Terrain Hazard Detection & Avoidance during the Descent & Landing Phase of the Altair Mission

Alan L. Strahan,[1] and Andrew E. Jhonson[2]

[1]NASA Johnson Space Center
2101 NASA Parkway, Houston, Texas 77058

[2]*Jet Propulsion Laboratory*
4800 Oak Grove Drive, Pasadena, CA 91109-8099
California Institute of Technology

This paper describes some of the environmental challenges associated with landing a crewed or robotic vehicle at any certified location on the lunar surface (i.e. not a mountain peak, permanently dark crater floor or overly steep terrain), with a specific focus on how hazard detection technology may be incorporated to mitigate these challenges. For this discussion, the vehicle of interest is the Altair Lunar Lander, being the vehicle element of the NASA Constellation Program aimed at returning humans to the moon. Lunar environmental challenges for such global lunar access primarily involve terrain and lighting. These would include sizable rocks and slopes, which are more concentrated in highland areas; small craters, which are essentially everywhere independent of terrain type; and for polar regions, low-angle sunlight, which leaves significant terrain in shadow. To address these issues, as well as to provide for precision landing, the Autonomous Landing and Hazard Avoidance Technology (ALHAT) Project was charted by NASA Headquarters, and has since been making significant progress. The ALHAT team considered several sensors for real-time hazard detection, settling on the use of a Flash Lidar mounted to a high-speed gimbal, with computationally intense image processing and elevation interpretation software. The Altair Project has been working with the ALHAT team to understand the capabilities and limitations of their concept, and has incorporated much of the ALHAT hazard detection system into the Altair baseline design. This integration, along with open issues relating to computational performance, the need for system redundancy, and potential pilot interaction, will be explored further in this paper.

American Institute of Aeronautics and Astronautics

Acronyms

AFM	Autonomous Flight Manager (software)		km	kilometer
Altair	Lunar Lander Vehicle		LDAC-3	Lander Design and Analysis Cycle-3
AL	Air Lock		LEM	Lunar Excursion Module
ALHAT	Autonomous Landing Hazard Avoidance Technology		LEO	low-Earth orbit
			LH2	Liquid Hydrogen
AM	Ascent Module		Lidar	Light Detection and Ranging
CARD	Constellation Architecture Requirement Documents		LLO	Low Lunar Orbit
			LLV	Lunar Lander Vehicle
CEV	Crew Exploration Vehicle		LOI	Lunar Orbit Insertion
cm	centimeter		LOX	Liquid Oxygen
DEM	Digital Elevation Model		MET	Mission Elapsed Time
DM	Descent Module		NASA	National Aeronautics and Space Administration
DOI	De-orbit Injection (burn)			
DRM	Design Reference Mission		ONSS	Optical Navigation Sensor System
DSN	Deep Space Network		OpNav	Optical Navigation
EDS	Earth Departure Stage		Orion	Crew Exploration Vehicle
ETDPO	Exploration Technology Development Program Office		PDI	Powered Descent Initiation
			RCS	Reaction Control System
FPGA	Field Programmable Gate Array		RPODU	Rendezvous Proximity Operations Docking and Undocking
FSW	Flight Software			
GN&C	Guidance, Navigation, and Control subsystem		TBD	To Be Determined
			TD	Touchdown
HDA	Hazard Detection and Avoidance		THDSS	Terrain Hazard Detection Sensor System
HRN	Hazard Relative Navigation		TLC	Trans-Lunar Coast
HUD	Heads Up display		TRL	Technology Readiness Level
IMU	Inertial Measurement Unit		TRN	Terrain Relative Navigation
JPL	Jet Propulsion Laboratory			

American Institute of Aeronautics and Astronautics

Table of Contents

I. Introduction

Following the 2004 request of President George H. W. Bush to return humans to the moon by 2020 and then travel to such destinations as Mars, NASA formed the Constellation Program[+] to oversee the various activities and Projects associated with this goal. Under Constellation, NASA formed the Altair Project to develop the Lunar Lander vehicle that will perform descent from and ascent back to low lunar orbit, much like the original Project Apollo Lunar Excursion Module (LEM). However, unlike the original Project Apollo, the Constellation Program has levied additional requirements on the lander to be able to perform a precision landing at any location on the Moon, including scientifically interesting polar regions, which may ultimately require the real-time detection of landing hazards during final approach, though in a lighting environment that may be very poor to the un-aided human eye. Fortunately there is the Autonomous Landing Hazard Avoidance Technology (ALHAT) Project, an exploration technology development effort funded by NASA headquarters and working closely with the Altair Project, that is working to address these problems of real-time hazard detection and precision landing on planetary bodies.

The Altair lander, as currently envisioned, is similar to the Apollo LEM in that it is a two-stage vehicle, comprised of a Descent Module (DM) and an Ascent Module (AM). Due in part to sizing constraints of launch vehicles, the Altair active mission phases will be more involved than that of the LEM. Initially the Altair vehicle will be delivered to Low Earth Orbit where is will rendezvous with the Orion crewed vehicle, similar to the Apollo Command and Service Module, and an orbital transfer stage that will accelerate the entire Altair/Orion stack onto a lunar transfer trajectory. Once on this transfer trajectory, the Altair DM will control the stack and implement trajectory adjustments and later a low lunar orbit capture maneuver, all functions that would have been performed by the Service Module of Apollo. For these reasons the DM is proportionately much larger relative to the total Altair vehicle than the Apollo DM compared to the Apollo-era LEM, which complicates landing area visibility from the AM during the final stages of landing. After the Altair/Orion stack is in a stable lunar parking orbit, the Altair vehicle will separate from Orion, conduct any orbital adjustment necessary to line up on target, then perform a de-orbit burn, followed by a coast and eventual powered descent leading to a soft landing on the lunar surface. Altair will be capable of landing four astronauts on the Moon and providing life support and a base for initial surface stays of modest duration. Using propulsion elements carried by the crewed AM, only the AM will ascend from the lunar surface, returning the crew to the Orion spacecraft that will bring them back to Earth.

[+]The future of the human space flight program, and thus the Constellation program, is currently being discussed at the highest levels of the U.S. government. For the purposes of documenting the Altair design, this paper is written without consideration of any forthcoming changes in the direction (or even existence) of the program.

American Institute of Aeronautics and Astronautics

The ALHAT Project has been overseen by the NASA Exploration Technology Development Program Office (ETDPO), and is chartered with developing sensors and algorithms that will guide a lander, with or without crew, to a precision landing on a planetary body. Furthermore this system will be able to detect landing hazards real-time at a slant range of approximately one kilometer from the landing site. The ALHAT Project originally preceded Altair by over a year, though since Altair was stood up, the two Projects, both managed out of the NASA Johnson Space Center, have cooperated where there were common goals, sharing information about potential mission and trajectory designs, as well as information about the lunar environment.

This paper will discuss the current Altair vehicle and mission design as it relates to the lunar landing task, and will discuss the lunar environment as it relates to landing, particularly that of terrain and lighting. This paper will then explore some of the hazard detection options considered by the ALHAT Project along with the overall system design they are developing to accomplish this as well as precision landing goals. Finally, this paper will review the potential integration of the ALHAT hazard detection system into the Altair lander vehicle, along with some outstanding details and follow-on work to be addressed to 'flesh out' that integration.

II.   Altair Reference Design for Landing

One of the most critical and dynamic phases of the Altair mission is the descent and landing phase. This phase starts just after de-orbit burn in Low Lunar Orbit (LLO) and ends with the vehicle's safe and precise touchdown near a predefined target on the lunar surface. The de-orbit burn immediately preceding this phase is a retro-grade burn changing Altair's orbit from a near circular orbit at 100 km above the reference surface into an elliptical transfer orbit down to 14.5 km (~47,500 ft) perigee where powered descent begins. [1] As envisioned by the Altair Project, the descent and landing phase consists of several sub-phases starting with the coast period along the elliptical transfer orbit, lasting about 56 minutes until reaching perigee. At this point Powered Descent Initiation (PDI) occurs as the powered flight begins at 92% throttle, thrusting into the velocity vector for the most efficient velocity reduction. This phase, with a slightly descending flight path to accommodate an optimal gravity turn, continues for just over 10 minutes until almost all the horizontal velocity has been eliminated. [2] The Altair vehicle then begins the Pitch Up sub-phase, a maneuver intended as part of the transition to the Approach and near vertical Terminal Descent sub phases. Also at this time, the vehicle is throttling down allowing it to continue to descend in the low lunar gravity. The Pitch Up sub-phase is designed to be complete at 280 meters alt and just under one km uprange from the target where the Approach sub-phase begins, which is the only period where the crew can have a reasonably close view of the landing area to make further assessments of its suitability and safety. It is during this period the crew could command a late re-designation maneuver (similar to Apollo P64 mode) where guidance, within the performance limitations of the vehicle, steers to a new landing location. The Altair Approach sub-phase nominally lasts 77 seconds, ending with the transition to final Terminal Descent at 30 meters altitude. During Terminal Descent, the vehicle descends near vertically at approximately 1 m/sec until soft contact on the surface, and with the main engine commanded to shut down at some modest altitude, 0.5 to 1 meters, to prevent thrusting at extremely close range that could introduce undesired touchdown dynamics. See Fig.1 regarding the descent profile. [2]
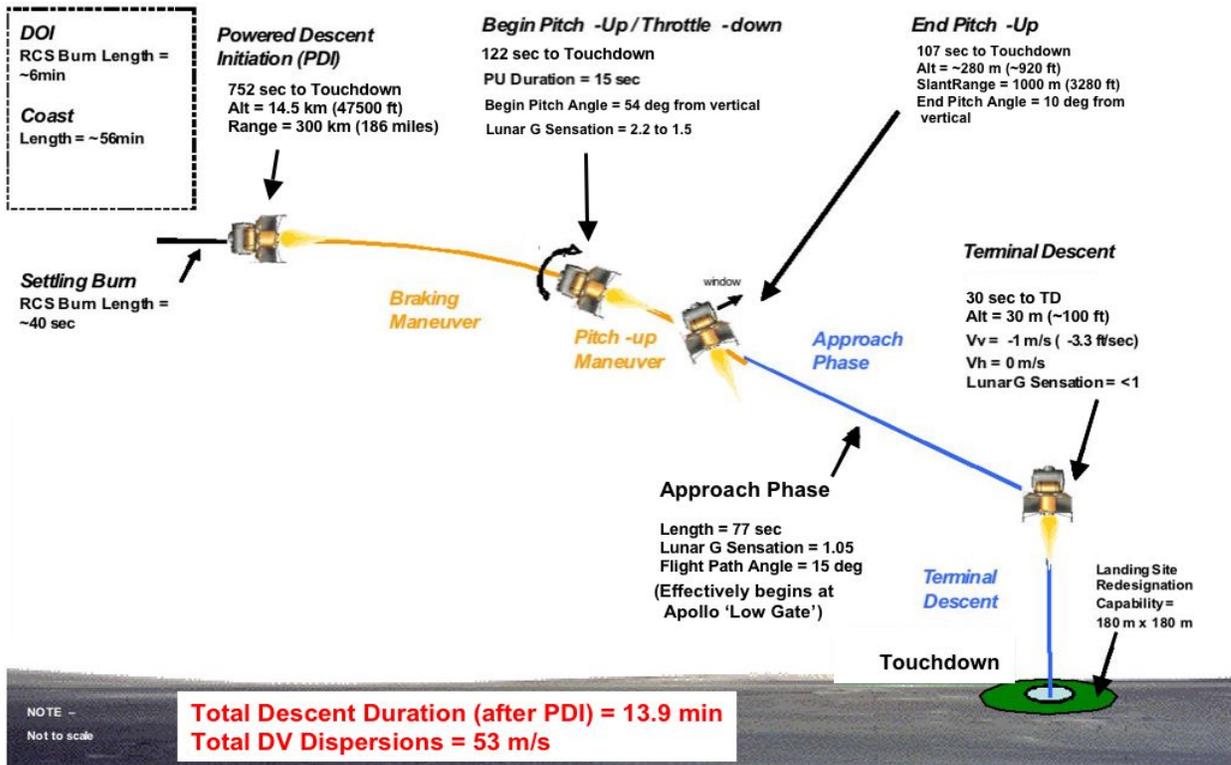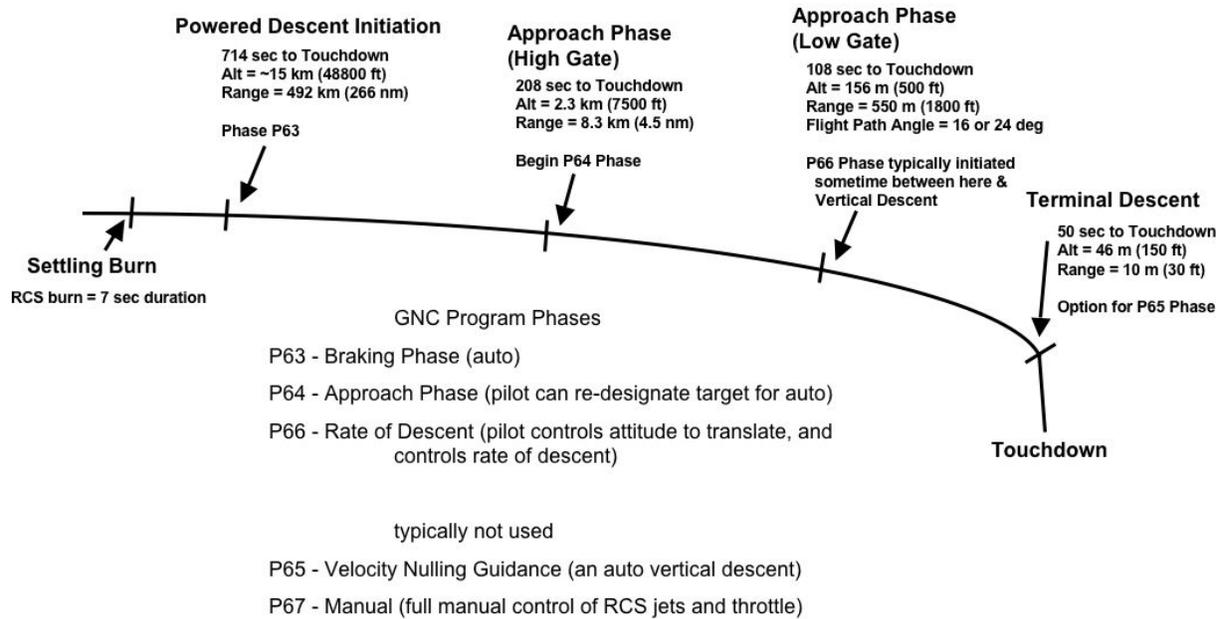
Figure 1. Altair Descent & Landing Profile

While the Altair Project, interpreting Constellation requirements, defined 3 lunar mission reference categories, including Outpost (crew delivery to a base) and Cargo (unmanned delivery to a base), the prime focus of the Altair and related ALHAT efforts has been the definition of the lunar Sortie mission, envisioned to be a first time arrival of a crewed mission to a previously unvisited location. A lunar Sortie mission could include the first mission to a new outpost site.[3] As this is a first visit, it is assumed to not benefit from any surface or orbital high resolution (sub 1 meter) a priori knowledge. Only that comparable to the Lunar Reconnaissance Orbiter (LRO) data, advertised as 1+ meter resolution in the best circumstances, is assumed available for a Sortie location.[4] That being the case, higher resolution data of the landing site, be it from a sensor or just the human eye, would not be available until the Approach and Terminal Descent portion of the descent trajectory when the landing zone is reasonably in view, which then defines when hazard detection and avoidance could begin to occur. Prior to this point in the trajectory, the target is either over the horizon, blocked by the vehicle, or subtends too narrow of an angle of view for any terrain details to be discernable.

For the current Altair reference mission described in Fig. 1 (consistent with the LDAC-3 design cycle), the 77 second Approach sub-phase initiates at a slant range of 1 km and a slant angle, relative to the local horizon, of 15 deg. This geometry works out to an average deceleration of approximately 1.05 lunar g's.[2] For the sake of full disclosure, only a very modest design trade was conducted by the Altair Project in defining this sub-phase trajectory, with the understanding that it would be revisited in more detail as the design matured. Still, the delta-v and corresponding fuel budget that Altair has been carrying since the closure of the LDAC-3 design cycle are based on this approach trajectory design.

American Institute of Aeronautics and Astronautics

Powered Descent Initiation
714 sec to Touchdown
Alt = ~15 km (48800 ft)
Range = 492 km (266 nm)

Phase P63

**Approach Phase
(High Gate)**
208 sec to Touchdown
Alt = 2.3 km (7500 ft)
Range = 8.3 km (4.5 nm)

Begin P64 Phase

**Approach Phase
(Low Gate)**
108 sec to Touchdown
Alt = 156 m (500 ft)
Range = 550 m (1800 ft)
Flight Path Angle = 16 or 24 deg

P66 Phase typically initiated
sometime between here &
Vertical Descent

Terminal Descent
50 sec to Touchdown
Alt = 46 m (150 ft)
Range = 10 m (30 ft)

Option for P65 Phase

Settling Burn
RCS burn = 7 sec duration

GNC Program Phases

P63 - Braking Phase (auto)

P64 - Approach Phase (pilot can re-designate target for auto)

P66 - Rate of Descent (pilot controls attitude to translate, and
controls rate of descent)

Touchdown

typically not used

P65 - Velocity Nulling Guidance (an auto vertical descent)

P67 - Manual (full manual control of RCS jets and throttle)

Figure 2. Apollo Descent & Landing Profile

For comparison, the first few Apollo landing missions (11, 12 and 14) each flew a 16 deg flight path angle and performed an initial pitch up much earlier, at a trajectory point denoted as 'High Gate', roughly 8+ km up-range from the target and about 86 sec earlier than that planned for the Altair pitch-up. See Fig. 2 for the Apollo Descent and Landing Profile [5] and Table 1 for a comparison of manual flight time budgeted for Altair vs Apollo. [1,2,5] This early pitch-up cost some additional delta-v due to gravity losses, yet was beneficial in allowing the Apollo astronauts extra time for local terrain recognition and orientation as the target area would come into view. Also during this extended Approach sub-phase, the Apollo crew could re-direct guidance via discrete steps while in the P64 guidance mode based upon their window view of the target area. At some point late in the Approach sub-phase, usually past the 'Low Gate' but before the Terminal Descent, the pilot would transition into the P66 guidance mode which added a significant degree of manual control where the pilot could directly command attitude rates, and use this to indirectly command vehicle translation. Additionally the pilot could increment or decrement the descent rate, with guidance adjusting the throttle to accommodate. [5]

For comparison, the Apollo crew nominally began viewing the lunar surface 200+ sec prior to touchdown, while the Altar base line would allow for surface viewing at only 120 sec out, comparable to when the Apollo crew would be transitioning through Low Gate. As evident in Table 1, comparing delta-V and manual flight time budgets for various nominal and off-nominal events, the Apollo approach and landing strategy, matured for actual flight, includes several bits and pieces of additional manual maneuver time, some to cover nominal strategies while others provide for contingencies and margins. Those that were intended primarily to allow for manual piloting margin, as indicated by Ref 5, are denoted with yellow, while other budgets were included to accommodate autonomous GN&C or hardware performance dispersions. Altair is not budgeting for several of these, or is carrying a smaller amount for others, such as for re-designation, which is understandable as such delta-v maps to hundreds of kilograms of propellant. Overall Apollo is carrying 53+ seconds of flight time for manual piloting post Low Gate relative to the flight time included in the Altair design. Furthermore the hardware dispersions budgets could add time if those systems are performing well. [1,2,5] Still the Apollo approach, which was very pilot-centric including using the pilot as the hazard detection system, found it necessary to add this propellant. As such, if Altair intends to maintain smaller manual flight budgets and margin and accomplish a higher degree of landing precision (< 100 meters), then some hazard detection automation and rapid target identification capabilities will likely be required. Adding to this is the Altair Project requirements calling for 100 meter landing precision [6] and with a design reference mission to the narrow crater rim (1 to 1.5 km wide) of Shackleton crater, a 19 km diameter crater encompassing the lunar south pole.

Table 1. Comparing Manual Flight Time Budgets between Altair and Apollo

Event or Off Nominal Occurrence	Altair ΔV (m/s)	Altair (approx) flight time (sec)	Apollo ΔV (m/s)	Apollo (approx) flight time (sec)
Pitch-up to TD	∼ 220	122	∼ 375	208
Low Gate to TD	∼ 190	107	∼ 190	108
Powered flight Dispersions	53	29	53	29
Target re-designation budget	5	3	18.3	10
Additional manual flight (hover)	---	---	26	15
Engine valve malfunction	---	---	11.4	6
Redline fuel sensor error	---	---	12.1	7
Additional flight margin	---	---	54	31

Another design facet distinguishing Altair from the Apollo LEM is the lander's much larger size. This is driven by mission requirements, including a larger crew size and longer mission timeline, and also by the Constellation Program requirement that the Altair Descent Module, as opposed to the Service Module of the Orion stack, provide the Lunar Orbit Insertion Delta-V, to accommodate size limitations of the Orion launch vehicle. The larger DM dimensions results in a larger footprint for the lander vehicle if reasonable landing stability is to be maintained. The present lander footprint is a circle of 5m radius, compared to that of the Apollo LEM being about 2.5m. A larger footprint decreases the chances of finding a safe touchdown location in a terrain of modest hazard density as a larger contiguous region free of obstacles must be found. This can be further complicated by the modest control and navigation dispersions that can manifest themselves even in the short time from when an ideal precision touchdown location might be identified at the beginning of the Approach sub-phase, to when the actual touchdown occurs. This could necessitate the addition of 1 or 2 meters onto the lander footprint that needs to be satisfied when searching for a suitable landing site real-time during the Approach sub-phase.

Also, as with most planetary landers, there is a height tolerance in reference to potential obstacles, either rocks or craters, that the landing gear can accommodate while attenuating landing shock and maintaining the lander reasonably level after touchdown. The most recent Altair design requirements protect for 0.3 meters for tolerable obstacle height, [6] though there has been much discussion about the possibility of increasing this to 0.5 meters despite the associated mass penalty.

In addition to obstacle height tolerance there is a maximum overall slope tolerance of the vehicle, measured basically as the maximum departure from local vertical by the vertical axis of the Ascent Module. The primary concern is to provide a reasonably level platform (within 12 deg) [6] from which the AM can lift off and not experience contact of its engine bell with any part of the DM, including the walls of the engine bell cut-out, or with any part of the Air Lock (AL), both of which remain on the surface.

The limitations of the Altair lander baseline design with regards to maximum slope, tolerable obstacle height and large footprint size, directly indicate the need for some type of terrain and hazard identification system. This was the case with the original Apollo lander where the human eye and cognitive mind served as the terrain and hazard identification system by viewing and interpreting the lunar terrain through the window. However, the time available for such identification, along with the trajectory shape and its range-to-target history, directly relate to the hazard detection capabilities necessary to support a safe landing. In addition, lunar environmental factors, such as the general terrain and the local lunar lighting environment, also drive the requirements for a hazard detection system.

III. Lunar Environment Challenges

In addition to vehicle and trajectory design, many aspects of the lunar environment can be challenging to the execution of a safe and precise landing, and feed back to the lunar lander and mission design. These environment challenges basically fall into the two categories, terrain and lighting. Much work has gone into researching and characterizing these environments and how they relate to hazard detection. That work will only be touched upon

American Institute of Aeronautics and Astronautics

here in an attempt to define the attributes of a hazard detection strategy that can support the Altair vehicle and lunar Sortie mission.

The lunar terrain can most generally be categorized into two classes, mare and highland. The mare consists of two sub-classes, smooth and rough. However, both are defined as relatively younger than the highlands and were formed primarily by volcanism. The highlands, consisting of a 'hummocky' or smoother and more rounded hilly terrain, and 'rough', being a more rocky terrain, are both generally older, having been formed primarily by impact craters. [7,8] Both the highlands, and to a lesser degree the mare, contain some large scale features that are detectable by remote observation from Earth or orbiting satellites, such as mountains, hills, or large craters, while just the mare includes large flat plains. In general, the large scale features are covered to varying degrees by smaller ones that are very difficult to detect from orbit. These smaller features are of primary concern as they can pose a hazard risk to a successful lunar landing by introducing the risk of vehicle damage, contact instability or excessive tilt. These small scale, potentially hazardous features consist mostly of rocks, craters and localized slopes, and have been the focus of several studies and statistical modeling efforts.

Of the three features, rock frequency, expressed as a percentage of area, appears to vary the most, with increased frequency near fresh craters of sufficient size to eject bedrock. Rocks are also, in general, more present in the lunar highlands. Rocks were observed, through empirical counts of Apollo era photographic data, to be between 3 and 17 % abundance (fraction of total surface area covers by rock) for various Apollo and Surveyor sites, which includes examples of both mare and highland terrain and which demonstrates the variability of lunar rock abundance. [9] Large craters appear to be more frequent in the older highlands which were exposed during early periods of heavier meteor activity. The frequency of smaller craters, of the 1 to 10's of meters range, are generally more constant across either mare or highlands at or near a saturation level, with an estimated value of ~0.1 craters, of 1 m size, per 100 meters square. [7] Mean slopes over long distances (tens to hundreds of kilometers) are generally the result of large scale observable features such as complex craters, basin rims, etc., and are rougher in the highlands due to the presence of a larger number of large scale impacts. In addition, mean slopes over smaller lander size distances (one to ten meters) have been estimated to demonstrate a slightly steeper value for highland terrain, with mean values of 6 to 8 degrees (versus 4 to 6 degrees for mare) over a 10 meter base length. [7] Based on these general terrain characteristics, a landing near the rim of Shackleton crater in the lunar highlands will statistically be more likely to experience modest size rocks and steeper localized slopes than other areas of the Moon, though it would experience the same general density of small craters.

Complicating the lunar environment further, particularly at the poles, are the extremes and limits to surface illumination. Over the period of a year, the lunar south pole will experience very low sun angles ranging from -1.5 to 1.5 degrees. [7] To characterize this environment and bound the extremes of lunar lighting in support of the ALHAT Project, Andrew Goldfinger of the Johns Hopkins University Applied Physics Lab quantified the irradiance (radiant flux or effective illumination per unit area) that can occur on the lunar surface resulting from various sources, ranging from direct sunlight, to that reflected from the fully illuminated earth (earthshine), to that reflected from other lunar topography, such as mountains, down to just starlight. These values are included in Table 2. The irradiance from a Liquid Oxygen / Liquid Hydrogen rocket engine, being the baseline for the Altair vehicle, is also included, as is the irradiance of a typical full moon as seen from the Earth. [10] These values are included here as they represent variations in the environment around the lunar poles, noting again that the rim of Shackleton Crater on the south pole is a reference mission target for the Altair Project, where at least the first mission will be a Sortie. With the low sun angle and the variations in local geography, it is evident that some areas will periodically experience direct sunlight while others will be temporarily or permanently shadowed from the sun. Some of these areas in shadow may still receive periodic illumination from earthshine or reflected lunar surface light from a nearby mountain peak or crater rim, while other areas will be in permanent shadow from all light sources other than starlight. It should also be noted that the plume of the Altair DM engine has vary limited irradiance and mostly in the infrared range, based on the ALHAT analysis. [10]

American Institute of Aeronautics and Astronautics

Table 2. Comparative Irradiance of Various Light Sources

Source	Band	Irradiance (W/m^2/micron)	Compared to Sunlight
Direct Sunlight	Visual	2.1×10^3	---
Reflected Earthshine	Visual	2.7×10^{-2}	1.3×10^{-5}
Reflected Sunlight from Topography	Visual	1.0×10^{-2}	4.8×10^{-6}
Full Moon on Earth	Visual	1.0×10^{-3}	4.8×10^{-7}
Starlight	Visual	2.2×10^{-6}	1.0×10^{-9}
LOX/LH2 Rocket Exhaust Plume	SWIR	1.0×10^{-4}	4.8×10^{-8}

While some robotic probes or cargo missions may land during lunar darkness and, as such, not utilize any passive optical hazard detection sensors, a crewed mission, as envisioned by the Altair Project, will land at least with minimal sunlight as there is a Constellation requirement to have the crewed surface time be during daylight. [3] With the understanding that the landing target will experience at least some light, and with the assumption that some Altair Sortie missions would land at other higher latitudes, the Altair Project has engaged the ALHAT Project about the feasibility of landing utilizing only human vision, possibly augmented with optically enhancing goggles. The ALHAT Project executed three different studies related to this question [8,10,11] exploring the limits of lunar lighting and the human eye. While much good work and detail exists in these references, only a few observations will be addressed here.
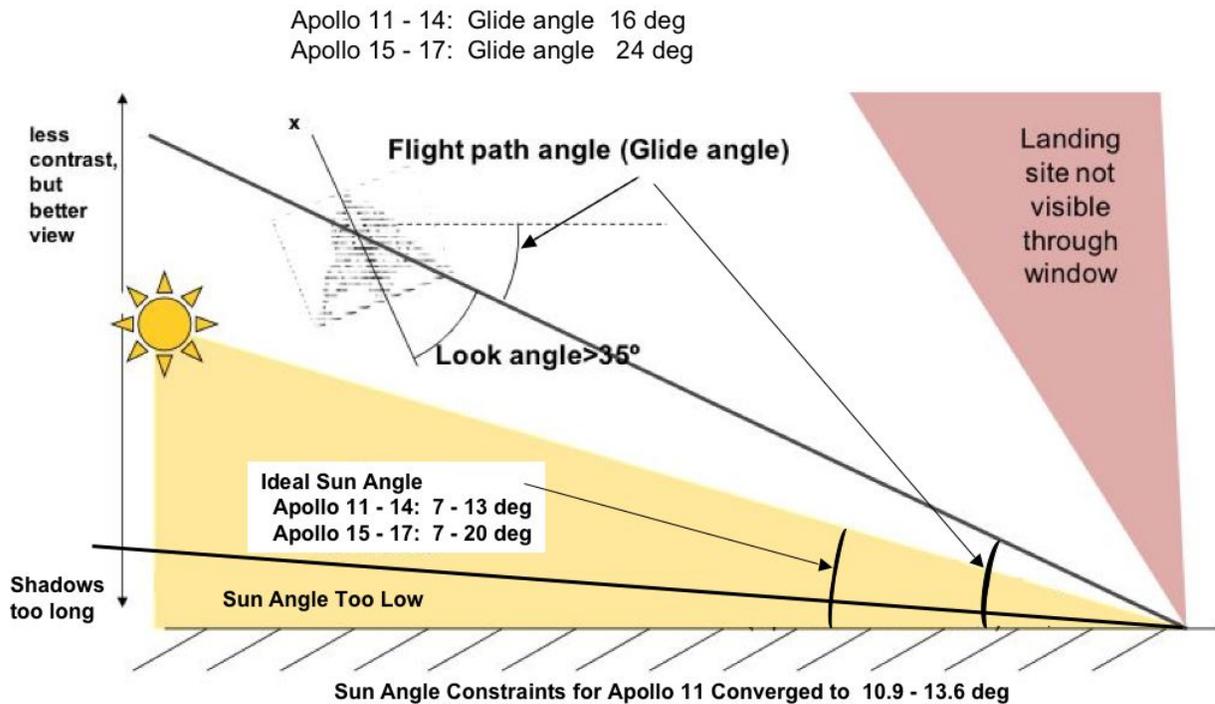
Figure 3. Preferred Sun Angle During Lunar Landing

One observation is that if direct sunlight exists, ideally it needs to have a certain geometric relationship, basically behind and below the viewing angle which effectively is the approach trajectory, to be of value in casting shadows that emphasize topography without generating glare. A sun angle directly behind or a little above the lander

American Institute of Aeronautics and Astronautics

approach angle would results in washout of lunar features or in glare off the surface. Still higher angles would cast little if any shadow, also limiting the visual identification of hazards. A sun angle below 7 deg to the surface begins to cast overly long and extensive shadows that hide surface features, according to an Apollo era analysis. [8] That same analysis determined the ideal sun angle to be between 7 and 13 deg, for a 16 deg Apollo 11 type approach, or between 7 and 20 deg, for a 24 deg Apollo 15 approach. See Fig. 3 which is mostly borrowed from one of the detailed ALHAT analyses on the lunar environment and how it effects landing, [8] demonstrating ideal sun-angle geometry for Apollo. Lunar Sorties to equatorial or mid latitude sites could satisfy this geometry by limiting launch windows (or utilizing extended loiter times on orbit). However, these are not consistent with Constellation requirements to perform a mission at any time during the month or year. [3] Also, the aggressive Approach sub-phase time line may compromise the ability of a human to satisfactorily assess the target area. Furthermore, it should be noted that even with the ideal lighting and additional assessment time provided during the Apollo landing missions, some of the Apollo crews struggled with the identification of a safe landing site. [11] Finally, lunar Sorties to Shackleton crater or other polar regions will not be able to satisfy this desired sunlight geometry for any launch window or loiter adjustment as the sun angle is always too low.

Setting aside the Apollo era recommendations for sunlight angle and further reviewing Table 2, it is evident that earthshine and even light reflected from lunar terrain can be several times brighter than the full moon on Earth, potentially up to 27 times and 10 times respectively, for certain beneficial geometries. [10] These values still would be low for the best performance by the unaided eye but could potentially work with certain types of night vision or visual NIR type goggles, [10] at least with regards to providing the human eye with an enhanced version of what is optically available. Issues still may arise regarding the orientation of shadows from different light sources, and how that would vary throughout the month and year. Also, reflected light from a broad source, such as a crater rim or ridge, could produce a somewhat diffuse or washed out illumination of the surface of interest due to the partial Lambertian nature of the lunar regolith where it scatters light in various directions if it is not from a point source. [10] Ultimately a more detailed analysis of the specific approach trajectory, coupled with the specific epoch, and its Earth-Sun-Moon relationship and resulting lighting environment, would be appropriate for exploring these issues further. Again, the optimization of lighting geometry may require significant constraints on launch windows, landing site locations, etc., that are not consistent with present Constellation or Altair requirements.

IV. Hazard Detection Sensor Concepts

As evident from the Altair vehicle and mission constraints, along with challenges posed by the lunar terrain and lighting environment, the rapid and detailed identification of hazards could offer significant benefit to the real-time actions of landing target assessment, selection and ultimate commitment. There would be additional benefit if such hazard identification could be derived from something other than passive optics (human or augmented) that rely on natural surface irradiance to provide topographic information. The ALHAT project has been exploring ideas along this line of reasoning, including a focus beyond passive optics, almost since its inception. [4] Furthermore the Altair Project, though not ruling out the possibility of passive optics including just the use of human vision, has generally acknowledged the difficulties posed with a lunar polar Sortie mission and, as such, has included in its baseline a hazard detection system and has been looking to the ALHAT Project to assist with its definition.

At the core of such a real-time, hazard detection system is a hazard detection sensor that lends itself to rapid utilization. Several ideas for such a core sensor have been considered or evaluated including some, for completeness, that utilize passive optics. Some of these are described here though additional details are provided in the references. [8,12] The following paragraphs list and discusses some of the key options for comparison, with the first four involving passive optical solutions.

Human eye: Though previously discussed with regards to lighting preference defined during Apollo, it can be further noted that the human eye has limitations both in spatial and contrast resolution. In ideal situations the human eye can discern 1 arc minute which maps to 0.3 meter objects at 1000 meter range, and discern 25 - 30 dB contrast in brightness once adapted to a lighting environment, though with the best contrast resolution (0.1 dB or 2 %) at the middle of the adapted range. With regions illuminated potentially from sunlight to earthshine to reflected light, the overall contrast range is likely to be comparable or greater than the discernable range with loss of resolution at the brighter and dimmer regions. [10] The spatial resolution is theoretically sufficient for the Altair mission, though

without a familiar reference, it may prove difficult to judge the size of hazards and even more difficult to discern slopes and depressions. Again, some Apollo crews struggled with this under ideal lighting. [12]

Human eye with Camera (or night vision) augmentation: A camera or night vision type goggles offer better performance over the human eye alone if some reflected light (via earthshine or terrain reflection) is present, and if the signal-noise-ratio can be tuned for the appropriate contrast range and low light region of that range. Large aperture and zoom optics could both be employed to improve sensitivity and spatial resolution. Discerning size without a familiar reference, and inferring 3-D topography including subtle depressions (craters) and slopes from a 2-D image, still is a potentially significant limitation. [12]

Human eye with Camera and Vehicle illumination: This option has similar strengths and limitations to the camera option just described, but is included to note that the use of a vehicle mounted light source, in lieu of relying on direct or reflected illumination of the target zone, is also problematic. One issue is that a light source co-located with the observer results in a washout effect of the terrain with shadows not visible to the viewer, a similar issue to sunlight directly along the viewing or approach trajectory. Additionally, it may take substantial power to illuminate the target from 500 to 1000 meters out, when target re-selection and divert maneuvers are most fuel efficient and effective. [12]

Stereoscopic cameras: If lighting of the target zone is sufficient, than this option could alleviate the difficulty of having to infer 3-D range and topographic information from a 2-D image. However, the baseline separation of the cameras to achieve this effect is prohibitive. For a range resolution of 30 to 50 cm (potential maximum tolerable obstacle size), even at a range of just 200 meters from the target zone, a camera separation of 10 meters is required. [11]

Radar: In some ways comparable to the geometric limitations of the stereoscopic camera, the radar signal has inherent diffraction limitations, such that to even achieve a 0.5 deg angular resolution, a 50 cm radar aperture would have to be employed. Achieving smaller resolutions, as required to detect a 30 - 50 cm obstacle out to a range of 1000 meters, would require an even larger aperture. [5]

Scanning Lidar: This option offers significant promise in that it can render a true 3-D topographic (or digital elevation) model of a target zone down to potentially a very small resolution, comparable to 30 - 50 cm. This technology, effectively launching a single laser pulse at a surface location being scanned and calculating range based on the signal time of flight, is also relatively mature. The issue with this approach is that to form a high resolution model or elevation map, as required for hazard detection, requires numerous (hundreds of thousands) of subsequent laser pulses, each aimed at a slightly different location by a rapidly articulating mirror. The estimated time required to scan a 180 x 180 meter target zone starting at 1000 meters is approximately 91 sec, by which time the vehicle would be on final vertical descent, if on an Altair trajectory. Additionally, individually correcting each return for vehicle motion and attitude change can be computationally significant and demanding. [13]

Flash Lidar: This technology, if it can be sufficiently matured, best addresses the above described issues and has been the baseline core sensor for the ALHAT approach to hazard detection. As such, it is the effective solution that provides placeholder specifications to the Altair vehicle and is in the latest baseline configuration. The concept effectively is a laser pulse launched and diffused, via optics, to strike and reflect off a region of the target zone, and then received by an array of pixel sensors. A series of these returns can be combined to render an elevation map of the entire 180 x 180 meter target zone, in what is estimated to be as little as 2 - 4 sec., vs 90+ seconds for the Scanning Lidar used in similar circumstances. Concerns with this approach, aside from the still developing maturity of the Lidar technology, also includes concerns about the significant computational overhead to process the returns and to generate useful hazard maps and usable digital elevation information. Still it is believed by the ALHAT Project, that 3-D terrain mapping and hazard detection processing can be accomplished for a target site of reasonable dimensions (180 x 180 meter) in less than 10 seconds, with a goal to get it under 5 seconds. [8,11,13]

While several of the evaluated hazard detection sensor options appear to have substantial or unresolvable issues, a few still may offer some potential utility, possibly as part of a back-up option, if the related risk posture proves acceptable, or even as a primary system, if mission and vehicle design requirements are modified. The human eye with camera or other visual augmentation may yet prove sufficient if adequate lighting (equatorial or mid latitude) is

available and if launch window constraints are applied to ensure optimal lighting angles. Object size estimation and 3-D inference of subtle hazards still poses a concern for this approach. But, with appropriate optics and with geometric assumptions on expected size based on attitude and trajectory, perhaps some of this can be compensated. Additionally, the Scanning Lidar may yet provide a solution if the scan area is significantly reduced or the tolerable hazard size significantly increased to reduce its execution time to a workable value.

V. ALHAT integrated System

The Autonomous Landing and Hazard Avoidance Technology Project was funded out of NASA headquarters as a technology development project to develop and mature technologies that would support autonomous precision landing on any planetary body in any lighting condition, with a near term focus on the moon, though with applicability to Mars and other planetary objects, including asteroids and Titan. While autonomous was in the title, the Project requirements call on the system to support either robotic or crewed missions, where for the latter the system would provide situational awareness at a minimum while also allowing for crew interaction ranging from just a flight manager approving a target to an active pilot using the ALHAT information as a reference. [4]

In supporting this charter, the ALHAT system evolved into three basic functions supported by a handful of candidate sensors and software algorithms. Some of these candidate components have now supported flight test while others are in the planning stages. These three basic functions necessary to accomplish autonomous precision landing include real-time Hazard Detection and Avoidance (HDA), the focus of this paper, along with Terrain Relative Navigation (TRN) and Hazard Relative Navigation HRN. Terrain Relative Navigation is a function that can be performed in lunar orbit as well as during descent coast and powered flight, and involves the refinement of the on-board navigation state via sensing surface topography and comparing it with onboard reference data generated from lunar reconnaissance missions, such as LRO. Finally Hazard Relative Navigation is a function that uses a subset of hazards or other surface features identified during final approach as navigation references, allowing the lander to steer to a safe target relative to the features identified in the HDA map. [4] Of these functions, the Altair Project is presently looking to ALHAT only as the source for the HDA function. While the Altair Project is interested in how ALHAT is pursuing the TRN and HRN functions, Altair has other strategies in its baseline for accomplishing these functions.

For reference, a high level System Architecture schematic of the GNC system as viewed by the ALHAT Project, showing reference sensors, software and data paths, is included in Fig. 4, generated by Tye Brady and Jana Schwartz of Draper Labs for the ALHAT Project. [14] This figure has been modified to emphasize a few relationships, with modifications mostly in red noting the addition of gimbal hardware, the general grouping of the elements into three ALHAT categories (separated by a solid red line), and the addition of some transparent red boxes indicating lander GN&C elements that ALHAT is developing per their reference concept. A brief description of the elements in the figure follows, with additional discussion in the next section focused on how Altair presently would presently implement these ALHAT elements.
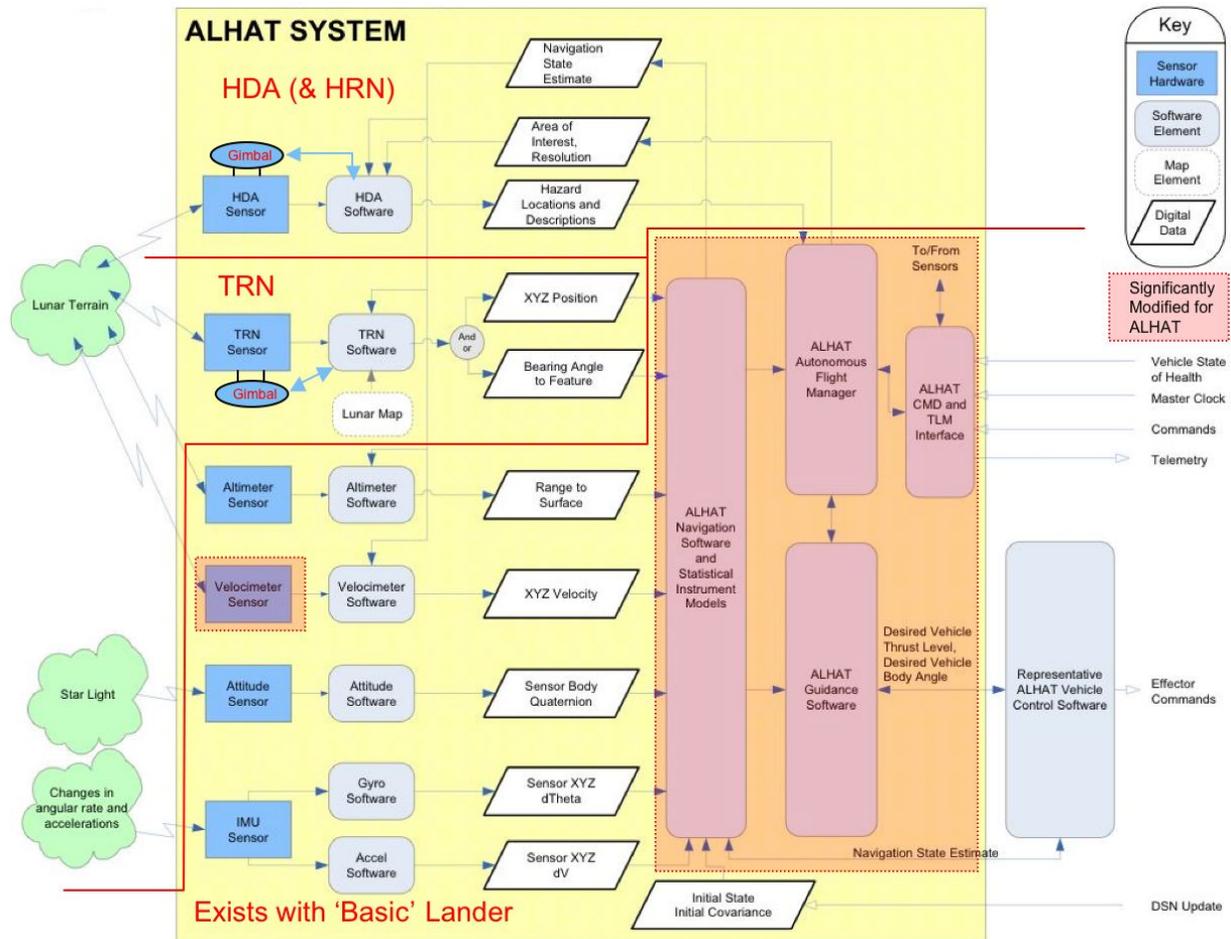
Figure 4. ALHAT Proposed GNC Architecture for a Precision Lunar Lander

The grey-blue boxes and ovals represent hardware, either sensor or gimbals; the light grey rounded boxes represent software elements, the white rounded box (only one in the figure) is an a priori map element or database, the parallelograms are digital data packages, and the transparent red boxes are software functions resident on a basic lander design as implemented by ALHAT. Data flows are represented by arrows. [14]

The figure is divided into three sections with the top being HDA (& HRN) previously described. This function consists of the HDA sensor, presently assumed to be a Flash Lidar as discussed in section IV, mounted on a gimbal. The primary ALHAT concept has this gimbal being a fast articulating platform for the Flash Lidar, allowing it to scan several sub-areas of the target area per second, guided by the navigation state and 'area of interest' defined by the Navigation and Autonomous Flight Manager (AFM) software. These sub-areas are combined together as a mosaic by the HDA software and processed to define hazards. The hazard information is then provided to the AFM software which in turn defines a guidance target. The alternative ALHAT concept still under investigation may only require a slow moving gimbal, to track the moving target area as a whole, and using variable optics while repeatedly flashing the entire target area at a high rate, allowing the repeated images to jitter and use image processing techniques to extract high resolution topography. Again the HDA software would provide hazard information to the AFM, that in turn would define targets for guidance to use. The current ALHAT operations concept would generate these full hazard maps only once or twice during approach, though that philosophy is still being evaluated. After the initial hazard map is generated, the Flash Lidar would effectively become an HRN sensor in that it would collect individual frames of the area (set by lidar optics) for correlation with the hazard map developed by the HDA function. During HRN, key easily recognizable features are repeatedly tracked with their position known very precisely relative to the target. Using the Flash Lidar gimbal angles and range to features of interest, the lidar (and

13
American Institute of Aeronautics and Astronautics

vehicle) position can be determined very accurately relative to those features and, ultimately, to the safe landing target. [14]

The ALHAT TRN concept, used primarily from post de-orbit burn until the approach phase, uses a yet to be defined terrain sensor, quite possibly a laser altimeter or a flash Lidar with different optics, to generate altitude profiles or 3-D surface contours derived from the terrain below. These are compared with an a priori reconnaissance data set, already resident in the lander data stores, to observe and correct the difference between the estimated onboard navigation state, and the one observed. This TRN sensor could be fixed to the lander structure, articulated to maintain a nadir pointing vector, or gimbaled to enable the collection of additional data in the crosstrack direction. The TRN measurements are provided to the navigation filter to update the vehicle state. [14]

Finally, the remaining elements are sensors and software that would typically be included in a lunar lander design, though ALHAT is suggesting a higher resolution velocimeter that will result in a smaller residual lateral velocity error at the start of terminal descent which, in turn, maps to a smaller safe landing site requirement. Otherwise, the core GNC software modules (navigation, guidance, telemetry, AFM) required for ALHAT system testing are also required by a lunar lander, although some modifications would be needed to support ALHAT functions. Some changes include the incorporation of lidar characteristics into the navigation filter, and the development of a guidance algorithm that can rapidly build a path to the precision safe target, as defined by the AFM software. [14]

VI.   Altair Integration

The Altair Project has interacted with the ALHAT Project for approximately three years, learning about the overall ALHAT system, component sensor and software element design, their assumptions and characterizations of the lunar environment and of the landing task, and all the while has provided feedback of their own Altair assumptions and occasional differences in perspective. The Altair Project, working to a modestly different set of assumptions (slightly less precision, landing with at least some lighting, etc), with different design philosophies and risk postures, and based on a strong priority to limit mass and a conservative philosophy of generally only using mature technologies, has sometimes differed with specifics of the ALHAT design solution. Additionally the Altair GNC design team has been working to design an overall GNC subsystem that can accommodate all Altair flight phases including orbital coast and powered flight ascent and rendezvous. If it is possible to use an already identified GNC component or software element to perform multiple functions, , then this different element may be substituted for that identified by ALHAT, based on specific circumstances. The Altair and ALHAT projects and their subsystem sensor and GNC teams have generally cooperated well, and the relationship has provided a valuable and productive exchange of ideas.

Acknowledging the excellent world-class work of the ALHAT team and the impressive integrated autonomous GNC system design they have developed, the Altair GNC team and Project has worked to integrate elements of the ALHAT concept that were judged appropriate and consistent with the Altair design and philosophies. As such, a slightly different Hazard Detection System design, through drawing substantially from that of ALHAT, has emerged for the Altair team. This modified system, along with brief references to other GNC functions defined by Altair and ALHAT as they are presently envisioned to be integrated in the Altair vehicle, are discussed here.

A.   Incorporation of the Basic Hazard Detection System
The basic HDA system, consisting of the upper elements as defined in Fig. 4, is currently envisioned to be integrated into Altair. The Altair GNC community has renamed it to be the Terrain Hazard Detection Sensor System or THDSS, but at present it is expected to be the core sensor developed and recommended by ALHAT. This would be a Flash Lidar mounted on a fast moving gimbal unless ALHAT determines an alternate configuration with a slow moving gimbal, also described in section V, works better. The only real difference regarding hazard detection is that the Altair team anticipates the HRN function will mostly shift to the ONSS (OpNav) system. Presently Altair is bookkeeping 10 kg mass for the THDSS assembly, though ALHAT field test articles (currently in the breadboard stage) are considerably more massive. Altair is presently carrying 150 watts for powering the hazard detection sensor and gimbal as well. Again the ALHAT development breadboard system is using considerably more power, although some of that is due to using less expensive terrestrial gimbals and thermal control approaches that must be optimized in terms of mass and power for spaceflight applications. So overall, the ALHAT team anticipates power numbers reducing significantly as well. The expected mounting location for the hazard detection sensor and gimbal is illustrated in Fig. 5 The sensor itself is not shown, though an arrow indicates its approximate location being very low on the forward facing structure of the Descent Module or even at the lower corner. This location

American Institute of Aeronautics and Astronautics

allows for maximum visibility of the target area starting with the powered pitch over and through the Approach and Terminal Descent sub-phase. If the instrument was mounted high on the Descent Module, or on the Ascent Module, then either the forward wall or the upper deck of the DM could block a portion of the hazard detection sensor view of the target area, particularly during early pitch over or later in the Approach sub-phase. The radar antennas, six total, serving as the sensors for both the altimeter and velocimeter functions for Altair, are located on a mounting platform, itself located on or near the lower aft corner of the DM, in a position where they can view the lunar surface during powered flight prior to, during, and after the powered Pitch Up, as it is critical to have an accurate altitude and velocity state to initiate the Pitch Up and subsequent Approach sub-phase.
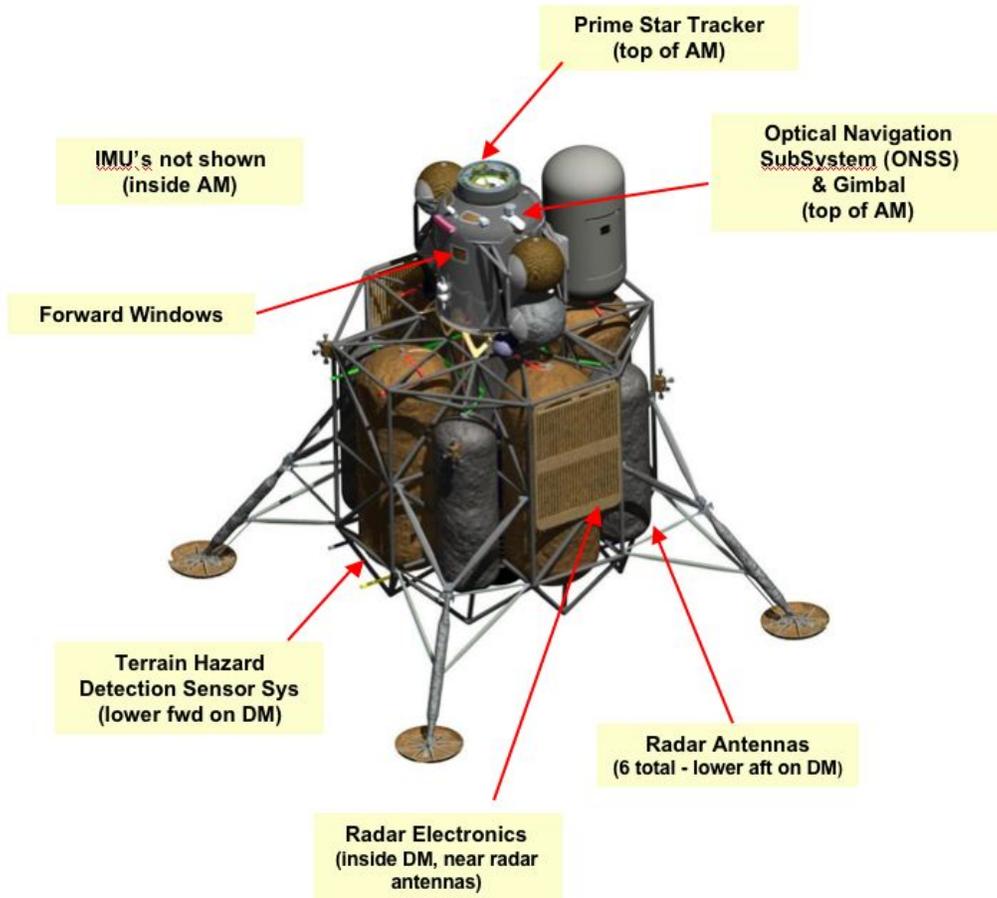
Figure 5. Altair Lander with Proposed Hazard Detection and Other Sensor Locations

B. A Brief Look at TRN and HRN

Fig. 6 below, revisits the system architecture layout previously defined by ALHAT, demonstrating how the Altair GNC and avionics teams presently envisions the support of the various descent and landing functions that Altair will have to perform, including those defined in the ALHAT architecture. Again, some of these ALHAT functions will be served by other Altair GNC systems, identified to cover multiple mission phases. A prime example of this are the TRN and HRN functions which, in the Altair baseline design, are achieved via the use of the ONSS or Optical Navigation system, relying on the use of passive optical cameras. In the ALHAT approach, the HRN function is achieved using the HDA Flash Lidar system. For Altair, the Optical Navigation cameras were originally included to acquire position estimates while on orbit or in cis-lunar transit, in the event that deep space tracking information became unavailable. As Altair assumed that most of the descent coast and powered flight would be over terrain with at least some surface lighting, it was decided that the Optical Navigation system (shown in light

American Institute of Aeronautics and Astronautics

tan), could also perform the TRN task for approach and landing. Furthermore, as it was assumed that at least some elements of the target zone and nearby region would be illuminated, it was decided that effectively the same TRN approach could be used for the localized HRN or surface and target relative navigation performed during the Approach sub-phase up until vertical descent, except that new optical sensing of reference surface features might be compared to those generated some tens of seconds previously with a higher resolution, rather then those generated before flight. [15] This assumes that a method is identified to capture the precise location of the HDA identified safe target in the surface navigation frame being used by the ONSS.

The remaining sensors were included in the Altair baseline as they would be required for descent and landing even if no HDA, TRN or HRN functions were to be performed, as any navigation system requires inertial sensors (gyros and accelerometer) for state propagation, and any planetary landing system requires ground relative altitude and velocity in order to control these key parameters for an acceptable touchdown. Altair assumed that both of these measurements could be sufficiently accomplished with the same radar system. However if the ALHAT requirement for a more accurate velocity sensor is later adopted by the Altair Project, then a different radar or a separate velocity sensor may be included in the Altair baseline. A GNC computer is required independent of HDA or TRN functions, as well.
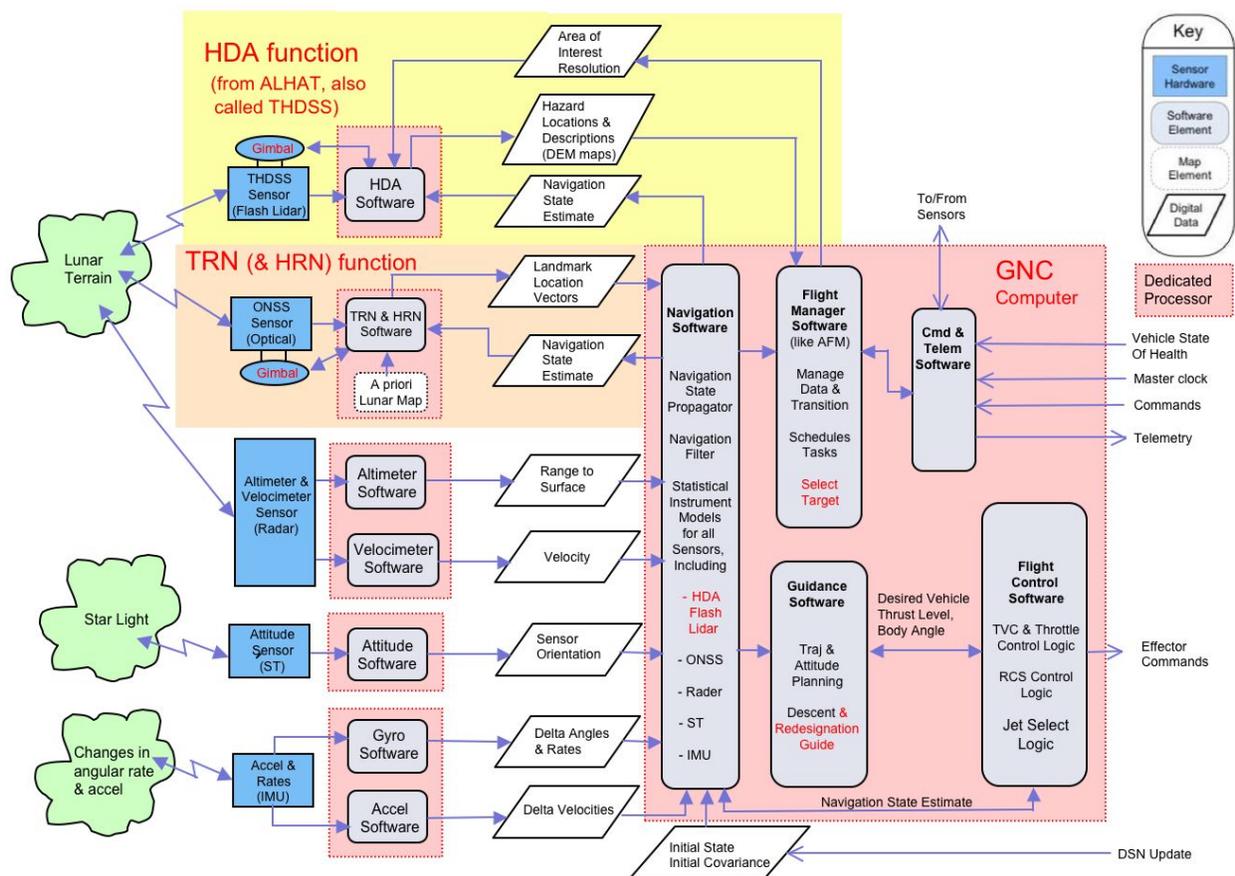
Figure 6. Altair High-level GNC Architecture with HDA, TRN and HRN

Fig. 6, also for reference, shows several dedicated processors as light red boxes. These could be anything from fully reprogrammable digital computers to embedded FPGAs. As such, it can be observed from the figure that there is an emphasis on a decentralized and distributed task architecture, where possible, if a task can be relatively isolated, particularly one that is computationally intensive, or if there is advantage to having the task close to a sensor or even in utilizing an available underused processor. This enables potential execution efficiencies through parallel processing. Even so, the architecture still has a traditional GN&C computer that processes navigation tasks,

including state propagation and the combination of sensor inputs into a large navigation filter; guidance tasks, defining and updating reference trajectories; and control tasks, commanding RCS jets and TCV gimbals to implement guidance commands while maintaining stability. Red text listed among the GNC computer tasks, are those generally specific to the hazard detection function, included for reference. The GNC computer likely will also include a Flight Manager function to schedule tasks, initiate mode transitions along with reconfiguring software and sensors, and respond to commands, either from the crew or mission control. Separated from the GNC computer is the intense computational task of Hazard Detection and digital elevation model (DEM) generation required to assemble and orthorectify the data acquired from multiple Flash Lidar frames to form an elevation map. Similarly the ONSS sensor, performing optical navigation, would benefit from a dedicated processor to rapidly compare real-time optical data images with those taken a few seconds to over a minute earlier, or with lower resolution digital imagery generated from an earlier mission and stored onboard the lander. [15]

C. Computational Performance Concerns

From the many face-to-face technology and integration discussions between both projects, an area of particular concern for Altair has emerged with relation to the computational performance required to support hazard detection. The concern basically is that there is no space qualified processor fast enough to process the data for a reasonably sized landing area, with sufficient resolution to detect hazards, and in a reasonable amount of time to support autonomous decision making and target redesignation. This concern is further amplified if it is necessary to provide fully processed landing site data to a crew member with sufficient time for them to assess and concur with any recommendations from the hazard detection and avoidance logic with regard to the selection of a safe precision target within the landing area. Preliminary lab benchmarks were showing time of roughly 1/3 to nearly 1/2 of the Approach sub-phase to complete all the hazard detection data processing such that a precision target could be selected and verified. While the Altair reference time-line of 77 seconds could be increased modestly to maybe 100 seconds while not exceeding the HDA sensor range, this would cost some fuel. [16] And while there is some indication that higher performance space qualified processors will be available by the time of the Altair Project CDR (around 2012 or 2013), the Altair Project still has concerns as this was not a guarantee and as the Altair Project has a more conservative philosophy to use existing technology whenever possible. Still, even with the use of existing technology for space qualified processors, there are some mission and vehicle design options that could help mitigate this concern, and some additional reason for optimism in that the hazard detection processing logic used in benchmarking the lab tests, has not been optimized. One very promising mitigation, appears to be an increase of the maximum tolerable hazard size of the lander, an option Altair is considering. A 30 cm maximum tolerable hazard was used for the initial benchmark. However if this is increased to 50 cm, processing times are reduced substantially. Another mitigation includes reducing the scan area from the baseline 180 x 180 meter, though this could increase the risk of not finding a satisfactory target site, possibly leading to an abort. Statistical analysis of the landing area, based on a priori remote sensing and hazard density models, would help in conducting such a trade as to the minimum size of a hazard scan area. More complicated operations strategies may offer some mitigation as well, where possibly a more coarse scan could be conducted early in approach and used to identify smaller target areas for subsequent detailed scans. Finally, there is good indication that a space qualified FPGA processor with sufficient performance could be made available in a reasonable amount of time.

D. Back-up Hazard Detection

Another Altair Project concern with the ALHAT Hazard Detection sensor relates to vehicle robustness and how to protect the crew, and possibly even the nominal mission in the presence of a prime Hazard Detection sensor failure. To this end, some type of back-up capability for the hazard detection function is judged necessary by the Altair Project. This could potentially be a full up redundant hazard detection system, possibly from the same vendor though more likely a different vendor, or perhaps a different vendor for certain critical sensor subassemblies. This concern can also benefit from reviewing the candidates sensors considered previously. Many of the ideas still would not work outright due to overly limited performance, but there may be a few that, when combined with a higher mission risk posture and, perhaps, accepting an increased risk of an abort to orbit, may be able to serve as a back-up hazard sensor. One idea discussed earlier is the Scanning Lidar. Though much slower than a Flash Lidar, if a much smaller area is scanned (increased risk of a mission abort) or a larger hazard tolerance is accepted and a lower resolution scan preformed (increased risk of landing on a hazard), then a Scanning Lidar might could be employed as a backup. With this scenario, the use of human vision aided by a camera or goggle magnification might become acceptable as large hazards may be discernable with this approach. Still another remote option, might be to change

American Institute of Aeronautics and Astronautics

to the Rendezvous, Proximity Operations and Docking (RPOD) sensor, from a Scanning to a Flash Lidar, making it more common with the Orion RPOD sensor strategy. However with this change, and if the RPOD Flash Lidar is shifted to a forward location on the upper Ascent Module (AM) surface, then it might could also serve as a backup hazard sensor, though it would more limited visibility due to vehicle blockage of some of the landing terrain.
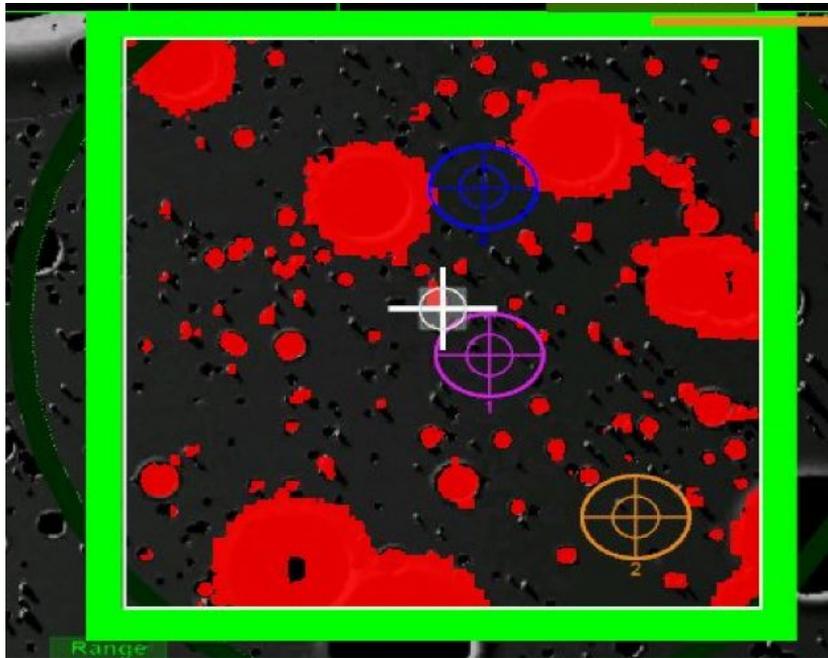

Figure 7. Representative ALHAT Hazard Scan Map

E. Pilot Interaction

One final consideration regarding hazard detection integration is how it may interface with the lander pilot. This question is already being explored extensively by the ALHAT team, which has focused primarily on crew supervisory control and landing data interfaces during the descent and landing trajectory. However, it warrants some mention here. One question that has only been touched by some of the ALHAT crew interaction studies, is what role will the future crew member have? Is the crew member just to monitor displayed information, perhaps to only concur with a decision or abort? Or is the crew to be a little more involved and select from a list of targets or even identify a new target (in a P64 manner)? Or is the crew member to fly the vehicle in some manner (commanding attitude like Apollo, or commanding desired velocity) using the hazard scan data just as reference? The second and third options could require additional display information, such as the inclusion of detected objects smaller than the threshold to better assess landing selection. Also these latter options would likely benefit from more time on Approach, even if just 10 or 20 sec. For reference, Fig. 7 shows an example of hazard scan data as utilized in an ALHAT crew interaction study, where red indicates a hazard, 'bulls eye' circles represent targets and where some objects (rocks, etc) are shown even though they were below the hazard threshold. The white crosshairs near the center of the hazard scan area represents the a priori landing target selected by mission planners using lunar reconnaissance data. [17]

With the expectation that at least some surface features will be illuminated prior to and during the Approach sub-phase, it is suggested that the out-the-window view could be used as an initial confidence builder with regard to the higher resolution, active terrain sensing. A crew member could perform general navigation cross-checks with larger craters and other illuminated features prior to the Approach sub-phase by simply comparing the window view to a rendered display of a prior data, corrected for local view geometry and lighting. Additionally such out-the-window cross checks could be performed against Lidar sensed elevation data rendered in a display at the appropriate approach angle, and possibly even rendered on a HUD overlay. Fig. 8, a lunar DEM used in a recent ALHAT crew interaction study, represents what a synthetic image could look like, correcting for viewing angle, etc, though likely features would be presented with greater contrast, and those outside the hi-resolution scan area (green box) would be

American Institute of Aeronautics and Astronautics

rendered at a lower resolution. [17] This again would be to gain some confidence in the the hazard detection system, before trusting it to identify objects un-discernable to the un-aided eye.
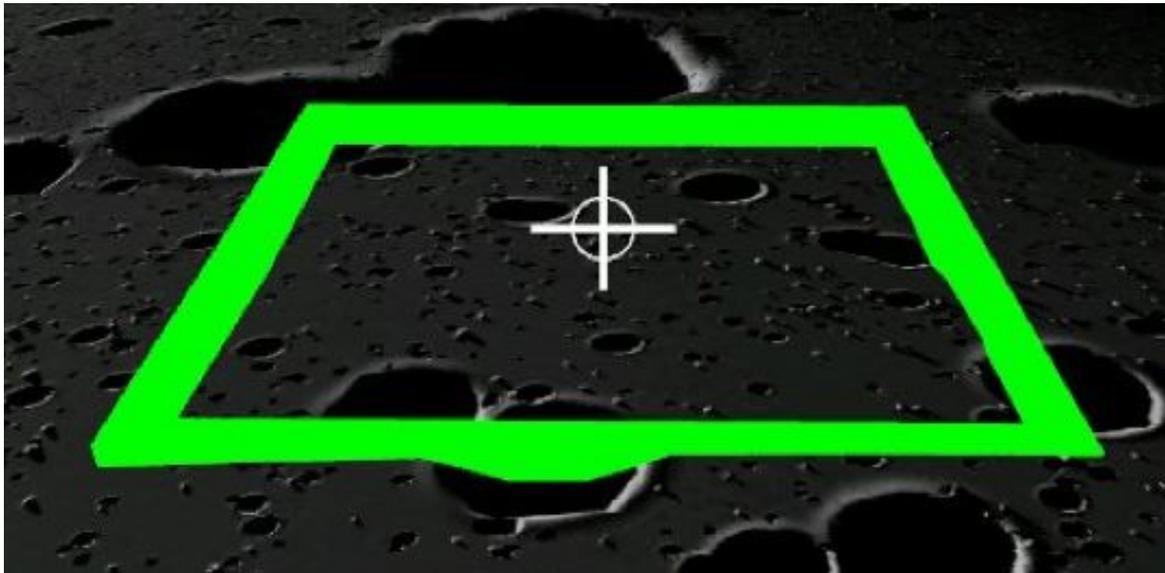
Figure 8. Potential Synthetic Imagery Example

Another area of in-depth discussion between the Altair and ALHAT projects is the lander flight path angle during Approach. The Altair Project still assumes 15 deg, which is better suited both for crew visibility and lower fuel usage. However, the ALHAT Project, based on analysis, prefers a 30 deg minimum flight path to achieve reasonable sensor performance. A 30 deg minimum angle for the Flash Lidar reduces blockage of hazards behind others (shadowing) and reduces the downrange stretching of the flash lidar images relative to a shallower approach angle. [16] While 30 deg trajectories can be executed with only a very modest performance penalty (< 5 m/s) relative to 15 deg Approach trajectories, the reduction of crew visibility due to the steeper angle may be a more substantial issue. Perhaps the crew could get comfortable with this via out the window cross checks building confidence early during the Approach before the target disappears, or where cameras could then be used. This question will likely benefit from some of the additional data presentation and crew visibility studiers using simulation, that both ALHAT and Altair are planning.

VII. Summary and Conclusions

The need for hazard detection has been demonstrated based on Altair vehicle and mission characteristics, as well as the challenging lunar terrain and lighting environments, particularly near the lunar poles. Candidate hazard sensors were reviewed along with the case for the selection of the Flash Lidar as the hazard detection sensor of choice by the ALHAT team. The overall hazard detection and precision landing system architecture, as proposed by the ALHAT Project, which also includes the TRN and HRN functions, was presented. Finally, a discussion of the manner in which elements of the ALHAT system, particularly the hazard detection portion, could be integrated into the Altair vehicle was provided. The integration included just the use of the ALHAT selected Flash Lidar and high rate gimbal, along with landing zone processing and imaging software, which would run on a dedicated processor. Some Altair concerns regarding observed slow performance benchmarks of the hazard detection processing logic on a currently available space rated processor were discussed including mitigation options such as increasing the hazard tolerance of the lander. Thoughts on how to implement a back-up hazard detection sensor, with a desire for dissimilarity if possible, were also discussed. Finally, a brief review of how such a hazard detection system may interact with a crew member on the Altair vehicle was provided, with a focus on how out the window crosschecks

American Institute of Aeronautics and Astronautics

could be used to increase confidence in the system, and how the Altair Approach sub-phase trajectory may have to increase its flight path angle to accommodate Hazard Detection sensor performance.

While some issues have been identified and reviewed here, overall it is believed that, should the Altair vehicle and project continue, its cooperation with ALHAT must continue with the likely outcome being the incorporation of their proposed Flash Lidar onto the Altair vehicle for hazard detection. Furthermore should the Altair Project go away due to changing NASA and Federal priorities, the hazard detection concepts developed by ALHAT should still be strongly considered for any planetary lander or asteroid encounter mission, and it is hoped that this study and review of how to integrate such a system into an overall vehicle, will be beneficial to some future effort.

References

[1]Kos, L., Braden, E., Sostaric, R., Merriam, R., Sullivan, J., "LDAC-3 Integrated Performance Summary / Conceptual Flight Profile," LDAC-3 Design Review Presentation to Altair Team , NASA-JSC, Houston, Tx., March 31, 2009.

[2]Derkowski, B., " R209: Human Piloting Descent/Landing Maturation," Presentation to End of RAC-2 Design Review by Altair Team, NASA-JSC, Houston, Tx., Dec 17, 2009..

[3]Constellation Architecture Requirements Document (CARD), CxP 70000, Release Version D, 2009, Johnson Space Center.

[4]Epp, C., Robertson, E., Brady, T., "Autonomous Landing and Hazard Avoidance Technology (ALHAT)," *Proceedings of the2007 IEEE Conference*, paper #1644, Version 5, Updated December 13, 2007.

[5]Bennett, F.,"Apollo Experience Report - Mission Planning for lunar Module Descent and Ascent," NASA Technical note TN D-6846, Manned Spacecraft Center, Houston, Tx., 77058, June 1972.

[6]Constellation Program Lunar Lander System Requirement document (Cx SRD), CxP 700XX, Release Version 0, 2009, Johnson Space Center.

[7]Hutton, R., "Lunar Surface Models," NASA Space Vehicle Design Criteria, NASA SP-8023, Marshall Space Flight Center, Huntsville, Al., May 1969.

[8]Brady, T., "Challenge of Crewed Polar Lunar Landing," ALHAT Whitepaper Delivered to Altair Project, Revision A., ALHAT-2.0-017, NASA-JSC, Houston, Tx., 77058, May 28, 2008.

[9]Johnson, A., Huertas, A., Werner, R., Montgomery, J., "Analysis of On-Board Hazard Detection and Avoidance for Safe Lunar Landing," *Proceedings of the 2008 IEEE Conference*, paper #1656, Version 2, Updated January 31st, 2008.

[10]Goldfinger, A., Blewett, D., Criss, T., Darlington, E., McEvaddy, P., McGee, T., Morse, B., Kumar, C., Taylor, J., Wirzburger, M., "Study of Low Illumination Sensing Aids Applicable to lunar landing," *Proceedings of the AIAA GNC Conference*, Chicago Il, Aug. 2009.

[11]Epp, C., Robertson, E., "ALHAT Alternate Scenario Architecture," ALHAT Deliverable #5 to the Altair Project, according to the ALHAT/Altair Customer Supplier Agreement, NASA-JSC, Houston, Tx., 77058, Juen 29, 2009.

[12]Brady, T., Robertson, E., Epp, C., Paschall, S., Zimpfer, D., "Hazard Detection Methods for Lunar Landing," *Proceedings of the 2008 IEEE Conference*, paper #1087, Version 4, Updated November 1, 2008.

[13]Cohanim, B., "Trade Report ALDAC-1 - HDA Methodology for the Autonomous Landing and Hazard Avoidance Technology (ALHAT) System," ALHAT-2.0-010, NASA-JSC, Houston, Tx., 77058, February 5, 2009.

[14]Brady, T., Schwartz, J., "ALHAT System Architecture and Operational Concept," *Proceedings of the 2006 IEEE Conference*, paper #1570, Version 4, Updated December 11, 2006.

[15]Riedel, J. E., Ely, T., Lee, A. Y., Werner, R. A., Wang, T.-C., Vaughan, A. T., Nolet, S., Myers, D. M., Mastrodemos, N., and Grasso, C., "Optical Navigation Plan and Strategy for the Lunar Lander Altair," *Proceedings of the AIAA Guidance, Navigation, and Control Conference, and Exhibit*, Toronto, Ontario, Canada, August 2–5, 2010.

[16]Cohanim, B., "Summary Report ALDAC-2 - HRN Methodology for the Autonomous Landing and Hazard Avoidance Technology (ALHAT) System," ALHAT-2.0-011, NASA-JSC, Houston, Tx., 77058, March 17, 2010.

[17]Hirsh, R., "Human System Interface (HIS) Status and Future Plans," Technical Interface Meeting ALHAT JPL designreview, NASA-JSC, Houston Tx., July 15, 2009.