AMERICAN JOURNAL OF MANAGEMENT AND IOT MEDICAL COMPUTING
Peer Reviewed, Referred & Indexed Journal
E-ISSN: 3069-0110
Vol.5, No.2(1) (2026)
www.ajmimc.com

An Adaptive Mobility Architecture for Uneven Surface Navigation Using Rocker–Bogie Kinematic Structuring

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Abstract

The development of mobile robots for rough terrain exploration has gained significant importance in recent years, especially in applications such as planetary exploration, military operations, and disaster management. Historically, robotic mobility systems have evolved from simple wheeled platforms to more advanced suspension mechanisms, notably the rocker-bogie system, which was popularized through its successful implementation in Mars rovers. Despite these advancements, conventional mobile robots using standard wheel or track mechanisms face challenges in navigating uneven and unpredictable terrains. The primary problem addressed in this project is the limited adaptability and stability of traditional robotic systems when operating on rugged surfaces. Conventional systems often suffer from poor traction, instability, and inability to overcome obstacles, which restricts their usability in critical environments. Additionally, these systems may require constant human intervention, reducing their efficiency in autonomous operations. To overcome these limitations, there is a need for a robust and intelligent robotic system capable of traversing complex terrains with minimal human control. The proposed system focuses on designing an autonomous mobile robot based on the rocker-bogie suspension mechanism. This system integrates a six-wheel configuration with independent motor control and sensor-based obstacle detection to ensure stability, flexibility, and adaptability. The significance of this project lies in its potential to enhance robotic mobility in challenging environments. By combining mechanical innovation with autonomous control, the proposed robot offers improved performance, reliability, and efficiency, making it suitable for real-world applications where human access is limited or hazardous.

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

1. Introduction

Autonomous mobile robots are increasingly being developed to function in environments that are irregular, unpredictable, and often unsafe for human access. Their evolution can be traced back to early navigation systems that relied heavily on direct human involvement. In initial stages, terrain-based operations were carried out using manually driven vehicles or remotely operated robots, where continuous human supervision was essential for movement and obstacle avoidance. While such systems provided basic functionality, their performance was closely tied to operator efficiency and situational awareness, limiting their effectiveness in complex terrains. Conventional robotic platforms, particularly those using simple wheel or track mechanisms, often struggled to adapt to uneven surfaces. These systems lacked the mechanical flexibility required to maintain stability on rocky, inclined, or loose ground, leading to frequent imbalance and reduced operational reliability.

Furthermore, dependence on manual control introduced delays in response time, especially in rapidly changing environments, making them less suitable for critical applications such as disaster response or remote exploration. Advancements in mechanical design and embedded technologies have significantly transformed this domain. The introduction of adaptive suspension systems, such as the rocker-bogie mechanism, has improved the ability of robots to traverse challenging landscapes by enhancing ground contact and weight distribution.

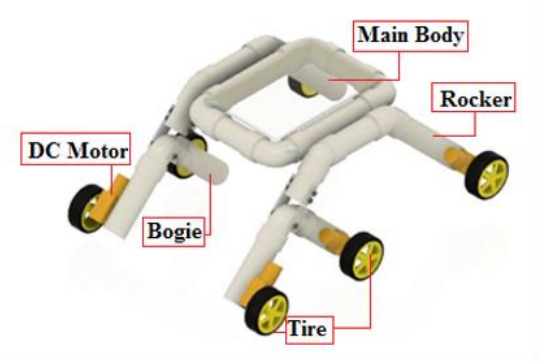


Figure. 1: Mobile robot based on rocker-bogie.

At the same time, the integration of sensors, microcontrollers, and intelligent control algorithms has enabled robots to operate with greater autonomy. These modern systems can sense their surroundings, process environmental data, and make real-time navigation decisions without constant human input. This shift toward autonomous operation highlights the growing need for robotic systems that are not only mechanically robust but also capable of intelligent and reliable performance in demanding terrain conditions.

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.

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. 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 proposed methodology presents a systematic framework for developing an autonomous terrain navigation system using a rocker-bogie based mechanical structure combined with intelligent control techniques. The process begins with the design and fabrication of the mechanical chassis, followed by integration of electronic components such as motors, sensors, and control units. The system operates by continuously sensing the surrounding environment and making navigation decisions in real time. Ultrasonic sensing is used to measure obstacle distance, while a servo-based scanning mechanism analyzes multiple directions to determine the safest path. The control logic processes sensor data and generates appropriate movement commands for the motors, as shown in figure 2. A communication interface is also incorporated to allow optional user control and monitoring. The complete system is structured to ensure stability, adaptability, and efficient movement across uneven terrains. Continuous evaluation of navigation behavior helps improve decision-making accuracy and system performance over time.

User Interface (Control Module)

- The system includes a communication interface that allows interaction through wireless modules such as Bluetooth.

- Users can send movement commands like forward, backward, left, right, and stop.
- It also enables switching between manual and autonomous navigation modes.
- The interface acts as a bridge between user input and control logic execution.

Microcontroller Unit (Processing Core)

- The microcontroller acts as the central processing unit of the system.
- It receives input signals from sensors and user commands from the interface.
- Based on programmed logic, it processes the data and decides the robot's movement.
- It controls motor drivers and servo mechanisms for execution of actions.

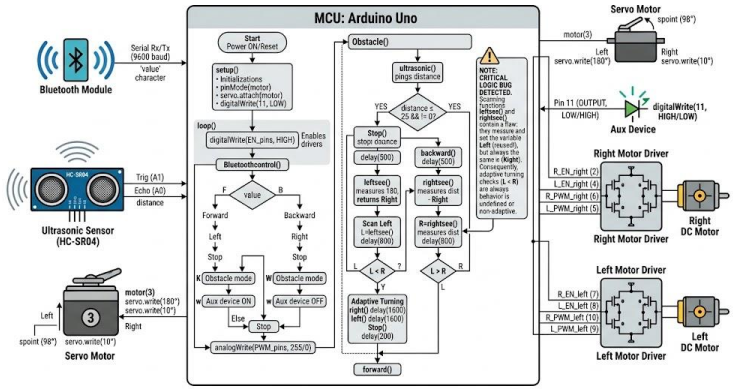


Figure. 2: System architecture.

Motor Driver Module

- The motor driver is responsible for controlling the speed and direction of DC motors.
- It receives signals from the microcontroller and converts them into motor actions.
- Separate channels are used for left and right motors to enable differential movement.
- This module ensures smooth navigation and precise turning operations.

Rocker-Bogie Mechanical Structure

- The mechanical framework is based on a rocker-bogie suspension mechanism.
- It consists of multiple linked arms and six wheels for better terrain adaptability.
- The structure maintains continuous ground contact across uneven surfaces.
- It improves stability and allows the system to climb obstacles efficiently.

Ultrasonic Sensor Module

- The ultrasonic sensor is used to measure the distance between the robot and obstacles.
- It sends sound waves and calculates distance based on echo time.
- This sensor enables real-time obstacle detection during navigation.

- It provides critical input for autonomous decision-making.

Servo Motor Scanning Mechanism

- A servo motor is used to rotate the ultrasonic sensor in multiple directions.
- It scans left and right areas to analyze alternative paths.
- This mechanism helps in selecting the safest direction when obstacles are detected.
- It enhances environmental awareness of the system.

Obstacle Detection and Decision Logic

- The system continuously monitors distance values from the ultrasonic sensor.
- When an obstacle is detected within a threshold range, movement is stopped.
- The scanning mechanism evaluates left and right paths.
- Based on comparison, the system selects the direction with maximum clearance.

Power Supply System

- The system is powered using a battery source suitable for motors and electronics.
- It provides stable voltage to all components including sensors and controllers.
- Proper power distribution ensures uninterrupted operation.
- It supports mobility in outdoor and off-grid environments.

Autonomous Navigation Workflow

- The system operates in a continuous loop of sensing, processing, and movement.
- It moves forward until an obstacle is detected.
- Upon detection, it performs scanning and selects an alternate path.
- This cycle repeats to enable continuous navigation without human intervention.

Performance Evaluation and Improvement

- The system performance is evaluated based on stability, obstacle handling, and response time.
- Observations are used to refine movement logic and sensor accuracy.
- Improvements can be made by adjusting threshold values and control parameters.
- This ensures better adaptability and efficiency in different terrain conditions.

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.

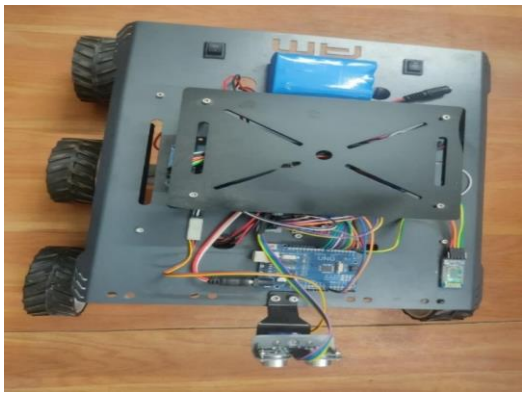


Figure. 3: Hardware prototype of gesture-based embedded system

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.

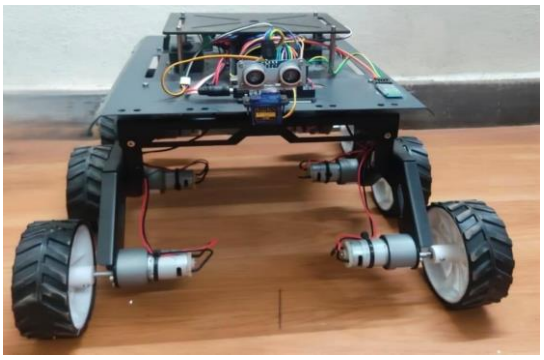


Figure. 4: Mobile embedded platform with sensor integration

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.

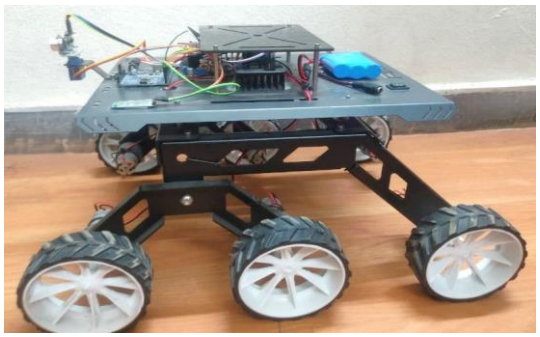


Figure. 5: Side view of integrated embedded robotic system

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.

5. Conclusion

The research successfully demonstrates the development of an autonomous mobile system capable of navigating uneven and challenging terrains with improved stability and control. The integration of the rocker-bogie suspension mechanism significantly enhances the ability to maintain continuous ground contact, resulting in better traction and reduced chances of imbalance. The implementation of sensor-based obstacle detection allows the system to respond effectively to real-time environmental changes. The control logic ensures smooth decision-making by selecting optimal paths during obstacle encounters. Performance observations indicate improved mobility, stability, and adaptability compared to conventional wheeled systems. The use of independent motor control contributes to precise movement and efficient turning operations. Additionally, the combination of mechanical design and embedded control improves overall system reliability. The system performs effectively in both manual and autonomous modes, offering flexibility in operation. The results confirm that the approach enhances navigation efficiency and reduces dependency on human intervention. The developed system provides a practical solution for terrain-based robotic applications.

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