System Acceptance Review
University Rover Challenge 2024

West Virginia University
Team Mountaineers

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Introduction:

Team Mountaineers from West Virginia University is composed of 70 undergraduate students from a variety of engineering disciplines. The team is divided into six technical subteams, each responsible for a different component of the rover's design. Additionally, there are two nontechnical subteams, Management and Green. Management is responsible for planning, purchasing, outreach, and documentation. The Green subteam focuses on training new members through introductory projects.

Using a systems engineering design process, the team designed and built a new rover from the ground up for the 2024 competition. The rover, Heimdall, is shown in Figure 1. The team also selected a commercial drone, Valkyrie, to assist the rover during the Delivery mission.

Core Rover Systems:

Following Team Mountaineers' success in the 2023 URC competition, the team has adopted a design approach that includes a focus on quality improvements and exploration of innovative and high-risk designs.

<u>Drivetrain</u>

Heimdall's drivetrain system utilizes a split-body, semi-monocoque style aluminum sheet metal chassis comprised of two separate compartments linked by a bearing mechanism. This allows each half to rotate independently to maximize contact between the drive wheels and the ground. The front half of the chassis is interchangeable, with two possible configurations: the first is used to complete the Delivery, Equipment Servicing (ES), and Autonomous Navigation (AN) missions, while the second is used for the Science mission. This modular design enables Heimdall to complete all four missions and allows the rover to be disassembled for shipping. Additionally, a central hinge allows the rover to maintain a large, stable drive base during operation while being able to fold to fit in the size requirement for weigh-in.

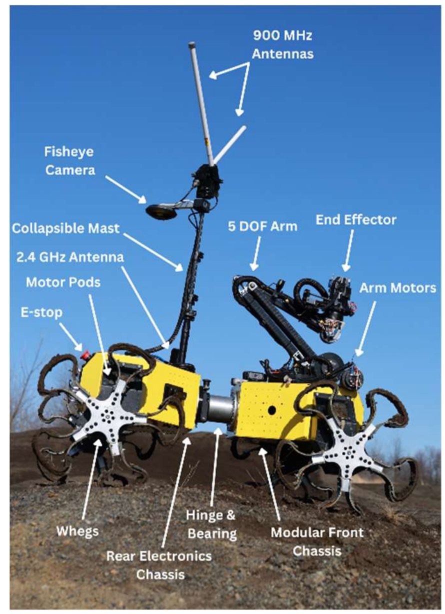

Figure 1. Annotated image of Heimdall

Motor pods containing the brushless drive motors and fans extend below the main chassis, increasing ground clearance. Rather than using traditional wheels, Heimdall uses wheel-legs or whegs. The whegs consist of an aluminum hub and five spokes, coupled with custom-fabricated carbon-Kevlar composite feet. These provide an improved ability to traverse both rocky terrain and loose soil. The foot shape is designed to minimize the vertical displacement of the rover body when driving on flat ground, allowing it to maintain stable movement. The composite construction of the feet and the rubber treads absorb ground impact, enhancing the rover's longevity. For missions with less challenging terrain, the team also has the option of using off-the-shelf airless tires for improved precision and reduced vibrations.

<u>Manipulation</u>

A five degree-of-freedom manipulator was designed for both the Delivery and ES missions. The manipulator is mounted on a linear rail which provides 52 cm of horizontal travel. Two brushless motors at the base of the arm control the shoulder and elbow joints while keeping the arm's center of mass near the rover body and reducing the torque required to lift objects. A two degree-of-freedom wrist, also powered by brushless motors, provides smooth pitch and roll control with torques of 18 Nm and 4.5 Nm respectively. The end effector is designed with two TPU-plated metal claws, actuated with a DC motor through a lead screw, providing a grip force of 54 N. The arm operates within a 74 cm radius cylindrical workspace, suitable for both the Delivery and ES missions, and can reach 13 cm below the wheel plane for retrieving lower-positioned items. The manipulator can lift and maneuver objects weighing up to 10 kg at full extension.

Electronics

An overview of Heimdall's electronics system is shown in Figure 2. The rover's primary electronics are housed in the rear chassis. The system is powered by three hot-swappable 40 V, 5 Ah batteries. Power to all electrical components passes through a power distribution board, which regulates voltage, monitors battery usage, and houses the emergency stop circuit (Figure 3). Onboard computation is managed by a LattePanda Sigma computer which communicates to major electrical components through CAN bus, ethernet, and USB. A custom printed circuit board manages motors, actuators, and sensor data for the manipulator and science payloads. An LED array indicates the rover's operational status and an LCD screen displays the status of internal components such as battery charge. The rover sensor suite includes two Pixhawk flight controllers with GPS modules, 12 webcams, a panoramic camera, a 3D LiDAR for mapping and terrain classification, and incremental encoders on all brushless motors.

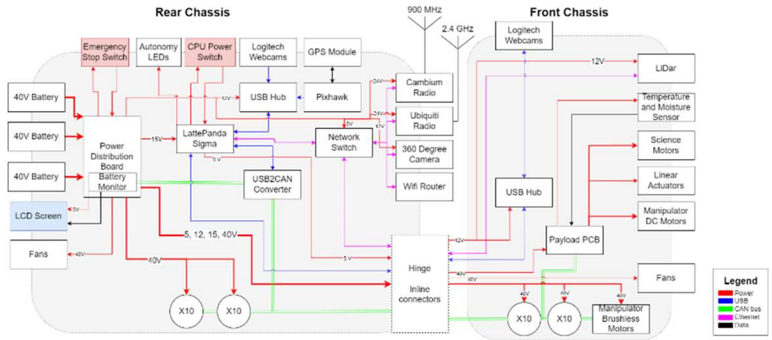

Figure 2. Electronics block diagram

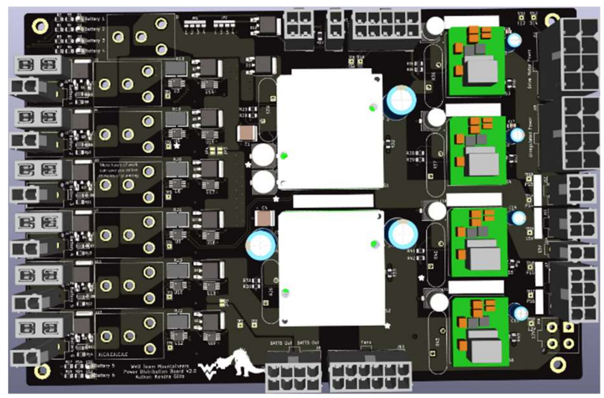

Figure 3. 3D rendering of power distribution board

The robot employs dual-band communication, utilizing both 2.4 GHz and 900 MHz systems to connect with the base station. This setup enhances redundancy and supports high data rates and non-line-of-sight applications. A 90-degree sector antenna at the base station serves the 2.4 GHz system, and a 120-degree sector antenna supports the 900 MHz system, each paired with an omnidirectional rover antenna setup. The 2.4 GHz system has been tested at ranges up to 250 m, while the 900 MHz system maintains connection at ranges up to 1 km.

Programming

Heimdall's software architecture is illustrated in Figure 4. The system is built around ROS 2 to leverage its strengths in inter-process communication and software modularity. Robot control and data collection is accomplished with a combination of open-source ROS 2 projects and custom ROS 2 packages. Packages related to robot manipulation and movement are designed to decouple high-level software from the underlying hardware drivers. Environmental data (*i.e.* moisture sensors, spectrometry, LiDAR, etc.) is logged for use in post-experimental analysis and identification of failure modes.

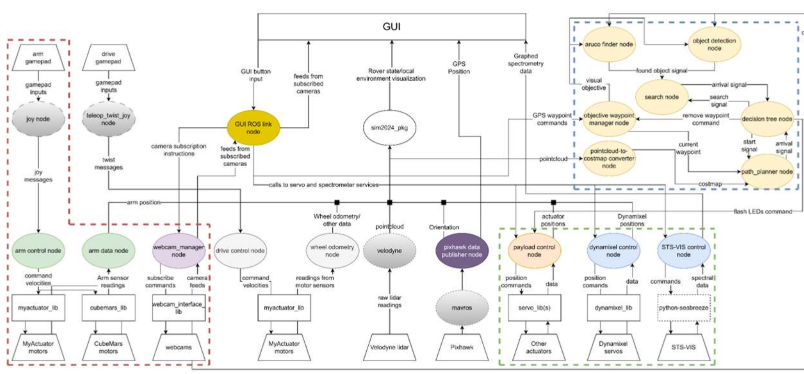

Figure 4. Heimdall software block diagram

A custom graphical user interface (GUI) allows rover operators to interact with software subsystems during each mission. The GUI displays up to six simultaneous camera feeds to provide rover operators with situational awareness. Operators may also save custom camera feed layouts, which can be reloaded for future missions. During the AN mission, a global map allows operators to input the GNSS coordinates of competition objectives. The rover's position and orientation are displayed on this satellite image map. The GUI also features a control tab for the Science mission that allows operators to control the science payload's actuators and to request data from its onboard spectrometer and soil moisture probes.

Approach to Competition Missions:

Delivery

To complete the Delivery mission, the rover must be capable of traversing diverse terrain, sustaining communication over long distances, effectively surveying for specified items, and manipulating and delivering all required objects. Heimdall's implementation of whegs and split body suspension system offers significant advantages in navigating challenging terrain. The dual-frequency radio systems allow the streaming of high-quality videos at shorter distances to support object search. This also ensures consistent connectivity over longer distances even in non-line-of-sight conditions, enabling Heimdall to navigate hills and valleys.

The control station's GUI provides operators with a map of the area along with displays including the search radius and a plot showing the path the rover has taken. Cameras placed around the chassis, including a panoramic camera and a ground facing camera, provide operators with information for object search.

The parallel clamping end effector allows the rover to handle and retain objects while traversing rough terrain. It enables the retrieval of objects up to 15 cm in width and up to 10 kg in mass. Equipped with compliant TPU material and a curved design, the clamps minimize slippage for secure grasping of irregular objects.

Heimdall is assisted by Valkyrie, a DJI Mavic 2 Pro drone. Valkyrie takes off from the control station and is capable of landing on the field to conserve battery life. The drone assists Heimdall by searching for objects, reading signs, and identifying rocks of geological interest by scouting ahead. As Valkyrie searches an area, the drone pilot communicates points of interest to the rover drivers.

Equipment Servicing

The ES mission requires the rover to perform precise maintenance operations as well as lift and transport objects. To complete this mission, Heimdall uses the same manipulator as the Delivery mission with additional end effector tools. A motorized screwdriver is used to lock the sliding drawer, while a solenoid is utilized to perform button and keyboard presses. The lead screw driven end effector and horizontal rail provide precise motion allowing Heimdall to quickly target and execute competition tasks.

Inverse kinematics and joint control are used interchangeably at driver discretion. Inverse kinematic control coupled with the horizontal rail allows the arm to precisely maintain a working plane while completing tasks. Joint control lets the drivers manually move each joint of the arm independently, allowing for more precise short travel motion control. Multiple cameras positioned at different locations on the chassis, arm, and end effector provide a full view of the lander workspace and visual feedback for controlling the arm.

Autonomous Navigation

The rover must be capable of autonomously traveling over varied terrain and implement search algorithms to succeed in the AN mission. It must also identify three ArUco markers as well as two objects: a water bottle and an orange rubber mallet. The rover's autonomous navigation system is driven by a behavior tree which takes in the GNSS goal points as input. This behavior tree handles transitions between path planning, searching, and arrival.

After navigating to the given GNSS coordinates of an object or ArUco post, the rover executes a search algorithm to locate the specified item. This search algorithm is based on a Gaussian probabilistic model of the item's placement within the environment. Desired search positions are provided by sampling this distribution. As the rover navigates between these positions, the probabilistic map is updated, redistributing probabilities from explored areas. This process is then repeated until the object is located.

The computer vision model was trained on a database consisting of 1,883 labeled images of ArUco markers, orange mallets, and water bottles at varying distances and angles. The dataset was then passed to a YOLOv8 training algorithm using the pre-trained weights from the Common Objects in Context dataset with progressive resizing. Distance and angle from the object to the rover is estimated using perspective transformation on bounding boxes from the model to aid in localization and path planning.

Testing and Training:

Team Mountaineers used a phased approach to prepare for the 2024 URC. In September, new team members fabricated, assembled, and tested a reproduction of the team's 2023 rover, Wanderer. Veteran team members trained new members on Wanderer's technical design details and operation, as well as field-specific skills, including SolidWorks CAD software, KiCad electronic CAD design software, and the ROS 2 software framework. New team members, divided into two teams, competed in a "mock URC" which simulated all four URC missions.

After the mock competition, each subteam transitioned into a research and design phase. During this phase, new concepts were generated and compared against Wanderer's existing systems. Trade studies were conducted to choose design concepts, in parallel with prototyping efforts.

Component level testing was conducted during the prototyping phase for each major design. This included the development of motor control libraries for all brushless motors to test CAN bus capabilities before integration into the drivetrain. Finite element analysis and prototypes were completed for all mechanical designs. Early in the design cycle, the communications system was tested to identify weaknesses. A ROS 2 Ignition Fortress simulation was implemented to test AN functions, while LTspice was used to simulate circuits for printed circuit board designs.

Following subsystem testing and in the months leading up to the SAR deadline, the team conducted significant system integration and testing efforts. Individual sub-systems were tested and verified before being integrated into full system tests. An on-campus rock garden was used as an initial training ground before moving to off-campus terrain testing. Critical subsystems were stress tested in conditions beyond the competition requirements, sometimes leading to component failures. This includes the testing of whegs, a split-body suspension system, and the manipulator. This process helped to advance the NASA Technology Readiness Level of the rover from TRL-1 to TRL-6 within a 7-month duration. Heimdall was successfully tested in an off-site environment with terrain like the Mars Desert Research Station to fulfill the TRL-6 readiness requirements.

The team has also participated in numerous outreach events to improve the visibility and impact of the project. These outreach events include a visit to the West Virginia State Capitol, as well as demonstrating rover capabilities for several K-12 visits. The team allows visitors to teleoperate the rover, which also serves to test its robustness. Additionally, Team Mountaineers open-sourced last year's rover design and software, with the hope of lowering the barrier of entry for new URC teams.

Future tests will be conducted to train operators and to identify system flaws and unexpected scenarios. Operators for each teleoperated mission will be required to log at least 100 hours of practice, while the rover will complete 100 hours of autonomy testing. These experiments will be performed at field sites including an on-campus rock garden and an off-campus site with aggressive inclines and isolated rock fields. Detailed operation procedures will be created for each mission to aid operators and streamline the information process during missions to ensure all requirements and goals are met.

Gantt Chart and Budget:

Table 1 summarizes the project budget as well as the rover expenses, additional expenses, and travel allocations. As can be seen, the team has sufficient funds to travel to URC if selected. The Gantt Chart in Figure 5 shows the planned and completed tasks to date.

Table 1. Budget Table

INCOME			
Actual Income to Date			
	WVU MAE Department		$20,000
	WVU CSEE Department		$20,000
Total Income Recieved to Date			**$40,000**
Anticipated Income			
	NASA Space Grant Consortium		$5,000
Total Additional Income Anticipated			**$5,000**
		TOTAL INCOME	**$45,000**
EXPENSES TO DATE			
1 Electronics			
	1.1 LattePanda Computer		$648.00
	1.2 Power Distribution Board		$541.97
	1.3 Payload PCB		$193.28
	1.4 Pixhawk		$513.98
	1.5 Webcams		$479.99
	1.6 Wiring and Connectors		$539.72
	1.7 Antennas		$910.97
	1.8 Radios		$1,346.56
	1.9 Miscellaneous		$603.92
		Electronics	$5,778.39
2 Drivetrain			
	2.1 Protocase Order		$1,458.82
	2.2 Motors		$2,516.00
	2.3 Hardware		$585.38
	2.4 Carbon Fiber and Kevlar		$780.00
	2.5 PLA Filament		$49.99
	2.6 Airless Tires		$115.62
		Drivetrain	$5,505.81
3 Manipulation			
	3.1 Brushless Motors		$2,199.00
	3.2 DC Motors/Solenoid		$35.88
	3.3 Hardware		$580.00
	3.4 Linkages		$85.00
	3.5 Linear Rail		$220.20
		Manipulation	$3,120.08
4 Science			
	4.1 Sensors		$79.00
	4.2 Linear Actuators		$360.00
	4.3 Linear Servo		$300.00
	4.4 Ocean Optics Spectrometer		$1,650.00
	4.5 Other		$483.22
		Science	$2,872.22
5 Other			
	5.1 3D Printing Filament		$374.40
	5.2 Machining Costs		$1,684.67
	5.3 Base Station Computers		$1,600.00
	5.4 Miscellaneous		$200.00
		Other	$3,859.07
	TO DATE		**$21,135.57**
6 Additional Costs			
	6.1 PPE		$199.88
	6.2 Carbon Fiber and Kevlar		$345.10
	6.3 Drone		$499.00
	6.4 Spare Motors		$1,500.00
	6.5 Miscellaneous		$1,026.19
		Additional	$3,570.17
	DATE		$24,705.74
ANTICIPATED EXPENSES			
	Travel to Utah		$12,000.00
	Rover Shipping		$3,000.00
	Backup Parts		$5,000.00
	EXPENSES		**$20,000.00**
FORECASTED BUDGET SURPLUS			**$294**

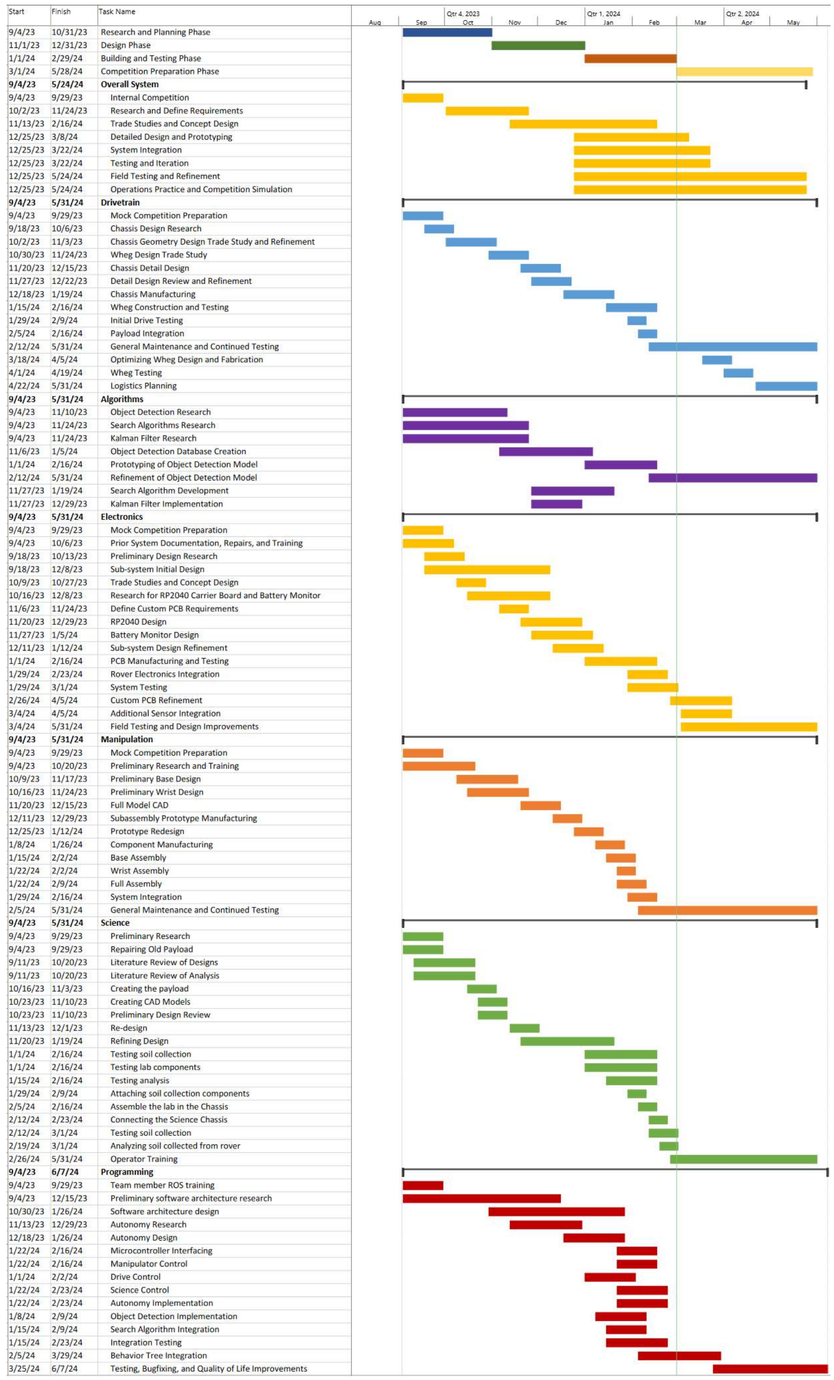

Figure 5. Gantt Chart

Science Plan:

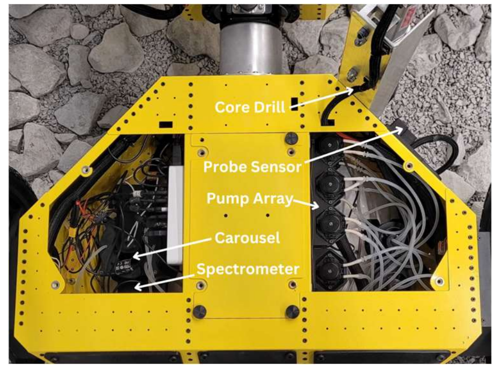

Figure 6. Annotated image of the science chassis

For this year's science plan, the team will collect soil samples from sites with geological characteristics suitable for supporting life. *The Regolith Geology of the MDRS Area* [1] and *MDRS Expedition Guide* [2] provided information about the lithology near the Mars Desert Research Station. Operators will examine cracking and non-cracking regolith in the area to determine signs of previous water and potential life. These observations will be used to justify the selection of sample sites and to determine past depositional environments. At each chosen site, the operator will use the rover's wide-angle cameras to create a stratigraphic profile with a panoramic photo at each site. Close-up images taken by on-board cameras will include cardinal directions, elevation, and scale indicators of sedimentary structures. Spectrometer and Biuret tests will be conducted at each site and the most favorable for life will be selected for the subsurface sample.

The first test to be performed on the rover will utilize the onboard spectrometer. A soil sample will be collected and deposited into a cuvette in the carousel. Pumps will dispense 70% isopropyl alcohol into the cuvette in preparation for spectral analysis. Biological pigments such as chlorophylls, which are necessary for photosynthesis [3], and carotenoids that are produced naturally by different organisms, are indicative of the presence of life and produce distinct spectra easily detected by a spectrometer [4]. Failure to detect chlorophyll rules out the presence of metabolic phototrophs, while failure to detect carotenoids eliminates a range of micro and macro living organisms.

Proteins are often found in soil to assist in catalyzing nitrogen fixation and other biochemical processes [5]. The team will be testing for proteins using the Biuret test [6]. The reagent utilized in the second test is composed of hydrated copper(II) sulfate, sodium hydroxide, and sodium-potassium tartrate. This reagent has a natural blue color when diluted in water. When in the presence of peptide bonds, which link amino acids to form proteins, the copper ions in Biuret reagent will form stable complexes between the bonds, creating a purple color [7]. From testing, the Biuret test provides readable results in approximately five seconds in protein containing soil samples. The result of the Biuret test will be visually inspected with an onboard camera. Spectrometry will serve as a secondary assessment to validate the color change, reaffirming whether there is substantial protein presence.

The science payload uses three scoops, seven peristaltic pumps, and three drums to collect soil samples from the surface as shown in Figure 6. Each scoop employs linear actuators to adjust height plus digital servos to rotate the drums and collect samples. Pumps connected to a reservoir will transport isopropyl alcohol to the drum, and the resulting solution will be pumped to a cuvette in a twelve-slot rotating carousel. Four samples can be taken from three sites. A halogen bulb provides light to each sample, and a spectrometer is used for analysis. Another pump adds the Biuret reagent to a sample, and a camera is used to view the ensuing reaction. The chamber of the chassis where the carousel sits will be lined with an alkali resistant plastic layer to contain a potential Biuret reagent spillage.

The selection of the subsurface soil collection site will be based on comparing life detection tests conducted on the rover with observations of geological features that suggest high moisture content, such as Vertisols and soil cracking displaying mud cracks on the surface. The subsurface conditions are investigated using a capacitive soil moisture probe. By employing a core drill, a subsurface sample is extracted. The drill is driven linearly via a 12 in. long actuator, with rotation driven by a high torque motor. Soil is drilled to a depth of 15 cm. A flexible 3D-printed resin core catcher is used to seal a 5 gram core sample within a tube inside the drill that will be detached, then presented to the judges for evaluation.

[1] J. Clarke, "The Regolith Geology of the MDRS Study Area", January 2003. [2] H. I. Hargitai, Ed., "MDRS Expedition Guide," Cosmic Materials Space Research Group, Eötvös Loránd University; Budapest-MDRS, 2008 [3] G. Bergtrom, "Basic Cell and Molecular Biology 3e: What We Know & How We Found Out". 2021. [4] M. Neveu, L. E. Hays, et al, The Ladder of Life Detection. 2018. [5] Y. Li, D. A. Collins, and K. Grintzalis, "A simple biochemical method for the detection of proteins as biomarkers of life on martian soil simulants and the impact of UV radiation," *Life*, vol. 13, no. 5, p. 1150, May 2023. doi:10.3390/life13051150 [6] A. Olszewska, J. Napora, K. Kamieński, K. Dzierżek, M. Rećko and A. Kawecki, "Influence of Soil Parameters on Protein Presence for a Mars Rover Analogue's On-Board Laboratory Setup," 2020 21th International Carpathian Control Conference (ICCC), High Tatras, Slovakia, 2020, pp. 1-6, doi: 10.1109/ICCC49264.2020.9257250. [7] "Biuret test," BiologyOnline, https://www.biologyonline.com/dictionary/biuret-test (accessed Feb. 28, 2024).