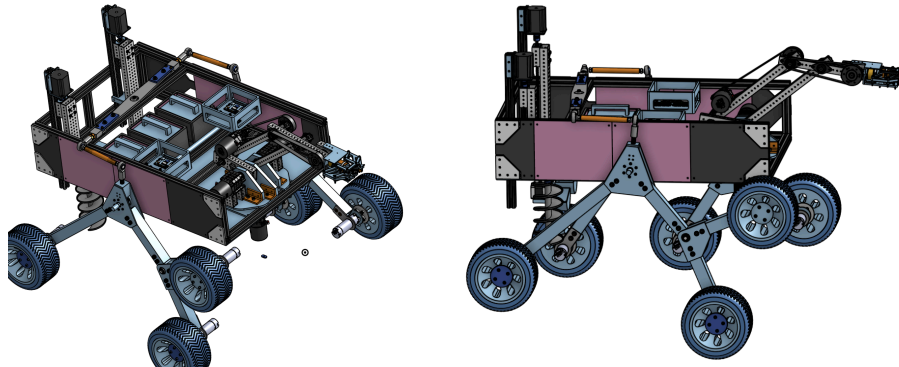


Yale University
New Haven, CT
United States of America

Yale Exploration Rover: System Acceptance Review

1. System Overview & Architecture

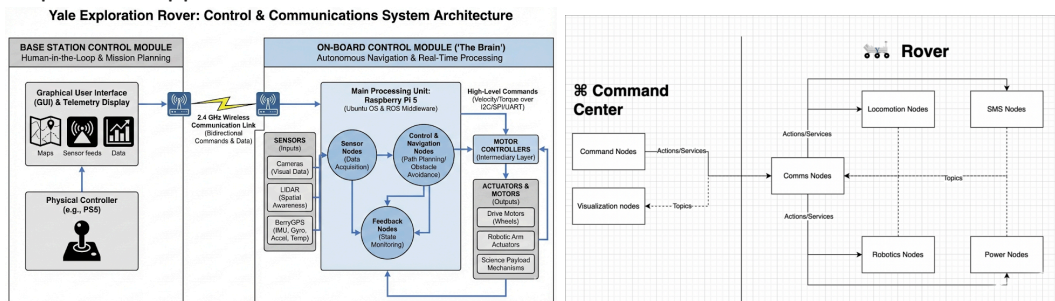
Description of System



Yale's rover project is divided into four primary technical subteams: drives, robotics, electronics & control (E&C), and science missions systems (SMS).

System Architecture and Communication

The command and control architecture has a hierarchy organized by a Raspberry Pi 5 brain running ROS2. High-level mission logic and sensor integration occur within the Pi, where telemetry and multi-camera feeds are transmitted via a high-bandwidth 2.4/5GHz radio link. The chassis is driven by goBILDA motor controllers while the arm utilizes SPARK MAX controllers to drive high-torque BLDC motors. Scientific instrumentation is handled by a Raspberry Pi as well, which interfaces with TB6600 drivers for precise stepper motor control.



Power distribution is done through a central “spinal cord”, which distributes power as needed to the drivetrain, arm, and SMS systems.

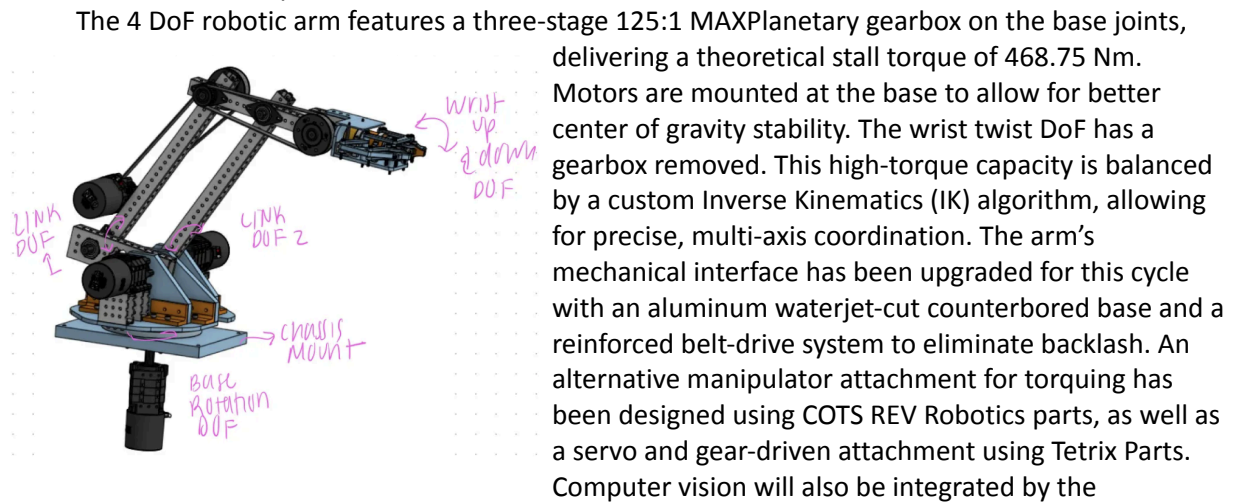
New vs. Reused Systems

Following the September 1 cutoff, the team has focused on upgrading the rover's precision and thermal reliability. The T-Slot chassis has the basic structural concept maintained with the internal mounting plates and layout redesigned for 2026. The 4 DoF linkage arm now has a more robust belt system with a custom waterjet base. E&C enclosures include custom modular 3D-printed housings with active thermal management using fans. The Science Missions System subteam has integrated a custom spectrometer and a custom linear actuator driven by stepper motors for precision.

Detailed description of new and novel features

The rover integrates several mission-critical components designed to strengthen field-serviceability, thermal resilience, and biological detection. These features are the result of a "bottom-up" engineering approach, utilizing \$7,156.67 in heritage hardware of the rocker-bogie suspension system while introducing novel environmental and analytical systems for the 2026 cycle.

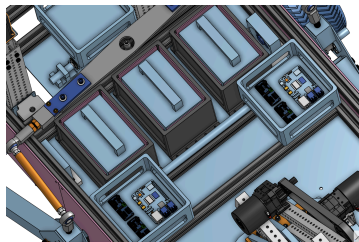
The rover's structural backbone is a 1-inch aluminum T-slot frame, providing a rigid and adaptable skeleton for payloads. A novel feature of the 2026 design is the addition of wooden mounting plates at the chassis base, side acrylic panels, and custom TPU printed airless tires. This approach allows the Electronics & Control (E&C) subteam to perform rapid layout changes and re-drilling as spatial requirements for the Raspberry Pi 5 and motor drives change, without compromising the structural integrity of the aluminum framing. This modularity makes sure that the rover can be reconfigured in the field within minutes to repair mechanical or electrical failures.



The 4 DoF robotic arm features a three-stage 125:1 MAXPlanetary gearbox on the base joints, delivering a theoretical stall torque of 468.75 Nm. Motors are mounted at the base to allow for better center of gravity stability. The wrist twist DoF has a gearbox removed. This high-torque capacity is balanced by a custom Inverse Kinematics (IK) algorithm, allowing for precise, multi-axis coordination. The arm's mechanical interface has been upgraded for this cycle with an aluminum waterjet-cut counterbored base and a reinforced belt-drive system to eliminate backlash. An alternative manipulator attachment for torquing has been designed using COTS REV Robotics parts, as well as a servo and gear-driven attachment using Tetrax Parts. Computer vision will also be integrated by the

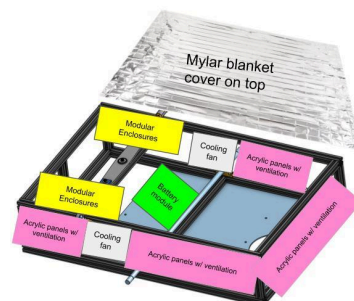
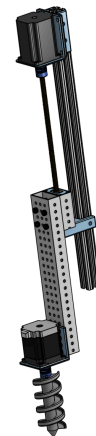
manipulator with a Raspberry Pi camera attached. Compliant rubber and limit switches have been mounted at the base to prevent damage to structural components.

A primary innovation for the Science Mission is the physically Isolated SMS payload. To mitigate the risk of water or chemical damage, the system is separated from the central electronics with internal structural walls. This isolation allows the team to conduct high-sensitivity Fluorescence Spectroscopy using a custom spectrometer, as well as collect samples using a drilling and scooping mechanism. The SMS payload uses modular designs using custom T-slot linear actuators mounted to the chassis with structural components from the robotic arm being used. The custom drill attachment will be machined. These actuators are mounted to the back of the chassis and are used for drilling and scooping mechanisms.



To combat the thermal loads of the Mars Desert Research Station, the rover utilizes a dual-layer environmental protection strategy. The top of the chassis is protected by heavy-duty Mylar blankets that are inverted,

reducing solar heat gain and provide a dust barrier for the drivetrain. Internally, critical logic components, including the Raspberry Pi 5 and motor controllers, are housed in modular 3D-printed enclosures with integrated active cooling fans. These housings are hinged and use M3 heat-set inserts for secure mounting and are optimized for airflow to prevent thermal throttling during high-current operations.



Command and control are distributed across specialized motor nodes, including goBILDA controllers for the drivetrain and SPARK MAX for the manipulator, connected via a high-bandwidth 2.4/5GHz radio link. This multi-node setup allows for simultaneous camera feeds and telemetry logging, ensuring the ground station maintains situational awareness even in high-latency environments.



2. Integration and Testing

Approach to Integration (2%)

The team utilizes a systems engineering framework to manage the transition from fabrication to a fully integrated mission platform. This approach centers on high-bandwidth collaboration between dedicated mechanical and electrical teams, where robotics and chassis hardware engineers work together during the assembly phase to ensure physical and functional compatibility. Cross-subteam collaboration is maintained through weekly synchronization meetings and extensive technical documentation within Notion.

Status of Integration (2%)

The project is currently in the active fabrication and initial integration phase. Electrical systems are progressing through a multi-stage validation path: initial logic is prototyped on breadboards, transitioned to protoboards for stability, and finally integrated into custom PCB designs to minimize footprint and eliminate point-of-failure wiring. Simultaneously, the mechanical integration of the Science Mission System (SMS) has reached a critical design milestone with the addition of isolated walls. Dust protection throughout the rover has been implemented with the use of laser-cut mirrored acrylic panels. In order to assess fits and prevent delays in incorrect manufacturing, we 3D print components as an initial prototype, then manufacture once validated in low-load testing. We currently have the majority of the chassis and arm parts manufactured, except for some robotic arm base components.



Test Plan (2%)

The project's test plan is governed by objective pass-fail criteria and a hierarchical validation strategy that integrates simulation with physical performance testing. Mechanical verification for the chassis uses incremental drive tests with speed ramping to evaluate drivetrain stability, while the robotic arm undergoes load-bearing tests to verify lifting capacity. Both are verified in Finite Element Analysis (FEA) and MATLAB reachability simulations to ensure structural and kinematic reliability. Additionally, a hardware-in-the-loop protocol was implemented for the robotic arm. First, MuJoCo simulations were started, then a fabrication of a COTS Tetrix, lower-torque robotic arm linkage system was done to better understand controls and physical mobility. This resulted in a better-informed design and physical intuition of center of gravity stability before the fabrication of the higher-torque REV robotics arm. Electronics development follows a disciplined prototyping path, progressing from initial breadboard logic to soldered protoboards and eventual transition to custom PCB designs with incremental ramping in power for all components. For the Science Mission System (SMS), chemical and biological sensors are

strictly validated in a controlled laboratory environment before being integrated into the rover. System-level testing and operational training take place at the Yale Center for Engineering Innovation and Design (CEID), where weekly cross-functional check-ins ensure that all subsystem interdependencies are addressed. This testing cycle is informed by Yale Rover design reviews with industry systems engineers and faculty, with all results and mechatronic insights exhaustively documented in Notion. We have also developed a 23-page safety plan describing all safety procedures and subsystem storage, which has been verified by Yale Environmental Health and Safety.

3. Project Management

Team Organization

The Yale Rover team comprises approximately 30 undergraduate students organized into four functional subteams: Drives, Robotics, Electronics & Control (E&C), and Science Mission Systems (SMS), to ensure parallel development and clear accountability for subsystems. We currently have about 10 active contributing members and 1-2 leads per subteam. Leadership is provided by two Project Leads and a Chief Engineer, who coordinate interdisciplinary integration and mission strategy. Each subteam has a designated integration person who facilitates communication with other subteams. The team's technical workflow is centered in the Yale Center for Engineering Innovation and Design (CEID), supported by professional staff and a distinguished advisory board including industry mentors from Lockheed Martin Space, the Johns Hopkins University Applied Physics Laboratory, and Yale faculty experts in mechatronics and mechanical design. Project management is streamlined through a high-transparency digital framework, utilizing Notion for centralized technical documentation and design heritage, while Jira serves as the primary tool for finance tracking to maintain the project's critical path.

Approach to Team Training

The team utilizes a multi-tiered approach to ensure technical proficiency and operational safety across all mission-critical domains. All members complete mandatory safety and tool certification through the Yale Center for Engineering Innovation and Design (CEID), establishing a foundation in laboratory protocols and precision machining under the guidance of specialized CEID staff. This is supplemented by intensive, subteam-led workshops at the start of each academic cycle, covering core skills such as Computer-Aided Design (CAD), PCB layout, and mechatronics. To ensure long-term technical continuity and minimize the impact of graduation or member transitions, all team members are required to be kept up to date with Notion documentation, with specialized responsible engineers for all subassemblies. This centralized source captures highly detailed records of design heritage, testing logs, and assembly protocols, resulting in seamless knowledge transfer and allowing the team to iterate rapidly while maintaining the rigorous engineering standards required for the URC.

Educational and Public Outreach

The team's educational and public outreach is anchored by the formation of Yale Undergraduate Robotics (YUR), an umbrella organization that integrates the rover project with service-focused groups like FIRST at Yale and Yale Assistive Innovation Design (Y-AID). This organizational structure positions the rover project as a central "home" for robotics on campus, facilitating interdisciplinary collaboration and broadening the scope of community engagement. Outreach is operationalized through high-visibility events at the Yale Center for Engineering Innovation and Design (CEID), including interactive demonstrations for Yale Engineering Week that showcase the technical progress of our rover. Additionally, the team maintains an active digital presence on Instagram, leveraging the platform to document the engineering process, share educational content, and recruit a diverse and motivated cohort of new members.

Gantt Chart (4%; page 5 only)

PROJECT TITLE	Yale Exploration Rover	COMPANY NAME	Yale Undergraduate Robotics
PROJECT MANAGERS	Diana Omar, Filippo Fonseca	DATE	2/27/26

WBS NUMBER	TASK TITLE	TASK OWNER	START DATE	DUE DATE	DURATION	PCT OF TASK COMPLETE	Preliminary Design				Critical Design				Integration & Testing (System Acceptance)												Integration and Testing (for Competition)																							
							September				October; Yale PDR 10/31/25				November Yale CDR 11/12/25				December - URC PDR 12/3/25				December				January				February - URC SAR 2/27/26				March				April				May							
							W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4	W1	W2	W3	W4								
1	Project Management															W																																		
1.1	URC PDR Submission	Diana O, Filippo F	9/1/25	12/1/25	90	100%																																												
1.2	URC SAR Submission	Diana O, Filippo F	12/3/25	2/27/26	84	100%																																												
1.3	Drives Notion Documentation	Cameron D	12/3/25	5/1/26	148	90%																																												
1.4	Robotics Notion Documentation	Nowyshin M, Sid P	12/3/25	5/1/26	148	90%																																												
1.5	SMS Notion Documentation	Murat K, Ryan N	12/3/25	5/1/26	148	70%																																												
1.6	E&C Notion Documentation	Filippo F	2/1/26	5/1/26	90	60%																																												
1.7	Social Media/Community Outreach	Diana O	12/1/25	5/31/26	180	40%																																												
1.8	Industry/Professor Collaboration	Diana O	1/31/26	5/31/26	120	50%																																												
2	Mechanical - Drives & Robotics																																																	
2.1	Drives Suspension and Linkage Design	Cameron D	9/1/25	12/1/25	90	90%																																												
2.2	Wheel Design & Testing	Carlos C, Orion B, Cameron D	9/1/25	5/1/26	240	80%																																												
2.3	Chassis Integration for Other Subteams	Darren K	10/1/25	5/2/26	211	50%																																												
2.4	Base System for Robotics Linkage	Stephen P	9/1/25	5/3/26	242	50%																																												
2.5	Manipulator Design	Melissa A	9/1/25	2/1/26	150	95%																																												
2.6	Manipulator Testing	Nowyshin M	11/1/25	4/1/26	150	60%																																												
2.7	Manipulator Alternative Attachment (for Torquing)	Diana O	12/1/25	5/1/26	150	70%																																												
2.8	Robotics Linkage	Sid P	9/1/25	5/29/26	268	80%																																												
2.9	MuJoCo Sim	Diana O	11/1/25	4/1/26	150	25%																																												
2.10	FEA/Structural validity of linkage system	Sid P	9/1/25	12/1/25	90	100%																																												
3	Electronics & Control (E&C)																																																	
3.1	Graphical User Interface – Base Station Control	Emir A	9/1/25	12/1/25	90	80%																																												



Project Budget Table

Yale Exploration Rover: URC SAR Budget As of February 2026	
INCOME	
Actual Income to Date	
Carryover from Last Year	\$7156.67
YSEA Rover Project Grant	\$4000.00
Yale SEAS Club Funding	\$2105.73
Total Received to Date:	\$13,262.64
Anticipated Income	
Yale Dept. of MechE (Travel)	\$7500.00
Residential College Donations (Travel)	\$3000.00
Misc Alumni Donations (YSEA travel)	\$2500.00
Total Anticipated:	\$13,000.00
TOTAL INCOME:	\$26,262.40
Expenses	
Anticipated Expense Categories	
Vehicle Structural Components	\$1000.00
Actuators & Transmissions	\$3500.00
Electronics & Hardware	\$1750.00
Science Missions Components	\$2500.00
Robotic Arm Components	\$2000.00
URC Rover Transportation	\$1000.00
URC Travel Expenses	\$12000.00
TOTAL EXPENSES:	\$23,750.00
DEFICIENT/SURPLUS	\$2,512.40

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4. Science Plan

The science mission for the 2025-2026 cycle focuses on the detection of extant life biomarkers through high-sensitivity biochemical analysis. The primary goal is to determine the presence and concentration of proteins within geological samples, providing a direct indicator of biological activity. The secondary goal is to determine the presence of carbonates, which are indicative of a warm and wet environment and may indicate past habitability.

On-Board Instrumentation: Fluorescence Spectroscopy and Acid Test

The rover's primary analytical instrument is a custom fluorescence spectrometer. This method was selected for its high sensitivity and ability to detect trace amounts of proteins that might be missed by traditional visual or basic chemical sensors. Proteins are detected using fluorescamine. Alone, fluorescamine is not a fluorophore, but, upon binding to the primary amine of a protein, it fluoresces blue when excited by ultraviolet light.

The fluorescamine dye will be dissolved in acetone, as it will slowly hydrolyze when exposed to moisture. Any incoming soil samples will be mixed in a phosphate buffer saline (PBS) solution to extract water-soluble proteins while maintaining a neutral pH to prevent the denaturing of fluorescamine. The sample will be irradiated with a 395 nm ultraviolet LED, and the light intensity will be measured by a Raspberry Pi camera viewing the sample through a spectroscope to separate incident UV radiation from the blue fluorescence. The intensity of the fluorescence correlates directly to the protein concentration.

The rover's secondary life detection mechanism is an acid test consisting of 1M hydrochloric acid (HCl). If carbonates are present in the soil sample, they will undergo an acid-base reaction with the HCl and effervesce, which we will detect with a USB camera.

Sample Acquisition and Cache System

To facilitate consistent analysis, the rover employs a specialized sample acquisition and caching hierarchy designed to prevent cross-contamination and protect sensitive electronics. Samples are acquired via a high-torque drill system. The sample is transferred into the Science Mission System (SMS) payload bay with internal structural walls that physically isolate the science payload from the primary electronics and control bay. This provides a "splash-proof" barrier, ensuring that the liquid reagents (acetone and PBS) and moisture from soil samples do not compromise the Raspberry Pi 5 or motor controllers. The cache system consists of a series of discrete containers with either HCl or PBS solution.

On-Board Experimental Procedure

The autonomous science sequence is programmed to follow a rigorous laboratory protocol optimized for a mobile platform. For the HCl acid test, a camera will directly look at relevant containers for effervescence. For the fluorescence spectrometer, 3-5g of soil deposited in 50 mL PBS solution will be stirred and transferred using peristaltic pumps to a cuvette in the fluorescence spectrometer. This cuvette will contain 0.3 mL of a 6 millimolar solution of fluorescamine in acetone. Then, a UV LED will shine through the solution and into a spectroscope, which will separate the incident light into its component wavelengths. A camera will view the intensities of each wavelength, and data will be processed onboard to filter out background noise and then transmitted via the 2.4/5GHz link for ground-truth validation by the science team.

Science Team Collaboration

The science mission is an interdisciplinary effort involving mechanical/biomedical engineers, chemists, biologists, and mathematicians. This collaboration ensures that the mechanical design of the cache system, such as the 4-wire bipolar stepper motors for precision motion, meets the delicate requirements of chemical assay execution. All protocols are validated in a controlled laboratory environment before field integration to ensure that the "pass-fail" criteria for biomarker detection are robust under competition conditions.