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Static and dynamic stability evaluation of an electric remote-controlled lawn mower robot

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ABSTRACT

Ensuring stability is a critical challenge for outdoor mobile robots operating on uneven terrain, where rollover and tip-over risks can compromise safety and performance. Despite extensive development of lawn mower robots, the quantitative evaluation of their static and dynamic stability under real operating conditions remains limited. This study proposes an integrated stability assessment framework that combines theoretical static and dynamic stability analysis with real-time inertial measurement unit (IMU) monitoring in a remote-controlled electric lawn mower robot. An MPU6050 sensor continuously measures roll and pitch angles during operation, enabling direct validation of theoretical predictions with experimental data. Experimental results show that the robot reaches rollover and tip-over limits of approximately ±44° and ±30°, respectively, under static conditions, consistent with predictions from the static stability factor (SSF) model. In dynamic testing, a maximum tilt angle of 4.3° was observed at 3.24 km/h, while theoretical analysis estimates a critical speed of 14 km/h at a tilt angle of 44.5°. These results demonstrate good agreement between theory and experiment and highlight the effectiveness of the proposed approach for real-time stability evaluation.

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1. INTRODUCTION

Mobile robots are increasingly used in agriculture and outdoor automation to improve efficiency, safety, and productivity. Conventional fossil-fueled lawn mowers are still widely used but produce harmful exhaust emissions and high noise levels [1]–[4]. Battery-powered electric lawn mowers offer a cleaner and quieter alternative with lower maintenance requirements [5], [6]. However, both traditional and manual mowing methods can be time-consuming and result in uneven cutting [7], [8].

To address the limitations of conventional and electric mowers, various lawn mower technologies have been developed. Lawn mower systems have evolved from manual and electric machines to remotely controlled and autonomous robotic platforms. One such technology is a remotely controlled lawn mower robot, which offers significant advantages for agricultural and plantation systems [1], [2], [9], [10]. This technology improves work efficiency, reduces manual workload, and reduces user risks under different environmental conditions [11]. In mobile robotics, operational stability is crucial, as outdoor robots must navigate uneven terrain safely without excessive roll or pitch angles that can cause accidents or system failures.

Despite these technological advances, existing studies mainly emphasize navigation capability, obstacle avoidance, and cutting performance, while comprehensive stability evaluation remains limited. Most previous studies analyze robot stability only under static conditions or use simplified theoretical approaches without continuous real-time validation during actual operation. Moreover, previous work rarely integrates theoretical stability analysis with sensor-based monitoring frameworks that can dynamically evaluate robot behavior in outdoor environments. Consequently, there is still a gap between theoretical stability prediction and practical robotic deployment in real operating conditions.

Operational stability is a key consideration in lawn mower robot design to prevent rollovers caused by excessive pitch and roll angles [12]. Stability is influenced by factors such as mass distribution, center of gravity, and dynamic forces during motion [13], [14]. Static stability can be evaluated using the static stability factor (SSF), which determines the maximum safe tilt angle before rollover [15], [16], while dynamic analysis considers in-motion forces such as centrifugal force [17]. Robot orientation can be monitored using an MPU6050 IMU, which measures acceleration and angular velocity [18], [19].

This study specifically focuses on operational stability and proposes an integrated approach combining static and dynamic stability analysis with real-time IMU-based monitoring for a remote-controlled electric lawn mower robot. By enabling continuous validation of stability behavior during operation, this method directly addresses the gap between theoretical analysis and real-world deployment. Therefore, the objective of this study is to develop and experimentally validate an integrated stability evaluation framework that combines SSF-based static analysis, dynamic stability analysis, and real-time IMU monitoring for a remote-controlled electric lawn mower robot. Additionally, the study quantitatively validates theoretical stability predictions against experimental sensor measurements to improve the reliability of outdoor mobile robotic systems operating on uneven terrain.

2. LITERATURE REVIEW

The development of robotics technology has driven innovations in agricultural automation, especially in lawn-mower robot systems. Previous studies have mainly focused on control methods, energy systems, sensing technologies, and navigation strategies. Chen [10] proposed a Bluetooth-based solar-powered lawn mower robot. This robot uses ultrasonic and PIR sensors for obstacle avoidance and motion detection, and an Arduino Pro Mini for motor control. In contrast, study in [20] developed an Android-operated robotic lawn mower. It uses Arduino Uno, Bluetooth communication, ultrasonic sensing, and cloud-based obstacle monitoring. Meanwhile, Bhosale *et al.* [21] focused on creating a smart lawn mower architecture. This design integrates solar energy, wireless smartphone control, and IR/ultrasonic-based obstacle detection. It also includes advanced features like path planning and smart-home connectivity. Unlike these studies, Jabbar *et al.* [22] emphasized the fabrication of a remotely controlled solar grass cutter. This mower uses an Arduino Uno and high-speed DC motors for extended operational endurance.

Meanwhile, Balakrishna and Rajesh [1] developed an Arduino UNO-based IoT lawn mower integrated with the Blynk application, Bluetooth communication, and ultrasonic sensors for obstacle avoidance. In contrast, study in [23] proposed a remotely operated lawn mower using NodeMCU ESP8266 and mobile-phone-based video transmission for real-time remote monitoring and control. Tahir *et al.* [24] introduced a solar-powered IoT lawn mower integrating a Raspberry Pi, an Arduino UNO, and Android-based remote operation, with edge computing capabilities for wireless data communication. Different from these systems, the study in [25] focused on a fully IoT-based autonomous lawn mower equipped with embedded sensors, cloud connectivity, mobile application control, and intelligent navigation for automated lawn maintenance.

Other studies have explored enhanced sensing, interaction, and intelligent behavior in lawn mower robots. For instance, Daniyan *et al.* [11] presents a prototype system integrating GPS, camera, infrared, and ultrasonic sensors for obstacle detection and navigation, while Kumar *et al.* [26] introduces gesture-based control, allowing users to operate the robot through hand movements without physical interfaces. In addition, Hutauruk *et al.* [13] develops an autonomous robot based on image recognition and infrared sensing, with multiple operational modes, including slow, inching, and obstacle-avoidance modes. Furthermore, Zushida *et al.* [27] applies machine learning techniques using a random forest algorithm to estimate grass height and soil conditions, enabling adaptive adjustment of cutting motor speed for improved performance consistency. Energy-efficient operation and path optimization are also addressed in [6]. ARM9-based architectures and optimal coverage path planning (CPP) methods are used to improve navigation efficiency, reduce

energy consumption, and ensure systematic area coverage [28].

Despite these developments, most of the existing studies focus primarily on control, navigation, sensing, autonomy, and energy optimization. The stability analysis of lawn mower robots is still underinvestigated. In particular, previous work rarely considers the effect of uneven or sloped terrain on robot stability. Most evaluations rely on static assumptions or are based on simulations. Additionally, dynamic stability during real robot operation has not been adequately analyzed. Integration of theoretical stability modeling with sensor-based real-time validation is still limited. Additionally, although several studies have developed advanced lawn mower robots, the issue of operational stability under real field conditions remains underexplored. Stability is a critical aspect of mobile robot design. It is strongly influenced by the mass distribution and the center of gravity (CoG) [13], [29]–[31]. A lower center of gravity improves resistance to rollover and tip-over, especially on uneven terrain.

A qualitative comparison of previous lawn mower robotic systems further indicates that existing studies primarily emphasize remote control, autonomous navigation, obstacle avoidance, IoT connectivity, and energy efficiency, whereas quantitative stability evaluation remains largely absent. In particular, most previous studies do not report critical roll or pitch angle limits, SSF, or experimentally validated stability measurements under real operating conditions. Consequently, direct numerical benchmarking of rollover-related performance is difficult because comparable stability metrics are limited in prior studies. This limitation highlights the need for a robotic stability evaluation framework that combines theoretical stability analysis with real-time experimental validation during actual operation.

Based on these gaps, this study focuses on the design and implementation of a remote-controlled electric lawn mower robot with integrated real-time stability monitoring. Unlike previous studies, the proposed framework integrates static and dynamic stability analysis with real-time IMU-based monitoring using an MPU6050 sensor, enabling continuous measurement of roll and pitch angles and experimental validation of theoretical predictions. This approach bridges the gap between theoretical stability analysis and real-world validation, and enhances operational safety and reliability in agricultural robotic applications.

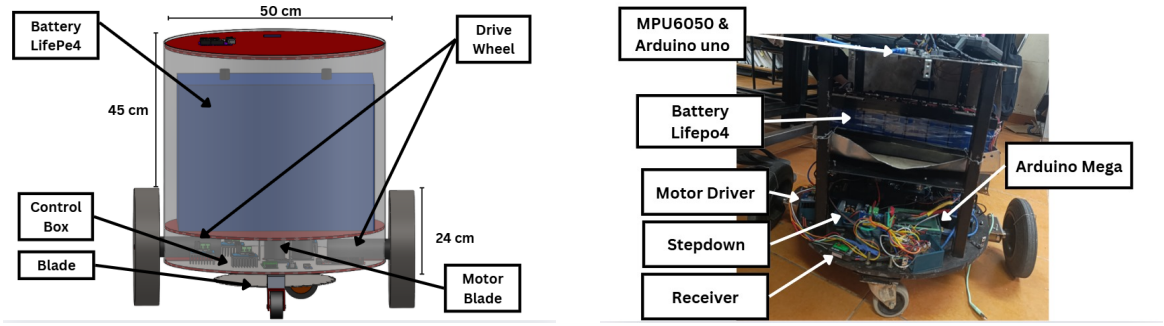
3. METHOD

3.1. Robot design

The lawn mower robot has a cylindrical design with a diameter of approximately 50 cm, a height of 45 cm, and a wheel-to-wheel spacing of 68 cm. The frame is made of lightweight metal to provide strength while reducing overall weight. The wheels are positioned about 9 cm above the ground, and a 25 cm cutting blade is mounted underneath to ensure uniform grass cutting on uneven terrain. Figure 1 presents the overall design and implementation of the robot. Figure 1(a) shows the 3D design developed in SolidWorks, enabling efficient visualization and component arrangement before fabrication. The mechanical design was developed for functional implementation and did not include advanced simulations such as finite element analysis (FEA) or virtual stability testing.

As a result of the design process, Figure 1(b) shows the final implementation of the lawn mower robot, shown without the casing, making the internal components clearly visible. The frame structure and outer casing are built from sheet metal, chosen for its durability under load and vibration, as well as its ease of cutting and shaping during fabrication. The drive frame system is designed to support stable and efficient movement on flat surfaces. The main components of the drive system include DC motors, motor drivers, the frame, and wheels, all arranged to ensure stability during operation. The proposed design provides a practical platform for evaluating stability, which is a key requirement for reliable outdoor mobile robotic applications.

In this study, the lawn mower platform is designed as a mobile robot intended for outdoor operation on uneven terrain. The mechanical structure and drive system were developed to support stable mobility and robotic safety monitoring during operation. Although the robot currently uses remote control, the system architecture is compatible with future integration of autonomous navigation and terrain-adaptive control through sensor-based stability monitoring and adaptive motion strategies. The robot is powered by a 24 V 100 Ah battery that supplies energy to both the drive system and the cutting mechanism. The drive system uses PG45 DC motors for high-torque operation, while the cutting mechanism is driven by an XD-3420 DC motor. The robot weighs approximately 45 kg, which helps improve stability by lowering its center of gravity. The robot was operated with consideration of operational safety and minimizing environmental impact during outdoor testing.



(a) (b)

Figure 1. Lawn mower robot development (a) 3D design model and (b) implemented robot

3.2. System block diagram

The block diagram in Figure 2 illustrates the overall workflow of the system, from the input of the control signal to the processing of the data from the stability sensor. The system design consists of four main subsystems: the motor system, power system, monitoring system, and user control system. The motor system uses DC motors to drive the wheels and rotate the cutting blade, controlled by motor drivers based on signals from the receiver. The receiver obtains commands from the FlySky remote control transmitter operated by the user. The power system uses a 24V LiFePO4 battery as the primary energy source, with a step-down module to supply 5V to the microcontroller and sensors.

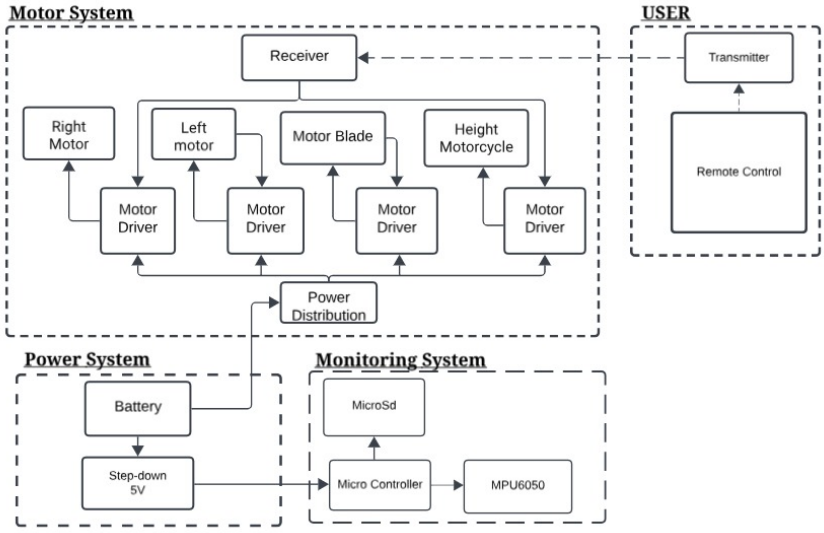


Figure 2. Block diagram of the lawn-mowing robot

The stability monitoring system is designed to detect the robot's orientation and tilt angle during operation using three main components: an MPU6050 sensor, an Arduino microcontroller, and a MicroSD storage module. The MPU6050 measures acceleration and angular velocity along the x, y, and z axes to estimate the robot's roll and pitch angles. The sensor was mounted near the robot's center of gravity on the main chassis to minimize vibration effects and accurately represent the robot's overall orientation. The sensor data are transmitted to the Arduino for processing and stored in real time on a MicroSD card at a fixed sampling rate for further stability analysis. During operation, the Arduino continuously processes the sensor data to monitor roll and pitch variations and evaluate stability under changing operating conditions.

Before data acquisition, the MPU6050 was calibrated using a reference inclinometer under controlled conditions. The robot was placed at several known tilt angles, and the sensor offsets were adjusted to reduce

measurement errors. Roll and pitch angles were calculated directly from the raw accelerometer and gyroscope data without using sensor fusion methods such as complementary or Kalman filters. This approach was selected because the study focused on validating the proposed stability evaluation framework, and the low operating speeds made the raw sensor data sufficient for stability assessment. However, sensor drift and vibration may reduce accuracy under dynamic conditions. Therefore, the analysis focuses on stability trends rather than precise orientation values.

3.3. Robot stability analysis

Stability analysis was conducted to assess the lawn mowing robot's ability to maintain balance under various operating conditions. Stability is crucial to preventing the robot from tipping over, particularly when moving or operating on uneven terrain. The slope testing was performed on a flat, dry surface with an adjustable inclination, allowing controlled variation in tilt angles. Using a dry surface ensures consistent friction between the wheels and the ground, minimizing slip during testing. Environmental conditions were kept as constant as possible throughout the experiments. Small differences between the theoretical and experimental results may arise from sensor noise, manual adjustment of the slope angle, and minor mechanical tolerances in the robot structure. Confidence intervals were not evaluated because this study focused on validating the proposed stability evaluation framework. To ensure safe and reliable robotic operation, the stability evaluation was conducted through three main aspects: CoG analysis, static stability analysis using the static stability factor (SSF) as a robotic rollover assessment tool, and dynamic stability analysis using motion-based stability equations to evaluate the robot's behavior under operating conditions.

3.3.1. CoG

The center of gravity is the balance point of the robot's mass, which significantly affects stability when stationary or moving. A lower center of gravity generally increases stability and reduces the risk of tipping. In this study, CoG analysis was conducted to ensure balanced mass distribution and to support operational stability, especially on sloped terrain [18], as in (1).

$$x_{Cg} = \frac{\sum m_i x_i}{\sum m_i} \qquad y_{Cg} = \frac{\sum m_i y_i}{\sum m_i} \qquad z_{Cg} = \frac{\sum m_i z_i}{\sum m_i} \tag{1}$$

3.3.2. Static stability

Static stability refers to a robot's ability to maintain its upright position when stationary on an inclined surface without tip-over. This test determines the maximum tilt angle tolerated before the CoG moves outside the support base. A larger critical angle indicates better static stability. This analysis is crucial for ensuring the robot's safety and reliability when stationary on uneven terrain [19]. The calculation of the Safety Factor of Flip was used to evaluate the risk of tipping, as in (2) and the maximum tilt angle before losing balance was determined mathematically and validated through testing, as in (3).

$$SSF = \frac{T}{2h_{cg}} \tag{2}$$

$$\theta_{\text{Kritis}} = \tan^{-1}\left(\frac{T}{2h_{cg}}\right) \tag{3}$$

3.3.3. Dynamic stability

Dynamic stability refers to the robot's ability to maintain balance while moving, such as during acceleration, turning, or traversing uneven surfaces. This analysis focuses on the robot's response to changes in forces and momentum during motion [20]. Real-time monitoring of roll and pitch angles using the MPU6050 was performed to detect potential instability. Determining the maximum speed of the robot, as in (4) and robot tilt angle during turning, as in (5).

$$V_{\text{max}} = \sqrt{\left(\frac{bg}{2h_{cg}}\right) R} \tag{4}$$

$$\theta = \tan^{-1}\left(\frac{v^2}{Rg}\right) \tag{5}$$

This formula is used to calculate the maximum speed of the robot before losing stability while turning. The value depends on the wheel track width (b), gravitational acceleration (g), center of gravity height (hcg), and turning radius (R). The lower the center of gravity and the wider the wheel track, the higher the maximum speed that can be achieved without tip-over. Meanwhile, the angle represents the robot's lateral tilt during turning, which is influenced by the travel speed (v) and turning radius. This angle is important for analyzing the robot's tendency to tip-over due to centrifugal force. By knowing this value, the operator can determine the safe speed limit to maintain the robot's stability during maneuvering.

4. RESULTS AND DISCUSSION

4.1. Robot stability analysis

In the design of the robot, determining the mass and center angle is essential for assessing the robot's stability. Therefore, before obtaining the center angle of the robot, the following calculations uses in (1) to obtain (6)-(8).

$$x_{cg} = \frac{(17 \times 21) + (19 \times 25) + (2.26 \times 10) + (1.2 \times 3.5)}{39.46} = \frac{858.8}{39.46} = 21.77\,\text{cm} \tag{6}$$

$$y_{cg} = \frac{(17 \times 8.5) + (19 \times 25) + (2.26 \times 2) + (1.2 \times 3.5)}{39.46} = \frac{628.22}{39.46} = 15.92\,\text{cm} \tag{7}$$

$$z_{cg} = \frac{(17 \times 47.5) + (19 \times 27.5) + (2.26 \times 10) + (1.2 \times 6)}{39.46} = \frac{1359}{39.46} = 34.43\,\text{cm} \tag{8}$$

Based on the calculation results, the CoG of the device is located at coordinates x = 21.77 cm, y = 15.92 cm, and z = 34.43 cm. This position indicates a balanced mass distribution between the front–rear and left–right sides, with a relatively low center of mass.

4.2. Static stability test

Testing is carried out by gradually tilting the surface until the robot loses balance and either rolls over or tips over. The tilt angle at which the robot falls is measured using an inclinometer mounted on the platform and MPU6050 sensor values stored on a memory card. The surface slope is gradually increased in 5° increments until the robot shows signs of instability. The robot is considered unstable if it cannot return to its original position or when its front or rear wheels begin to lift off the surface. These measurements were then compared with the theoretical critical angle calculated using the SSFformula to assess the robot's design's static stability level. It should be noted that the SSF model assumes ideal conditions (rigid body and uniform mass distribution), whereas in practice, factors such as mass distribution, vibration, and tire deformation may cause deviations between theoretical and experimental results.

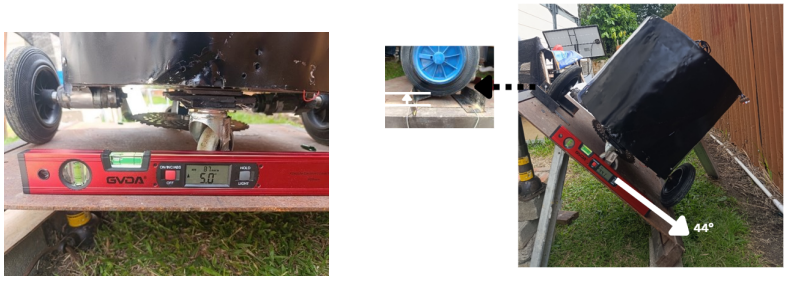
4.2.1. Lateral stability (Roll)

Testing is carried out by placing the robot on a surface that is gradually tilted to the side, aiming to determine the maximum tilt angle that causes the robot to rollover (fall). The theoretical result is consistent with the static roll stability test. Following the experiment with the distance between the left and right wheels (T) 68 cm and height of the center of gravity (Z value of CoG) = 34.43 cm, a theoretical calculation was carried out as follows (2) and (3).

$$SSF = \frac{68}{2 \times 34.43} = \frac{68}{68.86} = 0.987 \tag{9}$$

$$\theta_{\text{Kritis}} = \tan^{-1}(0.987) = 44^{\circ} \tag{10}$$

Figure 3 presents the experimental results of the static roll stability test. Figure 3(a) shows the test results at a 5° angle, where the robot remains stable. This indicates that the center of gravity remains within the support base, maintaining balance. In Figure 3(b), the test results show that increasing the tilt angle from 40° to 44°, at which point the robot tips over. At 44°, the right wheel lifted as the boat approached the Rolling Point. From this test, it can be concluded that the theoretical calculation also produced a value of 44° as the critical angle at which the robot would tip over.



(a) (b)

Figure 3. Static test for roll (a) 5° angle and (b) 44° angle approaching the rolling point

Table 1 shows the results of the experiment and can analyze the static stability behavior for roll angle of the robot. The test results show that at tilt angles between 0° and 35°, the robot remained stable, indicated by all four wheels maintaining contact with the test surface without any signs of imbalance. When the tilt angle reached 40°, the robot began to exhibit instability symptoms. One of the wheels appeared to lift off the surface, indicating a shift in the center of mass approaching the stability limit. Although the robot did not completely tip-over, this condition represents the transition threshold from stable to unstable. The robot was still able to return to its original position; therefore, the 40° angle can be categorized as the initial critical point of dynamic instability.

Table 1. Tilt angle measurement and robot condition

No	Tilt Angle (°)		Robot Condition
	Inclinometer	Sensor (MPU6050)	
1	0.0	0.62	Stable
2	5.0	5.09	Stable
3	10.0	10.09	Stable
4	15.0	15.04	Stable
5	20.0	20.01	Stable
6	25.0	25.39	Stable
7	30.1	30.28	Stable
8	35.1	35.20	Stable
9	40.1	40.34	Unstable Robot
10	44.1	44.10	Robot Rollover

The test results show that the robot began to lose stability and roll-over at a tilt angle of 44°. The test was carried out by gradually increasing the surface angle from 40° until reaching the critical point. This value is consistent with the theoretical calculation, indicating good agreement between analysis and experiment. However, minor deviations may occur due to sensor noise, slight variations in surface inclination, and structural flexibility of the robot frame during testing. In addition, measurement uncertainty during manual angle adjustment may introduce small errors. Overall, the results confirm that the critical lateral tilt (roll) angle of 44° is reliably validated through the static test. These results provide a quantitative reference for rollover prevention and the design of safer outdoor mobile robots operating on uneven terrain.

4.2.2. Longitudinal stability (Pitch)

The pitch test was carried out to determine the maximum longitudinal tilt angle (forward and backward) that the robot could tolerate while stationary before losing stability and being at risk of tipping over. The theoretical result is consistent with the static pitch stability test. Following the experiment with the distance between the front and rear wheels (T) 40 cm and the height of the center of gravity (Z value of CoG) = 34.43 cm, a theoretical calculation was carried out as follows (2) and (3).

$$SSF = \frac{40}{2 \times 34.43} = \frac{40}{68.86} = 0.580 \tag{11}$$

$$\theta_{\text{Kritis}} = \tan^{-1}(0.580) = 30^{\circ} \tag{12}$$

Figure 4 presents the experimental results of the static pitch stability test under different tilt angles. Figure 4(a) shows that the robot remains stable at a tilt angle of 10°, indicating that its center of gravity is still within the support base. Figure 4(b) shows the front wheel lifting as the robot approaches the tipping point, where the center of gravity shifts close to the edge of the support base, causing the robot to lose stability.



(a) (b)

Figure 4. Static test for pitch (a) 10° angle and (b) 30° sngle approaching the tipping point

Table 2 shows the results of the experiment and can analyze the static stability behavior for pitch angle of the robot. At a tilt angle of 30°, one of the robot's wheels began to lift off the surface, indicating instability. The test results show that the robot tips over at a tilt angle of 30°, consistent with the theoretical prediction. Minor differences may be caused by sensor noise, uneven load distribution, and mechanical vibrations during testing. Nevertheless, the results confirm the 30° critical pitch angle under the tested conditions. These results provide a quantitative reference for tip-over prevention and the design of safer outdoor mobile robots operating on uneven terrain.

Table 2. Tilt angle measurement and robot condition

No	Tilt Angle (°)		Robot Condition
	Inclinometer	Sensor (MPU6050)	
1	0.0	0.62	Stable
2	5.0	5.09	Stable
3	10.0	10.09	Stable
4	15.0	15.04	Stable
5	20.0	20.01	Stable
6	25.0	25.39	Unstable Robot
7	30.1	30.28	Robot Tip-over

4.3. Dynamic stability test

Dynamic stability testing is defined as a test conducted to determine the extent to which a system or robot can maintain a stable state while in motion. This test is used because, unlike statistical stability, which is influenced solely by mass distribution and the position of the center of gravity, dynamic stability is influenced by the forces acting during acceleration or changes in direction of motion. Under dynamic conditions, inertial forces resulting from linear and angular acceleration act on the system's center of mass. If the resulting force is large, the mass can shift out of the base of support, potentially leading to instability and even overturning. Specifically, during turning maneuvers, centrifugal forces act to push the system's mass out of its trajectory. If these forces cannot be resisted by the position of the center of gravity and the system's geometric design, the risk of instability increases significantly. Therefore, dynamic stability testing provides a deeper understanding of the system's operational stability limits and the extent to which the structural design and load distribution can accommodate dynamic forces.

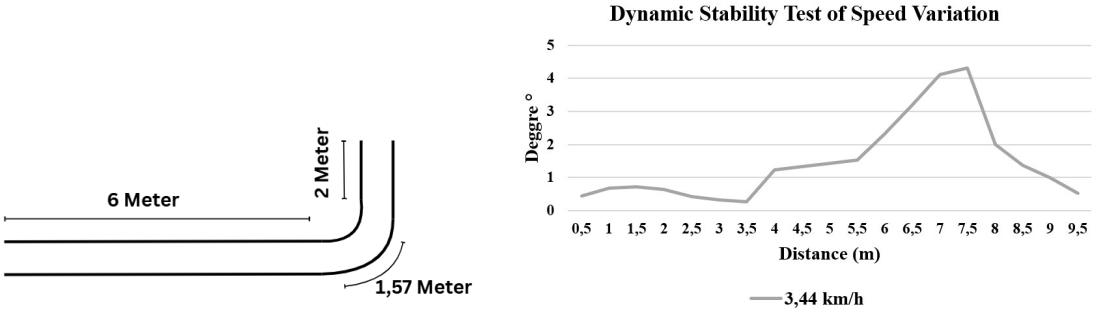
In conducting dynamic stability testing, it is necessary to verify the test results against theoretical calculation results, which were carried out as follows (4) and (5). Following this experiment, the distance between the left and right wheels (T) is 68 cm, and the height of the center of gravity (Z value at the center of mass) is 34.43 cm.

$$V_{\max} = \sqrt{\left(\frac{0,68x9,81}{2x0,3443}\right)1.57} = \sqrt{\left(\frac{6,6708}{0,6886}\right)1.57} = 3,89m/s^2 = 14km/h \quad (13)$$

$$\theta = \tan^{-1}\left(\frac{3,89^2}{1,57x9,81}\right) = \tan^{-1}\left(\frac{15,1321}{15,4017}\right) = 44,5^\circ \quad (14)$$

Based on the calculations and testing results, at a speed of 3.89 m/s (14 km/h), the robot reaches a critical tilt angle of 44.5°, which, theoretically, corresponds to a rollover condition. However, this value could not be fully validated experimentally. Due to the relatively high total mass of the robot (approximately 45 kg) and the typical operating requirement for effective grass cutting, the system operates at low speeds around 3 km/h to maintain cutting quality and stable motion.

Figure 5 presents the dynamic stability test of the lawn mower robot under practical operating conditions. Figure 5(a) shows the 9.56-meter-long test track used during the experiment. Figure 5(b) shows that the maximum tilt angle was 4.3° at a speed of 3.44 km/h, which is well below the predicted critical angle. This indicates that the robot operates within a stable region under normal conditions. The difference between theoretical and experimental results is mainly attributed to the limited operating speed, which reduces dynamic effects. These results demonstrate that the proposed framework can effectively evaluate robot stability and support the safe operation of outdoor mobile robots.



(a) (b)

Figure 5. Dynamic test (a) detailed track length size and (b) dynamic test at speed 3.44 km/h

4.4. Discussion

The results show that the proposed system maintains stable operation under both static and dynamic conditions. The MPU6050 sensor enables real-time monitoring of the robot's orientation, demonstrating that integrating sensor-based monitoring with analytical models is effective for practical stability evaluation. The close agreement between theoretical predictions and experimental IMU measurements confirms the reliability of the proposed framework. Small differences between theoretical and experimental results are mainly caused by sensor noise, mechanical vibration, slight load variations, and the absence of sensor fusion during dynamic operation. The robot's total mass (approximately 45 kg) lowers its CoG, improving rollover resistance, although increased mass may reduce maneuverability. These findings highlight the importance of balancing stability and mobility in outdoor mobile robots. Real-time monitoring of roll and pitch angles also improves operational safety by enabling early detection of unstable conditions. The proposed framework is applicable to agricultural robots, autonomous ground vehicles, and other mobile robotic platforms operating on uneven terrain.

However, this study has several limitations. The proposed framework was validated using a single remote-controlled robot prototype, and the experiments were conducted under controlled conditions without extensive evaluation on complex terrain or long-term operation. In addition, sensor fusion methods were not implemented, so measurement accuracy may be affected by IMU drift and vibration during dynamic motion. Future work will extend the validation to autonomous operation, multi-terrain testing, terrain-adaptive control, and advanced sensor fusion techniques to improve stability estimation and operational safety.

5. CONCLUSION

Based on the design, implementation, and testing results, this study demonstrates that the proposed system can effectively evaluate the stability of a remote-controlled lawn mower robot. The experimental results confirm that the robot maintains stable operation under static conditions, with critical tilt angles of approximately ±44° for roll and ±30° for pitch, in good agreement with the theoretical predictions. In dynamic testing,

the robot operates within a stable range, with a maximum tilt angle of approximately 4.3° at typical operating speeds. Although the theoretical analysis predicts a higher instability threshold, the experimental results indicate that the robot remains within a safe stability region during normal operation. These findings provide a proof-of-concept for the proposed integrated stability evaluation framework and demonstrate that combining theoretical analysis with real-time IMU monitoring provides a reliable method for assessing stability and supporting the safe operation of outdoor mobile robots. However, the results are limited to a single remote-controlled robot prototype tested under controlled conditions, and further validation is needed for autonomous operation on more complex terrain.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal Analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject Administration
Fu : **Fu**nding Acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest relevant to this research.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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