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Self-Guided Rover with Articulated Suspension for Uneven Terrain Navigation

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Abstract

The progression of mobile robotic systems designed for operation in challenging and unstructured environments has become increasingly important in areas such as space exploration, military missions, and disaster response. Early robotic platforms relied primarily on simple wheel or track-based locomotion, which, although effective on flat surfaces, often struggle to maintain stability and traction on uneven terrain. As a result, advanced mobility mechanisms like the rocker-bogie suspension system have gained attention due to their ability to distribute load efficiently and adapt to rough surfaces, as demonstrated in planetary rover missions. Despite these improvements, many conventional systems still face limitations in handling unpredictable environments, often experiencing instability, reduced grip, and difficulty in overcoming obstacles, which ultimately affects their operational efficiency and autonomy. To overcome these challenges, this work proposes an autonomous mobile robot built upon a rocker-bogie suspension framework, designed to enhance terrain adaptability and movement stability. The system employs a six-wheel configuration with independent motor control, allowing better traction and smoother navigation across irregular surfaces. Additionally, integrated sensors enable real-time obstacle detection and environmental awareness, supporting intelligent navigation without continuous human intervention. By combining mechanical robustness with sensor-driven autonomy, the proposed system aims to improve performance, reliability, and efficiency, making it highly suitable for deployment in hazardous or inaccessible environments where traditional robotic systems are less effective.

Keywords: Autonomous mobile robot, rocker-bogie suspension, rough terrain navigation, obstacle detection, robotic mobility.

1. Introduction

The development of mobile robotic systems capable of functioning in highly irregular, uncertain, and hazardous environments has become a critical area of innovation across domains such as space exploration, defense, mining, and disaster management. In the early phases of robotic evolution, navigation and terrain traversal were largely dependent on human-controlled mechanisms, including manually driven vehicles and tele-operated robots. These systems required continuous supervision for steering, obstacle avoidance, and decision-making, making their effectiveness strongly reliant on operator expertise, reaction time, and communication reliability. While such approaches enabled basic remote operations, they proved inadequate in environments where real-time human intervention was limited or impractical.

Conventional robotic platforms primarily utilized simple wheeled or tracked locomotion systems, which performed efficiently on flat and structured surfaces but exhibited significant limitations in

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unstructured terrains. When deployed on rocky, inclined, sandy, or uneven ground, these systems often experienced loss of traction, poor weight distribution, and instability, leading to slippage, tipping risks, and reduced operational reliability. Additionally, their rigid mechanical configurations lacked the flexibility required to adapt dynamically to terrain variations, making obstacle negotiation difficult. The dependency on manual or semi-autonomous control further introduced latency in response, reducing the system's effectiveness in time-sensitive and mission-critical applications.

To overcome these challenges, advancements in mechanical design have introduced adaptive mobility solutions, among which the rocker-bogie suspension mechanism has emerged as a highly effective approach. This mechanism enables continuous ground contact for multiple wheels, distributes load evenly, and allows the robot to climb over obstacles without requiring complex active suspension systems. Alongside mechanical improvements, the integration of embedded technologies has significantly enhanced robotic intelligence. Modern systems incorporate a combination of sensors such as ultrasonic, infrared, and inertial units to perceive environmental conditions, while microcontrollers and onboard processors handle real-time data processing and control execution. Intelligent algorithms further enable path planning, obstacle detection, and decision-making with minimal or no human intervention. This convergence of robust mechanical architecture and intelligent control systems represents a major shift toward autonomous robotic operation. Such systems are capable of sensing their surroundings, adapting to dynamic conditions, and executing tasks with improved precision and reliability. As a result, modern autonomous robots are better suited for deployment in environments that are inaccessible, dangerous, or impractical for human involvement, ultimately enhancing operational efficiency, safety, and mission success rates.

2. Literature Survey

Arunkumar et al. [1] focused on improving the design efficiency of stair-climbing robots by applying the Taguchi optimization method. Their work emphasized identifying the most influential parameters that affect climbing performance, such as wheel dimensions, motor torque, and structural alignment. By systematically analyzing these factors, they were able to enhance the robot's ability to climb stairs with better stability and reduced slippage. The approach helped in minimizing design errors and improving repeatability in performance. Their design considerations also contributed to smoother motion during vertical transitions. The robot demonstrated improved load-handling capability while maintaining balance on uneven steps. The optimization process reduced unnecessary design complexity and improved energy efficiency. Their contribution mainly supports structured terrain navigation where stair-like obstacles are present. However, adaptability to irregular natural terrains was not a primary focus in their design. Gao et al. [2] explored the mechanical and kinematic aspects required for ensuring continuous wheel-ground contact in wheeled planetary rovers. Their work concentrated on maintaining passive wheel attachment across uneven surfaces without requiring complex control systems. By analyzing suspension geometry and force distribution, they ensured that all wheels remain in contact with the ground during traversal. This significantly improves traction and reduces the chances of slippage. Their approach enhances rover stability, especially in rocky and inclined environments. The design also supports efficient load distribution across multiple wheels. Their findings are useful in designing robust exploration robots for extraterrestrial missions. The emphasis on passive mechanisms reduces the need for active adjustments and simplifies the system. Their contribution strengthens the reliability of rover mobility under uncertain terrain conditions.

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Bouton and Gao [3] introduced the MARCEL rover chassis with a focus on improving locomotion capabilities through advanced suspension techniques. Their design incorporated active suspension elements that adapt dynamically to terrain variations. This allowed the rover to maintain balance and traction even on highly uneven surfaces. The system also featured adaptable wheel configurations, enabling flexible movement strategies. Their approach enhanced obstacle negotiation and reduced the risk of tipping. The chassis design supported smoother transitions across rough terrain. It also improved overall mobility efficiency and operational stability. Their work highlights the importance of integrating mechanical adaptability into robotic platforms. The design is particularly useful in applications where terrain unpredictability is high.

Jeon and Lee [4] worked on improving the motion control of tracked mobile robots by introducing terrain gradient identification techniques. Their method focused on detecting slope variations and adjusting robot speed accordingly. This helped in maintaining consistent movement and avoiding instability on inclined surfaces. The system improved maneuverability by adapting to changes in terrain elevation in real time. Their approach reduced unnecessary strain on motors and improved energy efficiency. It also enhanced control accuracy during navigation. The technique supports smoother operation in uneven environments. Their work contributes to better coordination between sensing and motion control. It is especially beneficial in applications involving sloped or hilly terrains. Nicolella et al. [5] provided a detailed kinematic understanding of the rocker-bogie suspension mechanism used in six-wheeled rovers. Their analysis focused on how the system behaves while encountering obstacles and uneven surfaces. They explained how the linkage mechanism helps in distributing weight evenly across all wheels. This improves stability and prevents the robot from tipping over. Their work also highlighted the ability of the system to climb obstacles efficiently. The design ensures continuous ground contact, which enhances traction. Their explanation supports the effectiveness of rocker-bogie systems in harsh terrain conditions. The kinematic insights are useful for designing more reliable robotic platforms. Their contribution strengthens the theoretical foundation of terrain-adaptive mobility systems. Cosenza et al. [6] introduced an improved rocker-bogie suspension system by integrating spring-based mechanisms. This addition enhanced shock absorption when the robot moves over rough or uneven terrain. The design helped in reducing the impact forces transmitted to the chassis. As a result, the robot maintained better stability and smoother motion. Their approach also improved the durability of the system components. The spring-loaded mechanism allowed better adaptability to sudden terrain changes. It enhanced overall mobility performance in challenging environments. Their work demonstrated the importance of combining mechanical flexibility with suspension systems. The design is particularly useful for applications requiring long-duration operation on rough surfaces.

Cosenza et al. [7] further extended their work by developing a modified version of the rocker-bogie system using theoretical modeling and simulation techniques. Their focus was on improving adaptability under different terrain conditions. By analyzing system behavior through simulations, they identified performance improvements in mobility and stability. The modified design showed better obstacle-handling capability compared to traditional systems. Their work also explored optimization of linkage parameters. This contributed to improved balance and smoother traversal. The simulation-based approach allowed testing under multiple terrain scenarios. Their contribution supports the development of more efficient robotic suspension systems. It highlights the importance of theoretical analysis in mechanical design improvements. Pandey et al. [8] presented a newly designed six-wheeled robot based on the rocker-bogie mechanism with enhanced structural features.

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Their design aimed to improve both stability and obstacle negotiation capability. The robot demonstrated effective performance while climbing over obstacles and moving on uneven terrain. Their work also focused on optimizing wheel arrangement and chassis structure. This resulted in improved load distribution and reduced chances of imbalance. The design supported better traction and smoother movement. Their approach is suitable for exploration tasks in challenging environments. It also contributes to improving efficiency in planetary rover applications. Their work emphasizes practical implementation along with performance evaluation.

Lim et al. [9] developed a simplified version of the rocker-bogie mechanism by reducing the number of actuators required for operation. Their design focused on minimizing mechanical complexity while maintaining effective mobility. By reducing components, they improved system reliability and reduced maintenance requirements. The robot still demonstrated strong terrain adaptability despite fewer actuators. Their approach also simplified control strategies. This made the system easier to operate and more energy-efficient. The design supports cost-effective robotic solutions. It is particularly useful in applications where simplicity and reliability are important. Their work highlights the balance between performance and system complexity. Wani et al. [10] designed and implemented a rocker-bogie robot specifically for navigating rough terrain conditions. Their work focused on practical construction and real-time testing of the system. The robot demonstrated strong obstacle-climbing ability and stable movement across uneven surfaces. Their design ensured continuous wheel-ground contact for improved traction. It also showed good adaptability to different terrain types. The implementation validated the effectiveness of the rocker-bogie mechanism in real-world scenarios. Their approach combined mechanical design with functional testing. This made the system suitable for various terrain-based applications. Their work highlights the practicality and reliability of rocker-bogie robots in challenging environments.

3. Proposed System

The system architecture is designed as an integrated embedded control framework that combines sensing, actuation, communication, and decision-making modules for autonomous navigation. At the core, the Arduino-based controller coordinates all operations by interfacing with motor drivers, sensors, and communication modules. The mobility subsystem consists of DC motors driven through BTS7960 motor drivers, enabling high-current handling and precise bidirectional control. An ultrasonic sensor is employed for real-time distance measurement, providing continuous feedback about obstacles in the robot’s path. A servo motor is integrated to rotate the ultrasonic sensor, allowing environmental scanning in multiple directions for better situational awareness as illustrated in Figure 2.

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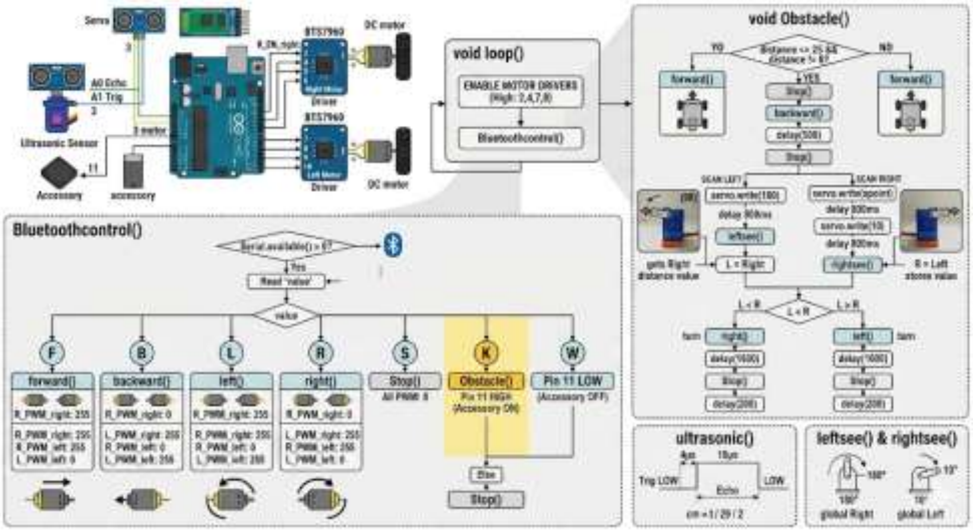

Figure. 2: System architecture.

The control flow is divided into multiple functional blocks, including loop execution, Bluetooth-based manual control, and autonomous obstacle handling. During normal operation, the system initializes motor drivers and continuously checks for incoming Bluetooth commands. The Bluetoothcontrol module interprets user inputs such as forward, backward, left, right, and stop, translating them into PWM signals for motor actuation. Additionally, specific commands trigger accessory control or activate obstacle avoidance mode. In autonomous mode, the obstacle detection logic evaluates distance thresholds obtained from the ultrasonic sensor. If an obstacle is detected within a predefined range, the robot halts, reverses, and performs directional scanning using the servo mechanism. Distance values from left and right scans are compared to determine the optimal turning direction, ensuring efficient path selection. The ultrasonic timing principle is used to compute distance based on echo response, enabling accurate environmental perception. The system employs conditional decision-making to execute turning, stopping, and forward movement actions dynamically. Accessory control is also incorporated, allowing external device activation through designated pins. The architecture supports both manual and autonomous modes, providing flexibility in operation. Overall, the system ensures coordinated interaction between sensing, processing, and actuation components, resulting in reliable and adaptive navigation in dynamic environments.

4. Result and discussion

The results and discussion section presents the performance evaluation of the developed system under various terrain conditions. The analysis focuses on the robot's ability to navigate uneven surfaces, detect obstacles, and make appropriate movement decisions. Experimental observations highlight the effectiveness of the rocker-bogie mechanism in maintaining stability and continuous ground contact. The response of the control system to real-time sensor inputs is also examined to assess navigation accuracy. Additionally, the behavior of the system in both manual and autonomous modes is analyzed. The discussion interprets the outcomes in terms of efficiency, adaptability, and reliability. These findings provide insights into the overall effectiveness of the proposed approach in terrain-based navigation.

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Figure. 3: Hardware prototype of gesture-based embedded system

Figure 3 illustrates the hardware implementation of the embedded system integrating sensing, control, and communication modules in a compact platform. The setup consists of a microcontroller unit interfaced with multiple peripheral components including sensors, power supply, and communication modules. The structural arrangement supports efficient interconnection of components, enabling real-time data acquisition and processing. The system is designed to facilitate seamless interaction between hardware elements, ensuring synchronized operation of sensing and output mechanisms. The integrated architecture demonstrates a functional prototype capable of executing embedded tasks with reliability and scalability for practical applications.

Figure 4 depicts the mobile embedded platform designed for real-time sensing and control applications. The structure integrates a microcontroller-based control unit with multiple actuators and sensor modules mounted on a wheeled chassis. The configuration enables coordinated movement and data acquisition, supporting dynamic interaction with the surrounding environment. The system architecture allows seamless communication between motion components and processing units, ensuring efficient execution of control operations. This arrangement demonstrates the capability of the platform to function as a versatile embedded system suitable for automation, monitoring, and assistive applications.

Figure 5 illustrates the side view of the integrated embedded system highlighting the arrangement of mechanical and electronic components within the platform. The configuration demonstrates the alignment of the control unit, power source, and interfaced modules that collectively enable system functionality. The structural design supports stability and smooth mobility, allowing efficient operation across different conditions. The placement of components ensures effective signal flow and power distribution throughout the system. This representation emphasizes the compact and modular nature of the architecture, making it suitable for scalable embedded and assistive technology applications.

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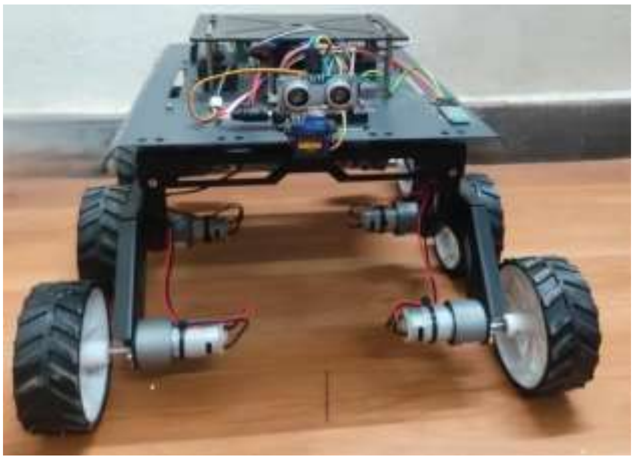

Figure. 4: Mobile embedded platform with sensor integration

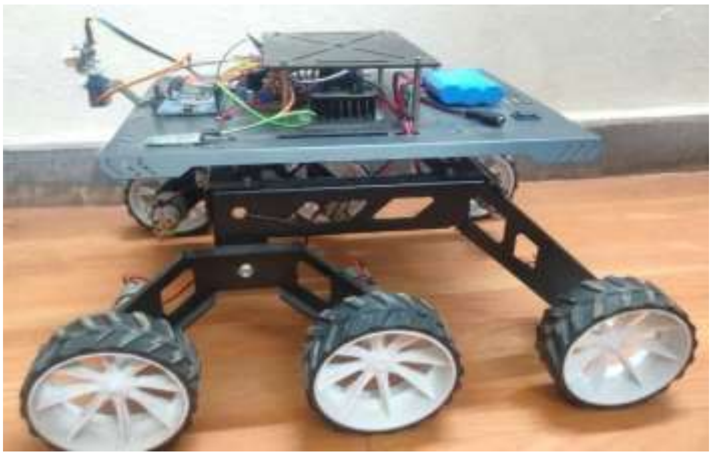

Figure. 5: Side view of integrated embedded robotic system

5. Conclusion

The study effectively presents the design and realization of a self-operating mobile robotic platform capable of traversing complex and irregular terrains with enhanced balance and maneuverability. The incorporation of the rocker-bogie suspension structure plays a crucial role in maintaining consistent wheel–ground interaction, thereby improving grip and minimizing the risk of instability. The inclusion of sensor-driven obstacle sensing enables the robot to perceive and react to dynamic environmental conditions in real time. An efficient control strategy is implemented to ensure appropriate decision-making, allowing the system to determine suitable paths when encountering obstacles. Experimental observations highlight noticeable improvements in mobility, structural stability, and terrain adaptability when compared to traditional wheeled robots. The adoption of independent motor actuation supports accurate motion control and smoother directional changes. Furthermore, the synergy between mechanical configuration and embedded control architecture enhances the robustness and dependability of the overall system. The robot demonstrates reliable performance under both user-controlled and autonomous operation modes, providing operational versatility. The findings validate that the proposed approach improves navigation capability while minimizing the need for continuous human involvement.

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