Crater-Pads: Using Lunar Craters as Unprepared Landing Sites to Mitigate Plume Surface Interactions.

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Introduction: Launching and landing spacecraft on the lunar surface presents a major hazard to nearby human-made objects due to the interactions between the rocket plume and the regolith-covered lunar surface, also known as Plume Surface Interactions (PSIs) [1]. This issue was first discovered during the Apollo 12 mission which landed near the robotic Surveyor III probe [2] where the astronauts noted sandblasting-like damage to the spacecraft, but only on the side facing the Apollo Lunar Module, with later studies concluding PSIs to be the culprit [3]. Subsequent numerical modeling and experimental studies [4,5,6,7] have indicated that some regolith grains could be ejected at speeds exceeding the lunar escape velocity (2.3 km s^{-1}) [8], which would likely cause damage to nearby infrastructure, especially during the repeated launches and landings required for a sustained human presence.

The leading mitigation strategy proposed for this problem involves using additive manufacturing techniques and locally sourced lunar regolith to construct landing pads to minimize the amount of ejected regolith, and protective walls or berms to protect sensitive objects from any ejecta that is mobilized [9,10]. Although this strategy will likely prove to be crucial in long run, it will face some challenges in the near future. Not only will this plan require the delivery of an excavator, extruder, melter, and power source, all of this equipment will also need to be mobile in order to build a sufficiently large landing site, as Artemis landers will have a landing precision of ~100 m [11]. All of this equipment would also need to be delivered on one spacecraft, as multiple landing deliveries would damage those spacecraft and equipment already present on the surface. Additionally, these logistical components and hardware remain untested in the lunar environment and must climb the TRL ladder before they can be fully relied on for lunar exploration missions. For these reasons, a more immediately available PSI-mitigation strategy should be formulated for crewed and robotic lunar exploration missions.

We propose using lunar craters as unprepared landing sites to mitigate the effects of plume surface interactions.

Methods: Using the python programming language, we calculated the 2-dimensional ballistic trajectories of regolith grains ejected due to PSIs. We used the results of numerical modeling studies of PSIs in literature [6,7,8] to inform our initial velocities (10-2380 km s^{-1}; 0-20°; with intervals of 10 m s^{-1} and 0.1°, respectively). We started the particles at 0.9 m above the lowest point within the crater and calculated their position every 10 ms until the particle struck the surface. In this initial modeling effort, we assume that the ejecta does not rebound off the surface, nor does it generate secondary ejecta via its impact. We also assume that gravity is the only force acting on the ejecta.

We extracted 2-dimensional crater profiles from Digital Terrain Models (DTMs; 2-5 m pixel^{-1}) produced by the Narrow Angle Camera (NAC) onboard the Lunar Reconnaissance Orbiter (LRO) [12]. We limited our selection of craters to those that had a maximum local slope below 20°, as this is the maximum traversable limit for the Artemis program's proposed Lunar Terrain Vehicle (LTV) [13]. We did however include craters that had an acceptable slope on only one side, since we envisioned a scenario where the LTV could drive out of the crater on the gentler side. We also took note of size of the crater floor where the slope did not exceed 6°, as this area would be reasonably and safely flat for a spacecraft to land.

Results and Discussion:

The results for one of our simulated landings in a lunar crater are shown in Figure 1. The top panel (with equally scaled x and y axes) shows a heat map for where the particles traveled during the simulation, while the second panel shows the local slope of the crater profile. The third panel shows a histogram of

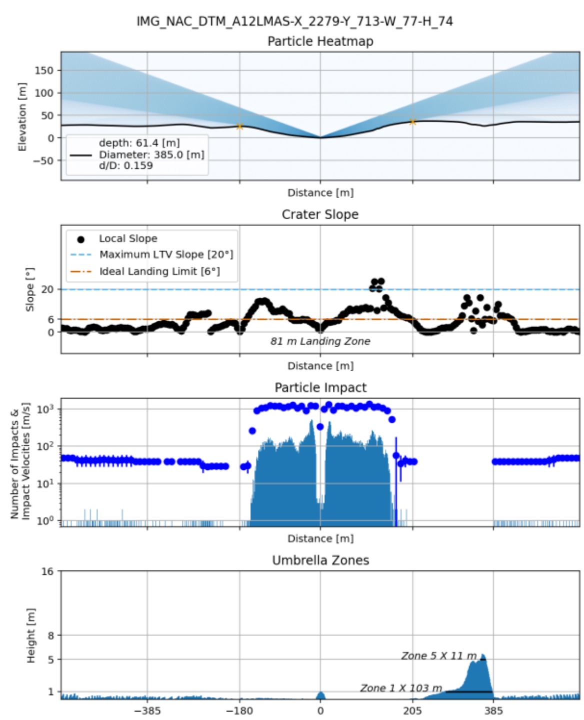

Figure 1. A crater landing simulation result.

particle impact locations, as well as their plotted impact velocities, note the logarithmic scale. The fourth (bottom) panel shows the umbrella zones, i.e. areas that are protected from regolith. The horizontal grid lines on this panel represent the heights for a rover (1 m), the diameter of an ISS module (5 m), and the heights of the Blue Moon Mk. 1 (8 m) and Mk. 2 (16 m) landers. The vertical grid lines on all panels represent multiples of the crater's radius.

In this simulation, a 103 m-wide umbrella zone exists to the right of our target crater where a 1 m-tall object would be protected. For some portions of this umbrella zone a 5 m-tall object could also be protected, though this area is only 11 m wide. It is also apparent that in the immediate vicinity outside the crater, the impact velocity is lower by an order of magnitude than the ejecta impacting the interior of the crater. This offers mitigation, though not full protection, to objects outside both the crater and the umbrella zone.

In Figure 2, we present the results from all 238 simulated crater-landings. In each panel, the x-axis represents the size of the umbrella zone for a given height, plotted against the crater's depth to Diameter ratio (d/D) in the y-axis. The intensity of the shading indicates the size of the safe landing area (slope <6°) within the crater, with white or light shading indicating little to no safe space to land. From this figure we can see that any crater with a d/D over 0.175 is guaranteed to produce an umbrella zone, though the most promising candidate craters that have both large umbrella zones and large safe landing zones, appear to be within the 0.11 to 0.17 range. We can also see that any crater with a d/D below 0.075 will produce an umbrella zone.

Conclusions and Future Work:

This preliminary work shows that some lunar craters could be used as unprepared landing sites for both crewed and robotic lunar exploration.

Of the 238 craters for which we simulated landings, slightly more than half (137) could produce umbrella zones. While d/D has given us some insight into the favorable characteristics of candidate craters, more work should be done to analyze the shape of promising craters (such as Chebyshev polynomials [14]) to help predict their utility as PSI mitigators.

These 238 craters also represent a microscopic portion of the millions of craters that mark the lunar surface [15]. Our work will be expanded to include more craters from existing databases, as well as more digital elevation sources such as the Lunar Orbiter Laser Altimeter (LOLA). We will also place more emphasis on analyzing craters near the Luna's southern pole, to help identify promising landing sites for upcoming Artemis and Commercial Lunar Payload Services (CLPS) missions.

Although this concept shows promise, further improvements must be made to the simulations to better assess its viability, namely: the inclusion of ejecta surface interactions. Incorporating hydro-code physics modeling [16] of ejected particles impacting the crater walls and lunar surface will help constrain the extent of secondary ejecta generated by said impacts.

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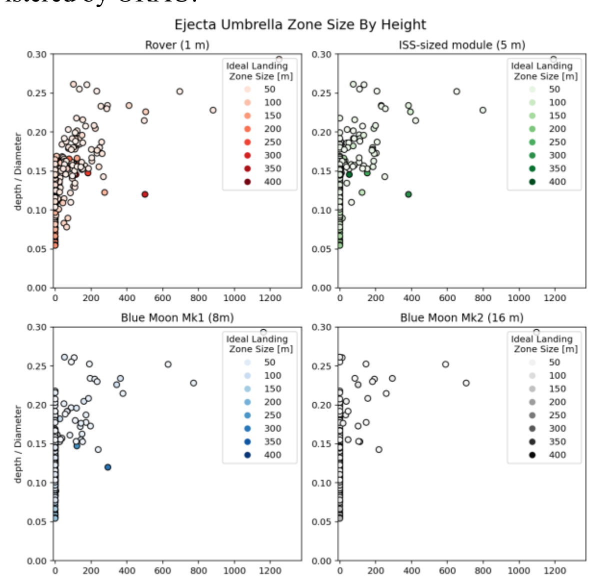

Figure 2. Results from all crater landing simulations.