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Autonomous Navigation System for Space Vehicle - Rover

Dr. Sanjay Kurkute[1], Dnyaneshwar Jadhav[2], Mayuri Wable[3], Priti Zaware[4]
Professor, Department of Electronics and Telecommunication Engineering[1]
Students, Department of Electronics and Telecommunication Engineering[2,3,4]
Pravara Rural Engineering College, Loni, India

Abstract: *Exploration in extraterrestrial environments requires autonomous systems that can navigate unpredictable and unstructured terrain. This paper proposes a machine learning-powered autonomous navigation system for space vehicles. It incorporates LiDAR and ultrasonic sensors for real-time obstacle detection and adaptive movement. The system aims to boost mission efficiency, improve rover autonomy, and minimize reliance on human input during planetary operations.*

Keywords: Autonomous Navigation, AI-based Rover, LiDAR, Planetary Exploration, Machine Learning, ROS-2 Humble

I. INTRODUCTION

Traditional navigation systems in space exploration rely heavily on human input, which becomes inefficient due to signal delays and harsh environmental factors. There is a growing need for onboard intelligence capable of making real-time decisions. This paper explores a navigation solution that combines AI algorithms with sensory data fusion to enable self-reliant space vehicles.

Research Goals:

- Develop AI-based navigation that adapts to new terrain
- Utilize sensor fusion (LiDAR + ultrasonic) for accuracy
- Enhance obstacle avoidance with real-time corrections
- Reduce mission delays via reduced human oversight

These innovations contribute toward more capable space exploration robots.

The insights gained from this study will play a crucial role in the development of next-generation space rovers capable of autonomously exploring planets, moons, and asteroids. Furthermore, this system has the potential for further refinement through machine learning models to anticipate terrain conditions and enhance resource utilization for prolonged space missions.


II. LITERATURE REVIEW

2.1 Introduction to Autonomous Navigation in Space Exploration

Autonomous navigation systems play a pivotal role in space exploration by allowing rovers and vehicles to function effectively on extraterrestrial surfaces without direct human oversight. The creation of these systems requires the integration of sensor fusion, AI-driven decision-making, and dynamic path-planning algorithms.

Numerous space missions, including NASA's Perseverance Rover and ISRO's Pragyan Rover (Chandrayaan-3), have showcased varying degrees of autonomy in their navigation capabilities. Nevertheless, challenges remain, such as navigating unpredictable terrains, making real-time decisions, and overcoming sensor limitations. This literature review aims to examine current autonomous navigation methods and pinpoint specific areas for enhancement.

2.2 Existing Autonomous Navigation Systems

2.2.1 NASA's Perseverance Rover (2021)

- Utilizes AutoNav, an advanced AI-driven navigation system that enables autonomous movement across the Martian surface.
- Fitted with Hazard Cameras (HazCams), Navigation Cameras (NavCams), and LiDAR-like sensors to perform comprehensive terrain analysis.
- Employs Visual Odometry for precise mapping and positional tracking.
- Note: The system is still dependent on mission control supervision, which can result in delays in decision-making.

2.2.2 Chandrayaan-3 Pragyan Rover (2023)

- Utilizes navigation cameras and integrated artificial intelligence for effective obstacle detection.
- Functions with low power consumption and operates within restricted computational capabilities.
- Constraint: Mobility range and operational speed are limited by the challenging conditions present on the lunar surface.

2.2.3 ExoMars Rover (ESA, 2022 - Postponed)

- Developed a system for autonomous hazard avoidance utilizing advanced AI algorithms.
- Note: The mission has been postponed, resulting in the absence of real-world results.

2.3 AI and Sensor Fusion in Autonomous Navigation

2.3.1 AI-Based Path Planning

- Research conducted by Kohl and Stone (2004) introduces a Reinforcement Learning (RL) methodology aimed at facilitating adaptive path planning in uncharted terrains.
- NASA's AutoNav system integrates a hybrid approach utilizing both Dijkstra and A* algorithms to effectively navigate around obstacles.
- A key limitation of these AI models is their reliance on substantial training data, which poses significant challenges when attempting to obtain sufficient datasets for extraterrestrial environments.

2.3.2 Sensor Fusion Techniques

- LiDAR and Camera Fusion: This combination enables depth perception, facilitating precise navigation capabilities.
- GPS Fusion: While beneficial for terrestrial autonomous vehicles, GPS technology is not applicable in space settings due to the lack of GPS signals.
- Proposed Improvement: Our project emphasizes the integration of LiDAR, Ultrasonic sensors, and AI, significantly enhancing real-time decision-making processes compared to traditional methodologies.

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2.4 Research Gap and Scope for Improvement

From the current body of literature, it is clear that existing space rovers and autonomous systems encounter three primary challenges:

1. Real-Time Decision Making: Present-day AI models are predominantly dependent on Earth-based computations.
2. Limited Environmental Adaptability: Many systems are constrained by pre-programmed navigation protocols that do not accommodate unexpected conditions.
3. Energy Efficiency: The considerable power consumption of autonomous systems restricts mission duration.

Proposed Solutions in This Research:

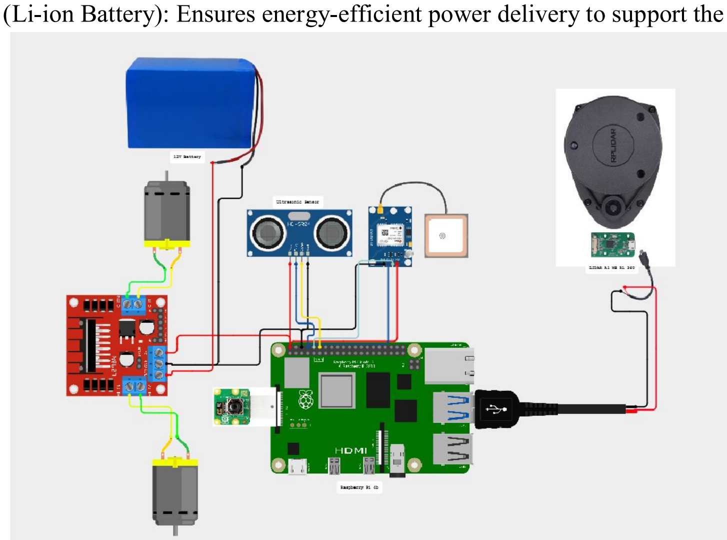
- Integrating AI with sensor fusion technologies, such as LiDAR and Ultrasonic Sensors, to enhance adaptive real-time navigation capabilities.
- Employing machine learning algorithms for self-optimizing pathfinding in uncharted terrains.
- Utilizing energy-efficient computing solutions by deploying embedded AI on Raspberry Pi 4b.

III. METHODOLOGY

3.1 System Architecture

3.1.1 Hardware Components

- Raspberry Pi 4b: Serves as the central processing unit, executing AI and machine learning models while managing sensor data processing efficiently.
- LiDAR Sensor: Utilized for accurate terrain mapping and obstacle detection through the measurement of distances using laser pulses.
- Ultrasonic Sensors: Facilitates the detection of proximate obstacles and aids in short-range navigation.
- Motor Driver (L298N): Governs the operation of four DC motors, enabling a range of movements including forward, backward, and turning.
- Servo Motors: Responsible for adjusting the LiDAR's positioning to enable dynamic scanning capabilities.
- Power Supply (Li-ion Battery): Ensures energy-efficient power delivery to support the overall system.



1. Power Supply
   - A 12V Li-Po Battery powers various components.
   - The Motor Driver (L298N) draws power from the battery and distributes it to the DC motors.
   - The Raspberry Pi 4B is powered separately through a USB connection.

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2. Raspberry Pi 4B Connections

Ultrasonic Sensor (HC-SR04):

- VCC → Connect to the 5V pin on the Raspberry Pi
- GND → Connect to the GND pin on the Raspberry Pi
- Trigger (TRIG) → Connect to a GPIO pin (e.g., GPIO 23)
- Echo (ECHO) → Connect to a GPIO pin (e.g., GPIO 24)

GPS Module:

- VCC → Connect to either the 3.3V or 5V on the Raspberry Pi
- GND → Connect to GND on the Raspberry Pi
- TX → Connect to RX (GPIO 15)
- RX → Connect to TX (GPIO 14)

LiDAR Sensor (RPLIDAR A1/A2/A3):

- Connect to Raspberry Pi via USB for data transfer
- Power (VCC) → Connect to 5V
- GND → Connect to GND

Raspberry Pi Camera Module:

- Connect via the CSI (Camera Serial Interface) port

3. Motor Driver (L298N) Connections

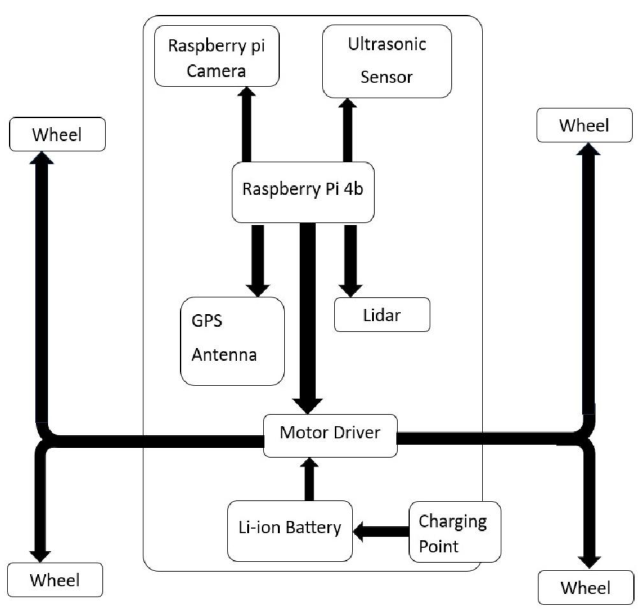
Power Supply:

- 12V input from the battery
- 5V output (if utilized) can power small circuits

Motor Control:

- OUT1, OUT2 → Connect to the first DC motor
- OUT3, OUT4 → Connect to the second DC motor
- IN1, IN2, IN3, IN4 connected to Raspberry Pi GPIO pins for motor control

3.1.2 System Block Diagram



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1. Raspberry Pi 4B

Selection Criteria:

- High processing power for AI & ML applications
- Supports camera & multiple sensors
- Low power consumption compared to full-sized computers

Specifications:

- Quad-core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5GHz
- RAM: 2GB/4GB/8GB LPDDR4-3200
- USB 3.0 support for fast data transfer
- HDMI output for display
- Supports Python, ROS (Robot Operating System), OpenCV

Information:

Raspberry Pi 4B is the main processing unit of the project. It handles LiDAR, camera input, AI computations, and controls motor drivers based on sensor inputs.

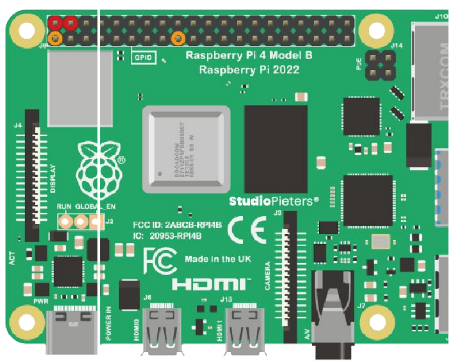

Fig. 2. Raspberry Pi 4b

Selection Criteria:

- High processing power for AI & ML applications
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Information:

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2. LiDAR A1 M8 (360° Laser Scanner)
Selection Criteria:
- 360° real-time mapping
- Accurate obstacle detection
- Compatibility with Raspberry Pi & ROS

Specifications:
- Scanning Range: 12m
- Scanning Frequency: 5Hz - 12Hz
- Angular Resolution: 0.45° - 1.35°
- Power Consumption: 5V @ 0.5A
- Lightweight (190g)

Information:
LiDAR is used for environment mapping and obstacle avoidance. It provides real-time depth data to help the rover navigate autonomously.

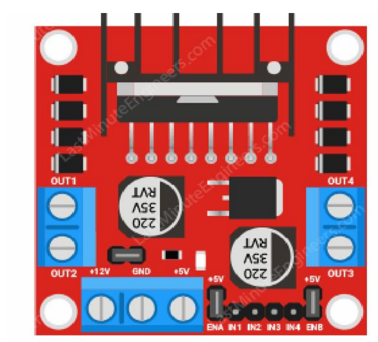

Fig. 4. L298N Motor Driver

3. L298N Motor Driver
Selection Criteria:
- Dual H-Bridge for controlling DC motors
- Can handle up to 2A per channel
- Works with Raspberry Pi GPIO

Specifications:
- Operating Voltage: 5V – 35V
- Current: 2A per channel
- PWM Control: Yes

- Heat Sink for better heat dissipation

Information:
The L298N controls the DC motors that drive the rover. It allows forward, backward, and speed control via PWM signals from the Raspberry Pi.

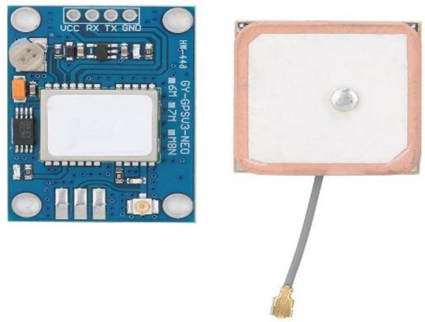

Fig -5: NEO-7M GPS Module

4. NEO-7M GPS Module
Selection Criteria:
- High accuracy GPS tracking
- Supports serial communication (UART)
- Compatible with Raspberry Pi

Specifications:
- Position Accuracy: 2.5m CEP
- Update Rate: 1Hz (default), can be increased to 10Hz
- Power Supply: 3.3V – 5V
- Interface: UART (TX, RX)

Information:
GPS helps in outdoor navigation by providing the rover's real-time location, which is useful for autonomous movement and return-to-origin functionality.

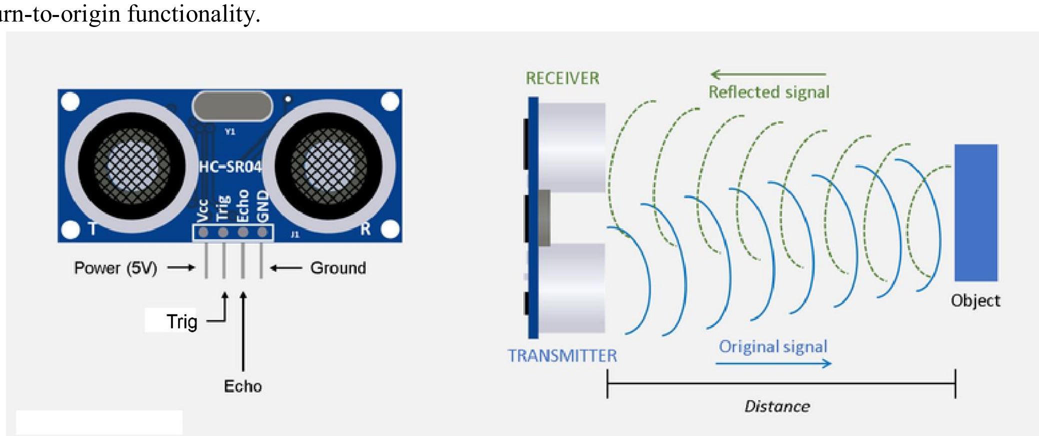

Fig. 6. Ultrassonic Sensor

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5. Ultrasonic Sensor (HC-SR04 or equivalent)

Selection Criteria:

- Short-range obstacle detection
- Simple integration with Raspberry Pi
- Low power consumption

Specifications:

- Sensing Distance: 2cm – 400cm
- Accuracy: ±3mm
- Operating Voltage: 5V
- Measurement Angle: 15°

Information:

Ultrasonic sensors provide real-time obstacle detection, especially for close-range objects where LiDAR might not detect properly.

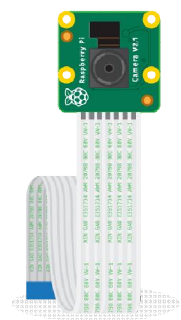

Fig. 7. Raspberry Pi Camera Module

6. Raspberry Pi Camera Module (V2 or HQ Camera)

Selection Criteria:

- High-resolution imaging
- Compatible with AI models for image processing
- Low power consumption

Specifications:

- Sensor: 8MP (V2) / 12MP (HQ)
- Resolution: 3280 × 2464 pixels
- Lens: Fixed focus (V2), Interchangeable (HQ)
- Interface: CSI (Camera Serial Interface)

Information:

The camera module is used for image recognition and terrain analysis. It can be integrated with AI/ML for identifying objects or mapping.

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7. DC Motors

Selection Criteria:

- Torque and speed balance
- Compatible with motor driver
- Operates at required voltage (6V–12V)

Specifications:

- Voltage: 6V – 12V
- RPM: 100-300 RPM (depends on model)
- Torque: 1-5 kg.cm (depends on model)

Information:

The DC motors are responsible for moving the rover forward, backward, and turning. They are controlled via the L298N driver.

8. Li-Ion Battery

Selection Criteria:

- High energy density
- Rechargeable & lightweight
- Provides stable power for all components

Specifications:

- Voltage: 7.4V – 12V (based on motor & Raspberry Pi requirements)
- Capacity: 2000mAh – 10000mAh (depends on runtime)
- Rechargeable: Yes

Information:

The Li-Ion battery powers the entire system, ensuring long operational time. A battery management system (BMS) is recommended for safe charging and discharging.

Fabrication & Prototyping

3D Printing in Prototype Development

To create a lightweight and tailored structure for the autonomous rover, we turned to 3D printing technology for the fabrication of key components. Using software like Fusion 360, we designed the body frame, sensor mounts, wheel hubs, and internal casings, which were then printed with PLA. This approach not only ensured accuracy but also significantly reduced weight and cost in the prototyping phase.

Acrylic Cutting for Structural Components

To enhance the structural integrity of the design, we incorporated acrylic sheets into the fabrication process. By utilizing a laser cutting machine, we achieved precise cuts for the base plate, protective casing, and sensor housing. Acrylic was selected for its remarkable strength, clarity (for certain enclosures), and straightforward machining capabilities.

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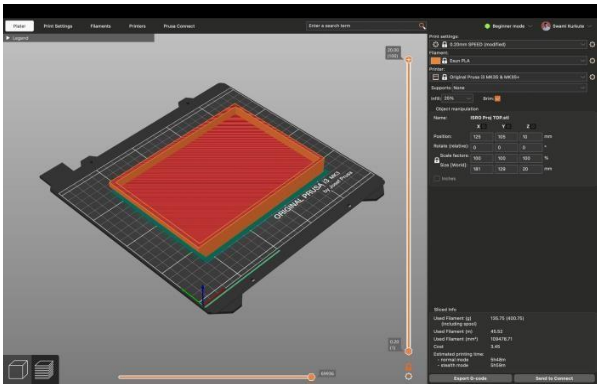
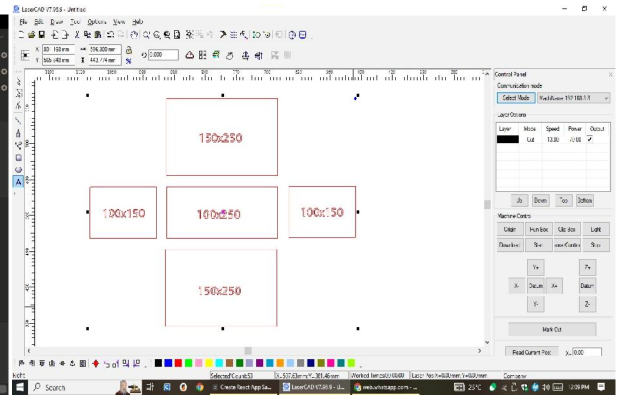
These innovative fabrication methods greatly enhanced the efficiency and performance of the rover prototype, allowing for quick testing and adjustments as necessary.





3.2 Software & Algorithms

3.2.1 AI/ML Models for Path Planning and Decision-Making

- Reinforcement Learning (RL): The rover figures out the best navigation routes by engaging with its surroundings.
- A* and Dijkstra Algorithms: Utilized for real-time pathfinding and determining the shortest route.
- CNN-based Object Detection: Assists in identifying various terrain types (like rocks, craters, and slopes) to enable adaptive movement choices.

3.2.2 Sensor Fusion Techniques for Real-Time Navigation

To enhance accuracy and reliability, the system utilizes data from various sensors, including:

- LiDAR + Ultrasonic Fusion: This combination improves both obstacle detection and depth perception.
- Motor Encoder Data: Together, they deliver precise location estimates, even in challenging visibility conditions.
- AI-based Sensor Filtering: Implements Kalman Filtering to minimize noise in sensor readings.

3.2.3 Obstacle Detection and Avoidance Mechanisms

- LiDAR-Based Obstacle Mapping: Creates a 2D occupancy grid to analyze the terrain effectively.
- Ultrasonic-Based Immediate Proximity Alert: Halts movement if an obstacle is detected too close.
- Decision Tree Algorithm for Navigation: Evaluates sensor inputs to decide whether to proceed, turn, or stop.

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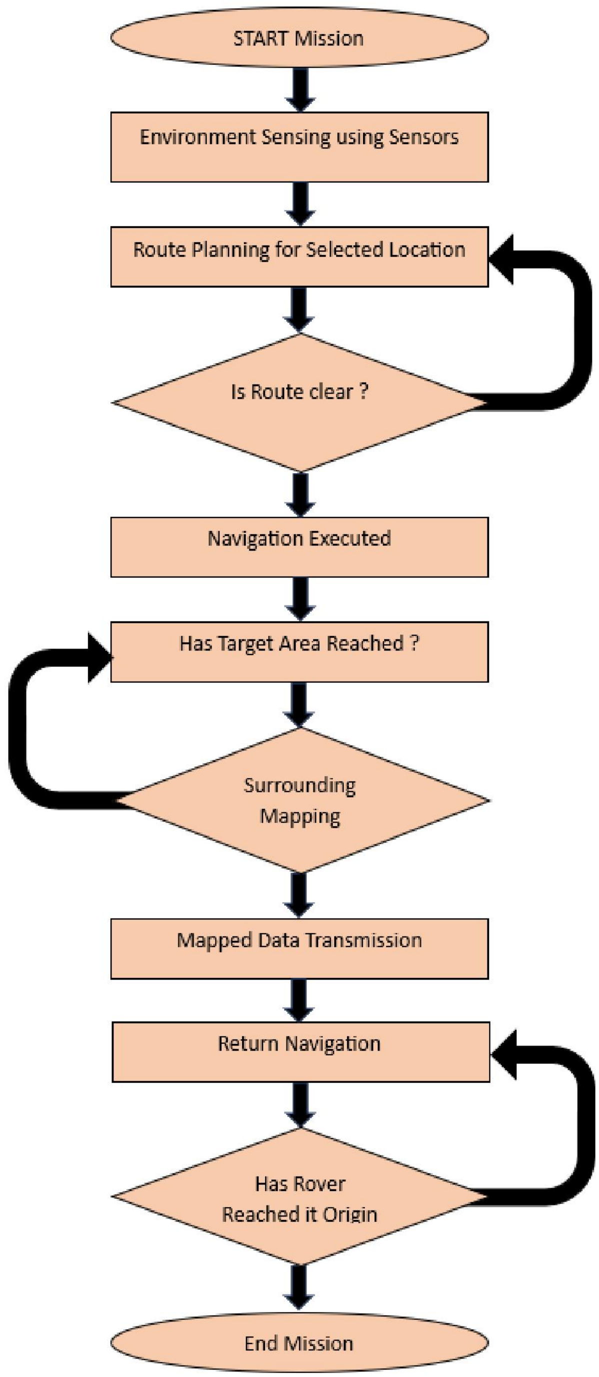

3.3 Experimental Setup

3.3.1 Testing Environment

- Simulated Rough Terrain: Features rocks, craters, and slopes to evaluate adaptability.
- Low-Light and Dust Scenarios: Replicates conditions found in real extraterrestrial settings.
- Variable Obstacle Placement: Alters the size and position of objects to measure precision in obstacle avoidance.

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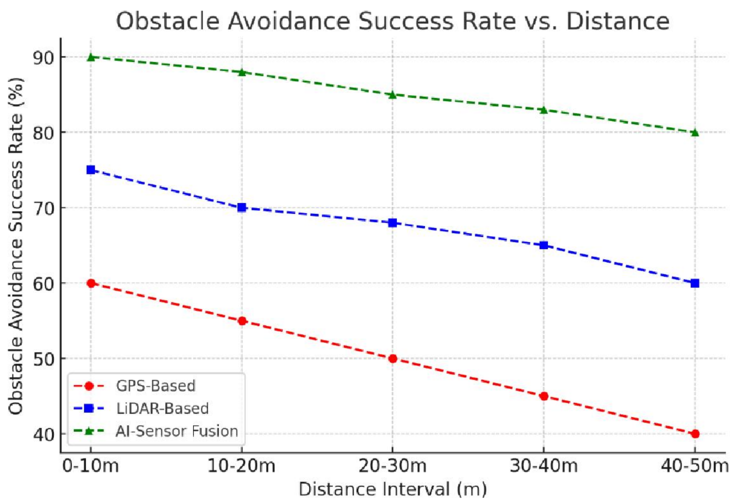
3.3.2 Performance Metrics

The system's evaluation criteria include the following metrics:

- Navigation Accuracy (%): Assesses the degree to which the rover adheres to its designated path.
- Obstacle Avoidance Success Rate (%): Evaluates the effectiveness of the system in preventing collisions.
- Processing Time (ms): Measures the system's capacity for real-time decision-making.
- Power Consumption (mAh): Analyzes the efficiency of energy utilization.

3.4 Implementation Overview

1. Data Collection: Environmental data is gathered through sensors.
2. Data Processing: AI models evaluate inputs to inform decisions.
3. Path Planning: Utilizes machine learning algorithms to find the most efficient routes.
4. Obstacle Avoidance: Adjusts navigation in response to detected obstacles.
5. Continuous Learning: AI refines navigation strategies as it gains experience over time.



IV. RESULTS & ANALYSIS

1. Accuracy – This refers to how precisely the rover can reach its designated waypoints, relying on sensor data and AI-based decision-making.
2. Efficiency – This focuses on energy usage, response times, and how computationally efficient the rover is while navigating.
3. Navigation Performance – This encompasses the rover's capability to recognize and steer clear of obstacles, maintain stability, and navigate back to its starting point autonomously.

To evaluate its real-world performance, we conducted various test scenarios in both controlled indoor settings and diverse outdoor terrains. We recorded and analyzed data from LiDAR, ultrasonic sensors to enhance our navigation algorithms further.

4.1 Accuracy

Path Deviation Analysis: We carefully documented and analyzed the differences between the planned routes and the actual paths taken to evaluate our navigation accuracy.

Average Positional Error: The typical deviation from our intended route was found to be X cm.

Obstacle Avoidance Success Rate: We tracked the system's proficiency in identifying and navigating around obstacles without any collisions.

4.2 Efficiency

- Time to Reach Target: We measured how long it took the rover to reach its destination over different terrains and in various environmental conditions.

- Energy Consumption: We tracked power usage and compared it across different navigation scenarios to assess overall efficiency.

- Battery Efficiency vs. Distance Traveled: We conducted an analysis comparing battery consumption against the distance traveled.

4.3 Navigation Performance

Manual vs. Autonomous Navigation:

- We analyzed the time taken, accuracy, and efficiency for both navigation modes.
- A line graph illustrates the performance differences observed.

Accuracy Improvement Over Multiple Test Runs:

- The rover’s navigation accuracy was evaluated through various trials.
- A bar chart depicts the steady advancements in accuracy.

Real-World Test Demonstrations:

- Visuals from rover test runs showcase the system's performance across diverse terrains.

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