Simulation for Planetary Robotic Perception: A Concise Survey of Capabilities and Gaps

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***Abstract*— Planetary robotics is an important enabler of scientific exploration in environments where direct human intervention is costly, hazardous, or infeasible. However, developing and validating planetary robotic systems remains difficult because representative field testing is expensive, limited, and often unrepeatable under mission-relevant conditions. In this setting, simulation serves as a central tool for perception and autonomy research, synthetic data generation, system integration, and pre-deployment evaluation. Despite its importance, the literature on planetary robotics simulation remains dispersed across different simulation engines, implementations, and application settings. This paper surveys simulation platforms for planetary robotic perception and autonomy across four practical axes: openness and availability, scenario and platform coverage, sensor and perception support, and environmental and operational realism. Our analysis reveals a growing use of simulation environments with higher visual and physical fidelity together with increased support for perception-oriented workflows, while also identifying that the literature remains largely rover-centered, with limited public availability, limited support for specialized sensing modalities, and limited treatment of operational constraints such as onboard computation, energy, and communication restrictions.**

I. INTRODUCTION

Space robotics encompasses robotic systems designed for operation beyond Earth. Prior reviews distinguish orbital and planetary applications as different autonomy contexts [1]: orbital robots operate in microgravity for spacecraft-relative tasks, whereas planetary robots must move on natural surfaces under uncertain terrain, variable illumination, limited communication, and long-duration operational constraints [1], [2]. This paper focuses on the latter: robotic systems intended for planetary surface or near-surface exploration, which is expanding beyond wheeled rovers toward legged, aerial, and heterogeneous systems [3], [4].

The importance of simulation follows directly from the difficulty of representative validation. Planetary autonomy depends on tightly coupled perception, localization, motion generation, and decision-making [2], and recent work on global localization, perception-aware planning, and multi-robot coordination reinforces this coupling [4]– [5]. Current simulator papers already support not only visualization, but also synthetic data generation, perception evaluation, and software-in-the-loop experimentation [6], [7].

Several high-quality reviews cover important parts of the broader field, including space robotics [1], decisional autonomy [2], active SLAM [21], and AI-enabled vision for space missions [22]. However, these works organize the literature around algorithms or missions rather than around simulation platforms. This gap affects practical research decisions, because simulator choice depends on sensing modalities, robotic platforms, environmental conditions, and autonomy-stack compatibility.

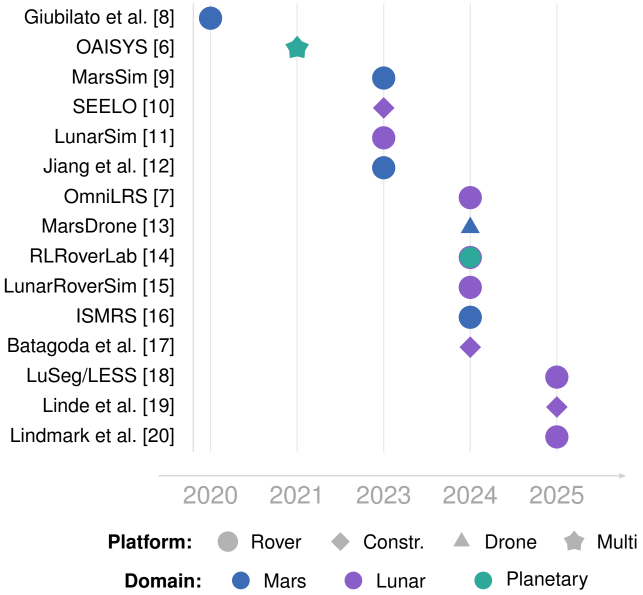

Fig. 1: Chronological distribution of surveyed simulation platforms. Marker position indicates publication year, shape encodes vehicle type, and color encodes target domain.

This paper addresses that need with two contributions:

1) A simulation-centered survey that organizes existing planetary robotic perception platforms across four practical axes — openness, platform coverage, sensing support, and operational realism.
2) An identification of critical gaps across these axes, including limited public availability, rover-centric scenarios, narrow sensing assumptions, and underrepresented operational constraints.

The paper structure and its logical flow are illustrated in Fig. 2. Section II introduces the mission context and simulation requirements. Section III surveys existing platforms from four analytical perspectives. Section IV discusses open challenges and future directions. Section V concludes the paper.

II. PLANETARY ROBOTICS PRELIMINARIES

A. Planetary Robotics as an Integrated Autonomy Problem

Planetary robotics concerns robotic operation on planetary surfaces, where systems must handle uncertain terrain

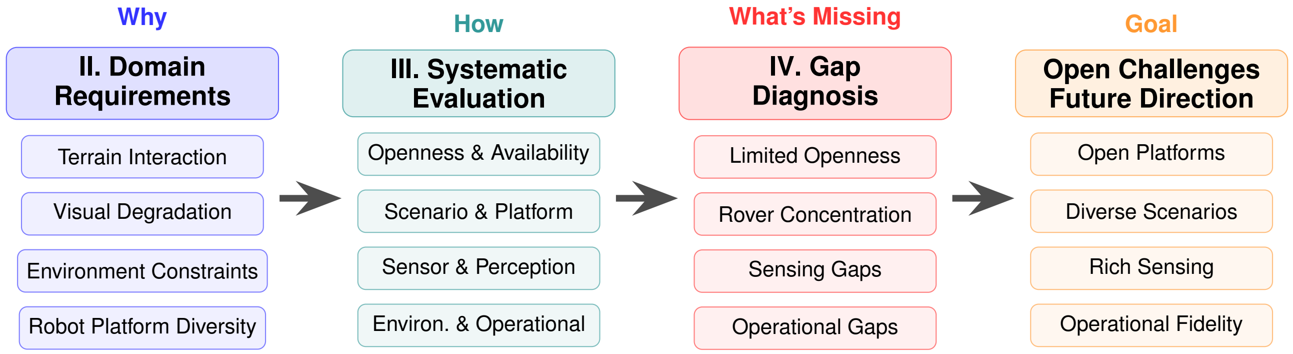

Fig. 2: Paper structure and logical flow. Each row traces a domain requirement (II) through its corresponding analysis axis (III) and identified gap (IV) to the open challenges and future directions.

TABLE I: Key factors distinguishing planetary from terrestrial autonomy and their implications for simulation.

Factor	Planetary Characteristic	Simulation Implication
Environmental conditions		
Terrain	Slip, sinkage, wheel–regolith coupling [24], [28]	Physics-based terramechanics
Visual conditions	Low texture, extreme illumination [5], [29]	Physically-based rendering
Remote Supervision	Comm. delay, limited bandwidth [2], [30]	Latency and autonomy modeling
Resources	Bounded power, compute, duration [31], [32]	Energy/compute-aware evaluation
Gravity	Low-gravity regimes [33]	Configurable gravity and contact
Operational constraints		
Remote supervision	Comm. delay, limited bandwidth [2], [30]	Latency and autonomy modeling
Onboard resources	Bounded power, compute, duration [31], [32]	Energy/compute-aware evaluation
System requirements		
Platform diversity	Rovers, legged, aerial, multi-robot [3], [34]	Heterogeneous platform support

interaction (e.g., slip, sinkage, and unknown surface properties), significant communication delays with Earth, GPS-denied localization, and extreme environmental constraints including vacuum, radiation, and wide thermal cycling — all under missions that span months to years with minimal human intervention. Early work already treated perception, localization, motion generation, temporal planning, and resource management as components of one operational system [2], and later studies on terrain-adaptive navigation, global localization, and perception-aware planning reinforce this coupling [5], [23], [24], [25], [26], [27].

The same literature makes clear why planetary robotics differs from terrestrial autonomy. Table I summarizes the key domain-specific factors and their direct implications for simulation design.

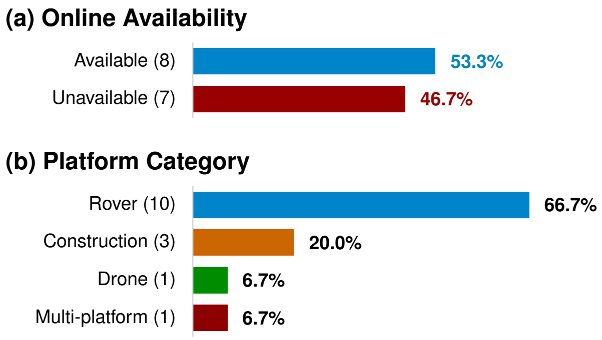

Fig. 3: Distribution of surveyed simulators by (a) online availability and (b) primary platform category.

B. Implications for Simulation

A planetary robotics simulator cannot be interpreted as a visualization tool alone. Three requirements follow from the preceding analysis. First, the simulator should represent terrain and robot–environment interaction at the level required by the target task [28], [35], [33]. Second, it should produce sensing conditions informative for the intended localization or scene-interpretation problem [29], [5], [26]– [36]. Third, it should support the operational assumptions of the target autonomy stack, including appropriate robotic platforms, software integration, and at least some representation of resource-constrained execution [2], [30], [34], [31].

These three requirements directly motivate the four analysis axes used in Section III, as illustrated in Fig. 2.

III. SURVEY OF EXISTING SIMULATION PLATFORMS

A. Taxonomy and analysis criteria

Building on the requirements identified in Section II, this section surveys existing simulation platforms from four practical perspectives, each mapping to a domain requirement as shown in Fig. 2. The purpose is not to rank platforms but to organize the literature consistently and clarify which aspects each platform addresses. Table II provides an overview of all fifteen surveyed platforms.

TABLE II: Overview of surveyed simulators: target domain, vehicle type, simulation engine, middleware support, and public availability. Publicly available platforms are annotated with repository footnotes.

Platform	**Year**	**Domain**	**Vehicle**	**Simulation Engine**	**ROS**	**Open**
Giubilato et al. [8][a]	2020	Mars	Rover	Gazebo	R1	✓
OAISYS [6][b]	2021	Planet.	Various	Blender	–	✓
MarsSim [9]	2023	Mars	Rover	Gazebo	R1	×
SEELO [10]	2023	Lunar	Excavator	Unity	–	×
LunarSim [11][c]	2023	Lunar	Rover	Unity	R2	✓
Jiang et al. [12]	2023	Mars	Rover	Blender	–	×
OmniLRS [7][d]	2024	Lunar	Rover	Isaac Sim	R1/R2	✓
MarsDrone [13]	2024	Mars	Drone	Unreal Engine	–	×
RLRoverLab [14][e]	2024	Lu./Ma.	Rover	Isaac Sim	R2	✓
LunarRoverSim [15][f]	2024	Lunar	Rover	PyBullet	–	✓
ISMRS [16]	2024	Mars	Rover	Isaac Sim	R2	×
Batagoda et al. [17][g]	2024	Lunar	Excavator	Chrono	R2	✓
LuSeg/LESS [18][h]	2025	Lunar	Rover	UE + AirSim	R1/R2	✓
Linde et al. [19]	2025	Lunar	Exc./Truck	AGX Dynamics	R2	×
Lindmark et al. [20]	2025	Lunar	Rover	OpenPLX + AGX	R2	×

[a] GitHub repository: `https://github.com/MorpheusPD/MarsSim`
[b] GitHub repository: `https://github.com/DLR-RM/oaisys`
[c] GitHub repository: `https://github.com/PUTvision/LunarSim`
[d] GitHub repository: `https://github.com/OmniLRS/OmniLRS`
[e] GitHub repository: `https://github.com/abmoRobotics/RLRoverLab`
[f] GitHub repository: `https://github.com/assawayut/LunarRoverSim`
[g] GitHub repository: `https://github.com/projectchrono/chrono`
[h] GitHub repository: `https://github.com/nubot-nudt/LuSeg`

B. Openness and availability

Within the surveyed set, eight of fifteen platforms are publicly accessible online, whereas seven are not (Fig. 3a). Publicly available examples include the framework of Giubilato et al. [8], OAISYS [6], OmniLRS [7], LunarSim [11], RLRoverLab [14], LunarRoverSim [15], Batagoda et al. [17], and LuSeg/LESS [18]. The remaining platforms are described without a corresponding online release.

This distribution shows that a widely adopted backend does not by itself imply public platform availability. A simulator may use a well-known engine and still remain unavailable as a released platform.

C. Scenario and platform coverage

The surveyed papers remain centered on rover scenarios (Fig. 3b), consistent with the historical role of rovers in planetary surface exploration. At the same time, OmniLRS reports multi-robot capability [7], SEELO addresses lunar excavation [10], MarsDrone considers aerial platforms [13], and Linde et al. and Lindmark et al. consider broader construction workflows [19], [20]. Even so, broader coverage still appears as specific extensions rather than default assumptions.

D. Sensor and perception support

Sensor and perception support is one of the clearest convergence points across the surveyed literature. Many papers are motivated directly by perception tasks: SLAM, visual localization, obstacle detection, segmentation, or synthetic-data-driven model development [8], [11], [7], [16], [18].

Table III contrasts the sensing modalities emphasized in current simulator papers against those discussed in planetary mission documentation and navigation surveys. The dominant supported modalities are cameras, RGB-D, LiDAR, and IMUs, together with perception-oriented outputs such as semantic labels, depth, and annotations. However, explicit support for more specialized modalities (radar, thermal, event-based, celestial-navigation sensors) is reported much less often. Table IV further details the supported sensors and perception outputs per platform.

TABLE III: Sensing modality coverage: simulator literature vs. real or planned planetary missions. Upper rows show well-supported modalities; lower rows highlight gaps.

Sensing Modality	**Simulators**	**Real Mission**
Mono / Stereo Camera	✓	✓
RGB-D	✓	✓
2D / 3D LiDAR	✓	✓
IMU	✓	✓
Wheel Encoder / Odometry	○	✓
Semantic / Instance Labels	✓	–
Star Tracker / Celestial Nav.	✗	✓ [37], [38]
Ground-Penetrating Radar	✗	✓ [39], [40]
Thermal / IR Sensor	✗	○
Event-based Camera	✗	○
SPAD / ToF Sensor	○ [17]	○
Radar (velocity/obstacle)	✗	✓ [40]

✓ = supported; ✗ = not addressed; ○ = limited support;
Simulators: fewer than three platforms; Missions: planned or prototype-stage.

E. Environmental and operational realism

The literature shows a visible progression from nominal scene generation toward richer treatment of terrain interaction, sensing conditions, and operational assumptions. Table V provides a per-platform comparison of realism features.

TABLE IV: Per-platform perception capability: terrain data source, supported sensor modalities, and primary perception outputs. St = Stereo; Sem = Semantic; Seg = Segmentation; Enc = Wheel encoder; Alt = Altimeter; Inc = Inclinometer.

Platform	**Terrain Source**	**Supported Sensors**	**Perception-Oriented Capability**
Giubilato et al. [8]	Real	St Cam, 3D LiDAR, IMU	Configurable multi-sensor perception testing
OAISYS [6]	Synthetic	RGB-D (extensible)	Synthetic data generation with semantic metadata
MarsSim [9]	Real	Mastcam	High-fidelity visual perception evaluation
OmniLRS [7]	Real	RGB-D, 2D/3D LiDAR, IMU	Multi-modal synthetic data and instance annotation
SEELO [10]	Real	Vision, IMU	Vision support for excavation monitoring
LunarSim [11]	Synthetic	RGB-D, IMU	Computer-vision algorithm prototyping
Jiang et al. [12]	Synthetic	RGB-D + Sem	Semantic scene generation and annotation
MarsDrone [13]	Real	Cam, Alt, Inc, IMU	Aerial visual perception and landing-scene evaluation
RLRoverLab [14]	Synthetic	RGB Cam	Vision-based observation generation for RL
LunarRoverSim [15]	Real	RGB-D + Seg	Segmentation-oriented data generation
ISMRS [16]	Real	St Cam, IMU, LiDAR, Enc	ML-oriented multi-sensor data generation
Batagoda et al. [17]	Real (Earth)	Cam, LiDAR, SPAD, GPS, IMU	Physics-based multi-sensor realism modeling
LuSeg/LESS [18]	–	RGB-D, 3D LiDAR, IMU	Lunar obstacle semantic segmentation
Linde et al. [19]	Synthetic	Observation sensor	Observation-driven task and resource evaluation
Lindmark et al. [20]	Real	RGB-D, LiDAR, IMU	Perception robustness under sensor non-idealities

TABLE V: Environmental and operational realism features across surveyed platforms, sorted by year. The rightmost two columns highlight the under-addressed operational constraints.

Platform	***Year***	***Terrain Deform.***	***Regolith/Slip***	***Visual Conditions***	***Sensor Non-Idealities***	***Power Constraints***	***Comm./Compute***
Giubilato et al. [8]	2020	✗	✗	✗	✗	✗	✗
OAISYS [6]	2021	✗	✗	✓	○	✗	✗
MarsSim [9]	2023	○	○	✓	○	✗	✗
SEELO [10]	2023	✓	○	○	✗	✗	✗
LunarSim [11]	2023	✗	✗	✓	○	✗	✗
Jiang et al. [12]	2023	✗	✗	✓	✗	✗	✗
OmniLRS [7]	2024	○	○	✓	○	✗	✗
MarsDrone [13]	2024	✗	✗	○	○	✗	✗
RLRoverLab [14]	2024	✗	✗	○	✗	✗	✗
LunarRoverSim [15]	2024	✗	○	✗	✗	✗	✗
ISMRS [16]	2024	○	○	✓	○	✗	✗
Batagoda et al. [17]	2024	✓	✓	✓	✓	✗	✗
LuSeg/LESS [18]	2025	✗	✗	✓	○	✗	✗
Linde et al. [19]	2025	✓	✓	○	○	✓	✗
Lindmark et al. [20]	2025	✓	✓	○	✓	○	✗

✓ = addressed; ○ = partial; ✗ = not reported.

TABLE VI: Key findings across the four analysis axes.

Axis	**Key Observations**
Openness	8 of 15 platforms publicly available; widely adopted engines do not guarantee platform release.
Scenario	67% rover-only; multi-robot, aerial, and construction scenarios emerging but not yet default.
Sensing	Strong camera/LiDAR/IMU support with annotation pipelines; specialized modalities (radar, star tracker, thermal) largely absent.
Realism	Terrain deformation and Visual Conditions increasingly addressed; operational constraints (compute, comms, energy) remain underrepresented.

Recent papers place increasing emphasis on terrain deformation [10], [41], physics-based sensor simulation [17], regolith interaction [42], and mission-oriented workflow analysis including energy consumption [19]. However, operational constraints such as onboard compute limits, multi-minute communication delays with Earth, and battery and energy budgets are reported less consistently.

F. Synthesis

Table VI summarizes the main characteristics observed across the four analysis axes. The surveyed platforms are not designed for a single common purpose; instead, different papers provide different combinations of capabilities depending on their target problem. These differences, together with the practical limitations identified, motivate the open challenges discussed in Section IV.

IV. OPEN CHALLENGES AND FUTURE DIRECTIONS

The four analysis axes of Section III reveal corresponding open challenges, as traced in Fig. 2. This section discusses each and concludes with a unifying direction.

A. Limited openness and reusable public ecosystems

Slightly more than half of the surveyed platforms remain unavailable through an online release. For planetary robotics, this is especially relevant because simulation plays a larger role in development than in many terrestrial domains. When a platform is publicly accessible, later studies can reuse its assets, compare methods under shared settings, and reduce repeated engineering. A practical future direction is broader release of simulation software, assets, scenes, and evaluation components whenever project constraints permit.

B. Rover concentration and limited scenario diversity

The surveyed literature remains rover-centered, but the broader planetary robotics community already considers cooperative exploration [3], [4], aerial vehicles [32], and multi-robot operation [34]. NASA reporting has shown that Ingenuity provided scouting support for Perseverance, illustrating the relevance of heterogeneous aerial–ground cooperation [43]. Future simulator development would benefit from broader platform coverage to capture the mission space now being discussed.

C. *Insufficient support for diverse sensing modalities*

As shown in Table III, the sensing assumptions in the simulator literature are narrower than the broader sensing possibilities discussed in planetary navigation and mission documentation. Star trackers, ground-penetrating radar, and radar-based velocity estimation are already part of real or planned mission hardware [37], [38], [39], [40], yet they are largely absent from current simulation platforms. A future direction is more explicit support for these modalities, including simulation outputs and evaluation workflows useful for the corresponding perception problems.

D. *Limited treatment of operational constraints*

VIPER documentation reports power, communication, and round-trip delay considerations [38]. The lunar surface navigation survey identifies computational cost and hardware requirements for several navigation modes [37]. Compared with these mission-level considerations, the current simulator literature reports onboard computation limits, communication delay, and energy constraints far less often than visual or terrain realism (Table V, rightmost columns). Greater attention to operational constraints would complement the recent progress in photorealistic rendering and terrain simulation.

E. *Toward sim-to-real planetary simulation ecosystems*

A more complete direction is the development of planetary simulation ecosystems that combine four properties more consistently: online availability, broader robotic platform coverage, richer sensing support, and more realistic operational constraints. These properties correspond directly to the analytical axes of Section III. Taken together, these observations point to several priorities for future planetary simulation development: broader online availability, wider robotic platform coverage, richer sensing support, and more realistic operational constraints.

V. CONCLUSION

This paper surveyed simulation platforms for planetary robotic perception and autonomy from four practical perspectives: openness and availability, scenario and platform coverage, sensor and perception support, and environmental and operational realism. The reviewed papers show that current simulation research increasingly supports perception-oriented workflows while placing greater emphasis on photorealistic rendering, terrain interaction, and physics-based sensing. At the same time, the surveyed platforms remain rover-centered, with substantially varying online availability.

These observations suggest that future progress should not be understood only as higher visual fidelity. Broader public availability, wider scenario coverage, support for diverse sensing assumptions, and more explicit treatment of operational constraints are necessary to better align simulation with the requirements of planetary exploration. Rather than pointing to a single ideal simulator, this survey indicates the need for a broader and more practically usable ecosystem of simulation platforms.

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