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ALHAT System Validation

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ABSTRACT -- *NASA has embarked on a multiyear technology development effort to develop a safe and precise lunar landing capability. The Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project is investigating a range of landing hazard detection methods while developing a hazard avoidance capability to best field test the proper set of relevant autonomous GNC technologies. Ultimately, the advancement of these technologies through the ALHAT Project will provide an ALHAT System capable of enabling next generation lunar lander vehicles to globally land precisely and safely regardless of lighting condition. This paper provides an overview of the ALHAT System and describes recent validation experiments that have advanced the highly capable GNC architecture.*

1. MOTIVATION

A return to the lunar surface will require increased capability beyond that of the previous lunar landings. Longer stay times and a greater flexibility with regard to landing locations are among the many improvements planned for a next generation lunar lander vehicle (LLV). A descent and landing system that can land the vehicle more accurately than Apollo with a greater ability to detect and avoid hazards is essential to the development of a future lunar infrastructure and also for increasing the number of potentially accessible Lunar sortie locations. A modern descent and landing system should allow landings in more challenging terrain and provide more flexibility with regard to mission timing and lighting considerations, while maintaining safety as the top priority. Recent NASA lunar landing projects have addressed the need by applying terrain-relative navigation measurements to enhance global-scale precision, an onboard hazard detection system to select safe landing locations, and an Autonomous GNC (Guidance, Navigation, and Control) capability to process these measurements and safely direct the vehicle to a landing location. This next generation lunar landing system will enable safe and precise lunar landings without requiring lunar infrastructure in the form of navigation aids or a priori identified hazard-free landing locations. A safe landing capability is also being considered by NASA which uses onboard active sensing to detect hazards that are large enough to be a danger to the vehicle but too small to be detected from orbit a priori. Algorithms to interpret raw active sensor terrain data and generate hazard maps as well as identify safe sites and recalculate new trajectories to those sites are included as part of the envisioned NASA System. These improvements to descent and landing will help contribute to repeated safe and precise landings for a wide variety of terrain on the Moon [1].

The Apollo lunar landings stand as one of our nation's greatest achievements and each of the missions signifies a hugely triumphant and successful engineering endeavor. In the end, all of the lunar surface missions were hugely successful because of incredible engineering, incredible piloting and maybe just a little bit of luck. Using recently obtained lunar imagery, Apollo surface pictures, and direct quotes from each landing crew member, a close look at each of the six landed Apollo missions is described and carefully depicts just how challenging each of the lunar landings were even under ideal lighting conditions and purposefully chosen relatively benign equatorial locales [2]. It is clear for this go around that NASA desires the LLV to land globally (not just equatorially) and desires the LLV to land under any lighting condition. As compared to Apollo, this is a significant change in expected lunar environment and greatly impacts overall mission objectives and design.

Fig. 1: *Apollo 15 Lunar Module Falcon at the Hadley-Apennine landing site with read pad in a crater*

Given the uncertainty in the performance of passive or human based sensing systems when applied to safe site identification during low lighting conditions (see figure 1), an active sensor hazard detection method should be developed to quickly trade between cost maps that define the performance, cost, and risk at landing while safely avoiding hazards and minimizing divert fuel costs. Coupled with an on-board hazard detection system, the hazard detection method would provide a powerful means for safe redesignation of the LLV during the approach phase of the mission to better achieve the goals of the mission. A modern LLV can leverage state-of-the-art sensor hardware and software to enable landing at more challenging locations than Apollo. These technologies of benefit are being pursued with a modest investment through NASA's ALHAT technology development program [3].

2. ALHAT PROJECT

The ALHAT (Autonomous Landing and Hazard Avoidance Technology) Project is a NASA technology development project which is investigating a range of lunar landing hazard detection methods by developing reference GNC architectures, trajectories, trade study reports, and analysis software in an effort to pursue and field test the proper set of relevant technologies that are in need of technology advancement for lunar landing. The project, managed by NASA Johnson Space Center, seeks to develop an integrated Autonomous Guidance, Navigation, and Control (AGNC) hardware and software system capable of detecting and avoiding surface hazards and autonomously guiding a manned or unmanned space vehicle, to a safe touchdown within 90 meters of a pre-designated planetary or asteroid site [4].

The overarching problem statement for the ALHAT project is to "*Develop and mature to TRL (Technology Readiness Level) 6 an autonomous lunar landing GN&C and sensing system for crewed, cargo, and robotic lunar descent vehicles. The ALHAT System will be capable of identifying and avoiding surface hazards to enable a safe precision landing to within tens of meters of certified and designated landing sites anywhere on the Moon under any lighting conditions.*" This problem statement allowed the ALHAT project to derive early in 2006 a set of high level requirements for the ALHAT System. These requirements, as shown in Table 1, have remained intact to date and have served as the primary reference set upon which all ALHAT System design is based [5].

Table 1: *ALHAT System High Level Requirements*

> *R0.001 Landing Location* – The ALHAT System shall enable landing of the vehicle at any surface location certified as feasible for landing.
> *R0.002 Lighting Condition* – The ALHAT System shall enable landing of the vehicle in any lighting condition.
> *R0.003 Landing Precision* – The ALHAT System shall enable landing of the vehicle at a designated landing point with a 1 sigma error of less than 30 meters TBR.
> *R0.004 Hazard Detection and Avoidance* – The ALHAT System shall detect hazards with a vertical height change of 30 cm TBR or more and detect slopes of 5 deg TBR and greater, and provide surface target redesignation based on detected hazards.
> *R0.005 Vehicle Commonality* – The ALHAT System shall enable landing of crewed, cargo, and robotic vehicles.
> *R0.006 Operate Automatically* – The ALHAT System shall have the capability to operate automatically.
> *R0.007 Crew Supervisory Control* – The ALHAT System shall accept supervisory control from the onboard crew.

The overall ALHAT project flow is depicted in figure 2. Highlighted on the right are the two major deliverables of the project. The first being a detailed description of the ALHAT System architecture such that it can be adopted by NASA designers for future lunar landers. The second being the actual validation of that architecture via a series of field tests over the life span of the project. This gives the designers the confidence that the newly developed technologies will operate as expected in the relevant environment.

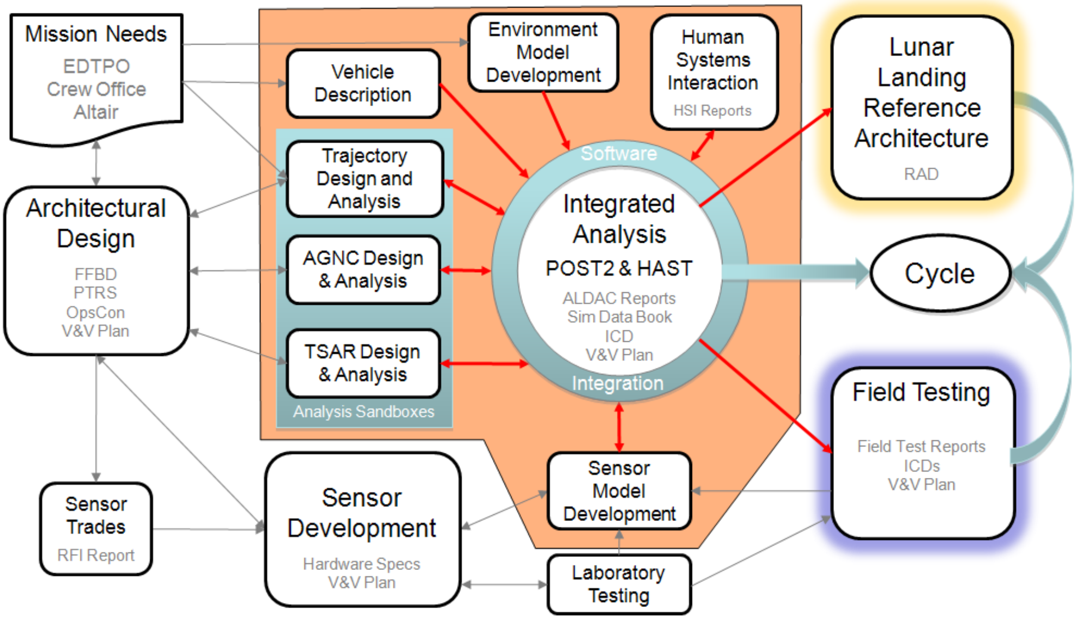

Fig. 2: *ALHAT Project program flow*

3. ALHAT SYSTEM

The ALHAT System under development by the ALHAT Project will use Terrain Relative Navigation (TRN) techniques to enable high-precision global navigation; will detect hazards at the landing site by utilizing an onboard Hazard Detection and Avoidance (HDA) sensor system; and will achieve high-precision local navigation using Hazard Relative Navigation (HRN) techniques. These TRN, HDA, and HRN capabilities operating in conjunction with the Autonomous Guidance, Navigation, and Control (AGNC) system will enable the next generation lunar lander vehicle (LLV) to land safely and precisely, independent from ground control, without lunar navigation infrastructure, and without a priori knowledge of a safe landing location. Further, the system will not be restricted by local lighting conditions, as was the case for Apollo. The design allows for crew interaction with the AGNC system so that the ALHAT system can support both robotic and crewed missions. The overall trajectory profile is a fundamental design parameter to the LLV system. The profile must be designed such that it provides a low ΔV solution to minimize consumed propellant mass during landing, while also accommodating the various other needs of the LLV. Some of these other needs are: terrain clearance during the deorbit and powered braking phases, dispersion correction margin for maneuver execution and navigation errors, and increased time and improved perspective of the landing site during the final approach when hazard avoidance maneuvers could occur.

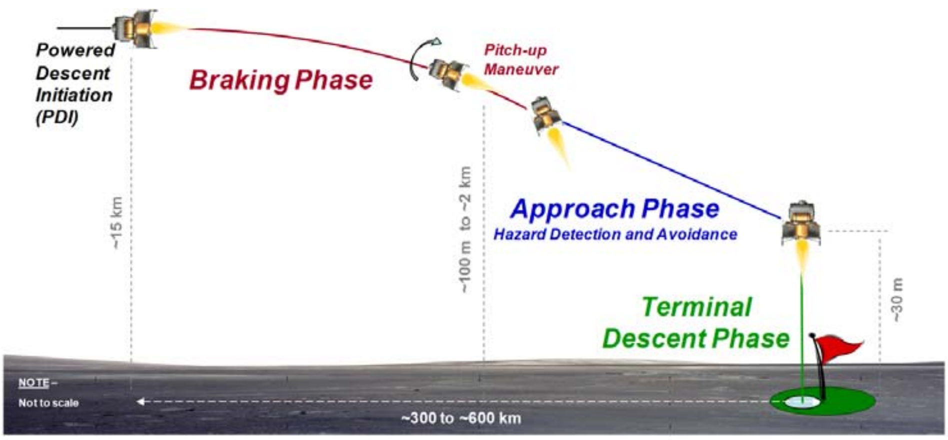

Fig. 3: *Major Phases of Trajectory Descent for the ALHAT System*

Figure 3 shows the major phases of a typical lunar descent trajectory from a parking orbit. For ALHAT, this initial orbit is assumed circular with a 100 km altitude. The deorbit burn begins the sequence of maneuvers necessary to land on the lunar surface. The deorbit burn targets a 100 x 15 km transfer orbit. The periapse of 15 km was chosen to minimize propellant usage without exceeding safety margin needed for terrain clearance, as well as a passive abort in case of a failed Powered Descent Initiation (PDI). The deorbit burn is followed by a coast to PDI of about one hour duration.

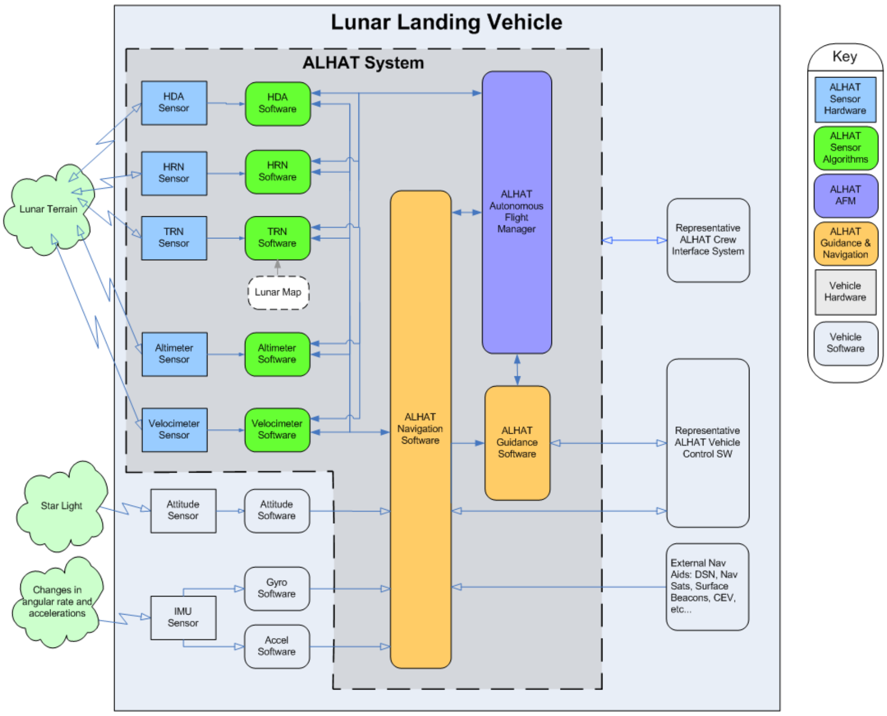

Fig. 4: *ALHAT System Block Diagram*

The powered descent phase begins at PDI and continues until touchdown on the lunar surface. The engine remains on throughout this phase. Powered descent consists of 4 sub-phases: Braking, Pitch-up, Approach, and Terminal Descent. The objective of the braking maneuver is to remove the majority of the orbital velocity as efficiently as possible while targeting a certain altitude and range from the landing site. The timing of PDI (i.e. the start of the braking maneuver) is chosen so that the trajectory meets these target conditions efficiently given the vehicle's thrust-to-weight ratio. During braking, the engine throttle remains at a high and relatively constant setting, and the vehicle is in a relatively horizontal orientation. 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 [6].

The approach phase is purposely designed to have a more vertical attitude and lower acceleration level than the braking phase. The vertical attitude provides better visibility of the landing area, while the lower acceleration level provides for both slower speeds and more observation time while approaching the target. The intermediate pitch-up maneuver phase provides a smooth transition in acceleration level and vehicle attitude from the high thrust, near horizontal braking conditions to these desired approach conditions. By this point in the trajectory, the closed-loop Guidance & Control systems have corrected trajectory dispersions to the level of the Navigation system accuracy [6].

The objective of the final terminal descent maneuver is to descend slowly to the landing site in a near vertical orientation, staying directly over 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 onboard the vehicle. This is because the vehicle is descending directly from above the target, and lunar dust scattered from the engine exhaust will likely obscure the terrain below. Based on Apollo experience the terminal descent maneuver for ALHAT begins at 30m altitude [6].

A functional block diagram of the ALHAT System in relationship to a host lunar landing vehicle is shown in Figure 4 in the context of a technology development testbed. For a crewed vehicle, the ALHAT System provides landing display data and accepts crew inputs. The figure also shows the overall relationship of the AGNC software with the other vehicle subsystems.

4. ALHAT SYSTEM VALIDATION

The ALHAT Project is responsible for the process of developing a system architecture, validated and verified to TRL 6, proposed for autonomous hazard detection and precision lunar landing. The TRL assessment objectives of the ALHAT Verification and Validation plan are to verify and validate that the ALHAT component technologies and the ALHAT System as a whole have reached a maturity level consistent with TRL 6 [7].

The achievement of TRL 6 is a primary goal of the ALHAT project in order to mature the technologies in time to allow future NASA projects to incorporate them into a future lunar lander design. It is recognized that the definition of TRL 6 is subject to interpretation, see figure 5. For ALHAT purposes, the selection of TRL 6 exit criteria is guided by the objective of reducing risk to a level that a future lunar lander program could choose to baseline ALHAT technologies at Preliminary Design Review [7]. The project has set the ultimate goal to achieve "system prototype demonstration in a relevant environment" via autonomous closed loop precision landing and hazard detection demonstration on a terrestrial rocket. To meet that goal, the ALHAT project has undergone a series of field tests using various test vehicles and facilities to incrementally build the ALHAT System capability via component demonstration initially. Ultimately, the field testing culminates in a closed loop terrestrial rocket ALHAT System demonstration to achieve TRL 6.

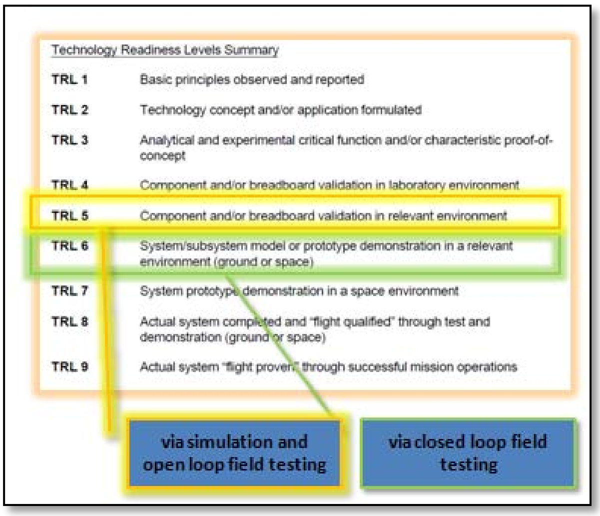

Figure 5: *Mankins TRL Levels and ALHAT Approach to Achieving them*

A. LAB TESTING

The ALHAT AGNC algorithms which support this safe and precise lunar landing capability have been successfully tested in 6-DOF simulation (figure 6) for many varieties of reference trajectories, both in nominal conditions and under the influence of sensor and vehicle Monte Carlo perturbations. In these tests the ALHAT system has been shown to be robust to knowledge errors and trajectory dispersions and capable of performing autonomous hazard avoidance maneuvers. In these situations, the system global landing precision was on the order of 90 meters 3-σ with local (safe site relative) precision on the order of a few meters 3-σ across a variety of landing trajectory profiles.

Fig. 6: *Draper Laboratory's Lunar Landing Vehicle cockpit simulator*

B. HELICOPTER TESTING

The ALHAT Project Field Test 1 (FT1) was conducted in April 2008. This test flew a Flash LIDAR on a helicopter over a variety of natural and man-made targets. The purpose of the test was to assess the performance of Flash LIDAR technology and algorithms for Hazard Detection and Avoidance (HDA) and Hazard Relative Navigation (HRN) in an environment that was relevant to lunar landing, with a secondary objective of verifying the concept of the passive optical APLNav TRN methodology. The primary environmental variables investigated were ranges and angles relative to the target and hazard feature size [8].

Fig. 7: *Initial ALHAT Field Test [9]*

To obtain a variety of slant ranges and path angles as well as descents toward the target a helicopter was used as the test platform. To obtain a variety of slant ranges and path angles as well as descents toward the target a helicopter was used as the test platform. Figure 7 shows an example test flight path over Dryden. An inertially stabilized gimbal was mounted to the front of the helicopter. The gimbal contained the Flash LIDAR, two Inertial Measurement and an analog camera. A Global Positioning System (GPS) antenna was attached on the fixed structure above the gimbal. To verify the concept of APLNav TRN, visible cameras were mounted to the helicopter to capture terrain images as the helicopter flew to, from, and around the HDA target areas. The visible camera images, along with IMU and GPS data, were collated and used as input to the APLNav algorithm for post-processing [8].

The FT1 analysis first assessed the flash lidar in terms of its sensitivity (pixel trigger fraction) and range measurement precision as a function of path angle and slant range. The results show that the lidar has a worst case range error (random noise) of 0.20m one sigma. When imaging though the gimbal window (28% loss), the lidar has a maximum range between 400m for nadir viewing and 250m for oblique viewing (15° from horizontal). These results are for dry lakebed material that does not necessarily have the same reflectivity as the lunar surface [9].

The data collected during FT2 proved to be highly valuable in demonstrating the capabilities of the Doppler LIDAR, and also served as a tool to test and develop signal processing and analysis algorithms. Analysis of the data showed velocity measurements in excellent agreement with the high accuracy GPS derived velocities. Ground relative altitude and attitude measurements were also demonstrated. The successful flight test of this Doppler LIDAR sensor established it at a TRL of 4 [8].

The next ALHAT field test, FT4, completed in July 2010, had four primary objectives. The first objective was to demonstrate the application of an integrated, real-time GN&C system (derived from a lunar lander implementation) for Earth-based flight testing over a range of vehicle approach conditions consistent with the ALHAT simulation studies to date. The second objective was to demonstrate precision pointing of the gimbaled flash lidar using real-time GN&C data (position, velocity attitude, and attitude rates) in combination with the gimbal manager and mapper components of the TSAR software. The third objective was to characterize the performance of second generation ALHAT sensors – Flash LIDAR, Doppler LIDAR, and laser altimeter – along with accessories such as Flash LIDAR zoom optics. The last objective was to demonstrate the ability to utilize the recorded ALHAT sensor data to generate a 3-D terrain map and perform the hazard detection, landing aim point selection, and local relative navigation functions required for an autonomous safe precision landing.
The FT4 instrument suite includes four distinct sensor subsystems: two Flash LIDARs, a three-beam Doppler

LIDAR velocimeter, and a laser altimeter. All of the sensors and support equipment were housed in an external pod attached to the bottom of the helicopter. The two Flash LIDARs are mounted on a shared gimbal mechanism [8]. {Erik -- need to find JPL reference that speaks of FT-4 results here}[9,10]

C. AIRCRAFT TESTING

To verify TRN performance in a moon-like environment, the Applied Physics Laboratory (APL), NASA Langley Research Center (LaRC) and the Jet Propulsion Laboratory (JPL), prepared two prototype TRN systems for use in an ALHAT sponsored field test conducted 20 June 2009 to 7 July 2009 over the Nevada Test Site (NTS), Nevada and Death Valley National Park (DVNP), California. Both TRN instruments used a King Air B200 aircraft equipped with four digital cameras, laser altimeter, and flash lidar to image well surveyed landscapes at various altitudes, under specific lighting conditions. In addition to the TRN instruments, other test equipment and sensors were flown during FT3 to provide a truth system to score the TRN results. Several GPS receivers were used, sharing a single GPS antenna, and multiple INS were employed so that each sensor had a primary and a backup position and attitude sensor suite. The camera configuration on the test airplane is shown in Fig. 8. In addition to the optical camera, the aircraft carried a LaRC built laser altimeter that used a JPL developed algorithm to do elevation correlation to estimate position [11].

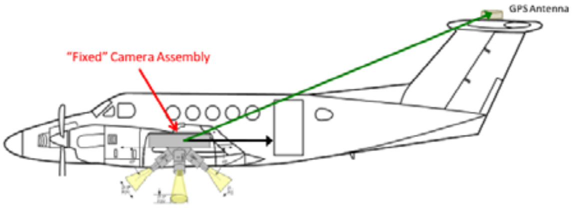

Fig. 8: *TRN Optical Camera Configuration on ALHAT Field Test Airplane [10]*

The field test clearly shows that both TRN algorithms will achieve the 90m ALHAT landing accuracy requirement. The airplane flight tests of the APLNav TRN algorithm successfully demonstrated that robust and accurate three dimensional position estimates can be generated using passive optical sensors [CRISS:6]. In both cases, TRN estimates have errors typically less than 50m, strongly driven by the quality and resolution of the reference digital elevation maps (DEM) [12,13].

D. TERRESTRIAL ROCKET TESTING

NASA has envisioned a suite of lander test vehicles that will be flown in Earth's atmosphere to incrementally demonstrate applicable lunar lander performance in the terrestrial environment. As each terrestrial rocket progresses in maturity, relevant space flight technology matures to a higher technology readiness level, preparing it for inclusion on a future lunar lander design [14].

The Draper Laboratory built GENIE (Guidance Embedded Navigator Integration Environment) successfully demonstrated accurate, real time, embedded performance of ALHAT navigation and guidance algorithms in a highly dynamic environment. The RR1 vehicle, built by Armadillo Aerospace, performed a successful 60 second free flight and gave the team great confidence in ALHAT's highly reliable and robust GNC system design and implementation. The GENIE was conceptualized in January 2010 to be an extensible platform capable of validating an assortment of navigation and guidance algorithms via simple software load for a variety of users. The integrated hardware and software platform was built to flight worthy completion within seven weeks via rapid prototyping effort at Draper Laboratory [14].

Fig. 9: *June 2010 RR-1 GENIE flight test in Caddo Mills, Texas USA [14]*

Since the successful flight of GENIE in June 2010 (figure 9) on the Armadillo Pixel vehicle, a significant effort has focused on applying the extensible system to demonstrate closed loop control on at least two independent terrestrial rockets. The first is a NASA Johnson Space Center developed, Armadillo Aerospace derived, terrestrial rocket known as Morpheus. Fundamentally Morpheus is a larger and more capable Pixel vehicle to be used as a general testbed, including validation of ALHAT approach phase trajectory execution. The second is a Masten Aerospace terrestrial rocket capable of both ALHAT approach phase trajectories and Martian approach phase trajectories. The Armadillo Aerospace Pixel, Masten Aerospace Xombie, and JSC Morpheus vehicle are pictured in Figure 10, are the basis for future NASA derived GENIE customized vehicles that allow full closed loop control to best validate a host of applicable space landing technologies [14].

Both GENIE enabled vehicles will incrementally raise associated technology readiness levels of suitable lunar and martian next generation technologies through closed loop payload testing. Potential payloads include ALHAT derived velocimeters, altimeters, terrain relative navigation sensors, hazard detections systems, and associated algorithms applicable to the Moon, Mars, or Near Earth asteroids. As each system progresses in maturity through repeated terrestrial flight, the desire is that the now TRL 6 advanced technology will be more readily adopted in future near term space missions, giving the spacecraft designer more capability and technology options to choose from [14].

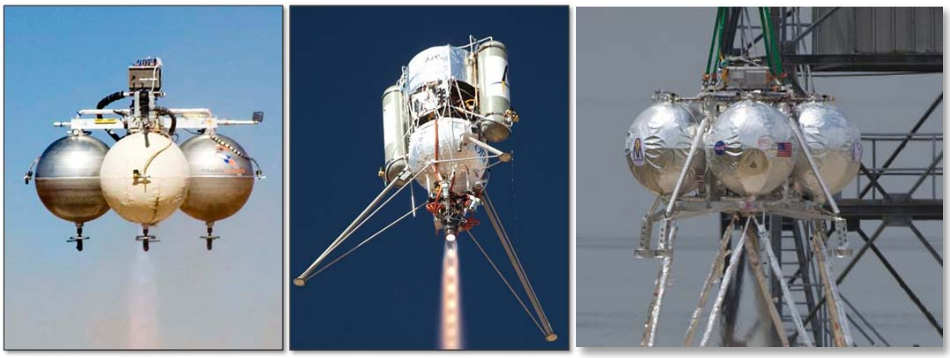

Fig. 10: *Aerospace Pixel (left), Masten Xombie (center), and JSC Morpheus (right) Terrestrial Rockets*

E. C. UPCOMING VALIDATION PLANS

In the 2013 timeframe, GENIE AGNC software aims to autonomously fly a terrestrial rocket by determining vehicle navigation state and calculating the when, where, and how to control the vehicle and to land using an ALHAT hazard detection system to help identify safe landing locales in the local terrain. Known as the “Precision Landing Demo”, a full suite of AGNC sensors including an optical camera based TRN sensor, a laser altimeter, and a Doppler radar will demonstrate a closed loop precision landing at significant downrange distances (2-5km) from the initial takeoff pad. Additionally during the representative approach phase of the flight an onboard ALHAT hazard detection system will carefully detect prepositioned hazards at the landing site allowing onboard AGNC to automatically pick a safe landing location and subsequently guide the vehicle to that safe locale while avoiding hazards. Referred to as the "Hazard Detection Demo", this demonstration can be combined within the same GENIE enabled terrestrial rocket validation flight after successful independent demonstration on the Morpheus vehicle. The successful completion of these two demonstrations (shown in figure 11), preferably in a single flight, will raise the TRL to 6 for the ALHAT System, completing the primary project mission statement set forth by the project in 2005.

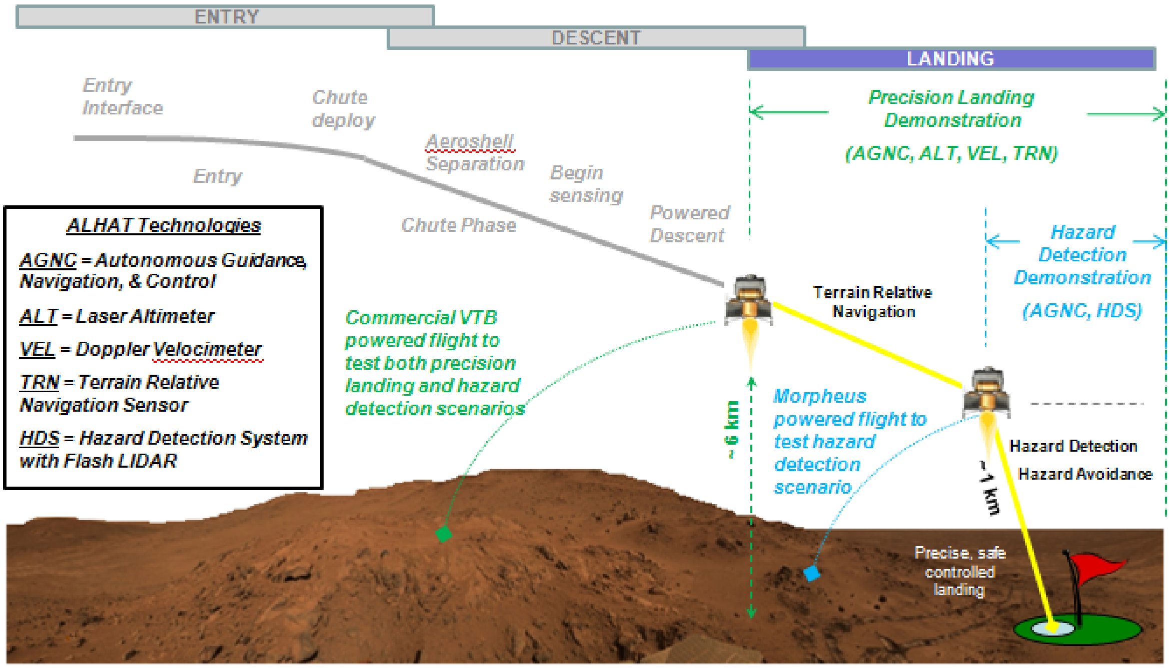

Fig. 11: *Planned demonstration flights of the ALHAT System in 2012-2013 timeframe*

5. CONCLUSION

The ALHAT System will enable safe and precise landing for the next generation lunar lander vehicles. The overall validation of the ALHAT System is necessary to prove that the highly integrated hardware and software components work together in concert to achieve 100m precision landings in hazardous locations, under any lighting condition. To accomplish this, a series of field tests over the past few years has occurred testing various key components of the ALHAT System. A final integrated validation campaign has begun that is using a commercially derived terrestrial rocket platform to demonstrate the ALHAT System capability. Once completed in the 2012-2013 timeframe, the ALHAT System will have raised its TRL to 6, successfully bridging the TRL 5-6 "valley of death" so common to technology development programs.

At TRL 6, the ALHAT System is more likely to be adopted by future spacecraft landing designers since successful validation will have occurred through integrated demonstration of the system in a relevant environment. Future spacecraft designers will then better understand demonstrated capabilities of the prototype ALHAT System allowing them to more easily integrate the highly autonomous landing capability into the next generation lander baseline at inception.

In order to validate the ALHAT System, the ALHAT project will have committed significant resources to best develop a capability for a terrestrial rocket to fly lunar and/or mars like trajectories. The payload capable terrestrial rocket will be able to travel at high speeds significantly downrange in a safe and controlled manner.
This ALHAT derived capability will mark a significant capability for NASA in that a terrestrial based lander will be able to raise the technology readiness level of other EDL flyable payloads intended for the Moon or Mars, not just the ALHAT System. Various EDL type sensors and payloads stand to benefit by having a validation mechanism to raise their TRL of their system, comparing ALHAT AGNC truth data to their own, and subjecting their payloads to a relevant trajectory environment here on Earth.

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