Trajectory Guidance for Lunar Descent and Landing

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A lunar descent landing guidance concept, evolved from Apollo and shuttle heritage, is being developed to support the Autonomous Landing and Hazard Avoidance Technology Project. The primary function of a trajectory guidance system is to determine trajectory path and issue steering commands to guide a lander to touch down safely and accurately on the lunar surface. This system must perform adequately as part of an integrated autonomous guidance, navigation, and control (AGNC) subsystem by contributing to meeting the desired landing accuracy and achieving a soft landing. Guidance allows for dynamic retargeting to maneuver in such a way as to avoid surface hazards, such as rocks, craters, and slopes. The trajectory design takes into account constraints to allow sensors to "see" the landing area, as well as the time and altitude margin to adjust the trajectory based on information determined by the sensors. The trajectory shape may also be constrained to permit a direct crew view of the landing site via a window during descent.

The lunar descent trajectory is broken into phases, as shown in figure 1. The lander is assumed to begin in a 100-km circular orbit. The deorbit burn sends the lander into a 100×15-km transfer orbit. Following a coast of slightly under 1 hour to near perilune, the lander engine is ignited; at this time, powered descent initiation (PDI) occurs. The powered descent phase, shown in figure 2, begins at PDI and continues until touchdown on the lunar surface. The vehicle engine remains on throughout this phase. Powered descent consists of four subphases: braking, pitch-up, approach, and terminal descent. The braking maneuver removes most of the orbital velocity as efficiently as possible while targeting a certain altitude and range from the landing site. The timing of PDI is chosen so

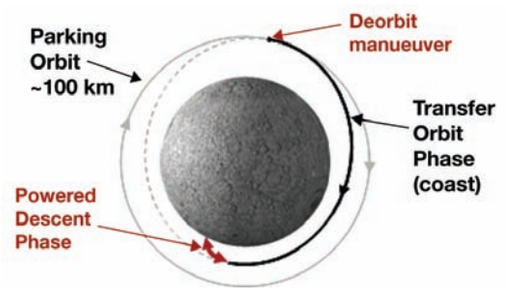

Fig. 1. *Lunar descent trajectory phases.*

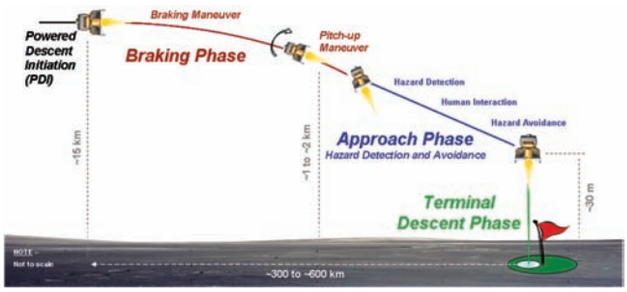

Fig. 2. *Lunar powered descent.*

that, given vehicle thrust constraints, the trajectory meets these target conditions efficiently. During braking, the engine is throttled to near the maximum available thrust, and the vehicle attitude is oriented roughly opposite to the velocity vector. During this maneuver, any trajectory dispersions due to burn execution errors or improved navigation state knowledge can be corrected. Errors in the along-track direction are mitigated by modulating the engine throttle, while cross-track errors are mitigated by directing the thrust out of plane to the trajectory.

The approach phase is designed to have a more vertical attitude and lower acceleration level than the braking phase. The vertical attitude provides better landing area visibility, while the lower acceleration level provides for both slower speeds and more observation time during target approach. The intermediate pitch-up maneuver phase provides a smooth transition in acceleration level and vehicle attitude from the high-thrust and near-horizontal attitude that affects these desired approach conditions during the braking phase.

The objective of the final terminal descent maneuver is to descend slowly to the landing site in a near-vertical orientation, staying above the landing target and nulling out any remaining horizontal velocity. At this point, the landing target will likely no longer be visible to the crew and/or sensors on board the vehicle. This is because the vehicle is descending from directly above the target (or nearly so) and lunar dust, scattered by the engine exhaust, is obscuring the terrain below. Based on the Apollo experience, the terminal descent maneuver begins at 30 m altitude.

During the approach phase, a series of critical functions necessary for safe landing is completed. These functions are collectively referred to as hazard detection and avoidance

(HDA). In the Apollo Program, the hazard detection function was completed by crew members who looked out the window at the landing area. Significant mission design and trajectory constraints were therefore placed on the Apollo missions to provide the best possible lighting conditions for viewing hazards during landing. One of the primary goals is to advance the state of the art in hazard detection technology by reducing the impact of mission design and landing location constraints and increasing safety and reliability for crewed, uncrewed, and robotic landings on the moon and other planetary bodies. NASA designers are pursuing the development of a flash light intensification detection and ranging (LIDAR) device; current research and analysis shows that this device is the best choice for performing hazard detection. The LIDAR generates a three-dimensional map of the landing area during the descent and is able to operate in virtually any lighting conditions. The sensor data provide the crew or an automated system information about potential landing sites, including a preferred target, at the time of the landing.

Hazard avoidance is the other major function completed during the approach phase. The trajectory guidance system provides an updated target based on any information obtained from the hazard detection scan. This target could come from an automated landing site prioritization algorithm or from crew input. The guidance system calculates the updated thrust vector command to steer the vehicle safely to the start of terminal descent directly above the updated landing site.

To effectively perform HDA, trajectory design must accommodate a set of constraints (figure 3). The slant range to the landing site during the scan must be such that the sensor can perform effectively. The hazard detection scan must then be completed with enough remaining time to choose a new landing location, if necessary, and perform an avoidance maneuver to achieve the new target. If a direct window view of the landing area is required, the trajectory must be designed accordingly. The exact limitation depends on the design of the window, but common sense and Apollo experience show us that there will be a limit on how steep the descent can be while still providing a direct window view (as there will be engine and vehicle structure below the crew). Conversely, there is a shallow limit at which the HDA sensor can perform effectively. Beyond this limit, hazard detection performance becomes degraded. Reasons for the loss of effective performance include stretching of the samples, which causes gaps in data, and obstruction of the smaller-size hazards behind the larger-size hazards due to the obliqueness of the angle.

NASA has ongoing work to assess the sensitivities to various trajectory constraints and sensor design parameters. At the same time, improvements in sensor technology are being made and tested on helicopters and aircraft. The end goal of the project is to demonstrate an integrated AGNC and sensor system, including hardware and software, that can safely land a crewed or an uncrewed vehicle on the lunar or other planetary surface.

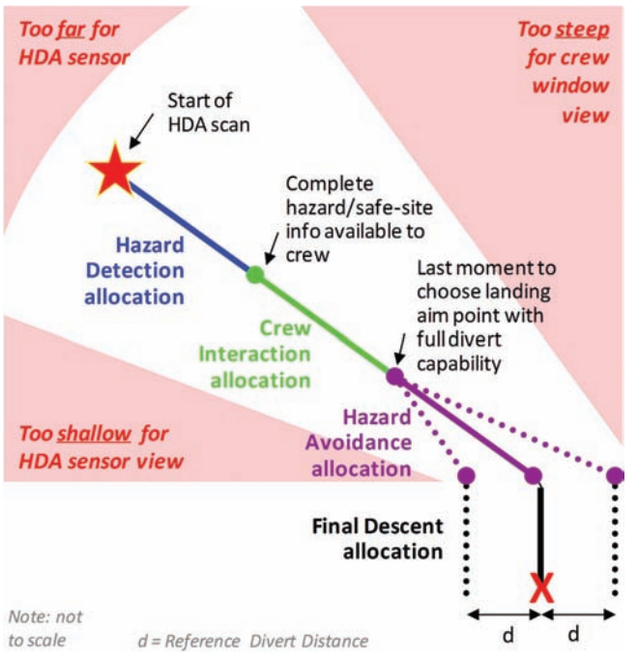

Fig. 3. *HDA functions and constraints.*

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