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A Modular and Scalable Validation Framework for Planetary Rovers: Application to the ARDITO System

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Abstract. Planetary exploration increasingly relies on autonomous robotic systems, yet the rigorous validation of end-to-end system behavior remains a significant bottleneck, par ticularly for small, multidisciplinary teams lacking the resources of large space agencies. This work addresses this challenge by tailoring established aerospace testing principles into a modular, scalable framework that balances thoroughness with agility. We demonstrate its application on the ARDITO rover, a platform developed by the DIANA student team at Po litecnico di Torino. Our approach provides a lean yet structured validation pathway, bridging the gap between ad-hoc laboratory tests and full-scale qualification campaigns governed by ECSS or NASA standards. The framework defines four distinct, interconnected testing layers: Design Validation (DEV), which focuses on component-level verification (e.g., finite-element analysis, bread board testing, test-driven development) within individual technical departments; Reduced Functional Tests (RFT), used as rapid control points to validate integrated subsystems after major events like transport or configuration changes; Full Functional Tests (FFT), which comprehensively evaluate the fully integrated rover under controlled laboratory conditions; and Mission Tests (MST), which simulate realistic task scenarios in environments like AL TEC Martian Terrain Simulator to evaluate performance under mission constraints. This hybrid agile-lean approach offers a clear academic and practical contribution for research groups and early-stage projects, ensuring reliable, mission-ready performance.

Introduction

Robotic systems with full or partial autonomy are becoming increasingly vital for planetary exploration. They are deployed to execute scientific, scouting, and support functions in remote, hazardous, poorly characterized locations (B. Hussain, 2025) (Ishigami, 2024). In the unforgiving space domain, where post-launch repair is impossible, Verification and Validation (V&V) are fundamental (R. C. Cardoso, 2021). Verification ensures a system is built according to its specifications, building the system right, while validation confirms it fulfills its intended purpose in its operational environ ment, building the right system. The state-of-the-art in V&V is polarized into two distinct paradigms based on mission scale and risk. The heavyweight standard, used for large-scale rovers, is exhaustive and requirements driven. Governed by NASA (Kapurch, 2010) and ECSS standards (ECSS, 2018), this multi-year process uses tiered f idelity testing, from simulations to hardware testbeds, consuming up to 80% of project timelines and creating a validation gap as system complexity outpaces testing capabilities. Conversely, the lightweight agile V&V for CubeSats is constraints-driven, prioritizing rapid schedules and fixed budgets. It relies on standardized tests and Commercial-Off-The Shelf (COTS) components. This polarization

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presents a significant challenge, particularly for the small, multidisciplinary teams in university and startup environments, which lack the resources for the heavyweight approach but cannot always afford the high risk of the lightweight model. The case study for this work is the rover ARDITO (Caraccio, 2025) (N. di Gruttola Giardino, 2024).

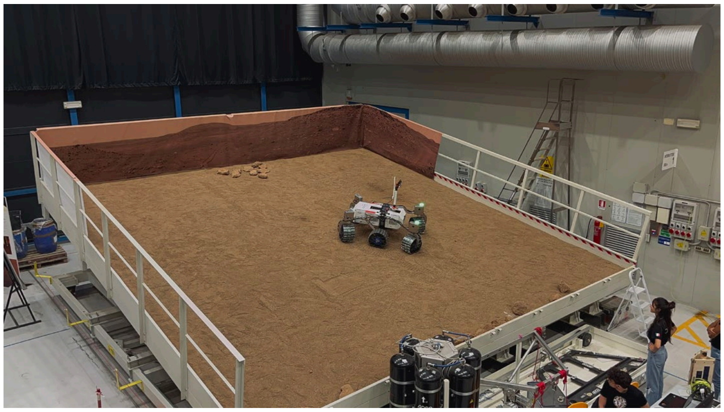


Figure 1: From left to right: ARDITO on the MTS Facility performing Science Mission Scenario. Ardito on the Tilting Platform . (These photos were taken at the ALTEC Mars Terrain Simulator - MTS Facility - which was developed for ESA ExoMars program under Thales Alenia Space Italy contract)

Layered Validation Framework

To bridge the gap between ad-hoc laboratory tests and full-scale qualification campaigns, we developed a modular, scalable validation framework tailored for resource-constrained robotic projects developed in an educational environment **(Corpino, IFAC Workshop on Aerospace Control Education WACE 2021)**. This framework is built on a progressive philosophy, systematically escalating the scope and complexity of testing from individual components to the fully integrated system operating under mission-like conditions. It provides a structured pathway to retire risk incrementally, ensuring that foundational elements are robust before they are integrate into more complex assemblies. The work starts with the system's functions prioritization coming from the European Rover Challenge (ERC) rules and some key core requirements identified in parallel by the team's board of directors. Aspecific functional analysis identifies which requirements and functions are relevant for the test plan, and consequently they are organized and divided by subsystems.

The framework is composed of four distinct yet interconnected layers: Design Validation (DEV), Reduced Functional Tests (RFT), Full Functional Tests (FFT), and Mission Tests (MST). Each layer serves a specific purpose, building confidence in the system's reliability and performance at critical stages of the development and operational lifecycle.

Layer 1: Design Validation (DEV). The foundational layer, Design Validation (DEV), focuses on component-level verification before any system integration occurs. This phase is executed internally by each technical departments, from mechanical subsystems designs **(Trentini, 2024)** to software autonomy modules creation **(Mustich, 2023)**. This allows for focused, discipline-specific analysis **(Festa L. M., 2022)** and testing. The primary goal of DEV is to confirm that each component meets its design requirements and specifications in isolation, preventing fundamental flaws from propagating to higher levels of assembly where they become more difficult and costly to diagnose and fix.

Layer 2: Reduced Functional Tests (RFT). RFTs serve as a crucial ”health check” on integrated subsystems. These are rapid, targeted tests designed to be executed after major events such as hardware configuration changes, software updates, or transportation. The purpose of an RFT is to quickly validate essential functions with minimal external depen dencies, providing prompt feedback on the system's baseline health. This allows the team to confirm that a recent change has not introduced a critical failure before proceeding with more time-consuming tests. For example, a typical RFT, performed after transporting the rover to a test site, is a 10-minute procedure that involves powering on the main computer and drive system, commanding each wheel to spin for five seconds, and confirming a teleme try is received from all critical sensors. This simple test quickly verifies the integrity of the power system, drivetrain, and core communication pathways.

Layer 3: Full Functional Tests (FFT). FFTs are designed to comprehensively evaluate the fully integrated rover and its payloads under controlled laboratory conditions. Unlike RFTs, which are narrow in scope, FFTs execute pre-programmed, end-to-end mission routines to stress-test every operational mode and verify complex software logic and inter-system interactions. These tests are performed on a flat, predictable surface to isolate the system's performance from environmental challenges, focusing purely on functional correctness and integration stability. An example FFT for the ARDITO rover involved a 1-hour autonomous sequence that executed a full mission profile to validate the entire chain of operations from navigation to payload deployment, ensuring that all subsystems work cohesively as intended.

Layer 4: Mission Tests (MST). The final layer, Mission Tests (MST), evaluates the sys tem's end-to-end performance under realistic task scenarios and environmental constraints that closely recreate actual mission parameters. For this critical phase, we had the oppor tunity to perform tests in ALTEC S.p.A Martian Terrain Simulator (MTS Facility**) (Bramante, et al., 2019)** in Turin, Italy. ALTEC, a center of excellence for space logistics and engineering, operates the Rover Operations Control Centre (ROCC) for the ESA ExoMars mission, and its MTS provides a high-fidelity Martian analogue terrain for testing and verification activities. The MTS hosts a ground test model of the ExoMars rover and is designed to rehearse surface operations in a terrain with Mars-like morphology. Within this facility, the ARDITO rover was subjected to mission scenarios derived from the rules of the European Rover Challenge, including navigating uneven terrain with slopes and obstacles, and operating under simu lated communication constraints, such as limited bandwidth and command delays. These tests were essential for validating the rover's performance and robustness in conditions that could not be replicated in a standard laboratory.

To manage this campaign within tight schedules and with limited personnel, we integrated lean operational practices, using physical Kanban boards **(Bacea, Ciupe, & Meza, 2017)** for real-time task prioritization and checklist-based reports to ensure traceability and facilitate anomaly tracking.

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Table 2: Mobility sub-system test summary

ID	Short Name	Test Description	Linked Reqs.
RFT			
RFT-M-01	MC&EL Steering	Steering	
RFT-M-02	MC&EL Feedback H7	Test H7	
RFT-M-03	MC&EL Feedback Webapp	Test Webapp	
RFT-M-04	Tracking	Test Tracking Service	
FFT			
FFT-M-N-01	WebApp Test	WebApp Feedback	R-GEN-060, R-OPS-110
FFT-M-N-03	Tracking	Tracking service	
FFT-M-N-04	POCO	Position Control mode	R-FUN-060, R-FUN-030
FFT-M-N-05	AUTONAV	Autonomous Mode	R-FUN-060, R-OPS-080, R-OPS-090
FFT-M-N-06	Performance Validation I	Precision in Velocity mode	R-GEN-060
FFT-M-N-07	Performance Validation II	Precision in Position Control mode	R-FUN-030
FFT-M-N-08	Performance Validation III	Precision in AUTONAV mode	R-FUN-250
FFT-M-N-09	Streaming	Streaming Cameras monitoring	R-OPS-110, R-FUN-170
FFT-M-N-10	Safety Button	Safety button does safely shut-off the rover	R-DES-020
MST			
MST-M-N-01	Navigation Task Test	Simulate Navigation Task	R-FUN-060, R-FUN-250
MST-A-M-01	Maintenance Task Test	Simulation of Maintenance Task	R-GEN-090
MST-A-P-01	Probing Task Test	Simulation of Probing Task	R-GEN-100
MST-A-S-01	Science Surface Sample Task	Simulation of Science Sample Task	R-FUN-150
MST-A-S-02	Science Construction Task	Simulation of Construction Task	R-DES-140

Methodology: Agile & Lean Process Management in the ARDITO project

To manage our complex four-layered validation campaign within a resource-constrained stu dent team, we adopted an agile-inspired approach. Our hybrid agile-lean methodology **(Festa G. P., 2025)** for the ARDITO project combines a high-level annual timeline with a dual-layered system built around major integration milestones called ”stable points” and two-week development cycles known as ”sprints.” The sprints were the engine of the project, where the low-level continuous work of the Design Validation (DEV) layer occurred. Within each sprint, techni cal groups focused on designing, building, and verifying their individual components through FEA, breadboarding, and test-driven development, ensuring quality was built in from the very beginning. The focus then shifted from the DEV layer to system-level verification, primarily using the Reduced Functional Test (RFT) and Full Functional Test (FFT) layers. This incremental approach was transformative for the project lifecycle; instead of a single, high-stakes integration event at the end of the year, we had multiple, lower-risk checkpoints. Each stable point provided a validated, reliable fallback configuration, systematically miti gating risk and ensuring we always had a functional rover baseline. This structure creates a powerful feedback loop DEV − > RFT/FFT − > DEV. System-level failures found at a stable point are documented and feedback into the agile backlog to be resolved at the component level in the next sprint. This makes validation a continuous, iterative process, allowing us to manage complexity by progressively and thoroughly validating the system at every stage.

Conclusions

The novelty of our work lies in structuring these established methods into a tailored frame work guided by three core principles: modularity, scalability and feedback-driven iteration. By decoupling validation layers, defining adaptable templates and embedding agile feedback loops, the framework can be adopted or modified based on project scale and constraints. We have already begun applying this paradigm to other DIANA demonstrators, such as aerial companions, to further test its generalizability. In conclusion, this work presents a reproducible multi-layered testing framework that enables robust and resource-efficient validation of complex robotic systems. Its successful deployment on the ARDITO rover underscores its potential for broader adoption across academic and small-scale industrial contexts. Future work will formalise quantitative met rics, integrate software tools to replace physical boards and conduct cross-project studies to benchmark efficacy

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