SYNTHETIC AND ENHANCED VISION SYSTEM FOR ALTAIR LUNAR LANDER

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Past research has demonstrated the substantial potential of synthetic and enhanced vision (SV, EV) for aviation (*e.g.*, Prinzel & Wickens, 2009). These augmented visual-based technologies have been shown to significantly enhance situation awareness, reduce workload, enhance aviation safety (*e.g.*, reduced propensity for controlled flight -into-terrain accidents/incidents), and promote flight path control precision. The issues that drove the design and development of synthetic and enhanced vision have commonalities to other application domains; most notably, during entry, descent, and landing on the moon and other planetary surfaces. NASA has extended SV/EV technology for use in planetary exploration vehicles, such as the Altair Lunar Lander. This paper describes an Altair Lunar Lander SV/EV concept and associated research demonstrating the safety benefits of these technologies.

Background

Synthetic Vision

Synthetic vision (SV) is a computer-generated image of the external scene topography from the perspective of the flight deck that is derived from vehicle attitude, high-precision navigation solutions and a database that includes terrain and may include obstacles, trajectory information, relevant cultural features, and other data (Figure 1). The SV display is unaffected by outside weather and environmental conditions (*e.g.*, fog, clouds, or dust) and thus, provides a clear day view regardless of the available outside visibility and can be complemented by real-time enhanced vision (EV) sensors (Prinzel & Kramer, 2006).

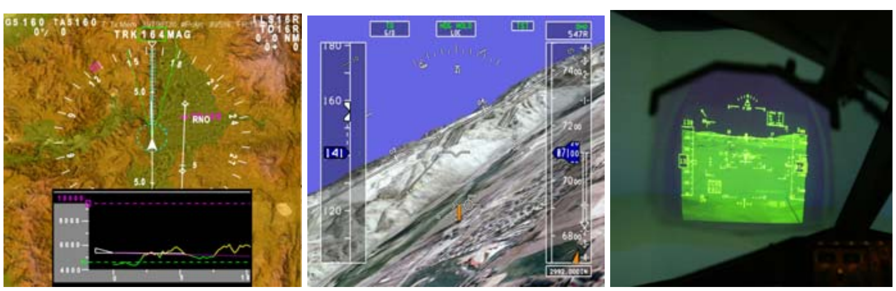

Figure 1. Commercial Aircraft Applications of NASA Synthetic Vision Display Technologies

Past research has demonstrated the substantial potential of synthetic and enhanced vision (SV/EV) for aviation (*e.g.*, Prinzel & Wickens, 2009a; 2009b). These augmented visual-based technologies have been shown to significantly enhance situation awareness, reduce workload, enhance aviation safety (*e.g.*, reduce propensity for controlled flight -into-terrain accidents and incidents), and promote flight path control precision. The issues that drove the design and development of synthetic and enhanced vision have commonalities to other application domains; most notably, during entry, descent, and landing on the moon and other planetary surfaces.

Altair Space Vehicle Synthetic Vision System

The Apollo lunar landings were an extraordinary achievement, requiring highly trained and skilled pilots. These astronauts were selected and trained to navigate a new vehicle in an unknown environment and adapt in the face of numerous potential failures and uncertain conditions with only basic flight instrumentation consisting mainly of "electro-mechanical" gauges (Figure 2). The lunar landing task relied on the pilots (equipped with large forward-facing windows and using operational flight profiles that allowed the pilot to see the landing zone for extended periods of time) to perform a visual, manual landing approach or to designate, and fly to, a new landing area if the original landing site was not suitable. The Apollo Lunar Module windows provided almost 70 degrees nose-down visibility.

Though there is no weather on the moon, thrusters can create a dust cloud that can significantly reduce visibility during a critical phase of the flight. Further, sun angles can create visually powerful shadow effects which may cause losses of depth cues, translational velocities, and landing zone awareness for the flight crew. The importance of pilot visibility was not only emphasized by trajectory design and window definition, but also by conducting the Apollo landing task only at specific times and locations to provide optimal sun light on the landing site. The mission was designed around lighting and shadow conditions that would provide optimal depth perception. These optimal lighting opportunities typically lasted about a week. If the opportunity was missed, the next opportunity to land would not be for another month.

Preliminary concepts for the Altair Lunar Lander (Figure 2), in contrast, provide significantly less external visibility for the astronauts. The Altair design will be significantly larger than Apollo and the size of the windows and their location may be severely constrained and non-optimal for pilot visibility. Mission requirements for fuel-optimized trajectories to polar regions for maximum scientific benefit further compound this problem. As envisioned, future space operations will require frequent trips to less than ideally lighted lunar surface locations (*e.g.*, lunar south pole), emphasizing the importance of providing technological capabilities for unfettered moon surface landings.

Synthetic vision may provide technological capability to enable such future lunar operations. With SV, the designer controls the computer-generated scene lighting, terrain coloring, and virtual camera angles. Visual cues for the landing site in the SV are independent of sun-angle. In addition, important vehicle state information such as forward and down velocities, altitude, and fuel remaining can be overlaid directly onto the terrain display to significantly ease pilot interpretation of the data and enhance situation awareness. Another advantage for using SV enhanced displays is that advanced precision guidance can be intuitively integrated into SV displays. With the US Space Exploration Policy goal of returning to the moon, frequent missions to the moon will require precise landing of vehicles (possibly within 10 meters accuracy). Several habitat modules, power generators, storage and surface mobility units are currently envisioned. Therefore, the landing task will involve not only landing on suitable terrain but avoidance of man-made obstacles and approach procedures to avoid over-flight and potential contamination. SV can be complemented by EV, such as a Forward-Looking-Infrared (FLIR) or Light Detection and Ranging (LIDAR), to provide both a database and real-time sensor representation of the lunar terrain surface, man-made objects and obstacles, and hazards (*e.g.*, boulders, craters).

Figure 2. Apollo Lunar Module and Altair Conceptual Flight Deck

Flight Deck Design Development

Research is being conducted at the NASA Langley Research Center to evaluate "aeronautics-domain" technologies and expertise which might benefit the Altair mission. To achieve this goal, preliminary flight deck design concepts have been prototyped and piloted evaluations have begun to establish data which can be used for informed decision-making in the Altair design process. This research is on-going – focusing principally on SV/EV technologies first – and these Lunar Lander flight deck concepts and potential technology applications continue to evolve.

Tactical Displays

Tactical displays are crucial for guidance and vehicle state information to aid the pilot in immediate navigation. SV and EV (Figure 5) tactical display concepts were evaluated using a head-up and/or head-down display, primary flight display (PFD), and ego-centric perspective display (Figures 3-5). Research to develop and optimize these display concepts is on-going and is continually being modified from the examples shown here. For instance, the first challenge for the Lunar Lander application is the extreme attitude variations during the approach and the critical role of vehicle attitude on deceleration and precision landing. Display concepts with a velocity-vector centered display concept were initially drafted but were discarded and replaced with attitude-centered concepts. The velocity vector display was difficult to interpret on approach and, especially near hover, exhibited a potential loss of spatial awareness, energy awareness, and display functionality. To date, a standard "eight-ball" is assumed as the head-down primary flight reference display to ensure uncluttered guidance and full spatial reference information. The conformal nature of the SV/EV information on the HUD (Figure 3) – even though attitude-referenced - provides critical head-out information especially useful during the final approach and hover transition maneuvers. Automatic transition of HUD imagery from SV to EV is used for optimal performance.

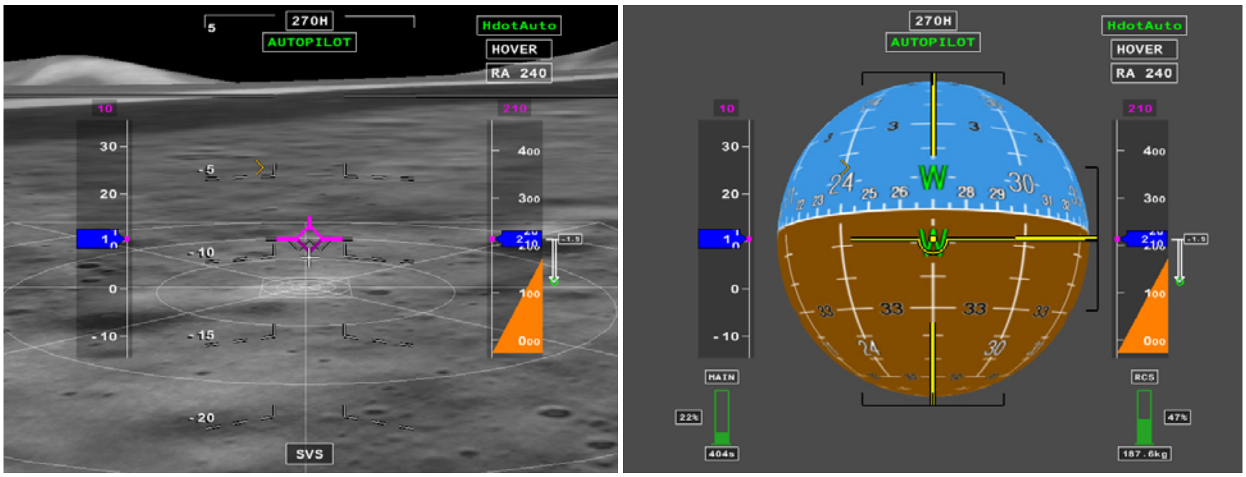

Figure 3. HUD (shown with SV) and Primary Attitude Flight Display

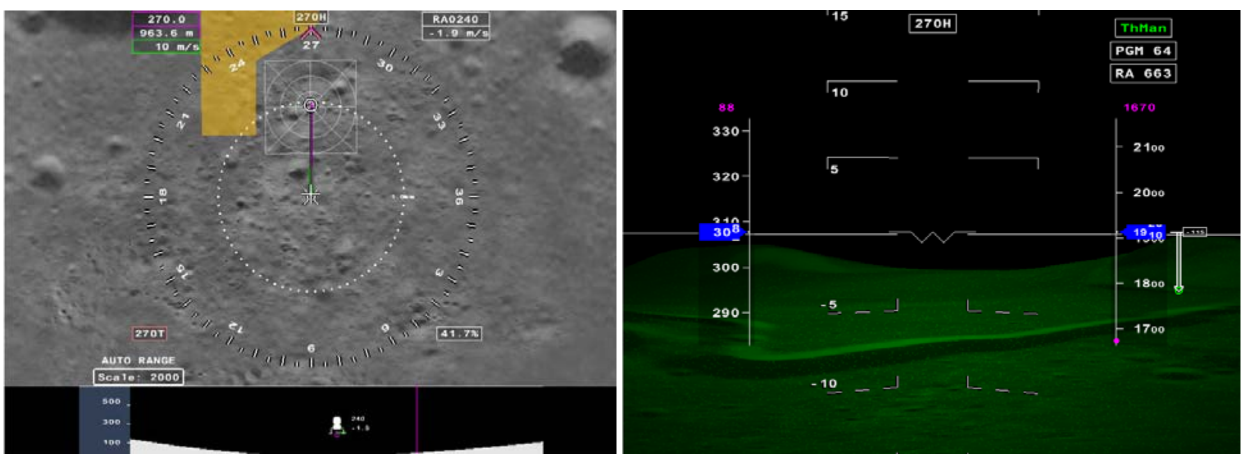

Figure 4. Navigation Display and HUD (shown with EV)

Two companion displays to the PFD and HUD appear to be ideal for introducing valuable SV/EV information for the Lunar Landing mission – the Auxiliary Display (AD) and Head-Worn Display (HWD). The AD (Figure 5, Left) provides ego-centric SV/EV information with a pilot-controllable reference frame. Attitude-reference, velocity vector-reference, or slewable views are provided. By using the AD and its variable viewpoint references, critical terrain and obstacle awareness is provided on a head-down display during the approach phase without the potential loss of spatial awareness or critical guidance information. The PFD is not compromised to accommodate the introduction of SV/EV and the attitude extremes of the planetary descent. Critical SV/EV information is provided by the AD with selected (*i.e.*, minimal) symbology to provide visual momentum between the AD and PFD and other displays. Symbology tailoring and control features are still being defined for the AD. The other important display is a head-tracker HWD. The HWD promises conformal, unlimited field-of-regard information. The formats for SV/EV on HWD displays are now being developed.

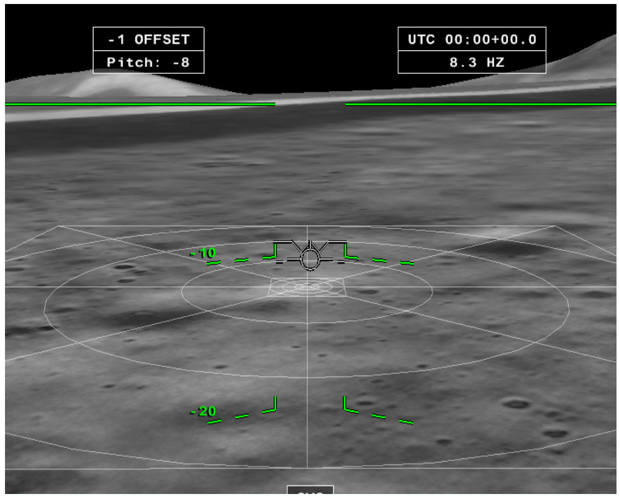

Figure 5. Ego- Centric Auxiliary Displays

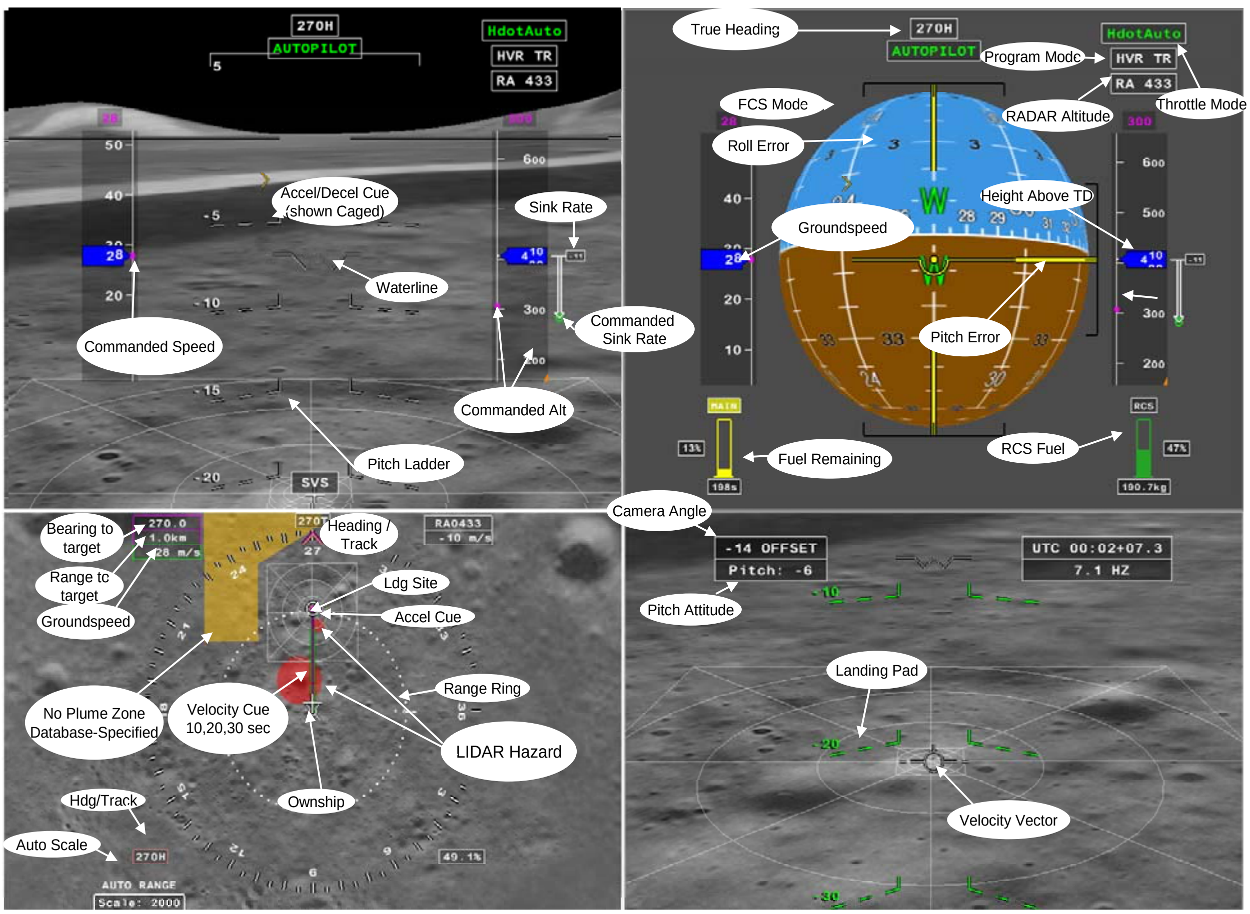

Figure 6. Select Symbology Elements for HUD (Upper Left), PFD(Upper Right), ND (Lower Left) and AD (Lower Right)

Navigation Display.

Initial navigation display (ND) concepts are also being developed using the “aviation-domain” as a point of departure in our investigations. In Figure 4, a simple two-dimensional, top down view with own-ship position located at the center of the display is shown. Synthetic lunar terrain is layered under the symbology. A touchdown zone is drawn centered on the designated touchdown site with a pilot-controllable range selection (500 meters is shown). The navigational display can be oriented track-up or heading-up as desired by the pilot. A vertical situation display shows a companion vertical profile of the lunar terrain surface, vehicle trajectory, and longitudinal and vertical rates (shown in Figure 4). Conformal overlay of critical task information, such as inhabited "no-plume" areas, hazardous landing areas, and critical descent abort areas are indicated by various symbology elements.

Figure 6 (lower right-half quadrant) presents the lunar navigation display symbology which is modeled after modern aircraft displays with the exception of the velocity vector and guidance information, critical to the Lunar Landing task.. During the initial part of the approach, a zero horizontal velocity symbol (white circle) is used to indicate the point where the vehicle's horizontal velocity will reach zero, based on its current lateral and longitudinal accelerations. This symbology provides a rough, first-order awareness of and verification for the pitch and thrust guidance law (computed by the guidance, navigation, and control system) by use of conformal symbology. The display concept is the subject of current research to refine the symbology to enhance the utility of display for navigation and guidance precision to desired touchdown location during the lunar approach. The symbology is being modified to include tailored hover symbology to show ground track velocities and an acceleration/guidance cue, similar to successful helicopter and Vertical/Short Take-Off and Landing (V/STOL) vehicle programs (*e.g.*, Schroeder and Merrick, 1992). Work is also progressing toward the use of exo-centric display concepts using SV/EV information as well as guidance data. The display concepts and symbology descriptions are shown in Figure 6.

Research Evaluations

Aviation research associated with SV/EV has demonstrated that these intuitive displays enhance situation awareness and detection and avoidance of hazardous terrain in high workload situations. To begin building a research database for Lunar Landing, these hypotheses were tested. The landing phase was identified by Neil Armstrong as being the most difficult part of Apollo 11 and, therefore, research has focused on the descent stage to landing. The Apollo 15 landing site was chosen for study because of the interesting terrain features and the availability of higher resolution lunar terrain data for this landing site.

Off-Nominal Testing

Eight participants were asked to fly 20 approaches to the Apollo 15 landing site with four display concepts (SV only; EV only (FLIR + LIDAR); baseline; SV + EV) which were factorially ordered and randomly presented to the pilots. The pilots were selected on the basis of having both fixed-wing commercial aircraft and V/STOL or helicopter flying experience which reflected the necessary piloting task skills. The scenarios required the pilots to either: (a) monitor the autopilot beginning at 170km from landing site to pitch-over maneuver (at 25km range) to clear mountainous terrain (Mt. Hadley); or, (b) monitor the autopilot from 15km to a hover transition point at 50m height-above-touchdown wherein the autopilot transitioned the lateral/horizontal position task to manual control (vertical sink rate was controlled by autopilot) for descent to the lunar surface. Each of these trials were flown with either: (a) an Apollo-like visibility condition which presented a larger out-the-window view (large field-of-view); or, (b) Altair-like visibility condition which presented a smaller field-of-view.

During the 20 experimental trials, six off-nominal situations were unknowingly presented to the pilots (3 off-nominal conditions X 2 visibility conditions): (a) guidance failure during landing, (b) guidance failure on initial approach, and (c) navigation failure during landing combined with either (a) low visibility condition or (b) high visibility condition. The guidance failures led the vehicle on a trajectory to a touchdown point on a hazardous terrain location. The navigation failure (a more difficult failure to detect) resulted from a poor navigation solution in which the vehicle calculated its position incorrectly. The failures were detectable by the pilot by either recognizing terrain cues (*e.g.*, velocity vector tracking toward hazardous terrain), symbology dissociations, or heading/track errors (Figure 7). Both synthetic vision and enhanced vision were correctly shown if present on the display condition for that trial. The navigation failure, however, resulted from erroneous vehicle data. Therefore, during this off-nominal condition, the synthetic vision was in error because it is a database-derived terrain representation based on the vehicle's erroneous navigation solution. The EV and EV+SV conditions, however, correctly showed the terrain because the EV (EV and LIDAR operative at 340m and 1000m, respectively in this experiment) was sensor-derived and independent of navigation solution

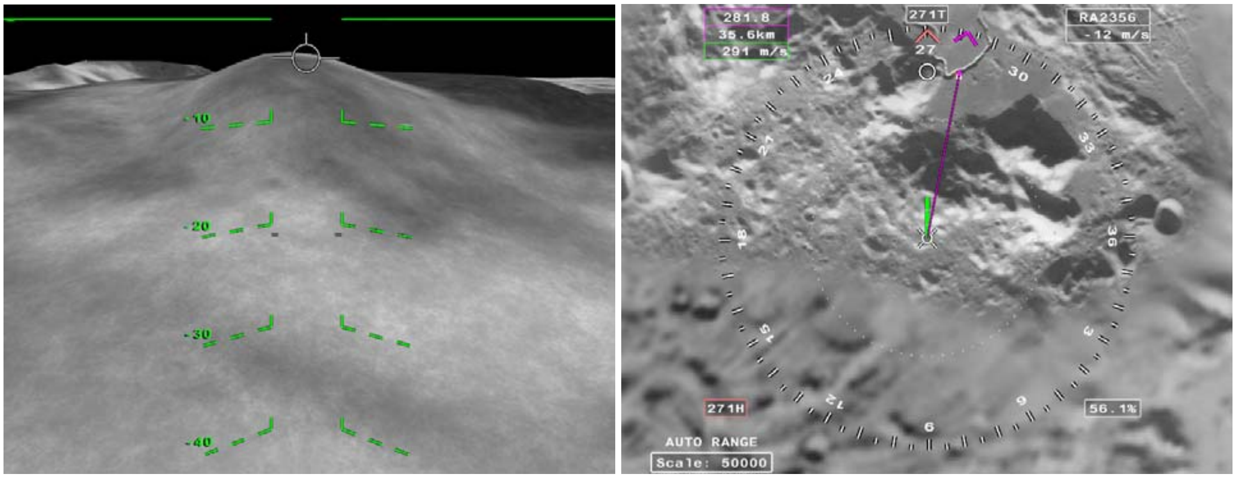

Figure 7. Example Guidance Failure on Approach 36 km from Landing Site (shown with SV)

The results evinced that the EV and EV+SV displays were significantly better for detection of navigation failures. All participants who experienced a navigation failure with either the SV-only or baseline display conditions either failed to recognize the failure or re-designated but landed on another hazard. None of the pilots with the EV or EV+SV display concepts failed to recognize the failures and all were able to re-designate and land safely and accurately (M = 0.1m from designated landing touchdown point). Paired comparison (SA-SWORD; Vidulich & Hughes, 1991) and Situation Awareness Rating Technique (SART; Taylor, 1990) results demonstrated that pilots significantly preferred the SV+EV display concept for both situation awareness and mental workload compared to the other three display conditions, [$F(3,32) = 36.158$, $p < 0.001$ for SA-SWORD; $F(3, 48) = 3.262$, p_$< .05$ for SART]. Pilots also reported better awareness of lunar surface and hazards with SV+EV display during navigation failure, ($F(3,16) = 8.080$, $p < .01$), and landing guidance failure, $F(3,16) = 5.140$, $p < .01$. For the off-nominal approach guidance failure, the baseline display concepts was rated significantly poorer for detection of hazards and awareness of lunar surface, $F(3, 16) = 6.78$, $p <.01$. These results support the requirement of incorporating both SV and EV for Lunar Landing, matching expectations based on aviation-domain research with these technologies. These data also emphasize the importance of having a real-time database or navigation integrity monitoring system, real-time sensors, or other suitable verification method to complement SV.

Future Directions

NASA research on SV and EV systems for space vehicles leverages on aeronautics research, which has repeatedly demonstrated both safety and operational benefits of the technologies. Although there are many commonalities between aeronautics and space applications, there remain numerous areas of research and opportunities to further refine and optimize the concepts for the Altair Lunar Lander. Future areas of research include further off-nominal testing, improved symbology, accuracy assessment for lunar terrain databases, fusion of database and external sensors, mission rehearsal visualization, and unlimited field-of-regard HWD concepts.

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