Institute for Aerospace Studies
UNIVERSITY OF TORONTO

The Importance of Adaptive Decision-Making for Autonomous Long-Range Planetary Surface Mobility

2024 International Symposium on Artificial Intelligence, Robotics and Automation in Space

Brisbane, Australia

November 19, 2024

Olivier Lamarre, Ph.D. Candidate
Space and Terrestrial Autonomous Robotic Systems (STARS) Laboratory

@olamarre

olamarre.com

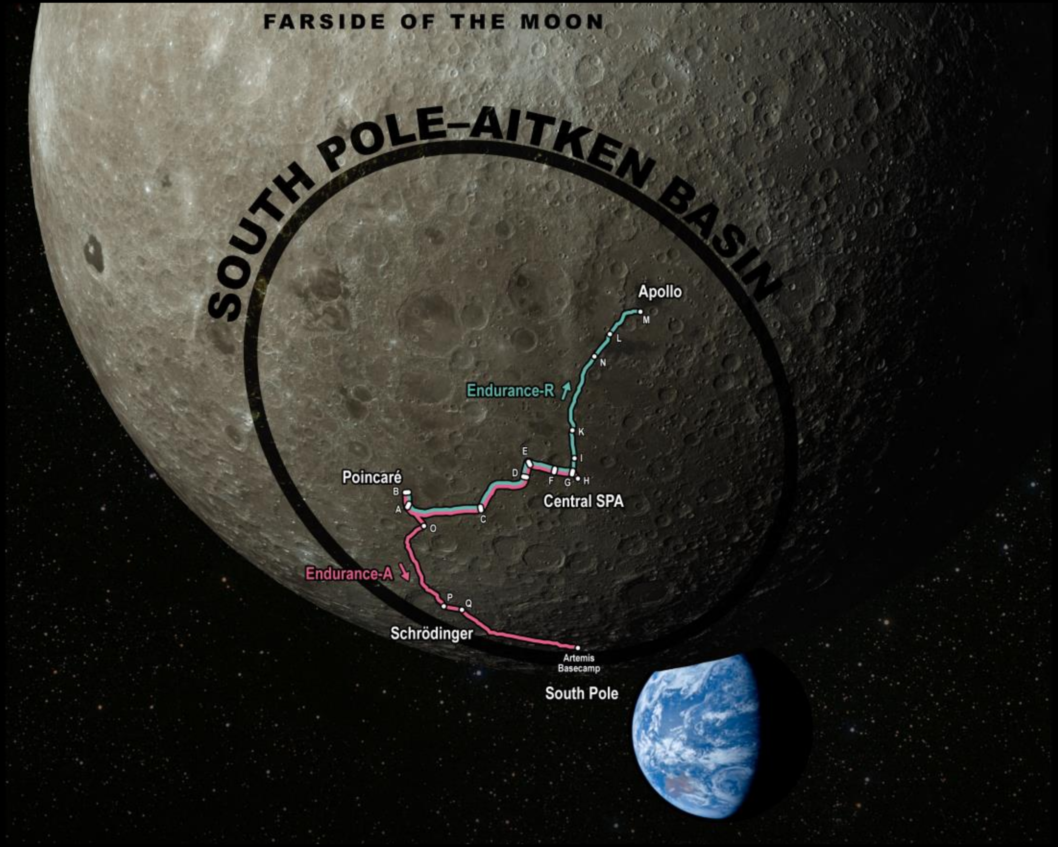
olivier.lamarre@robotics.utias.utoronto.ca

STARS

Autonomous Long-range Mobility: Science & Efficiency

Kilometer-scale mobility increases science return:

- Explore regions of interest unreachable with landing systems alone
- Diversify close-up observations in a cost-effective manner
  [Robinson et al., 2020; Keane et al., 2022; Matthies et al., 2022]

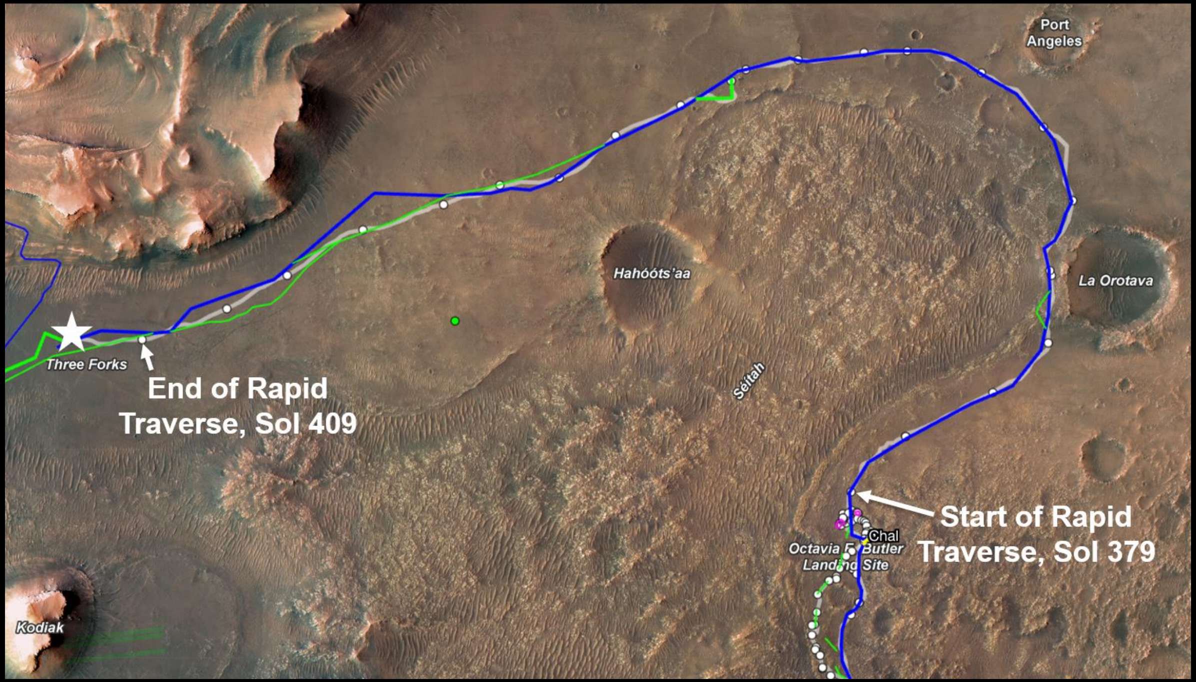


Endurance mission concept notional traverses
[Keane et al., 2022]

Autonomous Long-range Mobility: Science & Efficiency

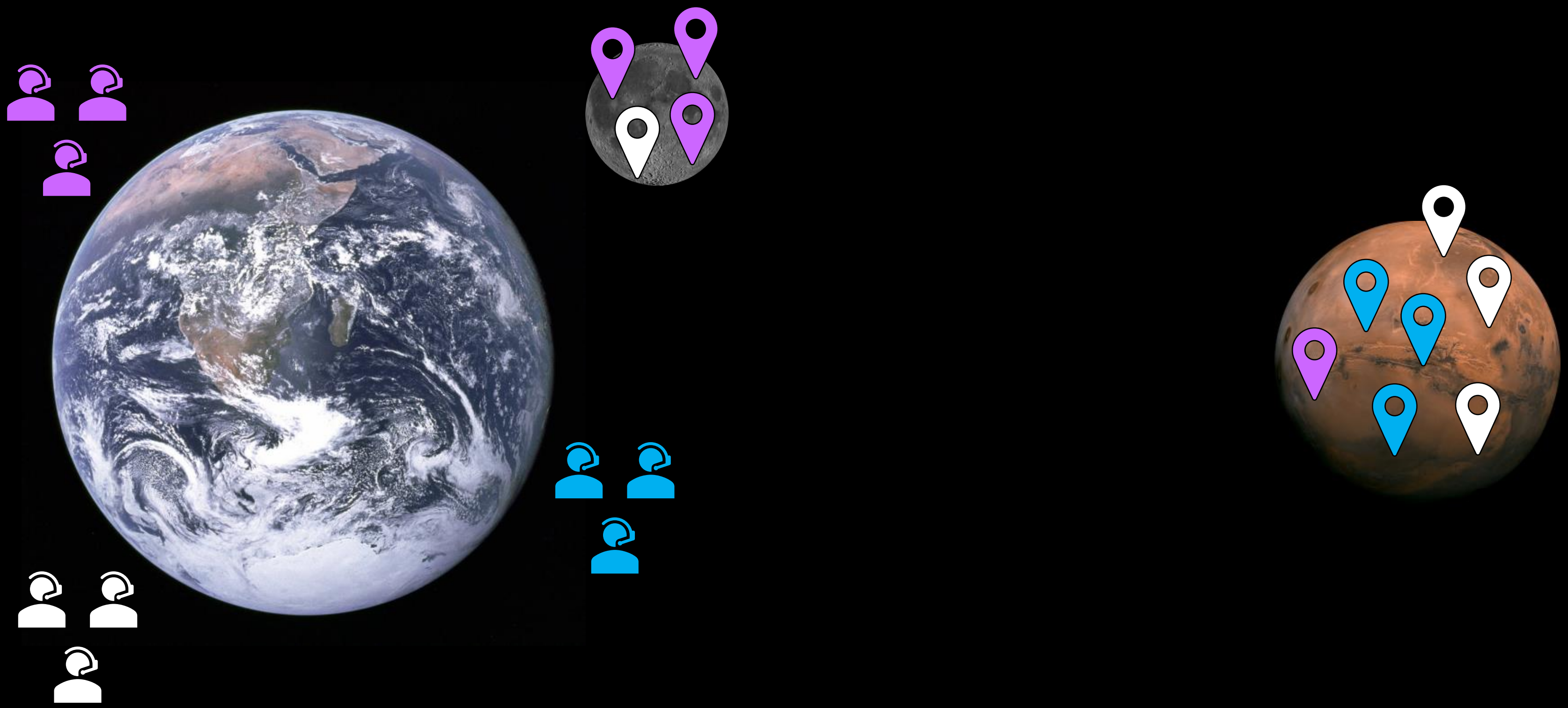
Autonomy reduces operational inefficiencies:

- 40-50% of sols during Mars Science Laboratory (MSL) & Mars 2020 (M2020) campaigns considered unproductive
  [Gaines et al., 2016; Sun et al., 2024]
- M2020 record-breaking autonomous drives mostly occurred in low-complexity terrain
  [Rankin et al., 2023; Verma et al., 2023]
- More autonomy does not replace operators, but refocuses their responsibilities
  [Nesnas et al., 2021]

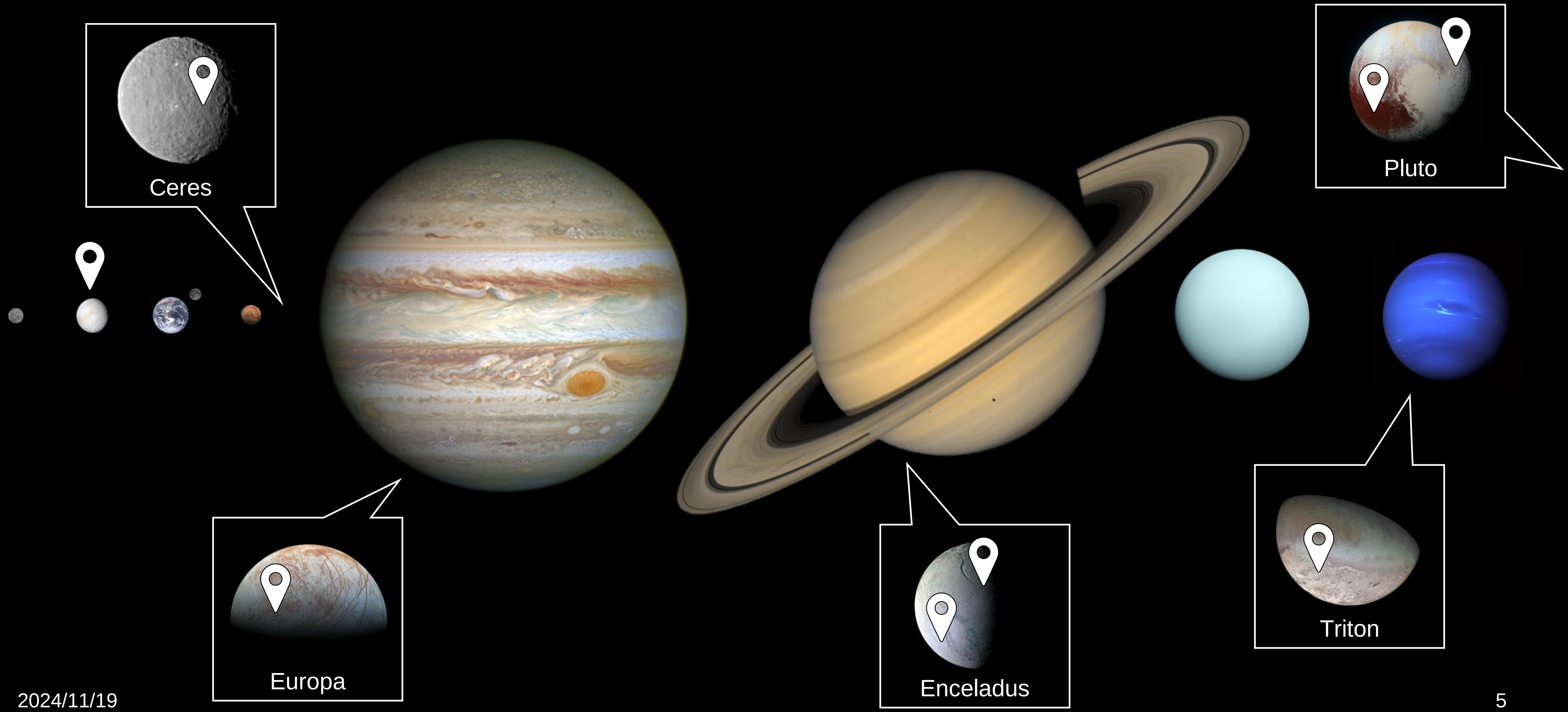


M2020 “Rapid Traverse” Campaign:
approx. 5 kilometers in 31 sols
[Rankin et al., 2023]

Autonomous Long-range Surface Mobility



Autonomous Long-range Surface Mobility



Many Ground Functions For Mobility Are Difficult To Replicate

- Science-driven mobility targets
- Semantic scene understanding
- Non-geometric hazard identification
- Event scheduling
- Global localization, subsystem health estimation

…

- **Adaptive decision-making**

[Wettergreen et al., 2014]

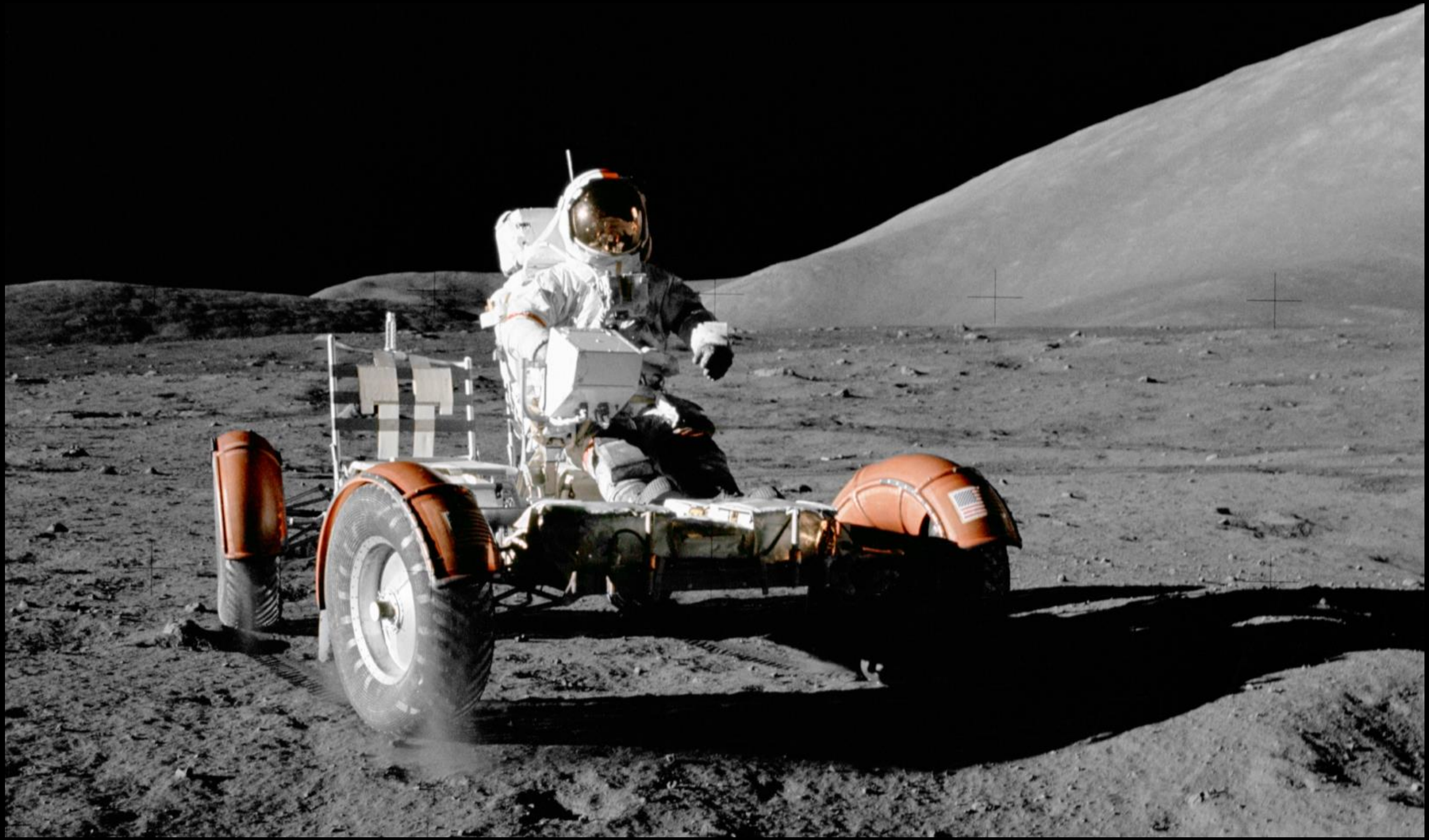
[Kolvenbach, 2021]

Terrain ← ? → Robot

[Reid et al., 2021]

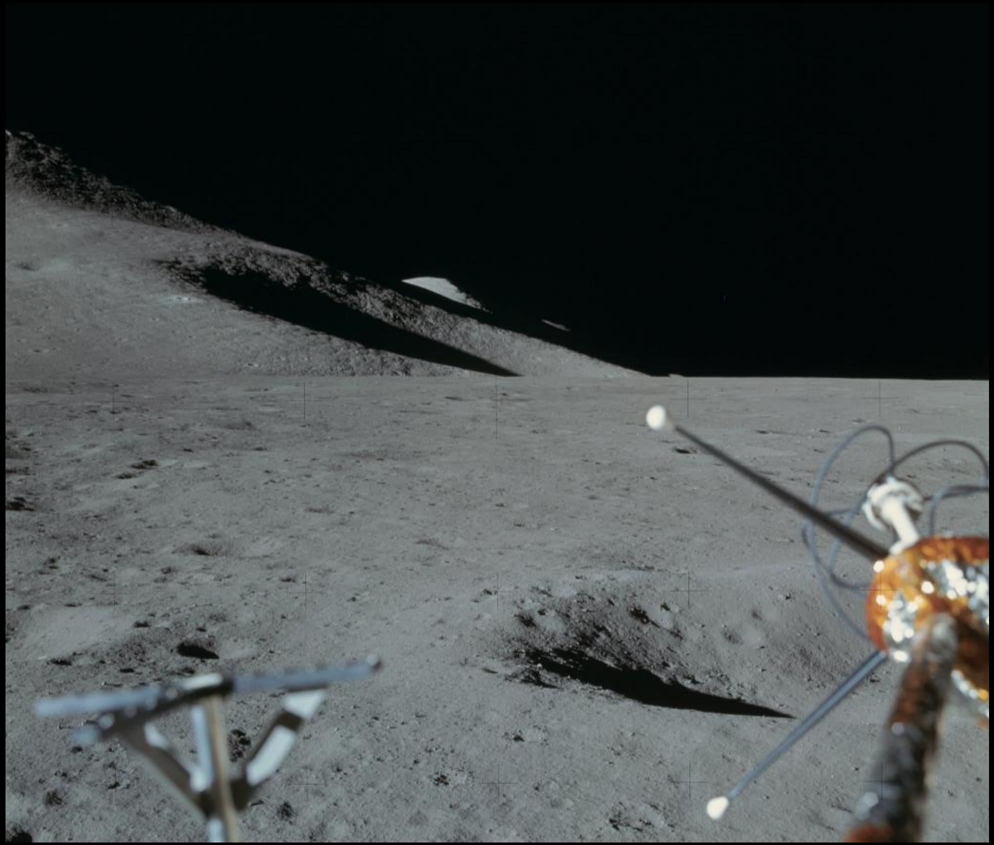
[Vaquero et al., 2024]

Adaptive Decision-making: Apollo J-type Missions

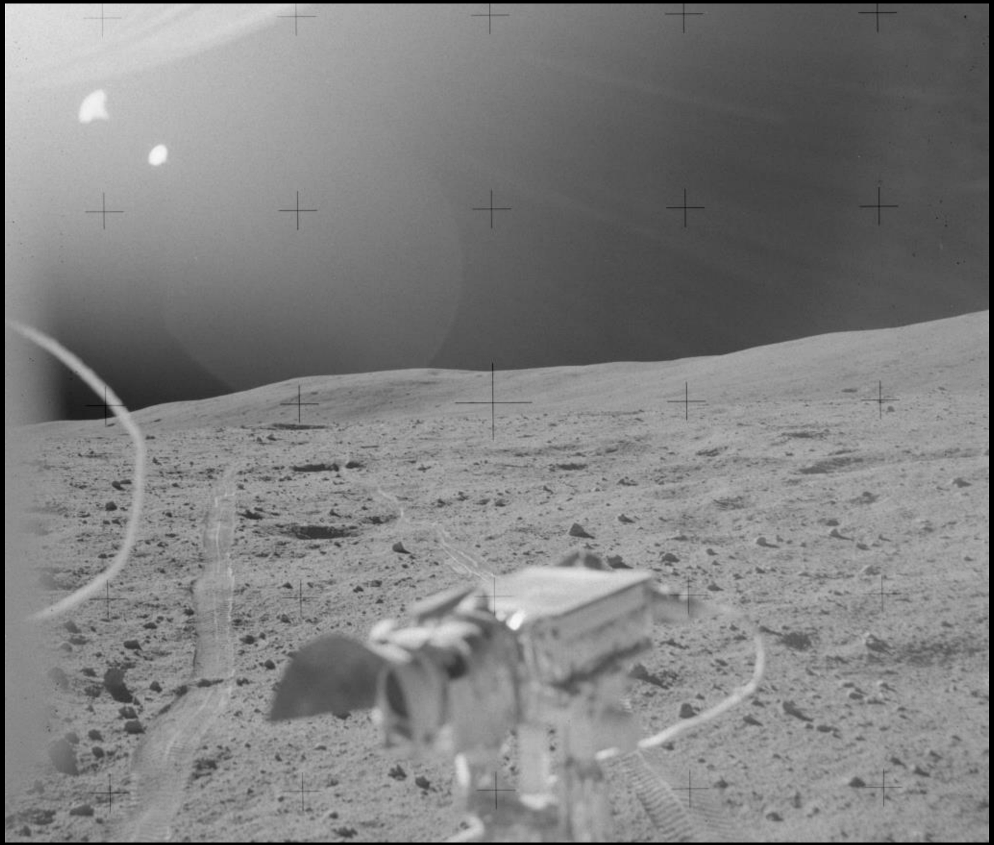


Apollo 17 Lunar Roving Vehicle (LRV), extravehicular activity (EVA) 1
[Credit: NASA]

Adaptive Decision-making: Apollo J-type Missions



Active traversability assessment
(Apollo 15 Stand-Up EVA)
[Jones, 1995a]



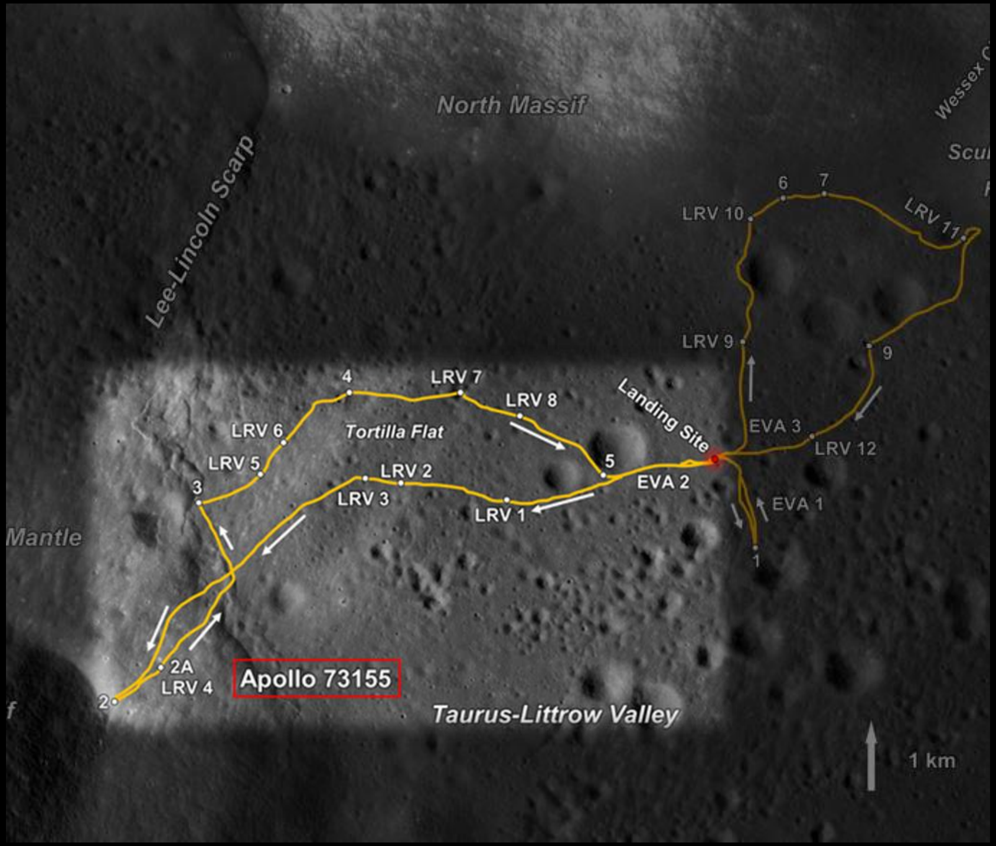
Following outbound rover tracks
(Apollo 16 EVA 1, return to lunar module (LM))
[Jones, 1995b]

Adaptive Decision-making: Apollo J-type Missions

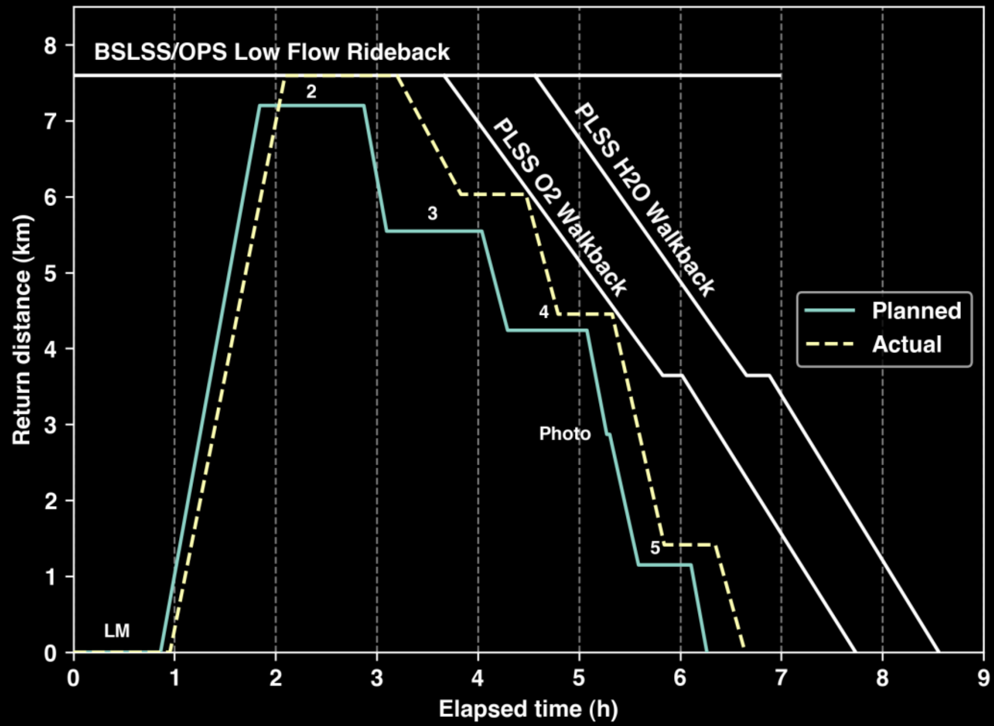
Highly unconsolidated soil on Mons Hadley
(Apollo 15 EVA 2, Station 6a)
[Jones, 1995a]

Parking the LRV in a depression on Stone Mountain
(Apollo 16 EVA 2, Station 4)
[Jones, 1995b]

Adaptive Decision-making: Apollo J-type Missions



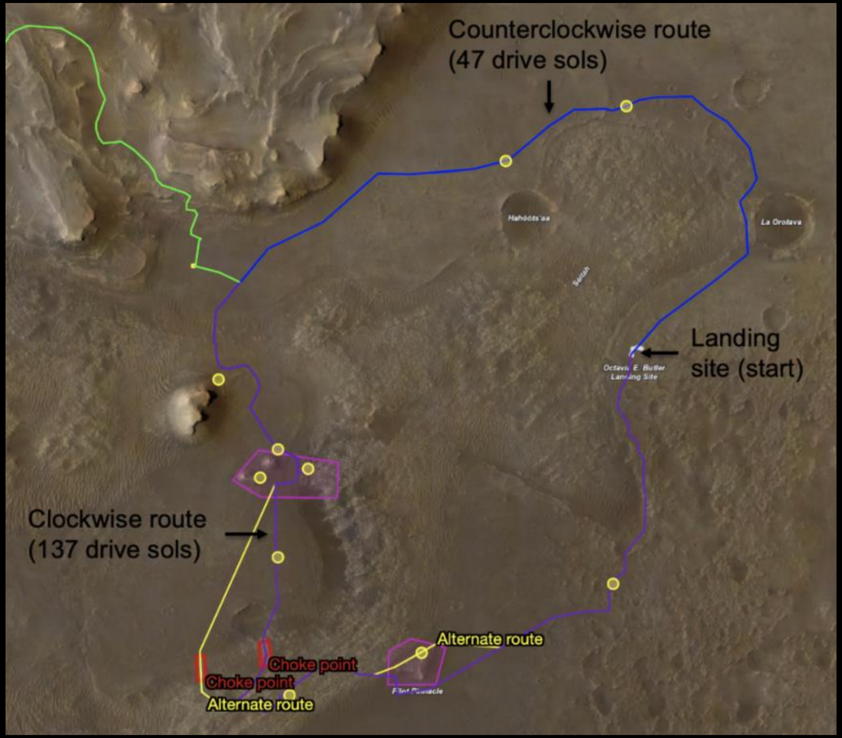
Apollo 17 traverse map
(EVA 2 region highlighted)
[Zhang et al., 2019]



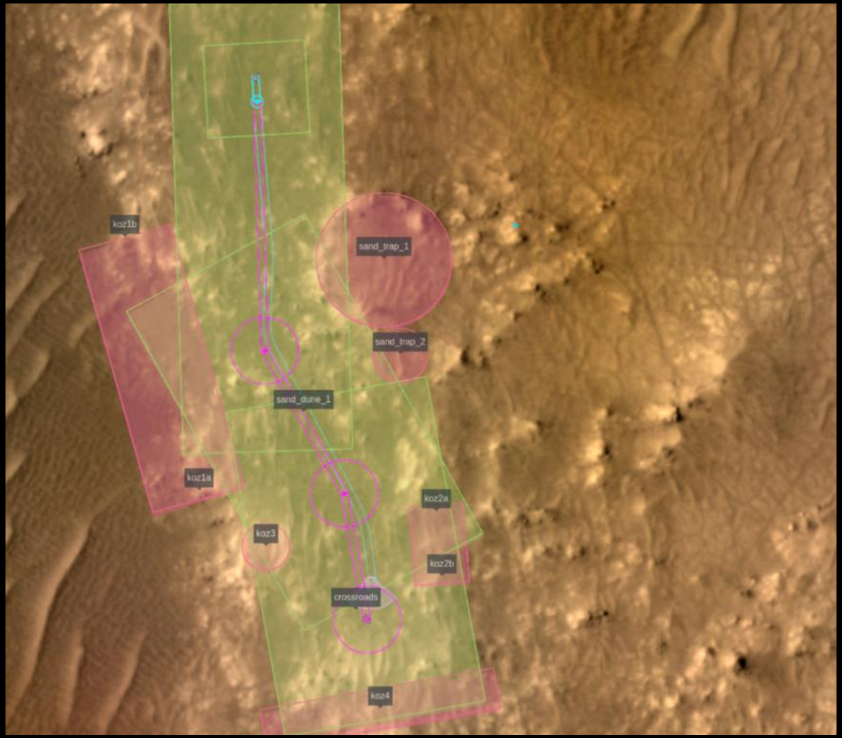
LM distance vs. EVA elapsed time
(Apollo 17 EVA 2)
[Jones, 1995c]

Adaptive Decision-making: Martian Robotic Missions

Human operator input/intuition required at every mobility planning stage (strategic & tactical)
[Biesiadecki et al., 2007; Verma et al., 2022]



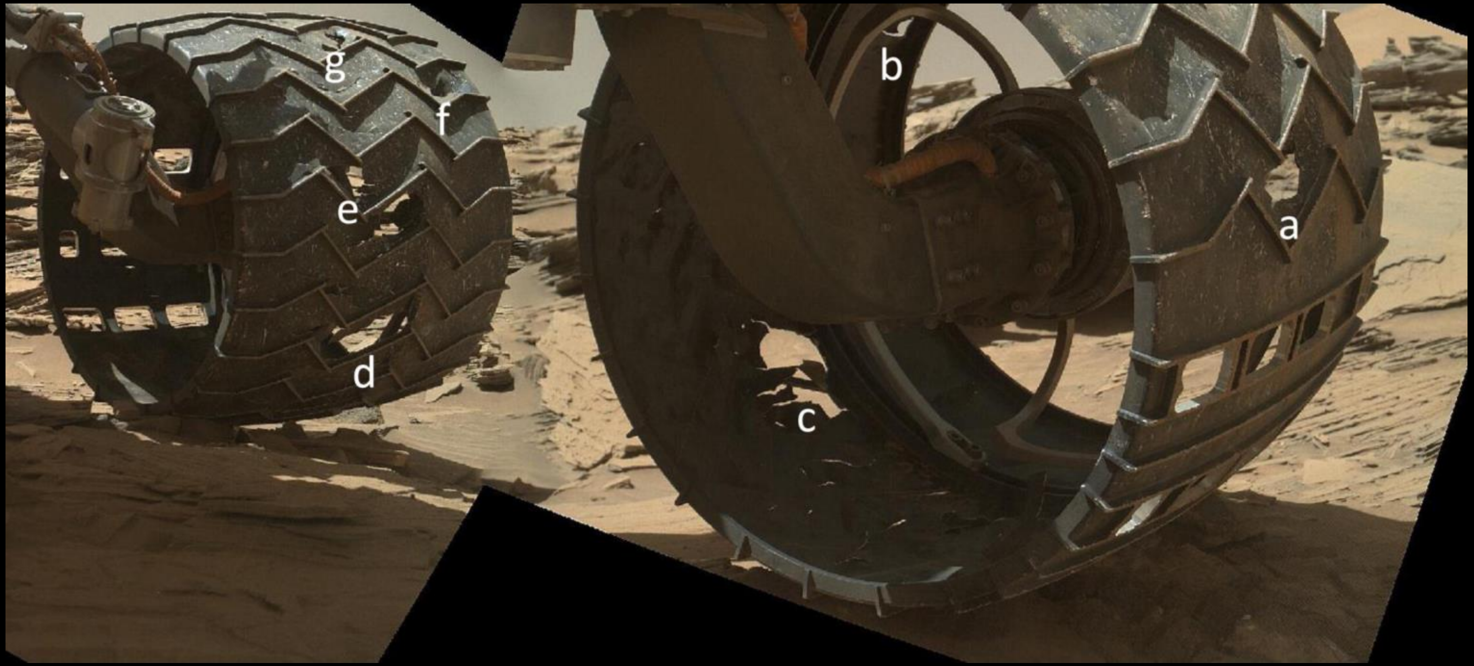
Early M2020 strategic traverse candidates in the Jezero Crater floor
[Verma et al., 2022]



Example M2020 tactical drive with human-designated keep in/out zones.
[Verma et al., 2022]

Adaptive Decision-making: Martian Robotic Missions

Mars Science Laboratory: unexpected wheel wear

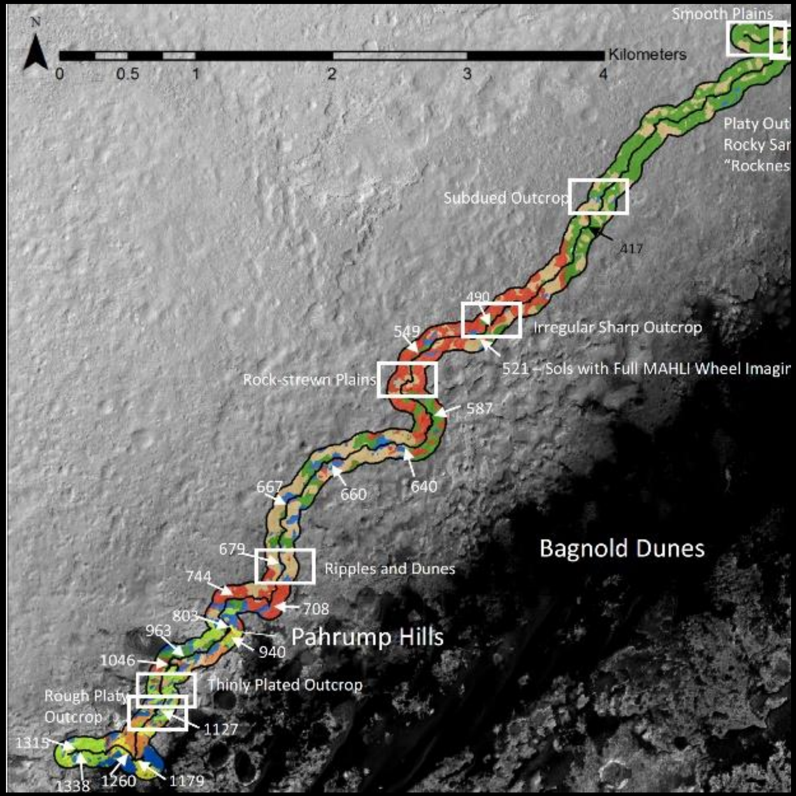


Wear on left front & middle wheels on MSL mission sol 1315
[Arvidson et al., 2017a]

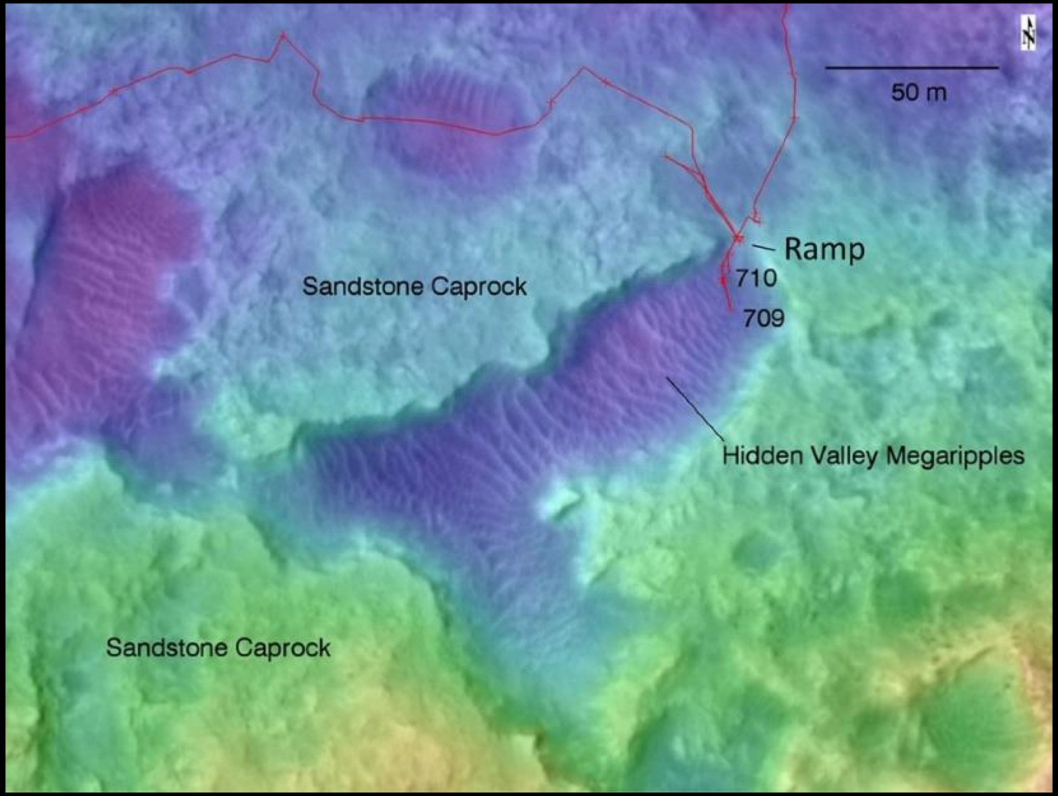
Angular embedded rocks
[Ono et al., 2015]

Adaptive Decision-making: Martian Robotic Missions

Mars Science Laboratory: unexpected wheel wear



Geologic units along MSL strategic traverse
[Arvidson et al., 2017a]

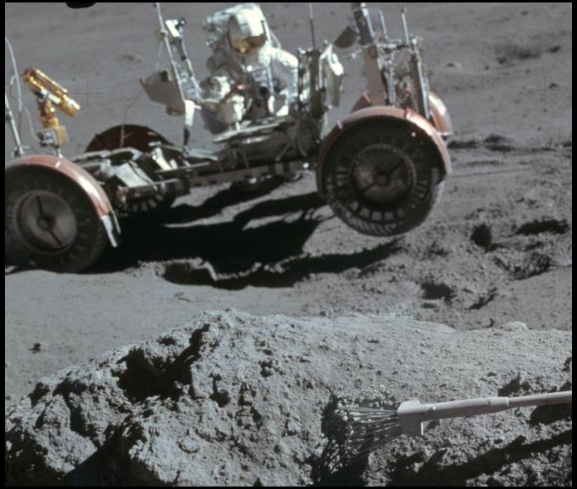


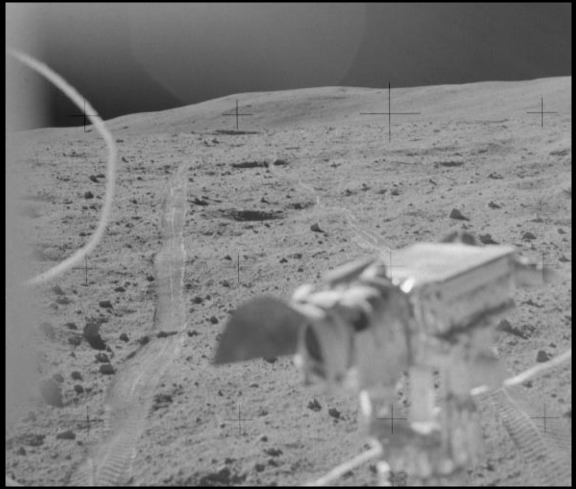
MSL detour around Hidden Valley
[Arvidson et al., 2017b]

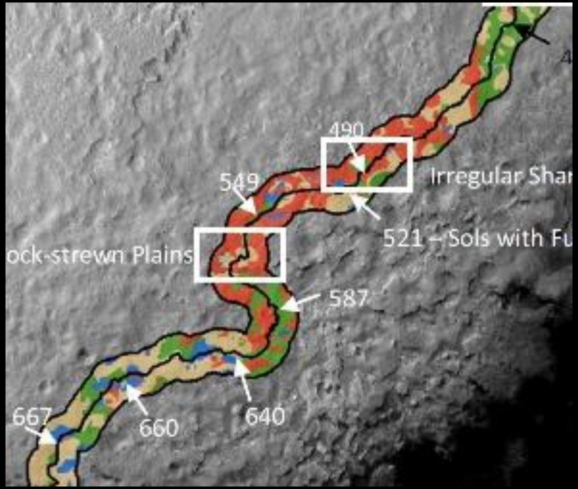
General Capabilities for Adaptive Decision-making

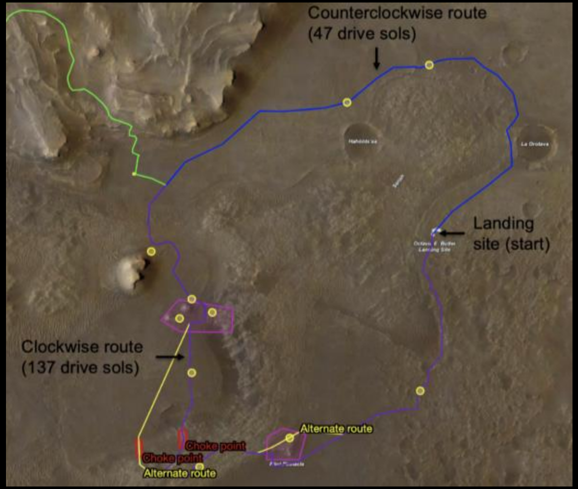
1. Unassisted learning from past experiences

2. Exploiting stochastic rover-terrain interaction models



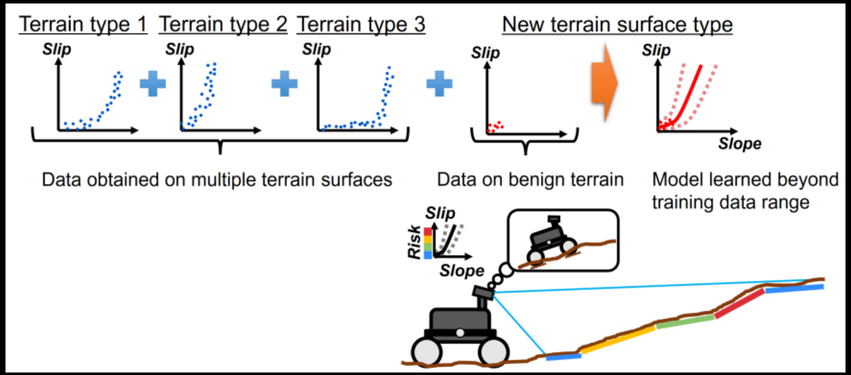




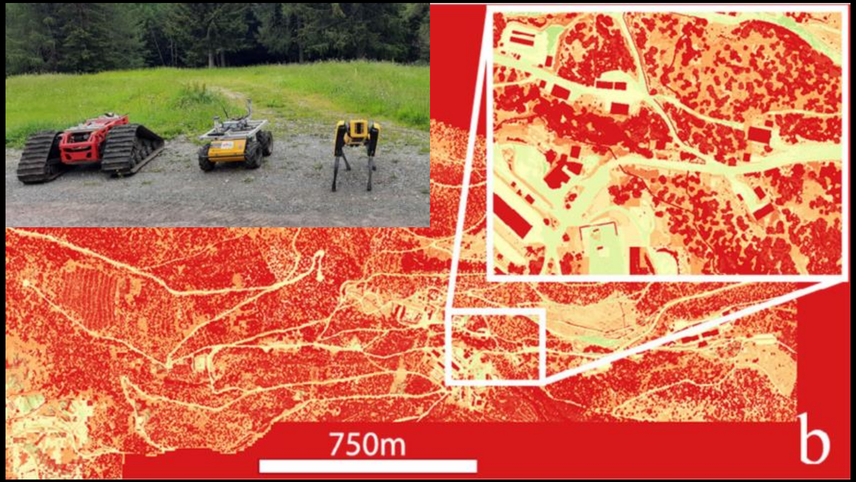


Key Capability #1: Unassisted Learning From Past Experiences

- Highly autonomous spacecraft should be able to learn from past experiences
  [Nesnas et al., 2021]
- Self-supervision is a core characteristic, especially in planetary exploration



Gaussian process-based slip estimation in unknown terrain types via transfer learning
[Inotsume & Kubota, 2022]

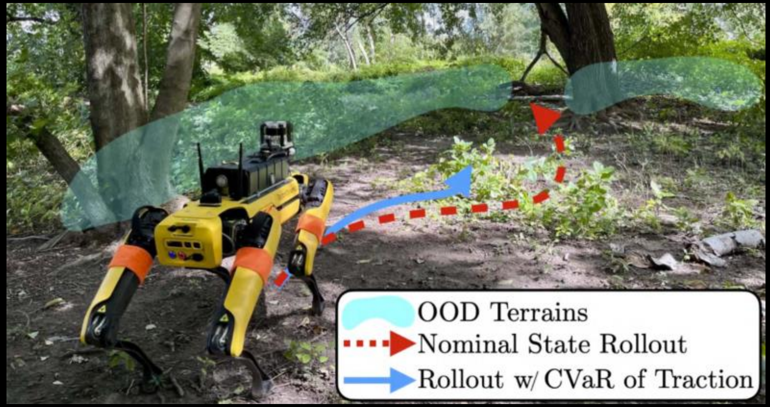


Traversability cost estimation from locomotion data on overhead global terrain maps
[Eder et al., 2023]

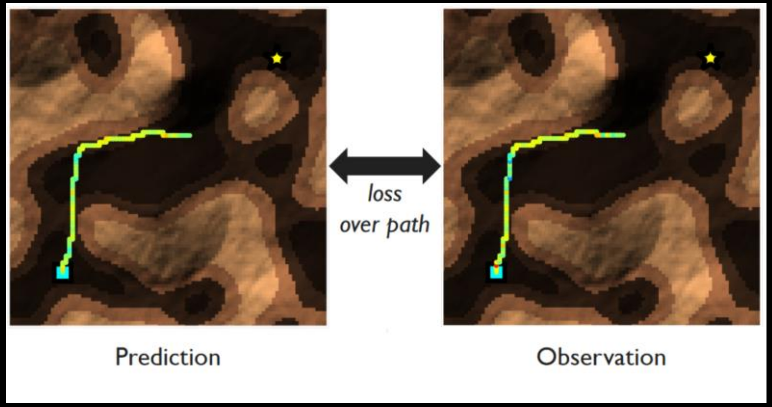
Key Capability #1: Unassisted Learning From Past Experiences

- Highly autonomous spacecraft should be able to learn from past experiences
  [Nesnas et al., 2021]
- Self-supervision is a core characteristic, especially in planetary exploration
- Deep learning-based self-supervised methods are on the rise

Fast traversability estimation from camera images and point clouds
[Frey et al., 2024]



Deep learning-based traction learning with out-of-distribution (OOD) terrain rejection
[Cai et al., 2024]



Deep learning-based slip predictions with test-time adaptation
[Endo et al., 2024]

Key Capability #1: Unassisted Learning From Past Experiences

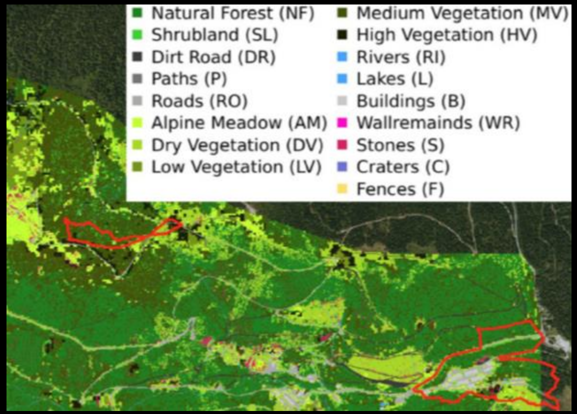
Shortcoming: assumption of background knowledge availability.

- Training data coverage representative of test cases
- Availability of (human-biased) discrete semantic terrain map

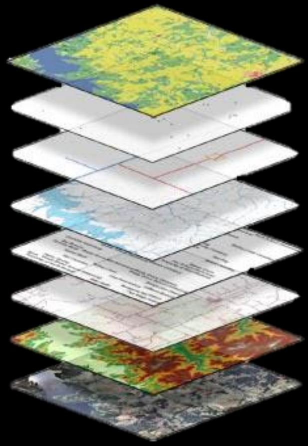
Provides assistance to the traversability inference framework.

Recommendations:

- Associate training data / observations with an unbiased description of the environment
- Traversability estimation through similarity of training and testing data features (e.g., kernel methods)
- Acquire observations useful for future traverses

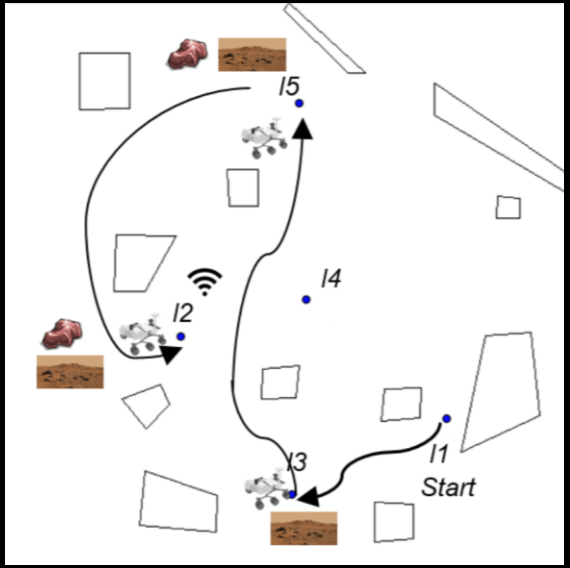


Example terrain category map
[Eder et al., 2023]



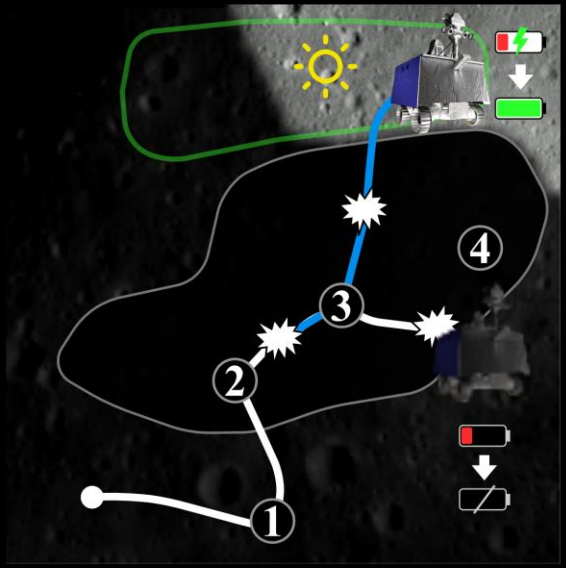
Key Capability #2: Exploiting Stochastic Rover-terrain Interaction Models

- Aforementioned work determinize traversability predictions to ease planning
- Repetitive calls to deterministic planners enables limited proactivity
- Stochastic (policy-based) planning methods provide insights about possible outcomes



Chance-constrained spatiotemporal planning applied to planetary rovers
[Santana et al., 2016]

Risk-averse policies for off-road mobility in uncertain graphs
[Guo & Barfoot, 2019]



Risk-bounded policies for safe mission-level path planning
[Lamarre et al., 2024]

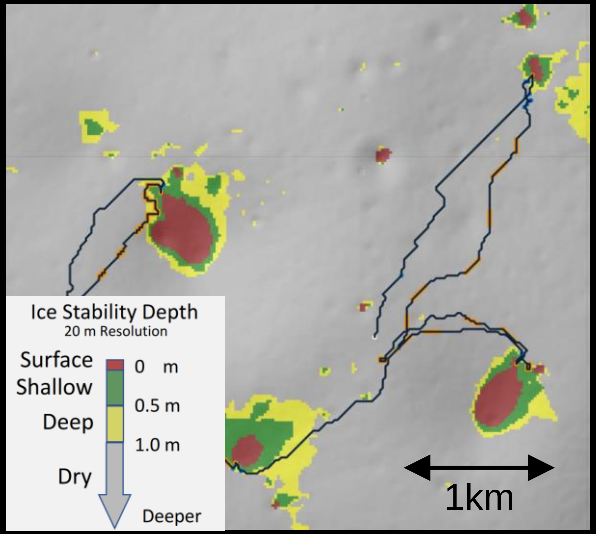
Key Capability #2: Exploiting Stochastic Rover-terrain Interaction Models

Shortcoming: oversimplification for computational tractability.

- Simplified disturbance models
- Simplified notion of rover safety, risk aversion is limited

Recommendations:

- Rollout-based methods to mitigate state space and dynamics complexity, similar to VIPER global planning efforts
  [Shirley & Balaban, 2022]
- Borrow notions from the emerging field of risk-sensitive control for long-range planetary mobility
  [Brunke et al., 2022 ; Wang & Chapman, 2022]



Example VIPER strategic traverse, overlay over ice stability depth map
[Shirley & Balaban, 2022]

Conclusion

Long-range surface mobility requires adaptive decision-making

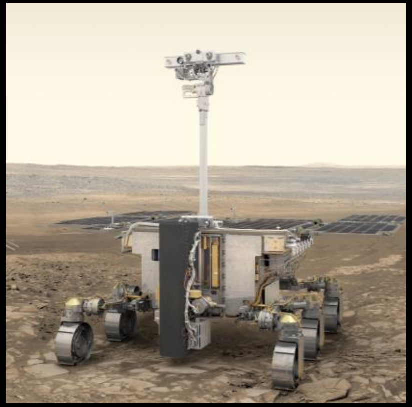
Two important capabilities:

- Learning from past experiences, with little to no external assistance or background knowledge
- Planning methods accounting for environment stochasticity

Other capabilities:

- Explainable adaptability
- Locomotion designs favorable to adaptation

VIPER
Credit: NASA/Daniel Rutter



Rosalind Franklin ExoMars rover
Credit: ESA/ATG medialab

Slides and references: https://starslab.ca/publications

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