ROBOT AUTONOMY FOR ACQUIRING IMAGERY FOR PLANETARY PIT MODELLING.

H. Sharma[1], A. Jhalani[1], S. S. Savla[1], H. Sheth[1], H.L. Jones[1], W.L. Whittaker[1] [1]Carnegie Mellon University (5000 Forbes Avenue, Pittsburgh, PA 15213, {harshsha,ssavla}@cmu.edu)

Introduction: Satellite imagery has provided concrete evidence for planetary caves, pits and lava tubes[1]. Lunar pits and lava tubes have caught the fancy of many space organizations as they plan to set-up a base on the moon for future space missions. Pits serve as a safe haven from the radiation, extreme temperature variations and probable micro-meteorite impacts. The inconsistent geometry and varying lighting conditions about the pit makes it challenging to obtain a high-resolution oblique views of the interior of the pit through satellites. This necessitates getting close to the edge of the pit. This abstract presents an autonomous robotic system which when released from the lander navigates to a lunar pit, avoiding obstacles and steep slopes on it's way. It then circumnavigates the pit, getting close to the edge of the pit at various vantage locations around the pit and captures the illuminated walls of the pit. These images can be used to generate a 3D model of the pit which would be of immense importance for future scientific missions. The entire mission is expected to be completed within a single lunar day devoid of human intervention. The major contributions of the work include novel algorithms to plan path around a lunar pit accounting for the changing illumination and validating the same in a simulated lunar environment.

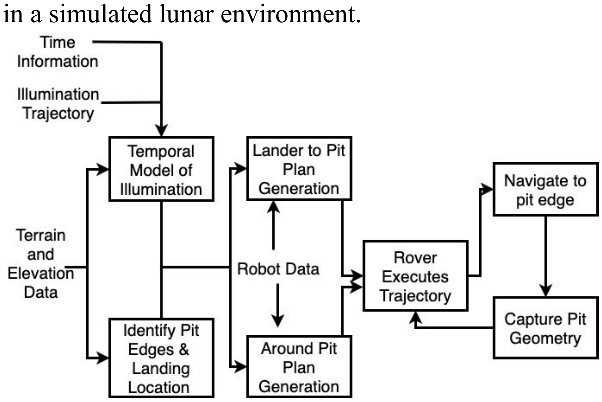

Figure 1. Mission Process

Waypoint Generation: The Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) provides images of the moon from an altitude of 50km at a nominal pixel scale of 0.5m[2][3]. The elevation map generated from the laser altimeter provides a high level notion of traversable areas and obstacles[4]. It also lays out a tentative location of the pit. An elevation gradient based approach is used to identify the edges and the interior of the pit. Waypoints can then be generated at any distance away from the pit edge based on the map digitization. To ensure appropriate pit coverage and waypoint navigability a two-pronged approach is followed. Untraversable waypoints are pruned off and suitably elevated waypoints are ensured around each quarter of the pit based on the variance of elevation of these waypoints.

Illumination Modelling: On the Moon, it is only possible to image surfaces that have been directly lit by an illumination source, primarily the Sun. It is essential to know the position of the Sun relative to the pit at all times to identify vantage points. For a pit with known coordinates and altitude information obtained by the LRO, it is possible to find the position of the Sun throughout the span of the day. The NASA tool CSPICE[5] provides the position vector of the Sun from the Moon. The tool also helps find the rotation of the Moon at the given time instants. With elementary vector arithmetic, the direction vector of the illumination of the Sun at the pit coordinates can be calculated.

Vantage points are defined as the possible waypoints the rover can be at a given time to capture a portion of the pit that is lit. The pit walls facing the illumination vectors are most likely to be illuminated, conditional to obstructions and local geometries. This is a fair assumption to obtain a sector of the pit that is likely to be illuminated. Previous work [6] has shown that the model of a pit generated from images is affected by the illumination angle relative to the surface. If the illumination is close to normally incident, images appear washed out; if too oblique, the surface is prone to shadowing; both resulting in images deficient of features. Generally circular pits will have a maximum depth illuminated towards the center of the sector. Waypoints that are facing these strongly lit points are classified as vantage points for that illumination direction. By modelling the illumination, at each vantage point, the sector of the pit optimally illuminated by the sun is estimated.

Illumination Based Path Planning: Capturing the illuminated sides of a lunar pit while ensuring complete coverage of the pit within a single lunar day is the prime goal of the planning algorithm. This necessitates a time based planning methodology which ensures that the rover captures the pit geometry when it is appropriately lit. At each time instant the algorithm evaluates each of the potential vantage points. Each vantage point is assessed for the cost to reach, time to reach, how centrally located is that particular vantage point compared to all the potential vantage point targets and the remaining time before the waypoint loses its vantage point status. A factor of pessimism is incorporated to take into consideration the increased time taken by the local planner to execute a collision free path. Doing this, we can ensure that the planner can be run offline and won't hog the on-board computational resources. Appropriate time is also allocated for capturing suitable images needed to create a 3D model of the pit later. The best vantage point is then selected. This ordered set of waypoints is then passed on to the local planner for traversal.

Local Planning: Local path planning is a mission-critical task as it has to take into account the local terrain, and define how the system will move on it. The presence of rocks, steep slopes, and craters make the problem onerous. Reliable perception is used to sense the environment, which enables the local planner to generate safe and feasible paths. The local planner has two major roles, namely, navigation between the globally generated vantage waypoints and navigation to the edge of the pit to take images of the interior of the pit.

The entire mission can be divided into three stages. The first is, traversal from the lander to a pit. The rover receives a set of ordered waypoints from the global planner which it tries to accomplish. The last waypoint of this global plan coincides with the first global vantage point around the pit. Once it is reached- the system transitions into the next state, which involves moving closer to the edge of the pit and capturing an image of the illuminated portion of the pit. If this step is successful, the system transitions into the third stage- which involves traversal around the pit from one vantage point to another. Once this is realized the system again cycles to the second stage and this process gets repeated till the entire pit is covered. The system shifts to achieve the next waypoint in case it fails to complete either of these transitions. The generated plan incorporates a dense collection of vantage points which have overlapping field of views. So missing a few vantage points would not impair pit coverage.

It is important to note that the pit edge generated from the LRO data is of low resolution. A low resolution map lacks information that is required to facilitate rover navigation to the edge of the pit. Navigation to the edge of the pit, from the given global waypoints, for capturing images of the inside of the pit, is handled by the local planner. It generates local waypoints which aid the rover to approach the edge of the pit while avoiding rocks and steep slopes on it's way and ensuring that it doesn't fall into the pit.

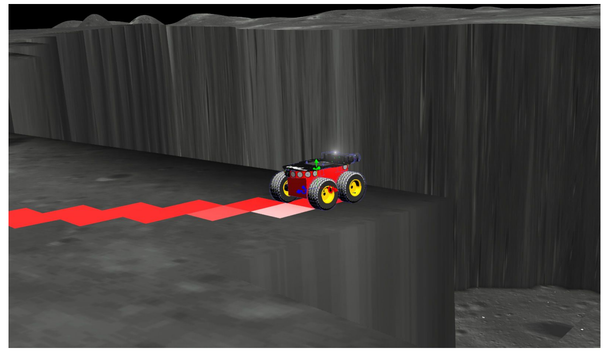

Figure 2. Rover navigating autonomously to the edge of a pit in the simulated lunar environment

Navigation to the edge of the pit requires defining what can be classified as the edge. The edge can be a vertical drop at certain regions or a gradual slope. The rover needs to be close to the edge of the pit while making sure that it does not fall inside. Going close to the edge of the pit demonstrates a risk-reward relationship. Going close to the edge of the pit increases the possibility of rover falling inside the pit, which would lead to mission failure but if done safely, it increases the depth of the coverage given the same field of view of the camera. This is achieved by using a perception system that can identify the edge of the pit using depth information generated from a stereo camera system, and an IMU which enables the robot to navigate to a safe angle of inclination.

Conclusions: The system was validated in a simulation environment with synthetically generated pits and illumination modelled at known coordinates of known lunar pits. The system was successfully able to generate plans for achieving complete coverage of the illuminated parts of the pit and traverse to the edge of the pit at the planned vantage points to image its interior. The images from the camera onboard the rover validate the capturing of the illuminated portions of the pit.

References: [1] Oberbeck et al. (1969) Modern Geology Vol. I [2] Robinson et al. (2010), Space Sci. Rev. doi: 10.1007/s11214-010-9634-2 [3] Wagner and Robinson. (2019) *LPI, Contrib. No. 2132* [4] Haris et al. (2008) Lasers and Electro-Optics and Conference on Quantum Electronics and Laser Science [5] Acton et al. (1996) *Plan*etary and Space Science, 44(1):65–70 [6] Jones H. (2016) Using Planned View Trajectories to Build Good Models of Planetary Features under Transient Illumination.