DEGRADED VISUAL ENVIRONMENT MITIGATION PROGRAM NATO FLIGHT TRIALS: U.S. ARMY FLIGHT TEST AND RESULTS

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ABSTRACT

A flight test was conducted by the U.S. Army as a part of the RDECOM Degraded Visual Environment NATO European Flight Trials in February of 2017. Three weeks of testing was conducted at WTD61, Manching, Germany in smoke, fog, and rain. One week of testing was conducted at Älggialp, Switzerland in whiteout. Sensor data was collected in each environment using the Sierra Nevada Corporation sensor system consisting of a radar, a ladar, and a long wave infrared camera. The sensor data was fused together with *a priori* terrain data to generate a 3D world model which was displayed to the pilot. Twelve test pilots from Germany, Switzerland, and the United Kingdom conducted qualitative evaluations of the Partial Authority Flight Control Augmentation system, Integrated Cueing Environment, ICE-LG landing guidance algorithms, and the Sierra Nevada sensor system installed on AFDD's EH-60L research Black Hawk helicopter. The radar was able to penetrate all obscurants except the rain which reduced its range. The ladar was unable to penetrate fog or whiteout and had reduced range in rain. The infrared camera had reduced range in the fog and rain, and was unable to penetrate the whiteout. The ICE-LG landing guidance and visual cueing together provided an intuitive and easy system for the evaluation pilots to make precise landing and hovers in reduced visibility with only minimal training. Additionally, the coupled collective control system reduced the pilot workload and resulted in improved hover and landing performance.

1 INTRODUCTION

In 2011, the U.S. Army Training and Doctrine Command, Concepts and Requirements Directorate defined a degraded visual environment (DVE) as[1] "an environment of reduced visibility of potentially varying degree, wherein situational awareness and aircraft control cannot be maintained as comprehensively as they are in normal Visual Meteorological Conditions and can be potentially lost." The 2010 Study on Rotorcraft Survivability[2,3] reported on U.S. Department of Defense rotorcraft accidents which occurred during Operation Enduing Freedom and Operation Iraqi Freedom between October 2001 and September 2009. Among the findings in this report were that controlled flight into terrain (CFIT) and DVE were the leading causes of combat, non-hostile and non-combat losses at 43%.

The Degraded Visual Environment Mitigation Program (DVE-M) is a collaborative, synchronized science and technology program of experimentation and demonstration across the U.S. Army Research, Development, and Engineering Command (RDECOM). The program's goals are to demonstrate effective and affordable solutions and provide a knowledge base to reduce program risk for PEO Aviation, DoD, and NATO members of a fully integrated DVE Mitigation system compatible with existing and future helicopter systems that enables full-spectrum rotary wing operations in all terrain, weather, and battlefield environments. To achieve this, the DVE-M program is working to develop and demonstrate three key technologies required for a comprehensive DVE pilotage solution: advanced flight control laws and guidance algorithms; advanced pilot cueing; and a multi-spectral, all-environment sensor system.

The RDECOM DVE-M program is led by the Aviation and Missile Research, Development, and Engineering Center's (AMRDEC) Aviation Development Directorate (ADD) and consists of three integrated product teams (IPT) for the three main technologies. The Flight Control and Guidance IPT is led by the Aviation Development Directorate's Aeroflightdynamics Directorate (AFDD), the Cueing IPT is led by the U.S. Army Research Laboratory's Human Research and Engineering Directorate (ARL-HRED), and the Sensor IPT is led by the U.S. Army Communications and Electronics Research, Development, and Engineering Center (CERDEC). Other organizations participating in the DVE-M program include the Aviation Development Directorate's Aviation Applied Technology Directorate (AATD) and U.S. Army Aeromedical Research Laboratory (USAARL). Additionally, the DVE-M program has been cooperating with NATO countries through the NIAG Study Group 193.

1.1 Yuma Flight Trials

The first segment of the NATO Flight Trials was conducted at the Yuma Proving Ground in Arizona, USA from 6–30 September 2016. Testing at Yuma Proving Ground was conducted in brownout and smoke conditions. Several technologies were tested during the flight trials including: two sensor systems; advanced flight control algorithms including coupled vertical axis guidance and flight controls; aural, tactile, and visual cueing; as well as head tracking and a helmet mounted display. Detailed analysis and results from the Yuma Flight Trials have been documented in a flight test report[4] and papers[5,6,7]. Some key results and conclusions from the Yuma Flight Trials were:

- Seventy-six brownout landings were successfully conducted with high precision and accuracy; the mean touchdown distance from the intended landing point was 6.4 ft (2.0 m) and only two of the landings were outside of 20 ft (6.1 m) from the intended point.
- Coupled collective accounted for the most significant performance improvement. It significantly reduced pilot workload and increased spare capacity which allowed the pilots more time to interpret the sensor image, aircraft state information, and follow the remaining cues resulting in greater internal and external situational awareness and more accurate landings.
- False returns from the sensors prevented sensor driven guidance from being effective. Both sensors and guidance need to improve the ability to filter out false returns.

1.2 European Flight Trials

The RDECOM DVE-M NATO European Flight Trials were conducted over the course of four weeks in Germany and Switzerland in February 2017. Teams from the United States, Switzerland, Germany, and the United Kingdom participated in the Flight Trials. The U.S. flight test team had the following objectives of the Flight Trials:

1. Demonstrate the state-of-the-art for an integrated system of flight control, sensor, and cueing in operational environments including whiteout, smoke, rain, and fog.
2. Collect qualitative and quantitative data to assist in determining which elements within the DVE trade space have the greatest effect on operator performance in DVE.
3. Record time-synchronized raw data to provide a data set to support future science and technology efforts, including analysis, simulation, and evaluation of sensor fusion algorithms.
4. Identify technology shortfalls or deficiencies that support development of independent vendor-developed technology that may contribute to the improvement of a rotorcraft DVE solution.
5. Promote international research, development, test, and evaluation cooperation, standardization, and interoperability.
6. Nurture relationships between the technical communities of the U.S. Government and other nations.

This paper will present the testing conducted on the U.S. Army EH-60L Black Hawk helicopter with two major focuses. First, sensor performance in different DVE conditions will be presented and discussed. Secondly, the results and pilot comments from qualitative evaluations will be presented and discussed.

2 SYSTEMS DESCRIPTIONS

2.1 Test Aircraft

The U.S. Army portion of the DVE-M European Flight Trials were conducted on the AFDD EH-60L (ASN 87-24657) Advanced QuickFix Black Hawk helicopter,

Figure 1: AFDD EH-60L research helicopter with landing gear skis

shown in Figure 1. The AFDD Flight Projects Branch (FPB) has removed all external antennas as well as all of the QuickFix equipment with the exception of the inertial navigation unit (INU) and associated navigation control panel and the control display unit (CDU) thus making the aircraft similar to a standard UH-60L. The main cabin computer racks have been re-used to house the numerous research and support systems.

Shortly after the EH-60L arrived at AFDD, the FPB removed the main and tail rotor de-ice systems. This was done in order to provide additional center console space and electrical power for the research systems. Without the de-icing capabilities the EH-60L was restricted to flight in non-icing conditions only; this was expected to limit the flight test opportunities during the Flight Trials based on the expected weather conditions. However, while icing conditions did delay the ferry flight to Manching by a few days it did not impact any of the test flights.

Additionally, the standard main and tail landing gear struts were replaced with UH-60M Upgrade struts, each of which has three integrated doubly redundant weight-on-wheel (WOW) switches. For the week of testing conducted in Switzerland, skis were installed on each of the landing gear. As discussed later, the installation of the skis on the main landing gear caused the WOW switches to be triggered when in flight.

Through the years, numerous additional sensors have been installed on the EH-60L to support various research projects including: an embedded GPS/INS (EGI), a GPS receiver with SBAS capability (both WAAS and EGNOS) as well as a receiver for differential corrections (RTK/DGPS), linear variable differential transducers (LVDTs) to measure pilot control position inputs, LVDTs to measure SAS servo positions, linear potentiometers to measure the input to the mixer, and string potentiometers to measure the positions of the primary servos. Specifically for the European Flight Trials, a certified electronic standby instrument system was installed outboard of the right cockpit control panel and a Garmin navigation radio unit was installed in the center of the instrument panel. These two additions made it possible to fly under Instrument Flight Rules (IFR) from the right cockpit; the left cockpit had maintained IFR capability by virtue of the standard UH-60L instrumentation.

Data acquisition is performed by the Research Data Acquisition System (RDAS). The RDAS records analog signals, digital signals, thermocouple measurements, MIL-STD-1553B messages, and Ethernet UDP messages. A single, continuous data file is collected over the course of a flight. Post flight processing extracts individual records based on an event marker inserted by the system operator during flight or by providing a list of time indices after the flight. The RDAS also outputs two identical PCM data streams, the first to a telemetry transmitter to drive ground station displays and the second to the internal aircraft LAN for use by any networked research system.

2.2 Flight Control

A Partial Authority Flight Control Augmentation (PAFCA) system was installed on the EH-60L with the purpose of testing advanced flight control laws on the UH-60 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 RFCC hosts the Modernized Control Laws (MCLAWS)[8,9] which provide an attitude-command/attitude hold response type in hover and low-speed flight. The SAS/trim interface box receives servo commands from both the standard UH-60 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 PAFCA system also includes an HH-60G collective trim servo and collective grips which allow for 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, or inertial altitude 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. The trim servo then drives the collective in order to automatically satisfy the vertical axis cues. For an approach which terminates at a hover, the coupled collective automatically transitions to a radar altitude hold mode. For landings, once the left main landing gear contacts the ground, as reported by the weight-on-wheel switches, the collective is commanded full down to complete the landing.

2.3 Pilot Cueing

The Integrated Cueing Environment (ICE)[7], which consists of visual, aural, and tactile cues, was used throughout the Flight Trials. All cues are generated by the same software hosted on the ICEBOX computer mounted in a cabin equipment rack, making the cueing truly integrated. The visual cues are presented to the evaluation pilot, who sits in the right cockpit, on a 10-inch primary flight display directly in front of the pilot. This display, along with a second display to the left, have replaced the analog instrument panel. Figure 2 shows an example of the primary flight display on an approach to a 50 ft (15.2 m) hover. The ICE symbology consists of 2D and 3D imagery. The 2D symbology consists of the white components excluding the text in the top corners and provides the pilot with aircraft state information. The 3D symbology consists of the green Earth referenced landing pad. Aural cueing comes through the standard aircraft intercommunication system (ICS) and can be heard by all members of the flight crew. Tactile cueing is provided through tactors embedded in the seat cushion, a belt, and a pair of shoulder harness pads.

The safety pilot in the left seat retains the analog instrument panel for safety of flight purposes, however he is able to see the same symbology on a monocular, monochrome helmet mounted display and/or on one 8-inch portrait display which is mounted outboard of the instrument panel. The tactile system components are installed on the left seat as well; using a center console switch, the safety pilot can opt to feel the same tactile cues which the evaluation pilot feels.

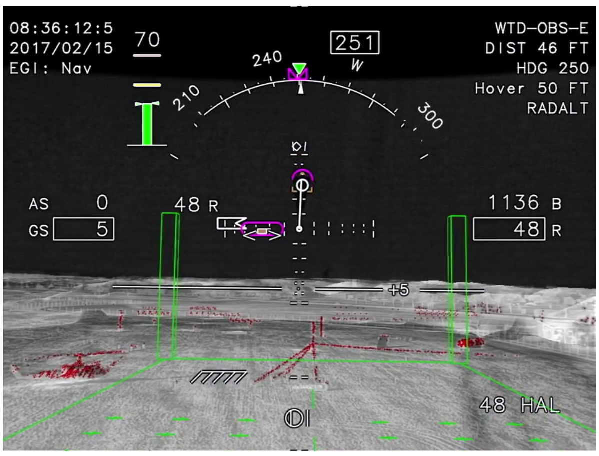


Figure 2: Primary flight display with ICE symbology, guidance cues, and sensor image

Figure 3: Sierra Nevada Corporation sensor suite on EH-60L

2.4 Sensor System

The sensor system used for these flight trials was the HALS-DM multi-sensor imaging system developed by the Sierra Nevada Corporation (SNC). This system consisted of a 94 GHz radar, a ladar, and a long-wave infrared (LWIR) camera. The system also uses *a priori* terrain database and obstacle data to generate imagery for terrain outside and beyond the sensors' fields-of-view. The radar data, ladar data, *a priori* data, and LWIR imagery are then fused to form a near-real-time complete see-and-remember terrain image out to the horizon. The generated sensor imagery consists of a grayscale, textured terrain world model with detected obstacles represented as colored points in space. This image, is output for display to the crew via the aircraft video system architecture allowing for overlay of symbology. Additionally, this image is used to provide terrain and obstacle elevations to the guidance algorithms.

2.5 Guidance

While visual cues can be partially restored through sensor imagery and cueing, it remains challenging for the pilots to judge the closure and/or sink rates necessary to achieve a safe approach and landing from these alone. The Integrated Cueing Environement Landing Guidance (ICE-LG)[10] was originally developed for the U.S. Air Force Three Dimensional

Landing Zone Joint Capability Technology Demonstration to provide the pilot with a navigation solution from approach entry (typically 0.8 nmi or 1.5 km) to the desired landing or hover point. ICE-LG was designed to enable pilots to consistently, safely, and precisely land a helicopter in DVE. Sensor-driven guidance algorithms can be used to determine and display flight guidance for pilotage based on sensed obstacles. This GeoGrid-based landing guidance manager enables obstructed-approaches and obstructed-landings (obstacles on or near the selected landing point). It uses active sensor data to identify obstacles within the approach path and calculates the required guidance to safely fly the aircraft over the obstacle(s), or modifies the termination-type to prevent the aircraft from landing on an obstacle identified at the landing point. Guidance is displayed to the pilot as dynamically-updated horizontal and vertical velocity 2D cues via the ICE symbology (magenta objects in Figure 2). The same guidance algorithms are used for the ICE symbology and to drive the flight control system for Coupled Collective mode.

3 FLIGHT TRIAL DETAILS

The European Flight Trials were conducted over the course of four weeks in two locations, Germany and Switzerland, with the goal of testing in different conditions at each location. Four countries participated in the flight trials: the United States, Germany, Switzerland, and the United Kingdom. The U.S. and Swiss test teams conducted flight tests at both locations, the German test team conducted flight tests in Germany, and the British test team conducted ground tests in Switzerland.

The U.S. Army flight test team conducted a total of 30.5 flight hours over the course of 25 flights including testing, checkout, and ferry flights. The flight crew for all flights consisted of an AFDD safety pilot, an evaluation pilot, two research system operators (at least one of which was from AFDD), and a Sierra Nevada sensor system operator. The winds during testing were generally 10 knots (5.1 m/s) or less. Temperatures ranged from 21 °F – 45 °F (-6.1 °C – 7.2 °C).

3.1 Germany

For three weeks, the DVE Mitigation test teams were hosted by the Wehrtechnische Dienststelle für Luftfahrzeuge und Luftfahrtgeät der Bundeswehr (WTD61) located at the Ingolstadt Manching Airport in Manching, Germany. The desired conditions for the testing conducted at WTD61 included rain, fog, and smoke. Testing was primarily conducted over the north runway (Runway 25R) which was closed to other traffic. Located approximately halfway along the runway, there was a control tower (the North Tower) which was approximately 100 ft (30 m) tall where AFDD set up a DGPS correction uplink station. Additionally, by installing a S-band telemetry transmitter on the EH-60L, it was possible to use WTD61's existing telemetry infrastructure to receive and display state and video data in real-time from the helicopter.

Just to the north of the departure end of the runway, WTD61 constructed an obstacle field in an area 100 m on a side which included: poles and wires, a UH-1 helicopter, an armored personnel carrier, a fence, and numerous smaller obstacles. This obstacle field was adjacent to a power substation which provided additional objects for sensor detection. On several occasions, smoke grenades were set off between the helicopter and the obstacle field to artificially generate DVE conditions.

Testing was additionally performed in a "sensor VFR" corridor which consisted of predefined boundaries and minimum altitudes in a left hand traffic pattern over the Manching Airfield; the downwind leg was directly over the southern runway. This sensor VFR corridor was developed to allow flight testing in IMC when normally this would not be permitted. This was possible due to the DGPS system which provided very precise position data and the telemetry system which allowed for real-time monitoring of the aircraft by a WTD61 controller located in the WTD61 telemetry station at all times. A procedure was developed by WTD61 and the U.S. Army such that if the ground controller determined that the helicopter had left the corridor or felt that it would imminently leave the corridor, he would instruct the helicopter crew to depart the airfield and immediately open an IFR flight plan to an alternate airport as discussed during the pre-flight briefing. This procedure was tested in VMC conditions but was not required during DVE testing since

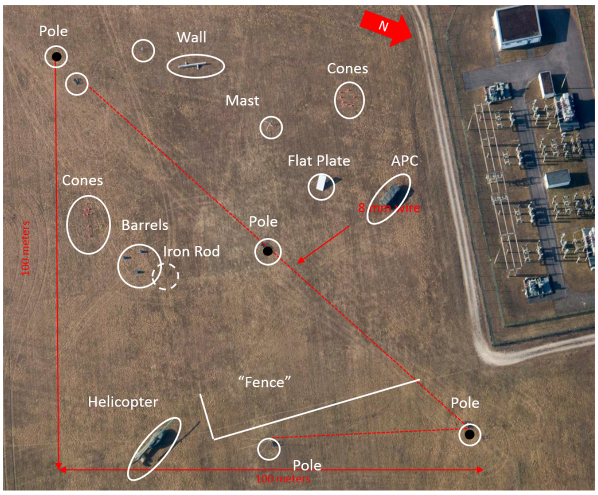


Figure 4: Obstacle field layout at WTD61

the pilots were able to stay within the boundaries using the tunnel-in-the-sky display

3.2 Switzerland

The fourth and final week of testing was conducted from the Alpnach Air Base located in Alpnach, Switzerland. The primary test site in Switzerland was Älggialp, an alpine valley approximately 8 nautical miles (15 km) south of the air base at an altitude of approximately 5,400 ft (1,650 m). Light whiteout conditions were obtained on the first two flights, however rain at the test site caused an ice layer to form preventing further whiteout at Älggialp. An obstacle field was not present at the whiteout testing zone, however many of the approaches were conducted to place several huts or a line of fence posts within the sensor field of view. One flight was conducted in remote area near Gauligletscher, approximately 20 nautical miles (37 km) to the southwest of Alpnach Airbase, during which additional approaches were successfully conducted in light whiteout conditions. Lastly, one qualitative evaluation was performed at Emmen Air Base. DGPS and telemetry were not used during the testing in Switzerland.

3.3 Qualitative Evaluations

As a secondary goal, 12 test pilots performed qualitative evaluations of the EH-60L system in GVE conditions. Six of the pilots were from the Swiss Air Force, four were from the German Air Force, and two were from the Rotary Wing Test and Evaluation Squadron in the United Kingdom. While the pilots were very experienced, they had limited to no experience in the UH-60 Black Hawk and none had any previous experience with the ICE displays or ICE landing guidance. Prior to each qualitative evaluation, the pilots received a detailed briefing on the ICE display and guidance algorithms and conducted several practice approaches using a desktop simulator.

All qualitative evaluation flights were conducted under VFR and with a UH-60 instructor pilot as the safety pilot. Each flight lasted for approximately 1.5 hr and consisted of traffic pattern approaches to the obstacle field or runway. After a brief familiarization with taxiing, takeoff, and landing, the first approach was flown by the EP from departure through about a 1 nmi (1.8 km) final approach at which point the SP took the controls and flew to a 50 ft (15.2 m) hover short of the obstacle field. During this approach, the EP was able to concentrate on and evaluate the sensor image. The remainder of the flight consisted of approaches flown by the EP to the runway and were a mixture of approaches to landing or hover, a standard right traffic pattern or the sensor VFR left traffic pattern, and with or without coupled collective. Following the flight each evaluation pilot was asked to answer a detailed questionnaire developed by the U.S. Army Research Laboratory.

4 Flight Test Results

4.1 Sensor Performance

Initial testing of the SNC sensor system at Manching Airfield revealed several issues including reduced EGI GPS position accuracy and degraded sensor imagery resulting from the implementation of a new object based fusion algorithm. The EGI accuracy was improved by reloading a cryptographic key which had expired at the new year and the fusion algorithm was reverted to the point based algorithm tested during the Yuma Flight Trials. These changes resulted in a greatly improved image on the pilot displays.

The sensor suite consisted of three sensors: a ladar, a radar, and a long wave infrared camera (LWIR). Sensor limitations were found in all environments and the sensor system was tuned to some degree prior to encountering each obscurant. However, due to the mostly clear weather, it was not possible to iterate these tuning adjustments and the results obtained during this testing are not necessarily indicative of the best possible performance for these conditions.

The ladar generally gave the most precise, highest resolution image, however it was unable to penetrate obscurants. The radar provided a relatively vague, low resolution image but was able to penetrate obscurants. The LWIR is a camera and can only provide a 2D image which can be useful but does not by itself aid in developing a 3D world model showing terrain and obstacles. The LWIR performance was generally reduced when obscurants were present. Table 1 summarizes the sensor performance for the different environments.

The image which is displayed to the pilot is the output of the sensor fusion algorithms which combines the different sensor data with the *a priori* data. This fused image consists of grayscale DTED data superimposed with the LWIR image also in grayscale. The ladar and radar returns show up as colored dots; the color changes based on mode of flight and height

Table 1: Effect of environment on sensor performance

	Ladar	Radar	LWIR
Fog	Obscured	No Effect	Reduced
Rain	Reduced	Reduced	Reduced
Whiteout	Obscured	No Effect	Obscured

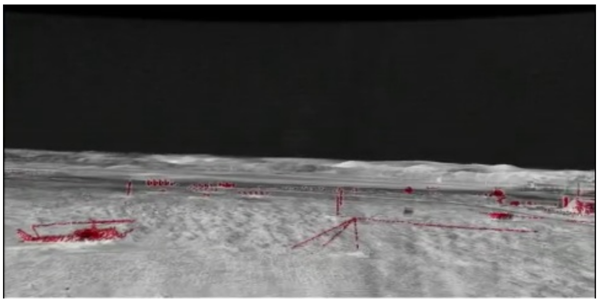
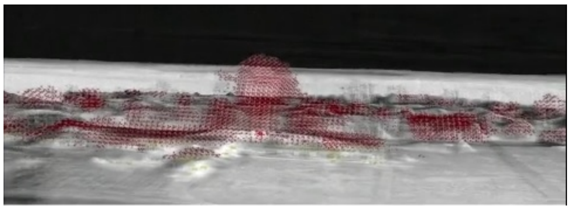
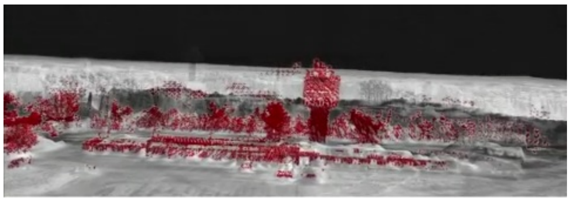


Figure 5: Sensor fusion image of obstacle field in clear air

(a) Day TV



(b) Sensor fusion output in fog



(c) Sensor fusion output in clear air

Figure 6: North Tower in fog

above the local ground plane. In enroute flight, obstacles which are detected but are below the aircraft are colored green while those above the aircraft are colored red. In low-speed and hovering flight, the obstacles are colored yellow up to 2 ft (0.6 m) and are colored red above that. Figure 5 shows an example of the fused sensor imagery presented to the pilot taken in clear air at the hover point near the obstacle field. In this image, most of the objects are well defined as a result of the high resolution ladar data. In the foreground, it is possible to make out the UH-1 helicopter on the left as well as a pole with guy wires and a wire stretching from the center of the image to the right. In the background are additional poles as well as returns from smaller obstacles and finally a fenceline in the far distance. On the right of the image, there is an armored personnel carrier, another wire stretching from right to left, and a power substation at the far right of the image. Just right of center is a flat plate which shows up in the LWIR image as a dark patch, but does not have any radar or ladar returns.

4.1.1 Fog

Moderate and heavy fog was encountered during one flight at Manching. Several approaches were conducted to the obstacle field which was generally in moderate fog resulting in variable visibility down to 100 ft (30 m). Additionally, pedal turns were conducted over the runway looking toward the North Tower which was completely obscured by heavy fog. In the fog, the LWIR image generally had reduced definition and range but it was still able to show large objects or structures which were not visible to the unaided eye. The ladar range was reduced in the moderate fog around the obstacle field and provided no useful returns of the North Tower in the heavy fog. The radar was unaffected by the fog.

Figure 6 compares the visual image and the fused sensor image when looking toward the North Tower in heavy fog with the sensor image taken on a clear day. In Figure 6a, it is not possible to see the tower in the center of the image due to the heavy fog. However, in Figure 6b, the radar returns show in very low detail, the tower in the center of the frame and some lower buildings to both sides. It is hard to distinguish with the overlaid radar returns, however the IR image does show the outline of the tower as well. Figure 6c shows the sensor fusion image in clear air which highlights the greater detail and resolution provided by the ladar. It is also possible to make out the central control tower in the LWIR image behind and to the left of the North Tower; it is not visible in Figure 6b

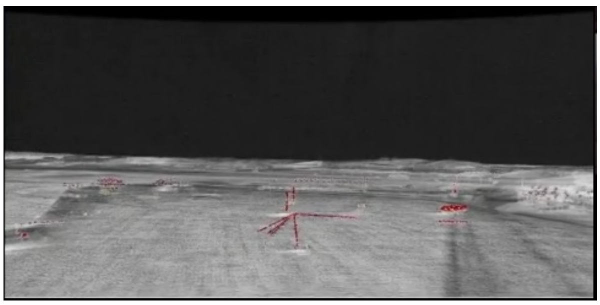


Figure 7: Sensor image of obstacle field in rain

4.1.2 Rain

Light rain was encountered on the final day of testing at Manching during which approaches were conducted to the obstacle field. Both the ladar and the radar demonstrated reduced range and the LWIR was somewhat blurry. The rain drops in the air did not result in any false returns.

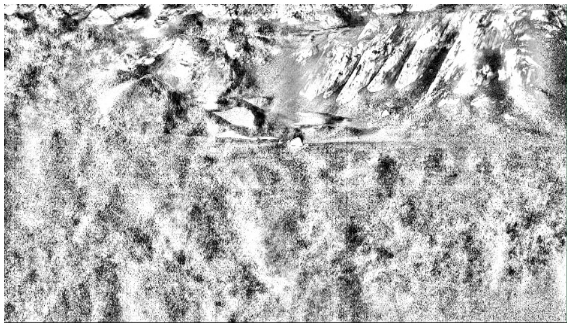
Figure 7 shows the fused sensor image of the obstacle field when at the hover point and overall shows the reduced range of the sensors when compared with Figure 5. In the image, it is possible to see the armored personnel carrier on the right as well as some poles and parts of wires in the center of the image in the high resolution provided by the ladar. Some radar only returns are present further away but the objects they represent are indistinguishable due to the low resolution and sparseness of the data. None of the smaller objects to the left of the poles provide any ladar or radar returns. The outline of the UH-1 helicopter is visible in the LWIR image on the far left of the image, though only a few ladar or radar returns were received from it. The flat plate to the right of the poles is not visible in the LWIR image.

4.1.3 Whiteout

Light whiteout conditions were encountered on the first day of testing at Älggialp in Switzerland. Due to rain at the test site causing a layer of ice to form on top of the snow later in the week, the first two flights at Älggialp offered the best whiteout conditions. Light whiteout conditions were also experienced in the vicinity of Gauligletscher which was at a higher elevation and received snow rather than rain, however there were very few obstacles for the sensors to detect.

In whiteout conditions, only the radar was effective as it was unaffected by the blowing snow and was actually able to penetrate the layer of snow and receive returns off the ground underneath. When in the whiteout, the ladar produced returns off the blowing snow which had to be removed and it was not able to penetrate the snow to scan the surroundings. The LWIR provided a degraded image even in clear air due to a relatively small temperature differential. When in whiteout conditions, the blowing snow completely obscured the LWIR image. Figure 8 compares the visual and LWIR image. In Figure 8a, while the whiteout is present, it is still possible to make out features in the foreground such as the tops of the snow banks and the large clumps of snow. In Figure 8b only the top right quadrant of the image shows terrain, while the rest is washed out by the blowing snow.

(a) Day TV



(b) LWIR

Figure 8: Images during whiteout approach

4.2 Qualitative Evaluation

This section covers the 12 qualitative evaluations conducted by the guest pilots. During these evaluations, the pilots were asked to only provide qualitative feedback. However, quantitative analyses of the performance during these evaluations was carried out and the results are presented in the following sections.

4.2.1 Approach Performance

The majority of the test points conducted during the qualitative evaluations were approaches to hover or landing during which the pilots were asked to follow the guidance cues as closely as possible. The landing guidance initiated at 0.8 nmi (1.5 km) from the desired

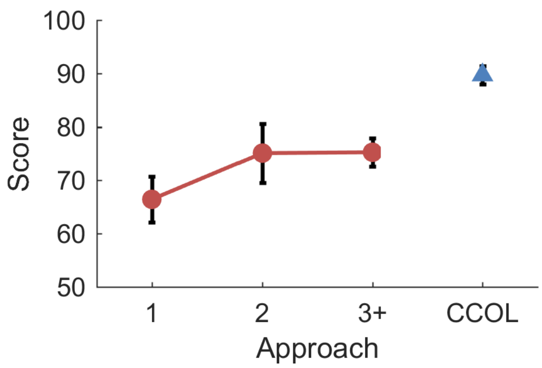


Figure 9: Approach scores

hover or landing point and consisted of a deceleration and descent schedule based on the distance to the termination point. As a method of quantifying the approach performance, an approach score was developed as a part of the Yuma Flight Trials. The score is calculated using the following equation:

$$S = 100\left[1 - \left(\frac{t_x + t_y + t_z}{t_{app}}\right)\right]$$

where t_x, t_y, t_z represent the amount of time on the approach which was spent outside of desired performance for the longitudinal, lateral, and vertical axes respectively and t_{app} is the total time of the approach. A score of 100 indicates that the entire approach was flown within the desired performance standards. A score of -200 indicates that the entire approach was flown outside of desired.

Figure 9 plots the average approach scores and standard error of the mean for the first, second, and subsequent uncoupled approaches performed by all 12 evaluation pilots, and compares this with the average approach score for all coupled collective approaches. Each pilot generally flew 3–5 uncoupled approaches and 2–3 coupled approaches over the course of the flight. The data in the figure show that the pilots quickly improved from an average score of 66 on the first uncoupled approach to an average score of 75 on the second uncoupled approach and then the average score stayed at 75 for the subsequent uncoupled approaches. By contrast, the average score when using the coupled collective was 90 indicating that the pilot was able to stay within desired for a greater portion of the approach. This improvement in performance results from the coupled collective keeping the vertical axis within desired condition automatically. This aiding in turn allowed the pilot to concentrate more on the lateral and longitudinal cues and therefore improve the performance in these axes as well.

4.2.2 Hover Performance

Approximately half of the approaches flown by each evaluation pilot finished at a hover over a desired point. While the pilots were not asked to maintain their position for 30 seconds as was the case in the Yuma Flight Trials, they did perform some extended hover maintenance prior to departing for the next approach. Figure 10 plots the horizontal and vertical RMS errors during the hover maintenance for the first, second, and subsequent (3+) approaches and compares the uncoupled performance against the performance with the coupled collective engaged (at hover the coupled collective reverts to a radar altitude hold mode).

A surprising result shown in Figure 10 was that the horizontal error was lowest on the first approach and

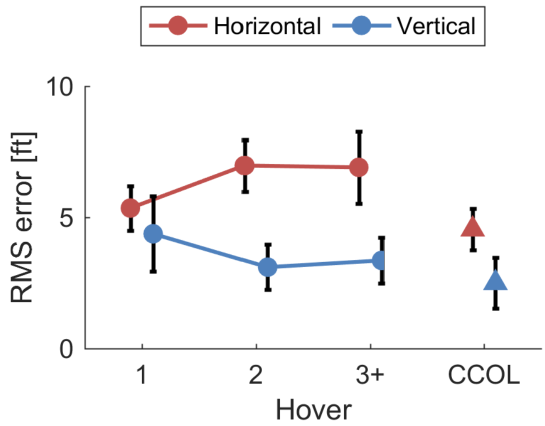


Figure 10: Horizontal and vertical RMS error at hover

it increased to approximately 7 ft (2.1 m) for the subsequent approaches. This contrasts with the vertical axis RMS error which shows improvement from the first to subsequent approaches. One possible explanation of the increase in horizontal error is that the pilots concentrated more on the vertical axis after the first approach.

When performing a hover after a coupled collective approach, the RMS error was reduced by 25% to 35%. This improvement in vertical performance was a direct result of of the altitude hold mode. The altitude hold mode also contributed to the improvement in horizontal performance as the pilots were able to focus on maintaining horizontal position knowing that the altitude hold would take care of the vertical axis.

4.2.3 Landing Performance

Figure 11 plots the lateral and longitudinal error at touchdown for all pilots. The red symbols represent uncoupled approaches while the blue triangles represent coupled approaches. The red uncoupled approaches are further differentiated as the first landing represented by diamond symbols and subsequent landing represented by circles; the first landing was always performed uncoupled. The data in the figure show that 76.3% of the landings were completed within one rotor radius (27.3 ft or 8.3 m) of the desired landing point. Notice however that of the seven landings which were outside this distance, five were the first landings as represented by the diamond indicator. It was found on the first approach that some of the pilots had difficulty in following the vertical cueing at the end of the approach and therefore had a tendency to float at about 3 ft (1 m) for some time resulting in landing long. When ignoring the first landing, 92.3% were completed to within a one rotor radius of the desired point.

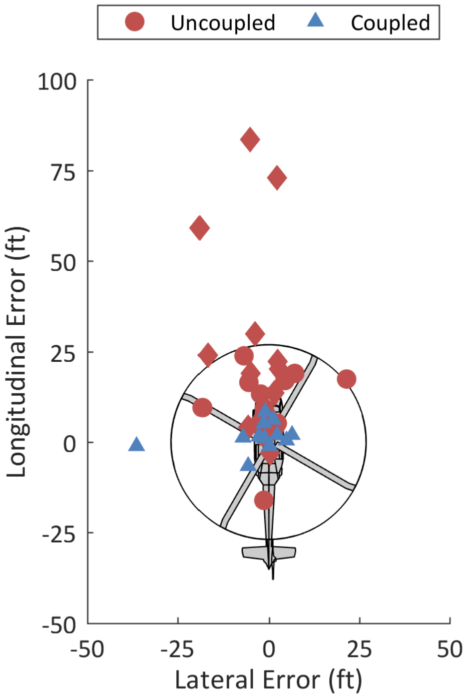


Figure 11: Landing distance error

Finally, the addition of the coupled collective further reduced the landing error; all but one coupled landing were completed within 10 ft (3 m) of the desired landing point. The coupled collective reduced the number of cues the pilot had to follow from two to one (heading hold was active for all approaches) thus allowing the pilot to focus on satisfying the horizontal guidance cues resulting in more accurate landings.

Figure 12 plots the average radial error across all 12 evaluation pilots against the landing sequence for the first, second, and all subsequent (3+) landings without the coupled collective engaged and compares this with the average radial error for all coupled collective approaches. The bars around each point represent the standard error of the mean. The data show

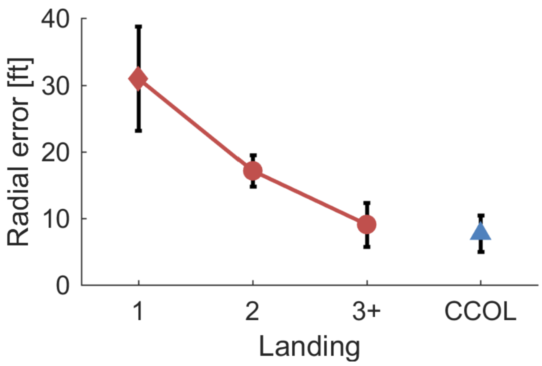


Figure 12: Landing distance error

a rapid improvement in uncoupled landing accuracy from an average error of 31.0 ft (9.4 m) on the first landing to an average error of 9.1 ft (2.8 m) for the third or subsequent landings. The coupled collective data point shows still further reduction in radial error to 7.7 ft (2.4 m) and a reduced standard error of the mean indicating more consistency.

4.2.4 Pilot Comments

During the flight, the evaluation pilots were encouraged to voice any comments they had to be captured on the audio/video recorder. Immediately after each flight, the entire test team participated in a debriefing during which the video recordings were reviewed and the evaluation pilots were able to expand on the comments made during the flight. Finally, following the debrief, the pilots were asked to complete a questionnaire developed by the U.S. Army Research Laboratory which focused primarily on the different aspects of pilot cueing.

The coupled collective mode was appreciated by all the evaluation pilots who described it as a “nice feature” and resulted in “much more relaxed” approaches. It was noted that the coupled collective made the approach “much easier” by allowing the pilot to concentrate on only one cue (lateral/longitudinal speed) and thus providing additional capacity. Some pilots used this spare capacity to try to more closely follow the horizontal speed guidance commands while other pilots were able to process more of the background sensor image.

The approach, landing, and hover guidance, when coupled with the 2D cueing proved to be relatively easy for the pilots to follow with one pilot commenting that it was “very intuitive to use, even with almost no training.” However, the pilots commented on the lack of guidance for takeoff or enroute flight. Visual cues partially compensated for this lack of guidance. When taking off, the pilot was able to use the two towers of the artificial landing pad to estimate height. In enroute flight, the lack of guidance was offset by a preprogrammed set of waypoints and a fixed airspeed command generated by the ICE cueing system.

Overall, the cueing systems were generally well received. Of the visual cues, the 2D cues were most useful to the pilots especially at the end of the approach and the transition to a hover or landing. The “very intuitive” and “well balanced” doghouse, velocity vector, and acceleration cues led to “good precision for hover and landing”, providing the ability to immediately detect and mitigate drift and “fly the helicopter very precisely within a few feet.” Numerical values were generally harder to interpret and several pilots noted that they only served to increase workload unnecessarily to precisely maintain altitude and airspeed to the resolution of the display. Additionally

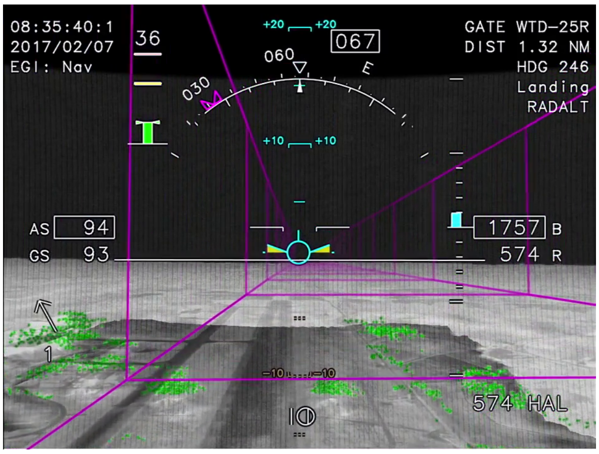


Figure 13: Enroute guidance

pilots commented that much of the text and numerical data simply added clutter to the display. The 3D cueing was most useful during the takeoff, specifically the two towers which helped the pilots climb and transition to the enroute cueing. Some pilots commented that the artificial landing pad lacked sufficient 3D cues for the pilots to maintain hover position or to determine relative motion.

Enroute cueing was minimal consisting of a "tunnel-in-the-sky" and a flight path marker as shown in Figure 13. Speed guidance during enroute flight was provided by the wings of the flight path marker which indicated velocity error through angular deviation from horizontal; in Figure 13 the wings are deflected up indicating that the pilot is flying faster than the desired airspeed. The sensor VFR corridor was set up as a traffic pattern with relatively sharp turns on the departure-crosswind-downwind leg and the base-final leg which are not realistic in DVE conditions. However the pilots noted that it would be beneficial to have a predictive type of flight path marker which they could line up with the upcoming boxes during turns; a predictor was available on the second screen which showed a bird's-eye-view but the pilots rarely looked at it. Several pilots also noted that it would be helpful to continue the enroute guidance past the initiation of the landing guidance (at 0.8 nmi or 1.5 km), especially early in the approach when the target velocity cue is near the top of the display.

Overall, most of the pilots rated the aural cueing positively, however two issues were mentioned. Some pilots felt that the radar altitude callouts at every 10 ft when below 50 ft to be excessive. Secondly, aural cues which "overlapped with other warnings and calls" were not appreciated. Tactile cueing was generally rated poorly by the evaluation pilots, especially at a hover, noting that the cueing was generally "unnecessary". During hover maintenance, most EPs stated that tactile cueing was overwhelming and "did not help at all" as rapid tactile cues in multiple axes were difficult to understand. The "distracting" tactile cueing tended to be the first cue which the pilots ignored as their workload increased. In enroute flight, it was less likely that multiple axes would be active at once and so some pilots felt it was somewhat more effective.

The pilots noted that the sensor visualization enhanced their situational awareness during every phase of flight to some degree. The pilots appreciated the colorization of points which conveyed obstacle height. However, the pilots noted that it was at times "difficult to interpret the sensor image and discern obstacles." With the exception of large objects such as the UH-1 helicopter or armored personnel carrier, the pilots were usually unable to identify obstacles based on the shape of the dots. Additionally, obstacles which were visible and obvious in the IR image did not always have ladar or radar returns superimposed. Errant red dots that appeared suddenly while hovering were "disturbing."

4.3 Discussion and Recommendations

An unexpected issue was discovered when the landing gear skis were installed for the testing in Switzerland. With the skis installed, the main landing gear struts were partially compressed which resulted in the WOW switches being triggered at all times and making it impossible to use the switches to determine when the aircraft had landed. This was problematic for the flight control system which uses the WOW switches for numerous mode changes, including a transition of the response types as well as an auto collective lowering mode to finish a coupled collective approach to landing; this auto collective reduction mode was disabled for the testing while the skis were installed. A new method of determining when the aircraft is on the ground would be needed for any system which depends on WOW switch information.

Throughout the European Flight Trials, all approach paths were clear of tall obstacles which would require deviation from the standard unobstructed approach profile which eliminated the need for the guidance algorithms to rely on sensor data to plan the approach. However in the future, a robust sensor driven guidance system, such as the Obstacle Field Navigation and Safe Landing Area Determination algorithms[11], will be needed to demonstrate the systems in a more realistic environment. To this end, several additional features would be beneficial. First, the rate of false returns from the sensor would need to be reduced while at the same time, the guidance will need to be able to handle some level of false returns. Next, the sensor fusion system should be able to provide information about the suitability of the intended landing point such as terrain slope and roughness enabling the guidance algorithms to select the best place to land. Additionally it would be beneficial if the sensor system could provide the guidance algorithms information on the performance of the individual sensors and a figure of merit or confidence value of the current sensor solution which could be used to tailor the guidance commands.

The coupled collective mode demonstrated the greatest impact on improving performance and reducing pilot workload. Further integration of the guidance and flight control is expected to provide further benefits. To achieve this, the fusion system should have the flexibility to accommodate maneuvering flight, rather than following a glide slope or predetermined route and should drive on-the-fly route planning and provide insight to the aircrew on the feasibility of a route change.

5 CONCLUSIONS

The DVE Mitigation Program successfully conducted a series of flight trials in Europe in fog, rain, and whiteout conditions. Based on the flight test results presented, the following conclusions can be drawn:

1. The coupled collective mode in which the collective automatically followed the vertical guidance command, helped to improve approach, hover, and landing performance, while reducing pilot workload and providing the pilot with spare capacity.
2. Coupled flight control and guidance in other axes would be expected to further improve performance and reduce workload; however, to take full advantage of coupled flight controls, improvements in sensor fusion and guidance such as improved false return rejection and landing point terrain characterization are needed.
3. The landing guidance and visual cues made precise landings and hovers intuitive and easy with minimal training; additional guidance and cueing are needed for takeoff and enroute flight.
4. Sensor performance varied in the different conditions: due to the different obscurants,the ladar range was reduced to completely obscured; the radar was able to penetrate the obscurants (and snow on the ground) though range was reduced somewhat in the rain; and the definition of the LWIR image was generally reduced though completely washed out in whiteout.

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