MISSION DESIGN FOR COMBINED LANDER-ROVER MODELING OF A SKYLIGHT Kevin M. Peterson, H.L. Jones, W.L. Whittaker, Carnegie Mellon University, Pittsburgh, PA; kp@cs.cmu.edu

Introduction: Combined lander-rover modeling is the transformational means for developing high resolution, color, three-dimensional representations of planetary features such as cave entrances and skylights. Lander-rover modeling combines registered overflight imagery with rover-based surface imaging techniques to build highly accurate co-registered models. The models produced by this approach exhibit high resolution from surface modeling, and high accuracy resulting from co-registration of surface and overflight models. Such models require specialized trajectories designed to provide high precision relative to the selected feature while supporting the requirements for safe landing.

The architecture detailed here combines lander flyover with extended investigation by robotic rover. Real-time data from cameras and LIDAR are combined with existing satellite imagery to navigate precisely to a selected landing zone, identify a safe landing location, and maneuver past hazards to safely touch down. While flyover provides birds-eye views of the feature, landing views are limited by fuel constraints. The rover provides low-angle, detailed views of specific areas of high interest detected from above. Rover and lander data are combined in post-processing to determine landing location to within 5m accuracy and to reconstruct the actual landing trajectory and feature models with 10cm precision. A specific case study of a Lunar skylight known as the Marius Hills Hole[1, 2] is detailed.

Targeting Skylights: Skylights are excellent candidates for the next generation of planetary missions. These accesses to lava tubes and expansive caves exist on planetary bodies throughout the solar system. Caves and lava tubes are safe havens that will protect astronauts from extreme temperatures, micrometeorite impacts, and radiation. Subsurface caverns also preserve unique geologic environments. However, skylight missions present challenges well beyond those of conventional missions.

Landing zones near skylights are typically hazardous precluding standard blind landing techniques. The tunnels themselves are too dangerously unknown to initiate exploration with humans. Rather, robotic landers will precisely land near these sites and deploy roving explorers to map and characterize these destinations for future human missions. Communication delay during landing, and complete communication blackout during underground operation demand unprecedented levels of autonomy above and below the surface. Development of highly accurate models requires new techniques for data fusion and localization.

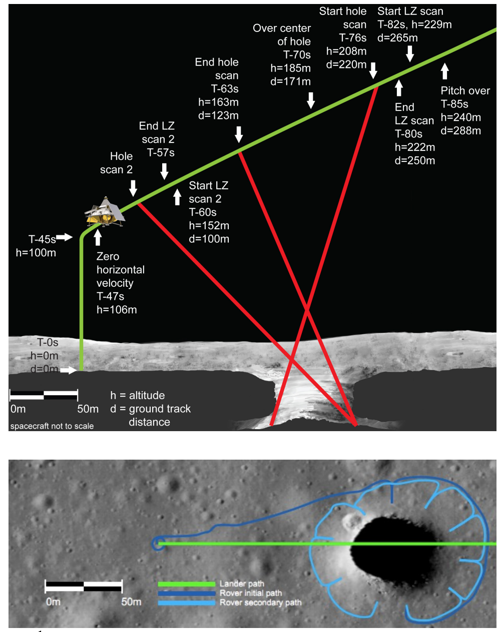

Figure 1: Trajectory for combining flyover and surface modeling of a skylight. Top: landing trajectory (green) with LIDAR views (red) of the skylight. Bottom: rover path (blue) overlaid on lander trajectory (green) as the rover circles around the skylight.

One approach to building highly accurate surface models is to fuse flyover data with surface data. In contrast to state of practice landing dispersions (1-2 km, Lunar), new terrain relative navigation techniques can achieve localization accuracies better than 50 meters during landing[3]. This accuracy enables overflight of the skylight. A rover traversing the skylight area can then register to descent imagery to develop highly accurate models.

Mission Architecuture: The Marius Hills Hole was selected for detailed analysis of this mission concept. This skylight is located in the Lunar Marius Hills region and is approximately 65 m in diameter[2].

The mission architecture consists of a lander that flies over the hole and a rover that egresses and returns to circle the hole. The lander also has 100kg of additional payload capacity that could be used for a robot that would descend into the hole.

Flyover Modeling: The lander has a camera and a 3° field of view flash LIDAR. A flash LIDAR is a sensor that uses laser light to capture a 3D image. For the sensor used in this analysis, the LIDAR image is 128x128 pixels. Both the camera and the LIDAR are mounted on a gimbal which enables scanning of wide areas of terrain.

Lander descent consists of four sub-phases: braking, pitch-up, approach, and terminal descent. Braking removes a majority of orbital velocity. A pitch-up maneuver at about 500m from the landing point provides a smooth transition in acceleration and vehicle attitude from the high-thrust braking to the constant-velocity approach with a 25° glide slope. Flyover surface modeling occurs during approach. Modeling pursues two objectives: feature modeling and hazard detection.

At 350m slant range, the lander uses LIDAR to map a 50m square area around the desired landing site for hazards. At this range, each LIDAR pixel will cover approximately 20cm on the ground, with the full LIDAR footprint covering 25.6m. Overlapping LIDAR images to improve resolution, 30 images are needed to cover the landing zone. The gimbal takes about 2 seconds to complete this scan. After the scan is completed, landing targets free of hazards are identified, an optimal target is selected, and a new trajectory is planned autonomously.

The lander then transitions to feature modeling as it flies over the Marius Hills Hole. The navigation and control precision during approach ensures that the lander will be within 35m of its intended trajectory. Thus, if the target trajectory passes over the center of the hole and the hole diameter is assumed to be 65m, the lander will pass no more than 2.5m from the edge of the hole, enabling it to easily scan the hole floor with gimbaled LIDAR and camera. A 13 second flight over the hole while capturing LIDAR images at 20 Hz results in 260 images over the hole. These images have a resolution of about 10cm/pixel. Camera images will also be taken with a resolution of about 5 cm/pixel.

At 180m slant range, after having passed over the hole, the lander transitions to hazard detection. The landing zone is scanned again, centering on previously identified safe landing targets, and the lander re-plans if necessary. At 180m slant range, each pixel will cover approximately 8.8cm, and the full LIDAR footpring 11.3 meters. Less image overlap is needed at this point, but since each image is smaller, 30 images are still needed to cover the landing site. Because the slew distance on the sensor is greater in this case, it is expected to take 3 seconds for this scan.

The lander turns its sensors back to the hole until it reaches about 100m altitude, when it zeros horizontal velocity and begins the final descent. This final scan of the skylight lasts 5 seconds and captures 100 images.

Rover Modeling: The rover has a stereo pair of cameras and the same flash LIDAR as used on the lander. These sensors are mounted on a mast at the top of the rover and have pan-tilt actuation.

Given allowance for hazard avoidance divert maneuvers, the final landing site will be within 170m of the skylight. This proximity enables the rover to reach the hole and perform significant exploration around the hole with only 1km of travel. Rover observations of the opposing skylight rim achieve a resolution of 4cm/pixel for LIDAR. Since the rover travels at 5cm/second and can remain stationary for arbitrary periods, the number of images that can be captured is not limited by time, as for the lander.

Fusing Flyover and Rover Models: Lander and rover models are fused by iteratively aligning 3D point clouds from lander and rover sensors to create a 3D model of the landing region including the skylight. The LIDAR and camera data are fused using a Markov Random Field (MRF) graphical model to create a 3D basemap for the Hole and the landing site. Rover navigation information is combined with image and heightmap correlation to overlay rover data onto the basemap.

Model synthesis requires that all data be synchronized, fused, and spatially registered into a global coordinate system. Data synchronization begins online while the lander or rover is collecting data. Every LIDAR and camera image is time stamped and logged. Handling data in this manner allows for complete offline playback of the data and provides a timeline to organize streaming data into discrete model-building blocks. Once data is blocked into time segments, these blocks are aligned and registered into a model. Point clouds from LIDAR data are filtered for outliers. Globally registered position estimates serve as the starting point for multi-view surface matching and for global iterative closest point algorithms.

Following scan registration, updated position and orientation information (obtained through the registration process) corrects position and orientation estimates for lander and rover sensors, thus improving trajectory estimates for flyover and driving. This step enables global registration of data from camera imagery, thereby visually representing texture on the 3D model. A MRF is again used to fuse LIDAR and camera data. This spatial visualization of non-geometric data greatly enhances the aesthetic appeal and contextual understanding of 3D models.

The final result is a 5m accurate 3D model of the Hole and the surrounding terrain, including the landing zone. Using incremental measurements from rover navigation, closing the loop on the rover path, and fusing the rover and lander data into a 3D map, the Skylight mission confirms the landing location with respect to prior imagery and elevation maps. It reconstructs the lander trajectory for approach and final descent and provides high-resolution data to evaluate lander perception of hazards in the landing zone.

References: [1] J. W. Ashley, et al. (2011) *42nd LPSC*. [2] Haruyama, et al. (2009) *JGR* 39. [3] R. S. Park, et al. (2010) *J Spacecraft and Rockets* 47(6).