Handling Qualities Assessment of Manual Lunar Landing with Display Augmentation

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Abstract—**Research and development is being conducted to support data-driven design decisions for manual control and human involvement in the lunar landing task under the Human Landing System (HLS) program within the Artemis campaign. A human-in-the-loop simulator evaluation of the manual control of a lunar landing vehicle in the final approach and landing phase was conducted at NASA Langley Research Center in the Lunar Flight Deck simulator using the Altair Design and Analysis Cycle (DAC)-2 government reference vehicle. The objective was to perform a direct comparison of control law types with display aiding for various rotational control powers being considered under HLS. Ten subjects (four NASA test pilots and six current pilot astronauts) provided Cooper-Harper ratings, NASA Task Load Index workload ratings, and qualitative comments. The piloting task was to assume manual control of the vehicle (including vertical descent rate) at 150 m above the landing zone, fly to a redesignated landing target (which was up to 75 m radially from the center of the landing zone) and to touch down within a position accuracy of 5m. The data showed that the display augmentation in the form of a "hover cue" significantly improved the pilot's ability to control translation and create satisfactory handling qualities for otherwise sluggish configurations; however, the investigation also showed that display augmentation is not a panacea. Handling qualities problems, including pilot-induced oscillations, and higher workload for the lowest control powers can still be evident.**

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1. INTRODUCTION

The Artemis campaign is the first step in the next era of human space exploration where NASA, in collaboration with commercial and international partners, will establish a sustainable presence on the Moon to prepare for missions to Mars. Artemis will land the first woman and person of color on the Moon.

The return of humans to the moon will be achieved by a combination of automatic and manual control [1], where manual control provides "the crew the ability to take control of the spacecraft, especially during critical phases, if there are issues with the automated system (failures or unexpected performance) to (1) protect crew survivability and (2) enable mission success [1]."

Research and development is being conducted to support data-driven design decisions for manual control and human involvement in the lunar landing task under the Human Landing System (HLS) program within the Artemis campaign. In support of the Crewed HLS Interfaces for Piloting (CHIP) working group under the Crew Compartment Office, a handling qualities (HQ) evaluation of control law and display concepts for the manual control of a lunar landing vehicle in the final approach and landing phase was conducted. These data complement existing data for Spacecraft Handling Qualities (SHaQ) and fill a gap in the existing lunar landing handling qualities criteria.

This human-in-the-loop (HITL) SHaQ test was conducted using the NASA Langley Research Center (LaRC) Lunar Flight Deck (LFD) simulator in March-April of 2022. Data from this test will support NASA and its HLS partners in manual control design insight and trade-space options for cost savings and efficiency.

Background

Handling Qualities (HQs) are defined as those qualities or characteristics of a vehicle (e.g., spacecraft) that govern the ease and precision with which a pilot is able to perform the tasks required in support of a vehicle / spacecraft role [2].

HQ research, as a precursor to Apollo, developed the Cheatham-Hackler criteria [3,4] for lunar landing vehicles (see Figure 1, reproduction of Figure 14 found in [4]) using the Cooper handling qualities rating scale [5]. This criteria maps out areas of acceptable HQs for combinations of time-to-reach maximum rate command (i.e., time constant) versus maximum rate command. The data essentially maps out the required attitude control power (e.g., rotational acceleration (deg/sec^2)) as typically provided by a Reaction Control System (RCS) or engine gimballing effectiveness for a given vehicle design (i.e., mass and inertia). For the Apollo Lunar Module (LM), the maximum rate command available to the pilot was 20 deg/sec. The operating points for two-thruster operation was at a time to reach a maximum rate command of ~4.7 seconds which was just within the satisfactory HQ boundary (see "2 thrusters" data point in Figure 1), while the four-thruster operation with a time constant of ~2.2 seconds was well within the satisfactory HQ region.

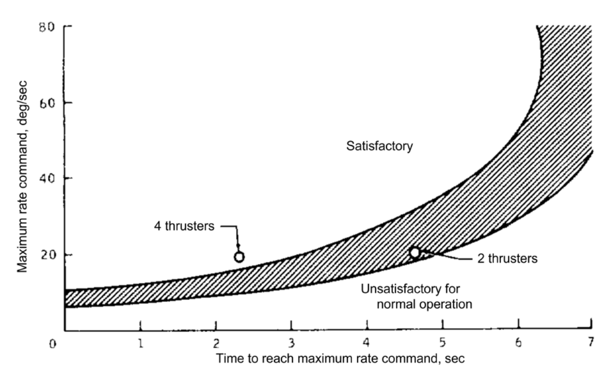

Figure 1. Cheatham-Hackler Approach Criteria [Credit: Figure 14 from NASA TN D-4131]

Under the NASA Constellation program, the Cheatham-Hackler criteria was re-validated [6] using the Cooper-Harper handling qualities rating scale [7]. This criteria is limited as it was developed principally with Rate-Command Attitude Hold (RCAH) control laws for vehicle attitude control.

The Constellation SHaQ evaluations also showed that lower control powers (CPs) were acceptable if new control law types and new display capabilities were employed [6,8]. In particular, better HQs were shown for the same CP, if a Translational Rate Command, Position Hold or Attitude Command, Velocity Hold (ACVH) control law was used instead of RCAH. The consequence is that good manual control can be attained using smaller RCS effectors than that are required for an RCAH control law, saving significant mass and propellent. The disadvantage to these new control law types is that the added control law complexity results in higher software and sensor costs in development and additional pilot training.

In the comparison of RCAH and ACVH control laws [6], the pilots were given explicit pitch and roll attitude guidance commands shown on the Primary Flight Display (PFD). By following the "fly-to" guidance, the pilot flies a precise trajectory to the planned landing zone.

Conversely, in a different experiment, the handling characteristics of RCAH control laws were evaluated using a hover cue in comparison to the explicit pitch/roll attitude directors [9]. The hover cue is a "fly-to" symbology element shown on the Navigation Display (ND) where the positioning and dynamics of the cue provide manual control guidance for the pilot to smoothly approach a desired landing position and achieve zero horizontal velocity (i.e., a hover condition) [9]. The pilot's task is to use the pitch and roll inceptor to place the hover cue and hold its position over the desired landing site.

The comparison of the hover cue versus explicit pitch/roll flight director guidance showed that the hover cue was significantly preferred, resulting in better performance and lower pilot workload [9]. The hover cue provided more time for the pilot to attend to other attentional demands because, unlike the attitude guidance, it was more intuitive as to the outcome of the commands (i.e., the hover cue explicitly shows the projected hover point) so it required significantly less attention. Level 1 handling qualities were shown for a much larger range of CPs and the landing target redesignation task was simplified and much more amenable with the hover cue.

2. TEST DESCRIPTION

A HITL simulation was conducted to explore the control and display interactions on the handling qualities of a lunar lander vehicle. This work builds from the previous work in this area as control and display interactions strongly impact several design considerations in a lunar lander design.

First, the previous work comparing RCAH and ACVH control laws were made using explicit pitch and roll attitude guidance commands shown on the PFD [6,8] and evaluated only using shallow 15-degree glideslope trajectories to the landing zone. This trajectory angle was flown for the initial Apollo LM missions, but the later so-called "J" missions used trajectories approaching 25 degrees glideslope. Future Artemis HLS vehicles may find it advantageous to use a higher glideslope approach trajectory. Second, the previous evaluations comparing the hover cue display augmentation versus explicit pitch/roll flight director guidance only used the RCAH control law [9], but it did evaluate variations in glideslope trajectories as high as 45 deg.

The objective of this HITL test was to perform a direct comparison of control law types with display aiding in the form of a hover cue for rotational CPs being considered under HLS. The variables tested were CP (1.1, 2.9, or 4.3 deg/sec^2)

and control law (RCAH or ACVH). A 30-degree glideslope trajectory to the landing zone was used for all runs. The HQ data collected from this simulation experiment extends Apollo and Constellation HQs work and will help inform the design of next generation lunar landers such as the Artemis HLS vehicle.

This test provided a direct comparison of control law handling qualities with both using the same display guidance element (i.e., the hover cue) a simpler, yet more adaptable form of flight guidance for precision lunar landings. If comparable handling qualities can be attained with the RCAH control laws, in comparison to the ACVH control laws, the simple RCAH control laws can be used – saving software development and pilot training costs – at the modest expense of a display augmentation.

In the following sections, the equipment configured for this ground simulation test is described.

Simulator

The HITL research was conducted using the LFD simulator (Figure 2). The simulator is a generic, rapidly-reconfigurable stand-up crew station with a parabolic out-the-window (OTW) presentation.

The OTW scene is projected on a 3.25-meter spherical projection screen using four edge-blended projectors creating a 135° horizontal x 67.5° vertical Field-of-View (FOV). The screen and projection system are biased to provide 22.5 deg up and 45.0 deg down angle viewing from the design eye reference point (DERP). A window "cut-out" is used so the pilot must move their head to view the entire OTW area. The multiple image generators and projectors are warped and blended to uniformly provide ~30 pixels per degree resolution across the field-of-view, referenced to the DERP.

Aural call-outs of vehicle height above the ground or above the landing target elevation are provided. The aural call-outs above 50 m height above the field elevation (AFL, i.e., the landing target) are in AFL, but change from AFL to height above ground level (AGL or radar altitude, RA) below 50 m AFL.

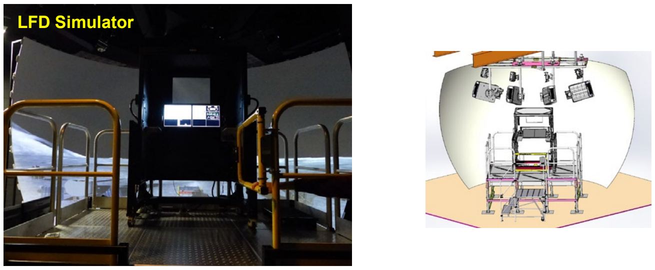

Figure 2. Lunar Flight Deck (LFD) simulator

The simulator is equipped with an Orion Rotational Hand Controller (RHC) on the right-hand side and a Translational Hand Controller (THC) on the left-hand side of the crew station.

The simulator is equipped with two head-down panels mounted adjacent to each other (referred to as the left-side head-down panel and the right-side head-down panel) and an Electronic Flight Bag (EFB) which is mounted to the right of the window.

The arrangement of the flight displays and controllers are shown in Figure 3 and Figure 4.

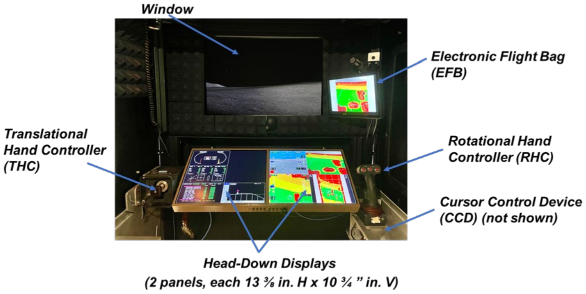

Figure 3. LFD displays and control inceptors

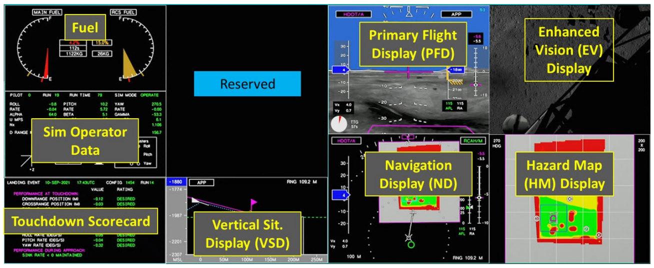

Figure 4. ***Displays on the left-side and right-side head-down panels***

Simulator Database

The approach and landing task was conducted to a landing area adjacent to the Apollo 15 landing site. This location was chosen because of the availability of relatively high-resolution terrain data and imagery.

The OTW lunar database was created using lunar topology and imagery data collected by the Lunar Reconnaissance Orbiter project. The OTW presentation for the planned landing zone used a spherical lunar database of approximately 2 meters per elevation post spacings, draped with 50 cm per pixel imagery. For distant scenery, the lunar database used reduced resolutions. For the physics-based Light Detection and Ranging (LIDAR) simulation, the 2 meter per elevation post spacings were up-sampled to 0.1 m and smoothed using a cubic sampling method. Boulders of various sizes were inserted experimentally into the OTW and corresponding LIDAR simulation using models.

Subsequent testing will be performed at Lunar South pole areas as sufficient data becomes available.

For this test, the sun elevation was 21.5 degrees, and the sun azimuth was 99.2 degrees (i.e., 9.2 degrees off from directly behind the vehicle on approach).

Simulator Cockpit Displays

The right-side head-down display panel was used as the primary display for experimental testing.

The right-hand panel (Figure 5) showed four equal-sized display formats: a PFD (upper left) which included a Synthetic View (SV) depiction of the terrain, an Enhanced Vision (EV) display (upper right), a Hazard Map (HM) display (lower right), and a ND (lower left).

The PFD pitch and roll flight director needles were shown during automatic flight, but they were removed once the pilot assumed manual control.

The EV display showed either external camera views or LIDAR-based EV views for this test.

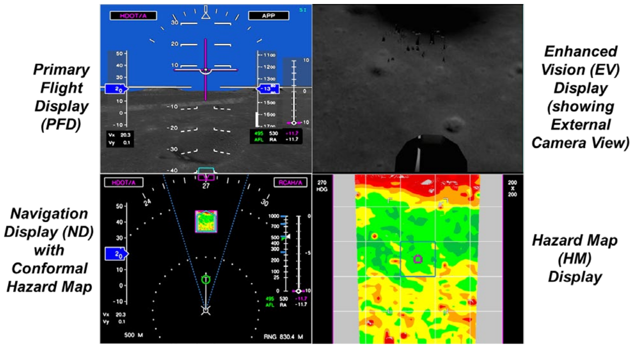

Figure 5. Head-down display layout showing ND with conformal Hazard Map

There were two camera views available. One camera was located in the front, middle of the vehicle, pitched down at 60 degrees with a field-of-view of 30 degrees Vertical (x 37 deg Horizontal) to provide more look-down visibility, augmenting the window view. The second camera was pointed straight down the vehicle, with a field-of-view of 70 degrees Vertical and 82.4 degrees Horizontal, for awareness during the vertical descent and landing phase. It was located 6.28 m up from the bottom of the lander "feet", 3.62 m forward of the center, and 3.62 m to the left of the center.

The LIDAR views showed the digital elevation models (DEMs) which were created from the simulated LIDAR point-cloud data, where the LIDAR was continuously pointing at the assigned landing target. The LIDAR model was a flash-type sensor of 512 x 512 pixels with a 5.5 deg x 5.5 deg field-of-view.

The HM display showed the top-down view of the hazard analysis of the LIDAR DEM, following [10]. The HM displayed the entire landing zone (200 m x 200 m) with color-coding of the terrain hazard risk using assumed values for allowable terrain slope, roughness, and smoothness.

The ND always showed a top-down view of the ownship with automatically changing range scaling to keep the landing target in view (Figure 6). The landing zone (200x200m square outline) and landing target (magenta "doghouse" outline) were conformally drawn and the ND included SV database imagery and a conformal hazard map, shown inside the landing zone symbol. (The term conformal is used herein to mean that the map and symbol set are all aligned and scaled together.)

The hover cue was part of an integrated symbology set shown on the ND (see Figure 6). (The hover cue description is given in [9].)

- Ownship Symbol: This symbol corresponds to the vehicle position; it was fixed on the display. A quartering position was used as shown in Figure 6 to emphasize information in front of the vehicle.

- Velocity Vector: The velocity vector provides a graphical depiction of the vehicle's horizontal velocity, changing in length and direction.

- Underlay Map and / or conformal landing zone/landing target symbol: The hover cue is referenced with respect to a conformal underlay map, conformal symbolic landing target/landing zone symbol (i.e., "doghouse" outline), or both as shown in Figure 6.

- Hover Cue: The hover cue (shown as green circle in Figure 6) is a graphical representation of where the vehicle will reach a zero translational velocity with respect to the conformal map/landing target; in essence, a continuously computed hover point. The pilot uses the pitch and roll inceptors to place the hover cue and actively hold its position over the desired conformal map point/landing target (i.e., "put the ball on the landing target").

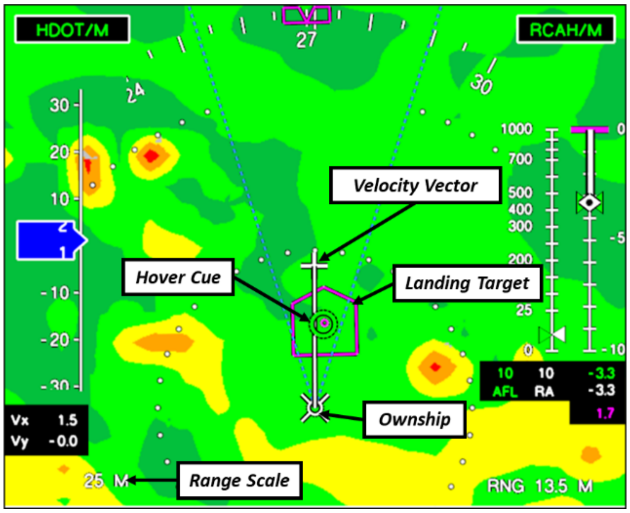

Figure 6. Hover cue symbology on Navigation Display with Hazard Map

The hover cue leads the velocity vector – that is, the tip of the velocity vector (i.e., the "plus" sign) will follow the hover cue symbol. When the hover cue and the "plus" sign overlay, the ownship is holding a constant velocity.

The ND range scale was automatically controlled to keep the landing target on the ND. When the ND range rescaled, the other conformal symbology rescaled accordingly.

Vehicle

A simulation model was built based on the Altair vehicle Design and Analysis Cycle (DAC)-2 configuration. This vehicle was used since it was the basis for the Constellation SHaQ work. The simulation model was built using object-oriented programming techniques within the Langley Standard Realtime Simulation in C++ (LaSRS++) software framework.

The vehicle model was composed of two interconnected stages: ascent and descent. The descent stage contained separate mass models for the main engine fuel, RCS fuel, and the airlock. Force models were provided for the main engine and each of the sixteen RCS engines. For simplicity, the throttle-able, thrust output of the main engine force model (18,627 lbf maximum) was placed on the lateral and horizontal axes of the stacked center-of-mass. Active gimbaling of the main engine was provided to trim the thrust vector through the center of mass (CM). All forces and moments were applied to the stacked vehicle's CM. Ascent stage modeling mirrors a similar configuration as the descent stage models but are used for ascent to orbit tasks and are therefore not detailed here.

The initial mass and inertia characteristics were approximately as follows:

Mass:	25,408 kg [1,741 slug]
Ixx:	253,055 kg-m^2 [186,644 slug-ft^2]
Iyy:	238,456 kg-m^2 [175,876 slug-ft^2]
Izz:	148,120 kg-m^2 [109,248 slug-ft^2]

The pilot, as defined by the DERP, was located 11.05 m above the extended landing gear position. Each gear was placed 4.87 meters offset in both x/y laterally from the centerline (i.e., 6.9 meters in distance from the center of the vehicle).

Four RCS jets were placed in a ring around the descent stage using an orthogonal quadrant of four individual thrusters for attitude control. The RCS jets were located at a 4.32 m radial from the centerline of the vehicle (i.e., the moment arm), approximately 2.35 m below the DERP. The RCS thruster size was experimentally varied.

Unit force vectors for the thrusters were created and a simplified thruster mapping dedicated RCS thruster firings to each moment command, as described in [9]. Because of the simplified logic, when simultaneous pitch and roll inputs were commanded, the control authorities were effectively halved in each axis. More elaborate mappings to use more jet combinations were considered but rejected for simplicity of design.

The RCS jet size was experimentally varied to create various angular acceleration control authorities, as shown in Table 1.

Table 1. RCS jet size and corresponding control power

RCS Jet Size	*Control Power*
391 N [88 lbf]	1.1 deg/sec^2
1036 N [233 lbf]	2.9 deg/sec^2
1535 N [345 lbf]	4.3 deg/sec^2

Inceptors

The RHC inceptor is an Orion-type controller. The mechanical characteristics of the RHC provide approximately ±9.0 deg total deflection in roll and ±9.0 deg total deflection in pitch. The roll rotation pivot point is approximately 12.87 cm and the pitch rotation pivot point is 3.8 cm below the controller reference point (a point just below the RHC trigger). The force characteristics are shown in Table 2.

Table 2. RHC force characteristics

Controller Direction	*Breakout Force*	*Max Force*
Roll Left	6.23 N [1.4 lb]	15.12 N [3.4 lb]
Roll Right	6.23 N [1.4 lb]	13.79 N [3.1 lb]
Pitch Forward	8.01 N [1.8 lb]	32.47 N [7.3 lb]
Pitch Back	12.01 N [2.7 lb]	32.47 N [7.3 lb]

A deadband function using 5% of the full-throw was applied to all three RHC deflections and scaled to create a normalized deflection value ranging ±1.0.

The pitch and roll normalized RHC deflection values (u) were parabolically shaped to create normalized pitch and roll rate or attitude commands (y) using the equation:

$$y = Ku|u| + (1 - K)u \quad where\ K = 0.9$$

This parabolic shaping mimics that used in Apollo.

The shaped pitch and roll inputs were multiplied by 12 deg/sec to create the pilot-commanded pitch and roll rate values to the RCAH control law. The normalized commands (y) were multiplied by 20 deg to form the pilot-commanded pitch and roll attitude values to the ACVH control law.

The linear yaw input was multiplied by 12 deg/sec to create the pilot-commanded yaw rate values in both the RCAH and ACVH control laws.

In RCAH, the scaled and shaped pitch and roll control inceptor inputs were tested to see if either met attitude latch conditions (e.g., inside detent). An attitude latching occurred in an axis when the appropriate inceptor was inside detent in that axis. The outputs of this test block were angular rate errors (the difference between actual and command rates) and commanded attitude (which tracked actual attitude in each axis if the inceptor was out of detent, or the latched attitude, if the inceptor was in detent). The RCAH used a phase-plane switching controller, characterized in [9], to command pitch, roll, and yaw RCS firings. The minimum coast rate limit for the phase-plane controller was 10 deg/sec in pitch and roll and 5 deg/s in yaw body rates. The angular deadband was 0.5 deg.

In ACVH, the scaled and shaped pitch and roll control inceptor inputs proportionally command pitch or roll attitude. When the RHC is released (or returns inside a small deadband) in either axis, the current horizontal velocity in that axis is latched and the attitude returns to level to maintain that velocity.

Both ACVH and RCAH control laws included a Hover Hold/ Incremental Position Control (IPC) mode. This capability was included because: a) testing has shown that IPC provides a significant workload reduction for the vertical descent task; and, b) IPC is an integral part of the ACVH control law and its inclusion in RCAH created a one-to-one comparison.

Hover Hold/IPC was armed in both RCAH and ACVH when the pilot pressed a button on the top of the THC. Hover Hold was automatically activated when the ground speed was less than 1.5 m/s and IPC was automatically activated when ground speed was less than 0.5 m/s, following the design concept employed in [11]. Once activated, the RHC no longer controlled the vehicle pitch/roll attitude (unless the pilot hit the IPC button again to get out of IPC). IPC moding was visually annunciated and crosshairs were shown on the ND near the ownship symbol (see Figure 7). Vehicle translational control in IPC was through THC inputs. THC inputs of left/right and in/out, changed the vehicle position by 1 m left/right and downrange/uprange, respectively.

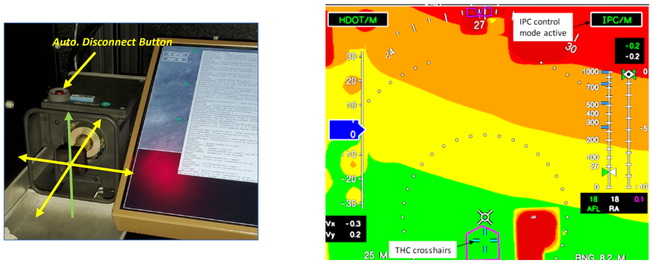

Figure 7. IPC mode

In both control laws, an autothrottle was mechanized to hold a pilot-commanded vertical descent rate (referred to as hdot).

THC up/down pilot inputs of the THC are converted into vertical descent rate (hdot) command increments. Each discrete THC input increments the value of hdot command according to this schedule: 1 m/s when more than 100 m AFL and 0.3 m/s when less than 100 m AFL.

The autothrottle used proportional and integral control to modulate a percentage of descent engine thrust. The integrator was limited if the thrust percent command was at a minimum or maximum. The throttle command was not limited and had full throttle authority from 0 to 100%. The engine throttle response rate was not limited.

Guidance

The approach phase for the lunar landing task was designed using a constant deceleration profile which allowed for a near-constant pitch (deck) angle, flight path angle and thrust-to-weight ratio. The guidance provided corrections to pitch angle, roll angle, and thrust level of the vehicle to correct for any deviations from the desired trajectory.

The approach was designed to achieve a hover approximately 30 m above a point 5 m uprange of the landing zone (i.e., the landing target), measured from the vehicle center of mass. The landing target for the guidance was the center of the 200m x 200m landing zone. A 30 deg trajectory to this hover point was used as the descent angle.

Landing Zone

The landing zone was a 200 m x 200 m area on the lip of the Pluton Crater (show outlined with red square in Figure 8).

In the landing zone, the terrain was augmented with the addition of boulder hazards to increase the visual density around the landing site. The boulders ranged from 0.1 meters in diameter to 9.9 meters in diameter.

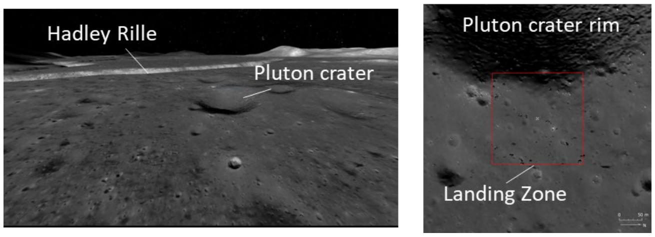

Figure 8. Landing site views – on approach (left picture) and from above (right picture)

Simulator Recording

Engineering unit (EU) data was recorded. All data was time-stamped for correlation and subsequent post-flight analysis. Engineering data was recorded at 100 Hz.

The video recordings of the head-down displays and OTW were recorded with time-code insertion for correlation.

Post-run, the pilot comments and rating scale responses were recorded using a hand-held digital audio recorder.

3. EXPERIMENT DESIGN

Evaluation Pilots

Ten Evaluation Pilots (EPs) flew this experiment, six current pilot astronauts (National and International) and four NASA test pilots. All subjects had graduated as pilots from military Test Pilot Schools and were experienced in aircraft handling qualities evaluations. Some had experience in rotary wing vehicles.

Test Conduct

The experiment duration (including training) was approximately 4 hours. The EP was given, at a minimum, a 10-minute break each hour and 60 minutes for lunch.

Before starting the experiment, the EP signed an informed consent, received both in-classroom and in-simulator cockpit briefings, and flew lunar approach and landing training runs.

Training

Classroom training included a briefing to explain the purpose of the test, the simulator and simulated vehicle characteristics, and controls. The EP was also briefed on expectations for the use of the Cooper-Harper scale [7] (i.e., definitions of desired and adequate performance standards) and the NASA Task Load Index (TLX) [12] being used for pilot workload assessment.

Following class-room training, each pilot flew both control laws with all variations in control powers and redesignations to proficiency in the LFD simulator.

Experiment Matrix

A full-factorial experiment matrix was planned with the independent variables of control law type (RCAH, ACVH) and CP (1.1, 2.9, 4.3 deg/sec^2). The CP levels spanned nominal Apollo RCS control power values down to those values that were considered for Altair and previously tested in [6] and [9].

The highest CP of 8.6 deg/sec^2 that was used in previous SHaQ work was considered but rejected for inclusion. The rationale is that this level of CP is excellent, yielding very good handling qualities, but is very unlikely to be an HLS option due to its expense in vehicle mass.

The experimental runs were blocked by control law type (i.e., three ACVH or three RCAH control laws configurations were run together with variations in control powers). The control law type block ordering was counter-balanced across the subjects (i.e., half the subjects started with RCAH and the other half started with ACVH). Within a control law type block, the runs were also blocked by CP (i.e., three sequential runs were flown for each control power). The ordering of CP blocks was randomized.

Crew Procedures

For each experiment run, the subject was told of the control law type.

Each run started at approximately 1000 m above the center of the landing zone using the following sequence of events:

- The simulation started with the vehicle under control of automation once the EP said they were ready.
- A constant deceleration profile with a 30 deg trajectory was flown with corrections by automation to pitch angle, roll angle, and thrust level of the vehicle for any deviations from the desired trajectory.
- The trajectory aimed toward a hover point 5 m uprange of the landing target in center of landing zone; however, at 150 m above the landing target, an automatic “redesignation” was introduced. The landing target was moved either 50 or 75 m radially from the center of the landing zone. Only downrange or cross-range or their combinations were used (i.e., no uprange redesignations were used). All landing targets were free of landing hazards. Simultaneously at 150m above the landing target, the automation was disengaged, and the pilot assumed manual control of flight path (including vertical descent rate) to fly to this new landing target.
- This redesignation serves two purposes: a) it provided a “stress test” for handling qualities assessment, and, b) it mimicked what might be an operational scenario wherein the pilot assumes manual control after a redesignation or manually redesignates.
- The EP used the THC and RHC and visual information OTW and head-down to fly the vehicle to the new landing target and perform a successful landing attempting to meet desired landing performance standards (Table 3).
- The EP was briefed that in addition to meeting the landing desired performance standards, they had to meet approach performance standards: a) maintain sink rate (i.e., hdot less than zero), b) have no pilot-induced oscillations (PIOs), and c) have no more than minimal overshoot of the landing target (crossrange/uprange/downrange) for desired task performance.
- The EP flew each configuration in the approach and landing task a minimum of three times, using 50 m offset for the first redesignation run and 75 m offset for the second and third runs. The 50 m offset run served as a training run for the configuration being

tested; and the two 75 m offset runs were used for pilot assessments of the configuration. After each approach, the landing "scorecard" was displayed so the EP had a quantified assessment of their landing performance. These data are measured at the vehicle center-of-mass once the lowest gear touched the terrain.

Table 3. Desired and adequate task performance standards

Parameter	*Desired Performance*	*Adequate Performance*
Range at Touchdown	< 3 m	< 5 m
Sink Rate	< 1.52 m/sec	< 2.13 m/sec
Forward/Side Velocity	< 0.61 m/sec	< 1.22 m/sec
Pitch/Roll Angle	< ± 3 deg	< ± 6 deg
Pitch/Roll Rate	< ± 3 deg/sec	< ± 6 deg/sec
Yaw Rate	< ± 1.0 deg/sec	< ± 1.5 deg/sec

At the completion of three runs, the EP provided a Cooper-Harper rating [7] (by verbalizing the rating scale logic tree), TLX workload ratings, and pilot commentary following a comment card. The comment card prompted the pilot to address specific items of interest in the experiment design and assign Likert ratings.

Perceived workload was measured using the NASA TLX rating scale [12]. There are six subscales of workload within NASA TLX: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Each subscale rating, except performance, is scored on a scale of 0 (low) to 100 (high). Performance is scored on a scale of 0 (good) to 100 (poor). Overall workload is calculated as the unweighted average of the ratings of the six subscales.

4. RESULTS

Handling Qualities Ratings

The Cooper-Harper scale and the pilot evaluation reflect the adequacy of the vehicle's handling qualities for the "selected task or required operation." For this HQ evaluation, the pilot's task was manual control of the lunar landing vehicle for safe touchdown at a *redesignated* landing target using a hover cue.

Individual pilot ratings (PRs) of HQs are shown using a bubble chart, in Figure 9, with the median for each test configuration indicated with a solid horizontal line. Note that all 10 EPs flew the three RCAH/CP configurations, but only 8 EPs flew the three ACVH/CP configurations. (Simulation set-up problems negated the ACVH experimental variation for 2 pilots.)

Figure 9 shows that the RCAH with hover cue exhibited mostly Level 1 HQ ratings (median PR < 3.5) for the 2.9 and 4.3 deg/sec^2 CPs albeit with a few Level 2 ratings. Desired performance was obtained in all cases.

The pilot ratings for the ACVH control laws at the 2.9 and 4.3 deg/sec^2 control powers were slightly worse compared to the RCAH control laws. The median rating for the 2.9 deg/sec^2 control power was borderline Level 1/Level 2 and the 4.3 deg/sec^2 control power was Level 2. The degradation in ratings from 2.9 to 4.3 deg/sec^2 with the ACVH control law is counter-intuitive in relation to the Cheatham-Hackler criterion. However, the pilot comments indicated that the hover cue for the higher control power was too sensitive. It increased the pilot workload and its characteristics warranted improvement. It is noted that the hover cue was designed to be "equal" across all control powers and not tailored. Simple filtering of the inceptor input could be used to ameliorate these undesirable tendencies

In some cases, the ACVH control law for the higher control powers exhibited only adequate performance. The ACVH control law requires constant stick pressure (using a spring-loaded RHC) for acceleration/deceleration. This characteristic caused higher workload compared to the RCAH control law especially, in the event of divided attention on the part of the pilot, where inadvertent or unintentional pilot inputs would induce disturbance in the vehicle trajectory and in the positioning of the hover cue.

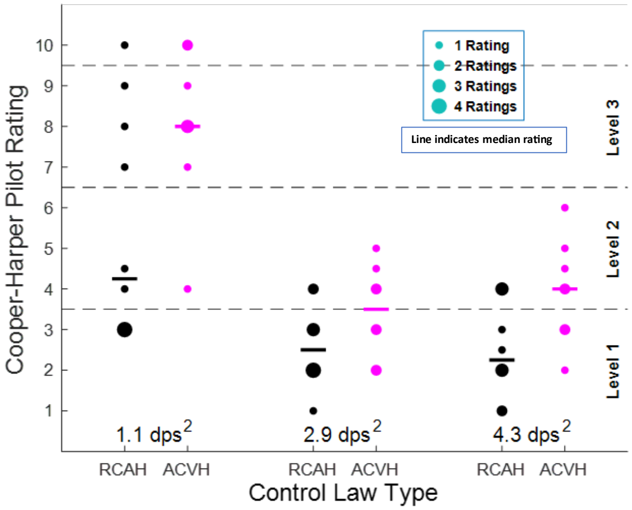

Figure 9. Cooper Harper Ratings

In comparison to previous work [9], the pilot comments supported the reduced workload afforded by the hover hold/ IPC mode. The mode virtually eliminated their requirement for control inputs for positioning in the vertical descent. Since the vehicle was stabilized and holding position without pilot input, when in IPC, it afforded the pilot time to scan OTW, the camera views, and LIDAR views to confirm the landing site was free of hazards.

The pilot rating data for the 1.1 deg/sec^2 control power exhibited classic "PIO cliff"-like effects. If an EP made too aggressive of an input with the lower CP during the manual redesignation task or inadvertently lost focus on the hover cue, they could find themselves in an overcontrol situation/ PIO resulting in Level 3 HQ ratings (PRs > 6.5).

On the other hand, if the pilot was "measured" in their control inputs, using predictive, smooth control inputs, and focused on the task, desired and adequate performance were obtainable.

For the RCAH control law, the pilots were more likely to avoid these cliff-like characteristics. Level 1 ratings were, in fact, assigned and the median rating was Level 2 (median rating of 4.25). However, Level 3 and PR=10 ratings were also demonstrated for this same configuration. These large rating differences are indicative of lurking HQ deficiencies. These characteristics are not desirable.

The ACVH control law with 1.1 deg/sec^2 control power also exhibited large "cliff-like" rating differences but more tended to be Level 3 in general, with a median PR of 8. The requirement for predictive, smooth control inputs to avoid overcontrol and PIO was much more difficult with the ACVH control law and the spring-loaded RHC inceptor.

One compensation strategy applied by the pilots to successfully fly with the lower control powers was to reduce their descent rate quickly once they got manual control to ensure that sink rate would be stable. This compensation allowed the pilot to relax sink rate monitoring and focus on flying the redesignation task with the hover cue. This pattern continued until successful positioning over the hover point where the IPC could then be engaged.

To illustrate the advantage that good HQ provides, the average ground speed from the onset of the redesignation to when the crews were within 5 m of the landing target is plotted in Figure 10. The figure shows the mean value (red line in the boxplot), plus/minus one standard deviation by the vertical box, and the max/min values with the boxplot whiskers. The data show that with better control, the pilots can maintain higher closure rates to the landing target. The RCAH with 2.9 deg/sec^2 had the highest average ground speed, followed by the 4.3 deg/sec^2 control power ACVH and RCAH control laws. Poorer controllability requires the pilot to be less aggressive in approaching the landing target, requiring more time and fuel.

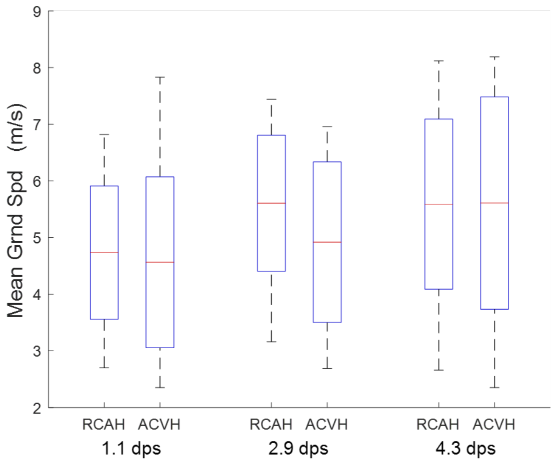

Figure 10. Average groundspeed from redesignation to when within 5m of the landing target

Workload Ratings

The mean TLX ratings are shown in Figure 11 for the RCAH control law using a spider chart format for the six individual workload components. The mean TLX ratings are shown in Figure 12 for the ACVH control law.

Analysis of Variance (ANOVA) analyses (using a significance value of 0.05) with control law and CP as the main factors were used to assess the TLX workload ratings. Only those factors or second-order interactions with significant differences are reported

An ANOVA revealed significant NASA TLX overall workload differences, F(2,48)=11.13, p<0.001, for CP. Moderate overall workload (mean=61) was reported for the CP of 1.1; while moderately-low overall workload was reported for the two higher CPs (both had mean=38). There were no appreciable workload differences (p>0.05) due to control law or the interaction between CP and control law.

Separate ANOVAs on the TLX component workload ratings revealed that CP was significant for mental demand (F(2,48)-4.77, p=0.013), temporal demand (F(2,48)=3.81, p=0.029), performance (F(2,48)=17.72 , p<0.001), and frustration level (F2,48)=14.20, p<0.001). Pilots reported increased mental demand, more time pressure (temporal demand), and greater frustration and rated their own performance poorer with the lowest CP of 1.1 deg/sec^2 as compared to the two higher CPs. There were no significant differences between the 2.9 and 4.3 deg/sec^2 CPs for these component workload ratings.

Control law was significant for the TLX component workload ratings of performance (F(1,48)=6.84, p=0.012) and frustration level (F(1,48)=5.70, p=0.021). Pilots reported better performance with RCAH (mean=26) versus ACVH (mean=40) and lower frustration with RCAH (mean=30) versus ACVH (mean=46) during the manual redesignation task.

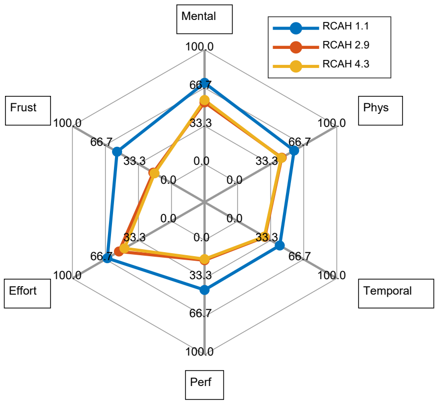

Figure 11. NASA TLX ratings for control power variations with RCAH control law

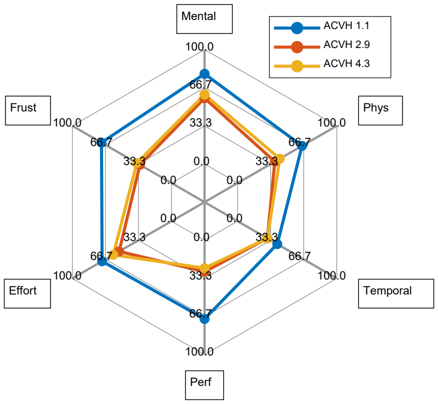

Figure 12. NASA TLX ratings for control power variations with ACVH control law

Acceptability and Utility Ratings

After assigning a Cooper-Harper rating for a test configuration, the pilots provided Likert-type ratings on 1) the acceptability of rotational control for translation (using a rating scale of 1 being very unacceptable; 4 being average; and 7 being very acceptable) and 2) utility of the display (using a rating scale of 1 being very poor; 4 being good; and 6 being excellent) for the manual redesignation landing task.

Kruskal-Wallis tests were used to identify any significant differences ($p<0.05$) due to control law type or CP for the acceptability and utility ratings, and only significant differences of the main factors are reported. Individual value plots of the acceptability and utility ratings are provided, with the median value for each test configuration indicated with a diamond symbol.

Acceptability ratings: Kruskal-Wallis tests revealed that both control law ($H(1)=4.27$, $p=0.039$) and CP ($H(2)=21.58$, $p<0.001$) significantly affected the acceptability ratings of rotational control for translation during the manually-flown landing redesignation task. Rotational control for translation was rated as being acceptable with RCAH (median=6.0) and approaching slightly acceptable with ACVH (median=4.5). It was rated as being acceptable for the 4.3 and 2.9 deg/sec^2 CPs (median ratings of 5.8 and 6.0, respectively) and slightly unacceptable with the 1.1 deg/sec^2 CP (median=2.8).

The individual pilot acceptability ratings and median values for the six combination of control law and CP are shown in Figure 13.

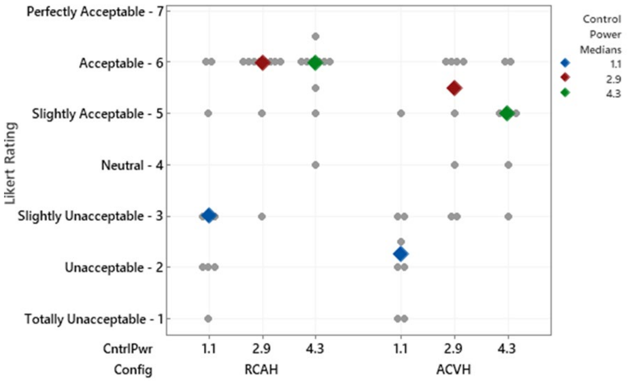

Figure 13. Acceptability Ratings

Display Utility ratings: Control law type ($H(1)=9.44$, $p=0.002$) significantly affected the display utility ratings for the manually-flown landing redesignation task. Display utility was rated as being very good with RCAH (median=5) and as good using ACVH (median=4).

CP ($H(2)=10.37$, $p=0.006$) was significant for this measure for the ACVH runs only, with a median display utility rating of good for the two higher CPs (median=4 for each one) and a rating of fair for the 1.1 deg/sec^2 CP (median=3).

The individual pilot display utility ratings and median values for the six combinations of control law and CP are shown in Figure 14.

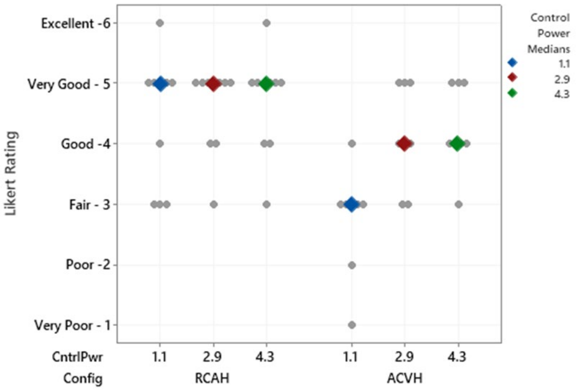

Figure 14. Display Utility Ratings

Pilot-Vehicle Performance

Over the course of testing, 16 occurrences of PIOs were observed by the pilots across the 113 HQ data runs completed with a 75 m landing redesignation distance from the original landing target.

Specifically, PIOs were reported:

- for 9 of the 10 EPs.
- all when using the lowest CP of 1.1 deg/sec^2, except for 1 ACVH run with 4.3 deg/sec^2 CP
- 8 times with RCAH
- 8 times with ACVH

In general, the low control power PIO runs were due to the pilot over-controlling the vehicle with a significant lateral correction. The pilot inputs became out of phase with the hover cue/vehicle response. One pilot referred to this as "a very long period PIO".

During PIOs, the pilot tended to fixate on the ND and not crosscheck attitude (either on the PFD or OTW) which resulted in lateral accelerations. Often times the hover cue would become display limited (i.e., off-scale and "pegged") resulting in pilot confusion on where it was actually leading the spacecraft. In essence, the pilots became task saturated.

In order not to enter a PIO with the lower control powers, pilots had to remove themselves from the control loop (i.e., go stick neutral) or fly less aggressively especially when presented with a large landing site redesignation distance (e.g., 75 meters).

As one pilot said regarding the PIO tendencies:

> *"I finished the attitude command/velocity hold runs not long ago. This control power [CP of 1.1], although it didn't seem ideal, the rate command/attitude hold, the transition from auto to manual is smoother and flying a vehicle with what seemed to me had lower control power worked better on rate command/attitude hold. So for this vehicle configuration, if I had to go with a vehicle with smaller thrusters or I had limits to the prop consumption/prop usage, this is the flight control regime I would want to use. I want better control power, but this seemed to work better than the attitude command."*

Displays

The head-down display design was a critical element of this operation. Based on Likert utility ratings and pilot comments, the displays, in general, were found to be good by all participants. The pilots felt that the displays provided sufficient information to determine whether you were going to make a safe landing or not based on the LIDAR and camera view for hazard detection and the integrated hover cue symbology set and rate of descent information for trajectory control.

- The hover cue significantly improved pilot's ability to control translation to hover. This result was clear from the pilot rating data. The hypothesis, based upon the simulation, is that reductions in control power, compared to the Cheatham-Hackler criteria, still yield good handling qualities because the hover cue provides the pilots with the clear and precise acceleration information and control guidance. In contrast, the Cheatham-Hackler criterion was developed with the pilot's principally using out-the-window visual cues. The hover cue provided a direct visual representation of acceleration, unlike the out-the-window, for precise translational control.

- Pilots commented they were mostly head-down during the redesignation task. Some pilots estimated 70% head-down/ 30% head-out; while others commented they were 100% head-down, especially with the lower control powers, until IPC was engaged and active.

- This head-down display fixation could also lead to loss of attitude awareness resulting in an overshoot or pilot-induced oscillations around the landing site especially for lower control powers. Crosscheck on the primary flight display could help the pilots verify where they were and to determine the proper inputs he needed to apply, especially when the hover cue was display-limited. Training was felt to be a possible mitigation.

- For this redesignation task, pilots suggested locating the ND closer to the window as that would help with easier pilot scanning OTW since the navigation display was being used as the predominant display for positioning during a divert.

- Pilots found the audio cueing during descent, in the form of the automated altitude callouts, was extremely useful in maintaining an acceptable descent rate as they manually flew the divert task. They said another crew member would be providing that altitude callout function if it was not automated.

5. CONCLUSIONS

The hover cue significantly improved the pilot's ability to control translation and create satisfactory handling qualities for otherwise, sluggish configurations. However, the investigation also showed that display augmentation is not a panacea. Handling qualities problems, including pilot-induced oscillations, higher workload, and lower display utility ratings for the lowest control powers can still be evident.

Comparable, if not better, handling qualities were attained with the RCAH control laws, in comparison to the ACVH control laws, when using the hover cue as a manual control display augmentation. Similarly, pilots self-reported better performance and lower frustration levels with RCAH as compared to ACVH during the manual redesignation landing task. These results, at least for the control powers tested, imply simple RCAH control laws can be used – saving software development and pilot training costs – at the modest expense of a display augmentation.

The IPC manual guidance mode with its hover hold capability provided stabilization to the vehicle during the vertical descent to landing; thus allowing pilots time to scan OTW and head-down with the EV and camera views to confirm the landing site was free of hazards. As such, IPC as a submode of RCAH control law is recommended.

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BIOGRAPHY

Lynda Kramer *earned her master's degree in aerospace engineering from The George Washington University in 1996 and a bachelor's degree in aerospace engineering from Auburn University in 1991. She is an aerospace research engineer at the NASA Langley Research Center in Virginia currently focusing on spacecraft handling qualities research for the Human Landing System Project under the Artemis campaign. Ms. Kramer specializes in crew-centered flight deck design techniques for advanced displays aimed at improving safety and operational efficiency. Technical duties include directing the design, development, testing, and overall integration of the advanced displays into piloted workstations, flight simulators, and flight test vehicles; and defining, conducting, analyzing and reporting on results of research to evaluate the human/machine interface performance effects. For 17 years, she served as a Principal Investigator for eXternal Vision systems, synthetic vision systems, and enhanced vision systems research aimed at improving aviation safety and increasing aviation operations in restricted visibility.*

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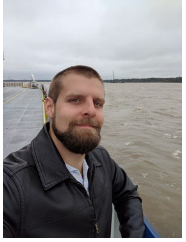
Jason Neuhaus *earned his B.S. and M.S in aerospace engineering from the Georgia Institute of Technology in 1997 and 1998. Mr. Neuhaus is an aerospace and software engineer at NASA Langley Research Center in the Simulation Development and Analysis Branch with 24 years of experience. He is a senior developer for the Langley Standard Real-time Simulation in C++ (LaSRS++) simulation framework to develop batch and real-time hardware-in-the-loop simulations for aircraft and spacecraft. Mr. Neuhaus is currently leading the Artemis Human Landing System simulation team at NASA Langley. He has worked on and led a variety of projects including simulation projects for a Boeing 737 Next Gen, Boeing 757, Dream Chaser, Ares-I-X, Ares-I, Planetary Lander, Lunar Surface Access Module, Orion Handling Qualities, Spacecraft Handling Qualities, HL-20, and Enhanced Automatic Ground Collision Avoidance System.*



Timothy Dugan *received a B.S. in Computer Engineering with a minor in Computer Science from Old Dominion University in 2010. In 2018, he received a M.S. in Computer Engineering from Old Dominion University. From 2013 to 2014, he was employed at NASA Langley Research Center (LaRC) as a Research Assistant focusing on Computer Vision Technology. Starting at the end of 2014 Mr. Dugan began employment as a Software Engineer with the Simulation Development and Analysis Branch (SDAB) at NASA LaRC where he manages the various simulators at the facility and the underlying software used to run them.*

Jesse Couch *is an Adaptive Aerospace Group, Inc. Research and Development Engineer, Computer Scientist, as well as an Instrument Rated Private Pilot, and Part 107 small UAS Operator. He joined AAG in 2012 and holds a B.S. in Aerospace Engineering and a B.S. in Computer Science from North Carolina State University and is currently pursuing a M.E. in Aerospace Engineering from Old Dominion University. He has developed flight test and data collection software for AAG's general aviation airplane, software and data systems for multiple UAVs, and contributed significantly to the simulation and control development of a low-boom supersonic demonstrator, UAVs, a hypersonic research vehicle, reentry vehicles, and lunar landers.*

Bruce Jackson *is an experienced flight control, flying qualities, modeling and simulation engineer and pilot with interest in spacecraft, aircraft, and remotely piloted vehicles. His 26-year career at NASA included design team lead for flight controls and flying qualities of blended-wing-and-body transport aircraft, lifting-body reentry vehicles, rendezvous and docking spacecraft, and a lunar landing vehicle. He has performed flying qualities testing for traditional and supersonic aircraft (including conceptual and real aircraft* *such as the Tu-144). Mr. Jackson is also very familiar with digital flight simulation, and helped develop an exchange format for flight simulation models (DAVE-ML) and led a NASA-wide team to generate verification data for multiple NASA high-fidelity aerospace simulations for the NASA Engineering and Safety Center. Prior to joining NASA Langley Research Center, he was lead simulation software engineer and helped develop the U.S. Navy's Manned Flight Simulator facility at Patuxent River NAS, Maryland. Mr. Jackson is proficient in several programming languages and a fan of extreme programming (XP). Mr. Jackson is the recipient of the NASA Exception Service medal and an Associate Fellow of the AIAA, having served on multiple technical committees.*