Paper ID: 114756
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student

IAF SPACE OPERATIONS SYMPOSIUM (B6)
Mission Operations, Validation, Simulation and Training (3)

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SIMULATION-DRIVEN VALIDATION FRAMEWORK FOR LUNAR ROVER PERCEPTION USING A DIGITAL TWIN AND PHYSICAL ANALOG TESTBED

Abstract

This paper presents a simulation-driven validation framework for AI-enabled robotic perception systems intended for future lunar surface operations. As lunar exploration missions increasingly rely on autonomous visual methods for navigation, terrain traversibility and hazard detection, there is a growing need for tools capable of generating mission-representative training data while supporting systematic validation of perception model performance. The limited availability of annotated extraterrestrial datasets and the difficulty of reproducing lunar surface conditions on Earth make simulation-based approaches particularly valuable for mission preparation and operational readiness assessment.

The work is conducted within the context of the European Space Agency (ESA) OSIP co-funded project "Leveraging Unreal Engine 5 to Develop Synthetic Data Tools for Lunar Surface AI enabled Robotic Applications." As part of this effort, we utilize ULYSSES, a planetary surface simulation environment being developed at Tartu Observatory of the University of Tartu. The framework leverages modern game engine technology, specifically Unreal Engine 5, in combination with digital elevation models and physics-based rendering approaches to generate large-scale photorealistic planetary surface environments suitable for synthetic dataset generation. These capabilities enable controlled creation of annotated datasets for robotic perception tasks including monocular depth estimation, object detection and semantic segmentation.

This study investigates the simulation-to-reality transferability of perception models trained using synthetic datasets. Several training strategies are explored, including models trained exclusively on synthetic data, mixed synthetic-real datasets and synthetic pre-training followed by limited real-data fine-tuning.

Model performance is evaluated using standardized task-specific metrics to quantify domain transfer effects and identify practical limitations.

To support experimental validation, a digital twin of the Tartu Observatory lunar analog facility was constructed using a high-resolution 3D laser scan of the physical test environment. Validation experiments are conducted using the KuupKulgur robotic testing platform operating within this facility. By performing matched evaluations across the digital twin environment and the physical testbed, the framework enables systematic characterization of simulation-to-reality performance degradation and provides insight into the influence of illumination conditions, terrain variability and dataset composition on perception reliability.

The proposed approach contributes toward simulation-driven validation and training methodologies for future lunar robotic missions by directly linking synthetic data generation with physical analog experimentation. The ULYSSES environment therefore represents a scalable platform for advancing AI-enabled robotic capabilities for planetary surface exploration, with future development targeting ROS2-compatible hardware-in-the-loop simulation for closed-loop testing of robotic autonomy software in mission-representative planetary environments.