefficient is adjusted to reach a settling time of less than 1 second, without oscillation. The operating current range ( $\sim 3.4$  A peak to  $\sim 2.2$  A steady-state) is chosen to trade between actuation and energy efficiency.

The self-balancing system is a dynamic system whose behavior is modeled by the representation of the bicycle body flywheel assembly as a coupled rotational system with rigid body motion and electromechanical actuation. The lean angle of the bicycle frame is indicated as  $\theta(t)$ , and  $\phi(t)$  is the angular displacement of the flywheel. The approach that is used to develop the system model is as follows. The first step was to define the generalized coordinates and physical parameters of the system which included mass, the lengths of the links, distribution of inertia, damping coefficients and the motor torque constants. Bicycle frame and flywheel were supposed to rotate in mutually perpendicular planes and the components of kinetic energies were considered separately. The total kinetic energy was then developed as  $T = T_1 + T_2$ , where  $T_1$  is associated with frame motion and  $T_2$  is associated with flywheel rotation. The gravitational potential energy of the lean of the frame was:

$$V = mgl(1 - \cos \theta)$$

where  $m$  is the equivalent mass,  $g$  is gravitational acceleration, and  $l$  is the effective height of the center of mass.

The system dynamics were formulated using the lagrangian expression:

$$L = T - V$$

and the governing equations of motion were derived using the lagrange–euler formulation:

$$\frac{d}{dt} \left( \frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} = Q$$

where  $q = [\theta, \phi]$  and  $Q$  represents generalized torques acting on the respective coordinates. Dissipative effects arising from frictional and aerodynamic losses were included through rayleigh damping terms of the form  $D = \frac{1}{2} C_1 \dot{\theta}^2 + \frac{1}{2} C_2 \dot{\phi}^2$ .

Motor torque was expressed using the electrical model of a BLDC drive as:

$$\tau_m = K_t I, V = K_b \dot{\phi} + I R_a$$

where  $K_t$  is torque constant,  $K_b$  is back-EMF constant,  $R_a$  is armature resistance, and  $I$  is supply current. This electromechanical contact allowed the flywheel actuation to be included in the dynamic system. With the small-angle assumption  $\sin \theta \approx \theta$ , the ensuing nonlinear equations were then linearized about the upright equilibrium (0 0). The controller development and stability analysis were then done using the linearized model. In this modeling technique, the dynamic interplay between tilt response, actuated flywheel torque and sensing feedback was determined which is the foundation of the analysis to optimize performance and verify it experimentally in the following sections.

## 4. RESULTS AND DISCUSSION

### 4.1. Gyroscope reading for tilt detection

The proposed autonomous self-balancing bicycle illustrates the possibility of using gyroscopic stabilization, feedback control and embedded electronics in the design of an intelligent system for personal transportation. The stability requires a correct tilt detection which is provided by the sensor MPU6050, a gyroscope that measures the angular motion that the robot undergoes around the X, Y and Z axis in real time. The X-axis plots the predominant lean-angle changes that are used for balance correction and the y-axis plots the secondary lateral motion that is related to recovery actions. These measurements allow for accurate estimation of the bike's orientation and offer the feedback for dynamic stabilization.

A small-scale 3D-printed bicycle prototype was developed including a flywheel, BLDC motor, servo motor, ESP32 microcontroller, gyroscope sensor, and rear drive motor as depicted in Figure 7 to validate the concept. The prototype shows the arrangement and integration of the subsystems proposed. The detailed experimentation set up of the proposed circuit is shown in Figure 8. Various working components used to build control system are presented as: Figure 8 (a) shows the L298N motor driver to drive BLDC motor which control flywheel, Figure 8(b) shows the ESP-32 microcontroller which is main processing unit, and Figure 8(c) shows the MPU6050 sensor. The MPU6050 integrates both gyroscope and accelerometer sensors to capture both tilt and rotational movements, and the ESP32 offers real-time processing and wireless communication. The L298N motor driver is used to control the BLDC motor speed and direction for balancing operations.

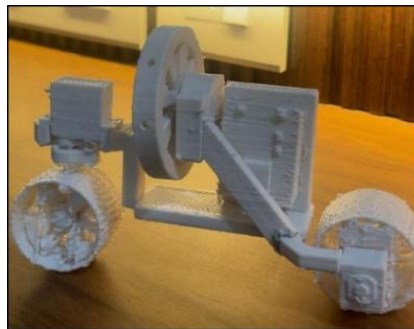


Figure 7. 3-D printed model

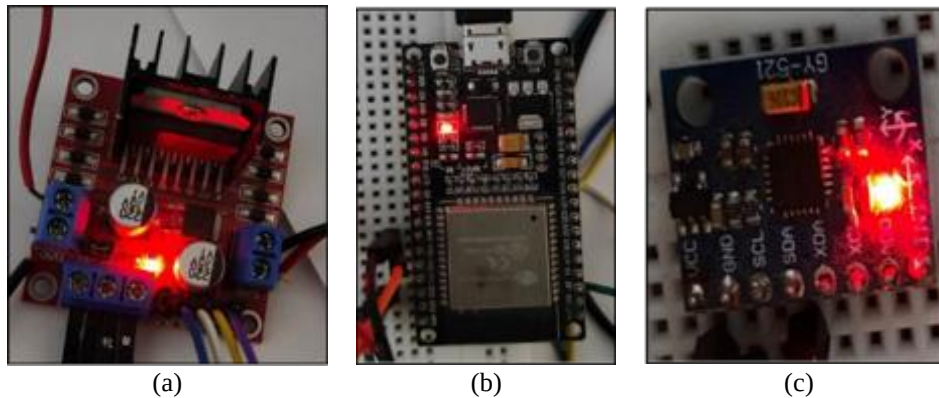


Figure 8. Circuit setup for experimental validation: (a) L298N motor driver, (b) ESP-32 microcontroller, and (c) MPU6050 sensor

The circuit configuration of these components was connected in a breadboard as illustrated in Figure 9. The core balancing mechanism is the integration of sensors, controller, BLDC motor and flywheel for autonomous response to disturbances. The gyroscope constantly detects the angular displacement and sends out the angle information to the controller, which controls the motor action to return to balance.

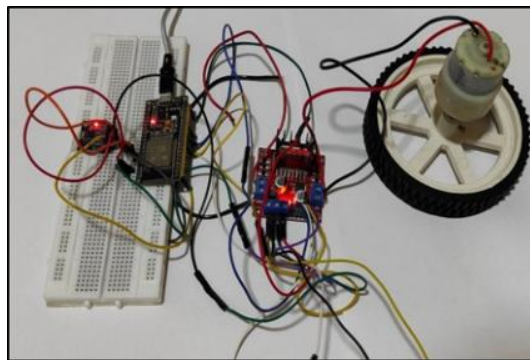


Figure 9. Experimental circuit setup for self-balance system

The values measured using the gyroscopes with X-axis rotational changes of around  $3^\circ$ , Y-axis of  $1^\circ$  and Z-axis of  $0.2^\circ$ . The larger X axis variation validates that the roll motion is the main balancing factor and the small Z axis response helps to ensure that there is no unwanted rotational drift. These findings show that the sensor can detect even slight deviations of the angle, allowing timely corrective measures so to keep the bicycle stable. The successful prototype validation validates the feasibility of the self-balancing design and paves the way for future applications in urban mobility, delivery systems, and intelligent robotic platforms. The flywheel-assisted balancing system, working with the electronic control system, increases stability, dynamic performance and efficiency of the energy utilization. Considering the huge scope of problem statement the experimentation and validation carried out for self-balancing is only described in this paper. The successful demonstration of a self-balancing design showcases the capability to provide stability and control in dynamic environments, laying the groundwork for future applications in transportation and robotics. If the project proves successful, it may lead to opportunities for commercialization, with the potential for autonomous bicycles to be used in various applications such as urban mobility, delivery services, and recreational activities.

#### 4.2. MATLAB simulation results

MATLAB simulations were carried out to analyze the dynamic performance of the proposed self-balancing mechanism. The tilt stabilization response to an initial leaning disturbance of  $\sim 8^\circ$  is shown in Figure 10. This reaction torque generated by the controller shows a damped oscillatory behavior and is able to restore equilibrium within about 0.8-1.0 seconds. There is a small negative under shoot because

momentum is transferred through the flywheel system, but the lack of sustained oscillations indicates that the damping and closed loop system is effective and stable. The fact that the zero-tilt point is reached so quickly shows that the gravitational destabilizing forces are overcome by the corrective torque. The stabilization response shows that the bike is able to withstand low-speed perturbations and initial instabilities before the onset of the usual velocity-dependent gyroscopic effects. The short settling time verifies the effectiveness of the mathematical model and demonstrate the use of the reaction-wheel balancing strategy in real time implementation. The response of the gyroscope while in the balancing operation is shown in Figure 11. The roll-angle corrections are the largest on the X-axis, where the roll angle varies by around  $\pm 3^\circ$ . The resulting Y-axis shows that the lateral adjustments are causing smaller oscillations and the Z-axis is close to zero, showing that there is not much yaw. The separation between the 3 axes is clearly defined, which shows that the sensor can detect an independent directionality from each of the three axes. These measurements send a more accurate tilt error to the controller, minimizing the delay for the controller to respond, and enhancing the stabilization performance.

The torque speed characteristics of BLDC actuator is depicted in Figure 12. The motor has maximum corrective torque of about 6 Nm at low rotational speed, providing a fast flywheel acceleration and immediate disturbance rejection. Torque slowly decreases with increasing rotational speed, because of the effects of back-EMF. This action validates that high power is required only during major correction events, and low torque and low power use are adequate when equilibrium is reached. Hence, the stabilization mechanism has inherent energy adaptive properties that are beneficial for battery operated systems. The transient current response of the actuator is displayed in the Figure 13. When the motor is subjected to disturbance correction, it pulls a peak current around 3.4 A for fast flywheel acceleration and corrective torque generation. The tilt error decreases, and the current consumption exponentially decreases to steady state value of around 2.2 A. Smooth stabilization without oscillatory control actions is verified as there are no secondary current spikes. This behaviour shows efficient use of energy, less heat stress of the power electronics and better life time of the actuators.

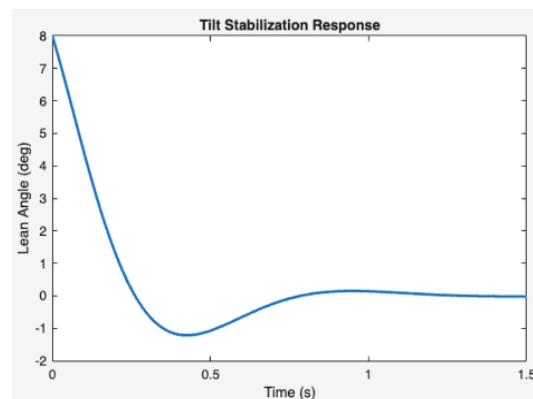


Figure 10. Tilt stabilization response curve showing the dynamic recovery from an initial lean angle disturbance of approximately  $8^\circ$ , converging to an upright equilibrium position through controlled damping

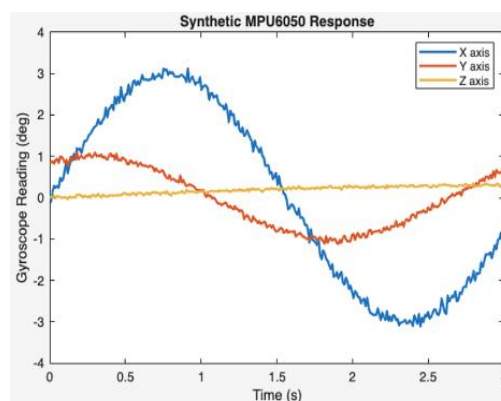


Figure 11. Synthetic MPU6050 gyroscope response showing dynamic tilt variations captured along X, Y, and Z axes during controlled balancing trials

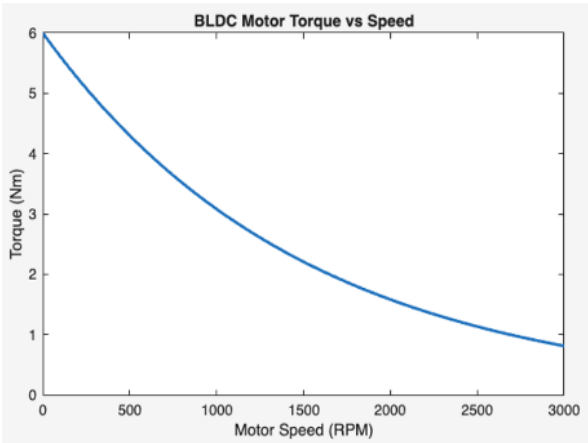


Figure 12. Torque–speed characteristic of the BLDC actuator demonstrating high resisting torque at low rotational speeds and exponential decay with increasing RPM

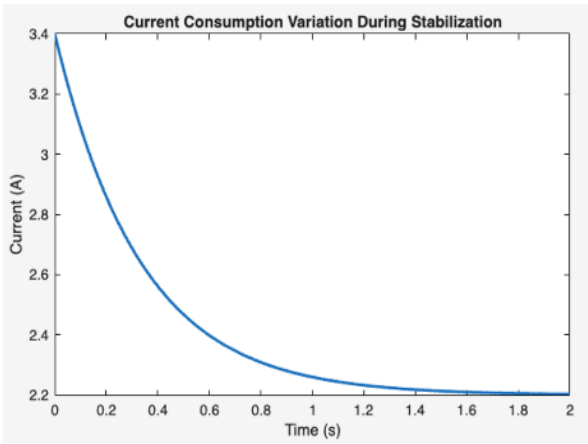


Figure 13. Transient current behavior showing peak demand at the onset of stabilizing action followed by exponential decay once equilibrium is achieved

The quantitative performance metrics obtained from simulation are summarized in Table 1. The simulation and experimental results validate, in general, the proposed stabilization framework based on a flywheel which shows fast rejection of the disturbances, reliable closed-loop control, accurate tilt sensing, and efficient use of the energy. It is a second order under damped dynamic system, which reaches equilibrium state in a quick manner and has high balancing precision. Although these positive outcomes have been achieved, some restrictions exist. Small-angle approximations are used in the mathematical model that could result in decreased accuracy for large tilt disturbances. The effect of sensor noise, latency, and calibration error were not explicitly addressed, and the analysis is mainly for stationary or low speed balancing conditions. Limitations in future work will include nonlinear dynamic modeling, further development in sensor-fusion techniques and experimental validation outdoors under realistic operating conditions.

Table 1. Performance evaluation metrics

| Parameter                 | Value      | Description                   |
|---------------------------|------------|-------------------------------|
| Initial tilt angle        | ~8°        | Input disturbance             |
| Settling time             | ~0.8–1.0 s | Time to reach steady state    |
| Maximum torque            | ~6 Nm      | Peak corrective torque        |
| Peak current              | ~3.4 A     | During disturbance correction |
| Steady-state current      | ~2.2 A     | After stabilization           |
| Sensor variation (X-axis) | ±3°        | Gyroscope response            |
| Oscillation count         | 1 cycle    | Indicates damping             |

## 5. CONCLUSION

The new design of self-balancing bicycles marks a new paradigm of sustainable and intelligent mobility, which supports road safety and increases the accessibility of riders. The current paper not only shows that autonomous stabilization is a viable method with the help of hardware integration, but also confirms the behavior of the system by mathematical modelling and simulation analysis. The resulting dynamic model, which was obtained by applying Lagrangian principles and electromechanical coupling, is valid in the dynamics of tilt, and the linearized version was used to evaluate the analytical stability. The theoretical model was supported by the MATLAB-based simulations that showed that an initial lean disturbance stabilizes in about one second with no secondary oscillation, which is the evidence of the high damping control and real-time responsiveness. Gyroscopic sensor reaction also confirmed the accurate measurement of tilt, and the profile of torque-speed and current variation confirmed the energy-efficient actuation, with the maximum demand confined to disturbance correction periods. These findings verify that the suggested architecture, which consists of gyroscope, flywheel, BLDC motor and embedded controller can be effectively used to provide autonomous stabilization.

## ACKNOWLEDGEMENT

The authors would like to acknowledge Marathwada Mitra Mandal's College of Engineering for providing the facilities and technical support required for conducting the 3D printing experiments and MATLAB-based analysis.

## FUNDING INFORMATION

No funding support is received for the conducting this research work.

## AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nvestigation

R : **R**esources

D : **D**ata Curation

O : Writing - **O**riginal Draft

E : Writing - Review & **E**diting

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

## CONFLICT OF INTEREST

Corresponding author declares that there no conflict of interest.

## DATA AVAILABILITY

The research related to animal use has been complied with all the relevant national regulations and institutional policies for the care and use of animals.

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