A Software Framework for Advancing Perception Capabilities for Rovers Operating in Harsh Lunar Environments

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Introduction and High Level Objectives

We report outcomes of a NASA project focused on developing a software suite for sensor modeling and simulation in lunar-like environments. This suite, which encompasses high-fidelity terramechanics and perception algorithms for hazard detection, is depicted in Fig. 1. The project's primary goals were twofold: firstly, to establish a simulator that replicates lunar conditions; and secondly, to devise and validate rover perception algorithms within this environment. In this contribution the focus is on the simulation framework, with particular emphasis on sensor modeling.

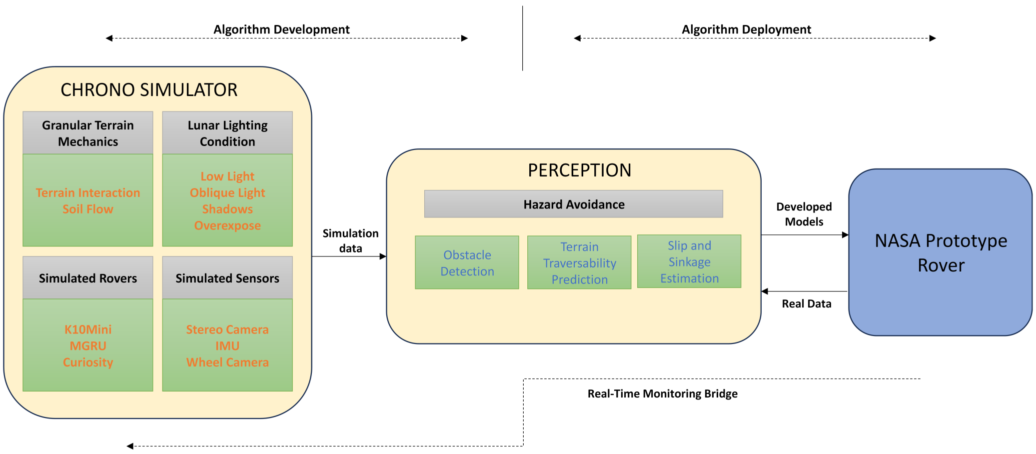
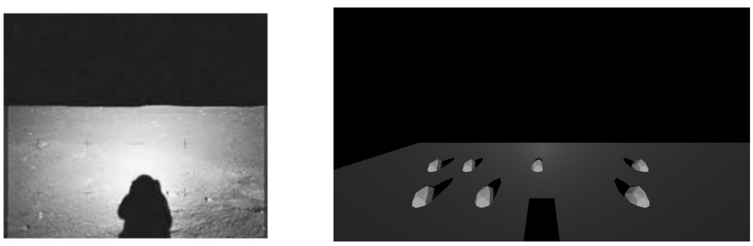


Figure 1: Conceptualization of key innovations and technologies.

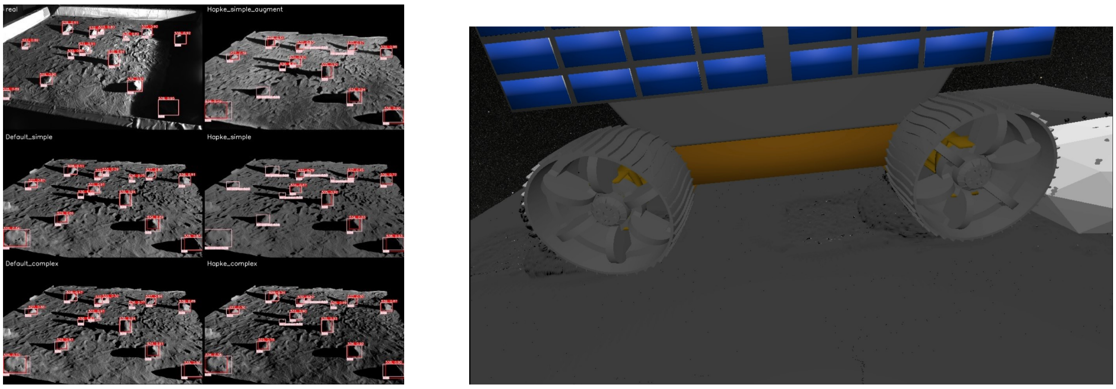
Chrono::Sensor Lunar Sensing Module: Due to the lack of lunar atmosphere as well as low albedo and retro-reflectivity of lunar regolith, lighting on the Moon exhibits the opposition effect where there is peak brightness when the viewing direction and lighting direction coincide. To capture these artifacts in a camera sensor simulator, we used the Hapke photometric functions [1] that model reflections of extra-terrestrial bodies. We implemented this in Chrono::Sensor [2] to augment the current camera model to be lunar capable (Fig.2). Furthermore, we modeled exposure and lens artifacts such as distortion, vignetting and depth of field for a more realistic sensor simulation. Finally, to enhance the photorealism of the synthetic lunar images, we use a GAN pipeline to augment the synthetic images generated by the physics-based camera model.



(a) (b)

Figure 2: (a) Real lunar opposition effect; and (b) Simulated opposition effect (right).

POLAR3D Virtual Worlds: NASA's POLAR Stereo dataset [3], is a set of imaged created using a physical analog of lunar environments. Specifically, since NASA doesn't have sufficient pictures taken on the Moon for testing perception stereo algorithms, artificial images were created in Ames. NASA's setup was created such that it mimics the lunar terrain and lighting conditions. We used POLAR as a reference when designing and validating our camera model. Further, we generated exact digital twins of the POLAR environments based on their LiDAR scans, so that these Chrono digital twins can be used in simulation (Fig.3a). We also introduced POLAR3D, a curated dataset where we labeled all the rocks and shadows in the POLAR dataset images, such that they can be used in downstream perception tasks [4]. By generating in POLAR3D the digital twin of the scenarios available in NASA's POLAR database, one can generated on demand synthetic images with Chrono::Sensor of the same setups used at NASA but this time around from different camera positions, with different exposures, and different "sun" locations. These images are subsequently used in training and testing machine learning-trained perception algorithms employed in the autonomy stack.



(a) (b)

Figure 3: (a) Labeled POLAR dataset terrain (left) and its digital Twin (right); (b) VIPER rover operating on CRM terrain.

Chrono::Sensor Lunar Sensing Module As a proof of concept for simulating lunar environments in Chrono, we created simulations of the NASA VIPER rover operating on deformable lunar terrain modeled using the Soil Contact Model (SCM) [5] and the Continuous Representation Model (CRM) [6], while the operation of VIPER was observed by a Chrono::Sensor camera (Fig.3b). The terrain mechanics capabilities and the sensing capabilities of Chrono, combine to enable the testing of perception algorithms such as wheel sinkage and wheel slip estimation, which are crucial for rover operations on the Moon. The image in Fig.3b captures a frame of the evolution of the rover while operating in a virtual world that is the digital twin of scenarios contained in the NASA POLAR dataset.

Conclusion and Future Work

To date, we have concentrated one core aspects of the simulator: developing a framework to accurately represent lunar terramechanics and appearance. We utilized Chrono to demonstrate its capability to simulate rover operations in harsh lunar environments. Looking ahead, we plan to improve the simulation framework to support features such as Human-Robot Interaction (HRI) with rovers, better sensing models, and testing full rover autonomy stacks in simulation.

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