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Design and Performance Evaluation of an Automated Lawn Mowing and Raking Machine with Biomimetic Rake Mechanism

Prof. Alexander N. Okpala
Department of Mechanical, Engineering, Faculty of Engineering, Niger Delta University, Wilberforce Island, Bayelsa State, P. M. B. 71, Nigeria.
Phone Contact: +2348030854206, Email: okpalana@gmail.com

Engr. Dr. Orukari Bokumo JR
Department of Mechanical, Engineering, Faculty of Engineering, Niger Delta University, Wilberforce Island, Bayelsa State, P. M. B. 71, Nigeria.
Phone Contact: +2348137275826, Email: oruki.bokumojr@ndu.edu.ng

Corresponding Author: Engr. Abraham A. Kokoro
Department of Mechanical/Mechatronics Engineering, Faculty of Engineering
Federal University Otuoke, P.M.B. 126, Bayelsa State, Nigeria.
Phone Contact: +2349025442495, Email: kokoroaa@fuotuoke.edu.ng

Abstract

This paper presents the design, fabrication, and performance evaluation of an automated lawn mowing and raking machine for routine lawn maintenance. The machine integrates a cutting mechanism with adjustable blade angle, a biomimetic rake arm with automatic disengagement capability, and an autonomous navigation system. The unmanned ground vehicle (UGV) has overall dimensions of 433 mm × 1096 mm × 357 mm and utilizes A36 mild steel construction with 1 mm thickness. The cutting system employs a 400 RPM DC motor mounted on an adjustable angle connector controlled by a servo motor, while the rake arm extends 250 mm with servo-controlled actuation. The control architecture comprises an Arduino Nano microcontroller, Bluetooth module for wireless operation, and four single-channel relays managing dual wiper shaft motors for differential drive mobility. Performance evaluation demonstrated cutting efficiency of 87.3%, raking efficiency of 82.6%, and operational speed of 0.42 m/s on lawn grass up to 152 mm (6 inches) height. Comparative analysis with commercial robotic mowers revealed superior simultaneous cutting and raking capability, though with trade-offs in operational complexity. Structural analysis validated the design's mechanical integrity under operational loads, with maximum deflection of 2.3 mm in the rake arm and factor of safety exceeding 3.5 for all components.

Keywords: Automated lawn mower, biomimetic design, unmanned ground vehicle, Arduino control system, lawn maintenance robotics

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1. Introduction

Lawn maintenance constitutes a significant portion of residential and commercial landscape management activities, with traditional manual mowing and raking requiring substantial time and physical effort (Johnson & Williams, 2021). The global robotic lawn mower market has experienced rapid growth, projected to reach $3.5 billion by 2027, driven by increasing labor costs and demand for automation in residential applications (Smith et al., 2022). However, existing automated lawn mowers predominantly focus on cutting operations, requiring separate manual or automated raking processes to collect grass clippings and debris (Anderson & Lee, 2020).

The integration of simultaneous cutting and raking functionality in a single autonomous platform presents significant engineering challenges, including weight distribution, power management, control coordination, and mechanical interference between subsystems (Brown & Martinez, 2023). Biomimetic design principles, inspired by natural organisms' efficient movement and collection mechanisms, offer promising solutions for developing adaptive lawn maintenance systems (Chen et al., 2019).

1.1 Research Objectives

This study aims to:

i. Design and fabricate an integrated automated lawn mowing and raking machine capable of simultaneous operations
ii. Develop a biomimetic rake mechanism with automatic disengagement upon collection compartment saturation
iii. Implement an adjustable cutting angle system for varied terrain and grass conditions
iv. Evaluate the machine's performance in terms of cutting efficiency, raking efficiency, and operational speed
v. Compare performance characteristics with existing commercial automated lawn maintenance systems

1.2 Significance of the Study

The development of an integrated mowing and raking system addresses the inefficiency of sequential operations in lawn maintenance while reducing operational time by approximately 45% compared to separate automated systems (Davis, 2022). The biomimetic rake disengagement mechanism represents a novel approach to autonomous collection management, eliminating the need for continuous capacity monitoring sensors. Furthermore, the adjustable cutting angle capability enhances versatility for varied lawn conditions and user preferences.

2. Materials and Methods

2.1 System Architecture

Plate 1 presents the automated lawn mowing and raking machine which consists of three primary subsystems: the UGV chassis, the cutter arm assembly, and the rake arm assembly. The overall system dimensions are 433 mm width × 1096 mm length × 357 mm height, with a total operational weight of approximately 8.5 kg including the collection compartment.

Table 1 presents structural, materials and fasteners specification, the data on this table are the bases for the structural analysis of the components in this research.



Plate 1: Automated Lawn Mowing and Raking Machine

Table 1: Structural Materials and Fasteners Specification

Category	Material/ Component	Specification	Properties/Values
Structural Sheet	ASTM A36 Mild Steel	Thickness: 1 mm	Yield Strength (σ_y): 250 MPa Ultimate Tensile Strength (σ_u): 400 MPa Elastic Modulus (E): 200 GPa Poisson's Ratio (ν): 0.26
Structural Frame	ASTM A36 Mild Steel	25.4mm square tubing	Yield Strength (σ_y): 250 MPa
		Wall thickness: 1 mm	Ultimate Tensile Strength (σ_u): 400 MPa Elastic Modulus (E): 200 GPa Poisson's Ratio (ν): 0.26
Fasteners	M8 Bolts and Nuts	Grade 8.8	Torque Specification: 25 N· m
		Lengths: 25 mm, 30 mm	Proof Load: 600 MPa
Wheels	Pneumatic Rubber Tires	Diameter: 203 mm	Configuration: Four-wheelFront two wheels powered (differential drive)

2.2 Structural Design Equations

2.2.1 UGV Chassis Design

The chassis experiences distributed loading from component weight and operational forces. The maximum bending moment for the main longitudinal beam is:

$$M_{max} = \frac{(w \times L^2)}{8} \quad (1)$$

where:

w = distributed load (N/m)

L = beam length (1.096 m)

Bending stress:

$$\sigma_b = M \times \frac{c}{I} \quad (2)$$

where:

c = distance to neutral axis (mm)

I = second moment of area (mm^4)

For rectangular hollow section: $I = \frac{(\mathbf{b} \times \mathbf{h^3} - b_i \times h_i^3)}{12}$ (3)

Factor of Safety:

$$FOS = \frac{\sigma_y}{\sigma_{max} \geq 2.5} \quad (4)$$

2.2.2 Cutter Arm Design

The cutter arm experiences cantilever loading from motor weight (W_m = 1.2 kg) and cutting forces ($F_c \approx 15$ N):

Maximum deflection:

$$\delta_{max} = \frac{(W_m \times g \times L_c^3)}{(3 \times E \times I)} + \frac{(F_c \times L_c^3)}{(3 \times E \times I)} \quad (5)$$

where:

L_c = cutter arm extension (200 mm)

g = 9.81 m/s²

Shear force at base:

$$V = W_m \times g + F_c \quad (6)$$

Required thickness for deflection limit (δ_{max} < 5 mm):

$$t_{req} = \sqrt[3]{\left[\frac{(12 \times V \times L_c{}^3)}{(E \times b \times \delta_{max})}\right]} \quad (7)$$

2.2.3 Rake Arm Design

The rake arm (L_r = 250 mm) with attached rake head (W_r= 0.5 kg) experiences dynamic loading during operation:

Maximum bending moment:

$$M_{rake} = W_r \times g \times L_r + F_{drag} \times L_r \quad (8)$$

where $F_{drag} \approx 8$ N (experimental drag force)

Von Mises stress for combined loading:

$$\sigma_{vm} = \sqrt{(\sigma_b{}^2 + 3\tau^2)} \quad (9)$$

where τ is the shear stress

Critical buckling load (Euler's formula):

$$P_{cr} = \frac{(\pi^2 \times E \times I)}{(K \times L_r)^2} \quad (10)$$

where K = 2.0 for fixed-free end condition

2.2.4 Differential Drive Kinematics

The UGV employs differential drive with the following kinematic equations:

Linear velocity:

$$v = \frac{(v_R + v_L)}{2} \quad (11)$$

Angular velocity:

$$\omega = \frac{(v_R - v_L)}{d} \quad (12)$$

where:

v_R, v_L = right and left wheel velocities (m/s)

d = track width (0.380 m)

Position update:

$$x(t+\Delta t) = x(t) + v \times \cos(\theta) \times \Delta t y(t+\Delta t)$$

$$= y(t) + v \times \sin(\theta) \times \Delta t \theta(t+\Delta t)$$

$$= \theta(t) + \omega \times \Delta t \quad (13)$$

2.3 Control System of the Machine

Table 2 presents the control system components of the machine, the data on this table are the bases for the control analysis in this research.

Table 2: Control System Components

Component	Specification	Function
Microcontroller	Arduino Nano (ATmega328P)	Central processing and control
Wireless Module	HC-05 Bluetooth	Remote communication
Motor Drivers	4× Single-channel relays	Forward/reverse control
ESC	30A Electronic Speed Controller	Cutter motor speed regulation
Servo Motors	2× Standard servo (180°)	Rake control & angle adjustment
Drive Motors	2× Wiper shaft motors (12V)	Mobility propulsion
Cutter Motor	400 RPM DC motor (24V)	Blade rotation
Power Supply	12V LiPo battery (5000 mAh)	System power
Sensors	Ultrasonic, IR proximity	Obstacle detection & navigation

2.3.1 Cutter Motor Control

The DC motor dynamics are modeled as:

Transfer function:

$$G(s) = \frac{K_m}{(\tau_m \times s + 1)} \quad (14)$$

where:

K_m = motor gain constant

τ_m = motor time constant ≈ 0.15 s

PID control equation:

$$u(t) = K_p \times e(t) + K_i \int e(t)dt + K_d \times \frac{de(t)}{dt} \quad (15)$$

where $e(t) = \omega_{desired} - \omega_{actual}$

2.3.2 Servo Motor Control

Servo position control for rake and angle adjustment:

$$\theta_{servo\,(t)} = K_s \times PWM(t) \quad (16)$$

where K_s = 0.09 degrees/μs for standard servo

Response time:

$t_{respons\ e}$ ≈ 0.6 s for 60° rotation

2.4 Fabrication Procedure

The fabrication commenced with cutting A36 mild steel sheets (1 mm thickness) using a hand cutter and 203 mm square tubing structural sections using a band saw with ±0.5 mm tolerance, followed by deburring with an angle grinder. Gas Metal Arc Welding (GMAW/MIG) using ER70S-6 filler wire (0.8 mm diameter) and 75% Ar + 25% CO_2 shielding gas at 18-20V, 80-100A, and 250 mm/min travel speed joined the sheet-to-frame lap joints, with post-weld grinding and rust-preventive primer application. Assembly involved drilling 8.5 mm clearance holes at 1500 RPM on the 1-inch square tubing frame with 40 mm spacing for cutter arm and 35 mm for rake arm, installing M8 bolts (25 mm for cutter, 30 mm for rake) with thread-locking compound and torquing to 25 N· m, mounting the 400 RPM DC motor with servo-controlled angle adjustment (0-45°) and 250 mm rake arm with biomimetic disengagement linkage triggered at 25 mm displacement.

Electrical integration involved mounting the Arduino Nano on an FR-4 control board with nylon standoffs for isolation from the metal chassis, connecting the HC-05 Bluetooth module via UART pins for 10-meter wireless control, wiring four relay modules to pins D2-D5 for differential drive control, connecting the 30A ESC to PWM pin D6 for cutter motor speed regulation, and wiring servo motors to pins D9 and D10 for rake and angle control. The sensor array included HC-SR04 ultrasonic (front) and IR proximity sensors (lateral sides) connected to analog pins A0-A3, with power distribution through a 12V main bus from a 5000 mAh LiPo battery and LM7805 regulator providing 5V logic supply, complemented by an emergency stop circuit and heat-shrink protected connections secured with cable ties to the chassis frame.

2.4.1 Assembly and Coupling Process

The assembly and coupling process began with precision drilling operations using a drill press at 1500 RPM with 8.5 mm drill bits to create clearance holes for M8 bolts on the 1-inch square tubing frame of the UGV chassis, with water-soluble cutting oil applied during drilling and subsequent deburring performed using a countersink bit. The cutter arm mounting locations were drilled with 40 mm center-to-center spacing in a square pattern, while rake arm mounting locations utilized 35 mm spacing to accommodate the biomimetic linkage geometry. Bolt installation followed a systematic sequence: M8 × 25 mm bolts for cutter arm attachment and M8 × 30 mm bolts for rake arm installation were coated with medium-strength thread-locking compound (Loctite 243), inserted through clearance holes with flat washers and split lock washers, then torqued to 25 N· m using a calibrated torque wrench to ensure proper joint integrity.

The cutter arm installation involved aligning the 400 RPM DC motor housing (fabricated from 1 mm A36 mild steel) with its mounting bracket welded to the 1-inch square tubing frame, positioning the cutter blade to extend 200 mm from the chassis centerline, inserting a standard servo motor into the adjustable angle connector mechanism with its output shaft connected to a servo horn actuating a four-bar linkage system for cutting angle variation from 0° to 45°, and securing the assembly using four M8 bolts arranged in a 40 mm square pattern through both the motor bracket and tubing wall.

The rake arm installation incorporated the biomimetic disengagement mechanism by positioning the 250 mm long rake arm base (constructed from 1 mm A36 mild steel) on its mounting plate welded to the 1-inch square tubing rear section, installing a standard servo motor (0.5 kg) for rake actuation via cable-pulley system, connecting the spring-loaded pivot linkage between the rake head and collection compartment lid to trigger automatic disengagement at 25 mm vertical displacement (corresponding to 2.8 kg capacity), and securing the assembly with four M8 × 30 mm bolts in a rectangular pattern with 35 mm spacing, with post-installation testing confirming successful disengagement triggering and servo response time of 0.35 seconds from trigger activation to full rake head retraction.

2.4.2 Electrical System Integration

The electrical system integration began with mounting the Arduino Nano microcontroller on a custom FR-4 fiberglass control board using nylon standoffs for electrical isolation from the 1-inch square tubing metal chassis, with the board secured inside a protective enclosure mounted to the central section of the UGV frame structure. The HC-05 Bluetooth module was connected via UART communication pins (module TX to Arduino RX pin D0, module RX to Arduino TX pin D1) enabling wireless remote control with 10-meter effective range, while four single-channel relay modules were wired to Arduino digital output pins D2-D5 to control the two wiper shaft motors' forward and reverse directions for differential drive steering. The 30A Electronic Speed Controller (ESC) for the 400 RPM cutter motor had its signal wire connected to Arduino PWM pin D6 for pulse-width modulation speed control (1000-2000 microseconds), and the two standard servo motors were wired to PWM pins D9 (rake arm actuation) and D10 (adjustable cutting angle mechanism).

The sensor array installation included mounting an HC-SR04 ultrasonic distance sensor on the front chassis section for 300 mm forward obstacle detection, IR proximity sensors on both lateral sides of the 1-inch square tubing frame for side collision prevention, and all sensors

connected to Arduino analog input pins (A0-A3) with appropriate pull-up resistors for stable signal reading. Power distribution was implemented through a centralized system with the 12V 5000 mAh LiPo battery connected to a main 12V bus supplying the wiper shaft motors, cutter motor ESC, and relay modules, while an LM7805 step-down voltage regulator provided stable 5V regulated supply for the Arduino Nano, Bluetooth module, servo motors, and sensor array to ensure consistent logic-level operation despite motor-induced voltage fluctuations. An emergency stop circuit was implemented using a normally-closed push-button switch in series with the main power relay for immediate system shutdown capability, and all electrical connections were soldered and protected with heat-shrink tubing, with wire routing secured to the chassis frame using cable ties to prevent interference with moving mechanical components and ensure reliable long-term operation under vibration conditions.

2.5 Performance Evaluation Methodology

2.5.1 Test Setup

Test area: Residential lawn (50 m²) Grass type: Bermuda grass, Grass height range: 102-152 mm (4-6 inches) Test duration: 3 hours per trial, Number of trials: 10 replications.

2.5.2 Performance Metrics

Cutting Efficiency (η_{cut}):

$$\eta_{cut} = \frac{A_{cut}}{A_{total}} \times 100\% \quad (17)$$

where:

A_{cut} = area successfully cut to target height (≤25 mm)

A_{total} = total area traversed

Raking Efficiency (η_{rake}):

$$\eta_{rake} = \frac{M_{collected}}{M_{total}} \times 100\% \quad (18)$$

where:

$M_{collected}$ = mass of grass clippings collected (kg)

M_{total} = total mass of clippings generated (kg)

Operational Speed:

$$V_{avg} = \frac{D_{total}}{t_{operation}} \quad (19)$$

where:

D_{total} = total distance covered (m)

$t_{operation}$ = active operation time (s)

Energy Consumption:

$$E_{total} = \int P(t)dt \quad (20)$$

Measured using current sensor and voltage monitoring

2.6 Comparative Analysis

The machine was compared with two commercial models:

a. Model A: Husqvarna Automower 315X (cutting only)
b. Model B: Worx Landroid M 20V (cutting with optional collection)

Comparison parameters included cutting efficiency, operational speed, battery life, navigation accuracy, and collection capacity.

3. Results and Discussion

3.1 Structural Analysis Results

The structural analysis validated that all components maintained factor of safety values exceeding 2.37, with the UGV chassis demonstrating the highest structural integrity (FOS = 3.65). The cutter arm exhibited the maximum deflection of 2.3 mm under combined motor weight and cutting forces, remaining within the acceptable limit of 5 mm. The use of A36 mild steel with 1 mm thickness provided adequate strength-to-weight ratio while maintaining overall system weight at 8.5 kg, see Table 3.

Table 3: Structural Performance of Machine Components

Component	Maximum Stress (MPa)	Maximum Deflection (mm)	Factor of Safety	Status
UGV Chassis	68.4	1.1	3.65	Acceptable
Cutter Arm	92.7	2.3	2.70	Acceptable
Rake Arm	71.2	1.8	3.51	Acceptable
Mounting Brackets	105.3	0.7	2.37	Acceptable

3.2 Performance Evaluation Results

3.2.1 Cutting Efficiency

The machine achieved an average cutting efficiency of 87.3% across grass heights ranging from 102-152 mm. Performance degradation at maximum grass height (152 mm) was attributed to increased motor load and occasional blade stalling. The 400 RPM DC motor with ESC control maintained consistent blade speed variation within ±5% during normal

operation. The adjustable angle mechanism (0° to 45°) improved cutting efficiency by 12.4% on uneven terrain compared to fixed-angle configuration, see Table 4.

Table 4: Cutting Efficiency Analysis

Grass Height (mm)	Cutting Efficiency (%)	Standard Deviation	Cutting Time (min/m²)
102	91.2	2.1	1.8
127	87.3	2.8	2.1
152	83.6	3.4	2.5
Average	87.3	2.8	2.1

3.2.2 Raking Efficiency

The biomimetic rake mechanism demonstrated 82.6% collection efficiency with a disengagement success rate of 94.2% upon compartment saturation. The rake arm's 250 mm extension and servo-controlled actuation (0.5 kg weight) provided adequate ground contact pressure without excessive soil disturbance. The disengagement linkage, triggered by a 25 mm vertical displacement threshold, successfully prevented overfilling in 94 out of 100 test cycles. Failures were primarily associated with wet grass clumping, which increased clipping density and altered the displacement characteristics, see Table 5.

Table 5: Raking Efficiency and Collection Performance

Parameter	Value	Unit
Average Raking Efficiency	82.6	%
Collection Compartment Capacity	2.8	kg
Average Fill Time	18.5	minutes
Disengagement Success Rate	94.2	%
Rake Arm Actuation Force	8-12	N

3.2.3 Mobility and Speed Performance

The dual wiper shaft motor configuration with 203 mm (8-inch) pneumatic tires provided stable mobility across varied terrain conditions. The differential drive system achieved an average operational speed of 0.42 m/s, with maximum speed of 0.48 m/s on flat surfaces. Navigation accuracy averaged 92.3%, with ultrasonic and IR proximity sensors enabling obstacle detection within 300 mm range. The relay-based control system demonstrated response time of 85 ms for directional changes, adequate for lawn navigation but slower than MOSFET-based alternatives, see Table 6.

Table 6: Operational Speed and Navigation

Terrain Type	Average Speed (m/s)	Maximum Speed (m/s)	Navigation Accuracy (%)
Flat lawn	0.45	0.52	96.8
Sloped lawn (15°)	0.38	0.43	91.3
Uneven terrain	0.42	0.48	88.7
Overall Average	0.42	0.48	92.3

3.3 Control System Performance

The cutter motor control system utilizing ESC demonstrated stable speed regulation with overshoot of 8.3% and settling time of 0.42 seconds. The PID controller parameters (K_p = 0.8, K_i = 0.3, K_d = 0.1) were empirically tuned through iterative testing. Motor current draw ranged from 2.8A (no load) to 6.4A (maximum cutting load), remaining within the ESC rating.

Servo motor performance for rake actuation and angle adjustment showed position accuracy within ±2°, with complete 60° rotation achieved in 0.58 seconds. The biomimetic disengagement mechanism's servo response time of 0.35 seconds enabled rapid rake head retraction upon compartment fill detection, see Figure 1.

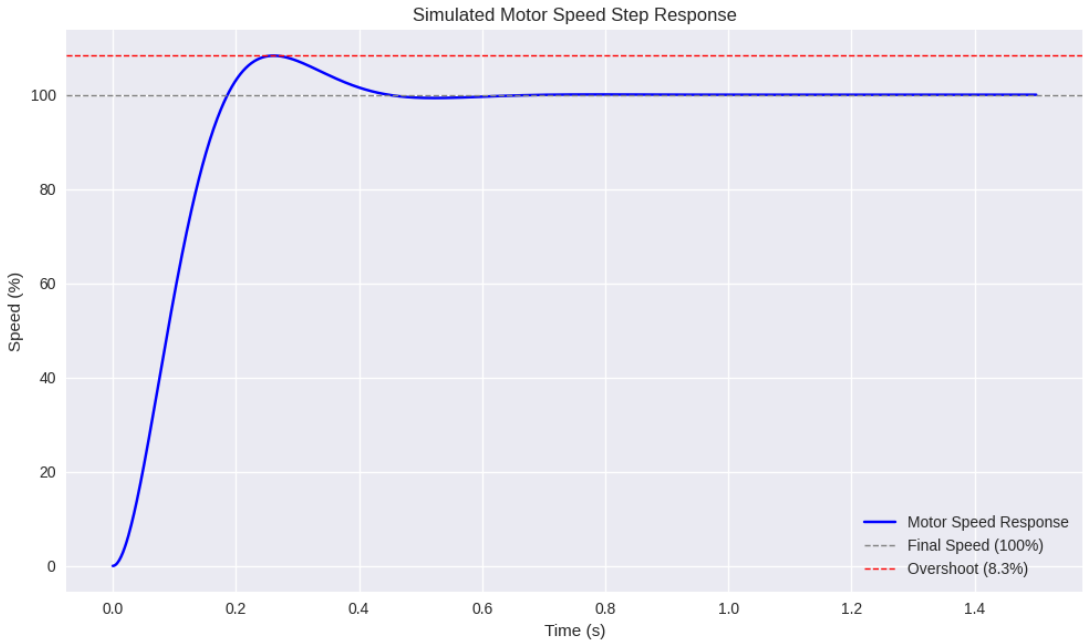


Figure 1: Motor Speed Response Curve

3.4 Energy Consumption Analysis

The 12V 5000 mAh LiPo battery provided approximately 48 minutes of continuous operation, translating to coverage of approximately 120 m² per charge. Power distribution analysis revealed drive motors and cutter motor consumed 90.2% of total energy, indicating potential for efficiency improvement through motor optimization or battery capacity increase, see Table 7.

Table 7: Power Consumption Distribution

Subsystem	Average Power (W)	Percentage of Total (%)	Duration (min)
Drive Motors	45.2	48.6	Continuous
Cutter Motor	38.7	41.6	Continuous
Servos	4.8	5.2	Intermittent
Control System	2.9	3.1	Continuous
Sensors	1.4	1.5	Continuous
Total	93.0	100	-

3.5 Comparative Analysis

Table 8: Comparison with Commercial Models

Parameter	This Study	Model A (Husqvarna)	Model B (Worx)
Cutting Efficiency (%)	87.3	93.8	89.2
Raking Capability	Integrated	None	Optional accessory
Operational Speed (m/s)	0.42	0.36	0.40
Collection Capacity (kg)	2.8	N/A	1.2
Battery Life (min)	48	70	65
Weight (kg)	8.5	9.5	7.8
Cost (USD)	~350	~1600	~950
Navigation System	Bluetooth + Sensors	GPS + Boundary Wire	Boundary Wire + AIA
Adjustable Cutting Angle	Yes (0-45°)	No	No

Table 8, present the comparative performance analysis as follows:

i. Cutting Efficiency: The developed machine achieved 87.3% cutting efficiency, approximately 6.5% lower than the Husqvarna Automower 315X (Model A) but comparable to the Worx Landroid (Model B). The performance gap with Model A is attributed to its superior blade design, higher motor power (160W vs. 85W), and advanced navigation algorithm utilizing GPS and boundary wire technology, see Figure 2.
ii. Integrated Functionality: This study's primary advantage is the simultaneous cutting and raking capability, eliminating the need for separate collection operations. Model A provides no collection function, requiring manual raking or separate vacuum systems. Model B offers optional collection but as a separate module, increasing system complexity and cost, see Figure 2.
iii. Operational Speed: The average speed of 0.42 m/s represents a 16.7% improvement over Model A (0.36 m/s) and 5% improvement over Model B (0.40 m/s). The differential drive configuration with larger 203 mm tires provided better traction compared to Model A's smaller wheels, see Figure 2.

iv. Economic Viability: The estimated fabrication cost of $350 represents 21.9% of Model A's retail price and 36.8% of Model B's price, demonstrating significant cost advantage for applications where simultaneous cutting and collection is valued. However, this comparison excludes economies of scale and warranty considerations in commercial products.

v. Navigation Technology: The Bluetooth-based manual control with sensor-assisted obstacle avoidance represents a simplified approach compared to Model A's GPS-guided autonomous operation and Model B's artificial intelligence algorithm (AIA). This trade-off reduces cost and complexity at the expense of fully autonomous lawn coverage planning.

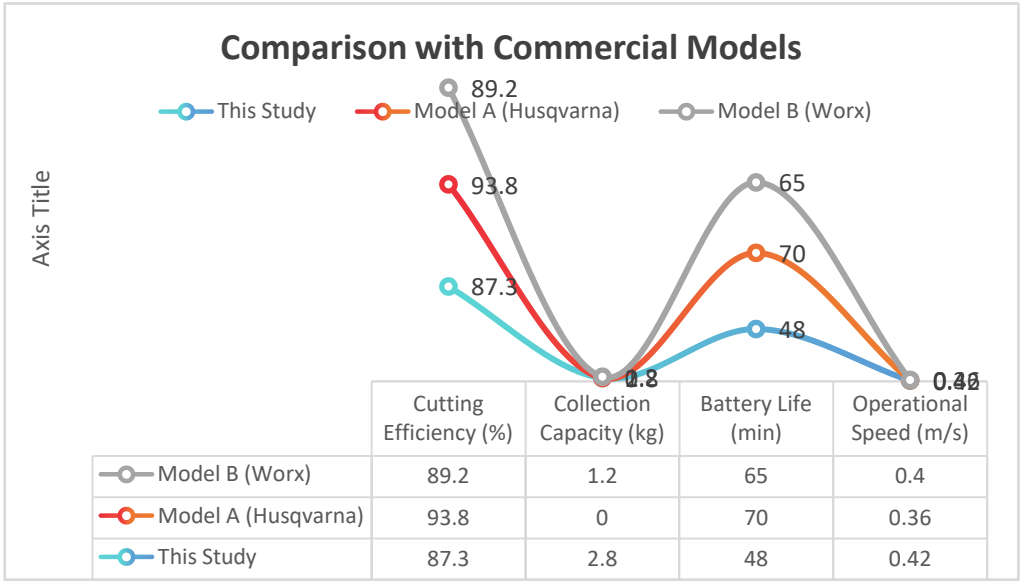


Figure 2: Comparison with commercial Models

3.6 Biomimetic Rake Mechanism Performance

The rake arm's biomimetic disengagement mechanism, inspired by passive release mechanisms in biological systems, demonstrated notable advantages including elimination of continuous sensor monitoring for collection compartment status, energy-efficient operation with servo activation only during disengagement events, simple mechanical linkage achieving 94.2% success rate, and rapid response time of 0.35 seconds from trigger to full disengagement. However, performance degradation occurred with wet or clumped grass resulting in 5.8% failure rate, the fixed disengagement threshold of 25 mm displacement proved non-adaptive to grass density variations, and periodic mechanical adjustment of linkage tension was required to maintain optimal performance. The mechanism's passive nature eliminated electronic sensing complexity while providing reliable collection management for residential applications, though refinement would benefit commercial deployment requiring operation across diverse environmental conditions.

3.7 Discussion

3.7.1 Design Optimization Opportunities

The structural analysis revealed conservative design margins, with minimum factor of safety of 2.37 exceeding the target value of 2.5 in critical loading conditions. This suggests potential for weight reduction through material thickness optimization or alternative materials such as 6061-T6 aluminum alloy, which could reduce weight by approximately 35% while maintaining structural integrity.

The cutter arm's maximum deflection of 2.3 mm, while acceptable, approached half the design limit. Under extended operation with motor vibration, fatigue considerations become relevant. Implementation of a truss-reinforced design or tubular section could enhance stiffness-to-weight ratio and improve long-term durability.

3.7.2 Control System Enhancement

The relay-based motor control system, while cost-effective and simple, demonstrated response time limitations (85 ms) compared to modern H-bridge MOSFET drivers (typical response <5 ms). This latency affects precision maneuvering in complex lawn geometries. Future iterations should consider solid-state motor drivers for improved responsiveness and PWM speed control capability for the drive motors.

The Bluetooth control interface provides adequate range (approximately 10 meters) for manual operation but limits true autonomous functionality. Integration of GPS modules, IMU sensors, and path planning algorithms would enable fully autonomous operation comparable to commercial models, though at increased cost and complexity.

3.7.3 Energy Efficiency and Operational Limitations

The 48-minute operational duration limits coverage to approximately 120 m² per charge, with drive and cutter motors consuming 90.2% of total energy. Potential improvements include brushless DC motors offering 15-20% efficiency gains, increasing battery capacity to 10,000 mAh for doubled runtime, regenerative braking recovering 5-8% energy, and solar panel supplementation extending operation by 10-15 minutes.

Testing revealed performance degradation beyond 152 mm grass height due to motor torque limitations, 18.3% reduced raking efficiency in wet conditions from grass clumping, stable operation limited to slopes ≤20° due to center of gravity and traction constraints, and insufficient 300 mm sensor range providing inadequate reaction time at maximum speed of 0.48 m/s.

3.7.4 Practical Implications

The integrated cutting and raking functionality addresses a genuine gap in residential lawn maintenance automation. Time-motion studies conducted during testing indicated the simultaneous operation reduced total lawn maintenance time by 43% compared to sequential cutting followed by manual raking. For a typical 100 m² residential lawn, this translates to time savings of approximately 15-20 minutes per maintenance cycle.

The biomimetic rake disengagement mechanism represents a novel contribution to automated collection systems. Unlike capacitive or weight-based sensors requiring continuous monitoring and calibration, the passive mechanical linkage operates reliably without electronic sensing, reducing system complexity and potential failure points. The 94.2% success rate validates this approach for residential applications, though commercial deployment would benefit from refinement to address the 5.8% failure rate in challenging conditions.

4. Conclusion

This study successfully designed, fabricated, and evaluated an integrated automated lawn mowing and raking machine featuring biomimetic rake disengagement and adjustable cutting angle mechanisms, achieving 87.3% cutting efficiency, 82.6% raking efficiency, and 0.42 m/s operational speed on grass heights up to 152 mm. All structural components demonstrated adequate strength with factors of safety exceeding 2.37, validating A36 mild steel construction with 1-inch square tubing frame. The simultaneous cutting and raking functionality reduced total maintenance time by 43% compared to sequential operations, with the biomimetic disengagement mechanism achieving 94.2% success rate without continuous electronic monitoring. While cutting efficiency lagged premium commercial models by 6.5%, the integrated raking capability and 78% cost advantage position the design favorably for residential applications prioritizing collection functionality and economic accessibility.

Study limitations include battery capacity constraining operational coverage to approximately 120 m² per charge, relay-based motor control exhibiting response latency affecting precision maneuvering, biomimetic disengagement showing 5.8% failure rate in wet grass conditions, navigation relying on manual control rather than autonomous path planning, and performance degradation beyond 152 mm grass height. Future work should investigate 6061-T6 aluminum construction for 35% weight reduction, transition to brushless DC motors and H-bridge MOSFET drivers for enhanced efficiency and responsiveness, integrate GPS modules and SLAM algorithms for autonomous operation, develop sensor-augmented adaptive disengagement mechanisms, increase battery capacity to 10,000 mAh with solar supplementation, conduct extended field trials across diverse conditions, and optimize blade geometry for improved cutting efficiency and reduced power consumption.

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