Hands-On Multidisciplinary Learning for Space Exploration: A Student-Driven Approach Using the JPL Rover

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Abstract

This paper presents a multidisciplinary undergraduate research initiative at the University of Maryland Eastern Shore (UMES), leveraging the NASA JPL Open-Source Rover as a platform for lunar analog exploration. The project engages students pursuing specializations in mechanical, electrical, aerospace, and computer engineering, offering hands-on experience in both hardware and software development. Students gain insights into mechanical design, sensor integration, and the implementation of the Robot Operating System 2 (ROS 2) on a Raspberry Pi 4.

The ultimate goal of the project is to enable autonomous navigation of the rover across lunar analog terrains through GPS and multi-sensor data fusion. Housed in the UMES Robotics and Mechatronics Lab, this student-driven project tackles complex, real-world engineering problems. The project efforts span embedded systems design, seamless hardware–software integration, and hands-on field validation. Students participate in the complete engineering lifecycle including design, implementation, testing, and data analysis while developing essential skills in teamwork, programming, and systems-level thinking.

By bridging the gap between theoretical coursework and applied research, the project enhances undergraduate preparation for careers in robotics, aerospace, and autonomous systems. Utilizing publicly available NASA-JPL resources, this initiative also serves as a scalable model for other institutions seeking to incorporate affordable, open-source platforms into experiential engineering education. Assessment through weekly discussions, milestone evaluations, and observed performance indicates that team members have gained confidence in applying engineering concepts to open-ended, real-world problems, while independently acquiring and integrating new knowledge as required to achieve project goals.

1.0 Introduction

As space exploration becomes increasingly central to modern engineering practice, there is a growing demand for engineers who possess not only strong theoretical foundations but also meaningful hands-on experience. Rapid advances in robotic systems for autonomous navigation and data collection have intensified the need for educational approaches that prepare students for multidisciplinary teamwork and real-world problem solving. However, traditional engineering curricula often emphasize theory at the expense of authentic application, limiting opportunities for students to engage with complex, open-ended engineering challenges. Addressing this gap aligns directly with ABET student outcomes, particularly those related to applying engineering knowledge, functioning effectively on multidisciplinary teams, and solving complex engineering problems in realistic contexts (ABET Outcomes 1, 2, and 5) [1].

NASA's Artemis mission aims to establish a sustained human presence on the Moon as a critical step toward future crewed missions to Mars. Central to Artemis are robotic systems designed to operate autonomously in harsh and inaccessible lunar environments. Land-based robotic rovers play a vital role in navigation, data collection, and environmental sensing due to their mobility, versatility, and capacity for autonomous decision-making. Complex engineering endeavors such as these can be leveraged for educational impact. Engaging students with the challenges aligned with the Artemis mission, learners are exposed to realistic mission concepts and robotics fundamentals that mirror those required in future space exploration initiatives [2].

The "DREAM: Developing Robotic Explorations with Agrobots and Moonbots" funded by NASA-MSTAR (MUREP Space Technology Artemis Research) and Maryland Space Grant supported "AIRSPACES: Autonomous Instrumented Robotic Sensory Platforms to Advance Creativity and Engage Students" initiatives at University of Maryland Eastern Shore support this mission-driven educational approach by creating multidisciplinary learning environments for undergraduate students [3-5]. These programs integrate real-world agricultural and interplanetary research problems, enabling students to learn through experimentation, iteration, and hands-on design. The approach closely aligns with Kolb's experiential learning model, in which knowledge is constructed through a cycle of concrete experience, reflective observation, abstract conceptualization, and active experimentation [6]. Through trial and error, students develop deeper conceptual understanding while simultaneously strengthening professional skills such as communication, teamwork, and ethical responsibility that are key components of ABET Outcomes 3, 4, and 7 [1].

Robotics-based educational endeavors have gained significant traction at both the K–12 and undergraduate levels. Programs such as Project Lead The Way (PLTW) [7], FIRST Robotics [8], and other competitive robotics programs have increased early interest in STEM disciplines by contextualizing classroom concepts within tangible engineering challenges. At the undergraduate level, externally funded experiential learning and research projects extend this engagement by emphasizing multidisciplinary collaboration and autonomous systems development. Together, these efforts enhance student motivation and bridge the gap between theory and practice and can better prepare students to meet ABET outcomes while cultivating the adaptive, experiential learning skills required of future engineers [1,2,6].

Project Planning

Efforts outlined in references [3-5] mentioned earlier largely involved commercially available advanced robotic platforms. An impactful approach for undergraduate project-based learning is to leverage open-source robotic platforms that require students to actively engage in mechanical assembly, wiring, sensor–actuator integration, and software development. One such platform that has become a benchmark for student-centered learning is NASA's Jet Propulsion Laboratory (JPL) Open-Source Rover (OSR) [9]. The JPL OSR is a multidisciplinary robotic system designed to support student-led innovation through mechanical assembly, electrical integration, and software development culminating in autonomous data collection. Its architectural and operational similarities to planetary exploration rovers establish a direct connection to real-world engineering challenges encountered in NASA's Artemis mission closely aligned with ongoing DREAM and AIRSPACES project undertakings at the UMES Robotics and Mechatronics Laboratory (RAM).

A small project team in the RAM Lab adopted the JPL OSR as a foundational platform and conducted preliminary investigations to understand its similarities to the Mars Curiosity rover, particularly the rocker-bogie suspension system and distributed actuation strategy. This phase allowed students to gain insight into the engineering lifecycle, including design trade-offs, system constraints, and iterative improvement.

The project team identified all the mechanical and electrical components from the JPL OSR website and worked with the PI to order the parts. While awaiting mechanical and electrical components to arrive, students constructed a full-scale cardboard prototype of the rover (Figure 1 a). This low-cost physical model enabled early visualization of the rocker-bogie wheel assembly, identification of structural weak points, and facilitated team discussion regarding system layout and integration. In parallel, an online simulation environment was developed using Gazebo on an Ubuntu operating system. The simulation employed a Unified Robot Description Format (URDF) derived from a CAD solid model of the rover and incorporated pre-built control code to apply actuator inputs and outputs (Figure 1b). This virtual environment was used to evaluate rover behavior under low-gravity conditions while operating all six drive motors and four steering servos, providing valuable insights prior to physical testing.

Figure 1(a): Cardboard Model

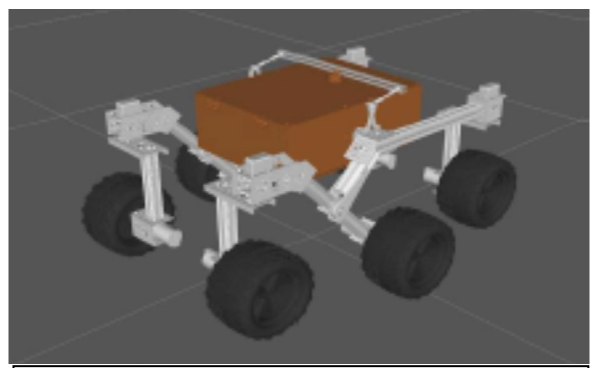

Figure 1(b): Online Simulation

The primary technical objective of the project was to implement a distributed control architecture in which a Raspberry Pi 4 served as the central processing unit for high-level control, while an Arduino microcontroller handled low-level sensor acquisition.

Teamwork and project organization were also critical components of the planning process. Initially, a team was formed under a project lead but disbanded due to limited engagement, resulting in delays and reduced productivity. This challenge highlighted the importance of sustained motivation and effective team dynamics in long-term engineering projects. Subsequently, a smaller but more committed multidisciplinary team was assembled under the same student lead which improved project execution and coordination. This experience enabled the students to understand that successful engineering projects depend not only on technical proficiency but also on motivated student lead and participants.

3.0 Current Status

Building upon the planning and development strategies outlined in the previous section, the UMES team has achieved full mechanical and electrical assembly of the JPL Open-Source Rover (OSR). The mechanical portion of the project focused on the physical construction of the rover, beginning with the development of a cardboard prototype used to model the rocker-bogie wheel assembly discussed earlier. This preliminary model provided an accessible means to visualize the suspension system that would later be implemented in the physical rover. The same rocker-bogie configuration is widely used on planetary exploration rovers, including NASA's Mars Curiosity rover, due to its stability on uneven terrain.

Using the CAD models provided in the JPL OSR repository, prefabricated components were sourced from GoBilda (https://www.gobilda.com/) and used to begin the mechanical assembly. The CAD model served as a reference throughout the build process, ensuring accurate alignment between the digital design and physical construction. During this construction phase, the project team had to be modified due to various reasons. The situation necessitated that the student-lead maintained communication and coordination among team members. From the initial concept stage, when the rover existed only as an idea, to the completion of the mechanical assembly, approximately six months elapsed, with much of this time devoted to project planning and team organization.

The OnShape CAD model, shown in Figure 2(a), was used from the earliest stages of the project through the completion of the mechanical build. This model will continue to serve as the foundation for future enhancements, including the integration of sensor housings for data collection. Figure 2(b) illustrates the completed mechanical assembly positioned on a steep incline to demonstrate the stability and effectiveness of the rocker-bogie suspension system.

The electrical phase of the project began with the procurement of essential components, including printed circuit boards (PCBs), resistors, transistors, and capacitors, which were sourced primarily through Digi-Key(https://www.digikey.com/) and similar suppliers. As components arrived, the team initiated the soldering process to populate the PCBs. Due to limited prior experience among some team members, a teambuilding exercise was conducted to introduce the fundamentals of soldering and electrical assembly. With guidance from provided wiring diagrams, the team successfully completed the electrical system and integrated it into the mechanical structure of the rover.

Development of the rover's software architecture centered on the brain board, which houses a Raspberry Pi 4 (RPi 4) running Raspberry Pi OS. At the system level, the rover interfaces with its sensors and actuators through the Robot Operating System 2 (ROS 2) middleware framework. For

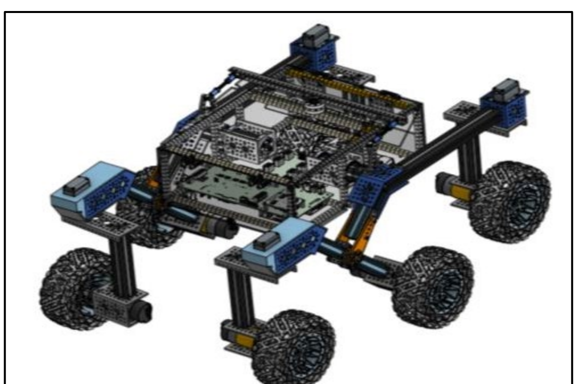

Figure 2(a): OnShape Model

Figure 2(b): Mechanical Assembly

this platform, the Foxy distribution was selected as the most recent stable release available at the time of development [10]. The ROS 2 environment is deployed using a preconfigured software snapshot image within Docker, allowing modifications to be made within a dedicated container that executes during each boot cycle of the rover. This containerized approach is intended to provide a stable and reproducible software environment while minimizing issues related to library incompatibilities and deprecated dependencies. Team members contributing to the project brought varying levels of experience in software development and system architecture, fostering collaborative learning and the exchange of technical expertise throughout the development process. While this architecture has enabled the team to establish a functional software framework for the rover, integration and debugging remain an ongoing aspect of the project, particularly due to evolving ROS 2 distributions and changes in the underlying Linux/Ubuntu environments. As development continues, these efforts are expected to further improve the robustness and reliability of the rover's software environment, provide a stable and repeatable software foundation while avoiding issues related to library incompatibilities or deprecated dependencies. Team members brought varying levels of experience in software development and system architecture, enabling collaborative learning and the sharing of technical expertise throughout the process. The ROS2 framework has posed significant challenges and the project team has been struggling with some of the debugging issues resulting from changes in ROS2 versions and underlying Linux /Ubuntu versions.

4.0 Instrumentation and Data Acquisition

At a system level, rover navigation and actuation are controlled by the brain board, which serves as the central processing and communication hub. The brain board houses a Raspberry Pi 4 (RPi 4) that interfaces with the printed circuit board (PCB) through a ribbon cable, enabling communication with the motor controllers and other connected components. The RPi 4 uses Inter-Integrated Circuit (I^2C) and serial (UART) communication protocols to transmit commands and receive feedback. It communicates with three RoboClaw 2×7A motor controllers, each responsible for driving two 5203 Series Yellow Jacket planetary gear motors. These motor controllers receive velocity commands from the RPi 4 and apply the necessary control signals to regulate motor motion.

External sensors and instrumentation provide the foundation for autonomous data collection by enabling the rover to sense, record, and interpret its environment. At this stage of development, the sensor and data acquisition system are being developed and tested independently from the rover's navigation and motion control system to allow focused validation of sensor performance prior to full system integration. The sensor and data acquisition system are being developed using an Arduino microcontroller. As mentioned, this subsystem was intentionally designed and tested separately from the RPi 4–based navigation architecture while motion control software issues are being resolved.

It is envisioned that the Arduino-based instrumentation system will incorporate a magnetometer, an inertial measurement unit (IMU), and a GPS module. The IMU will measure linear and angular acceleration, providing motion-related data that will later be used to validate navigation and control performance. The GPS module supplies continuous position information, which is critical for autonomous navigation in dynamic environments. Collectively, these sensors comprise the core sensing subsystem that will be interfaced with the RPi 4 to support autonomous navigation and decision-making. Preliminary discussions have also taken place with a NASA scientist at Greenbelt to mount one of the miniaturized sensors developed by them on the rover.

As shown in Figure 3(a), the Arduino microcontroller is currently used to interface with the GPS module to test and verify accurate location data [11]. For experimental purposes, a light sensor was also integrated to evaluate multi-sensor data collection and logging. During testing, the GPS successfully output navigational data, as shown in Figure 3(b), which was recorded and saved to an Excel file from an onboard microSD card. The logged data includes latitude, longitude, date and time, along with additional sensor measurements (not included here). Once the rover's motion software reaches a stable state, this instrumentation subsystem will be interfaced with the RPi 4 to enable fully integrated autonomous operation.

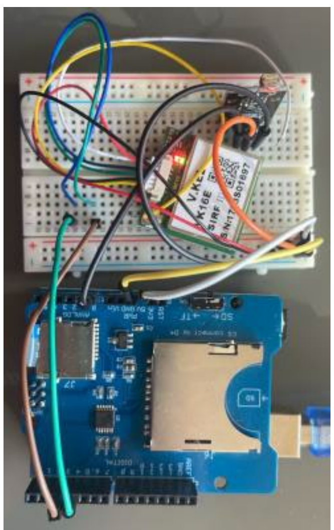

Figure 3(a): Arduino

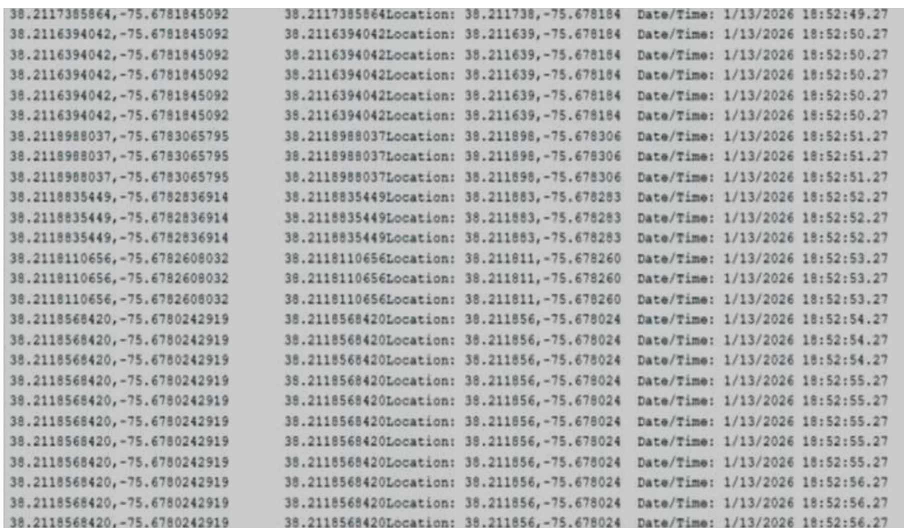

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Figure 3(b): Sample GPS and Time log Data

5.0 Troubleshooting

Troubleshooting and overcoming hurdles and bottlenecks played a significant role in student experiential learning while implementing the JPL Open-Source Rover (OSR) project. The student team has gained valuable technical and professional skills throughout the process. Challenges encountered during development improved the team's understanding of time management, particularly when faced with unpredictable bottlenecks such as missing components, electrical assembly failures, and software integration setbacks. While these issues initially appeared as delays, the team ultimately viewed them as opportunities to develop new and often unfamiliar skillsets. Throughout this process, teamwork remained essential.

Several complications arose during the logistical acquisition of required components due to deviations from the original JPL OSR assembly. Since the team implemented some variations from the baseline design, the quantities of materials specified in the original build list proved insufficient in some instances. This temporarily slowed progress with the mechanical assembly and required the team to redirect efforts toward other aspects of the project, including software development and the initialization of instrumentation systems intended for later integration.

A major technical roadblock was encountered later in the project cycle involving the functionality of the PCB. Although the PCB was receiving the required 15 V supply, several onboard components were not receiving power. Through careful examination of the PCB schematic, the team discovered that an unspecified connection was required for power to be properly distributed across the board. Identifying and resolving this issue significantly improved the team's understanding of PCB design and power distribution at a fundamental level, strengthening their ability to troubleshoot electrical connection issues in future projects.

Software setup presented additional challenges. While the rover software included an instructional guide intended to provide a functional system when followed, changes in software libraries and deprecated dependencies prevented the instructions from producing the expected results. To address this issue, the team transitioned to a version-controlled adaptation of the original software framework. This approach now allows a stable and functional software configuration to be replicated consistently, regardless of future updates or changes to the underlying libraries used to control the rover.

As part of diagnosing the PCB power distribution issue, the team conducted a detailed inspection of the board layers, as shown in Figure 4(a). Particular attention was given to the power distribution layer (Figure 4(b)), which was identified as the source of the problem. Further investigation revealed that a jumper was required to bridge the main battery connection to the board power input. This important detail was not specified in the online documentation provided. Resolving this issue restored proper board functionality and reinforced the importance of thorough documentation review and system-level verification.

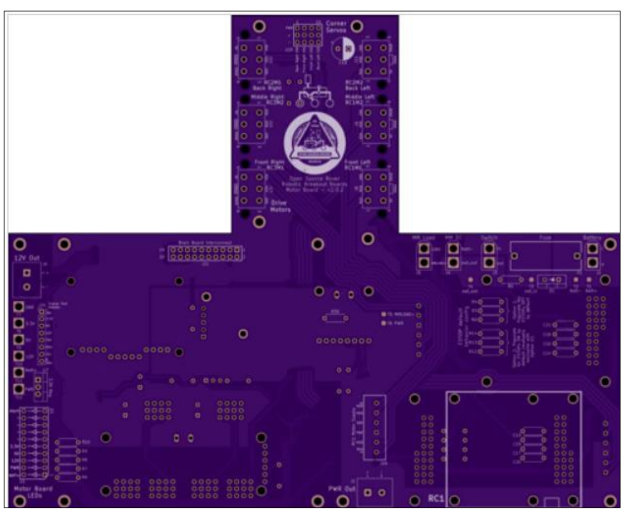

Figure (4a): Motor PCB

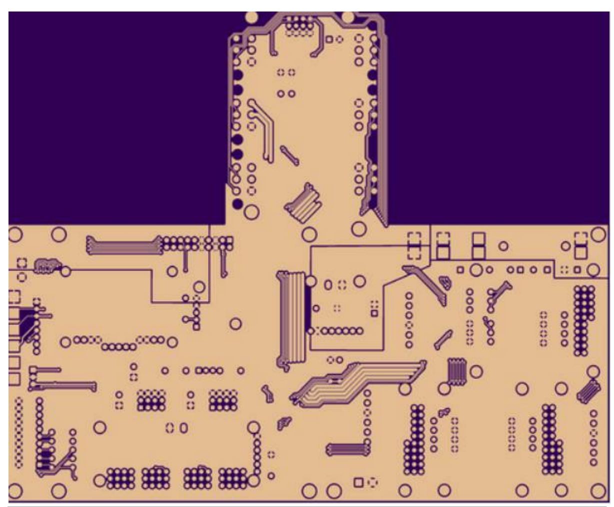

Figure (4b): Power Distribution Layer

6.0 Learning Outcomes

As with any complex engineering project, challenges and unexpected hurdles were an inherent part of the JPL Open-Source Rover (OSR) development process. The hurdles and bottlenecks encountered were closely tied to the diverse experiences and skill levels of individual team members. Rather than hindering progress, these challenges became opportunities for innovation, problem-solving, and growth.

The loosely based iterative framework of Kolb's experiential learning cycle provided the student team with rich learning outcomes, integrating both life skills and academic competencies. This approach encouraged reflection, experimentation, and iterative improvement, while also inculcating a sense of shared responsibility to progress toward the project's goals. Team members were exposed to a structured environment designed to simulate real-world engineering practice. This framework emphasized standard engineering operations, collaborative problem-solving, and accountability.

In alignment with real-world engineering practice, the team's collaborative effort highlighted the importance of flexibility, shared responsibility, and adaptive learning. Students not only applied technical concepts but also honed professional skills, including communication, leadership, and coordinated problem-solving. Through iterative design, testing, and troubleshooting the team cultivated a deep understanding of system-level integration, fostering both academic growth and practical readiness for future engineering challenges.

7.0 Future Plans

Future work will focus on integrating the sensor suite to improve autonomous navigation and enable the collection of relevant environmental data. The Arduino board will be interfaced with the RPi 4 to unify navigation and data acquisition, allowing the rover to operate more effectively in analogous extraterrestrial environment.

Robots navigating agricultural fields to collect agronomic data present comparable challenges, providing a practical framework for testing sensor integration, navigation algorithms, and data collection strategies. These efforts also align with UMES's land-grant mission, offering potential opportunities to connect the JPL OSR project with ongoing research in smart farming and precision agriculture.

The UMES JPL OSR student team looks forward to exploring these future possibilities while continuing to learn, collaborate, and develop new technical and professional skills.

8.0 Acknowledgements

The authors acknowledge the support provided by the NASA MSTAR grant titled "DREAM: Developing Robotic Explorations with AgroBots and MoonBots" as well as the "AIRSPACES: Autonomous Instrumented Robotic Sensory Platforms to Advance Creativity and Engage Students" project supported by Maryland Space Grant Consortium

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