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DESIGN OPTIMIZATION OF A BRUSHLESS DC MOTOR AND HIGH-CAPACITY BATTERY SYSTEM FOR A PAYLOAD-CARRYING UNMANNED GROUND VEHICLE ON UNEVEN TERRAIN

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ABSTRACT

This study presents a systematic approach to the design optimization of a propulsion system for a small-scale unmanned ground vehicle (UGV) intended for payload delivery over uneven terrain. Drawing on empirical performance data from an existing prototype, mathematical models were derived to characterize the relationships between payload mass, motor speed, and battery energy consumption. A speed–load regression model (Average Speed = −0.0806 × Load + 1.0341) and a battery drain model (Battery Drain = 2.5517 × Load + 5.7241) were used to quantify the degradation in system performance under increasing load conditions. At the maximum test payload of 6 kg, the vehicle velocity dropped to 0.5 m/s and battery drain reached approximately 23% per operational cycle. To overcome these limitations, design optimization parameters were computed analytically. With an assumed rolling resistance coefficient of $\mu = 0.2$ for uneven terrain and a total system mass of 21 kg, the required wheel torque was determined to be 6.28 N·m, with a corresponding electrical input power of 27.47 W. A 24 V operating voltage was selected to minimize resistive losses, requiring a continuous current draw of 1.14 A at steady-state maximum load. The optimized propulsion system specifies a Brushless DC (BLDC) motor with gear reduction, rated at 35–50 W mechanical output, paired with a 24 V Lithium-ion battery pack of 4–10 Ah capacity and a 5C–10C discharge rating. The proposed design is projected to achieve a target speed of ≥0.8 m/s at full payload with an operational endurance of 1.4–3.5 hours, depending on battery capacity selection. The outcomes of this study provide a replicable analytical framework for engineers designing energy-efficient mobile robotic platforms under payload and terrain constraints.

KEYWORDS: unmanned ground vehicle, BLDC motor, battery optimization, torque analysis, rolling resistance, payload capacity, mobile robotics, energy efficiency.

1. INTRODUCTION

The deployment of unmanned ground vehicles (UGVs) for material handling, last-mile delivery, and field operations has seen considerable growth in recent years, driven by advances in embedded systems, motor control technologies, and energy storage solutions (Fragapane et al., 2021; Trevizan et al., 2022). A core engineering challenge in UGV design is ensuring that the propulsion system delivers adequate tractive force and energy efficiency across a range of operating conditions, particularly when the vehicle is subjected to variable payload masses and irregular terrain profiles (Liu et al., 2020).

In small-scale robotic platforms, the selection of the motor type, gear ratio, and battery chemistry directly determines the performance envelope of the system. Brushless DC (BLDC) motors have emerged as the preferred actuator in such applications owing to their superior power-to-weight ratio, high efficiency at partial loads, and reduced maintenance requirements relative to brushed DC counterparts (Bose, 2017; Krishnan, 2010), see Plate 1. When combined with appropriate gear reduction systems, BLDC motors can deliver the high torque-at-wheel necessary to overcome the resistive forces imposed by uneven terrain and heavy payloads (Pillay & Krishnan, 1989).

Concurrent with motor selection, battery technology plays an equally critical role in determining the operational endurance of the vehicle. Lithium-ion (Li-ion) and Lithium Polymer (Li-Po) chemistries offer the highest energy density among commercially available rechargeable cells and are capable of sustaining the high discharge currents (C-rates) demanded by motorized systems during acceleration and load-bearing operation (Tarascon & Armand, 2001; Blomgren, 2017). However, the relationship between payload, current draw, and battery depletion rate must be rigorously characterized to achieve meaningful system optimization.

Plate 1: Key Components of Design Optimization

This paper addresses these interconnected design challenges through an analytical framework grounded in classical mechanics and electrical power theory. Using empirical data collected from an existing prototype UGV, regression models are derived to describe the functional relationships between load, speed, and battery drain. These models are then used to compute the minimum torque, power, and electrical specifications required to meet enhanced performance targets. The study concludes with a consolidated set of recommended motor and battery specifications intended to guide the development of an optimized next-generation propulsion system.

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 describes the methodology and analytical models; Section 4 presents the optimization results and recommended specifications; and Section 5 offers conclusions and directions for future work.

2. LITERATURE REVIEW

The performance of electrically driven mobile robots and UGVs is fundamentally governed by the interplay between actuator capability, energy storage, and the physical constraints imposed by terrain and payload (Siegwart et al., 2011). Several authors have investigated these factors in isolation and in combination.

Regarding motor selection, Krishnan (2010) provided a comprehensive treatment of permanent magnet synchronous and brushless DC motor drives, demonstrating that BLDC motors offer a flat torque–speed characteristic that is particularly well-suited to traction applications where the load varies continuously. This finding has been corroborated in the context of autonomous vehicles by Pillay and Krishnan (1989), who showed that fieldoriented control of BLDC motors enables near-constant torque delivery across a wide operating range, a key requirement for payload-carrying platforms navigating slopes and rough surfaces.

The significance of gear reduction in amplifying motor output torque has been highlighted by several investigators (Bose, 2017; Mohan et al., 2014). By selecting an appropriate gear ratio, a compact high-speed motor can be matched to the high-torque, low-speed requirement at the driven wheel, simultaneously reducing motor size and improving overall efficiency. This principle is directly applicable to the present design, where the required wheel torque of 6.28 N·m substantially exceeds the typical no-load output of small-frame BLDC motors.

In the domain of energy storage, Tarascon and Armand (2001) established the foundational electrochemical basis for lithium-ion battery technology, noting its high theoretical energy density and relatively low self-discharge rate. Blomgren (2017) provided a more recent survey of Li-ion cell developments, documenting specific energy values in the range of 150–250 Wh/kg for commercial cells, substantially higher than the 30–50 Wh/kg typical of sealed lead-acid batteries. For mobile robotic systems, where mass budget is constrained, this advantage is decisive.

The relationship between discharge rate (C-rate) and effective capacity has been studied extensively. High C-rate discharge, as occurs during motor starting and acceleration, leads to internal resistive heating and a reduction in usable capacity—a phenomenon known as the Peukert effect (Dufo-López et al., 2014). Battery management systems that monitor state of charge and current draw are therefore essential to prevent premature depletion and protect cell longevity (Plett, 2015).

In the context of terrain-induced rolling resistance, Wong (2008) demonstrated that the rolling resistance coefficient μ for wheeled vehicles on deformable surfaces varies widely (typically 0.1–0.3), depending on soil moisture, surface roughness, and tire pressure. This parameter directly enters the tractive effort equation and must be carefully estimated when sizing the drivetrain. The value $\mu = 0.2$ adopted in the present work aligns with established values for loose gravel or compacted earth surfaces (Wong, 2008; Liu et al., 2020).

3. METHODOLOGY AND ANALYTICAL FRAMEWORK

3.1 Empirical Performance Characterization

Experimental trials were conducted using an existing prototype UGV with a total vehicle mass of 15 kg. Payload masses ranging from 0 (No load) to 6 kg were applied incrementally, and the corresponding average vehicle speed (m/s) and battery drain (%) per run were recorded.

Two first-order linear regression models were fitted to the experimental data using the method of least squares:

$\text{Average Speed} = -0.0806 \times \text{Load} + 1.0341$ 1

$\text{Battery Drain (\%)} = 2.5517 \times \text{Load} + 5.7241$ 2

Equation (1) confirms the inverse relationship between speed and load, consistent with the torque–speed characteristic of DC motors operating near peak power. Equation (2) quantifies the progressive energy penalty imposed by heavier payloads, rising from approximately 7% at zero load to 23% at the maximum 6 kg payload.

3.2 Tractive Effort and Wheel Torque Derivation

The tractive effort F_T required to propel the vehicle against rolling resistance was computed using the standard rolling resistance model (Wong, 2008):

$F_T = \mu \times m_{total} \times g$ 3

where $\mu = 0.2$ (rolling resistance coefficient for uneven terrain),

$m_{total} = m_{vehicle} + L = 15 + 6 = 21$ kg, and $g = 9.81$ m/s². Substituting:

$F_T = 0.2 \times 21 \times 9.81 = 41.202$ N

The wheel radius r was converted from 6 inches to SI units: $r = 6 \times 0.0254 = 0.1524$ m. The required wheel torque τ_w is:

$\tau_w = F_T \times r$ 4

$= 41.202 \times 0.1524 \approx 6.28$ N·m

3.3 Electrical Power and Voltage Analysis

Table 1, present the summary of the design optimization parameters for the unmanned ground vehicle. To determine various optimization parameters;

The mechanical output power P_{mech} at the minimum observed speed $S = 0.5$ m/s is:

$P_{mech} = F_T \times S$ 5

$= 41.202 \times 0.5 = 20.601$ W

Accounting for a system efficiency $\eta = 0.75$ (a commonly used estimate for gear-motor combinations of this type; Mohan et al., 2014), the required electrical input power is:

$$P_{elec} = \frac{P_{mech}}{\eta} \quad (6)$$

= 20.601 / 0.75 ≈ 27.47 W

For a 24 V system (selected to minimize resistive I^2R losses relative to a 12 V alternative), the required continuous current draw is:

$$I = \frac{P_{elec}}{V} \quad (7)$$

= 27.47 / 24 ≈ 1.14 A

Table 1: Design Optimization Parameters.

Parameter	Value
Minimum Required Wheel Torque (τ_w)	6.28 N·m
Required Electrical Input Power (P_{elec})	27.47 W
Recommended Operating Voltage (V)	24 V
Corresponding Continuous Current Draw (I)	1.14 A

4. Optimization Results and Recommended Specifications

4.1 Motor Optimization

The analysis confirms that the existing motor is operating near its peak power limit under the 6 kg payload, producing the observed speed reduction. To achieve a target speed of ≥0.8 m/s at full payload, the motor output power must substantially exceed the 20.6 W mechanical minimum. A mechanical output power of 35–50 W provides adequate reserve for acceleration, incline traversal, and higher top speeds, see Table 2, for details. At the system efficiency of 75%, this corresponds to an electrical input power of 47–67 W.

A Brush Less DC (BLDC) motor paired with a gear reduction stage is strongly recommended. The gear ratio is selected such that motor output torque × gear ratio ≥ 6.28 N·m at the wheel, enabling a lighter, higher-speed motor core to be used while maximizing the power-to-weight ratio of the drive system. This approach is consistent with established best practice for small-scale robotic traction systems (Krishnan, 2010; Bose, 2017).

Table 2: Recommended Motor Specifications.

Parameter	**Recommended Specification**	**Remarks**
Type	BLDC Motor with Gear Reduction	High efficiency, excellent power-to-weight ratio; gear reduction amplifies wheel torque above 6.28 N·m
Mechanical Output (P_{mech})	35–50 W	Provides reserve power for acceleration and target speed ≥0.8 m/s at 6 kg payload
Electrical Input (P_{elec})	47–67 W	Calculated using 75% efficiency (e.g., 50 W / 0.75 ≈ 67 W)
Peak Wheel Torque	≥6.28 N·m (continuous)	Gear ratio selected: τ_{motor} × ratio ≥ 6.28 N·m

4.2 Battery Optimization

For the optimized motor (up to 67 W electrical input at 24 V), the maximum continuous current draw is:

$I_{max} = \frac{P_{elec}}{V}$ (Applying equation 7)

= 67 / 24 ≈ 2.8 A

Battery capacity (Ah) is determined by the desired operational runtime t and the maximum current draw, adjusted for depth of discharge (DoD):

$$C = \frac{I_{mzx} \times t}{DoD} \quad 8$$

For a 4 Ah battery at 2.8 A maximum draw, the estimated runtime is 4 / 2.8 ≈ 1.4 hours. A 10 Ah battery extends endurance to approximately 3.5 hours, see Table 3 for details. A high C-rate (5C–10C continuous) is specified to accommodate transient peak currents during motor starting and acceleration, preventing voltage sag that would otherwise reduce motor speed under load (Plett, 2015; Dufo-López et al., 2014).

Table 3: Recommended Battery Specifications.

Parameter	**Recommended Specification**	**Remarks**
Chemistry	Lithium-ion (Li-ion)	High energy density (150–250 Wh/kg); superior C-rate performance over lead-acid
Nominal Voltage	24 V (6S Li-ion pack)	Minimizes current draw (2.8 A max) and I^2R losses
Capacity (C)	4–10 Ah	4 Ah ≈ 1.4 h runtime; 10 Ah ≈ 3.5 h runtime at maximum 6 kg load
Required C-Rate	5C–10C (continuous)	Sustains peak current during acceleration; prevents voltage sag

4.3 Voltage Trade-Off Analysis

A comparative analysis of 12 V and 24 V operating voltages was conducted to assess the impact of voltage selection on current demand and resistive losses. As shown in Table 4, the 24 V system halves the required current at equivalent power, directly reducing wiring cross-section requirements and minimizing I^2R heat dissipation which is a critical consideration for compact robotic platforms where thermal management is constrained (Mohan et al., 2014).

Table 4: Voltage Trade-Off Comparison at P_{elec} = 27.47 W.

Design Voltage	Required Current (I = P/V)	System Implications
12 V	≈ 2.29 A	Higher resistive losses; requires heavier wiring; common for light loads only
24 V (Recommended)	≈ 1.14 A	Lower losses; lighter wiring; preferred for efficiency and thermal management

5. CONCLUSIONS

This study has presented a systematic analytical methodology for the design optimization of the propulsion system of a small-scale unmanned ground vehicle carrying payloads of up to 6 kg on uneven terrain. The empirical regression models derived from prototype trial data quantify the significant adverse effects of increasing payload on both vehicle speed and battery energy consumption, providing a quantitative basis for setting design targets that the existing system cannot meet. Applying classical rolling resistance mechanics with $\mu = 0.2$, the minimum required wheel torque was computed as 6.28 N·m, and the required electrical input power as 27.47 W. These values define the lower-bound specifications against which any replacement motor must be assessed. A 24 V operating voltage was identified as the preferred system voltage, delivering a practical continuous current draw of approximately 1.14 A at the minimum power requirement, with a projected maximum of 2.8 A for the fully optimized 67 W motor configuration.

The recommended motor specification is a Brush Less DC motor with gear reduction, rated at 35–50 W mechanical output which directly addresses the speed–torque limitations of the current prototype and is expected to enable operational speeds of ≥0.8 m/s at full 6 kg payload, compared to the 0.5 m/s observed in baseline trials. The recommended battery is a 24 V Li-ion pack of 4–10 Ah at 5C–10C discharge rating which provides both the energy density and the dynamic current delivery capability required to sustain the optimized motor across the full operational duty cycle.

Future work should include experimental validation of the proposed specifications using a fabricated prototype, incorporation of slope angle as a variable in the tractive effort model, and investigation of regenerative braking strategies to partially recover energy during deceleration on downhill terrain segments.

REFERENCES

1. Blomgren, G. E. (2017). The development and future of lithium ion batteries. Journal of The Electrochemical Society, 164(1), A5019–A5025. https://doi.org/10.1149/2.0251701jes
2. Bose, B. K. (2017). Power electronics and motor drives: Advances and trends (2nd ed.). Academic Press.
3. Dufo-López, R., Lujano-Rojas, J. M., & Bernal-Agustín, J. L. (2014). Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems. Applied Energy, 115, 242–253. https://doi.org/10.1016/j.apenergy.2013.11.021
4. Fragapane, G., de Koster, R., Sgarbossa, F., & Strandhagen, J. O. (2021). Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda. European Journal of Operational Research, 294(2), 405–426. https://doi.org/10.1016/j.ejor.2021.01.019
5. Krishnan, R. (2010). Permanent magnet synchronous and brushless DC motor drives. CRC Press.
6. Liu, Y., Zhu, Z. Q., & Howe, D. (2020). Instantaneous torque estimation in sensorless direct-torque-controlled brushless DC motors. IEEE Transactions on Industry Applications, 39(6), 1632–1639. https://doi.org/10.1109/TIA.2003.818982
7. Mohan, N., Undeland, T. M., & Robbins, W. P. (2014). Power electronics: Converters, applications, and design (3rd ed.). Wiley.
8. Pillay, P., & Krishnan, R. (1989). Modeling, simulation, and analysis of permanent-magnet motor drives, Part II: The brushless DC motor drive. IEEE Transactions on Industry Applications, 25(2), 274–279. https://doi.org/10.1109/28.25542
9. Plett, G. L. (2015). Battery management systems, Volume I: Battery modeling. Artech House.
10. Siegwart, R., Nourbakhsh, I. R., & Scaramuzza, D. (2011). Introduction to autonomous mobile robots (2nd ed.). MIT Press.

11. Tarascon, J. M., & Armand, M. (2001). Issues and challenges facing rechargeable lithium batteries. Nature, 414(6861), 359–367. https://doi.org/10.1038/35104644
12. Trevizan, R. D., Ruben, C., Bhatta, S., Bretas, A. S., & Meyn, S. (2022). Optimal battery energy storage system scheduling within islanded microgrids. International Journal of Electrical Power & Energy Systems, 141, 108121. https://doi.org/10.1016/j.ijepes.2022.108121
13. Wong, J. Y. (2008). Theory of ground vehicles (4th ed.). Wiley.