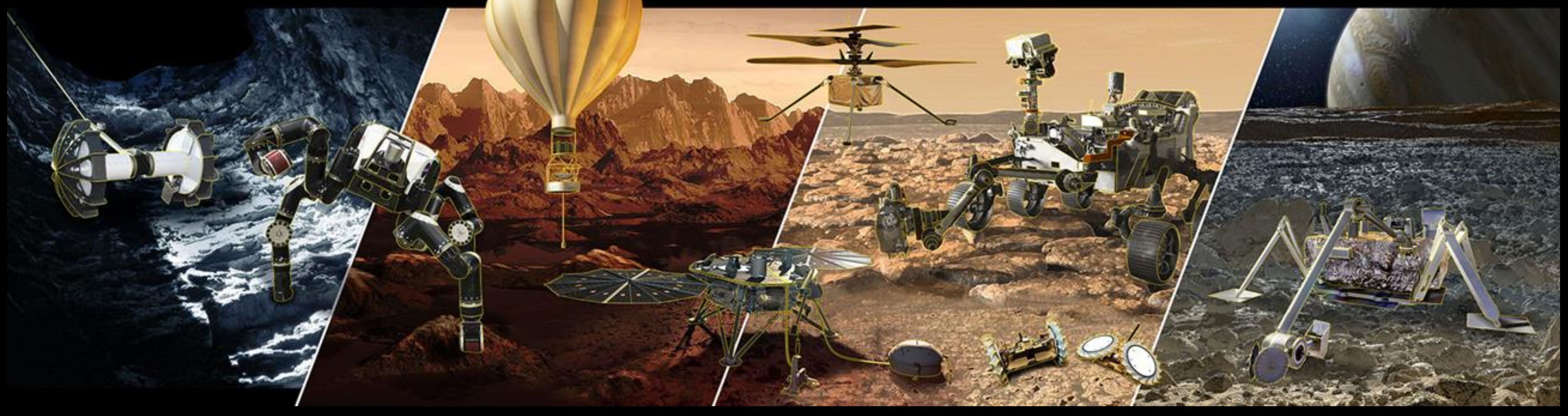

Remotely Controlled Mobility: Lessons from Mars

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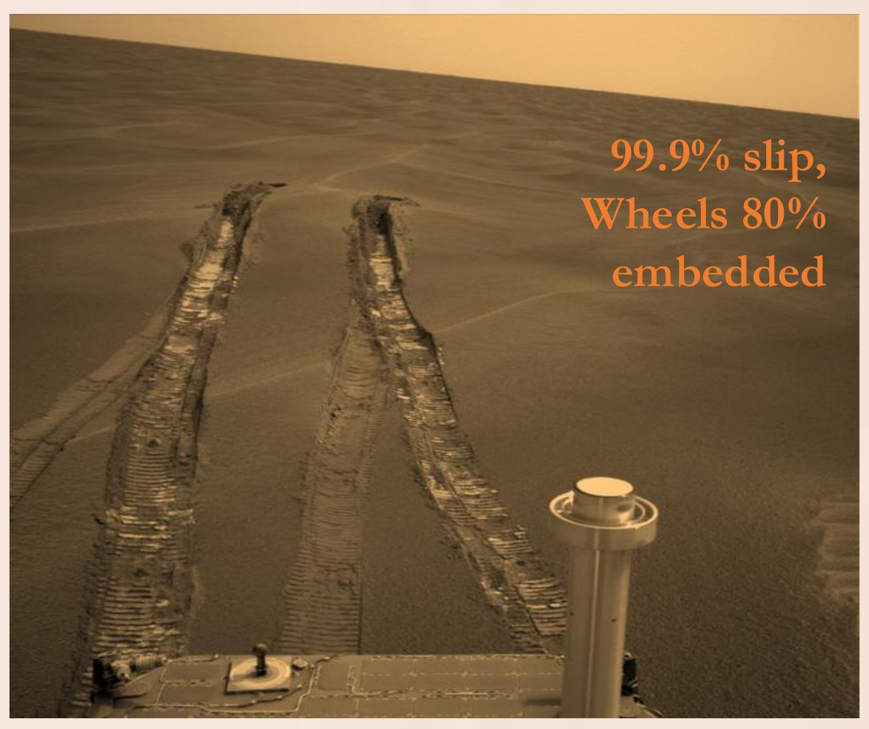
1997: Sojourner



2005: Opportunity

2005: Spirit – 30° slope

2024: Curiosity Rock Field

2023: Perseverance
1 sol, 347m total,
331m Autonav

JPL rovers have cruised the Martian surface since 1997. Over the course of two decades spent remotely driving Sojourner, Spirit, Opportunity, Curiosity, and Perseverance, JPL engineers have refined the processes and tools used for route planning and drive execution to achieve fast-turnaround command sequences free of collisions and errors. This contribution summarizes the challenges and risks of remotely controlled mobility and introduces the autonomy, processes, and tools used to overcome these challenges robustly. The rover mobility framework described is directly applicable to Lunar operations.

Assessment of Unfamiliar Terrains: The processes described below benefit from years of interaction with Martian terrains. Several types of terrain identified from orbital images have well-understood characteristics for mobility performance based on data from previous traverses. In the early years of Mars roving, operators were frequently surprised by unexpected slip or embedding, resulting in the development of best practices for assessing new terrains. Before crossing a unique surface texture, cautious experimental forays are executed to assess traversability, similar to the commissioning process used to assess performance of a newly-landed rover. Over time, the repertoire of known terrains has grown, building confidence for strategic and tactical route planning in orbital images of relatively low resolution.

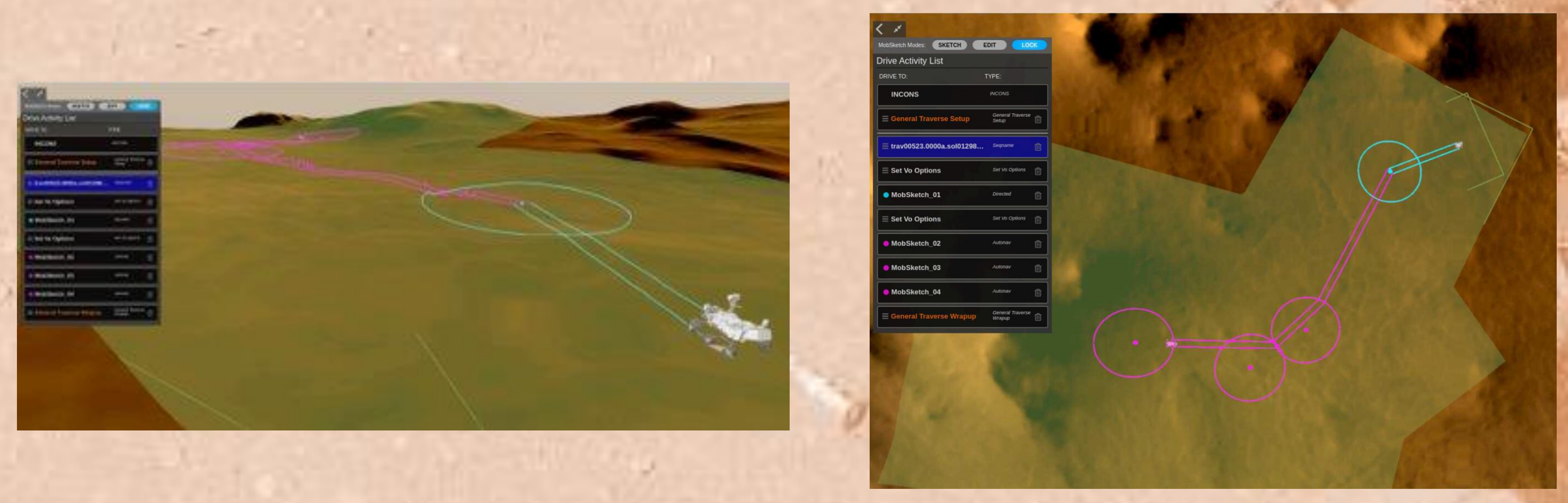


Figure 1. MobSketch planning tool showing Perseverance ascent of Jezero Crater rim (sol 1296, Oct 2024), the first use of AutoNav at >20° tilt. Light blue: DIRECTED drive, Pink: AUTONAV drive, Light green: keep-in zones, Black reference box summarizes drive segments and other commands. Graphical drive plans are expanded automatically into hundreds of rover commands in < 1 second after each change.

Strategic Route Planning: Long distance routes are planned using orbital maps and DEMs, including derived tilt knowledge. Science teams provide the areas of interest, and certified tactical Rover Drivers recommend driving routes and strategies based on expected terrain conditions.

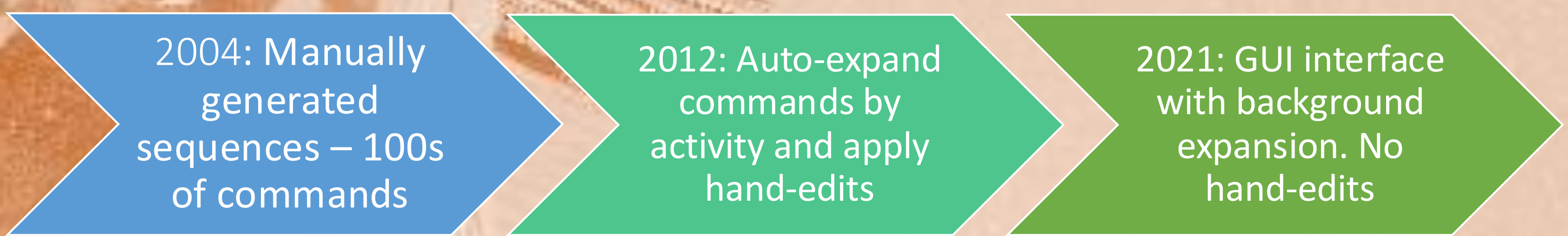
Tactical Route Planning: Operator-planned drives use close-range terrain meshes in combination with orbital maps to assess visible hazards and set waypoints relative to a local coordinate frame. MobSketch, a graphical ground tool, enables quick selection of waypoints and marking of hazards, as well as visualization of rover paths between waypoints (Figure 1). Command sequences are auto-generated from the graphical representation, then validated through a high-fidelity simulation of flight software seeded with the projected rover state at the time of execution. The simulation flags errors due to command/state incompatibility and enables correction of errors prior to finalization.

Precision Approach for Manipulation: Positioning for in situ target analysis can be done autonomously or by planning a precision approach in MobSketch. Autonomous terrain interaction employs a Go-and-Hover capability that analyzes terrain in onboard stereo imagery, safely unstows the arm, and provides target locations and collision-free arm placement strategies. Often, scientists prefer to stop and image a candidate feature with ground-in-the-loop before approaching, to optimize science target selection. For targets selected in advance, ground tools assist operators in selecting an approach location and distance that optimize reachability (modeling terrain interactions, gravity and thermal changes, intra-arm forces/torques, rover toggle). Precision approaches planned with this method are highly successful.

Dealing with Uncertainty: Driving distances over rocky, sandy terrain accumulates error in position and attitude knowledge. Rover software models uncertainty growth as increased vehicle size, visualized in dark blue in Figure 2. While onboard visual odometry corrects slip-induced errors and minimizes uncertainty growth per step, accumulation over long distances limits progress. Global localization, achieved on Mars by matching features in local imagery to orbital maps, resets the uncertainty. Onboard global localization enables daily uncertainty reduction without ground in the loop.

Figure 2. Uncertainty improvement through onboard global localization. (top) Dark blue shows drive uncertainty accumulation over a 3-sol, 655m traverse. (bottom) Reduced uncertainty achieved through onboard global localization after each sol's drive. [1]

Evolution of Operations Processes: Over time, the creation of mobility command sequences has evolved from laborious hand-coding to graphical sketching with commands auto-expanded in the background. Today, toolsets for robotics operations automate most hand calculations and command authoring, focusing operator effort on high-level route-mapping, precision approach to targets, evaluation of terrains, identification of hazardous areas, and tricky configurations like tuning of terrain-adaptive slip models.



2004: Manually generated sequences – 100s of commands

2012: Auto-expand commands by activity and apply hand-edits

2021: GUI interface with background expansion. No hand-edits

Key Elements for Error-Free Mobility: With commanding largely automated, operators focus on querying the local environment, achieving situational awareness, and validating command sets. 2D and 3D image viewing tools include pre-calculated overlays illustrating scale, slope, and rover pose. Surface Simulation (SSim) modeling ingests rover state data and executes queued commands at flight fidelity, drawing attention to potential execution errors. Key toolset elements are shown in Figure 3.

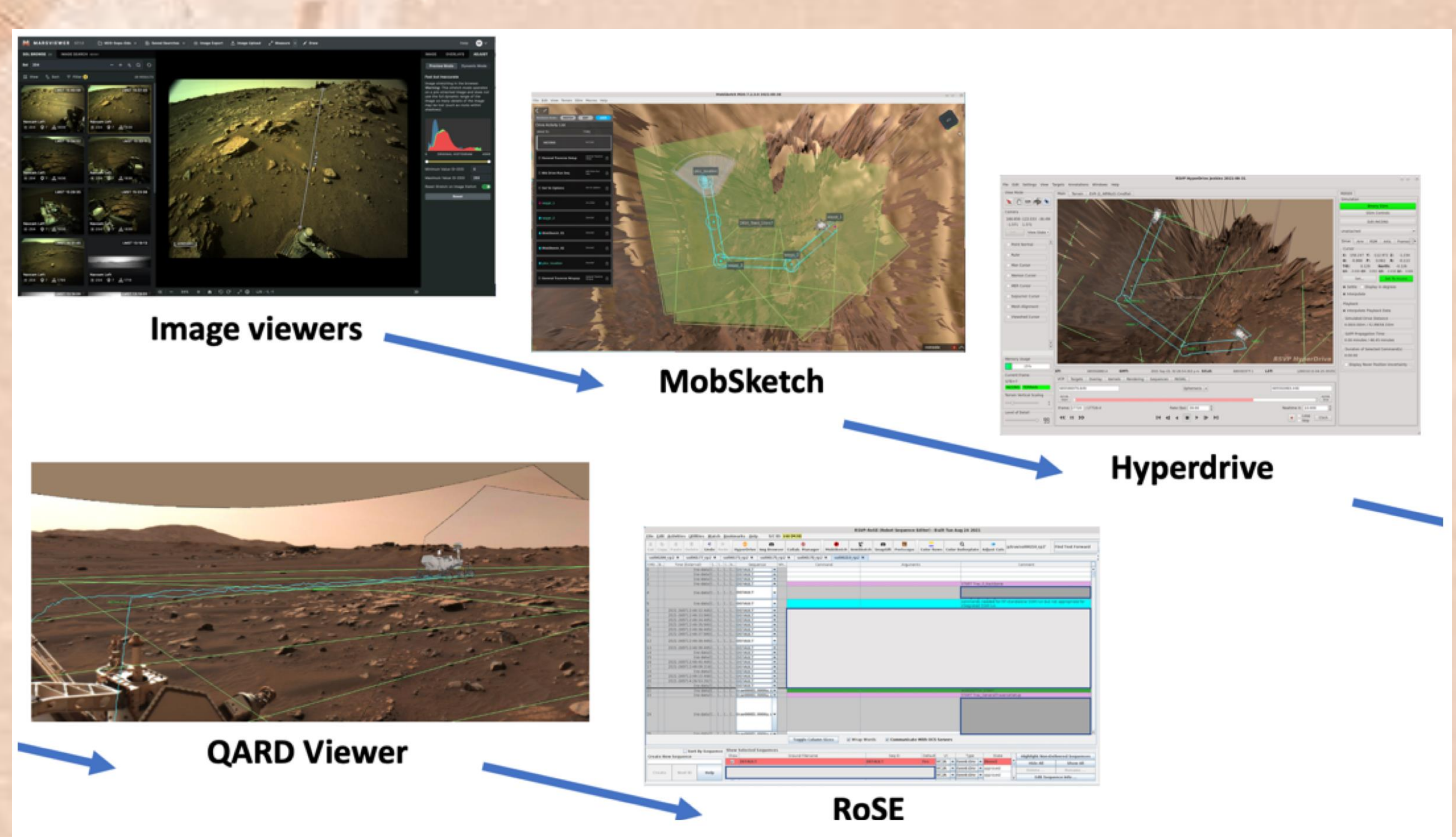


Figure 3. Robotics Operations mobility tools and simplified workflow [2]

References: [1] Verma, V. et al. (2024) *IEEE Aerospace Conf.*, pp. 1-18.
[2] Verma, V. et al. (2022) *IEEE Aerospace Conf.*, pp. 1-20.

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