System Acceptance Review
University Rover Challenge 2023

West Virginia University
Team Mountaineers

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Introduction:

Team Mountaineers from West Virginia University is composed of fifty undergraduate students encompassing a range of engineering disciplines. The team has three graduate students and a faculty advisor to support team operations. The students are divided into six technical subteams, each tasked with different aspects of the rover design. Additionally, a management subteam coordinates subteam collaboration, outreach, and documentation.

The team's rover, Wanderer, is shown in Figure 1; a photo of the team's drone, Cosmos, used for the autonomous navigation mission is shown in Figure 2.

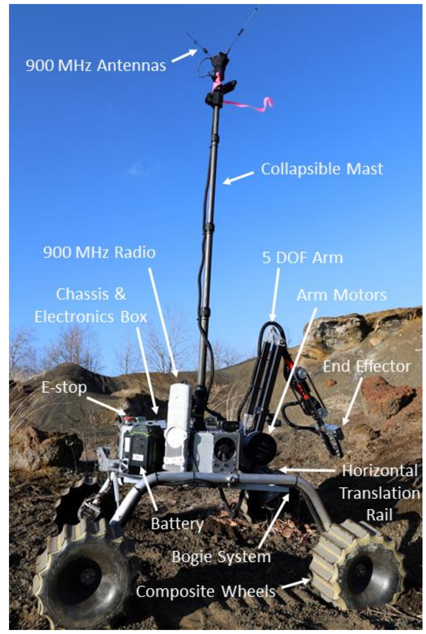

Figure 1: Annotated image of Wanderer

Figure 2: Annotated image of Cosmos

Core Robot Systems:

Following Team Mountaineers' debut participation in the final competition at the Mars Desert Research Station in 2022, the team has adopted design philosophies that include a focus on overall quality, complexity reduction, and exploration of new designs.

Wanderer's drivetrain features a semi-monocoque style sheet metal chassis supported by a differential-bogie suspension system. Custom composite wheels mounted to in-hub brushless motors allow Wanderer to traverse both soft soil and rocky terrain. The design of both the chassis and composite wheels exemplify the team's exploration of new fabrication techniques. Additionally, both the sheet-metal chassis and composite wheels provide a major reduction in weight and total part count when compared to last year's chassis and 3D-printed wheel designs.

A five-degree-of-freedom manipulator was designed to fulfill the requirements for both the Extreme Delivery and Equipment Servicing missions. The manipulator's main joints are actuated by two brushless motors located at its base. This placement of the main manipulation motors reduces the mass of the main links while decreasing the torque required to move and lift objects. The arm design also includes a linear rail with 500 mm of horizontal travel. A belt-driven differential mounted to the end of the manipulator provides a pitching force of 68 N and a rolling torque of 14 Nm in order to manipulate grasped objects. In this configuration, the manipulator can lift up to 8 kg at full extension. Additionally, the clamping end effector generates a grip force of 54 N. With this arm equipped, Wanderer weighs 33 kg, resulting in a 20 kg reduction from its predecessor.

An overview of Wanderer's electronics system is shown in Figure 3. The rover is powered by two 40 V and two 12 V commercial off-the-shelf batteries. Power to all electronic components on Wanderer passes through a power distribution board, which regulates battery power to necessary voltage levels. A custom battery monitoring printed circuit board (PCB) contains the emergency stop and monitors the voltage and current draw of all batteries (Figure 4). Battery status is displayed on the rover via an

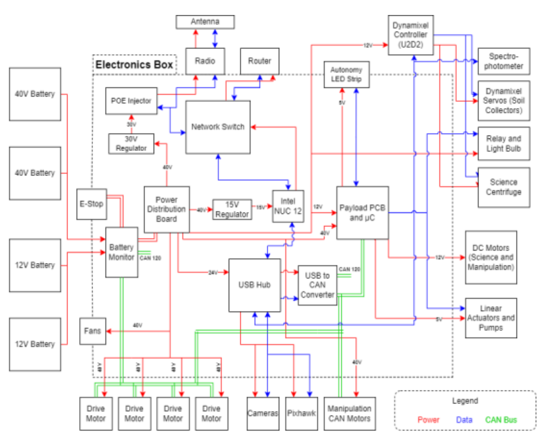

Figure 3: Electronics System Diagram

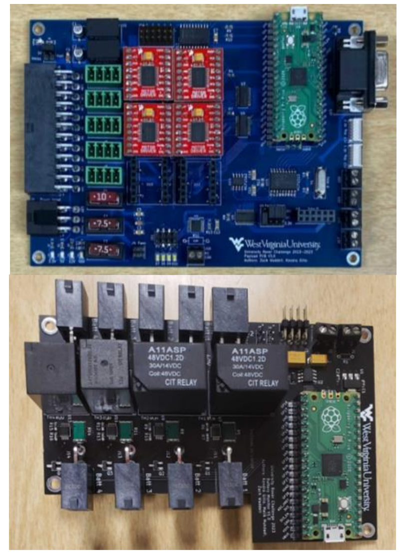

Figure 1: Payload PCB (Top) and Battery Monitoring PCB (Bottom)

LCD screen and is visible to remote operators on the graphical user interface (GUI).

The science package and manipulator both interface through a newly-designed payload PCB (Figure 4). This board manages the rover's LED strip as well as the DC motors, stepper motors, linear actuators, and sensors on each payload. The PCB uses a Raspberry Pi Pico microcontroller and communicates with the rest of the electronics system via a controller area network (CAN) bus. The CAN bus facilitates communication between the central computer, the payload PCB, the battery monitor, the primary manipulator motors, and the four drive motors.

Communication between Wanderer and the remote operators is provided by a pair of Cambium PTP 450 radios. This 900 MHz point-to-point communication solution allows teleoperated control with a tested range of up to 850 m and non-line-of-sight operation tested up to 300 m. Wanderer features six cameras in the base configuration to allow for front, left, right, back, under, and mast points of view. These camera views can be enabled or disabled, and the resolutions and framerates can be changed dynamically using the GUI in order to conserve bandwidth or provide drivers with suitable resolutions for different tasks. The 900 MHz radio transmits with a max power of 25 dBm and can maintain data rates of 40 Mbps. Wanderer has two omnidirectional 5 dBi whip antennas mounted on a five-segment telescoping mast to raise the antennas 2 meters above ground level while also being able to stow within the 1.2-meter bounding box. The base station antenna is a 12 dBi sector antenna with a 120-degree beam width that is automatically steerable in order to maintain communication over the entire competition field from the operation area.

The quadrotor developed for the Autonomous Navigation mission uses four 960 kV brushless motors powered by an 8000 mAh 4-cell lithium polymer battery. A Pixhawk 6C flight controller running PX4 is used for low-level sensor fusion and control, and a Raspberry Pi 4 model B is used as an onboard companion computer. The companion computer handles high-level control functions such as waypoint planning, state transition logic, and video processing. The drone's communication system uses a 900 MHz radio system for telemetry transmissions and a 2.4 GHz system for video streaming and control commands.

Extreme Delivery (ED):

The ED mission requires a rover system that is able to withstand and navigate a variety of terrain, maintain communication, and manipulate different objects. Wanderer's differential-bogie system maintains rover stability with four points of contact on uneven terrain. Traversing this terrain is made easier by the composite wheels which allow for custom-tuned aggressive treads. The radio system provides a stable connection without line-of-sight requirements, allowing Wanderer to traverse hills and valleys with reliable communication. The manipulator's horizontal cylindrical workspace includes 0.5 m^2 of working floor space. The large workspace allows the arm to access hard-to-reach locations where precise rover positioning is difficult. The arm is also capable of reaching 30 cm below the wheel plane to grasp objects which lie in crevasses between rocks.

The parallel clamping end effector enables Wanderer to grab objects of a wide range of shapes. The end effector also includes rounded cutouts for objects with curved features and compliant TPU material contact surfaces to reduce slipping of grasped objects. A camera mounted high on the antenna mast is used for long-range searching and for providing operators with greater situational awareness. Cameras underneath the first arm linkage and the chassis provide visual feedback of the end effector's alignment.

Equipment Servicing (ES):

The equipment servicing mission requires Wanderer to perform several tasks requiring both precision and dexterity on a mock equipment servicing lander. The equipment servicing mission will be performed using the same manipulator as the ED mission, but with a modified end effector. In order to tighten screws on the lander, a motor with a screwdriver attachment is added to the fixed portion of the clamping end effector. This attachment is also used to type on the keyboard. The manipulator's horizontal rail was designed to ensure that the manipulator could complete all of the tasks on one side of the lander without having to reposition the rover. This strategy increases the amount of time available for directly manipulating components on the lander.

The ES tasks of typing on a keyboard and inserting/removing a flash drive require precise manipulator control. Wanderer features two control schemes that an operator can choose from. The first employs joint control and the second utilizes inverse Jacobian velocity control. The joint control scheme allows the operator to control individual joints whereas the inverse Jacobian velocity control scheme allows the operator to control the manipulator using velocity commands in a cartesian coordinate system. The planar motion provided by the inverse Jacobian velocity and horizontal rail allows for the operator to position the arm intuitively relative to components on each panel of the equipment servicing lander.

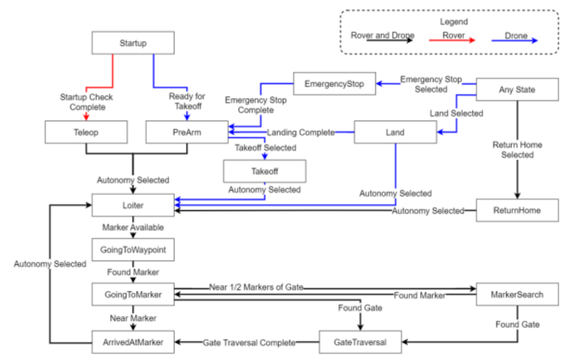

Figure 2: Autonomous Navigation state machine diagram

Autonomous Navigation (AN):

Wanderer and Cosmos are each capable of completing the autonomous navigation mission, with Cosmos being the team's primary choice to complete the mission. The team determined that the reduction in required obstacle avoidance capabilities and the increased traversal speed of a drone outweighed the reduced system endurance. In the case of high wind or system failure, the team can substitute Cosmos with Wanderer. Cosmos and Wanderer both use a Pixhawk 6c flight controller to obtain GPS information with a typical error of under 2 meters in testing. The two systems feature similar finite state machines responsible for making decisions to complete the mission (Figure 5). Goal positions input by the user through the GUI are stored in a marker manager, which performs coordinate transformations on the data points and passes them to a PID controller which outputs motor control commands.

When autonomous navigation mode is enabled, the vehicle will proceed to the next waypoint if any are available. The rover or drone then uses the Robot Operating System (ROS) ArUco_detect package to detect and locate markers. The last known position for each marker is stored and can be used after the markers leave the camera's view. In addition to ROS ArUco_detect, a YOLO object detection model has been trained to identify ArUco markers from longer distances and has a range tested up to 12 meters. If the vehicle arrives at a waypoint associated with a marker and a marker is not found due to the error associated with the provided coordinates, a sumo search path will be executed. This approach-independent randomized search pattern was selected to allow the vehicle to view markers from multiple perspectives. When traversing through a gate, the vehicle plans three goal points: one on the near side of the gate, one in the center of the gate, and one on the far side of the gate. To navigate around large obstacles, the vehicles can accept intermediate waypoints planned by the remote operator in the GUI using a preprocessed digital terrain map generated using United States Geologic Survey data as a reference for terrain difficulty.

Cosmos' control software has been designed to maximize operator and bystander safety. Cosmos requires a constant stream of commands, otherwise it will hover in place. If it does not receive commands for more than one minute, it lands at its current position. The drone will also respond to a software “emergency stop” command, which will immediately stop all motors and cause it to fall from its current position. A transmitter connects to the drone for an immediate manual control override as well.

Testing and Training:

At the start of the project in August, new team members were challenged with an internal competition based on URC requirements using last year’s rover. This was done to familiarize team members with the competition's requirements, understand weaknesses of the previous design, and quickly disseminate knowledge from experienced members.

The testing approach for Cosmos and Wanderer’s systems included component-level, subsystem-level, and full systems-level testing. Before the manipulation and drivetrain hardware were completed, a control library was created to communicate with the manipulation and drivetrain motors over the CAN bus to allow the motors and the relevant electronics to be tested and evaluated independently of the rover. Once library commands were tested thoroughly and the manipulator hardware was assembled, the strength of the arm was tested by incrementally lifting objects from 500 grams up to 8 kg. To test the ES mission, the team assembled a mock lander and completed all manipulation tasks within a 50-minute time limit.

To validate the composite construction techniques used for Wanderer’s wheels, a prototype wheel was designed and fabricated. Once these techniques were well understood, full-scale wheels were fabricated and their strength and deflection were tested by applying weight to the wheel up to twice what would be experienced during normal operating conditions. After the drivetrain was constructed, the wheels were tested by driving over a variety of terrains including a simulated desert environment consisting of gravel and varying-sized rocks.

To test the communications system, the team conducted signal strength testing on a local hiking trail with a Yagi antenna and sector antenna. Both antennas maintained communication up to a range of 800 meters. The sector antenna was selected for the final system for its higher performance and smaller form factor. The team conducted a full system test with Wanderer and the final communications system at a local farm where Wanderer was able to maintain connection over a range of 850 meters including portions of non-line of sight driving, reaching the edges of the permitted testing space.

The team utilized a Gazebo simulation environment including Aruco Marker models to test autonomous navigation for both robots. Simulated position information and camera data enabled the testing of Aruco Marker detection and path planning algorithms. Both Wanderer and Cosmos succeed in all autonomous navigation mission tasks in the Gazebo simulation. While Cosmos is in the early stages of physical testing, Wanderer completes all tasks reliably and with repeatability. Drone autonomous navigation testing was conducted over a range spanning 300 meters. In initial testing, Cosmos completed autonomous waypoint missions with top speeds of up to 40 mph and a total flight time of 9 minutes.

Subsystem readiness was determined based on NASA’s Technology Readiness Level (TRL) definitions. Based on the results of testing thus far, the current system is evaluated at TRL level 6, as both the rover and the drone have been field tested and their readiness for the URC competition in mission-relevant environments has been proven. Although new implementations such as the CAN network, new PCBs, composite wheels, the palletizer robotic arm, and the use of a drone for autonomy have introduced risks to the system this year, extensive field testing of these subsystems has allowed the achievement of a higher TRL level of the overall system. To reach TRL-8 prior to competition, the team will continue stress testing each mission in diverse environments, debugging issues that arise during these simulated tests to further improve the overall reliability of the system, training the operators, and fine-tuning each aspect of the mission strategies.

Team Mountaineers held two separate outreach events for a total of 64 current/incoming freshmen. At these events, students learned basic electronics and programming skills by assembling, wiring, and programming small introductory obstacle-avoidance robots that were designed by the electronics subteam.

Science Plan:

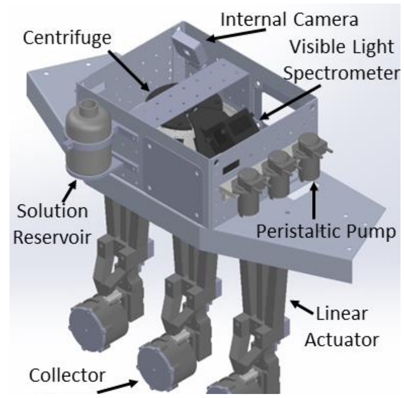

Figure 3: Annotated Drawing of science payload

In order to select a set of experiments suitable for identifying life in soil samples, a literature review was conducted with a focus on past NASA life-detection missions and the general problem of life detection. An especially useful paper in this pursuit was "The Ladder of Life Detection", which outlines a framework for designing life-detection experiments. The three most important criteria outlined by the paper are experiments that are repeatable, free of contamination, and sufficiently sensitive to identify lifeforms [1]. Based on these criteria, an Ocean Optics STS-VIS visible light spectrometer was chosen for the science payload. Visible light spectroscopy is a highly sensitive and repeatable technique capable of detecting organic compounds that reflect light, making it useful for life detection experiments [2].

The onboard spectrometer will be used to conduct two tests. The first test involves dissolving a sample in ethanol and performing a spectral sweep of this sample with the spectrometer. Natural biological pigments can be identified by their characteristic waveform produced by the spectral sweep [3][4]. Specifically, the detection of the biological pigment chlorophyll is indicative of photosynthesis, a metabolic pathway in photosynthetic organisms [5]. Chlorophyll is a biological pigment and an intermediate of a metabolic process, which is one of the strongest pieces of evidence for life [1]. If chlorophyll is not detected in a sample, this implies the sample does not contain a detectable concentration of photosynthetic life.

The second test aims to detect peroxidase through the use of a 3,3′,5,5′-Tetramethylbenzidine (TMB) assay for colorimetric analysis of the enzyme. The Ultra-TMB assay from Thermo-Fisher is used to detect the presence of peroxidase activity, producing a deep blue color when oxidized by the presence of peroxidase, and yielding absorption peaks at 370 nm and 672 nm [6]. Peroxidase is an enzyme found in many organisms that is responsible for breaking down hydrogen peroxide, which is a toxic byproduct in aerobic cellular respiration. Peroxidase is also an intermediate produced in aerobic cellular respiration [7]. The presence of peroxidase is a strong indicator for the presence of aerobic life.

The science package (shown in Figure 6) utilizes a collector array of three duplicated mechanisms to collect soil samples from up to three sites of interest while avoiding cross-contamination between sites. An additional collector array may be added to accommodate up to six sample sites. Each collector consists of a linear actuator that is used to lower a scoop drum to the ground. Each drum can be independently rotated to collect a soil sample and is actuated by a Dynamixel servo. The drums can be sealed with a sliding door and removed from the collector to serve as sample caches. After collecting a sample, a peristaltic pump is used to dispense ethanol into the drum. The drum spins to mix the soil and ethanol. By using a system of check valves, the peristaltic pump then runs in the reverse direction to extract soil solution and deliver it to the onboard science laboratory. Each solution sample is directed into a cuvette within a centrifuge in the onboard science lab, which is actuated using a servo.

After collecting samples from each site, a centrifuge spins at a high speed to separate the sample on a basis of density to reduce turbidity in the sample and allow for proper spectral analysis. The onboard spectrometer is used to observe the spectral response and the TMB Assay results for each sample. Waveform outputs are transmitted to the operator's graphical user interface for analysis. The ability to detect both chlorophyll and peroxidase allows for the identification of both photosynthetic and aerobic organisms, which covers a wide range of simple life forms. This broad coverage increases the likelihood of detecting life in life-positive samples while also reducing the chances of producing false negatives.

[1] M. Neveu, L. E. Hays, et al, *The Ladder of Life Detection*. 2018. [2] N. R. Council et al, "Signs of Life: A Report Based on the April 2000 Workshop on Life Detection Techniques". 2002. [3] A. Barron and A. Agrawal, 'Physical Methods in Chemistry and Nano Science, Volume 5: Molecular and Solid State Structure'. 2020. [4] T. Soderberg et al, *Organic Chemistry with a Biological Emphasis*. 2012. [5] G. Bergtrom, *Basic Cell and Molecular Biology 3e: What We Know & How We Found Out*. 2021. [6] Thermo Fisher Scientific – US, "1-step TM ultra TMB-Elisa Substrate Solution". [7] I. Bertini et al, *Bioinorganic Chemistry*. 1994.