Robotic Exploration of Martian Caves in the Search for Life

Ali-akbar Agha-mohammadi[1], Karl L. Mitchell[1], Penelope J. Boston[2]

[1]NASA Jet Propulsion Laboratory, California Institute of Technology; [2]NASA Ames Research Center

Planetary Cave Exploration

More than 200 lunar and 2000 Martian cave-related features have been identified.

Vents and fissures associated with water ice plumes on Saturnian, Jovian, and Neptunian moons also represent possible cave systems (e.g., Boston, P.J. "Extraterrestrial Caves" 2004; Wynne, et al., 2016)

Astrobiology interest

Stable physio-chemical environments, may trap volatiles, enhance secondary mineral precipitation and microbial growth, preserve biosignatures, and provide record of past climate (e.g. Boston et al., 2001; Leveille and Datta, 2010; Northup et al., 2011)

Volcanic processes

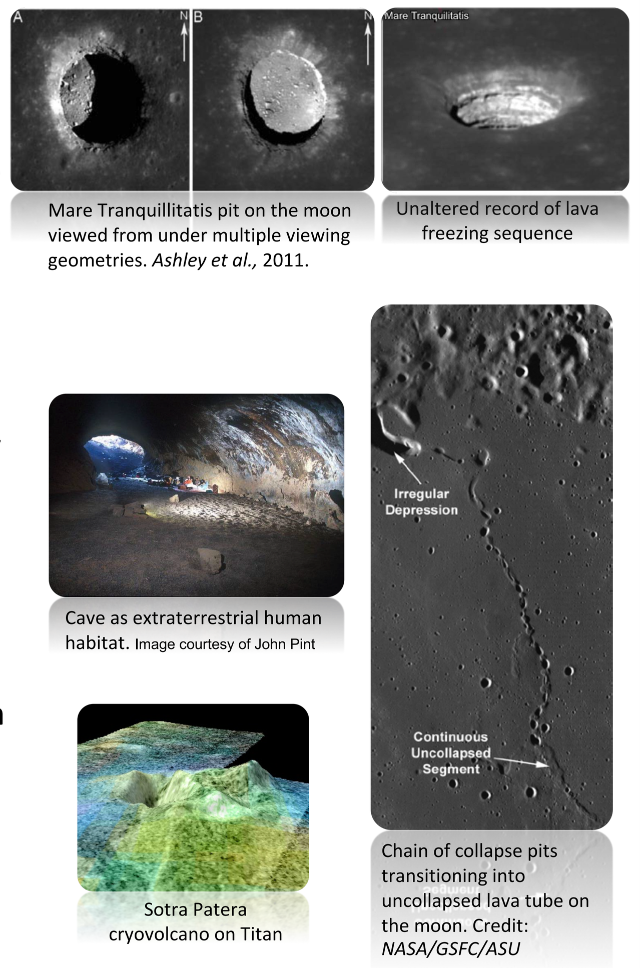
Petrology informs lava temperature and cooling history, would lead into insight into Martian magmatic processes and differentiation (e.g. Ashley et al., 2011; Kerber et al., 2016)

Potential environment for future human exploration

Expected stable, UV-shielding environment and potential to act as volatile traps may make caves ideal habitats for future human exploration (e.g. Boston et al., 2007; Boston et al., 2010)

Cryovolcanos

E.g., on Titan: Some of most pristine, earth-like environment in the solar system, with chance of finding pre-biotic chemistry



Mare Tranquillitatis pit on the moon viewed from under multiple viewing geometries. Ashley et al., 2011.

Unaltered record of lava freezing sequence

Cave as extraterrestrial human habitat. Image courtesy of John Pint

Sotra Patera cryovolcano on Titan

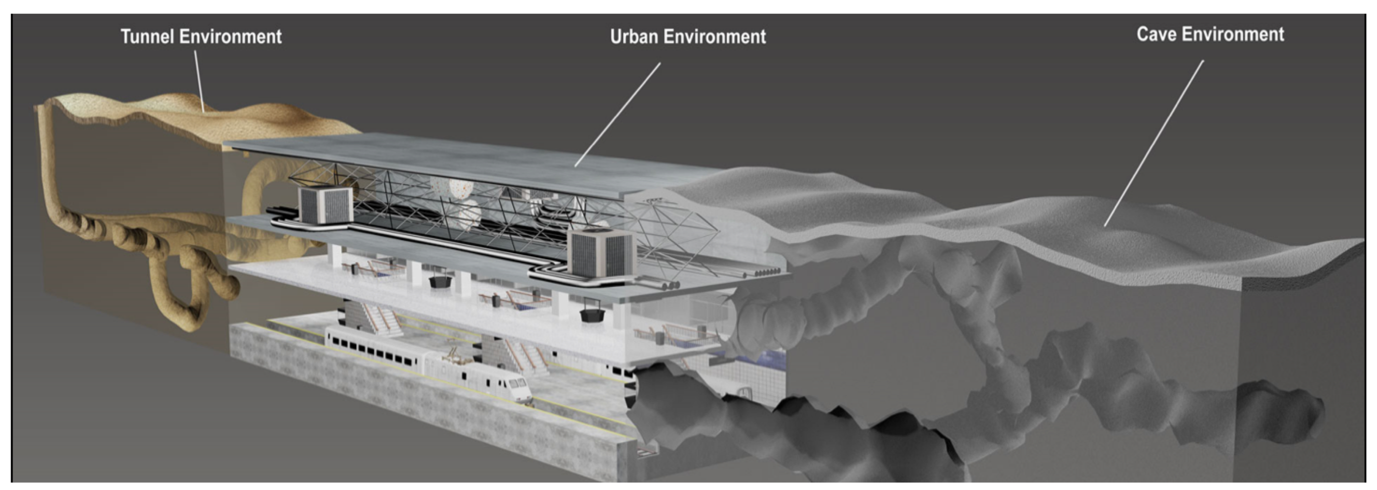
Chain of collapse pits transitioning into uncollapsed lava tube on the moon. Credit: NASA/GSFC/ASU

Terrestrial Subterranean Exploration

- Expedited Technology maturation in the last decade
- Synergistic collaborations with the rising commercial space sector, traditional mining companies, and other government agencies.
- Most prominently, DARPA SubTerranean (SubT) Challenge: NASA is participating in this challenge with a dual focus on the search for signs of extinct and extant life, and resource characterization and acquisition

CoSTAR team @ DARPA SubTerranean (SubT) Challenge

Objectives: to revolutionize autonomous robotic technologies needed for explore, map, and search fully unknown caves and underground environments
Duration: 3 years; 6 events (two trials; four competitions)
Scoring: 3D Geometric and semantic mapping, find artifacts and interesting objects in an 8-km-long cave network



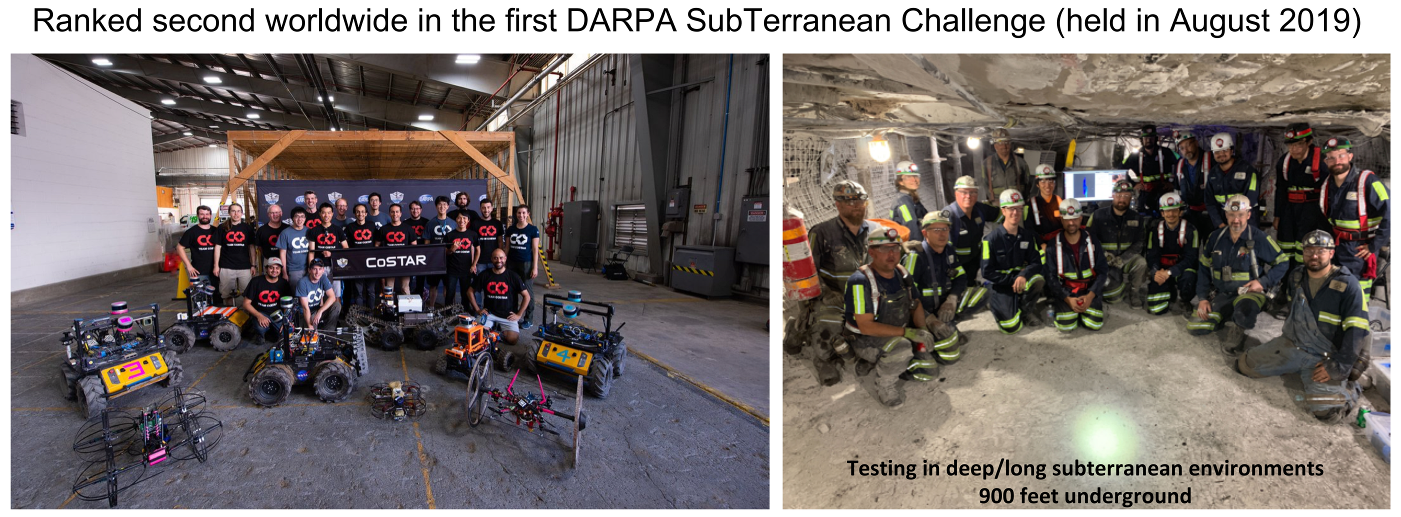
JPL Caltech MIT KAIST intel CLEARPATH TELEDYNE Velodyne

TEAM COSTAR

Collaborative SubTerranean Autonomous Robots

High-level approach: Adaptable, heterogeneous set of robots and instruments to enable various capabilities in an autonomous cave exploration mission.

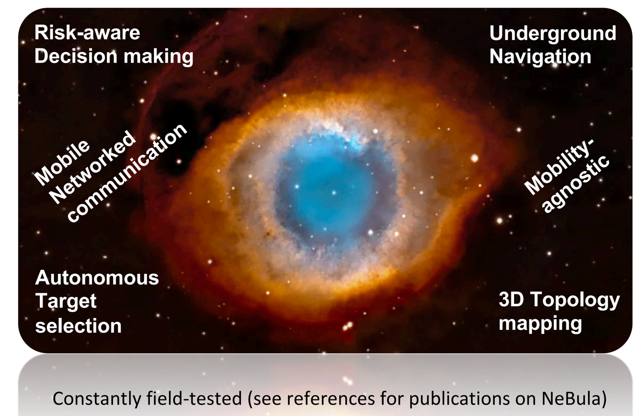
Ranked second worldwide in the first DARPA SubTerranean Challenge (held in August 2019)



Areas of Technical Fidelity and the NeBula Framework for Autonomy

Area of Technical fidelity	Operational Mode
Cave access/ Descent	Precision landing for limited-range/speed mobility solutions. Descent into a skylight
Cave mobility	Deep/long cave traverse over unknown challenging surfaces
Power	Extended operation without sunlight
Communication	2-way data transfer for operation and science return without line-of-sight from deep caves to surface and to Earth
Autonomy	Navigation within a previously unmapped environment; automation of complex path planning and hazard avoidance; 3D mapping and intelligent target selection and coverage
Instrumentation	Low/no light conditions, limited power, cave specific conditions/materials

Nebula: Autonomy stack (cloud of algorithms for planning/perception/etc)



Constantly field-tested (see references for publications on NeBula)

Networked: Handles multi-robot systems and communication

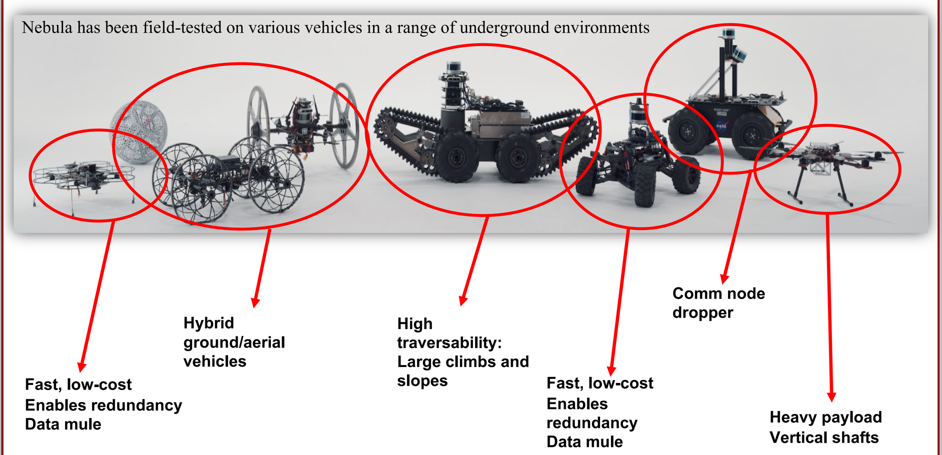
Perceptual: Handles noisy sensors and partial information (POMDP-based)

Nebula: Networked Belief-aware Perceptual Autonomy

Belief-aware: Probabilistic (Risk and confidence are encoded in messages)

1) NeBula is Mobility Agnostic

Objective
Integrate NeBula on low-cost long-endurance mobility systems to enable them to go through narrow passages (sub-meter width) and negotiate extreme cave environments (large climbs/drops/slopes)

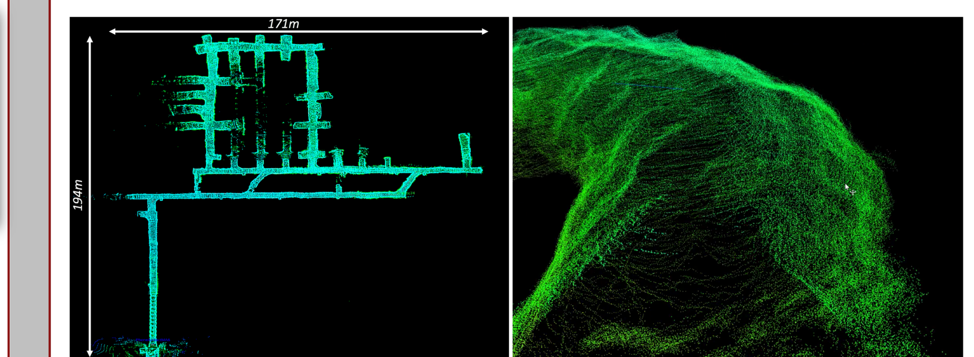


Requirements
- Long/deep caves (up to 8Km long)
- Time-constrained and long-endurance missions (30 minute to days)
- Terrain variations (terrestrial and planetary): Climbs/drops/slopes/vertical shafts/stairs, mud, dirt, rock, obstacle-laden, narrow passages (sub-meter width)
- Low-power small electronics: collision-prone environments

Approach
- Mobility-agnostic autonomy payload
- Integration with heterogeneous multi-robot systems; Multi-modal mobility (hop/roll/bounce/fly)
- Resiliency via redundancy and collision-tolerant
- Ruggedized, water-resistance, modular electronics

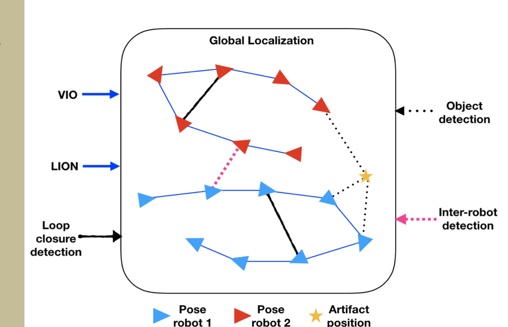
2) NeBula Topology Mapping Capability

Objectives
- Lightweight drift-free 3D topology mapping of multi-Km-long environments
- Global localization of areas of scientific interest
- Local surface feature mapping



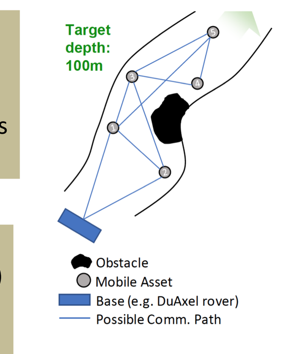
Requirements
- Error<5m in 8-kilometer SubT environment
- Distributed, multi-agent
- Multi-sensor fusion

Approach:
Large Area Mapping and Positioning (LAMP)
- Multi-constrained non-linear optimization (factor graphs)
- Include multi-robot, and multi-sensor input
- Revisited scene recognition - robust registration (loop closure)
- Local submap fusion from multiple robots
- Centralized or distributed computation

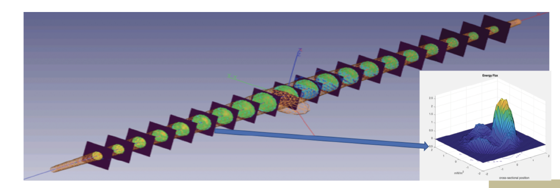


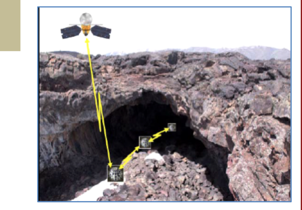
3) NeBula non-LOS Cave Communication

Objectives
- Reliable high-volume low-latency communication to the surface and between robots
- Reliable low-volume low-latency commands to robots
- Communication aware autonomy

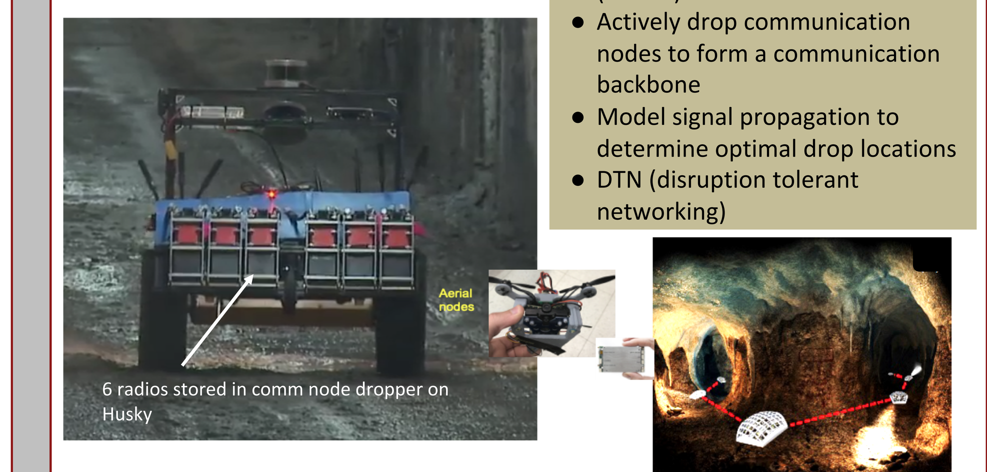


Requirements
- No direct line of sight (up to 8km long tunnels/caves)
- The signals are scattered in cave environment, generating unpredictable link qualities
- Multi-agent communication/coordination in an unknown environment


Waveguide effect in caves visualized with comms modelling



Approach
- Network radios supporting Multiple Inputs Multiple Outputs (MIMO)
- Actively drop communication nodes to form a communication backbone
- Model signal propagation to determine optimal drop locations
- DTN (disruption tolerant networking)

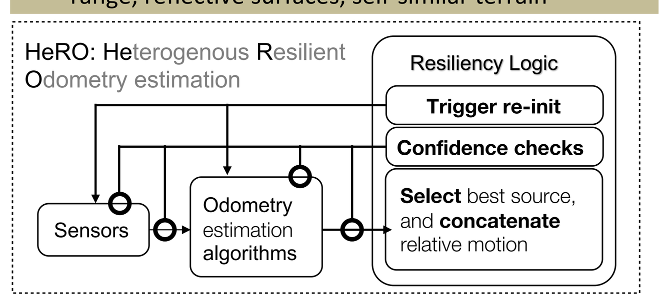


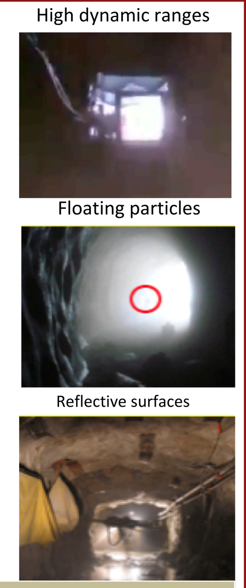
6 radios stored in comm node dropper on Husky

4) NeBula Navigation in Dark Caves

Objectives
- Navigation with lightweight sensors in sensing-degraded environments

Requirements
- GPS-denied, lightweight sensors
- Perceptually-stressing terrestrial and planetary environment: Dark, dust/fog/smoke, high-dynamic range, reflective surfaces, self-similar terrain

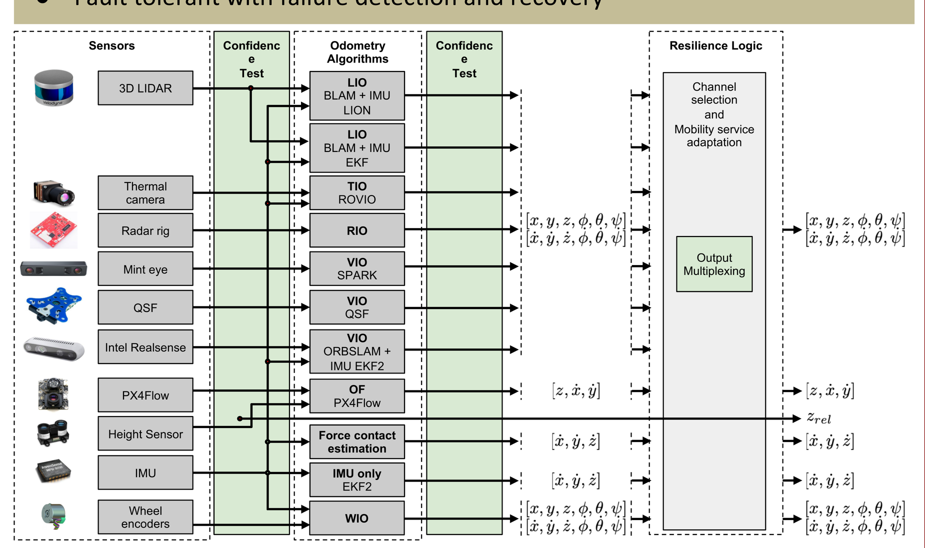



High dynamic ranges

Floating particles

Reflective surfaces

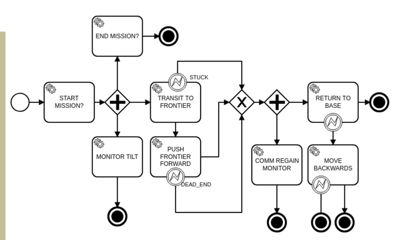
Approach
- Uncertainty-aware multi-sensor fusion: Failures considered by design
- Fault tolerant with failure detection and recovery

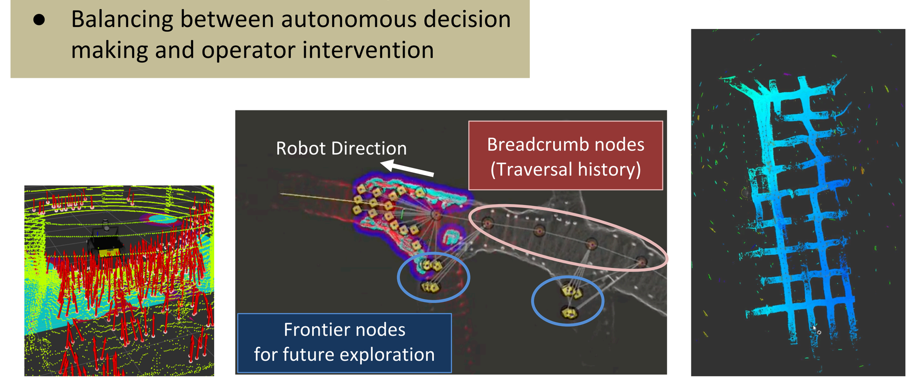


5) NeBula Autonomous Decision Making

Objectives
- Encoding science mission spec's and long-term comms-denied operations
- Minimal to no human intervention
- Time-changing objectives under hard and soft constraints
- Human-friendly mission specification

Requirements
- Unknown and unpredictable variables/environment
- Multi-agent, intermittent communication
- Losing full or partial capability/health of an agent
- Modeling and balancing risk in high-level mission and low-level mobility
- Balancing between autonomous decision making and operator intervention


Graphical representation of mission specification



Local motion planning (< 5m)

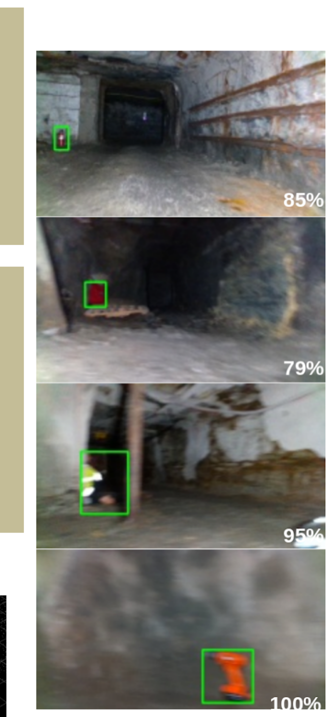
Mid-range planning (< 20m)

Long-range path planning (100m~1km)

Approach
- Accurate risk quantification under uncertainty in motion and mission
- Traversability assessment using Information Roadmap: IRM
- Frontier-based exploration strategy
- Intuitive and standardized science mission specification based on BPMN
- Autonomous health monitoring and fault recovery
- Centralized and distributed task allocation
- V&V under stochasticity (Simulation and field tests)

6) NeBula Machine Learning & Target Selection

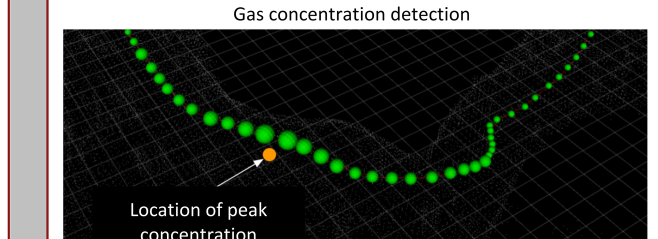
Objectives
- Scientist-guided or Automatic detection of areas of scientific interest
- Semantic understanding of the underground environment without human involvement
- Detecting risk areas
- Explainable human-level reasoning



Visual Terrestrial Anomaly Detection

Requirements
- Learn from database annotated by scientists
- Multi-modal sensing: various gas detection, visual, thermal, …, sensing
- Generalizing knowledge to new experiences
- Low-computation/ low-memory methods
- Detecting objects and new science in perceptually-degraded setting

Gas concentration detection



Approach
- Task-specific trained models
- Multi-sensor detection approaches
  - Directed observations
  - Ambient observations (gas, wifi, magnetic)
- Multi-robot information sharing
- Relative localization, fused with LAMP

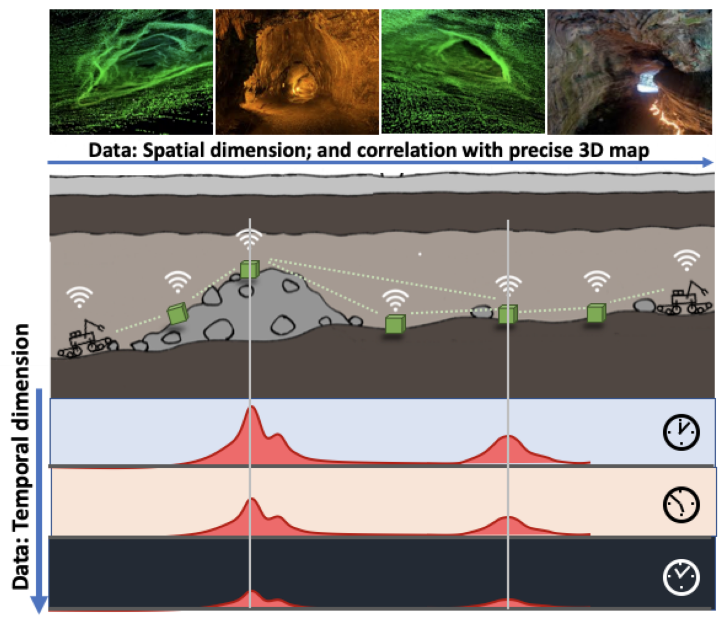
Task specific training dataset

What is Next? Future missions/capabilities

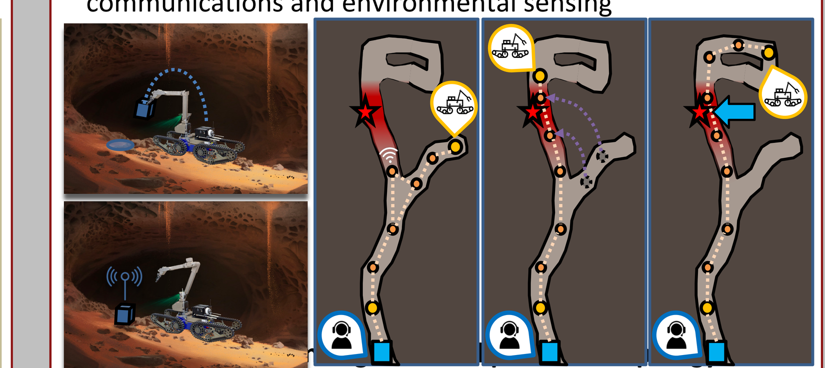
The existence of caves on Mars and Moon opens up new frontiers in planetary science of potential value to astrobiology, but also offers a series of technical challenges to enable access and detailed investigation of their interiors.

Opportunities and Capabilities:

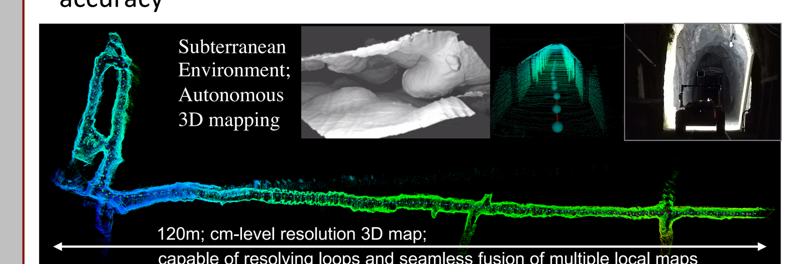
Spatiotemporal gradient sensing: Multiple (stationary or dynamic) networked science nodes equipped with miniaturized instruments; To characterize spatiotemporal fluid- and thermo-dynamics gradients and flows.



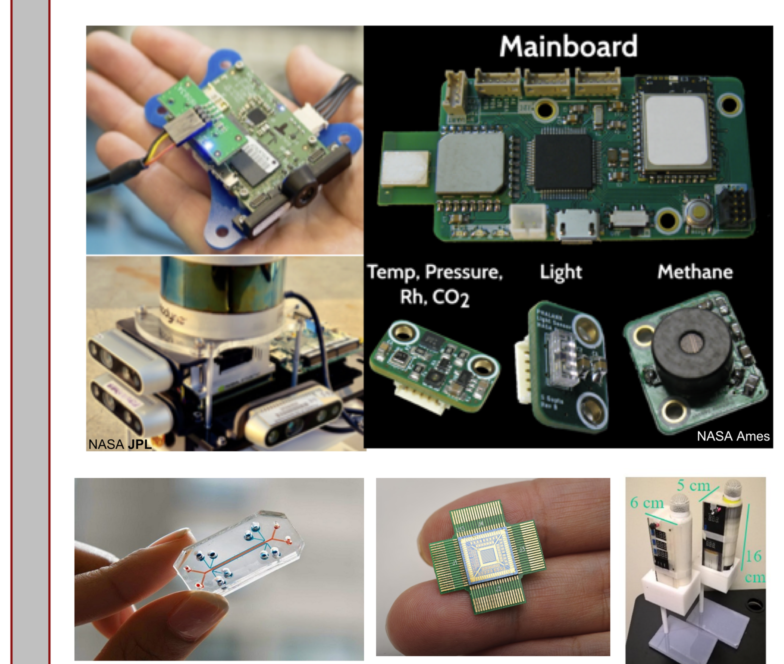
Non-LOS robotic operations in deep/long caves: including a paradigm in which mobile robot(s) perform science, whilst deploying, reconfiguring, and recharging a series of stationary low-power science nodes enabling mesh communications and environmental sensing



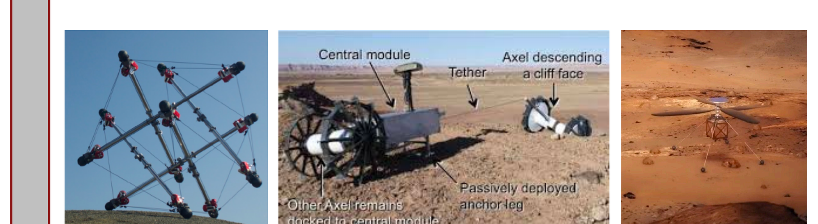
Autonomous navigation and precision-topology: cm-resolution map accuracy and sub-meter navigation accuracy



Next-gen Science instrument integration: From basic environmental sensing to search for signs of extinct and extant life



Access: From tensegrities to flight to tethered systems



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