The Autonomous Precision Landing and Hazard Detection and Avoidance Technology (ALHAT)

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Abstract—As NASA plans to send humans back to the Moon and develop a lunar outpost, technologies must be developed to place humans and cargo safely, precisely, repeatedly, on the lunar surface with the capability to avoid surface hazards. Exploration Space Architecture Study requirements include the need for global lunar surface access with safe, precise landing without lighting constraints on terrain that may have landing hazards for human scale landing vehicles. Landing accuracies of perhaps 1,000 meters for sortie crew missions to 10's of meters for Outpost class missions are required. The Autonomous precision Landing Hazard Avoidance Technology (ALHAT) project will develop the new and unique descent and landing Guidance, Navigation and Control (GNC) hardware and software technologies necessary for these capabilities. The ALHAT project will qualify a lunar descent and landing GNC system to a Technology Readiness Level (TRL) of 6 capable of supporting lunar crewed, cargo, and robotic missions.

The (ALHAT) development project was chartered by NASA Headquarters in October 2006. The initial effort to write a project plan and define an ALHAT Team was followed by a fairly aggressive research and analysis effort to determine what technologies existed that could be developed and applied to the lunar landing problems indicated above. This paper describes the project development, research, analysis and concept evolution that has occurred since the assignment of the project. This includes the areas of systems engineering, GNC, sensors, sensor algorithms, simulations, fielding testing, laboratory testing, Hardware-In-The-Loop testing, system avionics and system certification concepts.

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1. INTRODUCTION

As NASA plans to send humans back to the moon and develop a lunar outpost, technologies must be developed to place humans and cargo safely, precisely, and repeatedly on the lunar surface with the capability to avoid surface hazards. Exploration Space Architecture Study requirements include the need for global lunar surface access with safe, precise landing without lighting constraints on terrain that may have landing hazards for human scale landing vehicles. Landing accuracies of perhaps 100's of meters for sortie crew missions to 10's of meters for Outpost class missions will be required.

At the beginning of Fiscal Year 2006, NASA Headquarters, Exploration System Mission Directorate did some re-defining of technology projects for support of the Exploration Program. One of the new projects that came out of this process was the "Autonomous Precision Landing and Hazard Detection and Avoidance Technology" for landing on the lunar surface. This project was initially assigned to Claude Graves (now deceased) at JSC to define the team and the project plan that would provide the necessary capability for NASA to develop this technology to a Technology Readiness Level (TRL) of 6. (See Appendix A for TRL definitions.) During the project plan development, the acronym ALHAT "Autonomous precision Landing and Hazard detection and Avoidance Technology" was coined and is widely used today for the project.

The Apollo missions were tremendously successful, but had several operational restrictions, including landings limited to the lunar near-side, prescribed lighting conditions, and significant ground-in-the-loop operations. To meet the needs of the Exploration Program the ALHAT project will eliminate or mitigate these restrictions while enhancing the landing precision for future lunar missions

The ALHAT project will develop the new and unique descent and landing Guidance, Navigation and Control (GNC) hardware and software technologies necessary for these capabilities. The ALHAT project will qualify a lunar descent and landing GNC system to a (TRL) of 6, capable of supporting lunar crewed, cargo, and robotic missions (cargo missions are defined as uncrewed missions about the same size as human missions).

2. PROJECT DEFINITION

The ALHAT development project was chartered by NASA Headquarters in October 2006. The initial effort to write a project plan and define an ALHAT Team was followed by a fairly aggressive research and analysis effort to determine what technologies existed that could be developed and applied to the lunar landing problem. This paper describes the project development, research, analysis and concept evolution that has occurred since the assignment of the project. This includes the areas of systems engineering, GNC, sensors, sensor algorithms, simulations, fielding testing, laboratory testing, Hardware-In-The-Loop testing, system avionics and system certification concepts.

Utilizing known expertise within NASA, a team was formed to carry out the technology development. Johnson Space Center (JSC) took on the Project Management and System Engineering task along with the development of guidance algorithms, navigation algorithms, project avionics and a Hardware-In-the-Loop simulator. Langley Research Center (LaRC) was assigned responsibility for a full 6 Degree of Freedom (DOF) simulation using the Program to Optimize Simulated Trajectories (POST 2) software tool and assigned the project lead for Terrain Relative Navigation (TRN) sensors, Hazard Detection and Avoidance (HDA) sensors, altimeter and velocimeter sensors, including development, testing and procurement. The Jet Propulsion Laboratory (JPL) was assigned the responsibility of developing and/or procuring the software algorithms supporting the sensors and the lead responsibility for field testing of the sensors, algorithms and sensor systems. Draper Laboratories (CSDL) was assigned responsibility for the autonomous algorithms, control algorithms and the task of GNC integration. They also were assigned a significant support role in systems engineering because of their experience and earlier work on a Lunar Access Project. The Lunar Access Project, funded by NASA in 2005, fell victim to the realignment of exploration technologies beginning in 2006. However, much of Draper's work on Lunar Access was applicable to the ALHAT Project and was used as a starting point for much of the systems engineering.

The direction given to the ALHAT Team from NASA Headquarters was limited to a two and a half page white paper titled: <u>Autonomous Precision Landing and GN&C Technology Development Summary</u>. The essence of the white paper can be summarized with the following excerpt: *"This project includes development of precision landing and hazard avoidance landing system technologies for human lunar missions including crew and cargo and systems to support precision navigation relative to hazard. Technologies may be demonstrated on robotic lander missions prior to human missions."*

Primary development tasks in the white paper were given as:

1) *Hazard Detection Sensor Development - Demonstrate required performance of scanning system over relevant ranges, power requirements, and accuracy. Characterize performance through relevant plume optical paths.*
2) *Terrain Mapping and Site Selection – Demonstrate computations and display of terrain information along with logic for selection of safe landing zones. Demonstrate relevant computational speeds.*
3) *Autonomous Hazard Avoidance – Demonstrate closed-loop vehicle control characteristics by coupling site selection functions with vehicle targeting and GN&C systems.*

An initial ALHAT team face-to-face meeting was held at JSC in October, 2005, to define responsibilities and start the process of developing a project plan. Following the guidelines given by NASA HQ, a 90 page Project Plan was completed by mid December of 2005. By mid January, 2006, the Project Plan was signed by management and approved by NASA HQ. Money started to flow and the project team went to work on the defined tasks.

At first the budget seemed adequate, but as the project developed it became clear that sensor procurement and considerable sensor testing would be required, leading to requests for additional funding. As the project continues to develop the GNC system, it will make specific requests for funding as required.

3. PROJECT OBJECTIVES AND THEIR EVOLUTION

The basic objectives of the project were contained in the project title; the ALHAT system was to operate autonomously, perform precision landing, detect hazards and avoid hazards. This had to be performed in a highly dynamic environment under any lighting conditions anywhere on the lunar surface. These objectives raised many questions that needed to be quantified in order to proceed to anything meaningful. Does precision mean meters or kilometers and is a hazard a rock or a hole on the order of a few centimeters or a few meters? The project started with the Exploration System Architecture Study (ESAS) numbers and then began to look at what could possibly be done.

The current state-of-the-art for lunar landings from Apollo, is 1+ kilometer with a pilot in-the-loop and with landing site and landing lighting restrictions. The primary objectives for ALHAT, as originally stated in the Project Plan, were to develop a system enabling precision landing of robotic, cargo, and human missions that will:

- land autonomously anywhere, anytime within 10's of meters if there are lunar navigation assets in place and/or precise lunar maps
- land autonomously anywhere, anytime within <1 km if there are no lunar navigation assets or precise lunar maps
- detect and identify 0.5 meter tall surface obstacles, 10 º slopes (over a 10 meter baseline at 2 km) and pre-deployed assets at sufficient altitude to retarget the landing site to avoid undesirable landing areas and to efficiently maneuver to the re-designated target.

After further consideration, and based on better knowledge following several team meetings, a set of goals were defined in the form of level 0 requirements for the project. These level 0's are taken to be real requirements and everything is done with those numbers in mind. These requirements will be updated only if the ALHAT analysis, development and testing proves that they are too stringent. The level 0 requirements currently carry a landing accuracy requirement of 30m, 1 sigma, from any surface feature and a hazard detection requirement of a feature that rises 30 cm above the surrounding surface and a 5 degree or larger slope. These requirements were set assuming that lunar maps made by the Lunar Reconnaissance Orbiter (launches in 2008) will be available for the ALHAT System.

As the work plan developed it became clear that the project had key subsystems which would need to be developed individually but with strict attention paid to the eventual need for a fully integrated system. To insure that no subsystem developer went off on their own and did not take full account of their integration requirements, the centers identified representatives to support each subsystem. Thus, JSC, LaRC, JPL and CSDL all have members supporting the systems engineering team, the sensor team, etc. This has proven to be an effective way to organize a cooperative integrated team with everyone working together. A second factor that has significantly helped solidify the ALHAT team as a unified group of people working together for a common goal is face-to-face meetings held every 3 months. This not only builds personal ownership of the project goals, but team members get to know and respect each other, making disagreements and problems much easier to solve.

Early in the project a vision statement was defined and approved by the team. The vision statement is: "*Develop and mature to TRL 6 an autonomous lunar landing GN&C and sensing system for crewed, cargo, and robotic lunar descent vehicles. The 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.*"

Since one of the main goals of this system was to support human missions, the question of crew involvement in the landing process was of significant interest. The issue of funding and our desire to first prove the technology by demonstration on a robotic mission led to the decision to initially postpone integration of the crew role in the system development while recognizing that it would likely be a major factor when we got to human missions. So in the initial work, the crew was given a supervisory role which involved essentially "go, no go" decisions for things like aborts and decisions to proceed to landing. It is recognized that the crew will likely require a window with some view of the surface and most likely will want to fly the vehicle to the surface. With this in mind, the plan is to pursue the requirements for the crew cockpit, crew displays, the level of crew involvement, etc. at a later time. All possible data from the ALHAT system will be made available to the crew and their interactions will need to be interfaced with the ALHAT GNC system. In fact it is believed that the final phase of the lunar landing will not be defined completely until the crews get a chance to fly a simulated vehicle to landing and determine which trajectories work the best.

Another decision made early in the project was to not get consumed by failure scenarios and aborts for the ALHAT system. Since the project is developing a first of a kind system, it was considered high priority to get a system defined before spending time on FDIR (Fault Detection, Identification and Reconfiguration) and abort scenarios. These clearly will be necessary items to work and build into the design of any lunar landing system and will be added to the project at some point.

The ALHAT system development is proceeding with the assumption that we will not have navigation aids such as surface beacons or lunar orbiting navigation systems. Navigation aids in general would help with the precision landing but the project believes that there will very likely be missions when such systems will not be available or able to give the desired accuracy. The project acknowledges and is planning to use any navigation aids that may be available, but the ALHAT system goal is to perform the required functions without them. It is possible that the project will discover that they are necessary for certain scenarios and if so, that would be a recommendation coming out of the project.

4. SUBSYSTEM DEVELOPMENT

A precision landing and hazard avoidance system is dependent on the trajectory flown to the lunar surface. The ESAS architecture for human missions assumed there would always be loiter time in lunar orbit prior to descending to the lunar surface. There is good rationale for this, and so ALHAT made the assumption that the descent and landing phase of any lunar landing mission would begin from a 100 km circular orbit (ESAS assumption). The ALHAT Team continues to recommend that this be the trajectory approach for all lunar landing missions to insure commonality for the precision landing and hazard avoidance system.

The ALHAT System will operate in a lunar environment, will be initiated while the landing vehicle is in lunar orbit, and will continue to operate until the vehicle has landed on the lunar surface. Shown in the Figure 1 is a high level overview of the three mission phases; orbit, transfer orbit, and powered descent.

powered descent to the lunar surface. The powered descent includes a pitch over to vertical late in the burn and a terminal vertical descent to the surface. The engines do not shut down until contact with the lunar surface is achieved, but they are assumed to throttle as required for final control.

ALHAT assumes the vehicle has a good quality navigation state prior to the de-orbit burn. How this state is obtained is not part of the ALHAT project. It will be defined by the lunar orbit navigation and communications team. It should also be pointed out that the elliptical transfer orbit is a safe orbit and the vehicle could stay in this orbit for a few revolutions if desired. No real advantage to staying in this orbit could be determined so the ALHAT descent and landing always assumes a half orbit to the initiation of the powered descent burn. A possible abort scenario could be to stay in the elliptical orbit for one or more orbits, but the ALHAT Team is not considering aborts in their early work.

The guidance scheme for the ALHAT system will be an Apollo derived algorithm. The control algorithms will be different than Apollo because the vehicle properties will be different and the lunar landers will most likely have more than one engine.

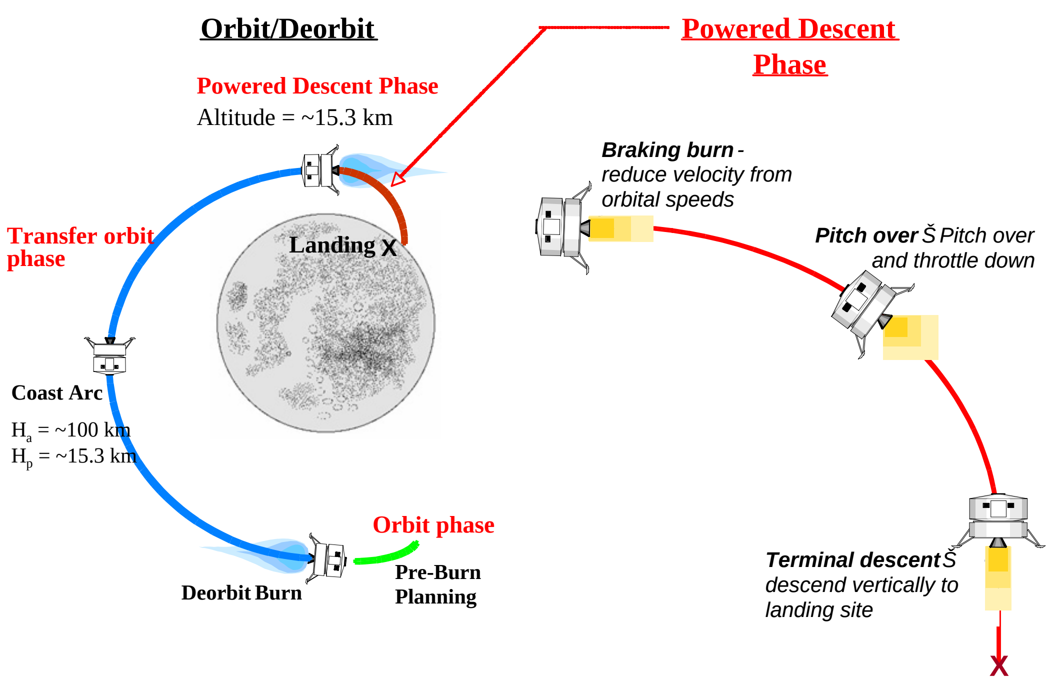

FIGURE 1

The ALHAT system will be initialized just prior to the de-orbit burn and will guide the burn to place the vehicle in an elliptical orbit with a perilune of approximately 15.3 km. ALHAT assumes a half rev to the start of the

The other important development for ALHAT is the Autonomous Flight Manager (AFM). The AFM must be capable of autonomously landing cargo and robotic vehicles safely with precision and hazard avoidance and

function as well as a provider of data and decision information to the crew for crewed vehicles.
There is a very large trade space on sensors and trajectories following the initiation of the powered descent maneuver. Trades that have been considered include a high trajectory which targets for the pitch over maneuver to be complete at altitudes ranging from 500 m to 2500 m with zero horizontal velocity and flying straight down from there. A second trajectory that has been considered is a more Apollo like trajectory which comes in lower and faster and completes its pitch over maneuver at 50 – 100 m altitude and then comes straight down. Trade studies have been done using linear covariance analyses and 3 DOF Monte Carlo analyses. These studies are preliminary and give some good initial insight into the sensor requirements for the powered descent phase. Higher fidelity simulations are planned for future work and will be used to determine the final ALHAT trajectory. It appears likely that there may be some variability in this trajectory and the terminal phase may not be completely determined until some crew-in-the-loop simulations are performed.

Determining how the final 1 to 2 minutes of the trajectory will be flown is the most difficult part of the trajectory analysis. The goal of defining a common trajectory for robotic, cargo and human missions tends to make human missions the driver on what this phase of the trajectory looks like. It is generally believed that the crews will want a window with visibility to the surface and the ability to fly the vehicle to the surface. Thus, ALHAT has the challenge of making the autonomous system for cargo missions fly similar to the way a crew member would fly for crewed missions to insure a common sensor and data output system.

Obtaining repeatable precision landing without lunar navigation aids requires the availability of very good lunar surface maps. As mentioned previously, ALHAT is assuming that Lunar Reconnaissance Orbiter (LRO) maps will be available to support the ALHAT system. The possibility that LRO maps may not be available is also being considered.

The ALHAT navigation system is dependent on some form of Surface Feature Tracking to converge the navigation state to required accuracies. Possibilities include passive imaging sensors and active ranging sensors. Passive imaging systems are mature but generally require an illuminated surface to function. “Active ranging sensors range from one dimensional altimeter sensors to 3-D flash or scanning LIDARs. The results of industry site visits and responses from an ALHAT Request For Information (RFI) have provided information on sensors that are available to consider for the needs of the ALHAT System. Testing and evaluation of promising sensors will be conducted to determine sensor availability, development potential and applicability to the ALHAT sensor needs.

The selection, development and utilization of software algorithms that take the raw sensor data and convert it to information that can be used by the GNC algorithms is another major development of the ALHAT project. These algorithms use techniques like pattern matching where an image is matched with a map stored in the permission database. Another technique is a correlation approach where a sensor produces an elevation map or contour map which is correlated with map information stored in the system database. The heritage on these kinds of algorithms comes from guided missiles and some of the robotic Mars missions.

The ALHAT Project recognized form the beginning the necessity of full time system engineering for the development of the ALHAT System. The ALHAT project is a technology development project and does not need the formality of an actual flight project; however, the system development is expected to evolve to a flight system so good system engineering will make this transition easier and focus the project.

Although ALHAT is a technology development project it is well positioned to produce a prototype system and eventually a flight system.

5. FUTURE PROJECT WORK

One of the most important aspects of any new project is to develop valid requirements, plans and objectives. This was done early on in the ALHAT project and included a Vision Statement, an Operations Concept, Configuration Management Plan, Level 0 and Level 1 Requirements. This extra effort will pay off in the long run as this technology moves to a prototype system and possibly a flight system The plan for future work is based on the most robust set of requirements that could be developed given the current state of lunar program planning. ALHAT Project managers will continue to maintain close contact with the LPRP and LSAM programs to ensure close alignment with developing mission requirements and objectives.

Based on knowledge gained from the RFI submits and industry site visits, the project will utilize testing, expert evaluation, simulations and analysis to define a sensor system that will meet the needs of the ALHAT requirements. It is expected that some engineering development will be required to meet the ALHAT requirements and ensure form, fit and function of the ALHAT System. With this in mind, an RFP will be released (est. 2007) to find candidate sensors for ALHAT that best meet the requirements for the system. If the RFP does not identify suitable sensors that meet the needs of ALHAT, or if otherwise deemed beneficial, the Project may decide to

develop the sensors in-house.
Algorithms that take the raw sensor output data and convert it to useful state data are an essential part of the ALHAT System. Considerable heritage, expertise and capability in this area exist within NASA and will likely be developed and supplied by NASA. However, it is possible that a commercial vender could supply this capability. Sensors like star trackers and IMU's which are commercially available in a complete package that gives desired state data will be purchased as COTS packages.

Many individual tasks are being performed in parallel since extensive trade studies will be needed to help determine optimal solutions. For example, the nominal trajectory may initially be optimized for maximum TRN algorithm performance, while other trades could indicate a different trajectory for optimized sensor performance. Furthermore, crew preferences, when addressed, could likely dictate an entirely different trajectory. Many other variables will be evaluated in this, and other trade studies throughout the course of this project.

Human Systems interface requirements are currently being considered for manned missions. Eventually, mockups and simulators will be developed to assist in development of these interfaces. Other long range activities are being planned for future development including integration of the ALHAT system with selected flight systems such as a crew cockpit with crew displays. This kind of interface with the ALHAT System will be used to address scenarios such as terminal phase and landing abort to ascent.

Once candidate hardware (sensors, avionics) and software have been identified, an extensive testing and evaluation process will take place to achieve TRL 6 for ALHAT.
Components of the hardware and software will be tested in laboratory configurations and in field configurations designed to be somewhat lunar like. These tests will proceed to higher and higher levels of component integration. The goal is to perform field testing on as much of the final configuration as practical. The final complete integrations and interface testing with other lunar landing systems will be done in a classical Hardware-in-the-Loop (HWIL) testbed with full integration of subsystems, including software.

An Avionics suite prototype will be developed starting in 2007. This will provide a system architecture which can be utilized in integrated systems testing including laboratory and field tests of the ALHAT System or parts of the ALHAT System. This avionics prototype architecture will also be utilized in the assembly and certification of the HWIL facility, expected to occur in 2008. Once certified, regular testbed operations will begin in full and utilized to verify the ALHAT System as a viable flight system.
Various field testing capabilities are being considered including helicopters, balloon lifts, moving gantries, airplanes, etc.. Helicopters have a lot to offer and will definitely be used. An early field test using a helicopter to test a scanning LIDAR mounted on a gyro stabilized platform was performed in FY06. These tests will be repeated for various sensors and sensor configurations.

As the GNC software algorithms, the software sensor models and the software environmental models are developed, they will be first hosted in the POST2 simulation and then in the HWIL testbed. The LaRC POST2 simulator has a long heritage of descent and landing trajectory analysis with NASA missions and will be one of the ALHAT primary analysis tools. The POST2 simulation will be used for Monte Carlo analysis of the integrated ALHAT System and to assess the overall system performance. The HWIL testbed will be designed to a flight like system with complete checks on interfaces and timing of the software components.

Another important consideration is dust and what effect it will have on how the final seconds of flight are flown. According to Apollo crew reports, visibility through the dust varied from visibility all the way down, to total obscuration from approximately 35 m altitude. Can sensors see through the dust or will the system have to be completely controllable with horizontal errors of 1 m or less coming down above a set altitude, assuming the landing point was defined above that altitude? These issues will be addressed.

A formal Verification and Validation (V&V) Plan will be developed to ensure that components, end items, and subsystems comply with their respective specifications, will function properly when integrated with the ALHAT System, and are ready for TRL 6.

- *Verification* is the formal process using the methods of test, analysis, inspection, and demonstration to confirm that system hardware and software components satisfy all documented performance, functionality, design and interface requirements.
- *Validation* is the process to ensure that the system meets the customer's expectations for its intended usage.

In addition to the formal V&V plan, ALHAT will convene a panel of independent experts to validate the overall approach. Other project controls include oversight of ALHAT by the ETDPO through monthly reporting (including Earned Value Management), Quarterly Reviews and participation in ALHAT weekly meetings, site visits, and Technical Interchange Meetings.

6. INFUSION WITH LUNAR MISSIONS

In order to support missions to the moon, the technology readiness level of landing systems must be developed beyond TRL 6. It is not the intent of the ALHAT project, or in the scope of this paper to layout a detailed plan, since there are still many unknowns at this phase in the project. Assuming the technology is proven feasible, then ALHAT will create a roadmap that will enable development beyond TRL 6.

Obvious elements of that roadmap will include flight demonstration on a lunar precursor mission. The best candidate is LPRP's robotic precursor mission which will land a vehicle on the lunar surface. To that end, ALHAT has been working closely with LPRP; in fact LPRP representatives are on the ALHAT team and regularly participate in ALHAT telecons, meetings and site visits. One of the risks however, is that the ALHAT prototype system may not be ready in time for the first LPRP lunar mission. When the schedule for this first LPRP mission is announced, ALHAT will readjust the work plan, if necessary, to best meet the launch date and fly as much of the ALHAT System as feasible.

Cargo missions will most likely precede crewed missions. Some questions that need to be answered pertain to the accuracy requirements for the first arrival cargo mission. Are the accuracy requirements more lax for the first landing? Will the first landing of an outpost include navigation aids (e.g. beacons) that would aid subsequent missions? All of these questions will be answered in conjunction with the customer requirements as they become available. A technology infusion plan has been developed that addresses these issues in more detail.

Crew requirements are going to be a major driver for the future development of ALHAT. The extent of crew involvement will affect not only hardware, such as crew displays, windows, and controls, but the overall GN&C system. How much time will the crew need to make the 'go-no-go" decision? How much control will the crew require, and how much should the automated system handle? ALHAT can make certain assumptions about the possible answers, but the final approach to these types of questions will be addressed later in the project. As mentioned earlier, they are not being ignored, but any in depth analysis is being postponed until the basic technology has been proven.

7. CONCLUSION

Having the capability to land on the moon autonomously and precisely while avoiding hazards not only opens the possibility for accessing more interesting lunar landing sites, it greatly aids, and may in fact be a prerequisite to the development of lunar outposts. Scientific features are typically hazardous to landing spacecraft and no mission would be attempted near these sites without the assurance of a safe landing – one that could only be provided autonomously by an ALHAT-like system. Building outposts on the moon will be impractical if assets cannot be placed accurately and autonomously in advance. It is for these reasons that NASA initiated the ALHAT Project. It is why the ALHAT team is dedicated to achieving the goals of NASA's vision for space exploration.

APPENDIX A

TECHNOLOGY READINESS LEVELS SUMMARY

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 9 Actual system "flight proven" through successful mission operations

BIOGRAPHY

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Thomas Smith is the Deputy Project Manager for the ALHAT Project. He worked 10 years in private industry designing automation equipment before going to work for NASA in 1989. At NASA's Johnson Space Center, he was a Group Lead in charge of space vehicle mockups and trainers, and later, Manager of the Exploration Division's Entry Descent and Landing Office. He joined the Aeroscience and Flight Mechanics Division of JSC's Engineering Directorate in 2005. Mr Smith earned his BS degree in Mechanical Engineering in 1977 and his Professional Engineering license in 1983.