CADRE: A Lunar Technology Demo of Multi-Agent Autonomy Enabling Distributed Measurements

Federico Rossi and Jean-Pierre de la Croix
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA, USA
Federico.Rossi@jpl.nasa.gov, Jean-Pierre.de.la.Croix@jpl.nasa.gov

***Abstract*— CADRE (Cooperative Autonomous Distributed Robotic Exploration) is a lunar technology demonstration of multi-agent autonomy on a team of three rovers and a base station. It will demonstrate that this team is capable of autonomously exploring the lunar surface, as well as has the capability to perform a distributed measurement together. This technology will enable future missions to achieve new science on the Moon, Mars, and beyond.**

I. Introduction

The CADRE (Cooperative Autonomous Distributed Robotic Exploration) technology demonstration mission [1] will deploy three carry-on-sized, solar-powered rovers to the Moon's Reiner Gamma region (roughly equatorial, Earth-facing at 7.5°N 301.0°W [2]) in April of 2024. The goal is to demonstrate cooperative surface exploration and the feasibility of performing distributed measurements autonomously: i.e., to show that multiple rovers can coordinate to collect spatially-distributed, temporally-synchronized measurements of a region of interest with minimal human intervention. The mission will be delivered to the Moon by Intuitive Machine's IM-3 CLPS lander [3] and is designed to last a Lunar day, or roughly 14 Earth days.

II. Mission

Each CADRE rover is equipped with sensors to support its autonomous functions and a ground-penetrating radar (GPR). The rovers are tasked with performing a surface mapping task with their stereo cameras and then a multi-static GPR survey of the sub-surface nearby. The multi-static GPR survey is achieved by rovers taking turns to radiate a radar signal into the Lunar surface while driving across it, and all three rovers (coordinating to maintain a prescribed distance from each other during the drive) will record the radar reflections from sub-surface features. Compared to a monostatic GPR survey, where a single rover simultaneously transmits and receives, a multi-static survey can be improved on its output by measuring cross-tracks between multiple GPRs, which will allow scientists to reconstruct a 3D sub-surface image with the surface map as context. After teleoperated deployment from the lander and manual commissioning, the rovers will autonomously produce a high-resolution traversability map of the surface with on-board stereo cameras. Ground operators will identify an approximately 500 square meter bounded region to explore.

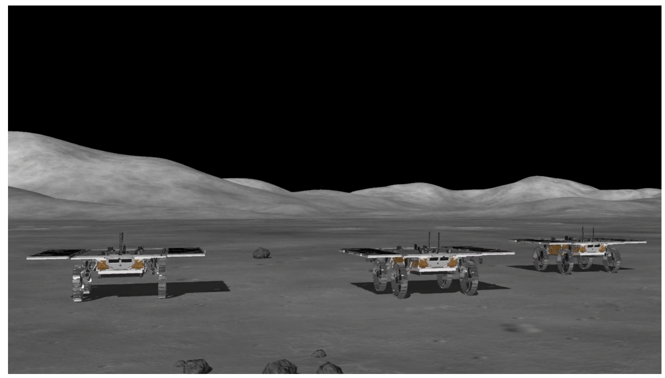

Figure 1: Illustration of three CADRE rovers in formation on the Moon.

The rovers will then autonomously coordinate to divide the area to explore in non-overlapping subregions, one per rover; and assign each subregion to a rover based on the rover's location and health state. Each rover will autonomously drive through its assigned region while mapping it through stereo imaging until it has fully characterized the presence or absence of obstacles that the rovers cannot drive over; and rovers will end the exploration by autonomously merging data from all vehicles to produce a global traversability map of the entire region. This merged map is downlinked to the ground station through a base station on the lander, and a copy is also saved on-board to be used for planning the multi-static GPR survey. Using ultra-wideband ranging measurement between rovers allows the system to improve the map quality by using inter-rover information to perform pose graph optimization, i.e., updating the history of all state estimates by correlating more data together than what can be done on-board a rover alone.

Once a traversability map is available, the rovers will autonomously perform a multi-static GPR survey. Ground operators will prescribe (i) a coarse path that the rovers should follow to achieve GPR coverage of the region, and (ii) the relative pose that the rovers should maintain during the measurement. The rovers will then autonomously drive in formation, following the ground-prescribed path while deviating from it as needed to avoid obstacles, and closely maintaining the prescribed relative poses; one rover will radiate with its GPR, and all rovers will record the radar reflections. The rovers take turns radiating, such that all rovers have can measure radar signals from other rovers. As they move, rovers will autonomously estimate their relative location and poses to cm-level precision through use of RF ranging, visual inertial odometry, and a Sun sensor. The radar data and pose estimates will be downlinked to the ground to reconstruct a 3D volumetric map of the sub-surface.

During both phases of the missions, the rovers will manage their thermal and power resources; specifically, rovers will autonomously and cooperatively alter the duration of their driving activities, periodically stopping to recharge and cool down to ensure that no rover drains its battery during the early and late hours of the Lunar day, or overheats during the Lunar midday. Coordination will be achieved by autonomously designating one of the rovers, or a "base station" located on the lander, as the leader; the leader will perform all coordination activities, gathering information from individual rovers and computing driving and sleeping schedules, regions to explore, and paths to follow to perform the GPR survey. The rovers will autonomously select a leader based on their health, battery level, and thermal state; and autonomously fail over to a new leader if the previous one is unable to performs its tasks—allowing the system to continue to operate autonomously without intervention.

III. Conclusion

Success of the CADRE mission will achieve two key goals:
- to demonstrate the scientific promise of multi-static GPR, a game-changing technique in planetary exploration; and
- to demonstrate the promise of on-board multi-agent autonomy to perform distributed measurements, reducing operators' workloads compared to traditional ground-in-the-loop operations, and enabling distributed measurements with larger number of agents for science on the Moon, Mars, and beyond.

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