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Using Vision System Technologies for Offset Approaches in Low Visibility Operations

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Abstract

Flight deck-based vision systems, such as Synthetic Vision Systems (SVS) and Enhanced Flight Vision Systems (EFVS), have the potential to provide additional margins of safety for aircrew performance and enable the implementation of operational improvements for low visibility surface, arrival, and departure operations in the terminal environment with equivalent efficiency to visual operations. Twelve air transport-rated crews participated in a motion-base simulation experiment to evaluate the use of SVS/EFVS in Next Generation Air Transportation System low visibility approach and landing operations at Chicago O'Hare airport. Three monochromatic, collimated head-up display (HUD) concepts (conventional HUD, SVS HUD, and EFVS HUD) and three instrument approach types (straight-in, 3-degree offset, 15-degree offset) were experimentally varied to test the efficacy of the SVS/EFVS HUD concepts for offset approach operations. The findings suggest making offset approaches in low visibility conditions with an EFVS HUD or SVS HUD appear feasible. Regardless of offset approach angle or HUD concept being flown, all approaches had comparable ILS tracking during the instrument segment and were within the lateral confines of the runway with acceptable sink rates during the visual segment of the approach.

Keywords: Enhanced Flight Vision Systems; Synthetic Vision Systems; Head-up Display; NextGen

1. Introduction

The U.S. air transportation system is undergoing a transformation to accommodate the movement of large numbers of people and goods in a safe, efficient, and reliable manner. One of the key capabilities envisioned to achieve this Next Generation Air Transportation System (NextGen) is the concept of equivalent visual operations (EVO). EVO is the capability to achieve the safety of current-day Visual Flight Rules (VFR) operations and maintain the operational tempos of VFR irrespective of the weather and visibility conditions.

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One research challenge for EVO is the definition of required equipage on the aircraft and at the airport. With today's equipment and regulations, significant investment is required in on-board equipment for navigation, surveillance, and flight control and on the airport for precision guidance systems and approach lighting systems for "all-weather" landing capability. The levels of equipment redundancy, capability, maintenance, performance and crew training dramatically increase as landing visibility minima decrease. Synthetic Vision Systems and Enhanced Flight Vision Systems (SVS/EFVS) offer a means of providing EVO capability without significant airport infrastructure investment while potentially increasing efficiency and throughput during low visibility operations.

SVS is a computer-generated image of the external scene topography that is generated from aircraft attitude, high-precision navigation, and data of the terrain, obstacles, cultural features, and other required flight information. EFVS is an electronic image of the external scene generated by imaging sensors, such as a Forward-Looking InfraRed (FLIR) or Millimeter Wave Radar, and presented on a head-up display (HUD). Synthetic and Enhanced Vision Systems (SEVS) technologies form the basis for an electronic display of visual flight references for the flight crew. The primary reference for maneuvering the airplane is based on what the pilot sees electronically through the SEVS, with conformal and other symbology, in lieu of or supplemental to the pilot's natural vision, in low visibility conditions.

NASA and others have developed SVS technologies and shown that they provide significant improvements in terrain awareness and reductions for the potential of Controlled-Flight-Into-Terrain incidents/accidents, improvements in flight technical error to meet required navigation performance criteria, and improvements in situation awareness without increased workload [1-3]. EFVS has also been shown to provide many of the same and other complementary benefits to SVS technology, using a real-time view of the external environment, independent of the aircraft navigation solution or database. Operational credit is available by use of an approved EFVS through Title 14 of the Code of Federal Regulations (CFR) Section (§) 91.175 such that operators conducting straight-in instrument approach procedures may descend below the published Decision Altitude (DA), Decision Height (DH) or Minimum Descent Altitude (MDA) down to 100 feet (ft) above the touchdown zone elevation (TDZE). The FAA has started a rulemaking project to expand this operational credit to permit an EFVS (i.e., electronic vision) to be used in lieu of natural vision during a straight-in instrument approach procedure which contains published vertical guidance.

Previous NASA work provided the foundation and efficacy for much of these activities [3,4]. This paper documents the findings of an experiment conducted to evaluate three critical corner cases in the application of these technologies. Specifically, the work evaluated head-up SEVS concepts while flying straight-in instrument approach procedures that contained offsets with variations in runway edge lines positioning and guidance cue implementation.

2. Method

2.1. Subjects

Twenty-four transport-rated pilots served as test subjects for the research, representing twelve flight crews. Crews were paired by airline to ensure crew coordination and cohesion with regard to operating procedures. The Captains were recruited on the basis of HUD experience (at least 100 hours), with preference given to pilots with EFVS experience. The Captain was the designated pilot-flying (PF) throughout all the trials and the First Officer served as the pilot-monitoring (PM).

2.2. Simulation Facility

Testing took place in NASA Langley Research Center's Research Flight Deck (RFD). The full-mission, motion-base simulator is modeled after state-of-the-art transport aircraft and is configured with a left-seat HUD and with four 10.5 inch Vertical (V) by 13.25 inch Horizontal (H) displays tiled across the instrument panel. The content on these displays was experimentally dependent, but followed standard primary flight display/navigation display (PFD/ND) design protocol. The aircraft model was a Boeing 757-200 aircraft, flown using NASA-developed fly-by-wire control laws and side-stick control inceptors. The Rockwell-Collins HGS-6700 HUD is collimated and subtends approximately 40° H by 30° V field-of-view (FOV). However, a reduced FOV (26° by 21°) was simulated to be directly comparable to the previous fixed-base SEVS simulation studies. The video input to the HUD was either a synthetic

vision (SV) or enhanced vision (EV) source. The symbology format was a modified version of the HGS Primary mode format and included runway edge lines, a flight path angle reference cue and a flight path-referenced guidance cue. PF had controls to adjust symbology brightness, imagery brightness and imagery contrast as well as a declutter control to independently toggle imagery and symbology on/off.

2.3. Simulation Databases

Operations were simulated at Chicago O'Hare International Airport (FAA identifier: KORD). The simulation was built around FAA source data for KORD, valid from 11 March 2010 to 8 April 2010.

Day simulations with experimentally varied visibility were flown using a collimated out-the-window (OTW) image generation system across approximately 200° H by 40° V FOV at 26 pixels per degree resolution. The weather consisted of low to moderate winds with either 10 knot headwind, 10 knot tailwind, 7.5 knot crosswind, or 15 knot crosswind, in light turbulence. Airport lighting was drawn using calligraphics.

A SV database used a 1 arc-second digital elevation model centered around KORD. The elevation model was draped with an elevation-based coloration texturing. Each KORD runway was modeled as an asphalt-colored polygon. Threshold lines, edge lines, and runway numbers were added.

The EV real-time simulation was created by the Evans and Sutherland EPX physics-based sensor simulation and mimicked the performance of a short-wave/mid-wave FLIR, using a ~1.0 to 5.0 micron wavelength detector. The KORD database was instantiated with material code properties. From this database, an IR sensor simulation, interacting with this material-coded database and the simulated weather conditions, created a nominal enhanced visibility of approximately 2400 ft.

2.4. Independent Variables

2.4.1. Head-Up Flight Display Concepts

Three HUD concepts (referred to as the Conventional HUD, SVS HUD and EFVS HUD) were tested, differing from each other only in the absence or presence and type of imagery (SV or FLIR) on the PF HUD. Both the PF and PM had Conventional PFDs (i.e., no SVS) and NDs head-down. The PM also had a head-down display of FLIR imagery for EFVS HUD runs and was blank (black in color) for Conventional and SVS HUD runs.

2.4.2. Instrument Approach Procedure Offsets

Testing included an experimental variation of instrument approach procedures (IAPs) offsets. The IAP offset was varied between 0-deg (no offset), 3-deg, and 15-deg - all within that allowable under straight-in IAPs. Each IAP used a 3-degree descent angle. Testing without offsets was conducted on KORD Runways 9R, 4R, 22L, and 22R with Medium intensity Approach Lighting System with Runway (MALSR) alignment indicator lights installed. Testing with offsets was conducted on Runway 27L with Approach Lighting System with Sequenced Flashing Lights (ALSF-2) installed.

The 0-deg offset approach used a 150 ft DA as allowable under Special Authorization Category I approach procedures. The OTW visibility levels were varied: 1800 ft, 1400 ft, or 1000 ft. The 3-deg offset approach was an ILS approach with a localizer offset to the right of the runway heading and 200 ft DA. A fixed OTW visibility of 1400 ft was flown. The 15-deg offset approach was a simulated LDA (localizer-type directional aid) approach with an offset to the right and used a 320 ft DA. A fixed OTW visibility of 4000 ft was used for the 15-deg offset so crews had sufficient visibility to continue beyond the DA (320 ft) using natural vision (as dictated by the experiment design, see reference 5).

2.4.3. Edge Lines Positioning Source on Offset Instrument Approach

The intended landing runway was depicted on the HUD by edge lines, 8000 ft long by 200 ft wide. The HUD edge lines positioning source was experimentally varied while flying an IAP. The motivation for testing this independent variable arose since there is not an industry standard.

In one case, the edge lines were positioned by the navaid source; thus, the edge lines do not overlay the runway of intended landing on an offset IAP, but are aligned with the offset localizer. In the other case, the edge lines are geo-referenced to the landing runway. The experiment assessed if there was any influence when using different HUD concepts and edge lines positioning sources on the decision to land and on performance.

2.4.4. HUD Guidance Cue Variation on Offset Instrument Approach

The presence or absence of the guidance cue below the DA was experimentally varied. There is no industry standard for removal of the guidance cue on the HUD.

The guidance was either removed at DA/DH or not removed, in which case, the guidance cue continued to function normally below the DA until it latched to the flare cue during landing. The experiment assessed if there were any effects from a guidance cue that may be directing the flight toward an IAP offset from the landing runway. In Figure 1, the worst case scenario is shown where the symbolic edge lines and guidance cue are referenced to or guiding toward the offset localizer and not the real runway (which is indicated by the EV image of the runway approach lights).



Figure 1. EFVS HUD with edge lines and guidance cue referenced to offset localizer navaid.

2.5. Evaluation Task

The PF hand-flew the approach from the left seat with the auto-throttle set to “speed-hold” at the approach speed of 130 knots indicated airspeed. The auto-throttle automatically reduced to idle thrust at 35 ft above ground level (AGL) for landing. The run was terminated once the PF completed the landing, roll-out and turn-off or upon go-around initiation. The aircraft was configured to land prior to each run (landing gear down and flaps 30 degrees).

The PFs were instructed to fly the aircraft as if there were passengers aboard, track the approach path, and land within the touchdown zone with an acceptable sink rate. After landing, they were to maintain the centerline and exit at the expected taxiway at a speed of 5 to 15 knots at the 90 degree exits or 30 knots at the high-speed exits. They were also instructed to initiate a go-around if the approach became unstable or if there were any safety concerns.

2.6. Crew Procedures

The PF flew the approach using the HUD as the primary flight reference. The PM monitored using the available head-down display information, including a FLIR repeater (when EFVS HUD was flown), and the OTW scene and assisted the PF as appropriate and necessary. There was no transfer of control from the PF to PM (or vice versa). The procedures for the Conventional and SVS HUD concepts were identical and followed normal crew instrument approach procedures. Training emphasized that the crews follow §91.175 procedures that the required visual references to continue the approach below the published DA/DH and for landing must be distinctly visible and identifiable by the pilot using natural vision. The EFVS procedures were built around common practice in current EFVS operations and FAA requirements (14 CFR §91.175 (l)) but extended to emphasize that to descend below the

DA/DH and to descend below 100 ft height above the TDZE depended upon the PF being able to recognize and identify the required visual references, using EFVS.

2.7. *Experiment Matrix*

The 0-deg offset experiment test matrix was a full-factorial combination of three visibility levels (1000, 1200, 1400 ft RVR) against three Vision System (None, SVS, EFVS) HUD concepts as crews flew no offset IAPs. The offset test matrix included 3-deg (10 total) and 15-deg offset approach runs (5 total). The 3-deg offset runs included a full-factorial combination of Vision System (None, EFVS), Edge Lines Positioning Source (georef, navaid), and Guidance Cue (remove at DA, retain and latch to flare cue), plus 2 additional runs of SVS with geo-referenced edge lines with either the ‘remove at DA’ or ‘retain and latch to flare cue’ guidance cue variations. All 15-deg offset approaches (5 total runs) had the guidance cue latched to the flare cue. Four approaches were a combination of HUD Vision System (None, EFVS) and Edge Lines Positioning Source (georef, navaid) and one approach was SVS HUD with geo-referenced edge lines.

2.8. *Test Conduct*

After an initial briefing, a 1.5 hour training session was conducted in the RFD to highlight crew EFVS and SVS procedures and practice approaches to landings with the HUD concepts. Each PF was trained to an acceptable standard of touchdown performance before data collection began.

3. **Results**

Linear Mixed Models (LMMs) – statistical models for continuous dependent measures in which the residuals are normally distributed but may not be independent or have constant (homogeneous) variance – were applied in the analysis. By-subject variance due to individual differences was accounted for by using a Random Intercept Model in the LMM analyses. Unless otherwise specified, all LMMs 1) employed the Identity (constant variance and independent residuals) covariance structure for the residuals, 2) were estimated with restricted maximum likelihood, and 3) met the assumptions of normality and constant variance for the residuals and for the random effects.

The within-subject fixed factors for this experiment were SEVS HUD display concept, visibility level, approach offset, HUD edge-line positioning source, and guidance cue removal variation. The random factor was crew.

Approach statistics, lateral deviation from centerline (in ft) and sink rate (in ft/min), were used to evaluate how effectively the pilots could fly an offset approach during the visual segment with the different SEVS display concepts. In addition, the number of landings and the number of go-arounds for the various combinations of fixed factors are provided. The dependent variables evaluated for approach performance were rms localizer error (in dots), RMS glideslope error (in dots), and lateral deviation from centerline (in ft) at two approach altitudes - 100 ft height above threshold elevation (HAT) and 50 ft HAT. The rms localizer and rms glideslope parameters were used to assess performance in the instrument segment of the approach and the lateral deviation from centerline at 100 ft HAT and 50 ft HAT were used to assess performance in the visual segment of the approach. Localizer error (rms) and glideslope error (rms) were calculated from 1000 ft AGL to 400 ft AGL for the analyses to ensure consistent comparison, including the 15-deg offset approaches. (The PFs initiated the turn toward the runway (away from the offset localizer) at or above the 320 ft DA for the 15-deg offset approaches.) Some analyses only used the 3-deg offset approaches; for these, rms localizer and rms glideslope error were calculated from 1000 ft to 200 ft AGL.

3.1. *HUD SEVS Concept and Offset Approach Effects*

For the HUD SEVS concepts in this analysis, edge lines were geo-referenced to the runway and the guidance cue was retained and latched to the flare cue during landing operations. The visibility levels were 1400 RVR for the 0-deg and 3-deg offset approaches and 4000 RVR for the 15-deg offset approaches.

Of the 108 approaches conducted, 103 resulted in a safe landing and 5 resulted in a go-around. There were 1) 0 go-arounds while conducting a 15-deg offset approach, 2) 0 go-arounds while flying with an EFVS HUD, 3) 3 go-arounds while flying the Conventional HUD (1 while conducting a 0-deg offset approach and 2 while conducting a 3-deg offset approach), and 4) 2 go-arounds while flying the SVS HUD (1 while conducting 0-deg offset and 1 in 3-deg offset approach).

Separate LMM analyses revealed significant differences in offset approach type for rms localizer deviation ($F(2,84)=5.10$, $p=0.008$) and rms glide slope deviation ($F(2,81)=4.26$, $p=0.017$) from 1000 ft AGL to 400 ft AGL. There were two unique subsets of rms localizer deviation for offset approach type: 1) 0-deg (mean, $M=0.016$ dots) and 3-deg ($M=0.015$ dots) and 2) 15-deg ($M=0.010$ dots). There were two overlapping subsets of rms glide slope deviation for offset approach type: 1) 3-deg ($M=0.04$ dots) and 15-deg ($M=0.05$ dots) and 2) 15-deg and 0-deg ($M=0.07$ dots). Operationally, these differences were inconsequential as crews had excellent tracking of the localizer and glide slope for all offset approach types. HUD SEVS concept and the interaction between HUD SEVS concept and offset approach type were not significant ($p>0.05$) for either rms localizer deviation or rms glide slope deviation.

The data show that all HUD concepts tested in motion-based simulation, regardless of offset approach type (0, 3, 15 deg) or HUD SEVS concept (Conventional, SVS, EFVS), were within the lateral confines of the runway (± 75 ft of centerline) at 100 ft HAT with an acceptable sink rate ($M=-656$ ft/min, standard deviation, $\sigma=94$ ft/min), and also at 50 ft HAT with an acceptable sink rate ($M=-608$ ft/min, $\sigma=91$ ft/min) (see Figure 2a, where the boxplot's central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to 1.5 times the height of the box or, if no values in that range, to the minimum and maximum values, and outliers are plotted individually. Asterisks are extreme outliers that represent values more than three times the height of the box.).

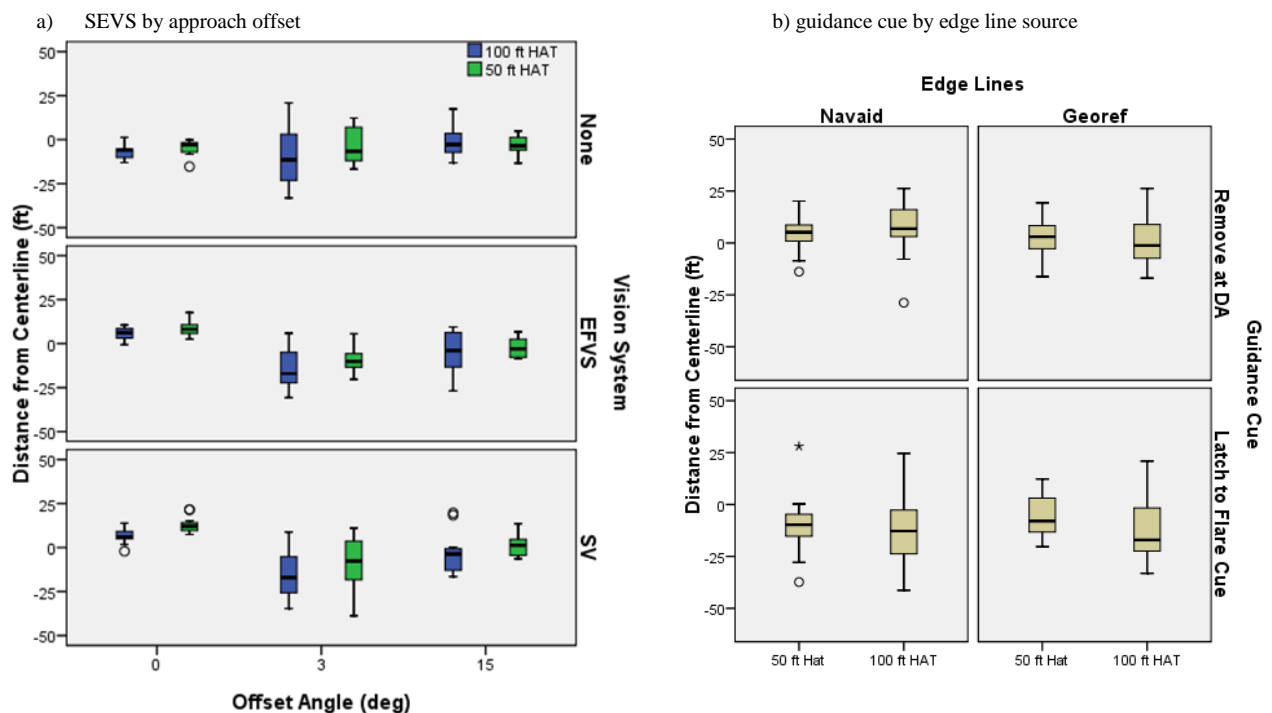


Figure 2. Distance from centerline at 50 ft and 100 ft HAT for a) SEVS by approach offset and b) guidance cue by edge line source.

At 100 ft HAT, a LMM analysis revealed significant differences in offset approach type ($F(2,83)=17.89$, $p<0.001$) and the interaction between offset approach type and HUD SEVS concept ($F(4,83)=3.91$, $p=0.006$) for lateral distance from centerline. There were two unique subsets for offset approach type: 1) 0-deg ($M=2$ ft) and 15 deg ($M=-3$ ft) and

2) 3-deg ($M=-13$ ft). Operationally, the significant differences for interaction between offset approach type and HUD SEVS concept were inconsequential as all means were within 15 ft of the centerline of the 150 ft wide runway. HUD SEVS concept was not significant ($p>0.05$) for this measure. At 50 ft HAT, a LMM analysis revealed significant differences in offset approach type ($F(2,83)=24.16$, $p<0.001$), HUD SEVS concept ($F(2,83)=4.25$, $p=0.017$), and the interaction between offset approach type and HUD SEVS concept ($F(4,83)=7.41$, $p<0.001$) for lateral distance from centerline. Similar to the results for this measure at 100 ft HAT, the differences were not operationally relevant as all means were within 13 ft of centerline at the 50 ft HAT altitude position. As previously reported in another paper [5], the means of the touchdown measures (lateral position, longitudinal position and sink rate) for all three HUD SEVS concepts were within autoland landing performance criteria.

3.1.1. Offset Approach on Approach Performance Discussion

The need to go-around appeared to be affected by visibility level (7% in 1400 RVR vs 0% in 4000 RVR) and not offset approach type being flown. It appears that having FLIR imagery on the HUD improved the go-around rate (0%) compared to when flying the Conventional HUD (8% go-around rate; 3 go-arounds out of 36 approaches) on approaches, with and without offsets. The data do indicate that the pilots are still working on runway line-up at the 100 ft HAT point on a 3-deg offset, but the deviation from the runway centerline is small. Regardless of offset approach angle (0, 3, or 15 deg) or HUD SEVS concept (Conventional, EFVS, SVS) being flown, all approaches flown: 1) had comparable tracking of the localizer and glideslope during the instrument segment, and 2) were within the lateral confines of the runway with acceptable sink rates at 100 ft HAT and 50 ft HAT altitude points during the visual segment of the approach. All landings were made within the lateral confines of the runway and within the touchdown zone (first 3000 ft of the runway).

3.2. Effects of Edge Lines Positioning and Guidance Cue Variation

All runs in this analysis were flown to a runway with 3-deg offset approach. Of the 96 approaches conducted, 92 resulted in a safe landing and 4 resulted in a go around. Go-arounds appear to be affected by the guidance cue variation with a 0% missed approach rate for the ‘remove at DA’ runs and an 8% missed approach rate for the ‘latch to flare cue’ runs (2 for Conventional HUD with geo-referenced edge lines, 1 for Conventional HUD with navaid-referenced edge lines, 1 for EFVS with navaid-referenced edge lines).

A LMM analysis revealed no significant ($p>0.05$) rms localizer error ($M=0.02$ dots, $\sigma=0.01$ dots) differences for HUD SEVS concept, guidance cue variation, edge lines positioning source, or their second order interactions. A LMM analysis revealed significant differences in edge line positioning source ($F(1,73)=9.85$, $p=0.002$) for rms glideslope error, with the geo-referenced edge lines ($M=0.09$ dots) having less glideslope deviation than the navaid-referenced edge lines ($M=0.13$ dots). There were no significant ($p>0.05$) rms glide slope error differences for HUD SEVS concept, guidance cue variation, or any of the second order interactions.

The data show that all Conventional and EFVS HUD concepts flown on a 3-deg offset approach, irrespective of edge line positioning source or guidance cue variation, were within the lateral confines of the runway (± 75 ft of centerline) at 100 ft HAT with an acceptable sink rate ($M=-667$ ft/min, $\sigma=132$ ft/min) and at 50 ft HAT with an acceptable sink rate ($M=-643$ ft/min, $\sigma=123$ ft/min)(Figure 2b).

A LMM analysis revealed significant differences in guidance cue variation ($F(1,72)=35.41$, $p<0.001$), for the lateral distance from centerline at 100 ft HAT, with the ‘latch to flare cue’ runs ($M=-11$ ft) further from the centerline than the ‘remove at DH’ runs ($M=4$ ft). Operationally, these differences are inconsequential. All other factors and their interactions were not significant ($p>0.05$) for this measure. A LMM analysis revealed significant differences in guidance cue variation ($F(1,72)=39.82$, $p<0.001$) for the lateral distance from centerline at 50 ft HAT, with the ‘latch to flare cue’ runs ($M=-8$ ft) further from the centerline than the ‘remove at DH’ runs ($M=4$ ft). SEVS HUD concept ($F(1,73)=9.41$, $p=0.003$) was also significantly different for this measure, with the EFVS HUD runs ($M=-5$ ft) further from the centerline than the Conventional HUD runs ($M=1$ ft). Operationally, these differences are inconsequential. All other factors and their interactions were not significant ($p>0.05$) for this measure. As previously reported [5], means of the touchdown measures (lateral position, longitudinal position, and sink rate) for the EFVS and

Conventional HUD concepts were within autoland touchdown performance criteria for each combination of HUD edge lines positioning source and guidance cue variation while flying an ILS approach with a 3-deg offset.

3.2.1. Edge Lines Positioning and Guidance Cue Variation Discussion

Although the approach and touchdown data shows few operationally significant differences, the pilot post-test briefing comments suggest some clear effects. All 12 PFs stated they preferred the geo-referenced positioned edge lines over navaid positioned during an offset approach. The PFs expressed that navaid positioned edge lines should never be used as they ‘gave you a false sense of reality,’ or were ‘very confusing and very dangerous,’ or ‘misleading and definitely a safety concern.’ In the post-test briefing, the vast majority of PFs (9) preferred that the guidance cue should be retained all the way to flare and not be removed at DH. Interestingly, 3 PFs stated they did not notice guidance cue variations as they were either visual at that point in the approach or using the flight path marker and glide slope reference line to make the landing after turning to the runway.

4. Concluding Remarks

An experiment was conducted to investigate the use of SEVS technologies as enabling technologies for future all-weather operations. The experimental objectives were to evaluate head-up SEVS concepts, instrument offset approaches, HUD edge lines positioning sources, and guidance cue variations on crew approach performance during terminal area operations.

Objective results indicate that making offset approaches in low visibility conditions with an EFVS HUD or SVS HUD appears feasible. Regardless of offset approach angle (0, 3, or 15 deg) or HUD SEVS concept (Conventional, EFVS, SVS) being flown, all approaches had comparable ILS tracking during the instrument segment and were within the lateral confines of the runway with acceptable sink rates during the visual segment of the approach.

No operationally relevant path maintenance differences were found due to HUD edge lines positioning source or guidance cue variation. Pilots preferred the geo-referenced HUD edge line and recommended that navaid-referenced HUD edge lines should not be used.

FLIR imagery on the HUD significantly impacted the go-around rate. The EFVS HUD had a 0% go-around rate, while the Conventional HUD (no imagery) had an 8% go-around rate. Similarly, guidance cue variation impacted the go-around rate while conducting an ILS 3-deg offset approach. The guidance cue latched to flare cue runs had an 8% go-around rate; while the guidance cue removed at DA runs had a 0% go-around rate.

FLIR-based sensor technology used in conjunction with the HUD (i.e., an EFVS) enabled successful no-offset approaches, without any go-arounds being performed, in visibility as low as 1000 RVR in this simulation experiment. Future research should investigate enhanced vision sensor technologies (other than FLIR) for improved all-weather operations when reported visibility is less than 1000 RVR.

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