ARCADIA: AI-based Real-time Analysis for Autonomous Space Systems

N. Parmiggiani[1], A. Femia[1], A. Bulgarelli[1], L. Castaldini[1], A. Di Piano[1], E. Medinaceli[1], M. Lombardi[2], A. Luise[2], S. Salti[2], A. Argan[3], R. Campana[1], G. Cremonese[4], F. Esposito[5], R. Falco[1], F. Fiore[6], V. Fioretti[1], M. Maniscalco[1,7], G. Mustafa[1,2], G. Panebianco[1], F. Pedichini[8], I. C. Popa[5], A. Rizzo[9], F. Tosi[10], and A. Trois[11]

[1]INAF OAS Bologna, Via P. Gobetti 93/3, 40129 Bologna, Italy
[2]Computer Science and Engineering - DISI, University of Bologna, Via Zamboni 33, Bologna, Italy
[3]INAF Central Administration - Viale del Parco Mellini 84 00136 Roma, Italy
[4]INAF O.A. Padova - Vicolo dell'Osservatorio, 5, 35122 Padova, Italy
[5]INAF O.A. Capodimonte - Salita Moiariello 16 – 80131 Napoli, Italy
[6]INAF O.A. Trieste - Via G.B. Tiepolo, 11 I-34143 Trieste, Italy
[7]Università degli Studi di Padova, Via VII Febbraio , 2, 35122, Padova, Italy
[8]INAF/OAR Roma, Via Frascati 33, I-00078 Monte Porzio Catone, Roma, Italy
[9]INAF OA Catania, Via Santa Sofia 78, 95123, Catania, Italy
[10]INAF IAPS Roma - Via del Fosso del Cavaliere, 100, 00133 Roma, Italy
[11]INAF O.A. Cagliari - Via della Scienza, 5, 09047 Cuccuru Angius, Selargius, Italy

AI-generated background image

ABSTRACT

The New Space Economy, enabled by the increasing availability of commercial launch vehicles and spacecraft, has renewed interest in lunar exploration. Within the Italian PRORIS program and the HARLOCK project, the Rare-earth & Heavy Elements Analyzer (RHEA) is being developed. RHEA is a payload comprising a suite of instruments designed for integration onto small rovers, enabling rare earth element (REE) and rare-metal scouting and prospecting through a highly coordinated, synergistic approach based on a progressive, multiscale observation strategy. Artificial intelligence (AI) is a key enabling technology for autonomous scientific operations and onboard data processing. We present the AI-based Real-time Computational Analysis platform for Decision Inference in Autonomous space systems (ARCADIA), which implements the Instrument Control Unit (ICU) and onboard Data Processing Unit (DPU) for the RHEA rover. Real-time onboard processing of scientific data, based on low-power Commercial Off-The-Shelf (COTS) computing platforms, enables ARCADIA to enhance the effectiveness of the scouting process by rapidly guiding the rover toward the most promising sites for further investigation, thereby accelerating target selection and exploration even during short-duration missions.

1. Context

Within the Italian PRORIS[1] program and the HARLOCK[2,3] project, a novel approach to lunar resource exploration is being investigated by developing the Rare-earth & Heavy Elements Analyzer (RHEA). Conceived as a compact scientific payload for small rover platforms, RHEA aims to support the detection and characterization of rare earth elements (REEs) and rare metals by combining complementary analytical techniques within a progressive, multiscale exploration strategy. The payload integrates gamma-ray spectroscopy, hyperspectral imaging, ultraviolet fluorescence screening, and X-ray fluorescence analysis to identify REE-bearing deposits and investigate their associated elemental and mineralogical signatures across different spatial scales. Given the demanding operational conditions of lunar exploration, such as power availability and Earth–Moon communication limitations, AI-based capabilities are being investigated to enhance onboard autonomy, optimize scientific data processing, and support decision-making during exploration activities.

2. ARCADIA

The AI-based Real-time Computational Analysis platform for Decision Inference in Autonomous space systems (ARCADIA), is a software system that implements the Instrument Control Unit (ICU) and onboard Data Processing Unit (DPU) for the RHEA rover. The ICU controls and monitors the scientific payload, while the DPU performs AI-enhanced onboard data analysis, including spectral identification of REEs, real-time multi-instrument data fusion, and data reduction. ARCADIA shall operate in a demanding lunar environment with stringent requirements:

1) Extreme temperature variations
2) Radiation exposure (higher than in LEO)
3) Limited power availability < 5 W
4) Limited bandwidth for data transmission
5) Limited onboard computational resources
6) Volume: ~0.5 U;
7) Weight: < 1 kg;

Main ARCADIA Tasks:

1) Payload control and monitoring.
2) Data Fusion: Analyzing data from different instruments in real time, providing better scientific results, even in low-statistics contexts.
3) Efficient Data Filtering for Transmission.
4) Communication with the rover to retrieve the status of the rover (moving or stopped) and the direction taken by the rover.
4) Perform automated decision-making, crucial for long-distance missions with communication latency. Based on onboard analysis results, ARCADIA will determine the rover's travel direction and duration. After each movement, new observations will guide the next maneuver. Once a target is reached, a new destination will be selected either autonomously or via ground

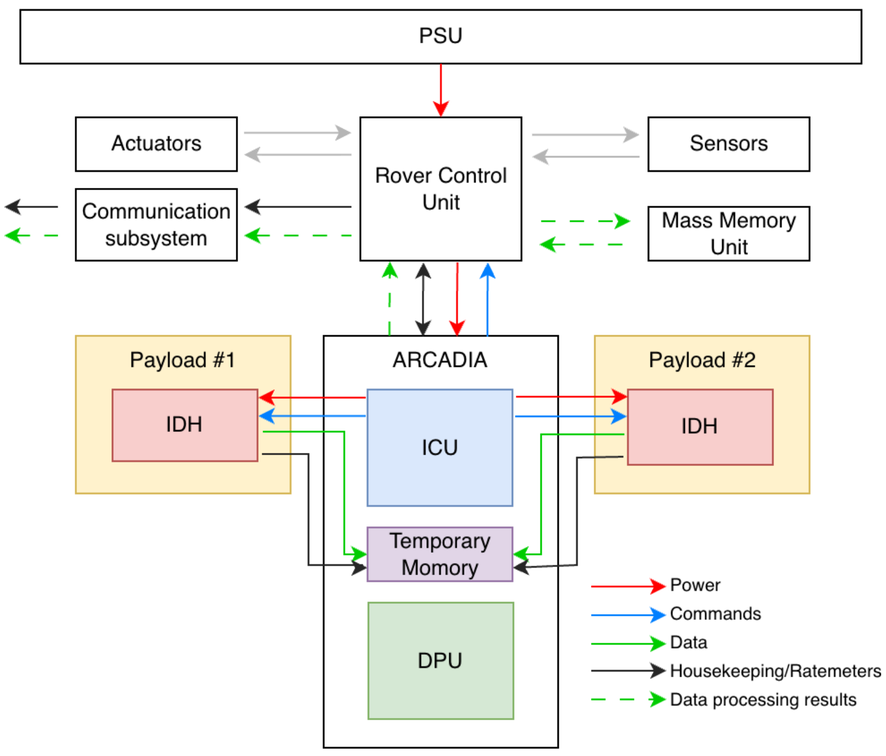
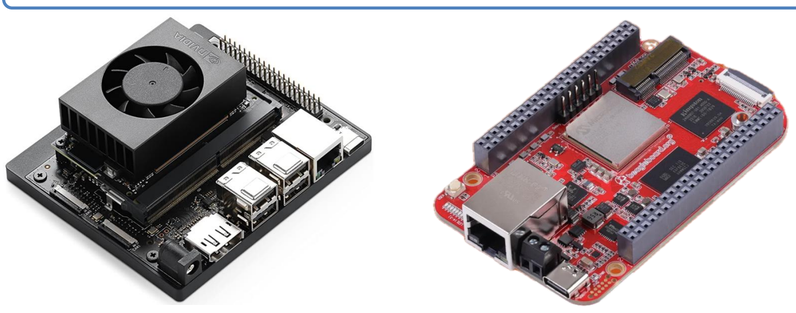


Fig. 1: ARCADIA high-level architecture.



Nvidia Jetson Orin Nano **BeagleV - Fire**

Fig. 2: Example of Edge Computers that we are evaluating considering the requirements.

3. ARCADIA Architecture

The ARCADIA architecture (Fig. 1) includes interfaces with the rover to receive power and housekeeping data. ARCADIA sends commands to the rover for movement and interfaces with the instruments (payloads). The ICU manages the life cycle of the instruments along with the power supply. The data produced by the instruments are stored in ARCADIA's Temporary Memory for real-time analysis by the DPU. The results are then sent to the Mass Memory Unit of the rover, waiting for transmission to the Ground.

4. Edge AI board

A market survey of low-power Commercial Off-The-Shelf (COTS) computing platforms was conducted to identify solutions meeting the project requirements for power consumption, computational capability, and environmental constraints. AI algorithms for onboard data analysis were evaluated on low-power edge computing platforms, including the NVIDIA Jetson Nano and RISC-V processors (Fig. 2), representative of flight-proven hardware such as the Skylab NANOhpc-obc. Candidate platforms target power consumption below 5 W while supporting AI models optimized through pruning and quantization to enable real-time onboard processing under lunar resource constraints.

5. Conclusions

Real-time onboard processing of scientific data enables ARCADIA to enhance the effectiveness of the scouting process by rapidly guiding the rover toward the most promising sites for further investigation, thereby accelerating target selection and exploration even during short-duration missions. The technologies and methodologies developed within ARCADIA are designed to be transferable to other autonomous space systems and adaptable to a broader range of future space missions.

ACKNOWLEDGEMENTS

We acknowledge support from INAF grant Progetto Strategico Programma di Ricerca Spaziale di Base (PRORIS) DM 789/2023 CUP C53C24001850005.

References:
[1] https://www.proris.it/
[2] Tosi, F., "HARLOCK: An Integrated Science Framework for In Situ Lunar Resource Exploration", in 57th Lunar and Planetary Science Conference, 2026, vol. 3160, Art. no. 1202.
[3] Fiore, F. et al., "The PRORIS-HARLOCK project for Moon resource prospecting", RESOURCES WEEK 2026, Book of abstracts.