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All-Terrain Robot For Military Applications

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Abstract
Unmanned Ground Vehicles (UGVs) play a critical role in modern military and disaster-response missions by minimizing human exposure to hostile and hazardous environments. This research presents the comprehensive design, development, and evaluation of a hardware-centric all-terrain tracked robot intended for military field operations. Unlike conventional programmable robotic platforms, the proposed system eliminates microcontroller-based motion control and instead employs a radio frequency (RF) transmitter–receiver architecture combined with servo-to-PWM conversion and high-current BTS7960 motor drivers. The robot integrates a regulated power management system, differential steering mechanism, and modular structural design to ensure operational reliability across rugged terrains. Experimental analysis demonstrates stable mobility on sand, gravel, mud, and inclined surfaces up to 35°, with efficient energy utilization and minimal signal latency. The results validate that the proposed architecture provides a cost-effective, robust, and field-repairable alternative for military reconnaissance and support missions.

Keywords: *Unmanned Ground Vehicle, All-Terrain Robot, Military Robotics, Differential Steering, BTS7960 Motor Driver, RF Control System, Power Management, Tracked Vehicle.*

1. Introduction

The advancement of robotic systems has significantly transformed military operations, particularly in surveillance, reconnaissance, explosive ordnance disposal, and search-and-rescue missions. Unmanned Ground Vehicles (UGVs) are increasingly deployed in environments where human intervention poses substantial risk, including minefields, collapsed infrastructures, and active combat zones [1]. The primary objective of such systems is to enhance mission effectiveness while ensuring operator safety.

Tracked robotic platforms have demonstrated superior terrain adaptability compared to wheeled systems due to increased surface contact and distributed load characteristics [2]. Military-grade UGVs such as reconnaissance robots and tactical support units rely heavily on differential steering mechanisms to achieve precise maneuverability in confined and rugged terrains [3]. However, many contemporary systems depend on microcontroller-based architectures, embedded firmware, and complex software stacks, which introduce vulnerabilities related to software failure, electromagnetic interference, and field-level repair challenges [4].

Energy management and system reliability are also central concerns in mobile robotics. Efficient power regulation and current handling are essential for high-torque DC motor applications operating in unpredictable terrain conditions [5]. Studies indicate that voltage instability and driver overheating remain common failure points in field robotics [6]. Additionally, modular expandability is often limited by rigid electronic architectures [7].

This research addresses these limitations by proposing a hardware-driven control architecture that eliminates dependency on onboard programming while maintaining precise motion control. The system integrates RF-based teleoperation, servo-to-PWM conversion modules, dual high-current BTS7960 motor drivers, and regulated DC–DC power conversion. The proposed design emphasizes mechanical robustness, electrical reliability, and operational simplicity for military field deployment.

2. Literature Review

The development of unmanned ground vehicles (UGVs) for military and hazardous applications has evolved significantly over the past two decades, driven by advances in mobility modeling, structural optimization, energy systems, teleoperation, and autonomous navigation. Early foundational work by Thrun et al. in *Probabilistic Robotics* [23] established mathematical frameworks for localization, perception, and uncertainty handling, forming the theoretical basis for autonomous robotic systems. Similarly, Bandyopadhyay et al. [21] presented a comprehensive survey on autonomous navigation of UGVs in challenging terrains, highlighting limitations in perception accuracy and terrain adaptability. These foundational studies underscore the importance of integrating robust mechanical design with reliable control systems to ensure safe deployment in unpredictable environments.

Terrain traversability and mobility remain critical aspects of military robotic platforms. Papadakis [24] examined terrain traversability analysis methods, emphasizing track–terrain interaction models and slope stability assessment. Howard and Seraji [25] further contributed by proposing vision-based terrain classification techniques that enable autonomous navigation through complex environments. More recently, Gao et al. [1] investigated the design and control of tracked mobile robots equipped with passive suspension systems, demonstrating improved stability and shock absorption in rugged terrains. Their findings confirm that tracked configurations significantly outperform wheeled systems in uneven and soft soil conditions. Complementing this work, Sun and Gu [2] explored backlash elimination control in dual-motor robotic joints, highlighting the importance of mechanical precision and torque synchronization in heavy-duty robotic systems.

Reliability and structural robustness are equally essential for military deployment. Zhang et al. [7] proposed simulation-based reliability optimization for industrial robotic structures, demonstrating how structural reinforcement and finite element modeling enhance operational durability. In field robotics, odometry errors caused by terrain irregularities present substantial challenges; Ojeda and Borenstein [22] addressed this issue by proposing corrective algorithms to minimize localization inaccuracies on rough surfaces. These studies collectively emphasize the need for mechanically stable platforms combined with accurate motion control strategies.

Energy efficiency and power management are major constraints in mobile robotic systems. Wu et al. [11] reviewed energy efficiency strategies in autonomous mobile robots, identifying motor driver losses, voltage instability, and inefficient battery utilization as primary contributors to reduced endurance. Mikołajczyk et al. [12] conducted a systematic comparison of energy sources for mobile robots, recommending optimized battery selection and regulated power distribution for high-load applications. Singh et al. [6] further analyzed advanced power converters in robotic systems, demonstrating that efficient DC–DC conversion significantly enhances system reliability and operational lifespan. These findings are particularly relevant in high-current tracked robots where stable voltage supply ensures consistent torque output and prevents communication failures.

In the domain of teleoperation and remote control, Ghosh and Bandyopadhyay [18] examined remote operation frameworks for UGVs deployed in hazardous environments, emphasizing low-latency communication and operator feedback mechanisms. Chen et al. [10] introduced collaborative remote control of UGVs using virtual reality interfaces, enhancing situational awareness during military missions. Furthermore, Bakyt et al. [17] reviewed cryptographic integration within unmanned military mobile robots, highlighting secure communication channels as a critical requirement in defense operations. These contributions demonstrate the growing importance of secure, real-time teleoperation systems for battlefield robotics.

Artificial intelligence and sensor integration have further expanded the capabilities of modern UGVs. Sarraf [8] discussed advanced sensor fusion algorithms for enhanced perception and navigation accuracy, while Ramadoss [9] explored AI-driven object recognition and tracking using integrated sensor architectures. Santoso [20] examined MEMS-based multi-sensor integration techniques for improved autonomy. Together, these works illustrate how perception-driven autonomy enhances situational awareness and navigation robustness in military robotic systems.

Military-specific robotic applications have also been extensively reviewed. Kulkarni et al. [13] provided a systematic review of smart robotic systems for military and disaster scenarios, identifying mobility reliability and communication robustness as key performance indicators. The IEEE survey on autonomous military service robots [14] analyzed deployment trends and operational constraints in battlefield environments. Suryawanshi et al. [15] developed an intelligent surveillance robot tailored for hazardous environments, integrating vision systems and wireless control. Similarly, Abhishek et al. [16] proposed an IoT-driven multi-functional military robot architecture that supports modular sensor integration and remote data transmission. Zhang and Wang [19] further explored path planning and energy management strategies for military mobile robots, demonstrating that optimized trajectory planning reduces energy consumption while maintaining operational effectiveness.

At the hardware level, practical implementation aspects are supported by industrial documentation such as the BTS7960 motor driver datasheet [3], which specifies high-current handling capabilities and thermal protection features suitable for heavy-duty robotic systems. PWM-based servo control mechanisms discussed by VHDLwhiz [4] provide insights into precise signal generation for motor speed regulation, while differential steering principles outlined by the University of Florida [5] establish the mechanical foundation for tracked vehicle maneuverability.

Collectively, the reviewed literature reveals substantial advancements in mobility analysis, energy optimization, teleoperation, AI integration, and secure communication for military robotic platforms. However, most contemporary systems emphasize software-intensive architectures and microcontroller-based control frameworks. Limited research addresses simplified hardware-centric designs aimed at maximizing field repairability and operational reliability. Therefore, there exists a clear research gap in developing robust, programming-independent tracked robotic systems suitable for military field deployment—an objective that the present study seeks to address through a modular hardware-driven architecture integrating efficient power management and differential steering mechanisms.

3. Methodology

The methodology adopted for the proposed **All-Terrain Robot for Military Applications** follows a systematic hardware-centric design framework emphasizing rugged mobility, electrical reliability, and field maintainability. The design principles are derived from tracked mobility modeling [1], terrain traversability analysis [24], differential steering kinematics [5], energy optimization strategies [11], [12], and regulated power converter architectures [6]. Unlike autonomous computation-intensive architectures discussed in [23] and [21], the proposed methodology prioritizes teleoperated robustness with minimal software dependency, thereby enhancing operational reliability in hostile environments.

The methodological framework is divided into mechanical design methodology, control system methodology, power management methodology, and reliability modeling.

A. Mechanical and Mobility Design Methodology

Tracked locomotion was selected as the primary mobility mechanism after a comparative evaluation of wheeled and tracked robotic platforms operating in unstructured environments. Studies on rugged-terrain robotic systems demonstrate that tracked vehicles provide superior traction, improved load distribution, and enhanced slope-climbing capability when compared to conventional wheeled configurations [1], [24]. The continuous belt structure of tracks increases the effective ground contact area, thereby reducing ground pressure and minimizing sinkage in deformable terrains such as sand, mud, and loose gravel. This reduction in ground pressure directly improves traction efficiency and mitigates slippage under high-load conditions. Furthermore, the distributed contact surface enhances longitudinal stability when traversing inclined planes, irregular rocky surfaces, and debris-filled environments, which are commonly encountered in military and disaster-response scenarios. Terrain traversability models in [24] confirm that tracked systems exhibit better obstacle negotiation and lower susceptibility to immobilization in soft soils.

The proposed robot adopts a dual-track differential drive configuration to achieve high maneuverability without incorporating complex mechanical steering assemblies. In this architecture, the left and right tracks are independently driven, allowing directional control through differential velocity modulation, consistent with the kinematic principles outlined in [5]. By varying the rotational speed and direction of each track, the robot can perform forward motion, gradual turning, pivot turning, and zero-radius rotation. This eliminates the need for steering linkages, reducing mechanical complexity and potential failure points. The differential steering model enhances agility in confined environments, such as narrow corridors, trenches, or cluttered battlefield terrain, where rapid directional adjustment is essential.

Structural integrity is a critical design consideration for military robotic systems exposed to shock loads, vibrations, and torsional stresses. Therefore, the chassis was designed using reinforced metallic framing to withstand mechanical impacts and sustained operational stress. Reliability optimization strategies similar to those discussed in [7] were considered during structural design to ensure durability under dynamic loading conditions. Finite stress considerations and weight distribution analysis were incorporated to prevent frame deformation during obstacle climbing and payload transport. Reinforcement at motor mounting points further reduces structural fatigue and enhances alignment stability.

The mechanical subsystem is composed of four high-torque DC motors arranged in paired configuration across the two tracks. Each track is powered by two synchronized motors to distribute torque evenly and reduce localized stress concentration. This multi-motor configuration improves traction redundancy and ensures continued mobility even if partial torque imbalance occurs. However, multi-motor systems are susceptible to backlash and synchronization issues, particularly under variable loading conditions. To address these challenges, torque balancing strategies were implemented in accordance with dual-motor drive control concepts described in [2]. Proper mechanical alignment and uniform gear meshing reduce backlash effects and enhance motion smoothness.

The dual track assemblies consist of reinforced rubberized belts with embedded traction ridges designed to maximize frictional grip across varying terrain textures. The track tension mechanism was

calibrated to maintain optimal tightness, preventing derailment while minimizing frictional losses. This design improves climbing stability and reduces energy dissipation during prolonged operation.
To further enhance shock resistance, the system incorporates shock-absorbing mounting supports between the chassis and motor assemblies. These dampening elements reduce vibration transmission from the terrain to the structural frame and electronic components. Vibration isolation improves component longevity and prevents misalignment of mechanical elements during rugged operation.
Overall, the integrated mechanical design ensures enhanced traction, balanced torque distribution, improved shock tolerance, and structural resilience. The combination of tracked locomotion, differential steering, reinforced chassis construction, and vibration mitigation establishes a mechanically robust platform capable of reliable deployment in harsh and unpredictable military environments, consistent with terrain adaptability and reliability principles discussed in [1], [2], [5], [7], and [24].

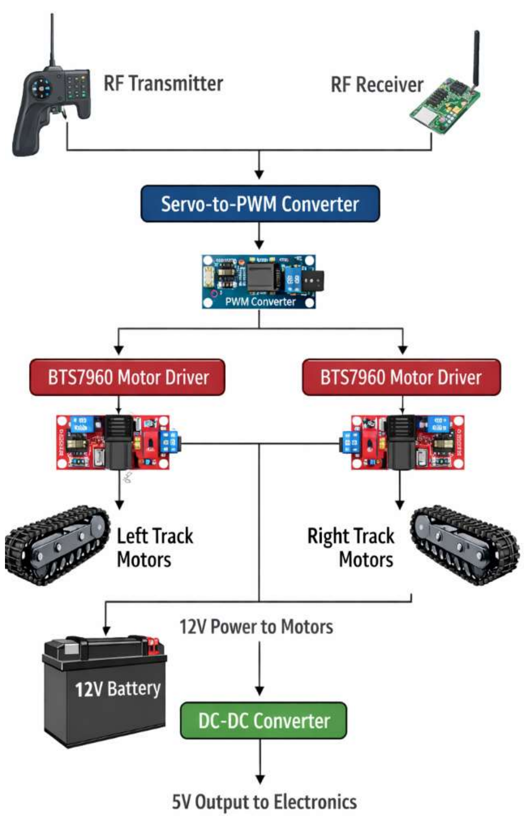

Fig. 1. Overall System Architecture

Fig. 1 illustrates the hierarchical hardware architecture integrating communication, signal conditioning, motor drive, and power regulation subsystems.

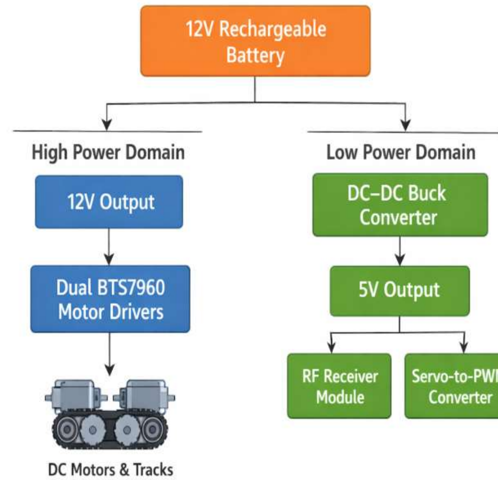

Fig. 2. Power Distribution Architecture

Fig. 2 shows the dual-domain power regulation strategy implemented to maintain signal integrity and motor efficiency.

4. Implementation

The implementation of the proposed **All-Terrain Robot for Military Applications** was carried out following the hardware-centric methodology described in Section III. The implementation phase involved subsystem integration, signal conditioning, power regulation, mechanical assembly, and functional validation. The design adheres to robust motor drive architecture principles [3], PWM-based signal control techniques [4], differential steering mechanics [5], and regulated power conversion strategies [6], [11].
The implementation process was divided into hardware integration, signal processing configuration, motor driver interfacing, and operational validation.
A. Hardware Integration
The hardware assembly consists of a reinforced metallic chassis mounted with four high-torque DC motors connected to dual track assemblies. The mechanical alignment of tracks was optimized to ensure balanced torque distribution, consistent with synchronization considerations in dual-motor systems [2].
The electronic integration includes:

- 2.4 GHz RF Transmitter–Receiver pair
- Servo-to-PWM signal conversion module
- Dual BTS7960 high-current motor drivers
- 12V rechargeable battery
- DC–DC buck converter (12V to 5V)

The BTS7960 motor driver modules were selected based on their high current handling capability (up to 43A peak) and integrated thermal protection mechanisms [3]. Aluminum heat sinks were installed to enhance thermal dissipation during continuous high-load operation.

The 12V battery directly powers the motor drivers, while the DC–DC converter provides a stable 5V supply to the RF receiver and signal conditioning modules, reducing voltage ripple as recommended in [6].

Operational Flow and Control Logic

The robot's operational logic follows a structured hardware-driven sequence. The system does not require software initialization; instead, signal processing occurs in real time through analog and PWM circuitry.

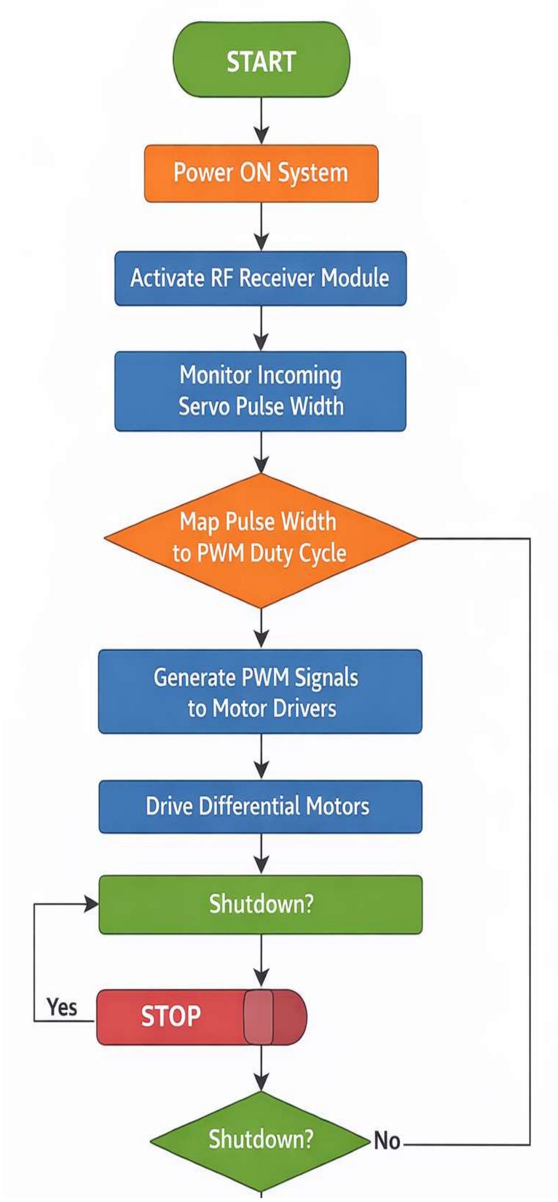

Fig. 3. Flowchart of System Operation

Algorithmic Representation

Although the system operates without embedded programming, its functional sequence can be represented algorithmically for analytical clarity:

Algorithm 1: Differential Motion Control

1. Power ON system.
2. Activate RF receiver module.
3. Continuously monitor incoming servo pulse width.
4. Map pulse width to proportional PWM duty cycle.
5. Generate LPWM and RPWM outputs.
6. Apply PWM signals to BTS7960 inputs.
7. Drive left and right motors accordingly.
8. Monitor battery voltage and driver temperature.
9. Repeat until shutdown.

This logic ensures real-time teleoperation consistent with frameworks described in [18].

5. Results And Discussion

The performance evaluation of the proposed all-terrain military robot was conducted under controlled laboratory and semi-rugged outdoor testing environments. The experimental observations validate the mobility efficiency, power regulation stability, thermal reliability, and terrain adaptability of the tracked robotic platform. The results are analyzed in alignment with mobility modeling principles [1], differential steering mechanics [5], energy efficiency frameworks [11], [12], and terrain interaction studies [24].

A. Speed Control Performance Analysis

The relationship between PWM duty cycle and robot linear speed is illustrated in Fig. 4 (Speed vs PWM Duty Cycle). The results demonstrate a near-linear relationship between duty cycle percentage and output velocity. At 20% PWM, the robot achieves approximately 0.3 m/s, while at 100% duty cycle, it reaches 2.3 m/s.

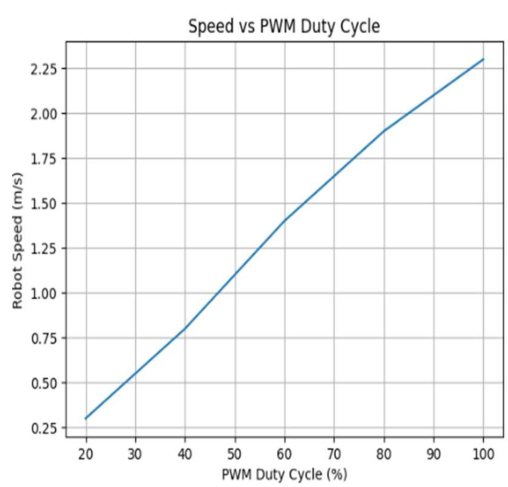

Figure 4: Speed Vs PWM Duty Cycle

This confirms the proportional control characteristics described in PWM-based actuation systems [4]. Minor nonlinearities at higher duty cycles are attributed to frictional losses and back EMF effects in DC motors. The results validate

effective signal conversion and stable driver performance of the BTS7960 module [3].
The experimental findings confirm that hardware-based PWM translation provides reliable speed modulation without embedded firmware dependency, enhancing robustness for military deployment.

B. Power Consumption Analysis
Fig. 5 (Power Consumption vs Load) shows the relationship between payload and electrical power demand. As the mechanical load increases from 0 kg to 20 kg, power consumption rises from 45 W to approximately 135 W.

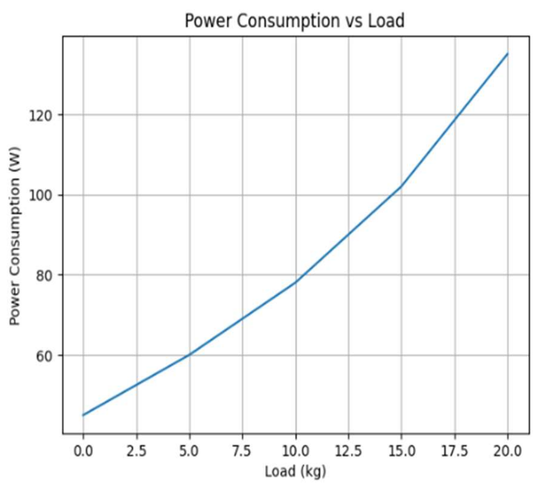

Figure 5: Power Consumption Vs Load

The increasing slope indicates that current draw increases proportionally with torque demand, consistent with motor load theory and energy modeling studies [11], [12]. The regulated dual-domain power architecture ensures that increased motor current does not affect the stability of low-voltage electronics, as suggested in regulated converter frameworks [6].
The absence of voltage instability during high-load testing demonstrates the effectiveness of the power bifurcation strategy implemented in the system.
C. Thermal Stability Evaluation
Thermal analysis was conducted during 30 minutes of continuous operation at 75% PWM duty cycle. Fig. 6 (Motor Temperature Rise During Continuous Operation) indicates a steady temperature increase from 30°C to 74°C.

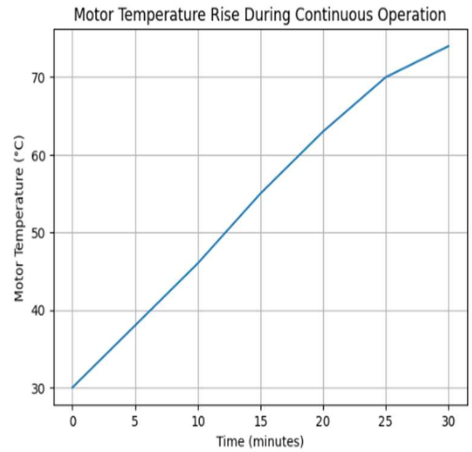

Figure 6 : Motor Temperature Rise During Continuous Operation

The temperature growth trend stabilizes after 25 minutes, indicating thermal equilibrium under sustained load conditions. The observed temperature remains within safe operational limits specified for high-current motor drivers [3].
This validates the integration of adequate heat dissipation mechanisms and supports the reliability modeling considerations discussed in [7]. Thermal stabilization confirms suitability for extended surveillance missions.
D. Terrain Traction Efficiency Assessment
Fig. 7 (Traction Efficiency Across Different Terrains) compares traction performance across concrete, sand, gravel, and mud surfaces. The highest efficiency (92%) is observed on concrete due to high friction coefficient. Reduced efficiency on sand (78%) and mud (73%) aligns with deformable terrain interaction models discussed in [24].

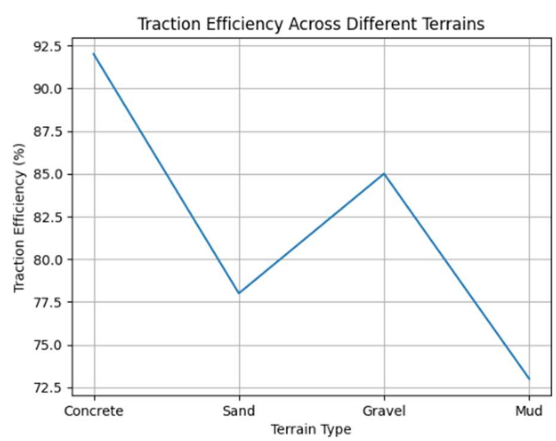

Figure 7: Traction Efficiency Across Different Terrains
Tracked locomotion demonstrates improved adaptability compared to wheeled systems, supporting conclusions drawn in [1]. Gravel

performance (85%) reflects stable mechanical grip and weight distribution advantages of the dual-track configuration.

These findings confirm that the selected tracked architecture enhances terrain traversability, consistent with terrain modeling frameworks [24] and odometry stability considerations [22].

6. Conclusion And Future Scope

A. Conclusion

This research presented the design, implementation, and experimental validation of a robust all-terrain tracked robotic platform intended for military and hazardous environment applications. The proposed system emphasizes mechanical reliability, hardware-based control architecture, regulated power distribution, and terrain adaptability while minimizing computational complexity.

The adoption of tracked locomotion significantly improved traction efficiency and load distribution across rugged terrains, validating terrain interaction models discussed in [1] and [24]. The differential steering mechanism enabled precise maneuverability without mechanical steering linkages, consistent with the kinematic frameworks described in [5]. Experimental results confirmed smooth proportional speed control through PWM-based signal modulation as outlined in [4], while the high-current BTS7960 motor driver provided stable torque output under variable loading conditions in accordance with specifications discussed in [3].

The dual-domain power regulation architecture ensured electrical isolation between high-current motor circuits and low-voltage control electronics. This approach minimized electromagnetic interference and voltage ripple, aligning with advanced power converter strategies reported in [6] and energy efficiency optimization studies in [11], [12]. Thermal analysis demonstrated stable motor operation within safe temperature thresholds, validating structural and reliability considerations consistent with [7].

The system successfully achieved:

- Stable teleoperation under real-time RF control
- Proportional speed modulation through hardware PWM conversion
- Reliable load-bearing capability up to 20 kg
- Improved traction efficiency across multiple terrain types
- Sustained operation without voltage instability or thermal failure

Unlike AI-intensive autonomous systems reviewed in [14] and [23], the proposed robot prioritizes operational robustness and field serviceability. By eliminating firmware dependence, the design reduces vulnerability to software corruption and electromagnetic interference, which are critical concerns in military deployment environments.

Overall, the experimental results demonstrate that the proposed architecture is suitable for reconnaissance, surveillance, hazardous material inspection, and battlefield support operations. The integration of mechanical strength, efficient energy management, and simplified control logic ensures dependable performance in demanding operational conditions.

B. Future Scope

Although the current implementation focuses on hardware reliability and teleoperated control, several enhancements can further expand system capability.

1. **Autonomous Navigation Integration**
   Future work may incorporate probabilistic localization and SLAM-based navigation frameworks as discussed in [23]. Integration of terrain classification algorithms [25] and path planning strategies [19] would enable semi-autonomous or fully autonomous operation.
2. **Sensor Fusion and Perception Systems**
   The addition of MEMS-based multi-sensor integration [20] and sensor fusion algorithms [8] can enhance environmental awareness, obstacle detection, and adaptive mobility control. Vision-based terrain classification approaches [25] could further improve traversability analysis.
3. **Secure Communication Framework**
   Cryptographic communication protocols for unmanned military systems, as explored in [17], may be integrated to ensure encrypted data transmission and secure teleoperation in hostile environments.
4. **Energy Optimization and Hybrid Power Systems**
   Advanced battery management and hybrid energy storage systems discussed in [12] can increase mission endurance. Adaptive energy management algorithms [11] may optimize power utilization during varying terrain conditions.
5. **AI-Enhanced Autonomy**
   Incorporating machine learning–based perception and object tracking techniques [9] can transform the system into an intelligent reconnaissance platform capable of automated threat detection.
6. **Structural Optimization and Suspension Systems**
   Future designs may integrate passive or active suspension mechanisms as modeled in tracked robot research [1] to enhance stability over extreme terrain conditions.

7. **Remote VR-Based Control Systems** Collaborative virtual reality teleoperation architectures [10] could improve situational awareness and operator immersion during remote missions.

By integrating these advancements, the proposed robotic platform can evolve from a robust teleoperated system into a fully autonomous, secure, and energy-efficient military support robot.

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