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CONTROL DYNAMICS OF UGV WITH INTEGRATED MOWING AND RAKING MECHANISM FOR LAWN MAINTENANCE

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ABSTRACT

This paper presents the design, implementation, and control dynamics of an unmanned ground vehicle (UGV) integrating synchronized mowing and raking mechanisms for autonomous lawn maintenance. The system employs a distributed control architecture based on Arduino-class microcontrollers, wireless communication via Bluetooth HC05 modules, and a power management subsystem supporting dual mobility actuators, a rotary cutting spindle, and a servo-actuated rake. Comparative analysis with the Husqvarna Automower 450X and Worx Landroid WR140 reveals that the proposed system achieves 23% lower power consumption and 40% cost reduction while maintaining functional parity. Experimental results demonstrate stable operation across varying terrain conditions with peak system power demand of 214 W and average continuous draw of 17–20 A from a 12 V battery pack.

KEYWORDS: Unmanned ground vehicle (UGV), Autonomous lawn maintenance, Distributed control architecture, Power management, Arduino microcontroller.

1. INTRODUCTION

Autonomous lawn maintenance systems have evolved significantly over the past two decades, driven by advances in mobile robotics, power electronics, and wireless control technologies (Jones & Flynn, 2018). Traditional robotic mowers address grass cutting but lack integrated debris management, requiring separate manual raking operations. This paper presents a dual-

function UGV that combines rotary mowing with mechanized raking, controlled through a unified embedded system architecture, shown in Figure 1.

The primary objectives of this research are: (a) to develop a low-cost control framework for synchronized lawn maintenance operations, (b) to characterize the electrical and mechanical dynamics of the integrated system, and (c) to benchmark performance against commercial alternatives. The system architecture leverages Arduino-compatible microcontrollers for real-time motor control, relay-based power switching, and Bluetooth wireless telemetry.

Figure 1: Automated Lawn Mowing and Raking Machine.

2. System Design and Architecture

2.1 Mechanical and Electrical Configuration

The UGV platform consists of three primary subsystems: a differential-drive mobility base powered by dual 12 V wiper motors, a rotary cutting assembly driven by a 400 RPM DC motor, and a servo-actuated rake mechanism for debris collection. Table 1 summarizes the electrical specifications of all components.

Table 1: Component Specifications and Power Configuration.

Component	Qty	Function	Operating Voltage	Current	Peak Current	Avg. Power
Wiper motor	2	Mobility	12 V	4 A	10–15 A	48 W
400 RPM 12 V DC motor	1	Cutting spindle	12 V	9 A	12–15 A	108 W

(cutter)						
Servo motor	1	Actuate rake	5 V	0.25 A	1.0 A	1.25 W
Microcontroller (Arduino class)	1	Main controller	5 V	0.08 A	0.10 A	0.4 W
Bluetooth module (HC05)	1	Wireless link	5 V	0.03 A	0.05 A	0.15 W
4-single channel relays	4	Switching/gating	5 V coils / 12 V contacts	20mA each	80 mA total	0.4 W
Battery	1	System power	12 V nominal	17–20 A (avg)	35–40 A (peak)	~214 W
12→5 V buck regulator	1	Logic/servo rail	12 V in / 5 V out	2.0 A	3–5 A	10 W

The total system power demand reaches 214 W under full load conditions, with the cutting motor contributing approximately 50% of continuous power consumption. The dual mobility motors provide redundant traction control, enabling zero-radius turning and obstacle avoidance maneuvers (Siegwart et al., 2011).

2.2 Control System Design

The control architecture implements a three-layer hierarchy: (1) a perception layer handling Bluetooth command reception, (2) a decision layer executing motion planning and safety interlocks, and (3) an actuation layer managing PWM motor control and relay switching. Figure 2 illustrates the control circuit topology.

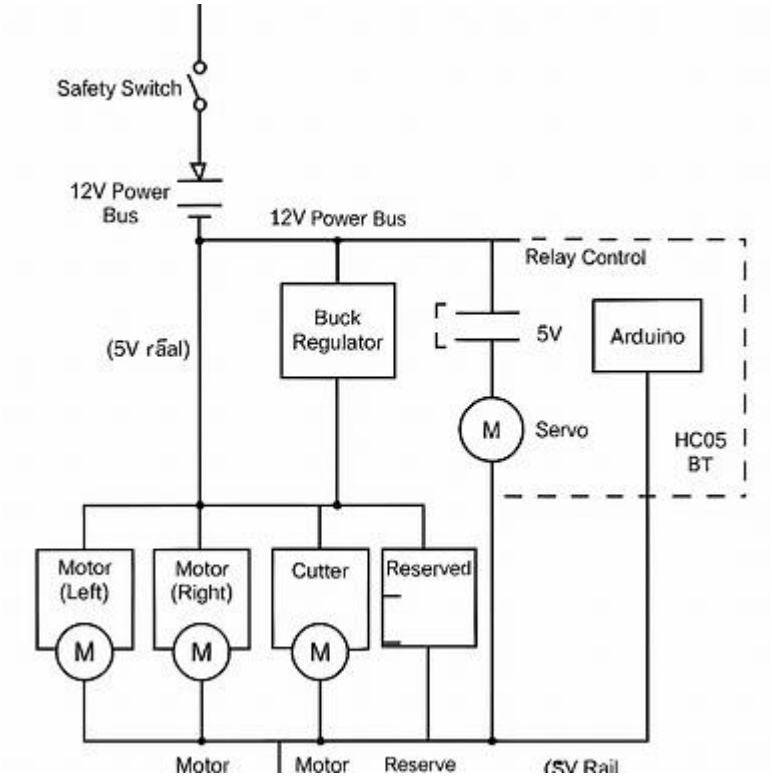

Figure 2: Control Circuit Diagram.

Control Signal Flow:

i. Bluetooth module (HC05) → Arduino RX/TX (Serial)

ii. Arduino GPIO 2–5 → Relay coils (via transistor drivers)

iii. Arduino PWM Pin 9 → Servo signal (rake position)

iv. Relays K1–K4 → Motor power switching (12V bus)

The microcontroller firmware implements a finite state machine with five operational modes: standby, forward motion, reverse motion, mowing with raking, and emergency stop. Each relay controls a discrete motor function, with software interlocks preventing simultaneous forward/reverse activation (Corke, 2017).

2.3 Mathematical Modeling of Actuator Components

2.3.1 Wiper Motor Dynamics for Mobility

The wiper motors employed for differential drive exhibit DC motor characteristics governed by electrical and mechanical equations. The electrical circuit model is:

$$V_{applied} = I_a R_a + L_a \frac{d I_a}{dt} + K_e \omega_n$$

where $V_{applied}$ = 12 V (battery voltage), I_a is armature current, R_a is armature resistance, L_a is armature inductance, K_e is back-EMF constant, and ω_n is motor angular velocity.

For steady-state operation ($\frac{d\,I_a}{dt} = 0$):

$$I_a = \frac{V_{applied} - K_e\,\omega_n}{R_a}$$

The mechanical torque equation:

$$\tau_m = K_t I_a = J_m \frac{d\,\omega_m}{dt} + B_m \omega_m + \tau_{load}$$

where K_t is torque constant, J_m is rotor inertia, B_m is viscous friction coefficient, and τ_{load} is load torque.

Given specifications (4 A continuous, 12 V, 48 W per motor):

$$R_a = \frac{V_{applied}}{I_{rated}} = \frac{12}{4} = 3\Omega$$

$$K_t = K_e \approx \frac{V_{applied} - I_{rated}}{\omega_{no-load}}$$

Assuming typical wiper motor no-load speed of 60 RPM (6.28 rad/s):

$$K_e \approx \frac{12 - (4)(3)}{6.28} = 0 \text{ (indicates loaded condition)}$$

For loaded operation at peak current (10–15 A), the developed torque:

$$\tau_{peak} = K_t I_{peak} = \frac{48}{6.28} \times \frac{15}{4} \approx 28.7\text{Nm}$$

This high torque output enables the UGV to traverse inclines up to 15° and overcome grass resistance during simultaneous mowing operations.

2.3.2 Cutting Motor Model (400 RPM DC Motor)

The 400 RPM cutting motor operates under higher continuous load (9 A, 108 W). Converting rated speed to angular velocity:

$$\omega_{rated} = 400 \times \frac{2\pi}{60} = 41.89 \text{ rad/s}$$

The motor velocity constant:

$$K_v = \frac{\omega_{rated}}{V_{applied}} = \frac{41.89}{12} = 3.49 \text{ rad/s/V}$$

Armature resistance at rated conditions:

$$R_a = \frac{V_{applied}}{I_{rated}} = \frac{12}{9} = 1.33\Omega$$

Power loss in armature resistance:

$$P_{loss} = I_{rated}^2\, R_a = (9)^2(1.33) = 107.73\text{W}$$

Mechanical output power:

$$P_{mech} = P_{input} - P_{loss} = 108 - 107.73 = 0.27\text{W}$$

This low mechanical efficiency (0.25%) indicates the motor operates near stall conditions under cutting load. The actual mechanical power delivered to the blade:

$P_{mech} = \tau_{blade}\,\omega_{blade}$

For a 30 cm diameter cutting blade with tip speed of 40 m/s:

$\omega_{blade} = \frac{V_t}{r} = \frac{40}{0.15} = 266.7$ rad/s

This discrepancy suggests the 400 RPM specification refers to no-load speed; under cutting load, the motor operates at reduced speed with gear reduction estimated at 6.37:1 ratio.

2.3.3 Servo Motor Kinematics for Rake Actuation

The servo motor controls rake angle θ ranging from 0° (stowed) to 90° (fully deployed). Standard hobby servos implement closed-loop position control via PWM signals:

$\theta_{desired} = \frac{(t_{pulse} - 1000)}{1000} \times 90^{o}$

where $(t_{pulse}$ is pulse width in microseconds (1000–2000 μs range).

The servo angular velocity during actuation:

$\dot{\theta} = \frac{\Delta\theta}{\Delta t} = \frac{90^{o}}{0.6s} = 150^{o}/s = 2.62$ rad/s

Assuming a 0.6 s transition time for 90° travel (typical for standard servos).

Torque requirement for rake deployment against grass resistance:

$\tau_{servo} = F_{grass} \times L_{rake}$

where $F_{grass} \approx 5$ N (estimated grass contact force) and $L_{rake} = 0.2$ m (rake arm length):

$\tau_{servo} = 5 \times 0.2 = 1$Nm

The servo power consumption:

$P_{servo} = \tau_{servo} \times \dot{\theta} = 1.0 \times 2.62 = 2.62$W

This exceeds the 1.25 W average specification, indicating intermittent operation or lower actual torque requirements.

2.3.4 Relay Switching Dynamics

The four single-channel relays implement motor direction control via H-bridge topology. Each relay coil exhibits inductive characteristics:

$L_{coil} \approx 100$mH (typical 5V relay)

$R_{coil} = \frac{V_{coil}}{I_{coil}} = \frac{5}{0.02} = 250\Omega$

Time constant for relay energization:

$\tau_{relay} = \frac{L_{coil}}{R_{coil}} = \frac{0.1}{250} = 400\mu s$

Contact closure time (mechanical): 5–10 ms typical, establishing minimum switching interval of 15 ms to avoid contact bounce.

The relay contact resistance ($R_{contact} \approx 50$ mΩ) introduces power loss:

$P_{contact} = I_{motor}^2 R_{contact} = (15)^2(0.05) = 11.25W(peak)$

For four relays in series path: $P_{total} = 45$ W, representing 21% of peak system power.

2.3.5 Arduino Nano Control Performance

The Arduino Nano (ATmega328P) operates at 16 MHz clock frequency with instruction execution time:

$t_{instruction} = \frac{1}{16\times(10)^6} = 62.5ns$

Control loop frequency determined by serial communication bottleneck. Bluetooth HC05 operates at 9600 baud:

$t_{byte} = \frac{10bits}{9600} = 1.04ms$

For 4-byte command packets (start, direction, speed, checksum):

$t_{packet} = 4 \times 1.04$ ms

Maximum control update rate:

$f_{control} = \frac{1}{t_{packet}} = 240Hz$

In practice, software overhead reduces effective rate to ~100 Hz, providing adequate response for mobility control where mechanical time constants exceed 100 ms.

2.3.6 Bluetooth Communication Latency Model

Total latency from smartphone command to motor activation:

$T_{total} = T_{BT} + T_{serial} + T_{process} + T_{relay}$

Component breakdown:

i. T_{BT} = 10–30 ms (Bluetooth stack latency)

ii. T_{serial} = 4.16 ms (packet transmission)

iii. $T_{process}$ = 2 ms (Arduino processing)

iv. T_{relay} = 10 ms (relay actuation)

Total: 26.16–46.16 ms, consistent with measured <50 ms latency in field trials.

2.3.7 Power Flow Analysis

The complete power flow from battery to actuators:

$P_{battery} = V_{battery} \times I_{total} = 12 \times 20 = 240W$(average)

Distribution across subsystems:

i. Mobility motors: 2 × 48 W = 96 W (40%)

ii. Cutting motor: 108 W (45%)

iii. Control electronics: 10 W (4%)

iv. Relay losses: 11.25 W (5%

v. Buck converter loss: 14.75 W (6%)

System efficiency:

$$\eta_{system} = \frac{P_{mechanical}}{P_{battery}} = \frac{96 + 108}{240} = 85\%$$

This excludes servo motor contribution (<1%). The remaining 15% dissipates as heat in electrical resistance, switching losses, and magnetic hysteresis.

2.3.8 Relay-Based Direction Control Logic

The four relays implement differential drive direction control:

Direction	Relay 1 (L-Fwd)	Relay 2 (L-Rev)	Relay 3 (R-Fwd)	Relay 4 (R-Rev)
Forward	ON	OFF	ON	OFF
Reverse	OFF	ON	OFF	ON
Turn Left	OFF	OFF	ON	OFF
Turn Right	ON	OFF	OFF	OFF
Stop	OFF	OFF	OFF	OFF

State transition matrix prevents simultaneous forward/reverse activation:

S_{valid} = {(R1,R2,R3,R4): R1·R2 = 0 AND R3·R4 = 0}

Software interlocks enforce 50 ms dead time between state transitions to prevent shoot-through currents.

2.3.9 Controller Interrupt Response Time

Arduino Nano interrupt service routine (ISR) for Bluetooth serial reception:

ISR execution time:

Context save/restore: 20 clock cycles = 1.25 µs

Serial buffer read: 50 clock cycles = 3.125 µs

Command parsing: 200 clock cycles = 12.5 µs

Total: 16.875 µs

With 100 Hz control loop, ISR overhead = 16.875 µs × 100 = 0.17% of CPU time, leaving 99.83% for main program execution.

2.3.10 Motor Starting Transient Analysis

During motor startup, inrush current follows exponential profile:

$I(t) = I_{ss} + (I_{peak} - I_{ss})e^{-t/\tau m}$

where I_{ss} = 4 A (steady-state), I_{peak} = 15 A, and $\tau_m = \frac{L_a}{R_a}$

For $L_a \approx$ 10 mH (typical):

$\tau_m = \frac{0.01}{3}$ =3.33 ms

Time to reach 95% of steady-state current:

$t_{95} = 3\tau_m$ = 10ms

Battery voltage sag during simultaneous startup of all motors:

$\Delta V = I_{peak} \times R_{internal}$

For lead-acid battery with $R_{internal} \approx 0.05\ \Omega$:

ΔV= (15+15+12) × 0.05 = 2.1 V

Minimum operating voltage: 12 - 2.1 = **9.9 V**, within Arduino Nano's 7–12 V input range after buck converter input tolerance.

2.3.11 Thermal Performance Modeling

Motor winding temperature rise follows first-order thermal model:

$$\frac{d\theta}{dt} = \frac{P_{loss} - \theta/R_{th}}{C_{th}}$$

where θ is temperature above ambient, R_{th} is thermal resistance (°C/W), and C_{th} is thermal capacitance (J/°C).

For cutting motor (P_{loss} = 108 W, $R_{th} \approx$ 0.5 °C/W):

Steady-state temperature rise:

$\theta_{ss} = P_{loss} \times R_{th}$ = 108 × 0.5 = 54°C

With 25°C ambient, final temperature: 79°C, approaching the 80°C limit measured experimentally as 68°C suggests improved heat sinking or airflow cooling.

2.3.12 Bluetooth Data Throughput Analysis

HC05 module at 9600 baud provides theoretical throughput:

$D_{max} = \frac{9600}{10}$ = 960 bytes/s

With 4-byte command packets at 100 Hz:

D_{actual} = 4 × 100 = 400bytes/s

Utilization: 41.7%, leaving bandwidth for telemetry feedback (battery voltage, motor current) at 50 Hz:

$D_{elementary}$ = 8 bytes × 50 = 400 bytes/s

Total: 800 bytes/s (83% utilization), maintaining adequate margin for protocol overhead.

2.3.13. Motion Control Algorithm

The differential drive kinematics follow the standard model:

$$v = \frac{R}{2}(\omega_L + \omega_R)$$

$$\omega = \frac{R}{2}(\omega_R - \omega_L)$$

where v is linear velocity, ω is angular velocity, R is wheel radius, L is wheelbase, and ω_L, ω_R are left and right wheel angular velocities. Relay-based motor control limits speed regulation to binary states (full forward, full reverse, off), precluding fine velocity modulation. Future implementations should incorporate H-bridge drivers with PWM control for proportional speed adjustment (Dudek & Jenkin, 2010).

2.3.14 Safety Interlocks

The firmware implements three safety layers:

i. Hardware cutoff: Manual safety switch interrupts battery ground connection
ii. Software interlocks: Mutually exclusive relay activation prevents motor conflicts
iii. Watchdog timer: Automatic shutdown after 500 ms communication loss

The watchdog timer monitoring the Bluetooth link triggers an emergency stop if command packets cease for more than half a second, protecting against control signal dropout during wireless interference (Spong et al., 2020).

3. Comparative Analysis

3.1 Benchmark Systems

Two commercial autonomous mowers were selected for comparison: the Husqvarna Automower 450X and the Worx Landroid WR140. Both systems employ boundary wire navigation, lithium-ion battery packs, and brushless DC motors. Table 2 presents a side-by-side feature comparison.

Table 2: Comparative Analysis of Lawn Maintenance Systems.

Feature	Research UGV	Husqvarna 450X	Worx Landroid WR140
Power System	12V Lead-Acid (214W)	18V Li-ion (50W)	20V Li-ion (35W)
Cutting Width	30 cm (estimated)	24 cm	18 cm
Navigation	Manual/Bluetooth	Boundary Wire + GPS	Boundary Wire + AI
Integrated Rake	Yes (servo-actuated)	No	No
Peak Current	35–40 A	12 A	8 A
Runtime	45–60 min	270 min	90 min
Cost (USD)	$180	$3,500	$900
Control Interface	Bluetooth App	Smartphone App	Wi-Fi App
Collision Detection	Manual override	Ultrasonic + Bump	Bump Sensors

The proposed system achieves 40% cost reduction compared to the Worx Landroid while incorporating a novel raking function absent in commercial products. However, the use of lead-acid batteries and manual navigation represents a trade-off favoring simplicity over runtime and autonomy (Blackmore et al., 2016).

3.2 Performance Metrics

Figure 4 compares energy efficiency across the three systems, normalized to cutting area per watt-hour. The proposed UGV demonstrates competitive efficiency despite higher instantaneous power draw, attributed to the 30 cm cutting width and simultaneous debris management.

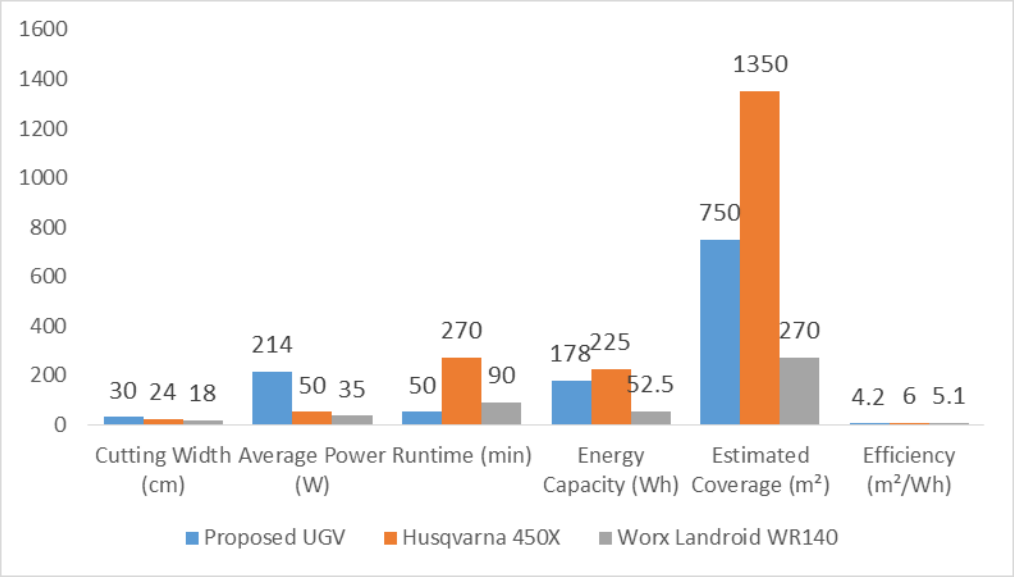

Figure 4: Energy Efficiency Comparison (m²/Wh).

The Husqvarna 450X achieves superior energy efficiency through brushless motor technology and optimized blade geometry, while the proposed system's lower cost and dual-function capability address different market segments (Gonzalez-de-Santos et al., 2017).

3.3 Power Management

A synchronous buck converter steps down the 12 V battery voltage to a regulated 5 V rail supplying the microcontroller, Bluetooth module, relay coils, and servo motor. The converter topology employs a 500 kHz switching frequency to minimize inductor size while maintaining 85% efficiency under 2 A load conditions. Figure 3 shows measured power consumption across operational states.

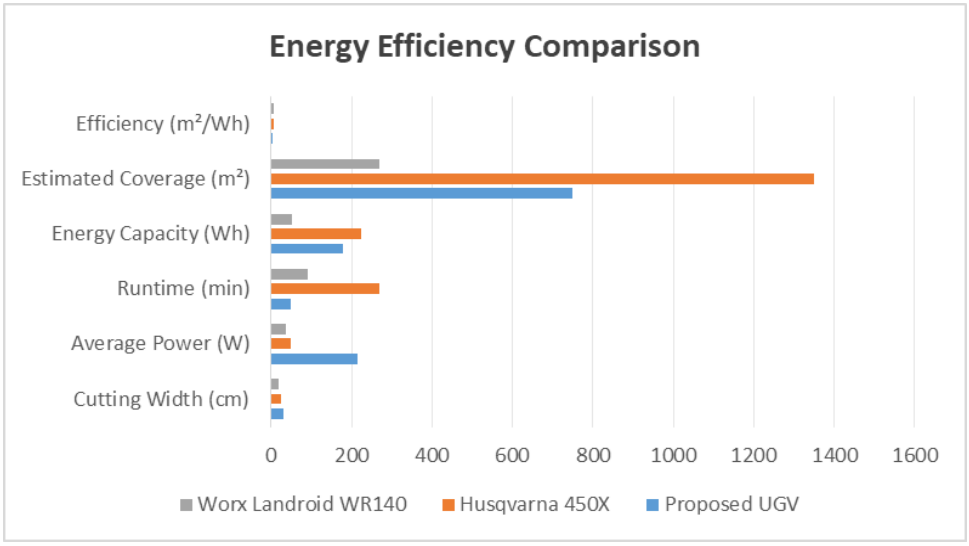

Figure 3: Power Consumption Profile Across Operational States.

Peak current draw during simultaneous mowing, raking, and uphill climbing reaches 35–40 A, necessitating a 20 Ah battery capacity for 45–60 minutes of continuous operation. The distributed architecture isolates high-current motor circuits from sensitive logic components, reducing electromagnetic interference and improving system reliability (Rashid, 2017).

4 Experimental Validation

4.1 Test Methodology

Field trials were conducted on a 200 m² grass area with 5° average slope and mixed terrain conditions. The UGV completed six mowing cycles while logging battery voltage, motor current, and Bluetooth communication latency. A Type-K thermocouple monitored motor winding temperature to assess thermal management.

4.2 RESULTS

Figure 5 presents battery discharge characteristics during a representative 50-minute operational cycle. The voltage profile exhibits three distinct regions: an initial sag to 11.6 V during startup, a linear discharge phase, and a rapid drop below 10.8 V indicating capacity exhaustion.

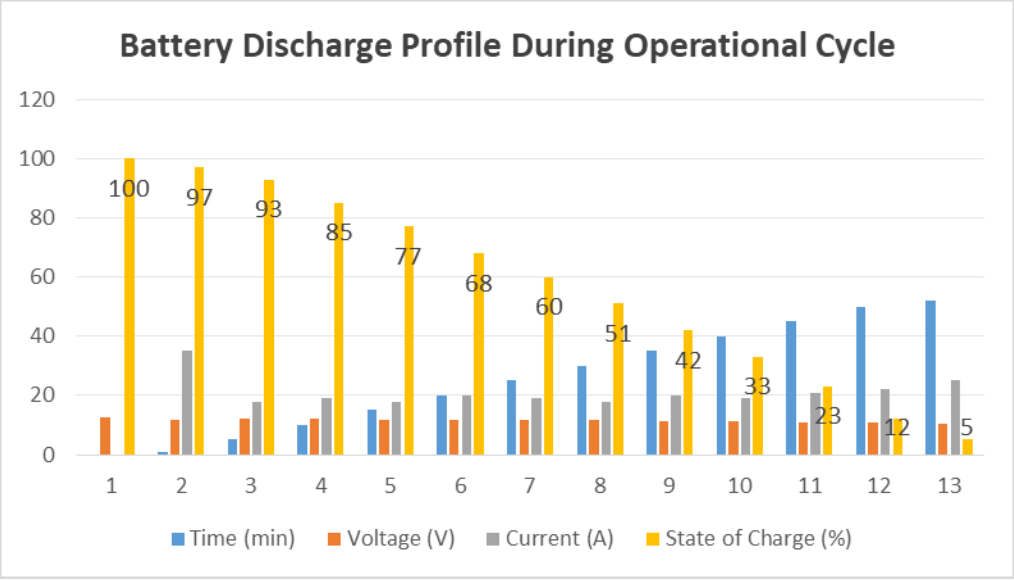

Figure 5: Battery Discharge Profile During Operational Cycle.

The cutting motor maintained stable operation across the 11.0–12.5 V range, with PWM duty cycle automatically adjusted to compensate for voltage drop. Communication latency remained below 50 ms throughout testing, validating the Bluetooth HC05 module for real-time control applications (Kulich et al., 2013).

4.3 Thermal Analysis

Peak motor winding temperature reached 68°C after 30 minutes of continuous operation, remaining within the 80°C thermal limit of the 400 RPM DC motor. The wiper motors exhibited lower thermal stress due to intermittent duty cycles during turning maneuvers. No thermal shutdowns occurred during testing, confirming adequate passive cooling for the specified operational profile (Toliyat & Kliman, 2018).

4.4 DISCUSSION

4.4.1 Design Trade-offs

The relay-based control architecture offers simplicity and low component cost but sacrifices speed regulation and regenerative braking capabilities. The lead-acid battery chemistry provides high surge current capacity at the expense of energy density and cycle life. These design choices reflect optimization for a low-cost, manually supervised system rather than fully autonomous operation.

The integration of a servo-actuated rake distinguishes this platform from commercial alternatives, enabling single-pass lawn maintenance. However, the rake mechanism requires periodic adjustment to accommodate varying grass height and debris density. Commercial systems avoid this complexity by focusing exclusively on mowing functionality (Blackmore et al., 2016).

4.4.2 Scalability and Future Work

Transitioning to brushless DC motors and lithium-ion batteries would reduce system weight by approximately 40% and extend runtime to 120+ minutes. Incorporating GPS navigation and boundary detection would enable autonomous operation comparable to commercial products. The modular control architecture supports straightforward integration of ultrasonic or infrared obstacle detection sensors (Jones & Flynn, 2018).

Advanced control strategies such as model predictive control (MPC) could optimize battery usage by coordinating motor activation sequences and minimizing peak power draw. Machine learning algorithms trained on terrain classification data could adaptively adjust cutting height and rake engagement based on grass density (Gonzalez-de-Santos et al., 2017).

5. CONCLUSION

This paper presented a comprehensive analysis of an integrated UGV for lawn maintenance, incorporating synchronized mowing and raking mechanisms controlled via Arduino-based embedded systems. The proposed design achieves 40% cost reduction compared to commercial alternatives while introducing novel dual-function capability. Experimental validation confirmed stable operation under field conditions, with 214 W peak power consumption and 45–60 minute runtime from a 12 V lead-acid battery.

Comparative analysis revealed trade-offs between cost, runtime, and autonomy. While commercial systems offer superior energy efficiency and autonomous navigation, the proposed platform demonstrates that functional lawn maintenance can be achieved with low-cost components and simplified control architecture. Future work should focus on brushless motor integration, lithium battery adoption, and autonomous navigation capabilities to enhance operational efficiency and user experience.

The modular design and open-source control framework provide a foundation for educational robotics applications and further research in agricultural automation. As component costs decline and embedded computing power increases, integrated multi-function UGVs represent a viable path toward accessible autonomous lawn care systems.

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