International Journal of Scientific Engineering and Science
Volume 7, Issue 9, pp. 48-54, 2023. *ISSN (Online): 2456-7361*

Design Concept of Lunar Multi-Rover Robotics System (MRRS)

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Abstract—*The Moon, with its vast potential for scientific discovery and resource utilization, demands advanced robotic systems for comprehensive exploration. This paper introduces the Lunar Multi-Rover Robotics System (MRRS), a preliminary prototype designed to traverse and operate on the Moon's diverse terrains. The MRRS, comprising both a rover for mobility and mounted robotic arm(s) for precision tasks, is envisioned to support a multitude of lunar exploration missions. This paper elucidates the design concepts, differentiating features, and the underlying testbed system used for evaluation and refinement of the MRRS. While the prototype exhibits promising capabilities, it necessitates further development of robust control algorithms. Future research endeavors will focus on calibration, testing, and validation of the hardware to ensure its readiness for lunar operations. This work serves as a foundational step towards the creation of versatile and efficient robotic systems for lunar exploration.*

Keywords— *Coordinated Control; Design of Lunar Rovers; Multi-Rover Robotics.*

I. INTRODUCTION

Space exploration has consistently pushed the boundaries of human knowledge and technological capability. A particular celestial body that has captured our collective imaginations and research interests is the Moon. Often viewed as the gateway to the larger cosmos, the Moon not only holds potential resources but offers insights into the origins of our solar system and Earth itself. To fully explore and harness the potential of lunar environments, advanced robotic systems, especially Lunar Multi Rover Robotics Systems (MRSS), are of paramount importance.

The Moon presents a unique set of challenges and opportunities for exploration. Its proximity to Earth positions it as a prime candidate for astrophysical research, resource extraction, and as a potential launch point for deeper space missions. The importance of lunar exploration is highlighted by the significant investments made by space agencies worldwide. Early endeavors, such as the USSR's Lunokhod program and NASA's Apollo missions, paved the way for modern lunar exploration [1-3]. These missions revealed the Moon's complex geological structure and underscored the need for advanced robotic systems to navigate its diverse terrains.

The diverse and rugged lunar surface necessitates mobile research apparatus. While stationary research equipment can yield valuable data in areas with stable geological properties, the Moon's varied rock complexes demand more mobile solutions. Predictions suggest that comprehensive lunar research could require route lengths of up to 400-500 km [3]. Such vast distances, combined with the need for intricate geological tasks like drilling and sampling, call for robust and versatile rovers. These rovers not only have to cover considerable distances but also need to navigate treacherous terrains, maintain the integrity of samples, and conduct on-site scientific investigations.

The evolution of lunar rovers has been marked by significant technological advancements. Early designs, such as the Lunokhod and Apollo Lunar Roving Vehicles, set the foundation for modern rover designs [4,5]. Over the years, the focus has shifted towards increasing mobility, adaptability, and autonomy. Modern rovers, such as NASA's Curiosity or the European Space Agency's ExoMars rover, are equipped with advanced locomotion systems to traverse challenging terrains, from sandy plains to rocky outcrops [6,7]. However, despite their advanced features, these rovers still face challenges in energy efficiency, obstacle navigation, and adaptability to the Moon's harsh conditions.

In addressing the multifaceted challenges of rover locomotion on lunar surfaces, a range of studies have delved into the dynamics and design principles of vehicular movement on such terrains. Irani and Bauer explored the dynamics of terramechanic models for lightweight vehicles with rigid wheels and grousers operating on sandy soil, establishing a foundation for understanding vehicular interactions with unconsolidated surfaces typically found on extraterrestrial bodies [8].

Building upon this foundation, Kojiro Iizuka, Kubota, and Takashi (2009) conducted a focused study on the running performance of flexible wheels and their varying deflections, contributing valuable insights into the adaptability and functionality of flexible wheels in the context of lunar exploration rovers [9]. This research was complemented by a subsequent study by Kojiro Iizuka, Kunii, Yasuharu, Kubota, and Takashi (2008), which scrutinized the traversal capabilities of wheeled lunar robots on soft terrains, thereby highlighting the significance of wheel design in overcoming the challenges posed by lunar surfaces [10].

Contributing to the practical applications of these findings, Patel, Slade, and Clemmet (2010) delved into the intricacies of the ExoMars rover's locomotion subsystem, providing a detailed examination of its design and operational parameters in relation to terramechanic principles [11]. Further expanding on conceptual designs, Torre (2010) presented the conceptual design of the Team ITALIA Rover, a candidate for the Google Lunar X Prize challenge, thereby showcasing the integration of theoretical principles into tangible lunar rover designs [12].

Underpinning these studies are the seminal works of Wong (2001; 2010), which provide comprehensive insights into the theory of ground vehicles and the interdisciplinary field of terramechanics. Wong’s extensive exploration into terrain behavior, off-road vehicle performance, and design serves as a foundational reference for understanding the complex interactions between vehicles and varied terrains, thereby informing the development and optimization of lunar rovers [13, 14].

Lunar rovers are differentiated by a range of attributes. These include their mode of locomotion, which may involve the use of legs, wheels, or even limbless movement. The suspension system of these robots can vary, with some employing a Rocker-bogie mechanism, while others might use independent or soft systems. Steering mechanisms can be diverse, spanning from Skid and Ackerman types to more explicit forms. The control algorithms determine the extent of human interaction needed, and these robots can either operate fully autonomously or require semi-autonomous control. The physical design of a robot can be either a unibody or a multi-body structure. Depending on their design and functionality, they can be suited for navigating rough terrains or smoother surfaces. Furthermore, their navigation capabilities can be anchored on various technologies, such as star fields, sun detection, GPS, or other sensor-based systems [15].

In recent years, innovative design methodologies have emerged, targeting enhanced rover performance, from the optimization of wheel structures to the incorporation of advanced suspension systems like rocker-bogie mechanisms [16-18]. These designs emphasize stability, energy efficiency, and adaptability to varying terrains. Additionally, the integration of advanced AI and machine learning algorithms has further augmented the autonomous capabilities of these rovers, allowing for more intricate exploration strategies and real-time decision-making.

Furthermore, as lunar exploration aims grow more ambitious, there's an increasing emphasis on multi-rover systems. A collaborative approach, where multiple rovers work in tandem [19-20], can optimize exploration tasks, distribute research objectives, and potentially cover larger areas in shorter timespans. However, designing such a system introduces added complexities in terms of communication, coordination, and energy management.

In this paper, we delve into the intricate design details of Mobile Robot Remote Systems (MRRS) and their applications. Section 2 elaborates on the MRRS Missions and associated Strawman Tasks, providing a comprehensive understanding of their objectives and functionalities. Moving on to Section 3, we present a detailed overview of the Testbed System. This encompasses the Remote Subsystem, which is further divided into the Rover—covering both its mechanical aspects and its electrical & electronics components, including Command, Control, and Communication (C^3)—and the Robotic Arms with similar subdivisions. In parallel, the Local Subsystem is discussed, highlighting the Control Workstation and the High-fidelity Unity Simulator paired with Virtual Reality functionalities. A pivotal part of this system lies in the Communication Interfaces, acting as a bridge between the remote and local systems, ensuring seamless integration and functionality. Lastly, Section 4 wraps up our discourse with a conclusion, summarizing the key points and potential implications of our findings.

II. MRRS MISSIONS AND STRAWMAN TASKS

The Mobile Robot Remote System (MRRS) emerges as a pivotal tool in this context, with a vast spectrum of operational tasks and missions tailored to serve and support the objectives of lunar exploration programs.

A central theme in the MRRS's mission portfolio is its dual capability: the rover, designed for mobility and exploration, and the mounted robotic arm, engineered for precision and dexterity in a variety of tasks. The confluence of these elements allows for a diverse range of operations, including:

- Astronaut Support: The MRRS can be the astronauts' terrestrial companion, ferrying equipment, and supplies, streamlining their exploration activities, and augmenting their operational range on the Moon.
- Infrastructure Building: Beyond mere exploration, the robotic arm is aptly suited for construction. It can assist in setting up structures, deploying lunar habitats, and conducting maintenance on established infrastructure.
- Resource Utilization: The confluence of the rover's mobility and the arm's precision can be harnessed for resource extraction, tapping into lunar assets such as water ice or valuable minerals.
- Lunar Surface Exploration: Beyond serving astronauts, the rover's autonomous capabilities enable it to undertake independent exploratory missions, mapping lunar topography and studying its geology.
- Sample Collection: The Moon's history is etched in its rocks and regolith. The MRRS, with its suite of tools, can collect and analyze these samples, providing insights into lunar evolution and potential resources.
- Mobility and Mapping: The rover's primary mission is exploration, and in its journey, it can produce comprehensive maps of lunar features, aiding future exploration missions.
- Scientific Instrument Deployment: With the robotic arm, the MRRS becomes a mobile science lab, capable of deploying various instruments for a wide range of experiments.
- Teleoperations and Remote Sensing: The MRRS's operability isn't limited to lunar proximity. It can be remotely operated from Earth, ensuring safe and precise operations even in the Moon's most hostile terrains.
- Technology Demonstration: Beyond its primary missions, the MRRS serves as a testbed, a platform to trial and validate next-gen space technologies.
- Collaboration and International Missions: In the spirit of global cooperation, the MRRS can integrate into collaborative missions, working synergistically with assets from international space agencies to further our collective knowledge of the Moon.

Expanding on the MRRS's potential tasks, the system is envisioned to undertake long-range locomotion, engage in deep drilling activities for sampling lunar cores, periodically sample surface soil, and execute a broad spectrum of scientific research, including gravimetry, magnetometry, and spectrometry. Additionally, the MRRS could deploy long-term monitoring stations, and manage the transportation and handling of collected samples to lunar transport spacecrafts at designated rendezvous points.

III. TESTBED SYSTEM OVERVIEW

The testbed system designed for our lunar exploration endeavors serves as an integral foundation for both the development and validation of the rover and robotic arm functionalities. This section provides an overview of the testbed system, covering its primary components, their interconnectivity, and their respective roles in the broader exploration mission.

The development of the MRRS entails a complex architecture encompassing both remote and local subsystems, as well as the interfaces enabling communication between these entities as shown in Figure 1.

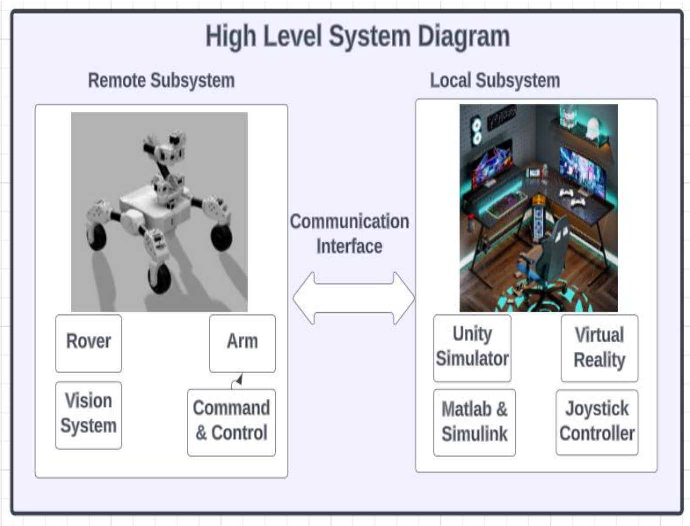

Fig. 1. High Level System Diagram

The physical system design process is illustrated in Figures 2 and 3 as follows:

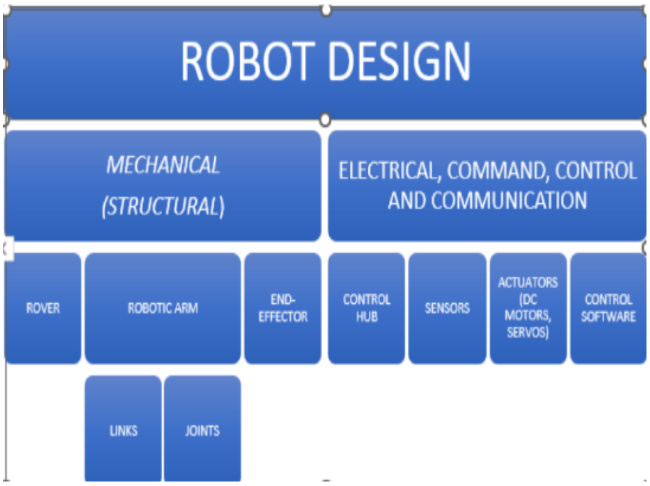

Fig. 2. Electro-Mechanical Design System Diagram

A. Remote Subsystem

The remote subsystem primarily comprises the rover, the robotic arm and the Command, Control and Communication C^3 components which are fundamental to the MRRS's operational capabilities.

Fig. 3. System Design Process

- Rover:

As illustrated in Figures 4a-c, the rover is designed to navigate various lunar terrains, serving as a foundational element for exploration missions. It incorporates several mechanical, electrical, and electronic components, integrated with Command, Control, and Communication (C^3) capability. These sub-system components are essential for efficient energy management, enabling autonomous navigation and facilitating real-time communication with the control station.

The chassis forms the foundational structure of the rover, encompassing both sides and incorporating the swerve modules, along with a central joint that connects the corresponding modules from each side. A swerve design was selected to optimize maneuverability in various directions, allowing each wheel to rotate independently along an axis perpendicular to its primary rotation. This design enables the chassis to execute turns while in motion, achieve strafing movements, and maintain stability amidst terrain irregularities.

The rover utilizes four ST3215^{TM} serial bus servos for steering, known for their precision and programmable torque. These servos contribute to the rover's ability to maneuver across diverse lunar landscapes, aiding in the adaptability and performance of the rover in different exploration scenarios due to its compact size, strength, and compatibility with a CAN bus.

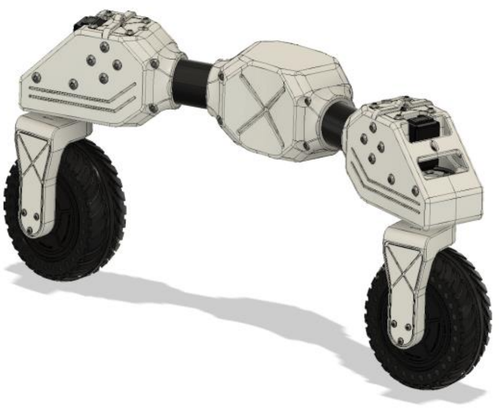

Fig. 4a. Rover CAD Chassis Design

Due to the absence of accessible screw holes on the bus servo, a 3D-printed mold was fabricated to ensure the servo's secure attachment. Additionally, hubs and bearings sourced from GoBilda^{TM} were utilized to assemble a servo block, facilitating smooth and stable rotation along its axis as shown in Figure 4b.

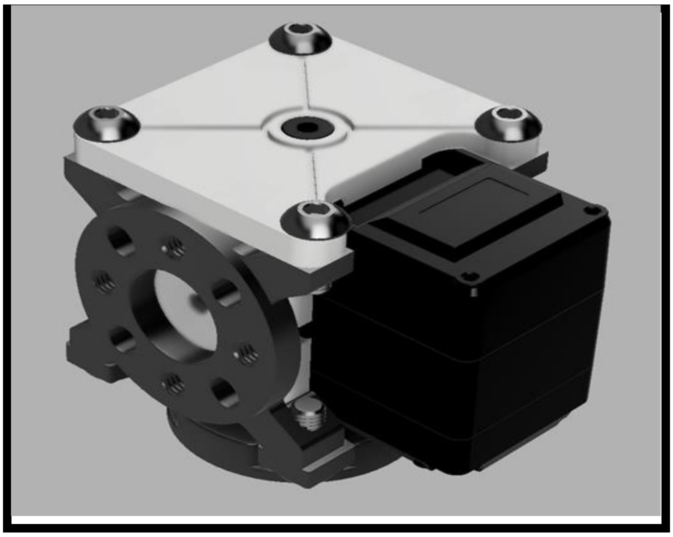

Fig. 4b Custom Made Servo Block

Additionally, the rover is equipped with four DDSM115^{TM} hub electric motors for controlling wheel rotation. These motors are characterized by their direct drive, low-speed, high torque capability, and low noise emission, features that are crucial for maintaining stability and control on uneven terrains while minimizing disturbances.

The integration of ST3215 serial bus servos with DDSM115 hub electric motors provides a balance between steering and rotational control, essential for the rover's adaptability to different lunar environments and ensuring its reliability in conducting exploration missions.

Figure 4c presents a visualization of the chassis integrated with the robotics arm, details of which are elaborated in the subsequent subsection.

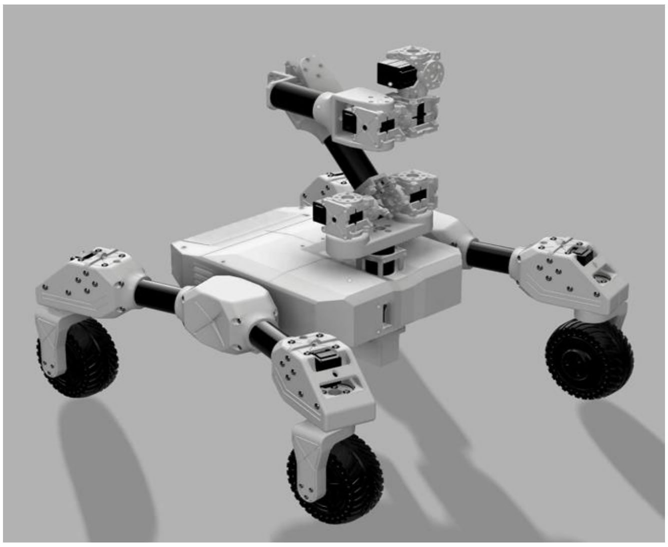

Fig. 4c. Rover with a Mounted Arm

In summary, the design of the rover, detailed in Figures 4a-c, combines advanced components and systems to navigate lunar terrains with precision and adaptability. Additionally, the rover is equipped with a vision system, designed to ascertain the position and orientation of both obstacles and targets, further enhancing its navigational capabilities and ensuring a more comprehensive and informed approach to traversing diverse lunar landscapes.

- Robotics Arm

Mounted on the rover, the Robotic Arm(s) are crucial for tasks that require precision, flexibility, and strength. Similar to the rover, they encompass mechanical components and are backed by advanced electrical & electronic systems, including their own dedicated Command, Control and Communication (C^3) module. These arms are designed to handle a wide range of tasks from sample collection to equipment deployment. The actual arm is shown in Figure 5a while the CAD model of the arms is provided in Figure 5b.

The robotic arm under development is characterized by a structure featuring 6 Degrees of Freedom (DoF).

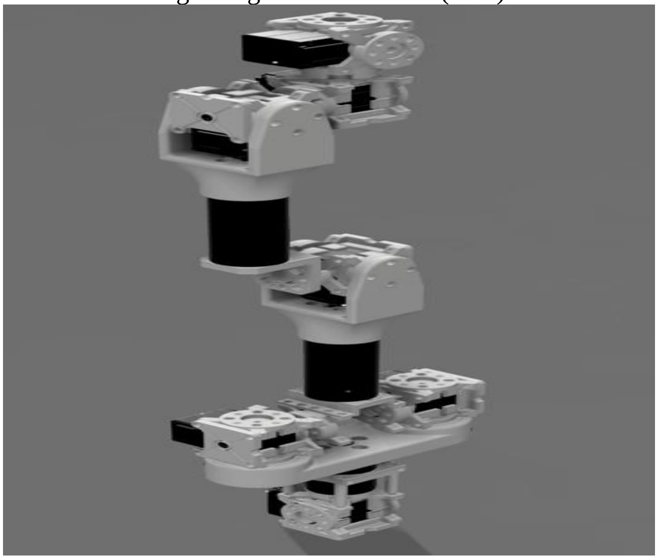

Fig. 5a. Robotics Arm Pictures

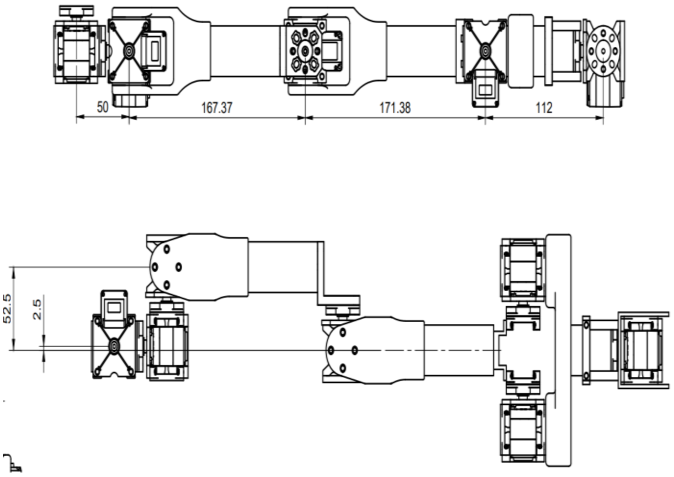

Fig. 5b. Robotics Arm CAD Model

The dimensions of the arm are provided in mm. Specific to this design is the integration of ST3215 serial bus servos. These act as high-precision, torque-programmable actuators, renowned for their steadfast performance and reliability. A distinguishing feature of these servos is the incorporation of 360-degree magnetic encoders, which are paramount for monitoring the rotational position of the servo output. This feedback is indispensable for maintaining precision and control throughout the arm's operational movements. The capability to program torque settings in the ST3215 servos enhances the arm's adaptability, enabling modulation of the exerted force to align with the specific demands of individual tasks.

The integration of 6 degrees of freedom, six revolute joints, high-torque direct-drive servos, and advanced ST3215 serial bus servos with magnetic encoders culminates in a state-of-the-art robotic arm. This arm is proficient in executing a diverse array of intricate tasks, demonstrating a harmonious balance of precision and adaptability, thereby marking a significant advancement in the realm of robotics.

- Command, Control and Communication C^3

The Command, Control, and Communication (C^3) system is a pivotal component of the rover, facilitating intricate operations and interactions. At the heart of this system lies the Jetson Nano processor, which serves as the central processing unit (CPU). This CPU is built on the quad-core ARM Cortex-A57 with MPCore processor architecture, enabling robust computational capabilities and efficient multi-tasking, essential for the diverse functionalities required by the rover. The MRSS Command, Control and Communications C^3 Architecture is illustrated in Figure 5c.

Equipped with a Graphics Processing Unit (GPU) based on NVIDIA Maxwell^{TM} architecture, the system boasts 128 NVIDIA CUDA cores. This advanced GPU architecture ensures high-performance graphics processing, enabling the rover to execute complex graphical tasks and simulations, thereby enhancing its visual and navigational capabilities. The integration of CUDA technology further augments the rover's computational prowess, allowing for parallel computing and enabling the acceleration of scientific simulations.

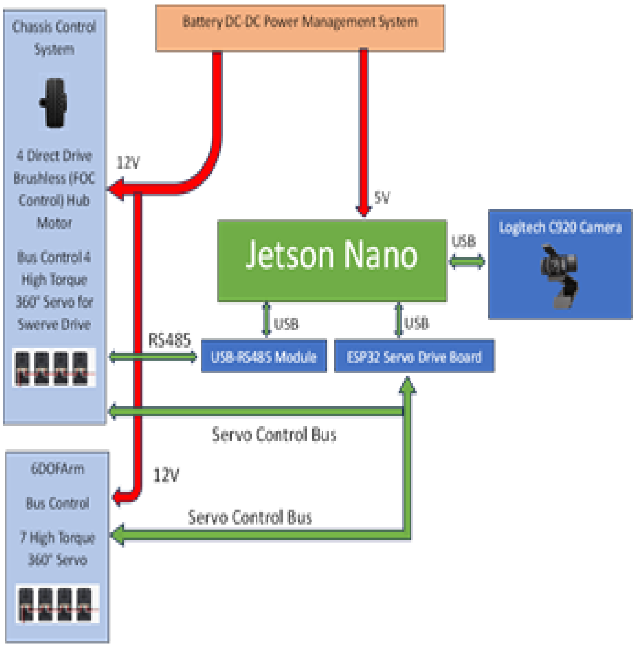

Fig. 5c. MRRS Command, Control and Communication C^3 Architecture

Complementing the CPU and GPU, the system is endowed with 4 GB of 64-bit LPDDR4 memory, operating at a frequency of 1600 MHz. This substantial memory bandwidth, amounting to 25.6 GB/second, is instrumental in handling large datasets and ensuring the smooth execution of memory-intensive applications. The support for CUDA and OpenCV is a notable feature, allowing for the development and implementation of computer vision applications, which are essential for the rover's navigational and observational tasks.

Additionally, the C^3 system incorporates an ESP32 Servo Driver^{TM} expansion board, enhancing the rover's connectivity capabilities. This board is equipped with built-in Wi-Fi and Bluetooth functionalities, enabling wireless communication and data transfer. Such connectivity features are vital for maintaining real-time communication with the control station, ensuring the rover's remote operability, and facilitating the seamless transmission of data and telemetry.

In summary, the Command, Control, and Communication (C^3) system, centered around the Jetson Nano^{TM} processor and complemented by advanced memory and connectivity components, forms the technological backbone of the rover. This system ensures robust computational capabilities, efficient communication, and versatile control, thereby enabling the rover to navigate and operate effectively in diverse lunar environments.

B. *Local Subsystem*

While the Remote Subsystem is directly on the lunar surface, the Local Subsystem remains at the base station, providing an interface for human operators and facilitating the management of the MRRS operations.

- Control Workstation:

This is the primary interface for human operators. Equipped with state-of-the-art software and hardware, the Control Workstation allows operators to monitor, guide, and intervene in the operations of the MRRS as needed. It provides a real-time feed of the rover's operations, the status of the robotic arms, and other crucial system diagnostics.

- High-fidelity Unity Simulator and VR:

This advanced simulation platform is integral to the testbed. Before actual lunar operations, the MRRS's tasks can be simulated in a virtual environment that closely emulates the Moon. This not only aids in training operators but also allows for testing and refining operational protocols. The VR (Virtual Reality) component further enhances realism, providing a 3D immersive experience that aids in understanding the challenges and refining the robot's operations.

C. *Communication Interface*

Linking the Remote and Local Subsystems is a robust Communication and Interface system. This ensures that commands from the Control Workstation reach the MRRS without latency and that data from the MRRS, including visuals, diagnostics, and other critical information, is relayed back in real-time. Given the vast distances and unique challenges of space communication, this system is fortified with redundancies and built to handle potential disruptions and maintain a consistent link with the MRRS.

In summary, the testbed system is a comprehensive setup designed to emulate, test, and manage the Moon Rover Robotics System in a controlled environment. It ensures that when the MRRS is deployed on the lunar surface, it operates at its optimum, ensuring the success of its missions and the safety of any supporting astronauts. A depiction of the system prototype can be found in Figure 6 below.

Fig. 6. A Rover System Prototype

IV. CONCLUSION

The Lunar Multi-Rover Robotics System (MRRS) represents a significant step forward in the realm of space exploration equipment, particularly for lunar missions. Combining the adaptability of a rover with the precision of robotic arms, the MRRS aims to address a variety of challenges presented by the Moon's rugged landscape. Each component, from the rover's mobility mechanisms to the robotic arms' functionalities, has been meticulously designed to cater to specific operational needs on the lunar surface.

The testbed system provides a structured framework for the evaluation, refinement, and validation of the MRRS's capabilities. The high-fidelity simulations, coupled with the interactive control interface, ensure that the system can be assessed in controlled conditions before its eventual deployment in real-world scenarios.

However, it is crucial to underscore the preliminary nature of this prototype. While the MRRS exhibits promising features and functionalities, it remains subject to rigorous testing and validation. The current iteration of the system still requires the development of more robust control algorithms to ensure optimal performance in diverse lunar conditions. Calibration, testing, and validation of the hardware components will be crucial in the subsequent phases of the project.

In the upcoming research activities, the focus will be on refining the system's performance, enhancing its reliability, and ensuring its readiness for lunar operations. The journey ahead involves iterating on the design, incorporating feedback, and continuously improving upon the prototype. In essence, while the MRRS offers a glimpse into the potential of advanced lunar exploration tools, it is just the beginning of a comprehensive research and development process.

REFERENCES

[1] Siddiqi AA. Beyond Earth: a chronicle of deep space exploration, 1958–2016 (PDF), The NASA history series. second ed. Washington, DC: NASA History Program Office; 2018. p. 1. ISBN 9781626830424. LCCN 2017059404. SP2018–4041

[2] G. G. Raykunav, “Fundamental Space Research”, Fismatlit, ISBN: 978-5-9221-1559-9, Moscow, p. 457, 2014.

[3] E.N. Slyuta, A.V. Vasilev and I. Y. Dalyaev, “Robot-Geologist”: scientific tasks and technical configuration,” in *Proceedings of 48th Lunar and Planetary Science Conference*, March 20-24, 2017.

[4] D.E. Wilhelms, “The Geologic history of the moon”, United States Government Printing Office, ISBN: 1495919854, Washington, p. 329.

[5] J. Wilson, “How we’ll get back to the moon”, *GoddardView*, vol. 1, no. 2 2 3, 2005.

[6] P. Putz, “Space robotics in Europe: A survey”, *Robot. Auton. Syst*., 23, 3–16, 1998.

[7] R., Siegwart, P. Lamon, T. Estier, M. Lauria, and R. Piguet, “Innovative design for wheeled locomotion in rough terrain”, *Robot. Auton. Syst.*, vol. 40, pp. 151–162, 2002.

[8] R. Irani, R. Bauer, R. and A. Warkentin, *“*A dynamic terramechanic model for small lightweight vehicles with rigid wheels and grousers operating in sandy soil*” J. Terramech.* vol. 48, p. 307–318, 2011.

[9] I. KojiroIizuka, L. Kubota, M. Takashi, 2009. “Study of flexible wheels for lunar exploration rovers: running performance of flexible wheels and various amount of deflection*”, J. Asian Electric Veh*. 7 (2), 2009.

[10] I. KojiroIizuka, K., Yasuharu, M. Takashi, 2008. “Study on Wheeled forms of lunar robots for traversing soft terrain”. In: 2008 *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Acropolis Convention Center, Nice, France, September 22– 26, 2008.

[11] N. Patel, R. Slade, C. Richard, J. Clemmet, 2010. The Exomars rover locomotion subsystem. J. Terramech. Vol. 47, p. 227–242. 2010.

[12] A. Torre, F. Della, G., Amalia Ercoli, C. Giancarlo, 2010. “AMALIA mission lunar rover—the conceptual design of the team ITALIA Rover”, *Acta Astronaut*. 67 vol. (7–8), p. 961–978, 2010.

[13] J. Y. Wong., 2001. Theory of Ground Vehicles, third ed. *John Wiley & Sons Inc.*

[14] J.Y. Wong, 2010. “Terramechanics & Off-Road Vehicle Engineering, Terrain Behaviour, Off-Road Vehicle Performance and Design”, second ed., Butterworth-Heinemann, UK., 2010.

[15] F. Barlas, “Design of a Mars Rover suspension mechanism”, M.S. thesis, Izmir Institute of Technology, Izmir, pp 11–18, 2004.

[16] D. Carrier, “Soviet rover systems”, in: *Proceedings of the AIAA Space Programs and Technologies Conference*, 24–27, Huntsville, AL, 1992

[17] A. Kemurdjian., V. Gromov, V. Mishkinyuk, V. Kucherenko, and P. Sologub. “Small Marsokhod configuration,” in: *International Conference on Robotics and Automation*, 1, 165–168, IEEE, Nice, France, 1992.

[18] D. Kim, H. Hong, H. Kim, J. Kim, “Optimal design and kinetic analysis of a stair-climbing mobile robot with rocker-bogie mechanism”, *Mechanism and Machine Theory*, Volume 50, 2012, p. 90-108, ISSN 0094-114X, https://doi.org/10.1016/j.mechmachtheory.2011.11.013.

[19] S. Kalaycioglu, A. de Ruiter, “Coordinated Motion and Force Control of Multi-Rover Robotics System with Mecanum Wheels,” in 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), IEEE: 1–9, 2022, doi:10.1109/IEMTRONICS55184.2022.9795804.

[20] S. Kalaycioglu, A. de Ruiter, “Nonlinear Model Predictive Control of Rover Robotics System”, *Advances in Science, Technology and Engineering Systems, Journa*l Vol. 8, No. 1, p. 44-56 (2023).