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An ESP32-Based Autonomous Mobile Robot for Rough Terrain Navigation Using Multi-Sensor Obstacle Avoidance and Hazard Detection

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Abstract

The research focuses on the design, fabrication, and implementation of an intelligent rocker-bogie mobile robot capable of navigating challenging terrains while performing real-time obstacle detection and hazard monitoring. The system is built around the ESP32 microcontroller, which serves as the central processing unit for sensor integration, decision-making, and control operations. The robot utilizes a six-wheeled rocker-bogie suspension mechanism that ensures continuous ground contact for all wheels, thereby enhancing stability and mobility over uneven, rocky, and inclined surfaces without the need for complex suspension systems. To enable autonomous navigation, the robot is equipped with an ultrasonic sensor that continuously measures the distance to nearby obstacles and adjusts its path accordingly to prevent collisions. In addition to obstacle avoidance, a fire detection sensor is incorporated to identify hazardous environmental conditions, making the system suitable for safety-critical applications. The robot operates in two distinct modes: an autonomous mode, where it independently navigates and responds to environmental inputs, and a manual mode, which allows user control for precise manoeuvring in complex scenarios. This dual-mode functionality increases the versatility of the system for applications such as disaster management, surveillance in hazardous zones, and exploration tasks. Experimental evaluations confirm that the robot demonstrates reliable obstacle detection, efficient navigation, and quick response times, validating its effectiveness as a robust and adaptable mobile robotic platform for real-world applications.\

Keywords: Rocker-Bogie, ESP-32, Obstacle Avoidance, Ultrasonic Sensor, Fire Detection, DC Motors, Autonomous Navigation, Mobile Robot, Suspension Mechanism.

1. Introduction

Mobile robotics has become a vital area of development in modern engineering, particularly for applications involving environments that are hazardous, remote, or difficult for humans to access. These robots are widely utilized in domains such as space exploration, disaster response, military surveillance, and industrial inspection, where safety and adaptability are critical. Designing an effective mobile robot for such conditions requires a strong combination of mechanical stability, accurate sensing systems, and intelligent control algorithms capable of responding to dynamic surroundings. One of the most efficient mechanical designs for rough terrain mobility is the rocker-bogie suspension mechanism, originally introduced by NASA for planetary rover missions. This system uses a six-wheel configuration that maintains continuous ground contact, allowing the robot to traverse uneven surfaces such as rocks, slopes, and obstacles with enhanced stability. Unlike traditional suspension systems, it operates without springs or complex actuators, thereby simplifying the design while improving durability and reliability. To achieve autonomous functionality, obstacle detection plays a crucial role. In this system, ultrasonic sensing technology is employed to measure distances by calculating the time taken for sound waves to reflect from nearby objects. Based on this input, the robot dynamically adjusts its path to avoid collisions. The entire operation is managed by the ESP32 microcontroller, which provides high processing capability along with integrated wireless communication features, making it well-suited for real-time embedded applications. Additionally, a fire detection sensor is incorporated to identify hazardous conditions by sensing infrared radiation emitted from flames. This feature enhances the

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robot's applicability in emergency scenarios such as fire rescue and industrial hazard monitoring. The system supports both autonomous and manual modes, offering flexibility in operation depending on the task requirements. the integration of a robust rocker-bogie structure with intelligent sensing, dual-mode control, and hazard detection results in a versatile robotic platform. This work presents the complete design, implementation, and testing of the system, highlighting its effectiveness in real-world applications.

2. Literature Survey

Bickler et al. [1] presented the development of the rocker-bogie suspension system for planetary exploration rovers, which is specifically designed to navigate highly uneven and rocky terrains. The mechanism ensures that all six wheels remain in continuous contact with the ground, thereby improving stability and traction. The passive differential system distributes load evenly without requiring complex actuators or springs. This design reduces mechanical failure and enhances durability in harsh environments. The rocker-bogie system also allows the robot to climb obstacles significantly larger than conventional wheeled robots. Its simplicity and robustness make it highly suitable for space missions. This work forms the mechanical foundation for modern rough-terrain robots. It is widely adopted in robotic mobility systems for exploration tasks. Borenstein et al. [2] introduced the Vector Field Histogram (VFH) method, a highly efficient algorithm for real-time obstacle avoidance in mobile robots. The method constructs a histogram grid using sensor data to represent the density and position of obstacles. Based on this representation, the robot selects a path for navigation. The algorithm enables smooth and continuous motion without abrupt changes. It is particularly effective in dynamic and cluttered environments. The VFH approach reduces computational complexity while maintaining high responsiveness. It supports real-time implementation in embedded systems. This method has influenced many modern navigation techniques. It remains a standard reference in obstacle avoidance research.

Hacot et al. [3] focused on the analytical modeling and simulation of rocker-bogie systems, providing insights into their kinematic and dynamic behavior. The study presents mathematical formulations that describe wheel movement and load distribution. Simulation results demonstrate how the mechanism adapts to uneven terrain conditions. The research highlights the importance of proper geometric configuration for stability. It also evaluates performance during obstacle climbing. The findings are useful for optimizing suspension design. This work bridges theoretical concepts with practical applications. It contributes significantly to rover mobility research. The study supports the design of efficient terrain-adaptive robots. Iagnemma et al. [4] examined the challenges associated with mobile robots operating in rough and unstructured terrains. Their work focuses on issues such as traction loss, wheel slip, and terrain interaction. The authors proposed models to predict and control these factors. They also discussed motion planning strategies for difficult terrains. The research emphasizes the importance of adaptive control systems. It highlights the need for accurate sensing and feedback mechanisms. The study improves understanding of terrain-robot interaction. It is highly relevant for exploration and off-road robotics. This work contributes to improving mobility performance in harsh environments.

Espressif Systems et al. [5] provided comprehensive technical documentation for the ESP32 microcontroller, which is widely used in embedded robotic systems. The manual explains its dual-core architecture and processing capabilities. It includes details about communication protocols such as Wi-Fi and Bluetooth. The document also describes GPIO, PWM, ADC, and other peripheral interfaces. These features enable efficient sensor integration and motor control. The ESP32 supports real-time data processing and decision-making. Its low power consumption makes it suitable for portable robots. This reference is essential for hardware and firmware development. It plays a key role in modern embedded robotics. Nagatani et al. [6] demonstrated the application of mobile robots in disaster response scenarios, particularly in hazardous environments such as nuclear accident sites. The study highlights how robots can safely replace humans in dangerous conditions. It discusses the use of sensors for monitoring radiation and structural damage. The research also addresses challenges like communication and navigation in complex environments. The robots were used for inspection and data collection tasks. The study emphasizes reliability and robustness. It shows the importance of autonomous operation in emergencies. This work validates the practical use of robots in real-world disasters. It contributes significantly to rescue robotics.

Shen et al. [7] developed a robotic system capable of detecting and localizing fire sources in hazardous environments. The system uses sensors to detect infrared radiation emitted by flames. It can determine the position and intensity of fire. The research integrates sensing with robotic mobility. It improves situational awareness in emergency scenarios. The system is useful in industrial safety and firefighting applications. The study discusses accuracy and response time. It enhances the robot's ability to operate in dangerous environments. This work contributes to hazard detection technologies. It is relevant for fire monitoring systems. Mujahed et al. [8] proposed the admissible gap navigation technique for obstacle avoidance in complex environments. The method identifies safe gaps between obstacles for robot movement. It uses real-time sensor data for decision-making. The approach improves navigation efficiency and safety. It is suitable for cluttered and dynamic environments. The study compares performance with traditional methods. It shows improved adaptability and collision avoidance. The algorithm enhances autonomous navigation capabilities. It reduces the risk of navigation failure. This work contributes to advanced path planning techniques.

Khaled et al. [9] investigated ultrasonic sensor-based obstacle detection for autonomous robots. The method relies on the time-of-flight principle of sound waves. It provides accurate distance measurement for nearby obstacles. The study evaluates sensor placement and detection range. It demonstrates reliable performance in real-time conditions. The approach is cost-effective and easy to implement. It requires low computational resources. The method is suitable for embedded systems. It is widely used in mobile robotics applications. This work supports practical obstacle avoidance systems. Braunl et al. [10] discussed the design and implementation of embedded robotic systems. The work covers microcontroller-based control, sensor interfacing, and motor actuation. It explains real-time programming techniques for robotics. The study emphasizes system integration and efficiency. It also addresses hardware-software interaction. The concepts are useful for developing autonomous robots. The book provides practical design guidelines. It supports embedded system development. This work is widely used in robotics education. It is essential for understanding embedded robotics.

Ali et al. [11] proposed an obstacle detection and avoidance system using ultrasonic sensors combined with PID control. The system improves navigation accuracy and stability. It continuously adjusts robot movement based on sensor input. The PID controller ensures smooth control. The study demonstrates improved performance over basic methods. It reduces collision risk significantly. The system is suitable for real-time applications. It enhances control precision. The approach is practical and efficient. This work contributes to control-based navigation systems. Campion et al. [12] analyzed the kinematic and dynamic models of wheeled mobile robots. The study provides a classification of different robot configurations. It explains motion constraints and strategies. The research helps in selecting appropriate robot models. It is useful for system design and analysis. The work also discusses stability and issues. It provides a theoretical foundation for robot motion. The classification is widely used in robotics research. This study is essential for understanding robot mechanics. It supports advanced robot design. Laubach et al. [13] developed a sensor-based path planning system for planetary micro-rovers. The system uses onboard sensors for navigation in unknown environments. It enables autonomous decision-making. The study focuses on real-time path selection. It improves navigation efficiency. The system

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adapts to environmental changes. It is suitable for exploration tasks. The research highlights the importance of sensing in navigation. It contributes to autonomous robotics. This work supports rover-based exploration systems. Chhaniyara et al. [14] presented a comprehensive survey of terrain traversability analysis methods for unmanned ground vehicles. The study reviews different techniques for evaluating terrain conditions. It includes both geometric and sensor-based approaches. The research helps in predicting robot mobility performance. It supports path planning decisions. The study highlights challenges in rough terrain navigation. It provides comparative analysis of methods. It is useful for system design. This work contributes to terrain analysis research. It is important for autonomous navigation.

Elfes et al. [15] introduced occupancy grid mapping for robot perception and navigation. The method represents the environment as a grid of probabilities. It helps in obstacle detection and mapping. The approach supports decision-making in unknown environments. It is widely used in autonomous systems. The study provides a foundation for SLAM techniques. It improves environmental understanding. The method is suitable for sensor integration. It enhances navigation accuracy. This work is fundamental in robotics research.

3. Proposed System

The proposed system is a six-wheeled Rocker-Bogie mobile robot controlled by an ESP-32 microcontroller that integrates ultrasonic obstacle detection, fire sensing, dual-mode operation (Auto/Manual), DC motor-driven locomotion, a Rocker-Bogie suspension mechanism, and an audible buzzer alert system, as shown in figure 1. In Auto mode, the ESP-32 continuously acquires distance data from the ultrasonic sensor and fire status from the fire sensor, executing real-time decision-making to navigate around obstacles and alert operators of fire hazards. In Manual mode, the operator remotely controls robot movement via wireless commands, while sensor monitoring remains active for safety.

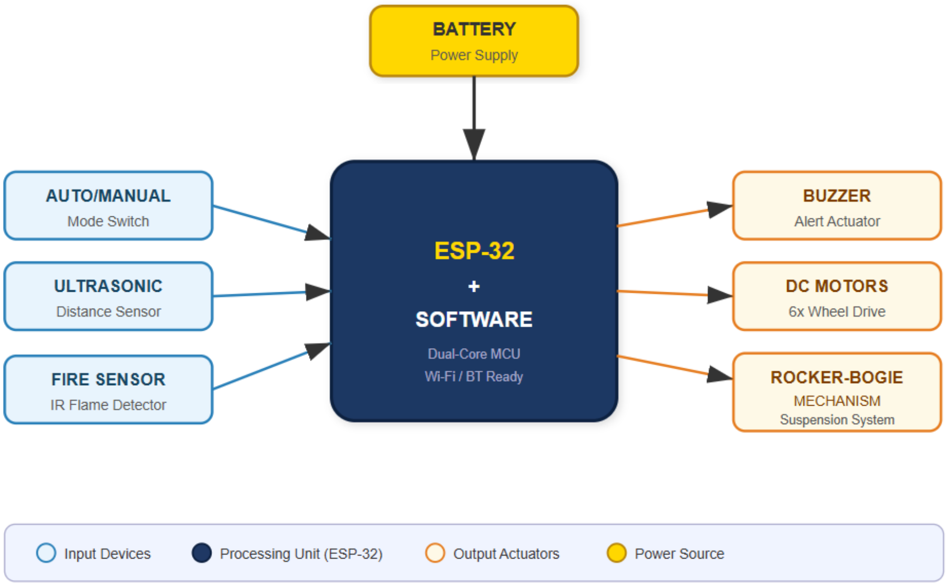

Figure. 1: System architecture

The Rocker-Bogie suspension passively adjusts to terrain variations, maintaining all six wheels in ground contact for maximum traction and stability on uneven surfaces, making the system suitable for indoor surveillance, outdoor patrol, disaster response, and research applications. The block diagram of the proposed Rocker-Bogie robot illustrates the interconnection of all major system components. The Battery provides regulated power to the ESP-32 microcontroller, which serves as the central processing

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and decision-making unit of the entire system. Three input modules feed data into the ESP-32: the Auto/Manual switch for mode selection, the Ultrasonic sensor for real-time obstacle distance measurement, and the Fire sensor for detecting infrared radiation from flames. Based on the processed sensor inputs, the ESP-32 drives three output modules: the Buzzer for audible alerts during fire detection or obstacle proximity, the DC Motors for locomotion control through PWM signals, and the Rocker-Bogie M/C (mechanism) that physically executes the motion commands, adapting to terrain variations through its passive suspension linkage system.

3.1 Workflow

The figure 2 represents the operational logic of a rocker-bogie mobile robot integrated with obstacle avoidance and fire detection capabilities using an ESP32 microcontroller. It illustrates how the system initializes hardware components such as sensors, motors, and communication modules before selecting the mode of operation. The robot can function in both manual mode, where user commands are received via wireless communication, and autonomous mode, where it independently navigates using sensor inputs. In autonomous operation, the ultrasonic sensor continuously monitors the environment to detect obstacles and guide movement decisions. Additionally, a fire sensor is incorporated to identify hazardous conditions and trigger alerts when necessary. The system follows a continuous loop to ensure real-time response and adaptability.

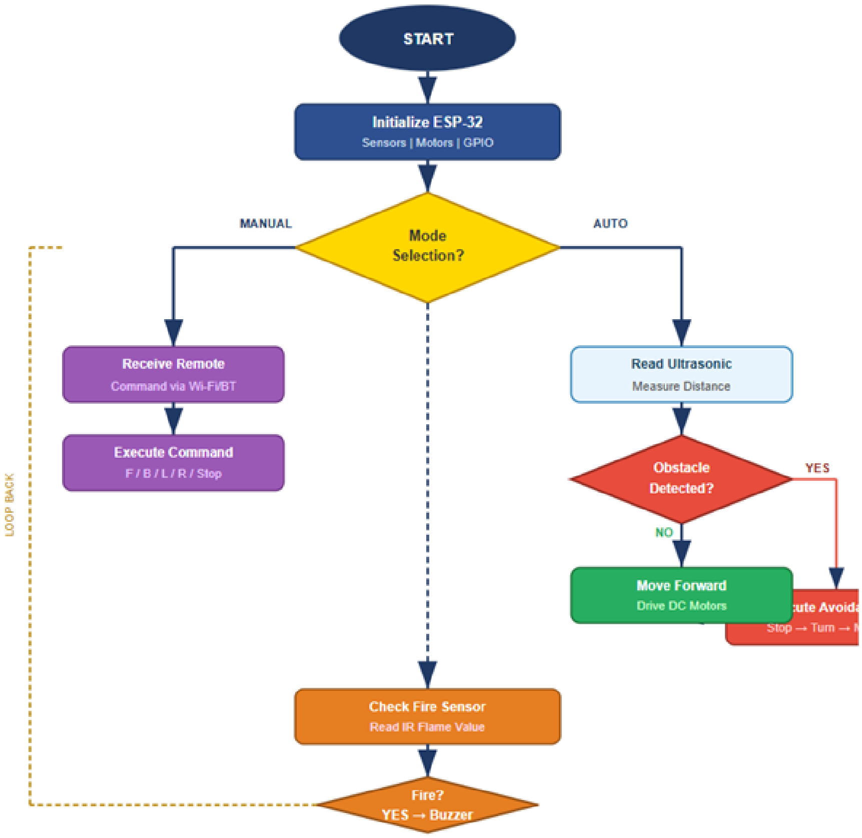

Figure. 2: Internal workflow

1. Start: The process begins with powering on the system. This initializes the robot and prepares all hardware components for operation. It ensures that the system is ready to execute programmed instructions. This is the entry point of the control logic.

2. Initialize ESP-32: The ESP-32 microcontroller is initialized along with all connected components. This includes setting up sensors, motors, and GPIO pins. Communication interfaces like Wi-Fi or Bluetooth are also configured. Proper initialization ensures smooth functioning of the system.

3. Mode Selection (Manual / Auto): The system checks which mode of operation is selected. The robot can operate either in manual mode or autonomous mode. This decision determines how the robot will receive commands. It acts as a control branching point in the system.

4. Manual Mode – Receive Remote Command: In manual mode, the robot receives commands from a user via Wi-Fi or Bluetooth. These commands are sent through a mobile app or remote interface. The system continuously listens for user inputs. This allows real-time human control of the robot.

5. Manual Mode – Execute Command: After receiving the command, the robot performs actions such as forward, backward, left, right, or stop. The ESP-32 processes the command and controls the motors accordingly. This ensures precise movement based on user instructions. The process repeats in a loop.

6. Auto Mode – Read Ultrasonic Sensor: In autonomous mode, the robot uses an ultrasonic sensor to measure distance. It continuously scans the environment for obstacles. The sensor works using sound wave reflection (time-of-flight principle). This data is used for navigation decisions.

7. Obstacle Detection Decision: The system checks whether an obstacle is detected within a threshold distance. If no obstacle is present, the robot continues moving forward. If an obstacle is detected, it triggers avoidance behavior. This ensures safe navigation.

8. Move Forward: If the path is clear, the robot moves forward using DC motors. The movement is continuous and stable due to the rocker-bogie mechanism. This step ensures efficient traversal of terrain. It keeps repeating until an obstacle is detected.

9. Obstacle Avoidance Action: When an obstacle is detected, the robot stops immediately. It then changes direction by turning left or right. After avoiding the obstacle, it resumes forward movement. This allows autonomous and collision-free navigation.

10. Fire Sensor Check: The system continuously monitors the fire sensor regardless of the mode. It reads infrared signals to detect the presence of flames. This adds an extra safety layer to the robot. It operates in parallel with movement logic.

11. Fire Detection Decision: If fire is detected, the system activates a buzzer as an alert signal. This warns users about hazardous conditions. If no fire is detected, the robot continues normal operation. This ensures real-time hazard monitoring.

12. Loop Back: After completing each cycle, the system loops back to continue operation. It keeps checking mode, sensors, and commands continuously. This loop ensures real-time responsiveness. The robot operates continuously until powered off.

4. Results And Discussion

The results and discussion section presents the performance evaluation of the developed rocker-bogie mobile robot under different operating conditions. The robot was tested in both manual and autonomous modes to analyse its mobility, stability, and responsiveness. Experimental observations show that the rocker-bogie mechanism effectively maintains balance and ensures smooth movement over uneven and rough terrains. The ultrasonic sensor demonstrated reliable obstacle detection with quick response time, enabling efficient collision avoidance. Additionally, the fire detection system successfully identified flame sources and triggered alerts, confirming its suitability for hazardous environments. The integration of the ESP32 microcontroller provided fast processing and seamless coordination between sensors and actuators. The system exhibited consistent performance with minimal delay in decision-making.

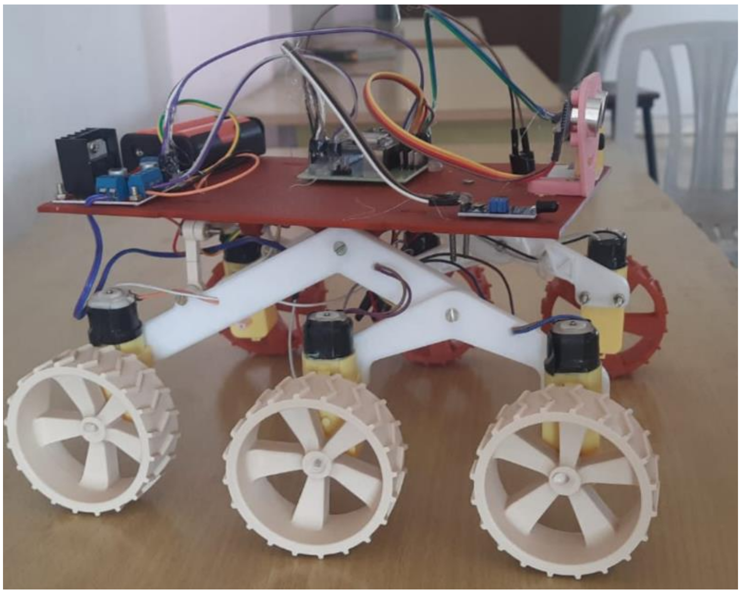

Figure 3: Rocker-Bogie mobile robot prototype with esp32-based control system

Figure 3 illustrates the developed rocker-bogie mobile robot prototype designed for rough terrain navigation and autonomous operation. The structure consists of a six-wheeled configuration arranged in a rocker-bogie mechanism, which ensures continuous ground contact and improved stability during movement. The robot is integrated with an ESP32 microcontroller that manages sensor inputs, motor control, and communication functions. Various electronic components, including motor drivers, sensors, and connecting circuits, are mounted on the top platform for efficient system integration. The design enables both manual and autonomous modes of operation, allowing flexible control and navigation.

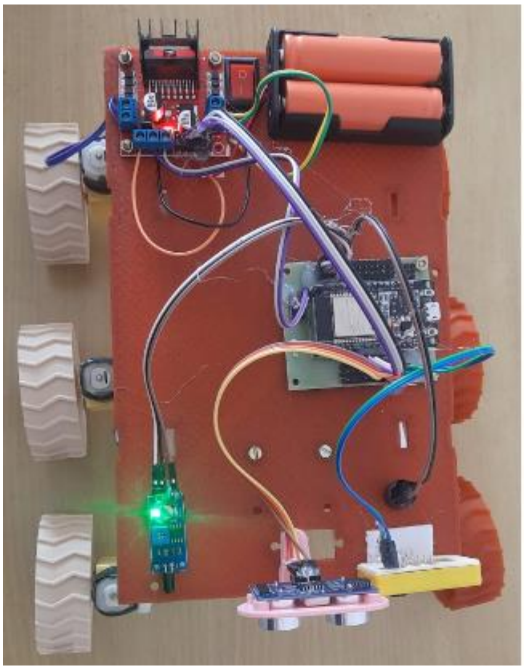

Figure 4: Top View of Rocker-Bogie robot showing electronic components integration

Figure 4 depicts the top view of the rocker-bogie mobile robot highlighting the arrangement of electronic components and control circuitry. The ESP32 microcontroller is centrally mounted and acts as the main processing unit, coordinating sensor inputs and motor operations. A motor driver module is

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integrated to control the movement of multiple DC motors efficiently through PWM signals. The power supply system, consisting of rechargeable batteries, provides the required energy for continuous operation. Additionally, sensors such as the ultrasonic module and fire detection unit are connected through interfacing circuits for environmental monitoring. The organized wiring layout demonstrates effective integration of hardware components, ensuring reliable communication and smooth functioning of the robotic system.

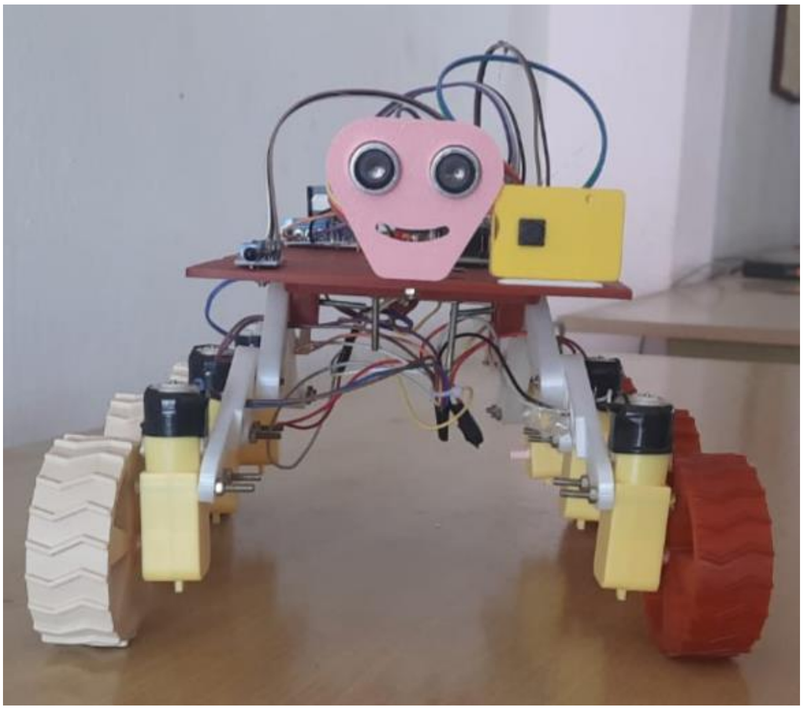

Figure 5: Front View of Rocker-Bogie robot with sensor and detection modules

Figure 5 illustrates the front view of the rocker-bogie mobile robot showcasing the placement of sensing and detection components. The ultrasonic sensor is mounted at the front to enable real-time distance measurement for obstacle detection and avoidance. A fire detection module is also integrated to identify hazardous conditions and enhance the robot’s safety features. The rocker-bogie suspension structure with six wheels is clearly visible, demonstrating its capability to maintain stability over uneven terrain. The arrangement of components ensures effective forward sensing and environmental interaction. This configuration supports both autonomous navigation and hazard monitoring, making the system suitable for real-world robotic applications.

5. Conclusion

The research successfully demonstrates the development of a rocker-bogie mobile robot equipped with an ESP32-based control system capable of autonomous obstacle avoidance and fire detection. The implementation of the rocker-bogie suspension mechanism enables the robot to traverse uneven and rough terrains with improved stability by ensuring continuous contact of all six wheels with the ground. The system supports both autonomous and manual modes of operation, providing flexibility for different application requirements such as disaster management, surveillance, and exploration tasks. The integration of ultrasonic sensing for obstacle detection and a fire sensor for hazard identification enhances the robot’s environmental awareness and safety capabilities. Real-time alerts using a buzzer further strengthen its response to critical situations. The overall system exhibits reliable performance, efficient navigation, and quick decision-making. Future enhancements may include the integration of vision-based systems, GPS-assisted navigation, SLAM techniques, and wireless communication modules to improve autonomy, accuracy, and adaptability in complex real-world environments.

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