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Autonomous Rover for Space Exploration in Unknown Terrains

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Abstract*– Space exploration has significantly expanded the understanding of the universe, with autonomous robotic systems playing a pivotal role in investigating extraterrestrial environments. This study presents the design and implementation of an exploratory rover, emphasizing navigation, terrain assessment, actuation, and data acquisition in uncharted environments. The development process was grounded in an extensive review of state-of-the-art technologies, which also resulted in the publication of a comprehensive review paper on the subject. The final prototype was showcased at the international competition Rover Innovation Challenge 2024, where it secured second place in the "Águilas" category. The results highlight the system's robustness and adaptability, demonstrating its potential as a valuable asset for future autonomous exploration missions in challenging extraterrestrial terrains.

***Keywords*-- Rover, Space Exploration, Terrain Navigation, Electronic Systems.**

I. INTRODUCTION

Space exploration represents one of humanity's greatest scientific and technological endeavors, enabling the continuous expansion of knowledge about the universe. Beyond advancing fundamental astrophysical understanding, current missions focus on investigating planetary origins and assessing the feasibility of human colonization beyond Earth.

The development of autonomous robotic systems has played a pivotal role in planetary exploration, particularly in studying celestial bodies such as the Moon and Mars, which have been extensively analyzed due to their potential for supporting future missions. Additionally, Europa, one of Jupiter's Galilean moons, has garnered significant attention due to its subsurface ocean, which may harbor conditions suitable for life.

The upcoming Europa Clipper mission aims to investigate this potential; although primarily conducted via satellite instrumentation, it underscores the vast opportunities in space exploration [1]. Planetary rovers are essential for missions in environments that pose extreme risks to human life, including resource prospecting and the establishment of extraterrestrial habitats.

While large-scale human settlements remain a distant objective, anticipating the challenges associated with autonomous exploration is crucial to mitigating mission failures and ensuring operational resilience [2]. Given the substantial costs and risks inherent to space missions, robotic explorers must integrate highly sophisticated autonomous navigation systems to operate with zero tolerance for failure.

These systems must generate reliable and precise environmental data, particularly in uncharted terrains where real-time decision-making is critical [3].

Furthermore, planetary rovers must dynamically assess and respond to diverse terrain conditions to optimize their operational performance. This includes maximizing traction, minimizing power consumption, and adapting to unpredictable surface characteristics, thereby ensuring mission success in extreme extraterrestrial environments [4].

This study presents the development of a space exploration rover designed for remote teleoperation over significant distances. The current phase of the project focuses on structural design, data acquisition capabilities, and real-time transmission of environmental information to a ground station, laying the foundation for future advancements in autonomous planetary exploration.

II. RELATED WORK

The rover's development and robotic systems for planetary exploration are a key area of interest for space agencies such as NASA (*National Aeronautics and Space Administration*) and ESA (*European Space Agency*). NASA has led the development of some of the most renowned Mars exploration rovers, including Curiosity and Perseverance, as shown in Fig. 1.

Fig. 1. Perseverance rover. Source: [5]

The design of such robotic systems involves multiple subsystems, including mechanical, electronic, power, and communication components. Each subsystem is critical in ensuring reliable operation during a simulated or actual space mission.

The communication system, in particular, is responsible for the exchange of information between the rover and a designated ground station, enabling the execution of commands and the transmission of collected data, such as images, environmental variables, and system status updates. The choice of communication architecture depends on mission objectives and hardware constraints.

One widely used approach involves an embedded web segment based on the *Transmission Control Protocol/Internet Protocol* (TCP/IP), where a dedicated server facilitates real-time data exchange between the rover and a teleoperator. This setup enables effective remote control and provides real-time feedback through an integrated camera stream, allowing operators to analyze the surrounding environment [6].

To enhance communication range and channel efficiency, this method can be complemented by a *Low-Frequency Array* (LOFAR), which employs multiple routers to extend the communication distance and optimize data routing. This approach is particularly effective in swarm robotics applications, where each rover functions as a networked node within a decentralized system [7].

The electronic system integrates all essential components required for mobility, data acquisition, power management, and communication with the ground station. These functions are controlled by embedded computing devices, which may include microcontrollers or microprocessors, depending on the mission's complexity and requirements [8].

For improved system performance, task-specific processing units can be employed. For instance, in the Explorer-0100 rover, multiple Arduino boards are dedicated to distinct tasks, while a Raspberry Pi serves as the central control unit, integrating a LiDAR sensor and a backup system [8]. A notable variation of this architecture is found in Dusty-TRON 3.0, a rover designed for mining applications. This system incorporates an NVIDIA Jetson Nano GPU (*Graphics Processing Unit*) as the onboard computing platform [9], [10].

The GPU-based architecture enhances data processing capabilities, making it suitable for implementing neural networks, image compression, dense stereo matching, multiview stereo, and triangle mesh compression—key features for autonomous navigation [11], [12]. Additionally, overall system efficiency can be further improved through the integration of a *Field-Programmable Gate Array* (FPGA), enabling parallel task execution and enhanced real-time processing [13].

III. Materials and Methods

The primary objective of this project is to develop a comprehensive review that consolidates existing research on wheeled robotic systems for space exploration, focusing on the key subsystems essential to their design and operation. Additionally, this study aims to leverage the collected data to initiate the design of a rover capable of navigating uncharted terrains with human-assisted control, thereby enhancing the adaptability and resilience of robotic systems in extraterrestrial environments.

To achieve these objectives, an extensive literature review was conducted using multiple bibliographic databases, including IEEEXplore, Scopus, Springer, and Google Scholar. The search strategy involved the formulation of refined queries targeting core research areas such as artificial intelligence, electronics, software engineering, and physics to ensure a comprehensive data collection. As a result, an initial dataset of approximately 502 relevant publications was compiled, forming the foundation for an in-depth analysis.

A systematic filtering process was then applied, incorporating a detailed examination of titles, keywords, and abstracts to refine the selection. This rigorous methodology narrowed the dataset to 160 key studies, which were thoroughly analyzed to inform the conceptual and technical design of the rover. Based on the insights gained, the construction of the first rover prototype has commenced, with plans to present it at the *Rover Innovation Challenge 2024*.

A. Rover Structure

The rover's structure was designed using a repurposed computer case as a housing unit for all necessary electronic components. This enclosure was constructed from aluminum, a material that offers significant resistance but is prone to deformation. To enhance structural integrity and prevent distortion, a series of parallel support bars were incorporated into the chassis.

As shown in Fig. 2, the rover's mobility system is based on the rocker-bogie mechanism, a configuration widely used in planetary exploration due to its ability to traverse uneven terrain efficiently.

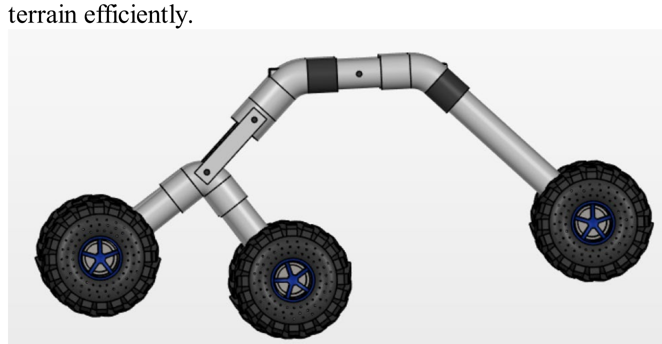

Fig. 2. Rocker-bogie structure. Source: Authors.

The bogie system was constructed using PVC tubes, selected for their structural adaptability and compatibility with standard components. This material facilitates the integration of motors and sensors, as its standardized dimensions allow for the design of custom adapters to reinforce the structure. Additionally, PVC provides sufficient strength to support substantial loads without compromising maneuverability.

A set of PVC connectors enabled the integration of a high-power DC motor, which was mounted on a gearbox to increase torque. Given that the rover was designed to transport heavy payloads, the selected motor and gearbox assembly are similar to those used in children's electric vehicles. As depicted in Fig. 3, this system operates with a 12V DC motor, simplifying motion control by allowing the use of a single H-bridge driver, which is further detailed in the hardware section. For optimal performance on rough terrain, the rover's wheels were custom-designed to enhance traction.

Fig. 3. Gearbox and motor implemented in the Amity Rover. Source: [14].

The prototype features a set of protrusions to improve grip, as illustrated in Fig. 4. The wheel design was developed using Fusion 360, selected for its versatility and ease of use in parametric modeling. The final version was 3D-printed in PET-G, a material chosen for its resistance to temperature and humidity, flexibility, and ease of fabrication.

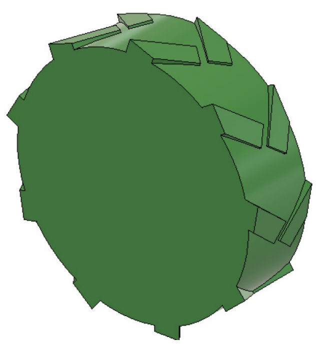

Fig. 4. Wheel Design for Amity Rover. Source: Authors.

A total of six wheels were printed and fitted to the gearbox assembly. The complete rover structure, as presented in Fig. 5, has final dimensions of 110 cm × 80 cm × 90 cm.

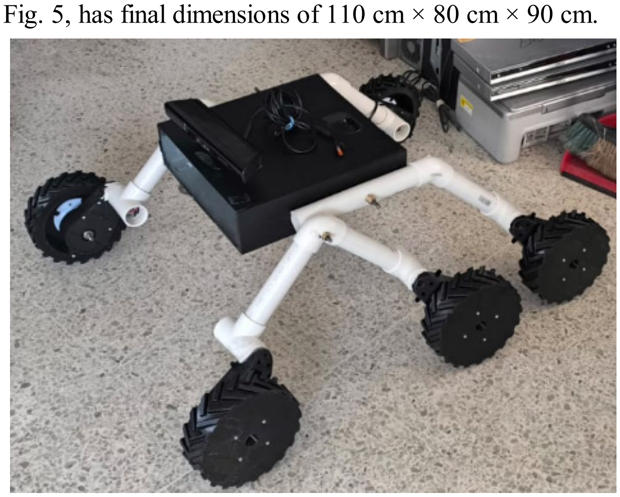

Fig. 5. Final version of Rover structure. Source: Authors.

B. Power Electronics System

The development of the rover requires the integration of several electronic components, which will be discussed in subsequent sections. However, the implementation of these components necessitates multiple voltage levels. Fig. 6 illustrates the distribution of power sources required to provide the nominal voltages for different subsystems.

To ensure an efficient power system, two types of batteries were incorporated, each serving a specific function. The primary battery is a lead-acid battery, responsible for supplying power to the rover’s motors and microcontrollers. This battery provides 12 V and 7.5 Ah. Additionally, a lithium-ion battery was integrated to power the onboard microprocessor. Furthermore, the lead-acid battery is connected to a set of high-efficiency voltage regulators that supply 3.3 V, 5 V, and 6 V, each dedicated to different components.

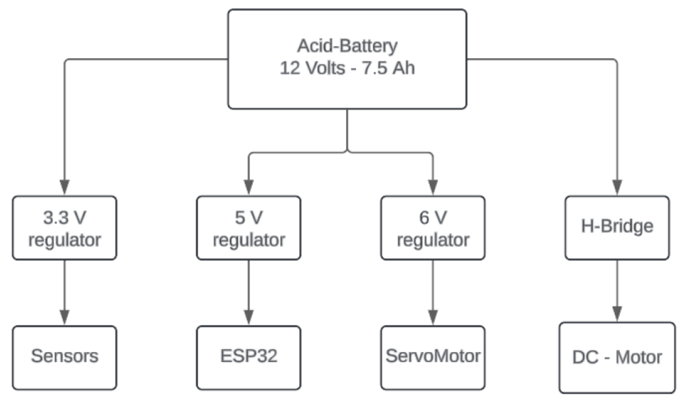

Fig. 6. Power electronics system for the rover. Source: Authors.

C. Hardware Control Architecture

The rover's electronic architecture is based on synchronized operation between a microprocessor and a microcontroller. The microprocessor is an Intel Core i5 (4th generation), salvaged from a repurposed laptop, while the microcontroller is an ESP32, selected for its extensive developer community and adaptability.

The main electronic components used in the rover's construction are listed below:

- ESP32 (x2)
- BMP180 (Barometric Pressure Sensor)
- DHT22 (Temperature and Humidity Sensor)
- Relay Module (x8)
- Laptop PCB
- MPU6050 (Inertial Measurement Unit)

The use of two ESP32 microcontrollers is justified by the need for parallel computation and modular system expansion. One ESP32 is dedicated to sensor management, allowing for future modifications such as the addition or replacement of sensors. The second ESP32 is responsible for actuator control, including servo motors and H-bridges. Fig. 7 depicts the hardware interconnections, while the power distribution follows the scheme presented in Fig. 6. The system incorporates a set of meteorological sensors and the necessary actuators for the rover's movement and operational tasks.

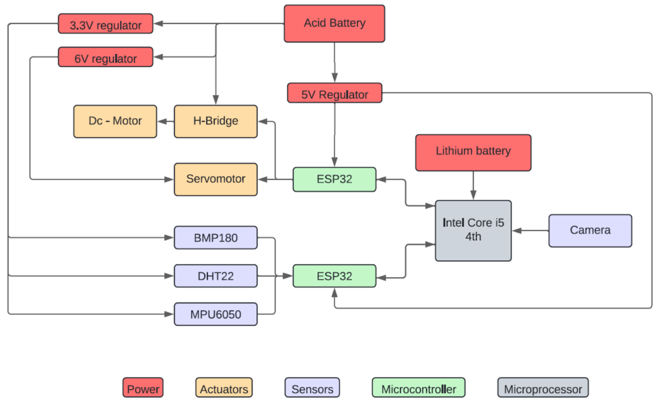

Fig. 7. Hardware architecture diagram. Source: Authors.

The ESP32 microcontrollers are connected to the processor via USB, providing a simple and cost-effective data exchange interface. The servomotor is responsible for controlling the camera's orientation, enhancing the operator's visual capabilities. The captured images are displayed in the *Human-Machine-Interface* (HMI) designed for the rover, which is further detailed in the software section.

At present, the rover lacks a speed regulation system, meaning that the motors receive direct power from the primary battery. During power consumption tests, it was observed that each motor can draw a maximum current of 5 A. Figs. 8 and 9 illustrate the motor connections to the H-bridge. As shown, the right-side motors are connected in parallel to one H-bridge output, while the left-side motors are connected to the other output. This configuration results in a peak current draw of approximately 15 A, which corresponds to the motors operating under maximum load conditions.

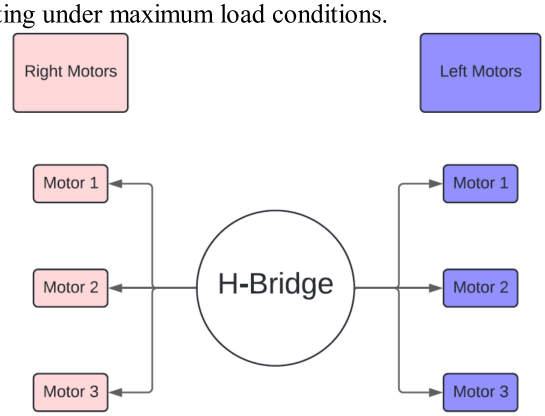

Fig. 8. Motor and H-Bridge connection. Source: Authors.

The relay module enhances system protection by isolating control signals from power signals, thereby preventing potential damage to low-power components (See Fig. 9). The selected configuration enables the rover to perform four types of movement: forward, backward, right rotation, and left rotation.

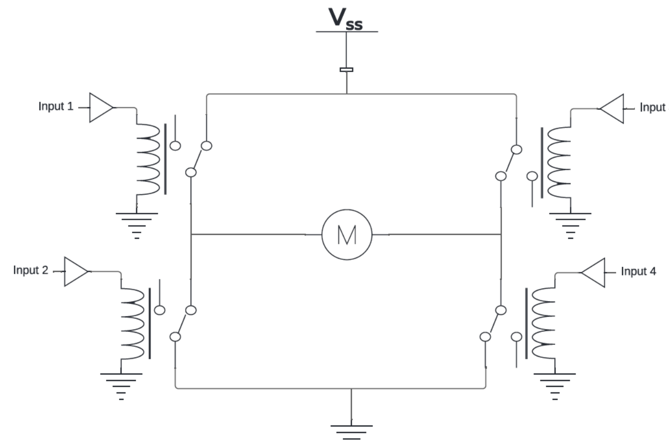

Fig. 9. H Bridge using Relays. Source: Authors.

D. Communication System

The rover's communication system is based on the TCP/IP protocol, which facilitates data exchange between the rover and a ground station. In this setup, the rover functions as a server, while the ground station operates as a client. The connection is established by configuring the rover as a Wi-Fi hotspot, allowing a direct wireless link between the two.

Through this Wi-Fi connection, the rover can stream real-time video from its onboard camera and transmit collected sensor data. The received data is displayed in chart format within the HMI. Simultaneously, the HMI enables remote control of the rover's movement via two interaction methods, depending on the connected device:

- *Mobile Interface*: Commands are sent via on-screen buttons (Fig. 10).
- *Computer Interface*: Movement can be controlled using keyboard arrow keys.

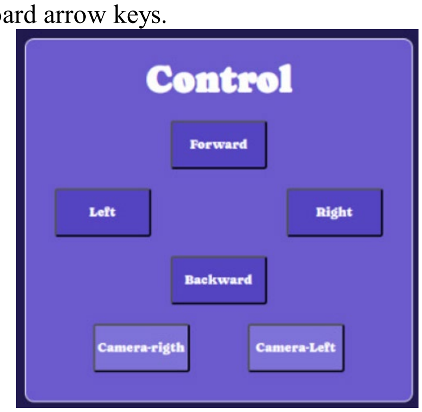

Fig. 10. Rover HMI control interface.

The described system represents the final version, integrating the visualization system and the HMI. However, during development, an alternative communication system based on ESP-NOW was also implemented. This protocol, developed by Espressif, enables connectionless communication with short-packet transmission, offering a simplified approach to testing motor control and sensor status [15]. Fig. 11 illustrates the ESP-NOW communication model.

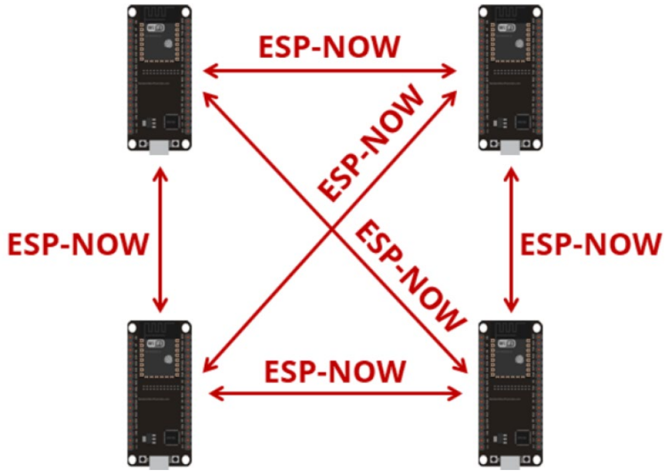

Fig. 11. ESP-NOW protocol. Source: [15].

To facilitate data exchange between the rover and the ground station using ESP-NOW, a third ESP32 was connected to a computer, establishing a streamlined communication link.

E. Software Architecture

To complete the rover's system, a Human-Machine Interface (HMI) was designed and developed. The software architecture includes implementations for both the rover and the ground station.

Onboard the rover, the software is built using the Flask framework, which provides a lightweight server architecture and facilitates the integration of Python libraries. For camera configuration, the OpenCV library was selected due to its extensive capabilities in computer vision and machine learning applications [16]. The Python-based implementation also enables direct communication with the ESP32 modules via USB.

The HMI design was developed using front-end technologies, including HTML, CSS, and JavaScript (JS). The final interface design, incorporating both the control system and camera visualization, is depicted in Fig. 12.

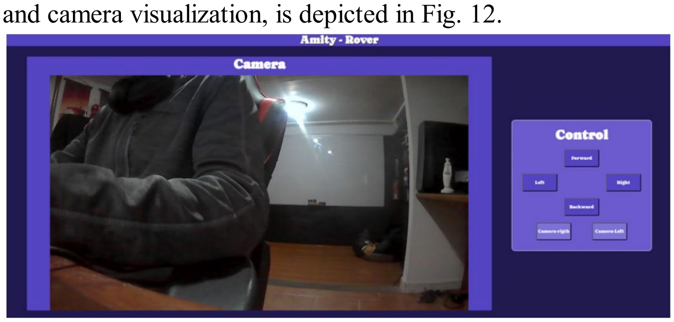

Fig. 12. Human-Machine Interface.

The camera feed from the HMI can be accessed from any device, ranging from smartphones to computers. To generate real-time data visualizations, the system utilizes the Highcharts JavaScript library, as shown in Fig. 13. This implementation enables the monitoring of critical environmental variables, including pressure, temperature, altitude, and humidity.

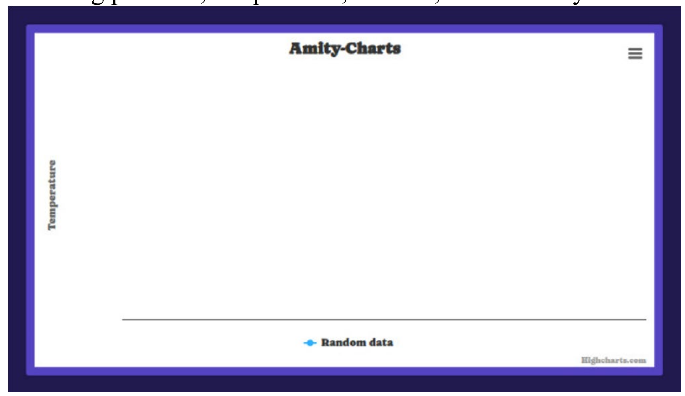

Fig. 13. Data visualization in the HMI. Source: Author.

The measurements obtained are essential for analyzing the environmental conditions encountered by the rover. The collected data is transmitted from the server to the client in JSON format, enabling real-time visualization and analysis. This facilitates the identification of trends and anomalies, enhancing decision-making processes and ensuring the rover operates optimally in its environment.

IV. Results Analysis

The robotic system, equipped with autonomous navigation capabilities, was tested in diverse and challenging terrains, including sand, rocky surfaces, grasslands, and sloped landscapes. These trials were conducted to evaluate the rover's adaptability, resilience, and overall performance in real-world conditions.

The rover successfully completed each terrain trial, transmitting real-time sensor data to a central ground station. During these tests, the system demonstrated an effective data transmission range of approximately 100 meters. However, to extend the communication range, the implementation of network relay stations or routers is recommended. This approach would ensure continuous and reliable data flow, even as the rover navigates more remote or obstructed environments.

In terms of operational performance, the rover's autonomous system maintained continuous functionality, including navigation, data acquisition, and transmission, for an average duration of 20 to 30 minutes. This operational window allows for comprehensive data collection before requiring battery recharging or external intervention.

The final version of the rover was presented at the Rover Innovation Challenge 2024, a prestigious competition held in Colombia under the "*Águilas*" category. This event evaluated the technical capabilities of rovers developed by leading universities across Latin America. Competing against highly innovative designs, the rover secured second place, demonstrating its advanced capabilities and robust performance.

Throughout the competition, the rover underwent trials on three distinct terrains: sand, rock, and grass. Despite the challenging environmental conditions, the system effectively captured and transmitted real-time data to the central ground station, validating its navigation and communication efficiency. The rover's resilient performance contributed to its strong placement in the overall rankings.

Fig. 14. Final version of the rover at the Rover Innovation Challenge 2024. Source: Authors.

The final version, depicted in Fig. 14, showcases the rover actively navigating the competition's terrain assessment course.

V. Future Work

The development of this Rover is ongoing, and during testing, several areas for improvement were identified. The primary concern is the limited communication range, which could prove insufficient for long-duration exploration missions.

To address this limitation, it is proposed that the rover deploy routers during specific missions, significantly increasing its communication range. However, this approach could introduce latency issues, which may negatively impact the quality of data transmission. To mitigate these issues, a router network could be implemented, creating multiple relay points that work collaboratively to prevent bottlenecks in the communication system. This distributed system would enhance the reliability of data exchange and ensure a continuous flow of information back to the control center, even in more challenging terrains.

Furthermore, to enhance the rover's functionality, it is essential to integrate an Artificial Vision system capable of autonomously navigating predefined paths. This can be achieved by incorporating advanced technologies such as artificial intelligence (AI), machine learning (ML) algorithms, and computer vision systems. By utilizing deep learning techniques, the rover could be trained to identify obstacles, terrain variations, and potential hazards, enabling it to make real-time decisions during exploration missions. This would not only improve the rover's efficiency but also increase safety by minimizing the risk of accidents or navigational errors.

Another crucial upgrade is the integration of a solar charging system, which would extend the rover's autonomy. Solar panels could be seamlessly incorporated into the rover's design without interfering with other components, enabling it to harness renewable energy during extended missions. To maximize energy absorption, a mechanical cleaning system could be implemented to periodically remove dust and dirt, preventing blockage of sunlight. Additionally, a smart energy management system could optimize power consumption based on solar availability, prioritizing critical systems during peak sunlight hours and conserving energy when sunlight is limited. Together, these innovations would significantly enhance the rover's operational efficiency and longevity in harsh environments.

Lastly, a speed regulation system needs to be developed to minimize power consumption during movement. It is recommended to use a Pulse-Width Modulation (PWM) controller with MOSFET technology. PWM offers high efficiency and can significantly reduce power consumption while providing smoother and more precise movement during missions. By dynamically adjusting the rover's speed and torque based on real-time data from sensors, the rover could optimize its energy usage and prolong its operational lifespan. This feature is crucial for remote exploration missions, where battery life is often the determining factor between mission success and failure.

Implementing these improvements will not only enhance the rover's capabilities but also pave the way for future exploration and research missions.

VI. Conclusions

The development of rovers is vital for navigation and exploration missions, particularly in environments that are too hazardous for human crews. The use of a rover in such scenarios significantly reduces the risk of injury to personnel and enables exploration in areas that would otherwise be inaccessible. In the space exploration context, where communication delays can be substantial, integrating AI systems ensures real-time decision-making and autonomous operations, thus minimizing the risk of delays during critical moments of the mission.

A basic navigation rover was constructed with the capability of being operated remotely by a teleoperator, over long distances. The system supports control from various devices, including smartphones, computers, or tablets, making it adaptable to different operational environments. Moreover, the rover can monitor and transmit environmental and climatic data back to a central terrain station using the TCP/IP protocol for communication.

The rover's system has been designed to function autonomously for 20-30 minutes, supporting efficient data collection and navigation within this time frame. While the current system fulfills the rover's fundamental exploration functions, further enhancements are necessary to optimize its performance. The integration of an artificial vision system would significantly improve the rover's ability to autonomously navigate more complex environments. Furthermore, the addition of a recharging system would extend the rover's operational duration, making it more suitable for longer and more demanding missions, particularly in remote or inaccessible areas.

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