Flyover Modeling of Planetary Pits

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Introduction: On the surface of the moon and Mars there are hundreds of skylights, which are collapsed holes that are believed to lead to underground caves. This research uses Vision, Inertial, and LIDAR sensors to build a high resolution model of a skylight as a landing vehicle flies overhead. We design and fabricate a pit modeling instrument to accomplish this task, implement software, and demonstrate sensing and modeling capability on a suborbital reusable launch vehicle flying over a simulated pit. Future manned colonies on other planets and moons will start in caves for their protection from the harsh space environment, led by the technology developed by this research.

While planetary caves have been hypothesized for decades, they have not been plausible exploration candidates due to lack of surface access, difficulty of operation, and obscurity from orbit. Newly discovered planetary pits might be key to accessing subsurface voids, caves, and lava tubes. While the existence of pits is now unambiguous, how to explore them and whether any lead to extended caves is unknown.

Pits represent an unparalleled opportunity to access enigmatic subterranean spaces, but their complex geometry makes them impossible to fully observe from orbit. Future robotic exploration missions will target one of these pits[3]. As a spacecraft is about to land, it flies at an altitude under a few hundred meters, traveling at a speed under tens of meters per second. As it flies over a pit during this time, it can collect high quality visual, inertial, and LIDAR data at unprecedented viewing angles from which to model the pit. This same sensor suite is used for precision navigation and terrain hazard avoidance. Reconnaissance from flyover modeling will be used to inform approach and entry paths for rovers[4]. It will be used to characterize geology, select likely locations for inhabitation, and inform follow on exploration.

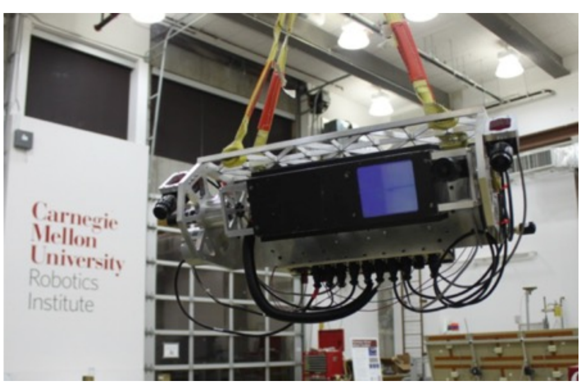

Figure 1. The developed pit modeling instrument.

Instrument Design: The pit modeling instrument design accounts for pit geometry, vehicle dynamics during scanning, and required data precision and resolution. The geometry of planetary skylights drives range and field of view of the sensors. Our work specifically studied lunar skylights, which are the best characterized and of high interest. Wagner and Robinson[5] used automated computer vision to detect 200 candidate skylights that are evenly distributed in both location and size. Based on these statistics, the sensor is designed to survey an area that is nominally 50m in radius and 50m in depth. This can model the majority of lunar pits.

The dynamical parameters of the landing phase determine sensor range and rate requirements. One example with publicly available data is the NASA ALHAT free flight campaigns on the Morpheus vehicle, which commanded an apogee of 245 meters and a 30-degree glide slope at 12.5 meters per second[1]. This trajectory has been designed to simulate the final landing portion of a robotic lunar mission and can be used as the nominal profile for a skylight scanning mission. From this nominal trajectory, we defined the maximum sensing range to be 260m. This is corresponds to a 45 degree pointing angle above vertical at 180m altitude.

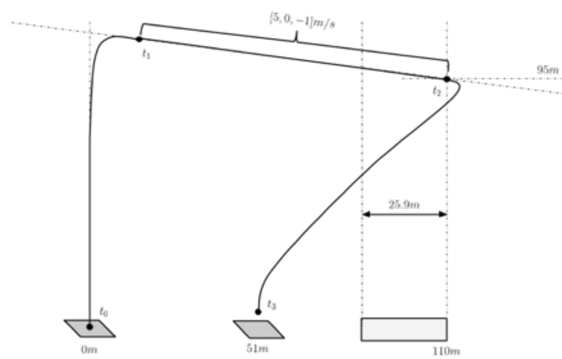

Figure 2. Terrestrial flight profile to test pit modeling instrument (Masten Space Systems).

Cameras provide image pixel values which can enhance the quality of a model through texture or be processed into geometric knowledge using structure from motion techniques. This allows the sensor to precisely reconstruct its trajectory without GPS and also helps build the model. With a calibrated stereo pair of cameras, the trajectory can be reconstructed with correct metric scale. We include a pair of monochrome stereo cameras and a higher resolution color camera to capture texture information.

LIDAR sensors provide a very accurate range measurement over a very long range and work in both shadows and light, unlike cameras. The LIDAR is used to generate a high resolution elevation map of the pit and its inner walls during the flyover.

An Inertial Measurement Unit measures linear acceleration and angular velocity throughout the flight. IMU data helps smoothly connect the relatively low frequency camera measurements to the higher frequency LIDAR measurements.

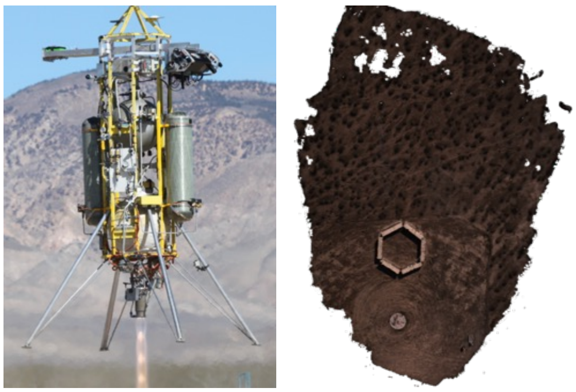

Figure 3. Left: Pit modeling instrument integrated with Masten Xombie flight test vehicle. Right: Top-down view of flyover 3D model.

Flyover Modeling: Sensor software utilizes modern graph-based optimization techniques to build 3D models using camera, LIDAR, and inertial data[2]. The modeling performance was validated with a test flyover of a planetary skylight analog structure on the Masten Xombie sRLV. Flight on the Masten Xombie sRLV provides the most relevant terrestrial testing environment possible. The trajectory profile closely follows that of autonomous planetary powered descent, including translational and rotational dynamics as well as shock and vibration. In addition, integration with and remote operations for a propulsive vehicle provide unique and valuable experience. A hexagonal structure made of shipping containers provides a terrain feature that serves as an appropriate analog for the rim and upper walls of a cylindrical planetary skylight.

The skylight analog floor, walls, and rim are modeled in elevation with a 96% coverage rate at $0.25m^2$ resolution. The inner skylight walls have $5.9cm^2$ color image resolution and the rims measure $6.7cm^2$.

Model precision is determined by comparing the dimensions of the shipping containers that form the skylight analog walls with surveyed ground truth measurements. The average reconstructed length is compared to the actual surveyed length for each dimension. The error for each container dimension is under 1m.

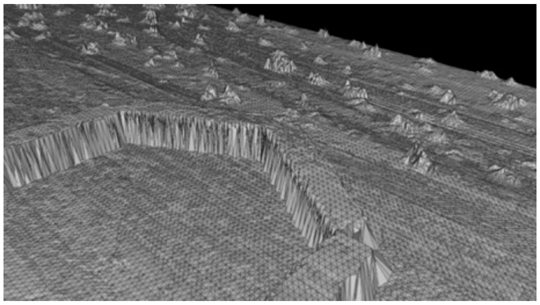

Figure 5. Elevation model generated from data collected during propulsive flight.

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References:
[1] Hosein, N. (2011, April). Morpheus: Lunar lander test bed takes flight. *LYNDON B. JOHNSON SPACE CENTER Roundup* , pp. 6-7.
[2] Indelman, V., Williams, S., Kaess, M., & Dellaert, F. (2013). Information fusion in navigation systems via factor graph based incremental smoothing. Robotics and Autonomous Systems , 61 (8), 721-738.
[3] Jones, H. L., et al. "Skylight: Mission to Investigate and Model a Lunar Pit." Lunar and Planetary Science Conference. Vol. 44. 2013.
[4] Peterson, K. M., H. L. Jones, and W. L. Whittaker. "Mission Design for Combined Lander-Rover Modeling of a Skylight." LPI Contributions 1640 (2011): 29.
[5] Wagner, R. V., & Robinson, M. S. (2014). Distribution, formation mechanisms, and significance of lunar pits. *Icarus, 237*, 52-60.

Figure 4. Planetary skylight analog structure.