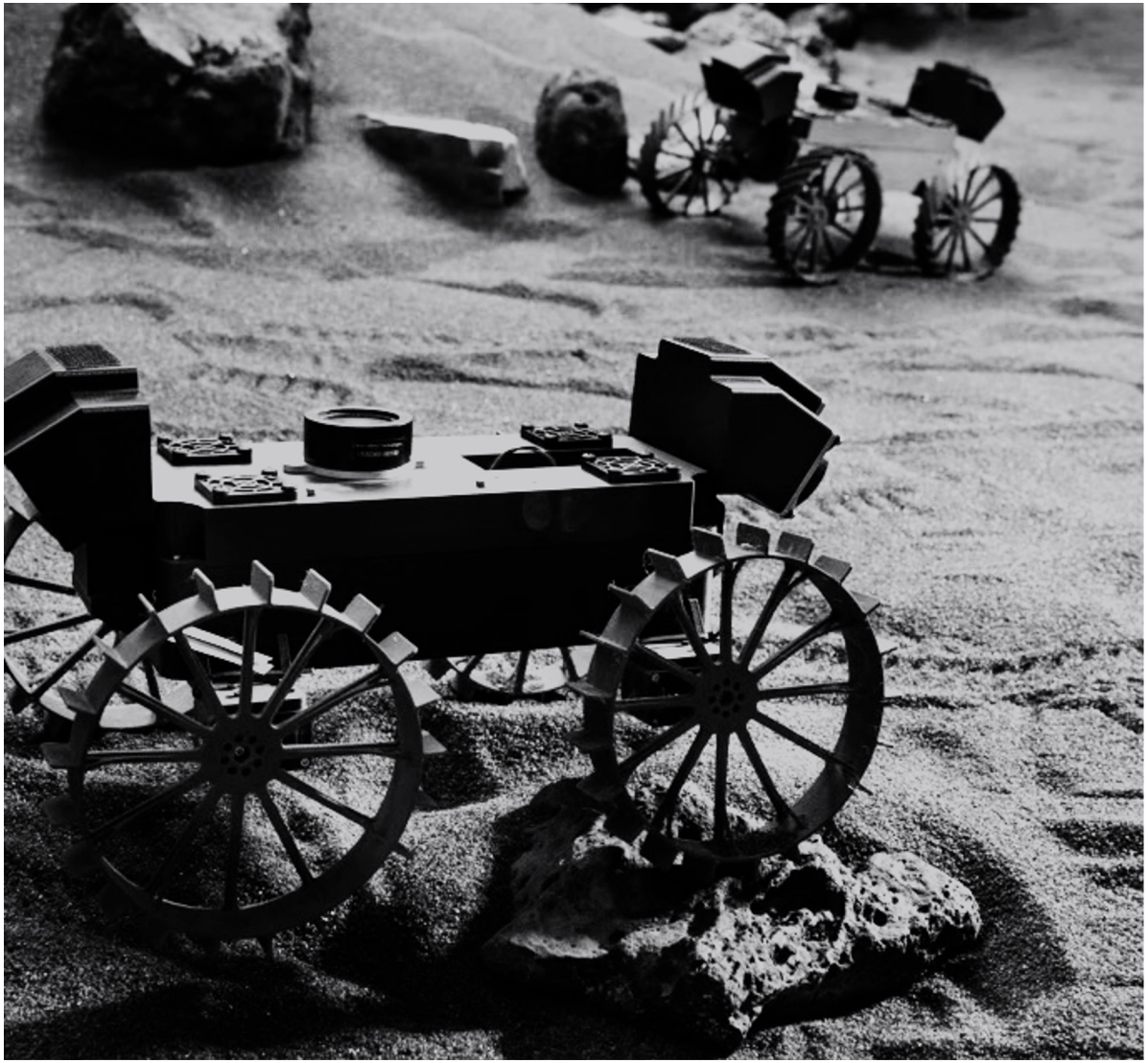

Planning, scheduling, and execution on the Moon: the CADRE technology demonstration mission

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Jet Propulsion Laboratory
California Institute of Technology

Presented at the 2025 Symposium on Advanced Space Technologies in Robotics and Automation (ASTRA)

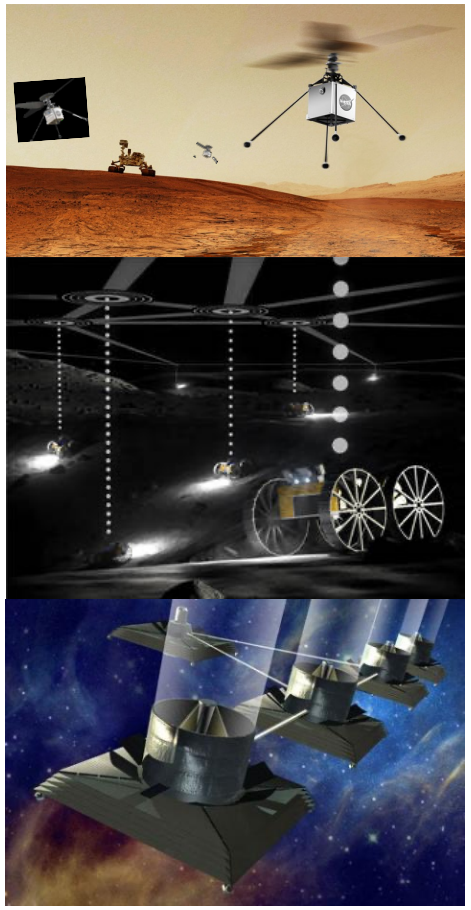
Jet Propulsion Laboratory
California Institute of Technology

Autonomous Robot Teams for Planetary Exploration

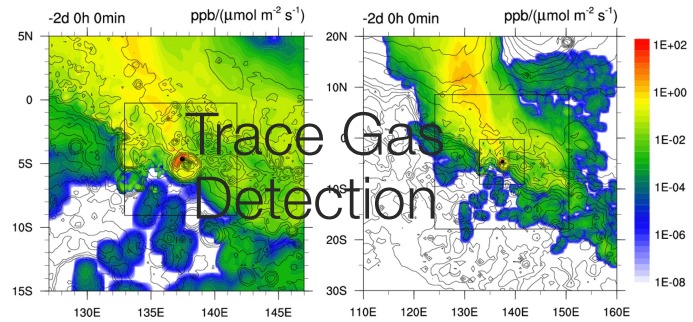
Robot teams are uniquely well-positioned to:

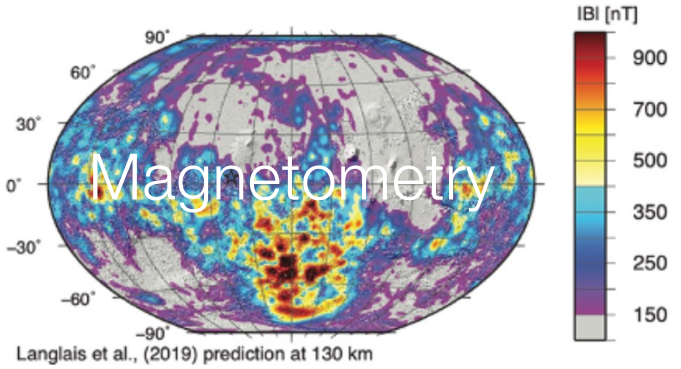
- Collect distributed measurements
  - Seismology
  - Weather and climate
  - Ground-penetrating radar
  - Distributed apertures (in orbit)
- Perform exploration and mapping
- Provide system-level resilience

Current operations paradigms do not scale: autonomy is enabling

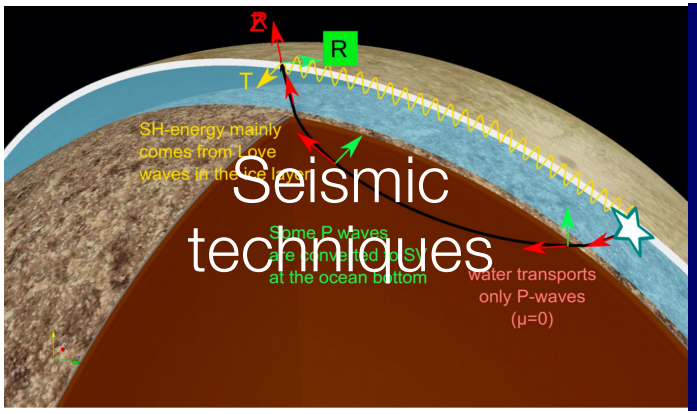


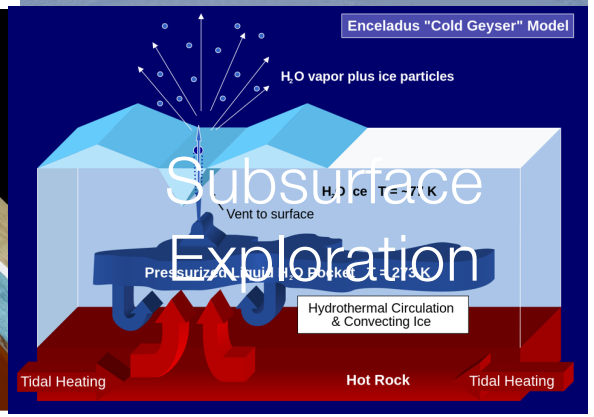
Multi-agent systems enable high-priority science





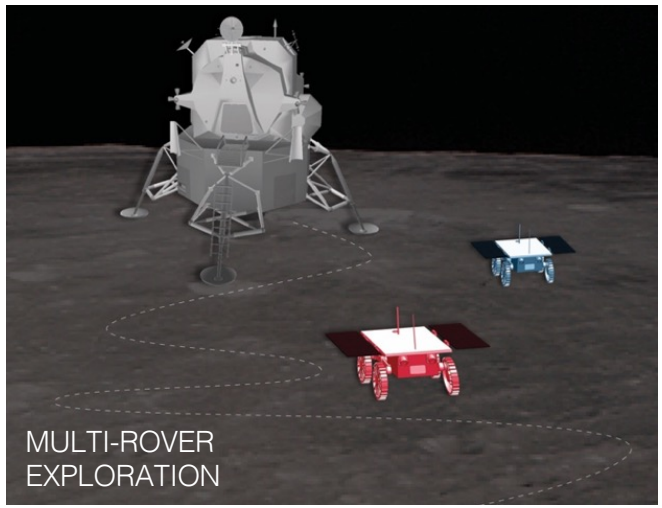
Langlais et al., (2019) prediction at 130 km

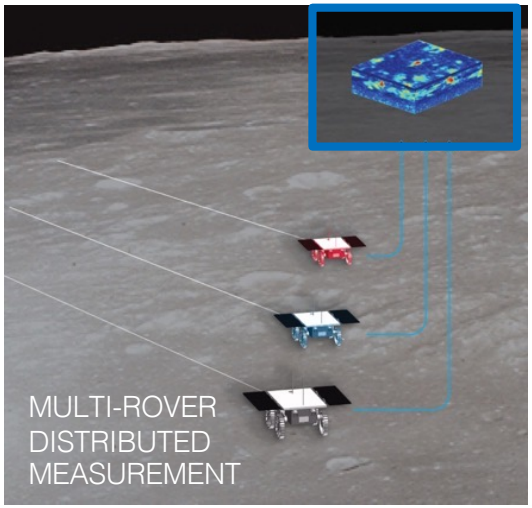


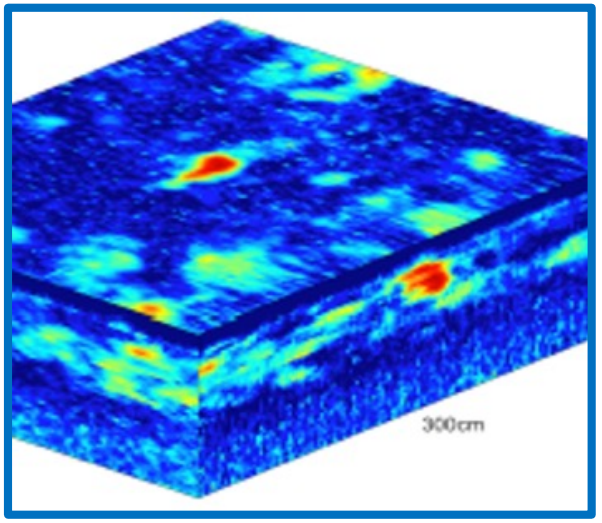


CADRE's Goal

DEMONSTRATE FIRST AUTONOMOUS EXPLORATION AND DISTRIBUTED MEASUREMENT WITH A TEAM OF ROVERS ON ANOTHER PLANETARY BODY



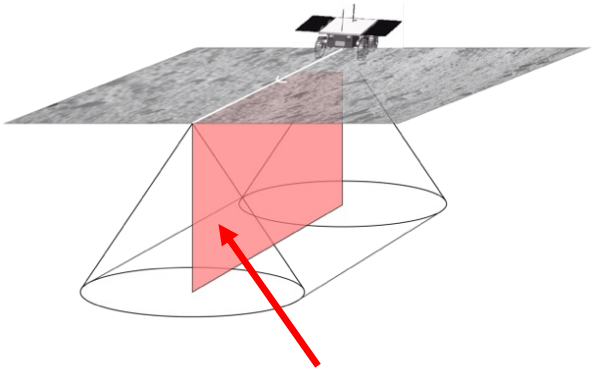




Multi-static Ground Penetrating Radar

Today.

Single Monostatic Measurements



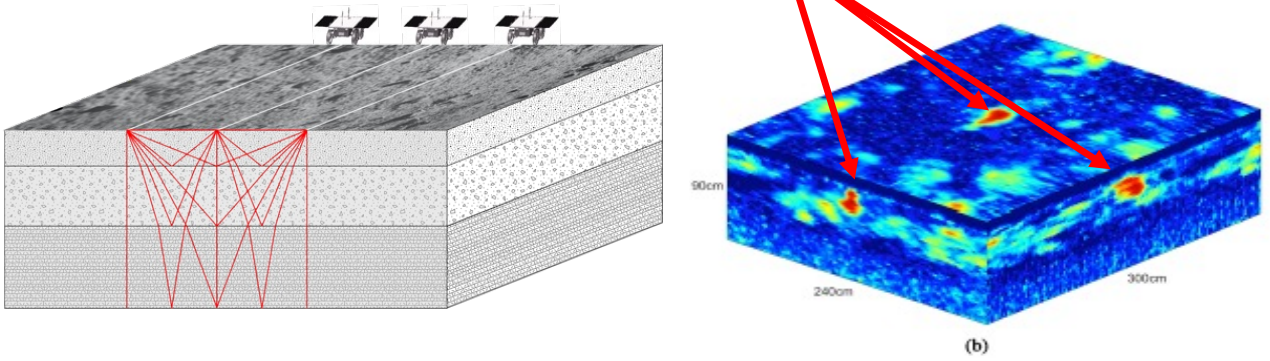
2-DIMENSIONAL DATA ONLY

STATE OF THE ART:
Chang'e 3 and 4 Lunar Penetrating Radar on the Moon
Perseverance RIMFAX on Mars
Zhurong Lunar Penetrating Radar on Mars

Tomorrow.

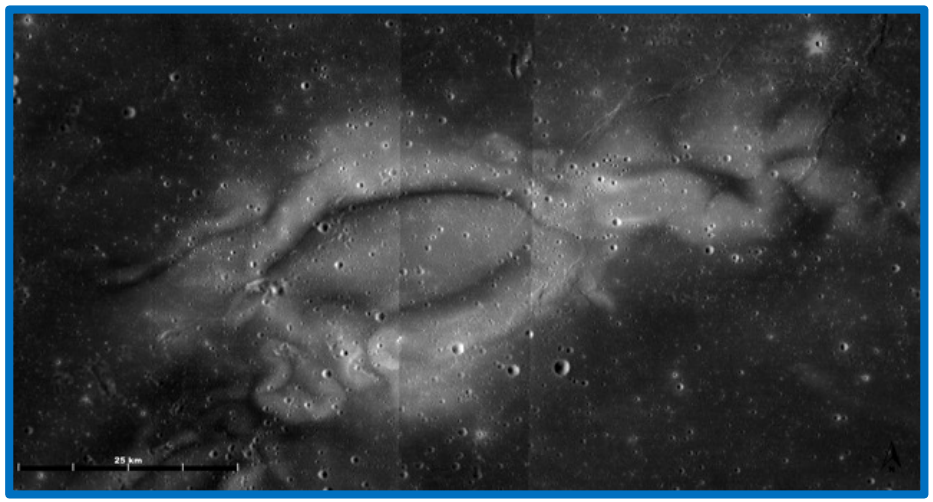
Distributed & Adaptable Multi-Static Measurements

3D SUBSURFACE IMAGERY FROM MULTIPLE GPRs WORKING TOGETHER



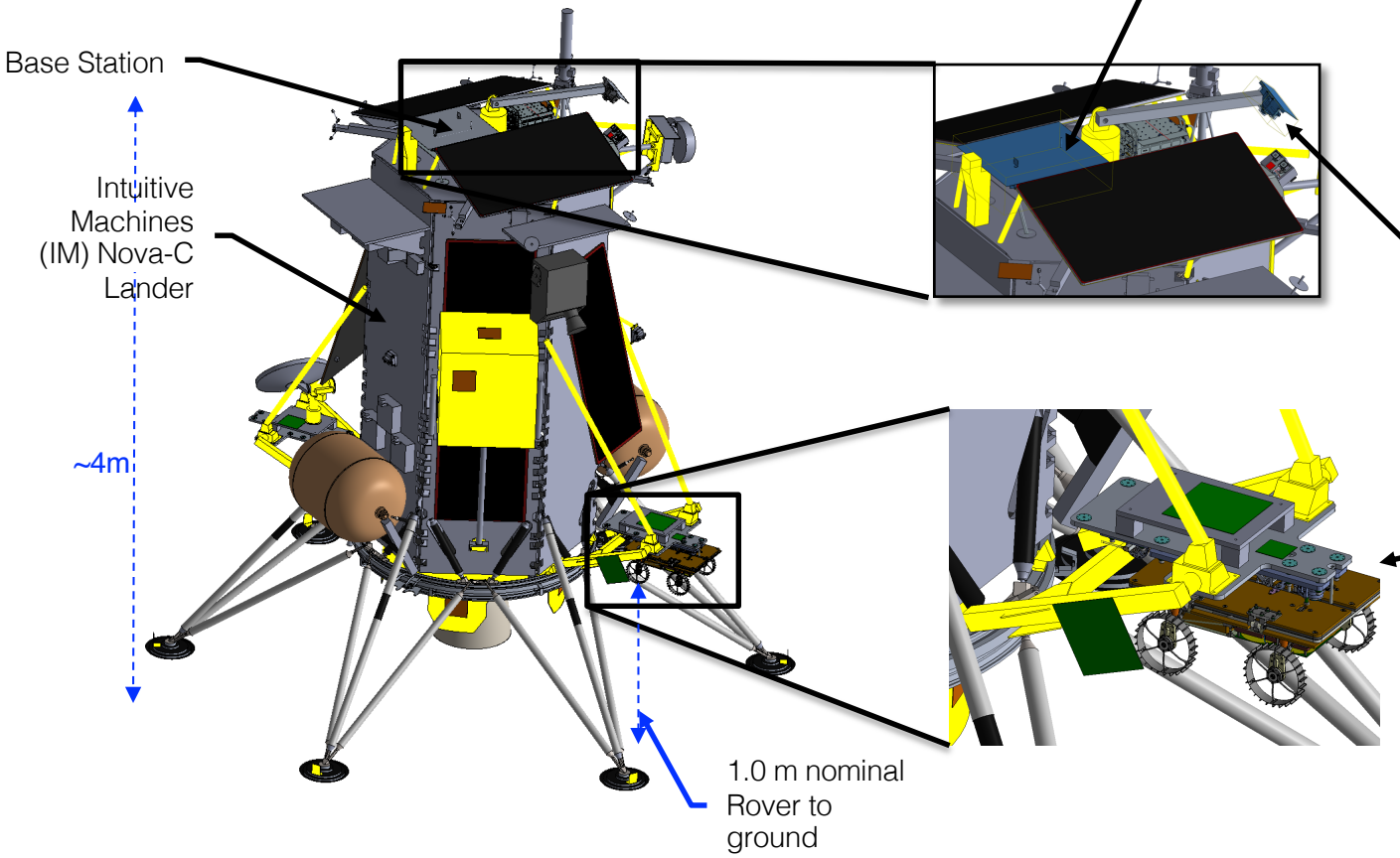
Rovers have to navigate across the lunar surface in a specific formation (separation dictates measuring depth) and maintain this formation within a certain threshold (derived from required Signal to Noise Ratio)

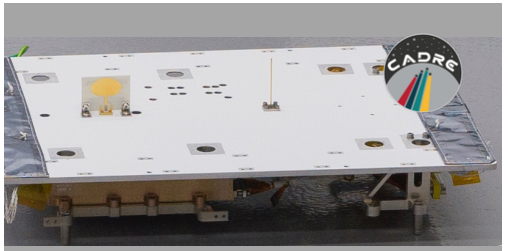
Lunar Technology Demonstration



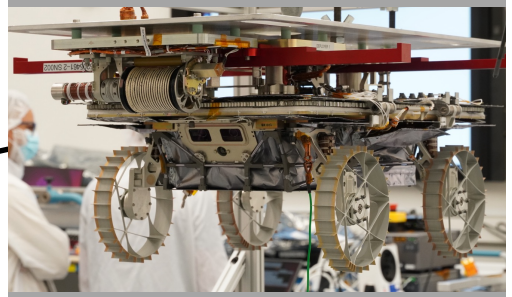
- CADRE is a flight technology demonstration manifested as a payload on CP11 (CLPS)/ Intuitive Machines (IM-3) mission, targeting **launch in the next year** on Falcon-9.
- CADRE is funded from Space Technology Mission Directorate (STMD) under Game Changing Development (**GCD**).
- Destination: Reiner Gamma is known for its mysterious lunar swirls, where dark and light regolith mix.
- Three rovers will work together to explore the surface nearby during a single Lunar day (about **10 Earth days**).

System Overview

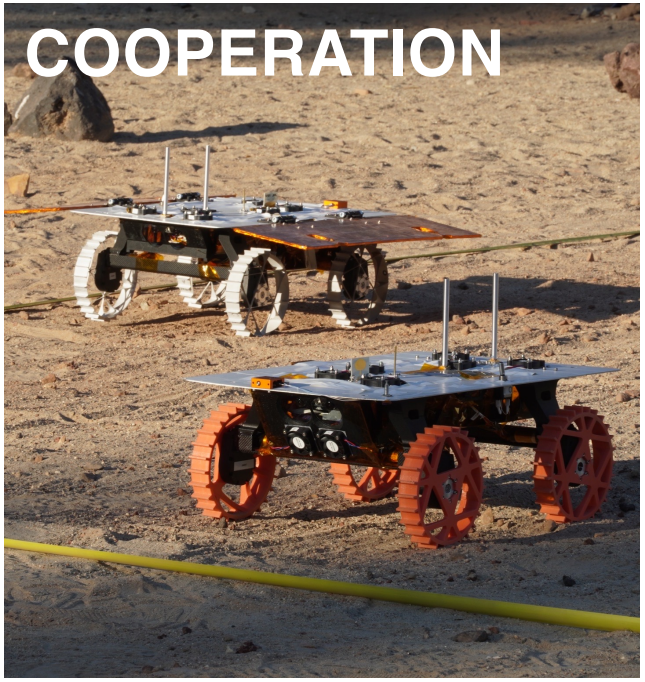




JPL provided SACA Situational Awareness Camera Assembly mounted to lander provided gimbal

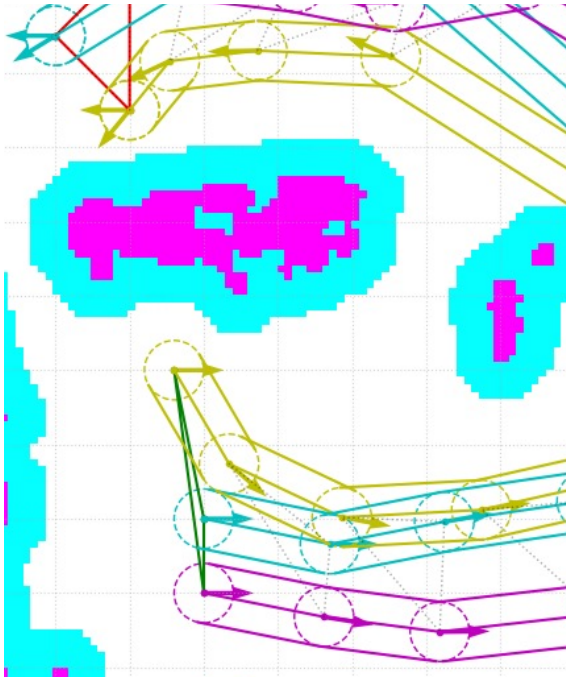


JPL provided Rover-Deployer assembly x3



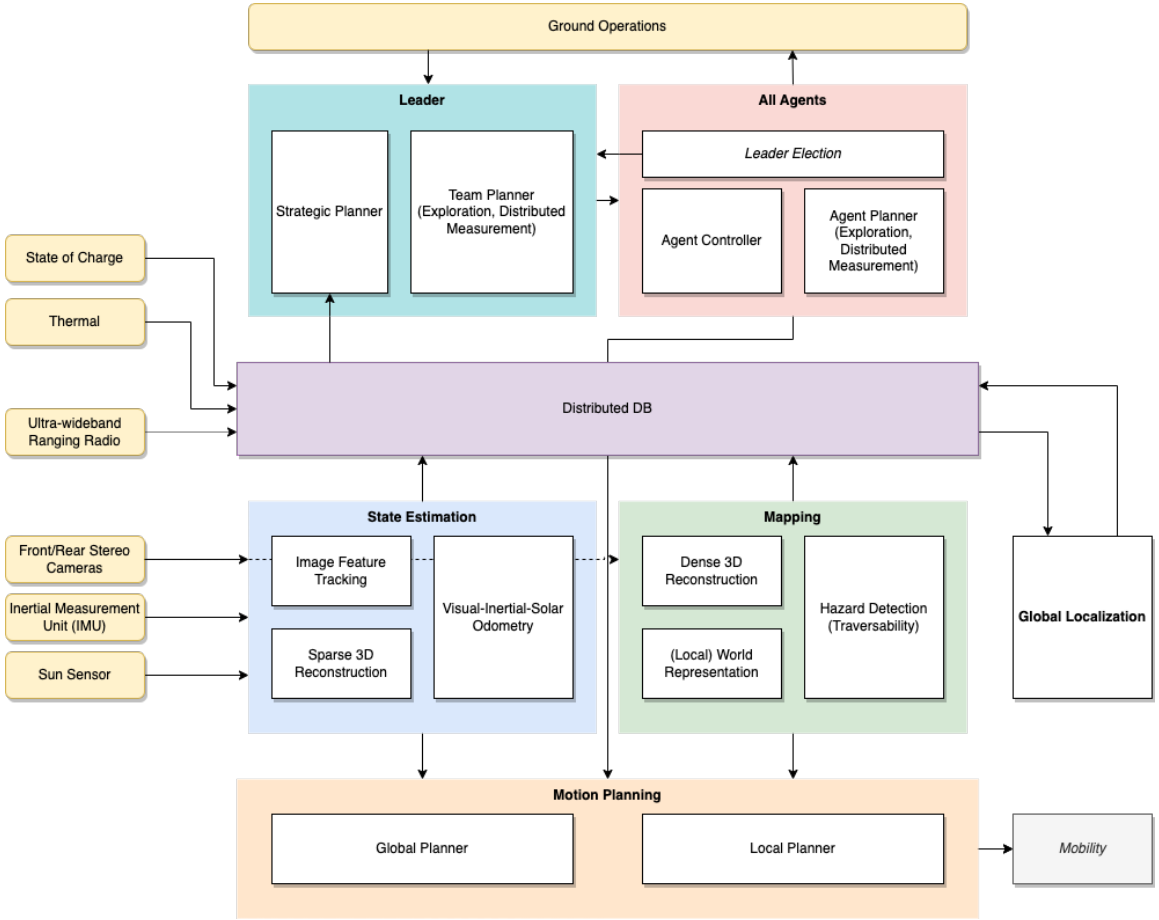
Cooperation is about autonomous agents working together to solve a problem by sharing information and making decisions that are consistent in achieving the goal as a team.

Cooperative exploration can be used to build a map of a previously unexplored location. Orbital imagery of IM-3's landing location is limited to approximately 1m per pixel in resolution, which is larger than a CADRE rover!



Distributed measurements with a multi-static GPR must maintain inter-rover distance within a specified threshold even in the presence of obstacles (rocks, craters, and other rovers on the Moon!) along the intended path.

The Autonomy Stack



Ground

Provide goals:
Explore this region
Follow this path in formation

Leader

Decide:
What can I do with all available resources?
Who goes where?

Every Rover

Communicate:
What do we all know?

Estimate:
Where am I?

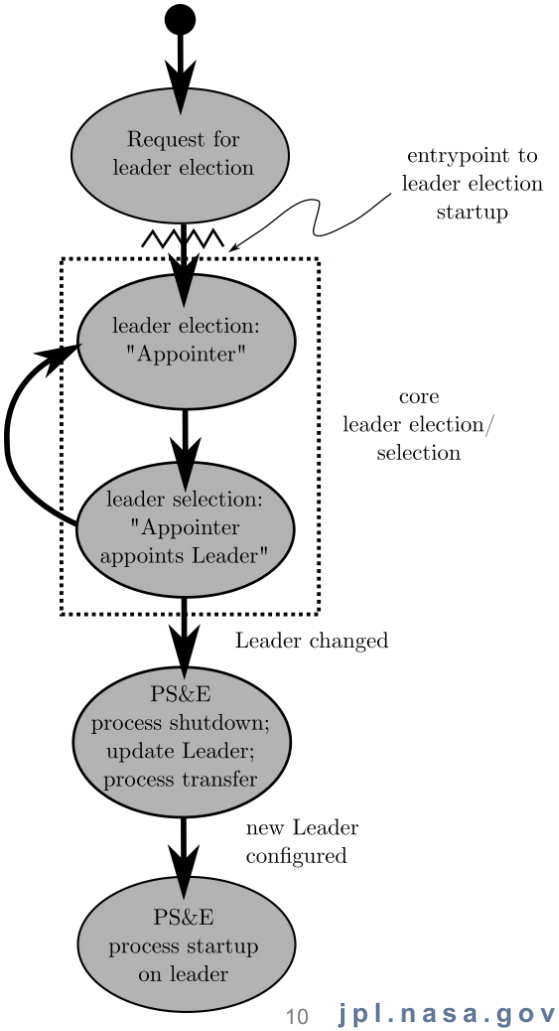
Estimate:
What does the Moon look like?

Decide:
How to get there?

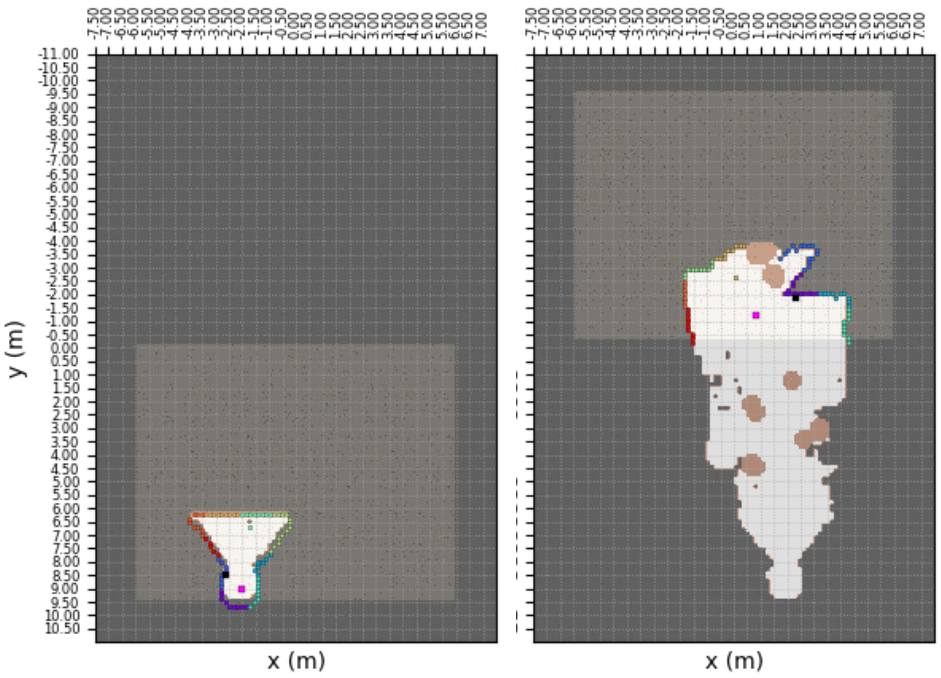
Leader Election

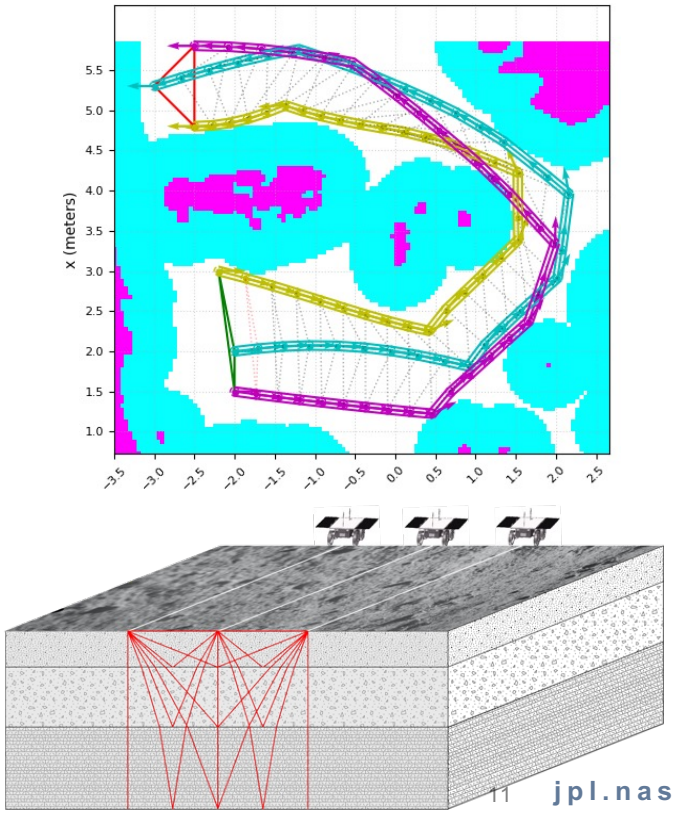
1. Leader election runs continuously in background
2. A unique agent is selected as “Appointer” via GHS MST
    1. Intuition: recursively merge trees O(log(n)) times
3. Appointer queries all other agents for health metrics (convergecast)
4. Appointer appoints leader and informs all agents (broadcast)
5. Process repeats periodically as a failsafe (e.g., leader has died)

Rationale: decouple (i) finding a unique agent from (ii) finding the best leader

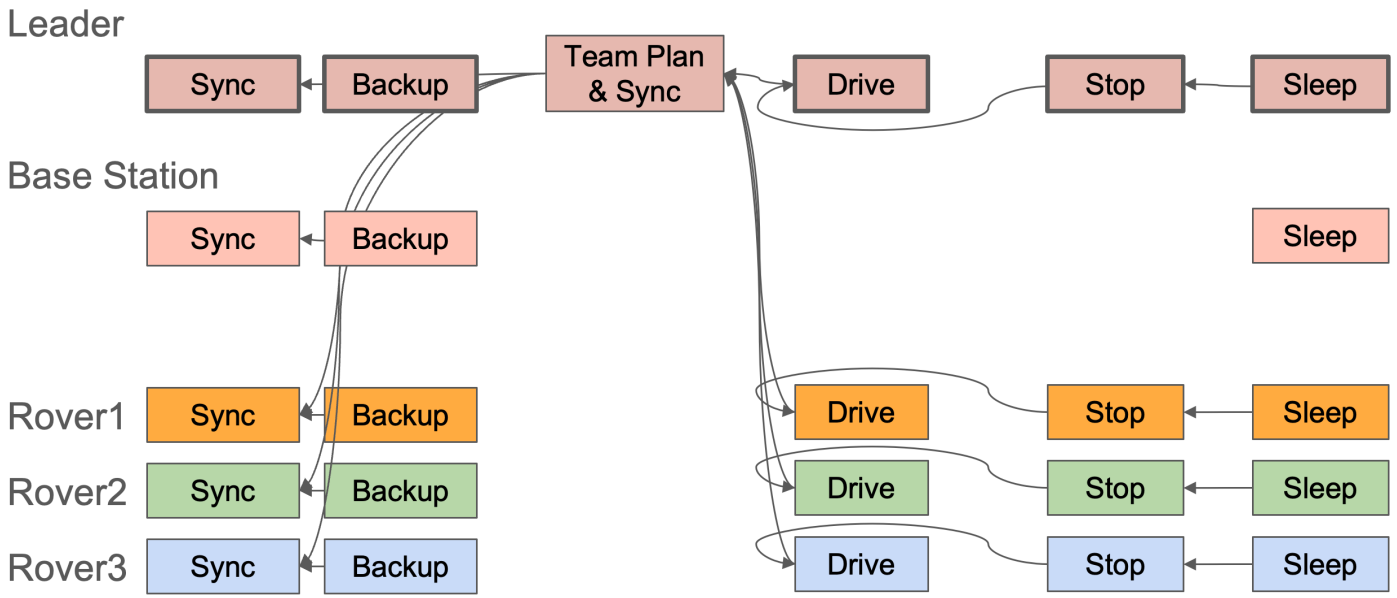


Exploration and Distributed Measurement

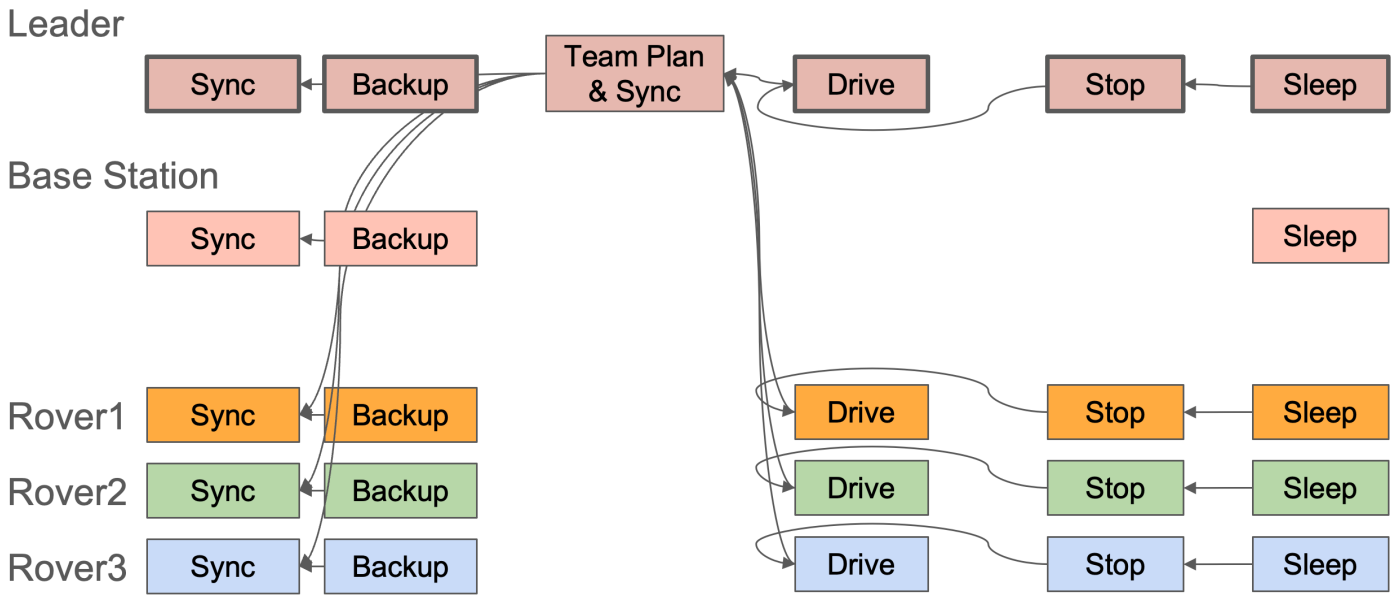




Exploration and Distributed Measurement



Exploration and Distributed Measurement



Exploration: *independent* drive tasks

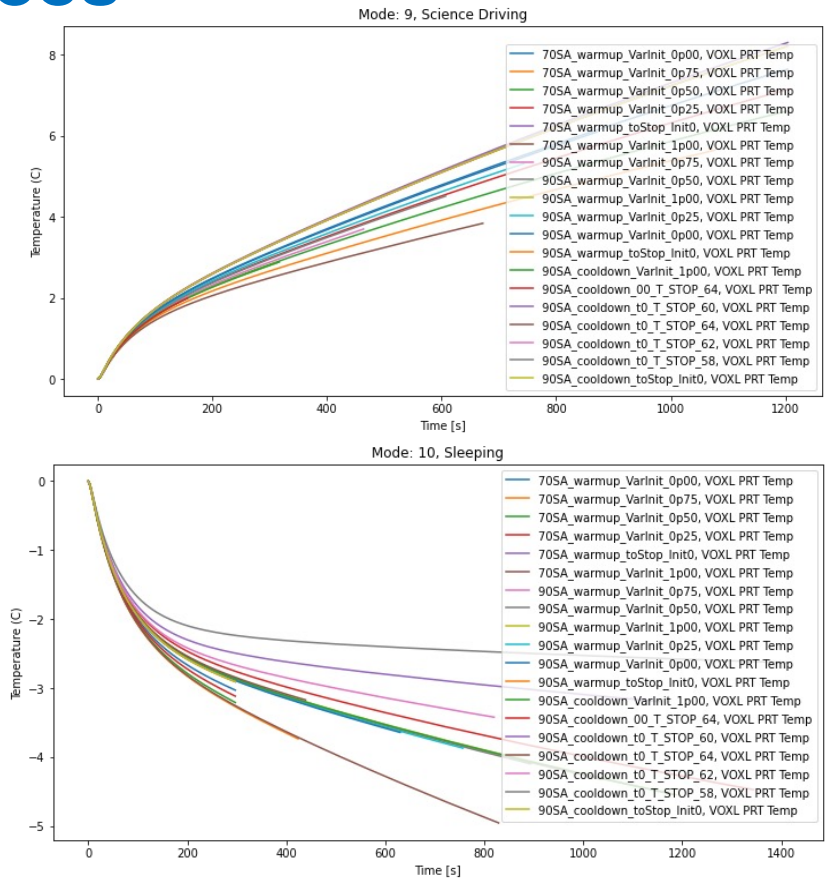
Distributed measurement: *coordinated* drive tasks

Planning: tasks and resources

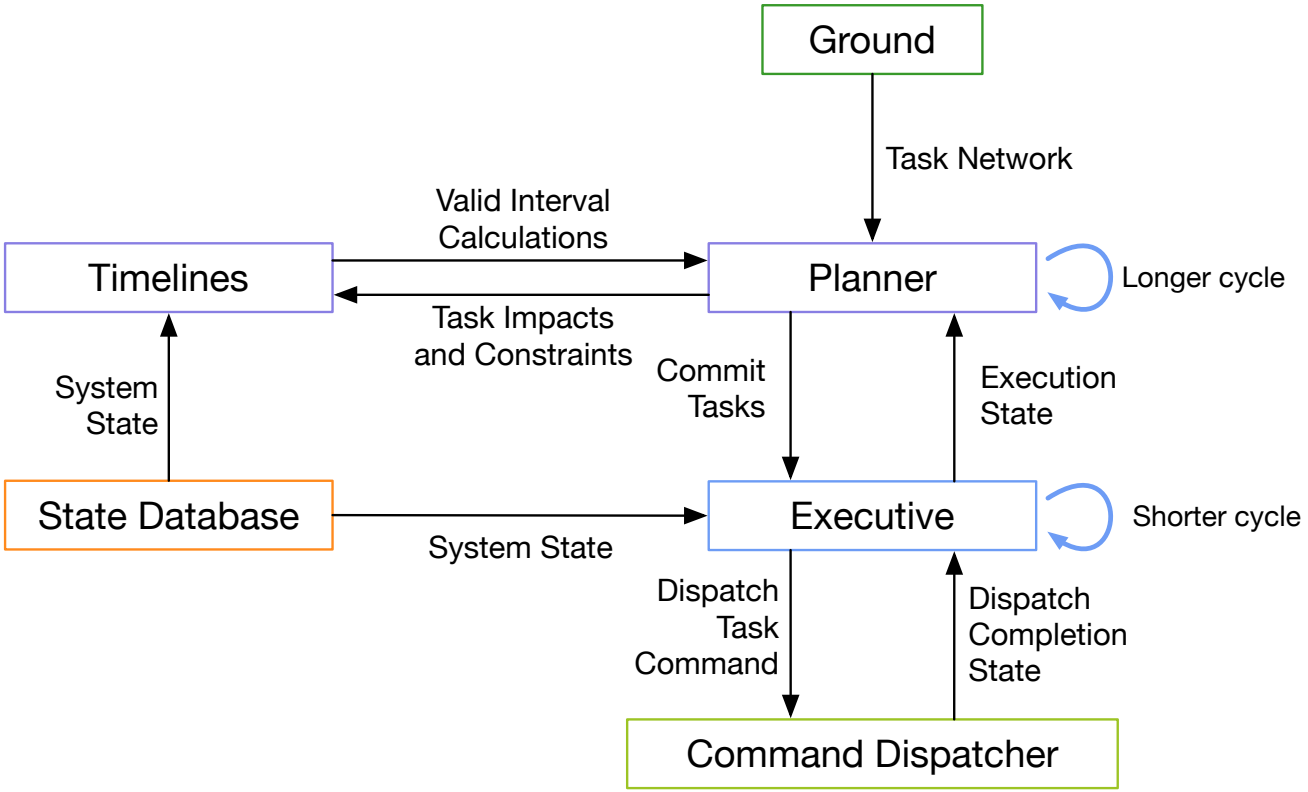
Resources:

- Time
  - Enforced reboots every 30 minutes
- Temperature
  - Limiting factor close to Lunar noon
- Power
  - Limiting factor at Lunar dawn, dusk

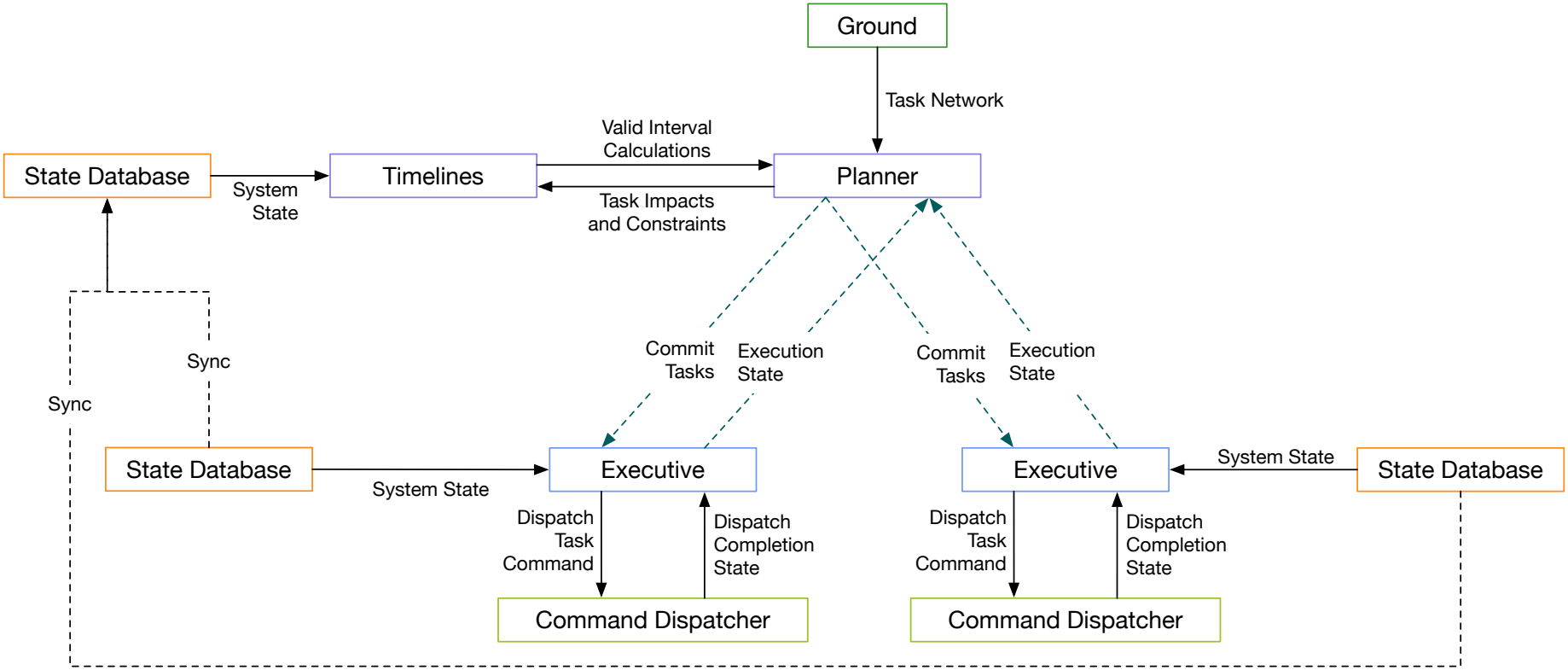
Linear models of resources evolution



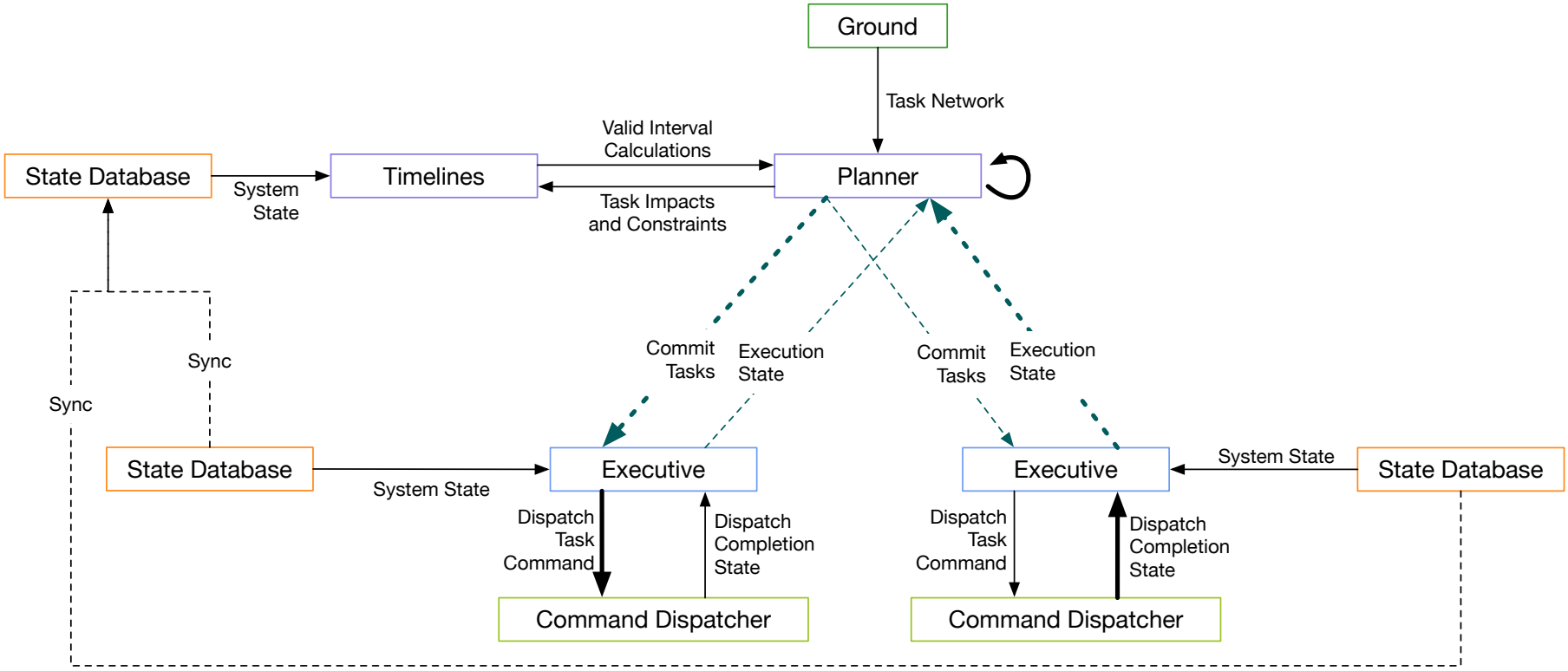
Centralized Planning, Decentralized Execution



Centralized Planning, Decentralized Execution



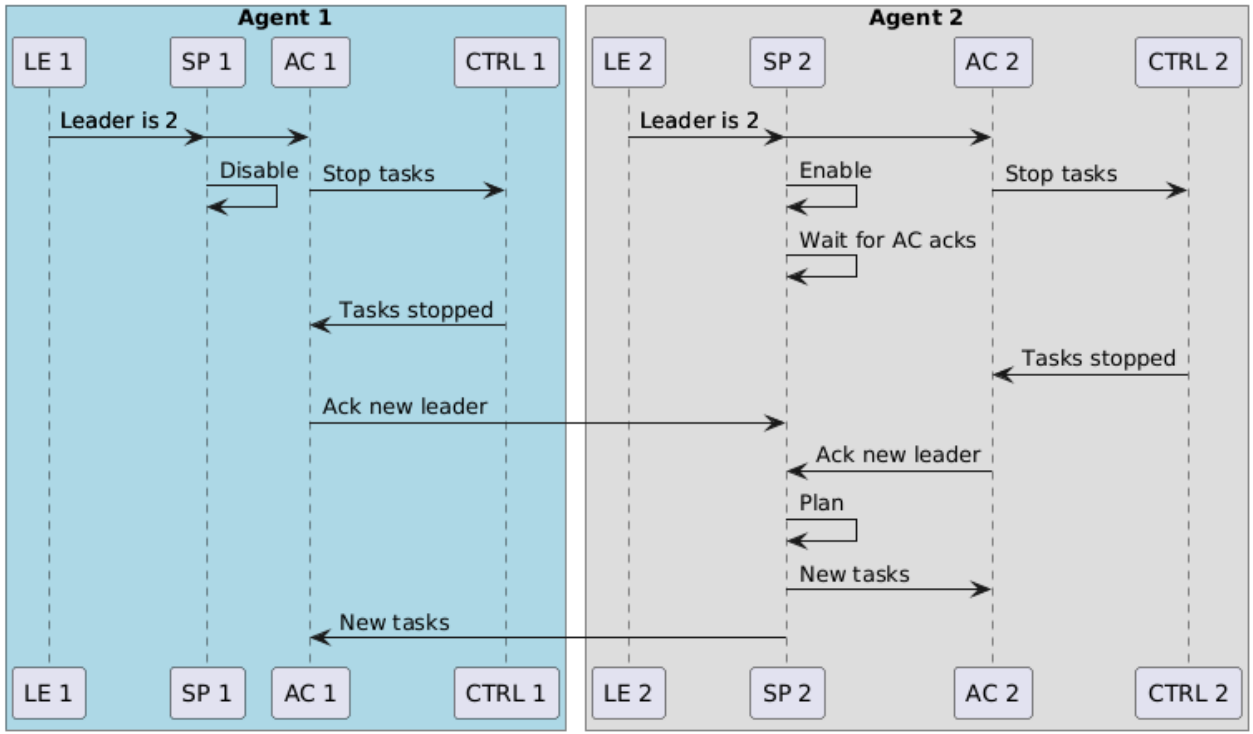
Multi-Agent Constraints



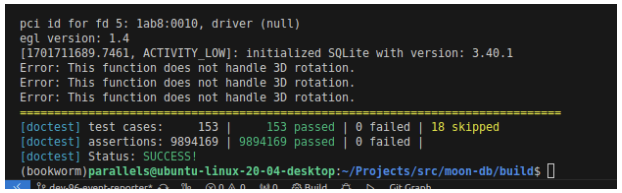
When the leader changes

When a new leader is elected:

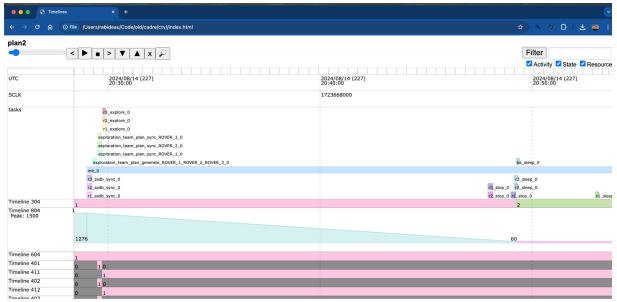
- Enable new planner
- Disable old planner
- Controllers flush all running tasks
  - No need to transfer state of running tasks
- New planner waits for all controller to flush tasks and acknowledge it
- State is maintained by shared DB



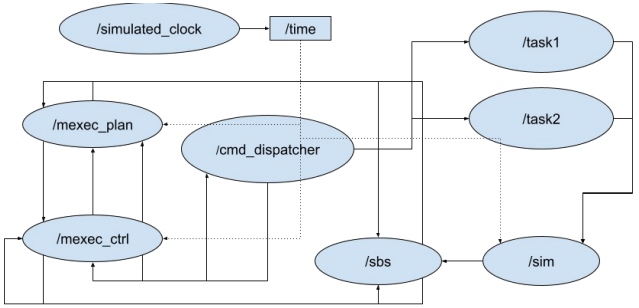
Testing for flight



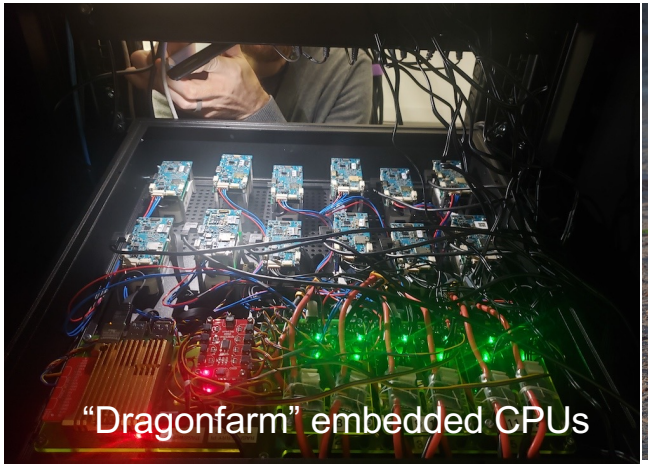
Unit tests

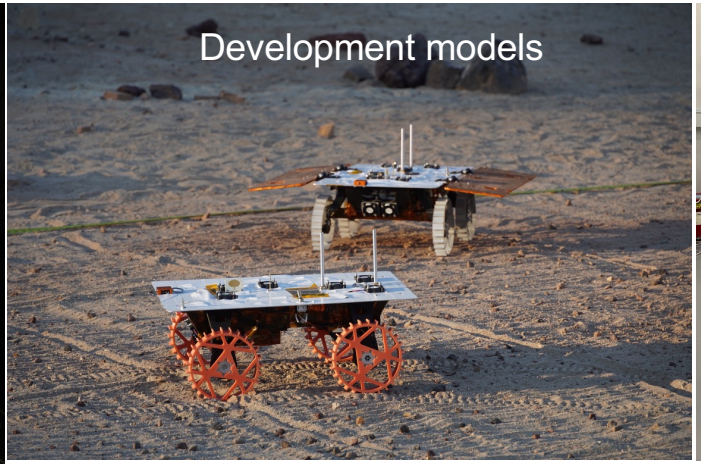


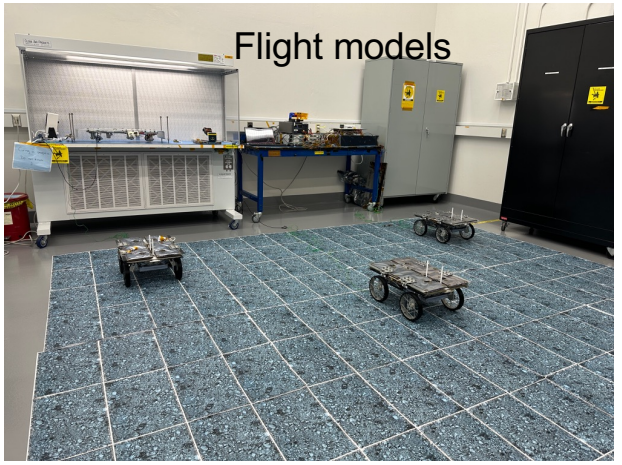
Batch Planning



ROS Simple sim







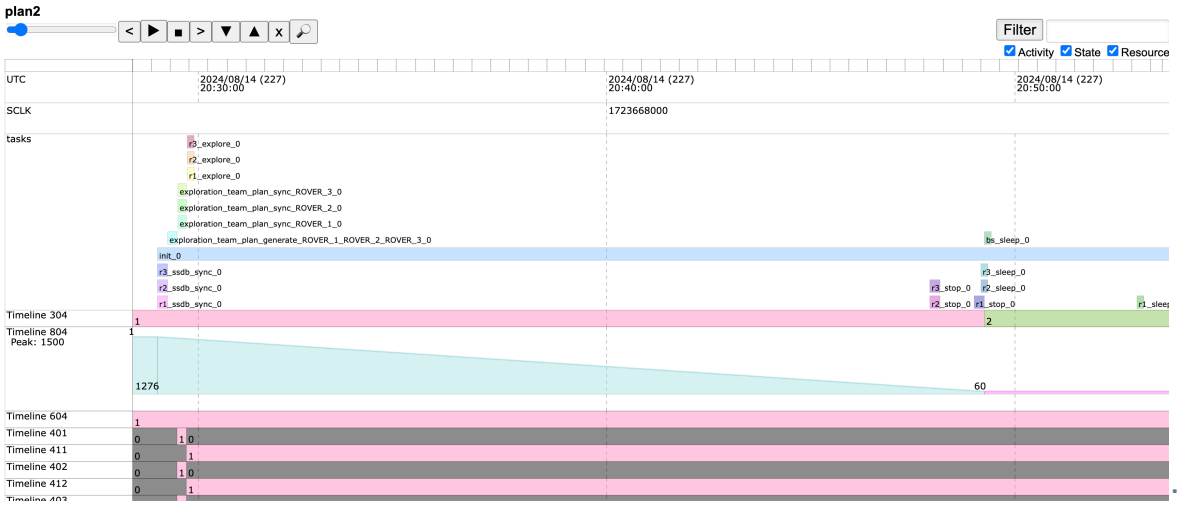
Testing for flight

	Scheduling	Nominal exec.	Off-nominal exec.	FSW integration	Actual driving	Outdoor driving	Full sensor suite	Specialized HW	Flight HW
Batch planning	✓								
ROS sim	✓	✓	✓						
Dragonfarm	✓	✓	✓	✓				✓	
Dev. Models	✓	✓	✓	✓	✓	✓		✓	
Flight Models	✓	✓	✓	✓	✓		✓	✓	✓

Testing for flight: batch and ROS planning

Exhaustive exploration of possible execution paths can uncover brittleness, bugs in the task network

Task	Nominal	Starts late	Runs late	Ends early	Fails
SSDB Sync	✓		✓	✓	✓
Team Planning	✓		✓	✓	✓
Formation	✓	✓	✓	✓	✓
Exploration	✓	✓	✓	✓	✓
Stop	✓	✓			
Sleep	✓	✓			



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