Degraded Visual Environment Mitigation (DVE-M) Program, Yuma 2016 Flight Trials

Zoltan Szoboszlay
U.S. Army Aviation Development Directorate
Mail Stop T12B-2, Ames Research Center,
Moffett Field, California 94035 U.S.A.
Zoltan.P.Szoboszlay.Civ@Mail.Mil

Bradley Davis, U.S. Army Research Laboratory
Major Michael Osmon, U.S. Army Aviation Development Directorate
Major Joseph Minor, U.S. Army Aviation Development Directorate
Major Zachariah Morford, U.S. Army Aviation Development Directorate
Brian Fujizawa, U.S. Army Aviation Development Directorate

ABSTRACT

A flight test was conducted by the U.S. Army Degraded Visual Environment Mitigation (DVE-M) program on an EH-60L helicopter at Yuma Proving Ground. The combination of terrain/obstacle imaging sensors, pilot cueing, and improved flight control was demonstrated. Sixty-four landings and fifty-five precision hover maneuvers were accomplished for data collection in heavy brownout conditions by four test pilots. All 64 landings were safe: all landings were within 22 ft (mean 5.8 ft) of the target landing point the guidance was directing the pilot toward as measured with the EGI inertial sensor. Lateral speeds were always within 1.5 knots (mean 0.3 knots), and vertical speeds at touchdown were always within 180 ft/min (mean 97 ft/min). Six go-around maneuvers due to pilot performance were conducted safely by the pilots using the cueing. Pilots reported that they had little spare capacity to interpret the sensor image since they were focused on following the guidance cues on the display. MCLAWS provided an improved flight control response in the cyclic, but did not free enough capacity of the pilot to interpret the sensor imagery. Coupled cyclic was not available at the time of the test. Coupled collective was available and compared to approaches with uncoupled collective; pilots reported a major improvement in workload as measured on the Bedford scale, and there was measured improvement in hover position error (by 2.1 feet). Heading hold was available and used. Audio cueing was rated highly as implemented in this test. Tactile (vibrating seat, waist belt, and shoulder strap) was rated poor on the subjective usability questionnaire, as implemented in this test. In particular, pilots requested that only one axis be active at a time.

1. INTRODUCTION

1.1 DVE-M Program

The Degraded Visual Environment Mitigation (DVE-M) Program is a U.S. Army Research, Development, and Engineering Command (RDECOM) science and technology effort. DVE mitigation is a potentially disruptive capability improvement that will allow vertical lift aircraft operators to maintain tactical advantages across diverse battlefield environments. The program's goals are to enhance survivability and enable deliberate operations in the DVE through advanced technologies. To achieve this, DVE-M is working to develop and demonstrate three key technology components required for a comprehensive DVE pilotage solution: modern flight control laws, multi-sensory pilot cueing, and a multi-spectral, all-environment "see-through" sensor system – all integrated in a new complex computing architecture. The end product of this

S&T effort is knowledge that informs and enables effective and affordable capabilities for the Soldier. The objectives of the 2016 RDECOM DVE-M NATO flight trials at Yuma Proving Grounds (YPG) were to:

a. Demonstrate the state of the art for integrated flight control, sensors, and cueing systems in an operationally relevant environment (brownout, sand/dust, smoke).

b. Collect qualitative and quantitative data to assist in determining which elements within the DVE trade space have a positive effect on operator performance and workload in DVE.

c. Record time-synchronized raw data (EGI inertial sensor, RADAR, LIDAR, infrared camera, color camera to provide a data set to support future science and technology efforts.

1.2 Participating Organizations

The DVE-M program was executed by the Aviation Development Directorate (ADD) of the U.S. Army Aviation and Missile Research, Development and Engineering Center (AMRDEC). AMRDEC is part of U.S. Army Research, Development and Engineering Command (RDECOM). The Army Research Laboratory (ARL) leads the pilot cueing element. The U.S. Army Communications-Electronics Research, Development and Engineering Center (CERDEC) leads the sensor element. The ADD also leads the flight control element using the aircraft and simulation facilities at Moffett Field, CA.

Additional technical support for this test effort includes: the Aeroflightdynamics Directorate (ADD-AFDD), the Aviation Applied Technology Directorate (ADD-AATD), the U.S. Army Aeromedical Research Laboratory (USAARL), and the Air Force Research Laboratory (AFRL). In addition, DVE-M cooperates with NATO countries for exchange of technical information for research, standardization, and interoperability through the JCG-VL and NIAG 193 studies.

1.3 Background

Typical DVE conditions include night, fog, falling snow, brownout (rotor downwash creates a cloud of dust near the ground), and whiteout (rotor downwash creates a cloud of snow near the ground). In a dust cloud the pilot may not only lose sight of visual references of the horizon and ground, but the dust cloud itself has a visible structure that is in motion. The strong sensation of self-motion (vection) caused by the visual flow field of the dust cloud is often in a direction that is different than the aircraft's motion with respect to the ground. Since the primary means that humans use to determine self-motion is the interpretation of the visual flow field, the false motion cues are difficult to ignore.

A study of rotorcraft accidents was conducted for the U.S. Department of Defense covering Operation Enduring Freedom (OEF) and Operation Iraqi Freedom (OIF), covering a period from October 2001 through September 2009 (Reference 1, Couch, M., Lindell, D., 2010). During that time period, there were 70 aircraft losses due to hostile action and 157 aircraft losses in combat theater in non-hostile situations. There were 145 fatalities due to hostile action and 219 fatalities in combat theater but in non-hostile situations.

For non-hostile situations in combat theater, the first event causes were determined. In this study, the authors limited the classification to only the primary causal factor and focused on the first item in the chain of events leading to the mishap. Results are shown in Figure 1. The red colored regions in the figure are mishaps due to human factors occurring in cruise flight while the yellow colored regions are mishaps due to human factors occurring in hover or low speed below effective translational lift. The blue region in the figure indicates mishaps due to mechanical failures and fire. Human factors causes accounted for 79 percent of aircraft losses and 80 percent of the fatalities, in combat non-hostile situations. The authors point out that human factor causes do not necessarily mean inadequate training, but rather something prevented the pilots from being aware of the event or chain of events leading to the accident.

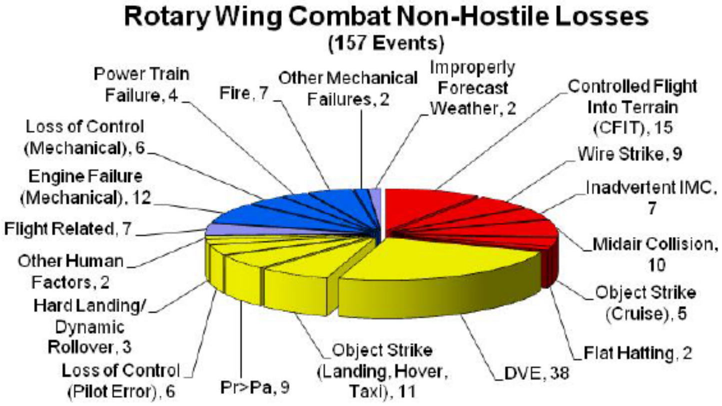

Figure 1: Number of aircraft losses for OEF/OIF (October 2001–September 2009), graph from Ref. 1 Couch and Lindell, 2010.

Referring to Figure 1, the four largest causes of accidents at cruise flight are: controlled flight into terrain, mid-air collision, wire strike, inadvertent IMC (DVE), and object strike. For low speed and hover, the four largest causes of accidents are: DVE due to brownout or whiteout, object strike, power required greater than power available, and loss of control due to pilot error. The category "DVE" is defined in the paper as brownout or whiteout, but was often also at night. According to the paper, 60 percent of mishaps occurred at night.

AFRL executed a program to develop a technical solution for brownout landings with flight tests conducted from 2009 through 2016. The 3D-LZ program included a LADAR see-and-remember sensor (Figure 2) developed for AFRL (Burns Technologies LLC, Orlando, FL), and the BrownOut Symbology System (BOSS) developed by the Army ADD as detailed in References 2-7. Much of the symbology for the test that is the subject of this paper, was first developed under the 3D-LZ program.

Figure 2: 3D-LZ sensor and test aircraft.

2. METHOD

This section details the test aircraft configuration, test site, maneuvers, test points, and demonstration points.

2.1 Test Aircraft

The test aircraft shown in Figure 3 is an EH-60L Advanced QuickFix helicopter, Army Serial Number 87-24657. Most of the original QuickFix equipment was removed and replaced with research equipment to support the new sensors, flight control, and pilot cueing systems. Equipment installed for DVE research included engine inlet barrier filters, an inertial measurement unit (Honeywell H-764GU EGI), a digital output version of the Army APN-209 radar altimeter, a GPS antenna mounted on the tail (with the signal split to various systems), two terrain imaging sets of sensors, a programmable flight control augmentation system, a programmable graphics generator, a video distribution system, video recorders, a voice synthesizer system, a tactile cueing system, and aircraft instrumentation for data recording. All symbology was driven from the EGI, radar altimeter, and the torque sensors.

Figure 3: EH-60L Black Hawk test aircraft.

2.1.1 Terrain Imaging Sensors

Two sensor systems were flown during the test which included 3D and 2D (infrared camera) sensors. For both systems, the 3D terrain/obstacle sensor data was fused with pre-stored terrain elevation data to populate the terrain rendering database for the displays. For both systems, the 3D terrain/obstacle data would also populate a separate small area terrain elevation database created around the landing/hover point, called GeoGrid, for the guidance. In practice, false-positive returns prevented the use of the sensor driven real time guidance. Instead, pre-stored obstacles were created in the GeoGrid database in the same locations as the real obstacles so the guidance algorithms would consistently guide the pilot over the real obstacles. For both sensor systems, obstacles at the landing area were artificially colored yellow or red if their height above the local ground plane exceeded thresholds corresponding to fuselage and rotor hazards, as shown in Figure 4 and 5.

One sensor system was developed by Sierra Nevada Corporation (SNC). As shown in Figure 4, the SNC sensor system included a radar (SNC, Sparks Nevada), a LADAR (Neptec Opal 120, Kanata Ontario Canada), an infrared camera (DRS 720p, Arlington Virginia), and pre-stored (a priori) terrain elevation data. The infrared camera input to the fusion algorithm was paused automatically once the brownout formed, to prevent the high contrast swirling dust cloud structure from being displayed and providing false-motion cues.

The second sensor system was developed by Areté, as shown in Figure 5. It included a LADAR (Areté, Colorado), an infrared camera (DRS 720p, Arlington Virginia), and pre-stored terrain elevation database. The infrared camera input to the image fusion algorithm was manually reduced in contrast by the sensor system operator once the dust cloud started to develop in order to diminish the image of the cloud on the display. Obstacles at the landing area were also artificially colored yellow or red if their height above the local ground plane exceeded thresholds, as shown in Figure 5.

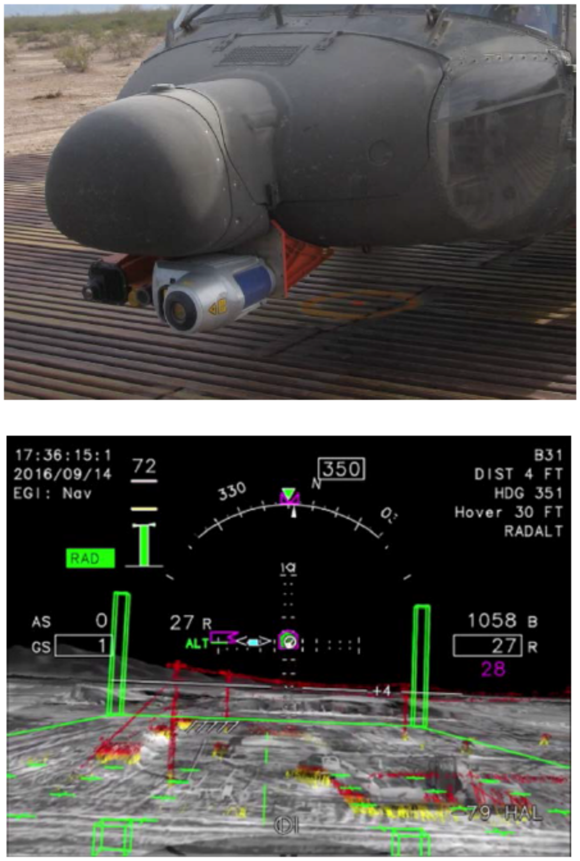

Figure 4: SNC sensor system and terrain image.

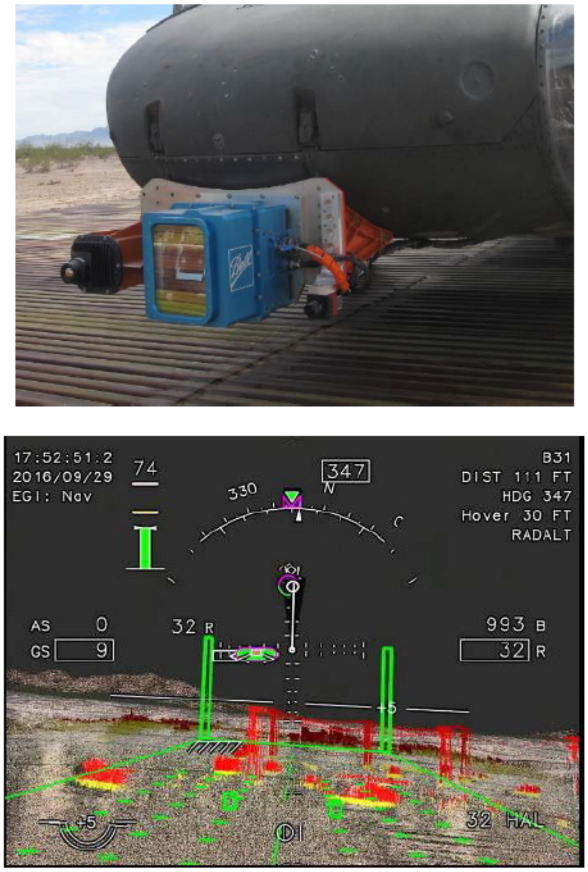

Figure 5: Areté sensor system and terrain image.

The sensor systems added obstacle information to the display, which was lacking in the symbology. The sensor image was expected to improve the situational awareness of the pilot of the landing area layout, aircraft attitude, and rate of closure toward the landing site. However, pilots commented that they did not have the capacity to interpret the terrain/obstacle image during the high workload task of tracking the guidance symbology. Small obstacles were difficult to see on the display from both sensor systems. Pilots recommended that small obstacles be highlighted with symbology to be more easily seen.

2.1.2 Research Flight Control System

A Partial Authority Flight Control Augmentation (PAFCA) system was installed on the EH-60L, which hosted the Modernized Control Laws (MCLAWS), as detailed in References 8 and 9. The design purpose of PAFCA was to bring advanced flight control laws to legacy aircraft, specifically the UH-60A/L, using the existing aircraft SAS and trim actuators. The PAFCA system consists of a SAS/trim interface box, a programmable Research Flight Control Computer (RFCC), and cockpit control panel. The SAS/trim interface box receives servo commands from both the standard Automatic Flight Control System (AFCS) and the RFCC. Relays within the box are switched via the cockpit control panel to select which commands are passed to the servos. Aircraft state data is provided to the RFCC and MCLAWS from the EGI and the radar altimeter.

The MCLAWS software changes the aircraft response type from the baseline rate damping response type with the AFCS to an attitude-command/attitude hold (ACAH) response type in pitch and roll up to 60 knots. Above 60 knots, the MCLAWS switches to a SAS-like rate response type. The MCLAWS directional axis provides a rate-command/direction hold (RCDH) response type at all airspeeds. The heading hold mode uses a frequency split approach in that the high rate SAS servos are used for rate damping while the slower trim servos are used primarily for the heading maintenance. Additionally, the MCLAWS has a position hold mode which can be engaged by the pilot and activates below 5 knots. When activated, the position hold decelerates the aircraft to a stable hover, before selecting a reference position.

The PAFCA system also includes an HH-60G collective trim servo and collective grips which provide vertical axis augmentation. A benefit of this additional collective trim servo is that its commands do not go through the SAS/trim interface box and thus allows it to be used with either MCLAWS or the baseline SAS/FPS system. The vertical axis augmentation consists of an altitude hold which can use three different altitude sources: radar altimeter, barometric altimeter, and inertial altimeter from the EGI. The system is engaged by the pilot and automatically switches from radar altitude hold at low speed to barometric or inertial altitude hold at high speeds; the pilot can manually override this automatic selection. Additionally the collective trim servo has been used to develop a coupled collective mode in which the altitude and vertical velocity commands from the ICE Landing Guidance are passed to the MCLAWS vertical axis control laws. These were the same commands that drove the pilot's symbology. The trim servo then drives the collective in order to automatically satisfy the vertical axis cues.

2.1.3 Integrated Cueing Environment

Figure 6 shows the two 10-inch diagonal panel mounted displays that were installed for the evaluation pilot in the right seat (Avalex Technologies, Gulf Breeze, Florida). These displays were full color, sunlight readable, with 1024x768 resolution. The evaluation pilot used the right display, which was directly in front of the seat, as the primary flight display. The left display showed the GeoGrid sensor data in plan view, and was not used by the evaluation pilot.

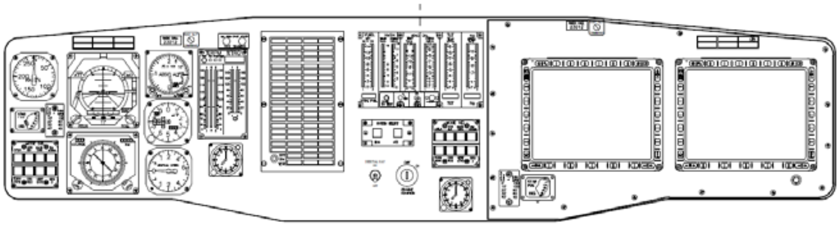

Figure 6: Two 10 inch diagonal panel mounted displays were added for the evaluation pilot.

There were two symbology pages with ICE, the enroute page (Figure 7) and the Hover/Approach/Takeoff (HAT) page (Figure 8). The enroute page was shown above 60 knots whenever the guidance to hover or landing was off. The HAT page was displayed at all speeds when guidance to hover or landing was active. The HAT page was also displayed whenever the aircraft was below 60 knots. The entire approach was flown on the HAT page from 1.0 NM to the hover/landing point. The most important distinguishing elements of ICE symbology are listed below:

a) Horizontal and vertical speed guidance were explicitly shown, in plan view, for approaches to hover or landing. Simultaneously, the current horizontal and vertical speed of the aircraft were also shown. Thus the pilot could close the control loop between the desired speeds and actual speeds.

b) The velocity indicators did not change scales during the approach. Using a blended linear and logarithmic scale, the velocity and position scales provided plenty of range (up to 160 knots to the top of the screen), while they also provided enough resolution at touchdown (indices are 1, 2, 4, 6, 8, and 10 knots).

c) The entire approach, which typically started at 80 knots at 0.8 NM, was performed using a single display and single page (HAT) on that display.

d) A perspective view (three dimensional), earth referenced, artificial landing pad was displayed which was always drawn level on the panel-mounted display.

Figure 7: Enroute (Cruise) page shown with artificial landing pad.

Figure 8: Hover/Approach/Takeoff (HAT) page shown with artificial landing pad.

Figure 9 shows the radar altimeter indicator in the form of a rising ground, and the corresponding target altitude symbol used during hover. Figure 10 shows the vertical speed tape, and the predictor for the vertical speed tape, driven by vertical acceleration. The figure also shows the target vertical speed symbol. All these vertical symbols are clustered together and are meant to work together. Their placement left-of-center was intentional so that the symbols map well with the placement of the cyclic and collective control sticks.

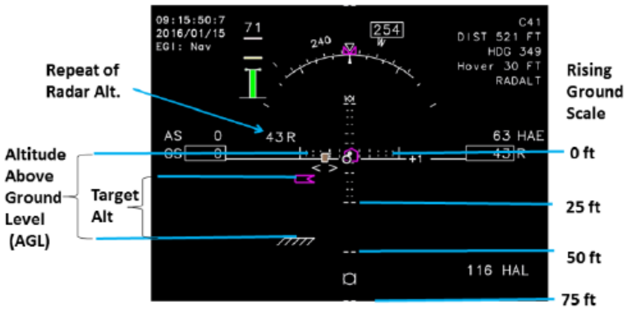

Figure 9: Radar altitude and target hover height symbols.

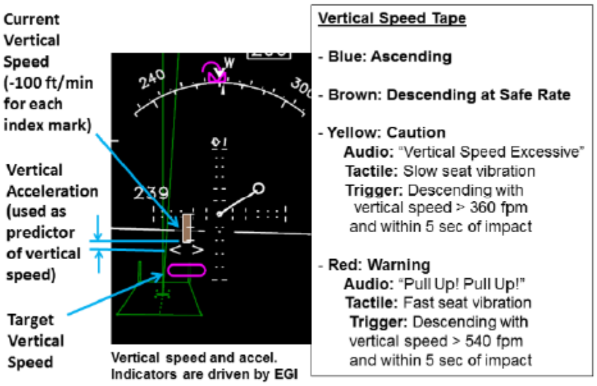

Figure 10: Vertical speed and target vertical speed symbols.

The ICE system would play audio files into audio channel 4 of the standard InterCommunication System (ICS). Most of the audio messages were produced with a voice synthesizer. There was one exception, which was a chime to indicate that a change occurred in the target vertical speed due to either the desired glide slope being intercepted or due to an obstacle being cleared.

Figure 11 shows the tactile system manufactured by Engineering Acoustics Inc. (Casselberry, Florida). The shoulder tactors were built into a sleeve that attached to the shoulder harness belt. Multiple tactors were built into the seat cushion which vibrated in unison. Pilots also wore a belt, with eight different directions of vibrations around the waist. The system is detailed in References 10 - 12.

8 direction belt

Figure 11: Tactile system.

Table 1 shows the two modes that the tactile system could be in: approach mode and hover position keeping mode. The tactile system automatically changed modes during an approach-to-hover maneuver. During approach to landing maneuver, the tactile system was always in the approach mode.

Table 1: Criteria for energizing tactors.

Approach	Advisory 1 Hz	Caution 2 Hz	Warning 4 Hz	
Seat	150 - 300	300 - 450	> 450	Excessive vertical speed (down) [ft/min]
Shoulder	150 - 300	300 - 450	> 450	Insufficient vertical speed (down) [ft/min]
Long. Belt > 10 knots	20 - 40	40 - 60	> 60	Long. speed error [%]
Long. Belt < 10 knots	3 - 5	5 - 7	> 7	Long. speed error [knots]
Lat. Belt > 10 knots	6 - 12	12 - 18	> 18	Lateral speed [knots]
Lat. Belt < 10 knots	3 - 4	4 - 5	> 5	Lateral speed [knots]
Hover Position Keeping				
Seat	3 - 6	6 - 9	> 9	Altitude too low [ft]
Shoulder	3 - 6	6 - 9	> 9	Altitude too high [ft]
Belt	3 - 6	6 - 12	> 12	Horizontal position error [ft]

2.2 Test Execution

This section details the Yuma test site, maneuvers, and the demographics of the test pilots.

2.2.1 Yuma Test Site

Figure 12 shows the test site at Yuma Proving Ground. The ground was composed of sandy soil, with a range of particle sizes including very fine. The top soil was tilled regularly, to reduce adhesion between particles, enabling large dust clouds to be formed. A smoke generator was also used on some of the approaches as shown in the figure. Obstacles were purposefully set up in defined areas including small buildings, poles, wires, palm trees, short posts, ground vehicles, helicopter airframes, dirt mounds, and ditches.

Figure 12: Test site.

2.2.2 Maneuvers

Figure 13 shows a profile of a typical approach-to-landing, without obstacles. All main test points were flown starting at approximately 200 ft radar altitude, and 80 knots ground speed at the approach gate which was 1.0 NM from the landing point. Approaches were conducted with and without obstacles below the flight path. If there was a detected obstacle, the guidance would modify the vertical profile to guide the pilot over the obstacle, and once clear, initiate a new descent angle. The touchdown vertical speed criteria was set by the limit in the operator's manual. The aircraft touchdown forward speed criteria was set at a speed much lower than the aircraft gear limit, to demonstrate that speeds can be reduced to decrease landing gear damage in an operational environment with uneven surfaces. Touchdown lateral speed criteria was set at the landing gear limit of the test aircraft. The landing position adequate limits were set to have a large safety margin away from obstacles even with expected worse case EGI position errors. The EGI position was compared to WAAS GPS position at low speeds, and alerted the pilot if differences exceeded 15ft (which never occurred during any landings).

Approach-to-hover maneuvers ended with a 30 second precision hover, followed by a take-off. These maneuvers also started at 200 ft radar altitude, and 80 knots ground speed at the gate 1.0 NM from the hover point. Table 3 shows the desired and adequate criteria for the hover parameters.

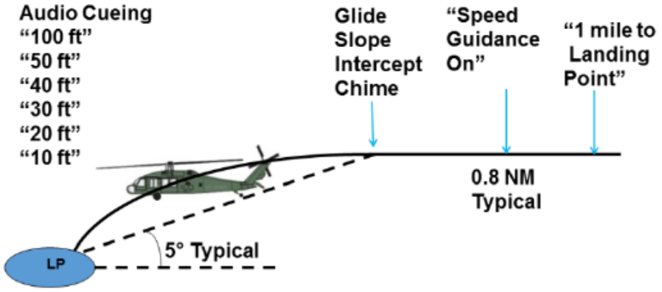

Figure 13: Approach-to-landing maneuver with voice synthesizer audio cueing in parenthesis.

Table 2: Landing criteria.

Parameter	Desired	Adequate
Vertical Speed	< 150 ft/min	< 300 ft/min
Forward Speed	< 2 kts	< 5 kts
Aft Speed	= 0 kts	< 0.5 kts
Lateral Speed	< 0.5 kts	< 1.0 kts
Long. Position	± 10 ft	± 20 ft
Lateral Position	± 6 ft	± 10 ft
Heading	± 5 deg	± 10 deg

Table 3: Hover criteria.

Parameter	Desired	Adequate
Altitude Error	± 3 ft	± 6 ft
Long. Position Error	± 3 ft	± 6 ft
Lateral Position Error	± 3 ft	± 6 ft
Heading Error	± 3 deg	± 6 deg
Time	30 sec	

2.2.3 Evaluation Pilots

There were four Evaluation Pilots (EPs) for the 2016 flight trials, all male, ranging in age from 35-46. Three of the pilots were active duty Army experimental test pilots (XPs) with the rank of O-4, and the fourth was a Department of the Army Civilian, retired CW4 Army XP. The EPs had a total flight hours of experience ranging from 1500 to 3100 hours. Pilot flight time in the H-60 airframe ranged from 75 to 2300 hours.

2.3 Test Matrix

2.3.1 Primary Test Points

The primary experimental design was a within-subjects (repeated measures), full factorial 2 × 2 × 2 × 2 combination of four independent variables: flight control response type, tactile cueing, aural cueing, and termination type. The resulting 16 unique evaluation points were flown by each evaluation pilot. The flight control response type was either the standard EH-60L SAS/FPS rate-command or the MCLAWS attitude-command (ACAH). Tactile cueing and aural cueing were either ON or OFF during each task. The termination type was either 30 ft AGL hover or landing.

An additional secondary experimental design was constructed to evaluate the effects of the coupled collective mode previously described. This coupled collective experiment included the full factorial 2 × 2 × 2 combination of three independent variables: coupled collective, flight control response type, and termination type. Coupled collective was either ON or OFF. The flight control response type was either the standard EH-60L SAS/FPS rate-command or MCLAWS attitude-command (ACAH). The termination type was either a 30 ft AGL hover or a landing. Tactile and aural cueing were both fixed to ON.

The presentation order of all of the test points was pseudo-randomized to control for learning/practice effects. All test points were flown to the DVE landing site using synthetic obstacles and radar altimeter driven guidance for consistency. Neither the nose mounted radar nor LADAR data were used to drive the approach guidance because of the false-positive data from the nose sensors. The two sensor sets flown provided a background image of the terrain and obstacles on the pilot's displays. Aircraft availability cut short the planned number of points with one of the sensor systems, while the other sensor system had reliability issues. Therefore, type of sensor system was not treated as an independent variable. All evaluation points were flown using the panel mounted display.

2.3.2 Demonstration Test Points

There were an additional twenty-three demonstration points that are not reported in this paper. Most demonstration points included the use of the helmet mounted display. Poor characteristics of the display included small (but noticeable) optical power when viewing the real world, minification of the sensor image compared to the real world, boresight registration issues, and noticeable head tracker delay. In addition to the use of the helmet mounted display, some demonstration points were flown starting at 70 feet and 70 knots, while other demonstration points were flown at starting at 350 ft and 100 knots.

2.3.3 Uncontrolled Confounds

Winds seemed to be the uncontrolled confounding variable with greatest impact on the workload and pilot performance. Winds affected when the dust cloud formed, and the direction of the false motion visual illusion. Another uncontrolled confounding variable was whether or not the dust cleared from the landing site from the prior approach. Near zero winds on one test day allowed the dust to linger for subsequent approaches. The characteristics of the terrain image was different between the two sensor systems. Due to maintenance issues, it was impossible to have the same number of landings and hover maneuvers with the two sensor systems; most test points were conducted with the Areté system. Another confound was that the quality of the terrain image varied from day to day with the Areté sensor set due to electrical and software issues, and variations in settings.

2.3.4 Measures

Objective measures for landing that are reported in this paper are position, horizontal speed, and vertical speed at the time of touchdown. Subjective measures for landing that are reported in this paper are a summary of usability ratings for the various components of ICE, as well as the Bedford workload scale (Reference 13). Handling qualities ratings (Reference 14) are not reported, as there was not enough flight time to repeat each condition to verify consistent performance as required for the rating.

Objective measures for hover, reported in this paper, were horizontal position and altitude. Subjective measures were the same as for the landing maneuver.

3. RESULTS ACROSS ALL CONDITIONS

Results in this section are shown for all evaluation points irrespective of the different conditions (independent variables) to give the reader the overall view of the pilot performance for 64 approach-to-landing and 55 approach-to-hover maneuvers. The next section (4) details differences found between conditions. All demonstration points and go-arounds were excluded from this data set. There were 6 go-arounds for evaluation points, and 1 go-around for a demonstration point due to either pilot not being comfortable with the progress of the approach or the maintenance of hover.

3.1 Landing

Figure 14 shows the distribution of touchdown position data for 64 brownout landings, as measured by the EGI. The same EGI drove the guidance equations, and symbology, so the data indicates how far off the pilots were compared to where they were being guided to. Therefore, in the data analysis, pilots were not penalized for any EGI position errors. As can be seen in the figure, the majority of the landings were within the desired region, and only three landings were outside of the adequate region. All landings were within the main rotor diameter of the aircraft, as measured with the EGI.

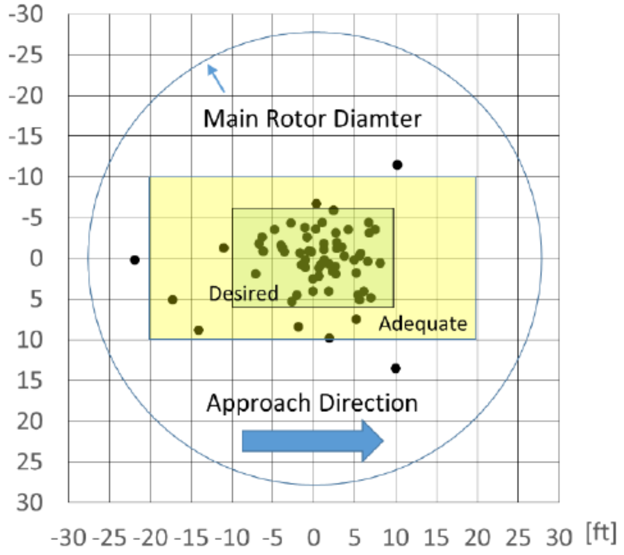

Figure 14: Touchdown footprint (64 landings shown).

Table 4 summarizes the performance data for the 64 landings. Heading is not included as heading hold was used. There were no criteria for radial distance to touchdown, but that data is included for completeness.

Table 4: Summary performance data for 64 landings.

	Abs. Long. Position Error [ft]	Abs. Lateral Position Error [ft]	Radial Position Error [ft]	Fwd. Speed [knots]	Aft Speed [knots]	Abs. Lateral Speed [knots]	Vertical Speed [ft/min]
Mean	4.3	3.0	5.8	1.5	0	0.3	-96.9
Median	2.8	1.9	4.9	1.5	0	0.2	-93.5
75th Percentile	6.1	4.3	7.3	2.1	0	0.4	-121.3
Maximum	21.9	13.5	21.9	3.8	0	1.5	-180.0
Desired Criteria	10	6	-	2	0	0.5	-150
Adequate Criteria	20	10	-	5	0.5	1.0	-300

Figure 15 indicates (in green) the percentage of landings that met all six desired criteria (53.1%). The yellow region (39.1%) indicates the percentage of landings that had at least one parameter in the adequate criteria and no parameters outside of adequate. The red region (7.8%) indicates the percentage of landings that had at least one parameter in the outside adequate criteria. As shown in the figure 92.2% of landings simultaneously met at least the six adequate criteria. One landing was outside adequate for longitudinal distance (21.9 ft). Two landings were outside adequate for lateral distance (max = 13.5 ft). Four landings were outside adequate for lateral speed at touchdown (max = 1.5 knots).

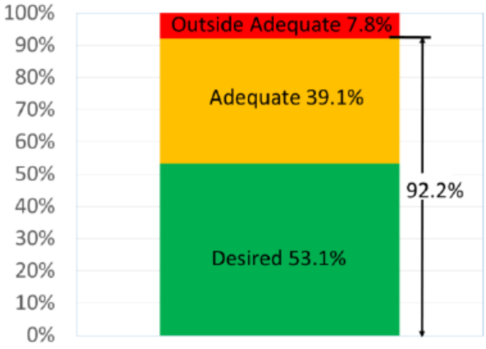

Figure 15: Percentage of 64 landings meeting all 6 performance criteria.

3.2 Hover

Table 5 summarizes the data for 55 hover maneuvers. The Root Mean Square (RMS) of the horizontal and vertical distance errors from the hover point were computed and are listed in the table.

Table 5: Summary performance data for 55 hover maneuvers.

	RMS Horizontal Position Error [ft]	RMS Vertical Position Error [ft]
Mean	3.2	3.1
Median	2.7	1.9
75th Percentile	3.2	2.7
Maximum	11.5	27.4
Desired Criteria	3	3
Adequate Criteria	6	6

3.3 Subjective Usability Ratings and Pilot Comments

Pilots were asked to rate the usability of various components of the cueing system after the last flight of the trial. Composite results are presented in Figure 16. The number in parenthesis is the number of questions for each topic; overall scores were averaged with equal weighting of each question.

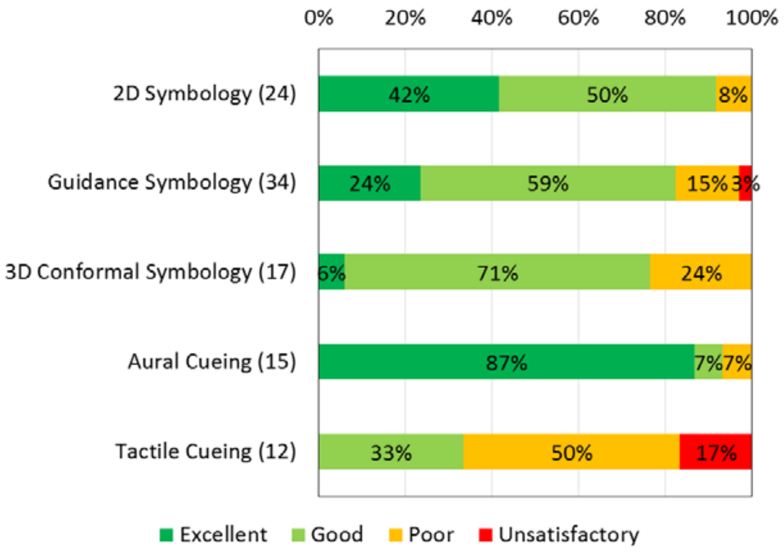

Figure 16: Summary usability ratings (number of questions composing each score shown).

Two dimensional symbols are all the symbols that do not appear to be fixed to a location on the terrain (earth-referenced). As shown in figure 16, the 2D symbology received mostly good and excellent ratings for usability (92%). One pilot commented, “The 2D symbology is the most useful portion of ICE. It does a good job of allowing you to track aircraft state without jumping around, and presents the information in an easy to decipher and logical manner.” Most pilots commented that they did not like the large separation between the target horizontal speed symbol and the target vertical speed symbol which occurs early in the approach. Those two symbols converge to the center of the screen near touchdown.

The guidance was rated predominately good to excellent on the usability questionnaire (83%). Guidance explicitly indicates what the horizontal and vertical speed should be throughout the approach. One pilot commented, “The guidance symbology is quite good and a great way to present the information to the pilot where it can be followed with few issues.” Another comment was, “Sensor-driven guidance should be added for take-off.” A third comment stated, “Performance model needs to be added to guidance.”

Three dimensional symbology are those symbols that are earth-referenced (fixed to the ground), and includes the artificial landing pad. Three dimensional symbology was rated as mostly good (71%) on the usability questionnaire, with an additional 7% rated as excellent. Several pilots commented that the artificial landing pad floated and shifted during the approach by a noticeable amount due to field-of-view and time delay mismatch between the sensor and the symbol generator. Having the sensor system draw the earth-referenced symbols would eliminate that mismatch, and is recommended in future tests. One pilot commented, “Would like to see conformal elements added to assist in determining the slope of the ground around the landing point.”

Aural cueing was rated better than any other feature of ICE on the usability questionnaire with 87% rated as excellent, and an additional 7% as good. One pilot commented, “The aural cueing was extremely helpful and sorely missed when it was turned off.” All pilots preferred to have aural cueing on all the time.

Tactile cuing received poor ratings 50% of the time on the usability questionnaire. One pilot commented, “Tactile cueing contributed best as a “safety net” to alert the pilot of position/velocity errors (focus attention on something that I missed).” Another comment was, “on occasions when tactile cued in multiple axes it became a distraction and completely unusable.” One pilot commented, “The implementation of the tactile cueing for the approach to hover task was not well integrated,” meaning that it cued the pilot that he was off the hover position, before the pilot got to the hover point (after it switched from approach mode to hover mode). Several pilots wanted an acknowledge button to temporarily turn off the tactile cueing. Turning off tactile when a parameter is off condition but converging toward the correct target value is another possible way of reducing annoying alerts.

4. RESULTS COMPARING CONDITIONS

This section details the differences in pilot performance and ratings between conditions as determined by the independent variables of the experiment.

4.1 Analysis of Variance Between Conditions

Data analyses of the performance measures and included descriptive statistics and a repeated-measures analysis of variance (ANOVA) to test for main effects of each independent variable, and all interactions. Since all of the independent variables had only two conditions, *post hoc* tests were not required. Where the ANOVA identified significant differences ($\alpha = 0.05$), the mean difference value and percentage difference are presented as statistically significant with the indicated *p*-value (highlighted in green). Due to the small sample size, additional *p*-values are reported up to 0.07 but are dubbed "marginally significant" warranting further investigation with a larger, more diverse pilot sample (highlighted in yellow).

The following limitations should be considered when interpreting the data presented in this report:

a. There was a small sample size of evaluation pilots ($N = 4$) who were highly trained XPs and not representative of the total Army aviator population.
b. The small sample size limits the power of the statistical analyses to find true effects.
c. The small sample size limits the confidence in generalizing results to a broader population.

The radial error at touchdown mean difference values (mean Δ) for the two conditions within each variable were calculated and are presented in Table 6. There was a significant main effect of coupled collective, $F(1, 3) = 15.626$, $p = 0.029$. The coupled collective ON condition had a lower mean radial error at touchdown by 1.8 feet (31% difference).

The vertical speed at touchdown mean difference values (mean Δ) for the two conditions within each variable were calculated and are also presented in Table 6. There was a significant main effect of flight control response type, $F(1, 3) = 10.615$, $p = 0.047$. The MCLAWS condition had a smaller (closer to zero) mean vertical speed at touchdown by 10.3 feet per minute (9% difference). While statistically significant, this difference is not operationally relevant.

Table 6: Landing performance.

	Coupled Collective *Δ = Uncoupled - Coupled*		**Flight Control** *Δ = SAS/FPS – MCLAWS*		**Tactile** *Δ = Off - On*		**Aural** *Δ = Off – On*	
Measure	**Mean Δ**	***p-value***	**Mean Δ**	***p-value***	**Mean Δ**	***p-value***	**Mean Δ**	***p-value***
Longitudinal Error at Touchdown [ft]	-1.2	N.S.	1.7	N.S.	0.2	N.S.	-2.8	N.S.
Lateral Error at Touchdown [ft]	-0.9	N.S.	0.7	N.S.	-0.3	N.S.	0.3	N.S.
Radial Error at Touchdown [ft]	-1.8 (31%)	$p = 0.029$	2.4	N.S.	0.4	N.S.	-2.3	N.S.
Longitudinal Speed at Touchdown [knots]	-0.1	N.S.	-0.1	N.S.	-0.2	N.S.	0.3	N.S.
Lateral Speed at Touchdown [knots]	0.0	N.S.	0.0	N.S.	-0.2	N.S.	0.0	N.S.
Vertical Speed at Touchdown [ft/min]	22.5	N.S.	10.3 (-9%)	$p = 0.047$	6.5	N.S.	21.8	N.S.

Table 7 lists the ANOVA results for the hover maneuver. There were no significant main effects between conditions. There was a marginal effect of coupled collective, $F(1, 3) = 8.864$, $p = 0.059$. The coupled collective ON condition had a lower (better) mean hover horizontal RMS error by 2.1 feet (44% difference).

Table 7: Hover performance.

	Coupled Collective *Δ = Uncoupled - Coupled*		**Flight Control** *Δ = SAS/FPS – MCLAWS*		**Tactile** *Δ = Off - On*		**Aural** *Δ = Off – On*	
Measure	**Mean Δ**	***p-value***	**Mean Δ**	***p-value***	**Mean Δ**	***p-value***	**Mean Δ**	***p-value***
Hover Horizontal RMS Error [ft]	-2.1 (-44%)	$p = 0.059$	1.1	N.S.	0.6	N.S.	0.9	N.S.
Hover Vertical RMS Error [ft]	-4.6	N.S.	0.2	N.S.	1.6	N.S.	2.3	N.S.

4.2 Bedford Workload

As a part of the pilot questionnaire completed after each approach, Bedford workload ratings were collected. A total of 47 approaches were analyzed which included both unobstructed and obstructed approaches using both MCLAWS and SAS/FPS flight control systems. These ratings are plotted in Figures 17 and 18. Red triangles indicate uncoupled collective conditions while blue circles indicate coupled collective conditions. The star (*) indicates the mean score for a particular pilot, while the bars indicate min and maximum ratings for a particular pilot. An "A" indicates that audio was ON. A "T" indicates that tactile was ON.

During the unobstructed approaches, those approaches conducted with the coupled collective received Bedford Workload ratings of predominantly 3 while uncoupled approaches received 4 or greater as shown in Figure 17. Due to the way the Bedford scale is structured via the questions the pilot must answer, a change in rating from 4 to 3 is a significant improvement indicating that the workload is satisfactory without reduction and that the pilot still has spare capacity to conduct additional tasks. Note that there is little difference in the workload rating for flight control response type (SAS/FPS vs. MCLAWS).

For the obstructed approaches, the coupled approaches received Bedford Workload ratings of 3 and 4 while uncoupled approaches received ratings of predominantly 5 or greater, again indicating a sizeable reduction in workload with coupled collective, as shown in Figure 18. Again, there is little difference in the workload rating for flight control response type (SAS/FPS vs. MCLAWS).

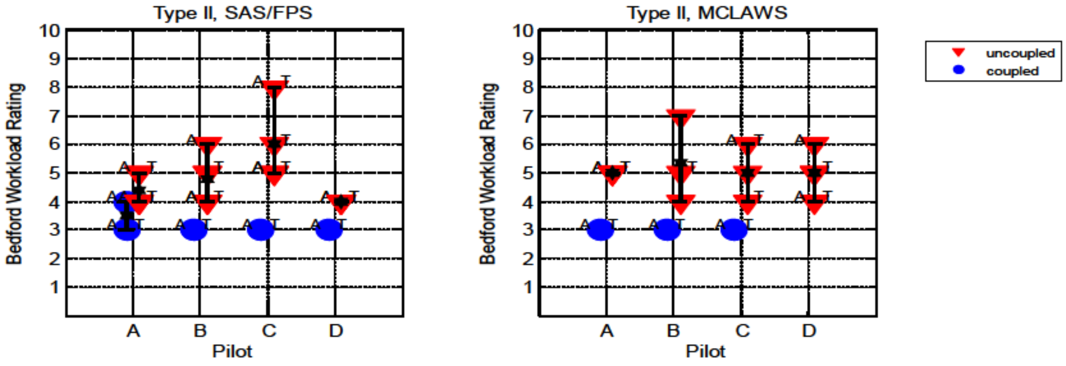

Figure 17: Bedford workload ratings for unobstructed approaches.

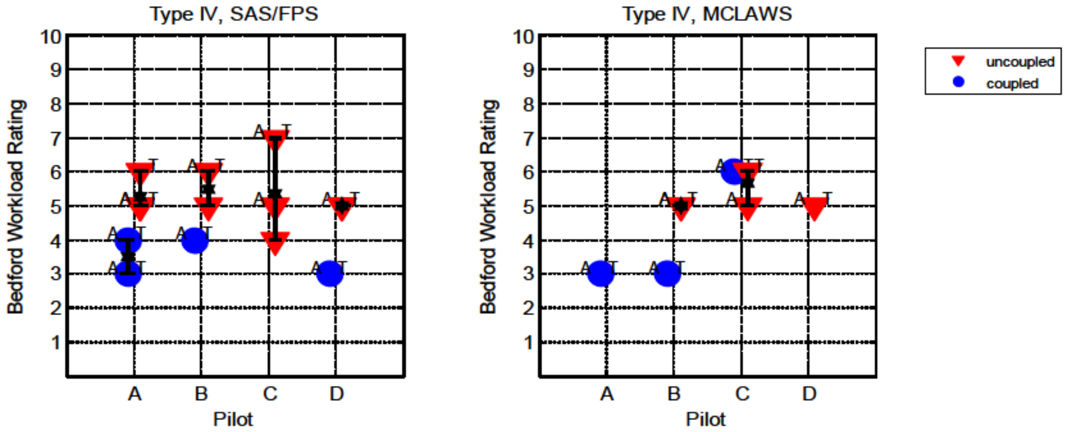

Figure 18: Bedford workload ratings for obstructed approaches.

5.0 INTERPRETATION OF RESULTS

All 64 landings analyzed were performed safely in heavy dust conditions using the panel mounted display. All landings were within 4.0 knots forward speed, 1.5 knots lateral speed, and 180 ft/min vertical speed as measured by the EGI. All landings were within 22 ft of the intended landing point as measured with the EGI. Six go-around maneuvers were safely conducted using ICE displays during evaluation points as a result of pilot performance.

Ninety-Two percent of the landings met all six of the criteria defined as "adequate":

- Touchdown within 20 ft longitudinal distance and 10 ft lateral distance from the landing point.
- Longitudinal speed less than 5 knots
- Lateral speed less than 1.0 knot at touchdown.
- Vertical speed less than 300 ft/min at touchdown.

Mean landing performance was precise:

- Mean touchdown position was 5.8 ft from the landing point.
- Mean forward speed at touchdown was 1.5 knots.
- Mean lateral speed at touchdown was 0.3 knots.
- Mean vertical speed at touchdown was 96.9 ft/min.

Mean hover performance was mostly good but with occasional large deviation:

- Mean horizontal RMS error was 3.2 ft, with a maximum of 11.5 ft.
- Mean vertical RMS error was 3.1 ft, with a maximum of 27.4 ft.

Automatic hover hold was available, but intentionally not turned on to determine how well pilots could maintain the hover using the ICE symbology and manual control. Engaging hover hold in the DVE is recommended.

Coupled collective ON vs. OFF was the variable that most significantly impacted the greatest number of measures. Mean radial distance error at touchdown improved by 1.8 feet (31% difference) with coupled collective ON. A marginally significant improvement in RMS hover horizontal position error of 2.1 feet (44% difference) was seen with the coupled collective ON. Pilots reported reduced workload with the coupled collective as measured with the Bedford scale.
The automation provided by the heading hold frees the pilot from having to control another axis of the helicopter. All pilots used the heading hold capability of the aircraft.

The aural cueing system showed little effect on task performance. Subjectively 87% of the usability ratings were recorded as "excellent" for the audio system, with an additional 7% of the ratings as "good." Pilots often commented that they missed the audio cues, as implemented in this test, when they were turned off.

The usability for the tactile cueing system were rated as "poor" 50% of the time, with an additional 17% of the ratings as "unsatisfactory". Further improvement of the tactile cueing algorithms are needed. In particular, pilots requested that only one axis of the tactile system be active at any given time using a priority scheme. An acknowledge button to temporarily turn off tactile was also requested.

The sensor systems provided a stable image of the terrain and obstacles throughout the maneuvers despite the dust cloud. Pilots commented that workload associated with satisfying the guidance cues on the display was high, leaving little spare capacity to interpret the sensor image.

6.0 CONCLUSIONS

The combination of terrain imaging sensors, pilot cueing, and improved flight control to land a helicopter was successfully demonstrated in the brownout degraded visual environment. Pilots primarily used the ICE displays to accomplish the task. With the ICE cueing system the pilots are explicitly shown the current horizontal and vertical speed compared to what they should be (guidance) throughout the approach. Imagery of terrain and obstacles were shown on the panel-mounted display throughout the landing, hover, and take-off. In contrast, the out-the-window view provided strong false-motion cues (vection) due to the motion of the dust, while also preventing the pilots from seeing obstacles. Pilots reported that they had little spare capacity to interpret the sensor image since they were focused on following the guidance cues on the display. MCLAWS provided an improved flight control response in the lateral and longitudinal axis, but did not free enough spare capacity for the pilot to interpret the sensor imagery. Heading hold was available and used on all approaches and hovers. The collective was coupled to vertical flight path guidance and a comparison was made between approaches with and without coupled collective. Pilots reported a substantial improvement in workload as measured on the Bedford scale (1 or more points), and there was measured improvement in hover position error (by 2.1 feet). However, with coupled collective and heading hold (and missing coupled cyclic), there still was insufficient capacity of the pilot to interpret the sensor image.

All 64 landings were performed safely in heavy dust conditions using the panel-mounted display. All landings were within 4.0 knots forward speed, 1.5 knots lateral speed, and 180 ft/min vertical speed as measured by the EGI. All landings were within 22 ft from the intended landing point (EGI sensor drift errors not included). Six go-around maneuvers were initiated due to pilot performance and were conducted safely with the pilots using the ICE displays. Demonstration points were not included in this paper.

Audio cueing was rated good or excellent in the usability scale 94% of the time. Audio cueing was restricted to altitude callouts, guidance mode changes, flight control mode changes, cautions and warnings of over-torque, and cautions and warnings of excessive vertical speed near the ground. Audio was intentionally not used to inform the pilot of deviation from guidance as pilots commented in the prior studies that this resulted in an excessive amount of audio messages when the aircraft was off guidance.

The usability ratings for the tactile cueing system were rated as “poor” 50% of the time, with an additional 17% of the ratings as “unsatisfactory”. Further improvement of the tactile cueing algorithms are needed. In particular, pilots requested that only one axis of the tactile system be active at any given time using some priority scheme. Better integration with guidance, and a way to acknowledge and turn off tactile cueing were requested.

REFERENCES

[1] Couch M., Lindell D., “Study on Rotorcraft Safety and Survivability”; *Proceedings of the American Helicopter Society 66th Annual Forum*, Phoenix, AZ, 2010.

[2] Szoboszlay Z., McKinley R., Braddom, S., Harrington, W., Burns H., Savage, J., “Landing an H-60 Helicopter in Brownout Conditions Using 3D-LZ Displays,” *Proceedings of the American Helicopter Society 66th Annual Forum*, Phoenix, AZ, 2010.

[3] Harrington W., Braddom S., Savage J., Szoboszlay Z., McKinley R., Burns H., "3D-LZ Brownout Landing Solution," *Proceedings of the American Helicopter Society 66th Annual Forum*, Phoeniz, AZ, 2010.

[4] Savage J., Harrington W., McKinley R., Burns H., Braddom S., Szoboszlay Z., "3D-LZ Helicopter LADAR Imaging System, " *Proceedings of the SPIE Defense and Security Symposium*, Orlando FL, April 2010.

[5] Szoboszlay Z., Neiswander G., "A Comparison of Linear and Logarithmic Scale Display Designs for Rotorcraft Landing in Brownout," *Proceedings of the European Rotorcraft Forum*, Milan Italy, 2011.

[6] Savage J., Goodrich S., Ott C., Szoboszlay Z., Perez A., Burns H., "Three-dimensional landing zone joint capability technology demonstration," *Proceedings of the SPIE Defense and Security Symposium, DVE Sensors II*, Baltimore, Maryland, May 2014.

[7] Szoboszlay Z., Fujizawa B., Ott C., Savage J., Goodrich S., McKinley R., Soukup J.,"3D-LZ Flight Test of 2013: Landing an EH-60L Helicopter in a Brownout Degraded Visual Environment," *Proceedings of the American Helicopter Society 70th Annual Forum*, Montréal, Québec, Canada, May 2014.

[8] Fujizawa B., Tischler M., Ott C., Blanken C., "UH-60 Modernized Control Laws for Improved Handling Qualities in the Degraded Visual Environment", *Proceedings of the American Helicopter Society 70th Annual Forum*, Montréal, Canada, 2014.

[9] Fujizawa, B., Tischler, M., and Minor J., "Outer-Loop Development and DVE Flight Test Assessment of a Partial Authority Model-Following Control System for the UH-60," *Proceedings of the American Helicopter Society 72th Annual Forum*, West Palm Beach, FL, May 2016.

[10] McGrath J., Estrada A., Braithwaite M., Raj A., Rupert A., "Tactile Situation Awareness System Flight Demonstration Final Report." *USAARL Report No. 2004-10*, U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL, 2004.

[11] Russell D., Keegan J., Ramiccio J., Henderson M., Still D., Temme L., Ranes B., Crowley J., Estrada A., "Pilot Cueing Synergies for Degraded Visual Environments," *USAARL Report 2016-10*; U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL, February 2016.

[12] McAtee A., Russell D., Feltman K., Swanberg D., Statz J., Ramiccio J., Harding T., "Integrated Cueing Environment Testing: Pilot Cueing Synergies for Degraded Visual Environments," *USAARL Report 2017-04*; U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL, November 2016.

[13] Roscoe A., Ellis G., "A Subjective Rating Scale for Assessing Pilot Workload in Flight: A Decade of Practical Use," *Royal Aerospace Establishment*, Bedford, UK, 1990.

[14] Cooper G., Harper R., "The use of pilot rating in the evaluation of aircraft handling qualities," *Technical Report TN D-5153*, NASA, April 1969.