POST2 END-TO-END DESCENT AND LANDING SIMULATION FOR ALHAT DESIGN ANALYSIS CYCLE 2

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ABSTRACT

The ALHAT project is an agency-level program involving NASA centers, academia, and industry, with a primary goal to develop a safe, autonomous, precision-landing system for robotic and crew-piloted lunar and planetary descent vehicles. POST2 is used as the 6DOF descent and landing trajectory simulation for determining integrated system performance of ALHAT landing-system models and lunar environment models. This paper presents updates in the development of the ALHAT POST2 simulation, as well as preliminary system performance analysis for ALDAC-2 used for the testing and assessment of ALHAT system models. The ALDAC-2 POST2 Monte Carlo simulation results have been generated and focus on HRN model performance with the fully integrated system, as well performance improvements of AGNC and TSAR model since the previous design analysis cycle.

1. INTRODUCTION

The Autonomous Landing and Hazard Avoidance Technology (ALHAT) [1] project is a multi-center team with NASA, academia, and industry, working toward the same goal to develop an autonomous precision-landing system for robotic and crew-piloted lunar and planetary descent vehicles. This system will have the capability to detect and avoid surface hazards for safe lunar and planetary landings. Program to Optimize Simulated Trajectories II (POST2) [2] is used as the end-to-end, six-degree-of-freedom (6DOF) descent and landing trajectory simulation, which is used to determine system performance of the lunar landing subsystem models and environment models for the ALHAT project. The landing subsystem is comprised of Autonomy, Guidance, Navigation and Control (AGNC) and Terrain Sensing and Recognition (TSAR) with an Hazard Detection and Avoidance (HDA) algorithm, flash LIDAR and Hazard Relative Navigation (HRN) capability, along with an IMU, star tracker and sensor models such as an altimeter, velocimeter, Terrain Relative Navigation (TRN). The HRN function included in TSAR and implemented in the POST2 simulation is one of the main focuses of the ALHAT Design Analysis Cycle 2 (ALDAC-2) results discussed in this paper. This paper only includes updates to the simulation, highlighting the models implemented in the simulation and results new to ALDAC-2 [3].

2. TRAJECTORY SIMULATION DEVELOPMENT

The current ALHAT POST2 descent and landing nominal simulation begins with initialization of the vehicle state (i.e., position, velocity, attitude and attitude rate). The simulation is based on a series of trajectory events and criteria that define key phases of a representative ALHAT trajectory sequence. The current reference trajectory is derived from an optimal descent profile initiated from a circular lunar orbit. A de-orbit burn event, with a nominal ΔV of about 20 m/s from a low lunar orbit (100 km), is performed to reach a periapsis altitude of 15.24 km. Altitude measurement updates begin at an altitude of approximately 20 km. The braking phase (which also includes the TRN portion of the trajectory) begins with powered descent ignition (PDI) to reduce velocity from orbital speeds at a nominal altitude of approximately 15 km. During the braking phase, TRN sensor measurements begin at an altitude of 15 km and terminate at 5 km. Fig. 1 illustrates the ALHAT trajectory described above. Velocity measurement updates begin at an altitude of 2 km. The navigation filter uses these altitude, velocity and terrain-relative measurements to update the estimated state (inertial position and velocity) of the lander during descent. While the velocimeter remains active, the vehicle pitch-up and throttle-down initiation event begins at an altitude of about 800 m.

The nominal trajectory used for ALDAC-2 can be characterized as having an initial path angle of 30 deg, maximum deceleration of 1.1 lunar g's and initial slant range to target of 1 km, defined at the start of the approach phase. Hence, the approach phase of the trajectory is triggered at a nominal altitude of 500 m, concluding pitch-up and throttle-down, targeting a point in space directly above the landing site. During this phase, the HDA and HRN functions (TSAR) of the trajectory occur and the altimeter and velocimeter are deactivated. The vehicle remains in the approach phase until HRN is complete and the start of vertical or terminal descent to the targeted landing site begins, with constant rate of descent beginning at approximately 30 m above the lunar surface.

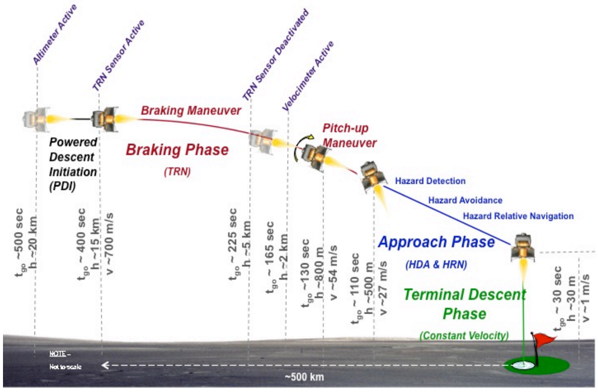


Fig. 1. ALHAT POST2 Trajectory Illustration

3. ALDAC-2 SIMULATION MODELS

The ALHAT POST2 6DOF simulation incorporates environment models such as a 150x150 spherical harmonic gravity field model and 0.25 deg grid-spacing lunar topography, as well as ALHAT-specific lunar subsystem models such as an Altair-based vehicle configuration and low-fidelity IMU, star tracker, altimeter and TRN model. Higher fidelity models included in the ALDAC-2 POST2 simulation updates are the Doppler LIDAR velocimeter model, AGNC and TSAR with HRN and flash LIDAR.

3.1 AGNC

Autonomy, Guidance, Navigation and Control (AGNC) used for ALDAC-2 contains updates to the navigation filter, guidance algorithm and controller. The navigation filter [4] was updated to handle and process HRN measurements and changes to the measurements produced by the velocimeter (3-beam relative velocity interface), in addition to the other sensor measurements from ALDAC-1. The guidance algorithm was enhanced to improve command transients when transitioning to different phases of the ALHAT trajectory (i.e, de-orbit, braking, pitch-up, terminal, constant velocity and touchdown phases). The controller was also updated to support the new Altair-based vehicle model used for ALDAC-2.

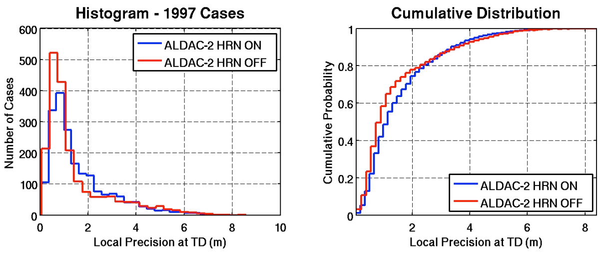
3.2 TSAR

The Terrain Sensing and Recognition (TSAR) [5] software used in ALDAC-2 adds the ability to perform HRN to the existing capability of HDA used in ALDAC-1. HRN essentially creates digital elevation maps as the vehicle descends and aligns them using digital correlation of elevations to estimate a position error change in the navigation state. The HRN function keeps the spacecraft knowledge of its position from drifting so that the vehicle can land in as small an area as possible. At the start of HRN, the velocimeter and altimeter are deactivated to also help keep the spacecraft position knowledge consistent throughout the phase. There were also significant improvements to the simulation model of the flash LIDAR based on behavior observed with the real hardware in Field Test 1. Along with optimization of the runtime performance, the flash LIDAR model was updated such that the Gaussian beam shape more closely matches diffuser output, along with an update to the Gaussian beam footprint calculation with respect to the incidence angle.

4. ALDAC-2 SIMULATION RESULTS

The ALHAT Design Analysis Cycle 2 (ALDAC-2) includes POST2 Monte Carlo results that assess the ALHAT integrated system performance, in particular, HRN function performance impact and sensor sensitivities. The Monte Carlo results highlighted in this paper are based on the full-up, end-to-end nominal ALHAT POST2 trajectory discussed previously, varying and perturbing vehicle properties such as engine thrust, specific impulse and mass properties, as well as sensor errors and the navigated initial state. Comparisons of high-fidelity HRN active versus HRN off Monte Carlo results are discussed. To assess the performance of the ALDAC-2 Monte Carlo results, the requirements being addressed are global and local landing precision. The ALHAT *global landing precision* requirement is to enable landing of the vehicle at a landing target with a 3-sigma error of less than 90 m in the absence of a hazard avoidance maneuver. The ALHAT *local landing precision* requirement is to enable landing of the vehicle at an intended landing point with a 3-sigma error of less than 3 m.

The comparison of the high-fidelity HRN on and active versus HRN off Monte Carlo results show that, for cases where the navigation position error (or knowledge error) was low at the start of the HRN phase, the landing precision showed little to no difference compared to the HRN off results, on the order of about 0.2 m (3-sigma) for local and global landing precision (seen in Fig. 2 and Table 1). In both sets of results, shown in Table 1, the global landing precision requirement of a 3-sigma error less than 90 m was met, highlighting the performance of AGNC and the use of the TRN sensor. However, both cases, even with HRN active, did not meet the 3-sigma error less than 3 m local landing precision requirement.



Statistics for
Local Precision at TD (m)
ALDAC-2 HRN ON:

Mean = 1.625
1-Sigma = 1.28
3-Sigma = 3.84
Minimum = 0.048621
00.13 %-tile = 0.092992
50.00 %-tile = 1.1891
99.87 %-tile = 6.8771
Maximum = 7.9064

Statistics for
Local Precision at TD (m)
ALDAC-2 HRN OFF:

Mean = 1.4861
1-Sigma = 1.3916
3-Sigma = 4.1747
Minimum = 0.059564
00.13 %-tile = 0.07711
50.00 %-tile = 0.91858
99.87 %-tile = 7.3879
Maximum = 8.5623

Fig. 2. HRN on vs. HRN off Local Precision Metric

The HRN active case has turned off altimeter and velocimeter measurements at the start of the HRN phase to touchdown (to keep spacecraft position knowledge from drifting), which may have a hindering impact on performance since the HRN off case utilizes altimeter and velocimeter measurements to touchdown. In Table 1, the change in navigation position error from the start of HRN (HRN never activated for HRN off cases) to touchdown for both Monte Carlos shows only a 0.4 m (3-sigma) difference in change in error. Also, the change in navigation position error during the HRN phase for the HRN active case is only 0.31 m (3-sigma). While these values show the influence of HRN when it is active, the overall implication is that the navigation position error remains low when it starts low, resulting in approximately the same change in navigation position error whether HRN is on or off.

Table 1. HRN on vs. HRN off Monte Carlo Results

	(meters)	ALT ON VEL ON HRN ON	ALT ON VEL ON HRN OFF
NAV pos error before HRN start	mean	6.88	6.88
	+3σ	18.72	18.72
	99.87%	37.62	37.62
	max	49.27	49.27
ΔNAV pos error (TD - HRN)	mean	1.01	0.96
	+3σ	4.15	4.54
	99.87%	6.73	9.04
	max	6.99	9.37
ΔNAV pos error (during HRN)	mean	0.09	N/A
	+3σ	0.31	
	99.87%	0.43	
	max	0.51	
Local Precision	mean	1.65	1.50
	+3σ	5.50	5.69
	99.87%	6.83	7.24
	max	8.15	8.57
Global Precision	mean	28.85	28.93
	+3σ	45.60	45.81
	99.87%	50.69	50.72
	max	51.03	54.59

5. CONCLUSIONS

The ALHAT POST2 end-to-end simulation provides descent and landing simulation capability to assess integrated ALHAT lunar subsystem performance to optimally design and operate an autonomous system for precision lunar landing. Updates to the AGNC and TSAR subsystems, which include and accommodate the HRN model of focus, have been integrated and validated in the ALHAT POST2 simulation used for ALDAC-2. As shown in the above Monte Carlo results from ALDAC-2, using HRN shows little to no difference in touchdown statistics (e.g., true local and global landing precision) for cases with low navigation position error at the start of the HRN phase. Further investigation is required to determine if performance could be improved by re-activating the processing of altimeter and velocimeter measurements after HRN completion. For both HRN active and HRN off Monte Carlo results, the ALHAT global landing precision requirement was met. However, the local landing precision requirement was not met for either the HRN off or the HRN active case (where improvement was expected for HRN active), and the HRN function definition needs to be revisited and revised for the next ALHAT analysis cycle.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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