Autonomous Landing and Hazard Avoidance Technology

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NASA plans to develop an integrated autonomous guidance, navigation, and control (AGNC) hardware and software system capable of detecting and avoiding surface hazards. This system will also be capable of guiding a crewed or robotic lunar lander to a safe touchdown at designated lunar landing sites.

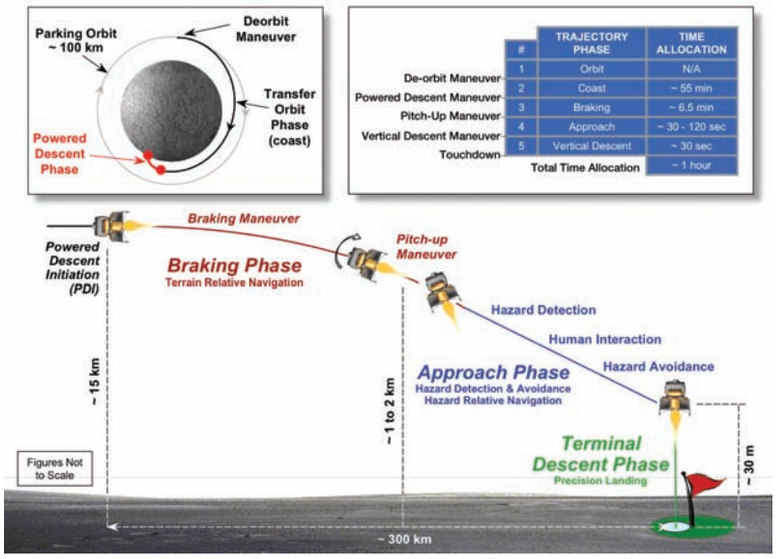
To address both crewed and robotic missions, the AGNC system must be capable of operating in several modes from fully automatic to supervisory crew control to an advisory/standby mode. For crewed landers, the system must effectively communicate landing site hazard data to operators in a manner that facilitates timely integration with situational awareness information gathered from other sources.

The proposed global lunar lander will be used for sortie and outpost lunar exploration missions. To support global access, the lunar lander must be able to operate over a wider range of terrain and natural lighting conditions than was typical for the Apollo Program lander. For instance, NASA identified permanently shadowed craters near the lunar poles as attractive scientific targets. However, these locations are associated with more challenging surface hazard distributions, steeper local slopes, and more limited natural lighting conditions that produce long shadows. In contrast to the Apollo Program use of near-dawn (i.e., 7- to 20-deg) optimal lighting conditions to highlight surface hazards to provide visual identification, the solar incidence angle near the rim of Shackleton Crater will briefly peak at only approximately 1.5 deg. As a result, illumination of a landing site in that region of the moon will be very sensitive to local slopes and roughness. When these considerations are combined with the requirement for automatic operation and an ability to function autonomously, the result is a need for a highly capable, on-board, active sensor system that can perform both hazard detection and avoidance (HDA) and hazard relative navigation (HRN).

The flexibility and extensibility of the lander AGNC system are important considerations. The evolution of the Exploration program may lead to emplacement of navigation assets in lunar orbit and on the lunar surface. The AGNC system is designed to incorporate such inputs into the navigation filter, when one is available, but is not dependent on external navigation sources for mission success.

Multiple missions to a given area will result in more detailed and accurate knowledge of the terrain, knowledge that can be used to designate safe landing sites for future Exploration missions. However, reliance on assets specific to a local landing site may not support off-nominal mission scenarios in which a lander cannot reach its designated landing target.

We established five phases of the lunar descent trajectory, as shown in figure 1. The lander starts in a 100-km circular orbit. The deorbit burn sends the lander into a 100×15-km transfer orbit. The powered descent burn is initiated near perilune, and the lander then enters the braking phase during which the lander bleeds off most of its orbital velocity. The autonomous landing and hazard avoidance technology (ALHAT) system, during the braking phase, performs the terrain relative navigation (TRN) function that significantly improves the map tie between the lander



#	TRAJECTORY PHASE	TIME ALLOCATION
1	Orbit	N/A
2	Coast	~ 55 min
3	Braking	~ 6.5 min
4	Approach	~ 30 - 120 sec
5	Vertical Descent	~ 30 sec
	Total Time Allocation	~ 1 hour

Fig. 1. *Lunar descent trajectory.*

inertial state and the lunar surface. A map tie error is the uncertainty between the actual position of a feature on the lunar surface and the position shown on a lunar map due to measurement errors in the mapping process. This knowledge enables the lander to efficiently steer out the majority of the map tie error prior to the approach phase.

The lander pitches up to a more vertical orientation to begin the approach phase. The initial slant range from the lander to the landing target is expected to be in the range of 500 to 2,000 m. The duration of the approach phase depends on the initial slant range and the lander acceleration (throttle setting), which defines the lander velocity profile. Longer approach phase durations can be achieved at the expense of increased lander propellant (i.e., delta-V). A wide range of flight path angles is being investigated from a vertical descent (90 deg) down to an Apollo-type surface-skimming approach (~15 deg). Although higher flight path angles are more costly in terms of lander delta-V, they may provide a better view of the lunar surface for an HDA sensor. Moderate to low flight path angles are more efficient in terms of lander delta-V; they also provide greater opportunity for direct viewing of the landing site by the crew via a window. However, lower flight path angles also stretch the samples received by an HDA sensor, and can lead to overlooked hazards or false positives due to cracks/gaps in the high-resolution digital elevation map (DEM).

Note that high-resolution DEMs are generated "on-the-fly" by the ALHAT system to support the identification of safe landing sites and enable precision local relative navigation. These high-resolution DEMs are not the same as the lunar DEMs developed via lunar reconnaissance that are used for the pre-mission certification of a landing site and to support the TRN function.

During the approach phase, the ALHAT system uses these real-time-generated, on-board, high-resolution DEMs of the landing site to perform both the HDA and the HRN functions. The HDA algorithm evaluates the initial DEM and identifies safe landing areas based on lander hazard tolerance thresholds.

The HRN function enables precision local relative navigation using surface feature(s) tracked in successive DEMs to guide the lander to a spot directly above the landing target. The approach phase includes a "human interaction interval" to enable crew members to integrate safe landing site data from the ALHAT system with their own situational awareness information, and then decide whether to continue to the original landing target, divert to a new landing target, or abort the landing mission. The approach phase also includes the time/distance necessary to efficiently execute a short-range diversion to an alternate landing site.

The approach phase ends when the lander is precisely located 30 m above the landing target with a near-zero lateral velocity relative to the lunar surface. The low lateral velocity enables the lander to precisely descend the final 30 m using inertial navigation without additional HRN inputs. We conservatively selected this landing approach to avoid the complications associated with the potential impact of dust kicked up by the lander engine exhaust plume on the operation of the active sensor used for HRN. If the HRN function can be performed below 30 m, landing accuracy will improve.

The AGNC system must function in an integrated manner with the lander vehicle. Design factors such as lander hazard tolerance (slope, roughness), dimensions (footprint diameter), window location and field of view (visual piloting), and engine throttling range (acceleration profile for the approach trajectory and terminal descent) are critical to defining the sensor characteristics needed to perform HDA and HRN functions.

All lander designs necessarily represent a compromise between competing performance objectives. A large footprint provides increased landing stability at the expense of increased lander mass, but it also increases the required diameter for a safe landing site. Similarly, longer legs increase the hazard tolerance of the lander, but at the expense of decreased landing stability and increased mass.

We are investigating a wide range of sensor technologies (passive optical, radiometric, and light intensification detection and ranging (LIDAR)) with the objective of defining a sensor package that efficiently performs the TRN, HDA, and HRN functions in terms of mass, power, volume, cost, and complexity. Analysis and testing activities completed and planned are intended

to characterize applicable sensor technologies and algorithms, and to identify key performance parameters and sensitivities, leading to a preliminary definition of the ALHAT reference architecture.

From a sensor and algorithm standpoint, the HDA function is more technically challenging than TRN, as it involves the collection and processing of a large quantity of digital elevation data in a short period of time. The slant range, flight path angle, and acceleration selected for the approach phase directly affect the design and performance requirements of the HDA sensor. Scanning and flash LIDARs are the only known sensors that can produce the required DEMs in real time during the short dynamic landing phase. Flash LIDAR technology is capable of gathering thousands of pixels of data in a single cycle, and ALHAT current research and analysis shows that it is the best choice for this sensor. The potential advantages of flash LIDAR make it an attractive candidate for a technology development project.

As previously stated, the ALHAT trajectory targets a highly precise location for the start of the terminal descent phase with a near-zero lateral velocity relative to the lunar surface. This low lateral velocity enables the lander to descend the final 30 m using inertial navigation without additional HRN inputs while still maintaining a high degree of landing accuracy. In addition to the TRN and HDA sensor(s) data, highly accurate velocimeter and altimeter information is needed to meet the ALHAT requirements for landing safety and precision. Lateral velocity errors, measured in the range of centimeters per second at the start of the terminal descent phase, can accumulate to several meters of additional landing error at touchdown. We are developing and testing a Doppler LIDAR velocimeter that is capable of determining the velocities required by the lander prior to terminal descent.

NASA is working with industry to develop state-of-the-art flash LIDARs that will meet the needs of the ALHAT HDA and HRN functions. These LIDARs, together with the Doppler LIDAR velocimeter and other sensors, have been and are being tested on helicopters and winged aircraft by the ALHAT Team. The final goal of this testing is to demonstrate an integrated AGNC lunar landing hardware and software system that can safely land a crewed or uncrewed landing vehicle on the moon.

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