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MULTI-ROBOT COOPERATIVE AUTONOMY ON THE MOON: THE CADRE TECHNOLOGY DEMONSTRATION MISSION

Gregg Rabideau, Joseph Russino, Andrew Branch, Nihal Dhamani, Tiago Stegun Vaquero, Jean-Pierre de la Croix, Federico Rossi *

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA

ABSTRACT

NASA's Cooperative Autonomous Distributed Robotic Exploration (CADRE) mission is a technology demonstration designed to land on the Moon's Reiner Gamma region on a commercial lander in 2026. CADRE aims to to demonstrate multi-agent autonomous exploration of the Lunar surface and sub-surface. A team of three small robots and a base station will autonomously explore a region near the commercial lander, with only high-level input from humans. The rovers will autonomously collect imagery required for 3D reconstruction of the surface; and then drive in formation to collect multi-static ground penetrating radar (GPR) data to create a 3D map of the subsurface.

Key words: Autonomy, multi-agent systems, planning and scheduling, robotics, distributed instruments, multi-static radar, Moon.

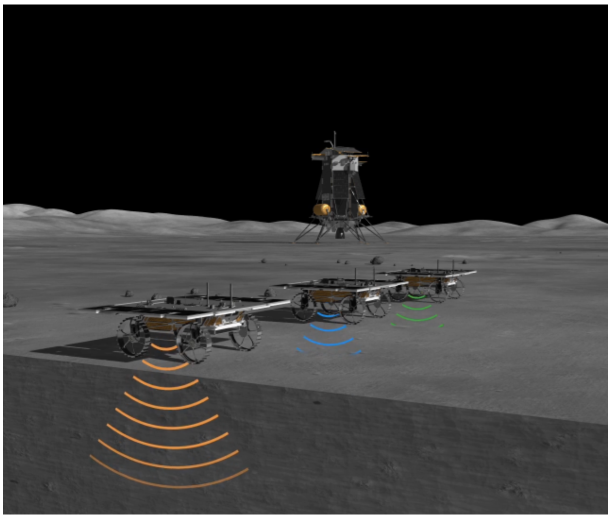

Figure 1. CADRE's concept of operations: three rovers will drive in formation operating a multi-static ground penetrating radar to image Reiner Gamma's sub-surface.

1. INTRODUCTION

The CADRE technology demonstration mission aims to demonstrate autonomous, coordinated operations of a team of autonomous robotic vehicles to collect data of scientific interest.

Distributed instruments (i.e., instruments that collect scientific information from multiple locations at synchronized times) hold great promise to unlock key questions in planetary science that are inaccessible to single-point measurements. The ability to collect time-synchronized and cross-calibrated measurements from spatially distributed, and potentially moving, locations is critical to investigations of subjects as diverse as atmospheric circulation on Mars, Venus, and Titan; sub-surface compositions of rocky and icy moons; and seismic activity on Venus.

Traditional operations paradigms for space exploration missions relies on on-board execution of sequences, developed by operators on the ground, that specify which activities should be performed at which time by the spacecraft or rover; such an approach generally does not scale to multi-agent systems and in particular to distributed instruments, which must cope with bandwidth and latency constraints between individual agents; heterogeneous availability of resources (e.g., thermal and power conditions that may vary among agents); and potentially time-varying team composition, as some agents may become temporarily, or permanently, unavailable.

These considerations motivate the development of multi-agent autonomous planning, scheduling, and execution (PS&E) tools for future space exploration missions. Many approaches for multi-agent PS&E have been proposed in the literature; however, to date, no approach has been developed and tested to a level of technology readiness sufficient for infusion in future spaceflight missions.

NASA's Cooperative Autonomous Distributed Robotic Exploration (CADRE) mission aims to fill this gap. CADRE proposed flying a team of four agents, including three mobile rovers and a static base station, to the Moon's Reiner Gamma region in 2025/2026. The goal

*Corresponding author: Federico.Rossi@jpl.nasa.gov.

of CADRE is to demonstrate the high technology readiness of cooperative autonomy, that is, the ability for a team of autonomous agents to elaborate high-level commands from ground (e.g., "explore this region") into commands for the rovers' mobility system and on-board instruments. Specifically, the rovers will cooperatively explore a prescribed region and collect multi-static ground penetrating radar measurements (Figure 1); the base station will act as a communication gateway between the rovers and Earth, and aid the team by performing computational tasks.

2. PLANNING, SCHEDULING, AND EXECUTION ARCHITECTURE

CADRE's PS&E architecture features a centralized planner on an elected leader (which may vary during operations), and decentralized execution on each agent (i.e., every rover and the base station). Figure 2 shows the overall autonomy architecture, and Figure 3 provides a detailed view of the PS&E architecture. The architecture is based on JPL's MEXEC [6] planning and scheduling architecture, extended to support multi-agent operations.

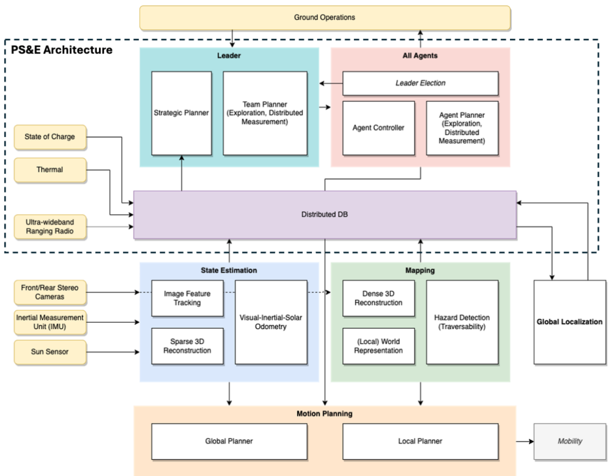

Figure 2. CADRE's autonomy architecture features a leader-election mechanism to select a leader, which performs planning for the team; a lightweight distributed database to share and persist data across the system; and an execution engine on every agent. From [4].

Ground-based operators provide a high-level description of the mission to the team in the form of a task network (tasknet) and a set of parameters describing regions of scientific interest. The task network includes data synchronization tasks, coordinated geometric planning tasks (to assign regions to explore to the agents during surface mapping, and in-formation trajectories during radar mapping), and individual tasks for the robots (exploring a region and driving in formation during surface and subsurface mapping respectively).

The centralized planner collects state information from all agents, using a distributed database, and computes a

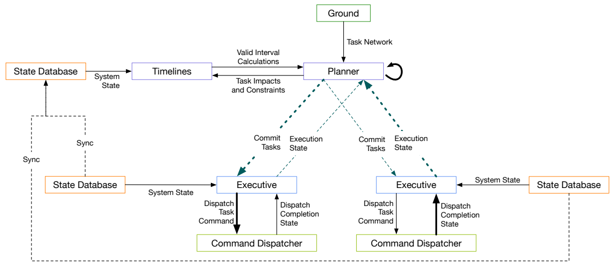

Figure 3. Detail of CADRE's PS&E architecture. A planner located on the leader uses state information, provided by the distributed DB, to devise a feasible plan for the team, and transmits tasks to individual agents; the agents' executive keeps track of running tasks and enforces constraints.

feasible plan for the team. The plan is distributed over radio links to all agents, which execute the tasks and monitor satisfaction of task constraints (e.g., thermal and power limits). If any constraint is violated, or if flight software reports that the task has failed, the agent contacts the leader, which stops all agents and triggers a replan (Figure 3).

The leader election mechanism selects one agent to act as the planner, privileging agents farther from their thermal and power constraints. If, at any point, the leader becomes too close to these constraints, or otherwise stops operating, the leader role is transferred to another agent (Figure 4); in-progress tasks are stopped, and the new leader replans for the system.

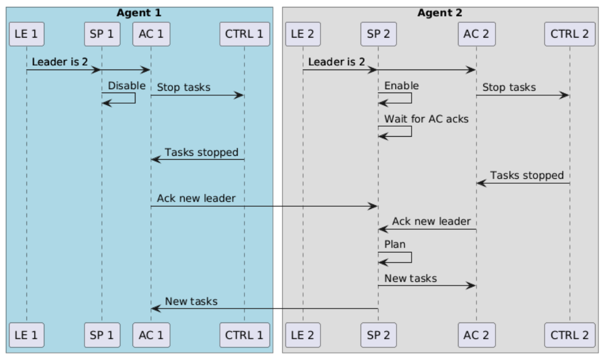

Figure 4. Leader change process. When a new leader is elected, agents stop all tasks started by the old leader; once all tasks have concluded, they acknowledge the new leader, which produces a new plan for the system.

This brief abstract only provides a high-level description of CADRE's mission architecture. We refer the interested reader to [2] for a detailed description of CADRE's overall autonomy architecture; [4] for a discussion of CADRE's planning, scheduling, and execution; [5] for the distributed database, and [1] for the leader-election mechanism. The paper [3] presents CADRE's exploration behavior, one of the two key science-gathering behaviors that will be exercised by the system on the Lunar surface.

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