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LUNAR NAVIGATION ROVER

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Abstract: Reliable navigation is essential for lunar rovers, ensuring both safe remote operation and effective autonomous movement. This project highlights a navigation system implemented for a prototype wheeled lunar rover capable of traveling over a kilometer in natural outdoor terrain. The system uses stereo terrain mapping for obstacle detection and integrates steering inputs from both the user and the rover for optimal navigation. Additionally, advancements in robotics and automation are replacing tasks previously controlled by humans. This project focuses on a robot controlled via Android technology, where commands are transmitted through Wi-Fi from an Android device to the hardware's Wi-Fi receiver, enabling the robot to execute the corresponding actions seamlessly.

Keywords: Stereo Terrain Mapping, Obstacle Avoidance, Arbiter, User Interface

I. INTRODUCTION

Humans are once again captivated by the idea of exploring the Moon, and plans are underway to send two rovers on a multiyear mission covering 1,000 kilometers of its surface. The goal is to visit historic sites like Apollo 11, Surveyor 5, Ranger 8, Apollo 17, and Lunokhod 2. In this mission, one rover would drive and send live video, while the other stays stationary to capture detailed images and act as a communication link with Earth. The roles would alternate as they explore the lunar terrain. While building the hardware for such a mission presents significant challenges—such as ensuring reliable communication, power, thermal management, and durability—the software control systems are equally critical. Advanced capabilities are needed to navigate diverse terrains and ensure safe operation. Past experiences, like operating Lunokhod 2 and the Viking arm, highlighted the difficulties of time-delayed teleoperation. This has led to a preference for supervised or autonomous operations, where the rover can make independent decisions to sustain progress and safety.

We are working on developing and demonstrating advanced technologies for remote teleoperation and autonomous driving in lunar-like environments. The goal is to provide effective methods and evaluations to help mission planners assess the cost and benefits of different rover control strategies. So far, our focus has been on autonomous operation, and we have successfully tested a system that uses stereo vision to navigate a prototype lunar rover over one kilometer of natural outdoor terrain. This achievement, powered by SPARC 10 processors running at 11 MFLOPS, marks a significant milestone in autonomous cross-country navigation using stereo vision and standard computing hardware.

We are exploring a mixed-mode operation where both a human operator and an autonomous system provide driving inputs, with the system mediating these to generate actual steering commands for the rover. This approach aims to create a more adaptable user interaction model, minimizing operator fatigue and errors that might harm the rover. Additionally, we are addressing the challenge of accurately estimating the rover's position, which is particularly critical for long- distance navigation to specific sites. Unlike Earth, where GPS is widely available, lunar missions require alternative solutions. Our research focuses on utilizing and refining sensors like gyroscopes and inclinometers, employing sensor fusion to enhance accuracy, and developing innovative techniques such as skyline navigation and Sun tracking. These efforts have provided valuable insights that are shaping our upcoming developments, including a demonstration of safeguarded teleoperation over distances of up to 10 km, with increased terrain complexity and operational delays.

II. LITERATURE REVIEW

F. Cozman et al [1] investigates how Sun altitude can be used for robot localization in completely uncharted areas. By analyzing a series of time-stamped sky images, the Sun's altitude is determined, which places the observer on a specific circle on a celestial body's surface, known as the circle of equal altitude. The intersection of multiple such circles helps pinpoint the observer's location. Applied to Earth, this method utilizes altitude measurements, refined through least-squares estimation to address noise in the data.

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The paper explores the foundational concepts of Sun-based localization, details the challenges in camera calibration and image processing, and shares initial findings based on real-world experiments.

L. Katragadda et al [2] reviewed that, Humans are once again drawn to the Moon, with an exciting near-term plan to land two rovers and embark on a 1000-kilometer journey across significant lunar sites like Apollo 11, Surveyor 5, Ranger 8, Apollo 17, and Lunokhod 2. In this mission, one rover will move across the surface, transmitting live video continuously, while the other remains stationary, capturing high-resolution images and acting as a communication relay with Earth. The roles of the rovers will be swapped periodically, allowing both to contribute to the ongoing exploration of the Moon's terrain.

A. Kelly et al [3] reviewed that, the challenge of enabling high-speed autonomous navigation using range image data from stereo and lidar sensors. To ensure safety, a high-speed vehicle must detect even the smallest obstacles, process sensory information quickly enough for its speed, and respond rapidly to avoid collisions. Additionally, the vehicle must maintain an accurate model of its environment to make correct decisions. The report analyzes these requirements in a nondimensional way, showing that meeting all of them simultaneously involves significant computational complexity. Specifically, the vehicle's reaction time and speed will determine the necessary processing power, and faster speeds will lead to an exponential increase in computational demands. This highlights the trade-off between speed, resolution, and reliability when working with limited computing resources. The findings support the design of an adaptive, real-time controller for the RANGER cross-country navigation system.

E. Krotkov et al [4] reviewed that, This paper introduces two novel methods for enhancing planetary rover perception. The first method focuses on stereo driving without relying on 3D reconstruction. It begins with stereo images that are only weakly calibrated and assesses the terrain's traversability using indicators like slope and elevation. It then evaluates potential paths based on this analysis to determine the optimal route. The second method estimates the rover's position by observing the Sun. By measuring the Sun's altitude at different times, the rover's location is confined to a circle on the Earth's surface, known as the circle of equal altitude. The rover's position is then determined by intersecting these circles from different time points. Both approaches are being tested in real-world, outdoor environments with wheeled rovers, and the technology is planned to be adapted for Lunar Rover missions in the future.

J. Purvis et al [5] reviewed that, The Robotic All-Terrain Lunar Exploration Rover (RATLER) is an innovative four-wheeled vehicle designed for lunar surface exploration. It features a unique chassis articulation system that ensures all four wheels stay in contact with the ground, even when navigating obstacles up to 1.3 times the wheel diameter in height. This design incorporates skid steering and modular construction, making it a simple, durable, and highly maneuverable vehicle. Compared to other planetary exploration vehicles, RATLER reduces the number of parts, contributing to a more efficient and cost-effective design.

L. Robert et al [6] reviewed that, This paper presents a vision system for autonomous navigation that relies on stereo perception without the need for 3D reconstruction. The system works with weakly calibrated stereo images, where only the epipolar geometry is known. It begins by rectifying the images, matching specific points between them, and calculating the relative elevation of these points in relation to a reference plane. Additionally, it determines the projections of these points onto the plane. The vision system is integrated into a full navigation system, where the relative elevation serves as an indicator of the terrain's shape, helping to determine steering directions as new stereo pairs are processed. Initial experiments were conducted in unstructured, outdoor environments using a wheeled rover.

Cabrol N A et al [7] reviewed that, The Nomad rover was active for 45 days in the Atacama Desert, Chile, in the summer of 1997. During this time, it achieved a significant milestone by completing the longest traverse ever recorded by an automated vehicle, covering 220 km. The rover's operations were managed remotely by teams at NASA Ames and Carnegie Mellon, while between June 20th and 27th, it conducted scientific experiments. A Field Science Team was stationed in the desert to verify the rover's activities on the ground, working alongside the Science and Operations Teams at NASA Ames.

Kassel S et al [8] reviewed that, On November 17, 1970, the Soviet Luna-17 mission successfully delivered the Lunokhod-1 lunar exploration vehicle to the Moon's Sea of Rains. This marked a significant achievement, as the Lunokhod-1 managed to traverse nearly 10 kilometers of rough lunar terrain. The mission demonstrated the effectiveness of using a remote-controlled drone to explore an unknown and hostile environment. Equipped with a variety of scientific instruments, including narrow-band television systems, mechanical probes, a chemical analysis system, X-ray and cosmic ray detectors, and various temperature and pressure sensors, the vehicle provided valuable data about the lunar surface. The ongoing success of the Lunokhod-1's journey highlighted the viability of unmanned exploration in space.

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Ellery A et al [9] reviewed that, Planetary exploration, especially through robotic rovers, presents unique challenges in terms of mobility across harsh planetary surfaces like Mars. One important aspect often overlooked is how these robots maintain movement in such hostile environments. In this context, I explore and compare three mobility systems: the wheeled rocker–bogie system used in Sojourner, a tracked vehicle design, and a new concept known as the Elastic Loop Mobility System (ELMS). Additionally, I discuss the limitations of using Bekker theory to assess the mobility performance of different vehicle locomotion systems, pointing out how it may not fully capture the complexities involved in real-world planetary terrain.

Volpe R et al [10] reviewed that, this paper presents an overview of the new Mars rover prototype, Rocky 7. It covers various system aspects including the mechanical and electrical design, computer systems, software infrastructure, navigation and manipulation algorithms, science data collection, and outdoor testing. Each section highlights the new or enhanced features, detailing how they contribute to the rover's readiness for space missions while considering the specific requirements of the planned scientific goals.

III. SYSTEM ARCHITECTURE

It takes a team effort to create an Lunar Navigation Rover using an ESP 32, Power Supply, and other sensors. An overview of a high-level system architecture that will direct the creation of one is provided below:

- **Power Supply: 5V DC**

The system operates on a 5V DC power source, providing the required energy to all components, including sensors, the microcontroller, and actuators.

- **Microcontroller: ESP32**

The ESP32 is a powerful microcontroller with built-in WiFi and Bluetooth capabilities. It acts as the brain of the system, processing data from sensors and controlling outputs like relays and motors.

- **Temperature Sensor**

This sensor monitors the temperature of the environment, helping to track changes or detect unusual conditions, such as overheating.

- **Obstacle Sensor**

An obstacle sensor detects objects in the system's path, commonly used for safety or navigation in automation applications.

- **WiFi Technology**

WiFi enables wireless communication between devices, allowing the system to transmit and receive data over a network or connect to other IoT devices.

- **Motors**

The motors perform mechanical actions, such as moving objects or activating equipment, based on commands from the microcontroller.

- **Relay and Relay Drivers**

Relays are switches that control high-power devices like motors. Relay drivers are circuits that help the microcontroller manage these relays effectively.

- **Fire Sensors**

These sensors detect the presence of fire or smoke, providing an early warning to prevent potential hazards.

- **Fire Alarm**

A fire alarm is activated by the fire sensors, producing an audible or visual alert to notify users of a fire emergency.

- **Soil Moisture Sensor**

This sensor measures the moisture content in soil, typically used in agriculture or irrigation systems to monitor and maintain optimal soil conditions.

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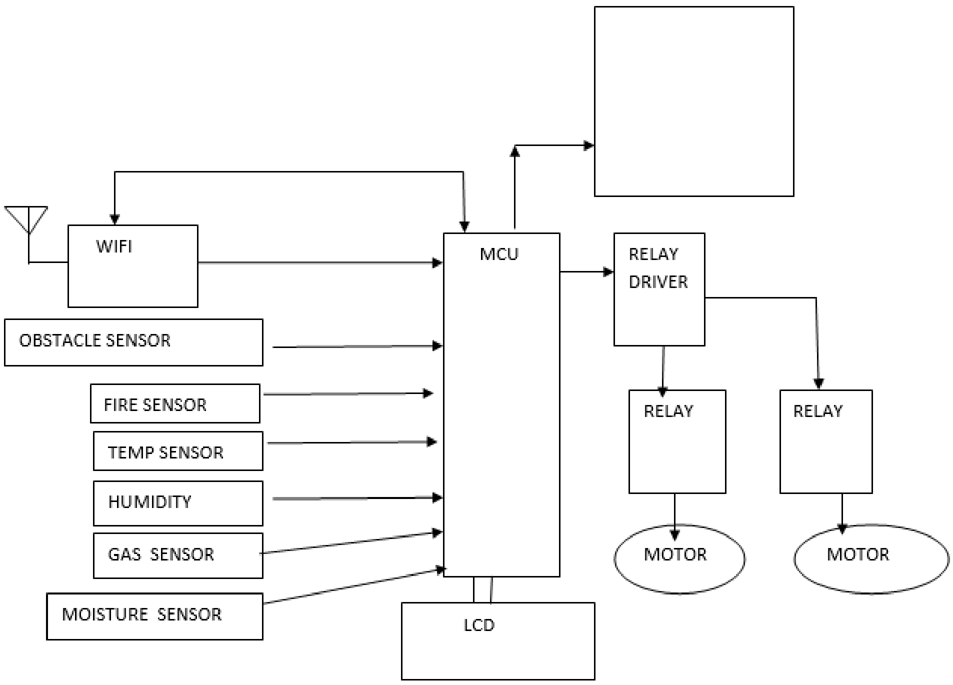
- **Gas Sensor**

A gas sensor detects the presence of harmful or combustible gases, helping ensure safety by identifying potential leaks or hazardous conditions.

IV. THE NAVIGATION SYSTEM

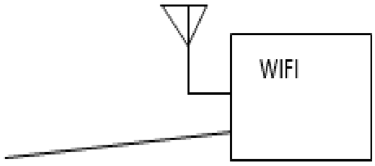
Receiver Side:



Receiver side block diagram

The receiver side of the system consists of various components that work together to ensure effective data processing and control. A WiFi module enables wireless communication between the receiver and transmitter, while an MCU (Microcontroller Unit) acts as the central controller, receiving and processing data from various sensors. These sensors include an obstacle sensor for detecting objects, a fire sensor for early fire detection, a temperature sensor to monitor environmental temperature, a humidity sensor to measure moisture levels in the air, a gas sensor for detecting hazardous gases, and a moisture sensor for tracking soil or environmental moisture. All the sensor data is displayed in real-time on an LCD screen for easy monitoring. The MCU processes this data and controls actuators, such as motors, via a relay driver, enabling automated actions based on specific conditions, such as activating motors when an obstacle or fire is detected.

Transmitter Side



Transmitter side block

The transmitter side of the system includes an IoT device, typically a microcontroller that integrates sensors to collect data, and a WiFi module that enables wireless communication. The IoT device gathers information from the sensors, while the WiFi module transmits this data to the receiver, ensuring seamless communication without the need for physical connections. This setup allows for efficient and remote data transfer in various applications.

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Working Principle

An IoT device gathers sensor data continuously and sends it over WiFi to a receiver. The receiver, equipped with an MCU, processes this data and takes action based on predefined conditions such as detecting high temperatures, fire, or obstacles. It activates appropriate relays to control motors or other actuators, enabling automated responses. This system ensures real-time monitoring and decision-making, making it suitable for applications in automation, safety, and environmental management.

Stereo Terrain Mapping

The stereo system used by Ratler collects data from two black-and-white CCD cameras with autoiris, mounted on a mast that averages motion. The cameras capture sets of (x, y, z) coordinates in the camera's frame, along with the robot's pose at the time of image capture. Using the pose, these coordinates can be converted into world coordinates to create a terrain elevation map, though the distribution of data may not be uniform. To speed up the process, only part of the image at reduced resolution can be analyzed. The images are first rectified to ensure that the scan lines align with the epipolar lines. A normalized correlation method is used to compute the best disparity match within a specific window. This method is robust against exposure differences and can provide confidence measures for the disparity values. To minimize false stereo matches, techniques like setting lower bounds on correlation values, eliminating ambiguous matches, and smoothing the values are applied. These methods ensure the elevation maps are accurate, with errors typically no more than a few centimeters.

Obstacle Avoidance

To ensure safe navigation, techniques from ARPA's Unmanned Ground Vehicle (UGV) program have been adapted for the rover's obstacle avoidance. The method involves assessing potential hazards along several possible paths the rover could take within the next few seconds. Each path is evaluated and assigned votes, with unsafe paths receiving vetoes to prevent selection. This system enables the rover to steer clear of obstacles like craters or mounds that it cannot safely traverse. The planning process combines multiple elevation maps, generated by the stereo vision system, into a comprehensive terrain map covering up to seven meters ahead. This merging process compensates for the cameras' limited field of view and ensures the rover uses the most current terrain data for effective decision-making.

Arbiter

The arbiter module determines the optimal steering angle for a rover by analyzing path evaluations from multiple sources, such as obstacle avoidance systems, route planners, and user inputs. Each evaluation includes a steering angle, a value, and a speed. If a value is marked as "veto," that steering angle is excluded. Otherwise, recommendations for each angle are combined using weighted sums. The arbiter selects the midpoint of the largest set of steering angles within 90% of the highest value, favoring wide, traversable paths to minimize errors due to the rover's limited path-tracking accuracy. Path evaluations are only considered if they match the rover's current pose; mismatched evaluations are ignored. If all evaluations are invalid, the rover halts to prevent issues caused by module failures. The arbiter also ensures continuity by sending steering commands for specific distances, stopping the rover if no new commands arrive. In cases where no valid paths are detected, such as due to noisy sensor data or unexpected obstacles, the arbiter commands the rover to turn incrementally until valid paths are identified again.

User Interface

The user interface for controlling the lunar rover is designed to support mixed-mode operation, allowing both the human operator and the rover to share control responsibilities. The interface includes an "electronic joystick," operated with a mouse to control the rover's speed and direction, along with various indicators displaying speed, roll, pitch, position, and status information. A rear-mounted color camera provides a live feed of the terrain, transmitted via a microwave link. The system offers three driving modes: direct teleoperation, where the operator has full control for handling complex situations like navigating out of craters; autonomous mode, where the rover independently chooses its path using stereo input; and safeguarded teleoperation, the default mode, which merges human input with obstacle avoidance. In this mode, the software can override unsafe commands while enabling autonomous navigation if the operator does not actively control the rover, thus reducing fatigue during straightforward operations.

V. CONCLUSION

We have developed a system for autonomous and semi-autonomous operation of the Ratler, a four-wheeled articulated prototype designed for lunar exploration in natural outdoor environments. The navigation system combines onboard and external computing to manage vehicle control, process stereo images, plan obstacle avoidance, and integrate inputs from both machine algorithms and human operators for directional guidance. While initial experiments show promise in avoiding hazards like cliffs and mounds, significant work is required to ensure long-term reliability over extended distances and durations.

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Further research is needed, particularly in safeguarding and remote teleoperation, to enhance the system's performance. Although these technologies can simplify remote rover operations and improve reliability, they also increase the complexity of hardware and software. Rigorous testing is essential to validate their benefits for upcoming lunar missions.

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