

Design and Flight Test of a Primary Flight Display Combined Vision System

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ABSTRACT

A series of flight tests were conducted to design and evaluate a Combined Vision System (CVS) that integrates a forward looking infrared video image with synthetic vision on a primary flight display. System features included colorizing the video image to mesh with the synthetic terrain background, decluttering the approach symbology to facilitate the detection of the approach lights and runway markings, creating a semi-transparent IR sky to ensure continuous situational awareness of the surrounding terrain, and annunciating the decision height to facilitate the transition to the actual runway environment. Over 100 approaches were flown during three flight test sessions. For the first flight test session pilots reviewed early CVS proofs of concept on Honeywell's Citation Sovereign. During the approach in low visibility conditions, the Pilot Flying remained head-down to 100 ft AGL, at which time he lifted his head and made a subjective judgment of whether he could easily and safely complete the transition to land before making a go-around. In the second flight test session enhancements included IR image coloring, IRS/GPS navigation system integration, and display annunciations. The series of flight tests culminated in a CVS integration on Honeywell's Gulfstream G450 aircraft for a direct head-up display (HUD) versus head-down display (HDD) comparison of the IR imagery. The HUD location is currently the standard for low visibility approaches with IR imagery. The G450 evaluation had three highly experienced pilots with an average of over 12,000 flight hours and over 2,500 hours with a HUD. They flew a total of 46 approaches, most to full-stop landings and many were in high workload conditions - low visibility weather or strong crosswinds. Again the Pilot Flying stayed head-down to 100 ft AGL and then transitioned to the outside view of actual runway environment before

landing. Pilot performance with the CVS was equivalent to performance with the HUD on all flight parameters including glideslope deviation, airspeed deviation, configuration to land at the crossing threshold, and the landing footprint on the runway. Workload scores and display ratings were equivalent between the two displays, giving a strong indication that the Honeywell CVS provides equivalent performance and an alternative means to the HUD for displaying the IR imagery.

INTRODUCTION

The goals of both the Federal Aviation Administration's NextGen program and Europe's Single European Sky Air Traffic Management (ATM) Research (SESAR) Joint Undertaking aims to increase air traffic efficiency through more optimal routing and fuel burn and emissions reduction, while increasing safety and capacity (1). A key to increasing capacity is to minimize the effect of weather on flight operations. For decades air carriers have been looking for comprehensive solutions to low visibility conditions to enhance operational capabilities independent of airport facilities (2). In order to incorporate the advancing technology and capabilities, the Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) continue to update the aircraft and ground equipment requirements, pilot training and procedures necessary to achieve lower minimums under instrument flight rules. For instance, in 2007 FAR §91.175 was revised to include a means to go below the authorized decision height (DH) or minimum decision altitude (MDA) using an Enhanced Flight Vision System (EFVS). The instrument flight rules under §91.175 enables that the pilot to use an electronic device to see the runway environment as compared to the traditional requirements that the pilots must see the runway out the window with the naked eye. The intended runway must be

“distinctly visible and identifiable” in order to go below DH or MDA. §91.175 defines an EFVS as a system having an electronic means to display the forward external scene through the use of a sensor, where the imagery and flight symbology are presented on a head-up display or equivalent display and the display affords the pilot the ability to manually control the aircraft. Therefore, if an aircraft is equipped with an EFVS, the pilot can descend below the MDA by 100ft once he or she detects and identifies the runway environment from the sensor imagery. Currently the FAA has only certified aircraft installed with a HUD to meet these regulations. The present study provides evidence for an equivalency of performance of a head-down, primary flight display with synthetic vision (SV) and Enhanced Vision (EV) - a Combined Vision System (CVS) - to the performance with a HUD with IR imagery. If certified, the CVS would enable pilots flying with an aircraft equipped with a sensor but not equipped with a HUD to visually acquire the necessary cues in order to land in lower visibility conditions. The CVS is described below.

TECHNOLOGY

Synthetic Vision

In January 2008 the first synthetic vision system (SVS) display for Part 25 operators was certified with the integration of Honeywell's SV technology on Gulfstream's aircraft (3). Synthetic vision is an electronic means of perspectively displaying topographical data through computer-generated imagery of an onboard terrain and navigation database. The development of SV technology (5,6,6) and the resulting safety and performance benefits have been well documented (7, 8, 9). SVS displays provide pilots a new level of terrain awareness regardless of the outside visibility conditions. Such a capability will help eliminate Controlled Flight Into Terrain (CFIT) accidents due to loss of situation awareness (10). Adding advances in navigation precision, runway guidance, and symbology to these terrain displays has led the RTCA Special Committee 213, in collaboration with EUROCAE Working Group 79, to begin exploring operational benefits for SV displays. Authorizing landing credit would be one way to achieve equivalent visual operations (EVO) and make flying less dependent on weather conditions.

Enhanced Vision

An Enhanced Vision System (EVS) is an electronic means to provide the flight crew with a sensor-derived image of the external scene through the use of imaging sensors such as forward looking infrared (FLIR), millimeter wave (mmW) radar, light detection and ranging (LIDAR) or low light level imaging. An EVS provides real-time data regarding the runway environment. By definition EVS displays are not required to be integrated with flight guidance information, however only systems with sensor imagery and flight

parameters offer operational credit through §91.175 and are defined as enhanced Flight Vision Systems (EFVS). In 2001 Gulfstream certified the first EVS, which incorporated a forward-looking infrared (FLIR) image on a Head-Up Display (HUD). Such a system, with precision guidance and control symbology, offers the ability to maintain a stabilized approach while providing real-time data of critical information in the runway environment.

Combined Vision

A Combined Vision System integrates Synthetic Vision and Enhanced Vision to offer the best of both worlds. The synthetic offers full-time terrain awareness in all weather conditions and advanced symbology for a stable approach and the enhanced vision adds the real-time information to confirm accuracy and integrity of the onboard database and navigational position. This paper describes the development and flight testing of a CVS presented in the head-down location that Honeywell is exploring for further enhanced safety and enabling the flight crew to operate in lower visibility conditions. If the technology is to meet the regulatory guidance, the system must provide detailed and reliable information regarding the environment with the integrity to support decision-making with regard to the aircraft position in relation to the runway environment. The integration of the sensor technology must meet all the requirements of an EFVS as established by the FAR Part §91.175 of clearly displaying the runway environment without adversely obscuring the flight crew's view of the outside environment. The research question remains whether the head-down location affords the same benefits as that which is provided in the head-up location.

Head-up versus Head-down

The head up versus head down debate has been studied for decades determining both the costs and benefits yielded from the location of the information (11, 12). The advantages of head-up displays have been noted for commercial, business, and military operations for flight path tracking and scanning the forward field of view (13, 14, 15, 16). One advantage noted is that the conformality of the display elements can facilitate the divided attention between the environment and the flight instrumentation (17). HUDs, by the nature of their location, facilitate the pilot to rapidly switch his or her attention between the symbology and the out-the-window environment. Add those benefits to the fact that HUDs are also known for supporting precise aircraft control and landing performance, they are a valuable tool on the flight deck (16, 18). However, innovative display designs and the development of synthetic vision are reducing, if not removing, the performance gap between head-up and head-down displays. In fact, by enabling precise control of the aircraft with the information head-down, you get many of the HUD's benefits and the added advantage of always having the pilot's forward field of view clear and unobscured by

symbology and synthetic and/or sensor imagery. In doing so, you can potentially avoid the well-documented negative phenomenon of cognitive tunneling, in which the pilot fails to disengage his or her attention from the HUD instrumentation to adequately scan the environment (11, 15, 19). Studies have shown the consequences of cognitive tunneling are the delayed response or failure to notice unexpected events, such as a runway incursion. Adding additional information to the display further clutters the pilot's forward field of view only exacerbating the cognitive capture problem (20, 21, 22).

Some of the advantages of head down displays are the multiple solutions and integration opportunities for the IR image. Combined Vision System as a head-down primary flight display enables multiple colors and multiple shades to be applied to the imagery improving the integration of the sensor data and providing a clear and unambiguous difference between the imagery and symbology. Through advanced signal processing the contrast can be dramatically improved enhancing the detection of objects in the runway environment. In the head-down location you are not limited to the 1:1 conformal presentation of information in the head-down location so information can be enlarged and enhanced to further improve the detection of critical information on the display while still enabling a clear view of the out-the-window scene.

While the head down location requires a transition between the inside and outside the cockpit, priming the pilot with a naturalistic display that looks and behaves like the elements in the real-world can facilitate the transition to the outside environment. Doherty and Wickens (2000) noted several advantages of a fully immersed egocentric display including its natural view and the realistic sense of motion of the objects in space being salient and representative of the actual environment (23). The realistic depiction enables a mental integration of the information enhancing the processing and detection of the matching cues in the actual environment when they become available. The information primes the pilot to drive expectancy for the position of objects in runway environment. The performance advantages of this phenomenon, known as visual momentum, have been well documented (24, 25, 26). The benefits have been noted in the reduction in go arounds with SVS when the pilots were aided in directing their attention on where to look for the runway (16).

A recent EFVS study conducted by DLR showed an equivalency of the HUD and HDD depiction of infrared (IR) imagery (27). The study found no difference between flying with a HUD and a HDD in lateral deviation or in subjective workload ratings when clear roles for pilot flying and pilot not flying were established. Research has also been conducted to use the sensor technology as a means to monitor the integrity of the synthetic vision database. Theunissen, et al. (2004) found that using sensor data as an overlay to the

SV provided the information needed to detect discrepancies between the synthetic and sensor images (28). Given the promising initial findings, further investigations of the potential advantages of the CVS capability for enabling EVO is worth additional research and development.

APPROACH TO COMBINED VISION SYSTEM DEVELOPMENT

Honeywell team applied human factors design principles to the conceptual design, prototyping, and evaluation of CVS display. The team began with a prototype version of the currently certified synthetic vision display. The prototype included enhancements in the orientation of the display, which was centered on the track of the aircraft, and was shown to enhance the PFD stability and reduce workload. Using a blended altitude solution with multiple sensor sources improved accuracy and fault tolerance and enabled enhanced runway approach symbology to be created. The team was tasked with the integration of the IR image with the synthetic vision display that was acceptable to pilots and facilitated their performance in the approach and landing phase of flight. After encouraging findings from an initial empirical study in the laboratory revealing advantages of the head-down display location for the detection of the approach lights, the team went to flight test to further enhance the CVS features. An overview of the iterative human factors approach used in flight testing the CVS concept was conducted in 2010 and is described below.

EARLY FLIGHT TESTS

The first series of flight tests of the CVS prototype system took place in a Cessna Citation Sovereign aircraft in the month of June in 2010. Figure 1 shows the experimental installation of a Kollsman EVSII camera on the top of the aircraft nose in a forward storage compartment. Though this is not a typical installation location for the IR camera, the location was used to simplify the installation and de-installation on the aircraft. With the assistance of the manufacturer, the camera was calibrated to align within specifications. The IR image from the camera was integrated onto the synthetic vision display on the primary flight display on the left side as shown in Figure 2. The objective of the evaluation was to evaluate the system performance in flight in both VMC and IMC in the Phoenix, AZ area and the west coast of California. The integration included symbology improvements to declutter elements of the display to optimize the detection of the approach lighting system, the development of the colorized infrared imagery to improve the integration into the SVS background, and the creation of a semi-transparent the sky portion of the image to improve the pilot's awareness of the synthetic terrain in low visibility conditions. See Figure 3. In addition, a variety of symbology designs were considered for the approach symbology including the variations of the flight path marker and

approach runway target. The experimental CVS display was shown on the modified primary flight display on the left. The right side PFD remained as a certified Honeywell CDS-R configuration with a traditional blue over brown format. Both displays are certified Honeywell DU1080 display (approximately 7×9 inch). The CVS was driven by a ruggedized flight test desktop computer located in the aft cabin. The single desktop flight computer was used to render combined SVS/EVS images, acquire real-time video streams, acquire flight and FMS data from the aircraft data bus, record and analyze all the relevant flight test data and video data. The aircraft was equipped with an AHRS and standard GPS (i.e., non WAAS) units. During these flight tests four Honeywell flight test pilots flew 50 approaches to six different airports.



Figure 1. Installation of Kollsman EVS II camera on the Cessna Citation Sovereign



Figure 2. CVS integrated on Sovereign Flight Deck



Figure 3. Honeywell CVS showing the colorized the IR image inside the center window of the SVS display

The local flights originated from Phoenix Deer Valley (KDVT) to Prescott (KPRC) or Williams Gateway (KIWA) and then returned to KDVT. These local flights were used primarily to optimize the display color scale, improve the IR integration image quality over variety of weather and terrain conditions, and to optimize primary flight and flight director guidance symbology for their dynamics, size, shape and usability. The goal was to ensure the overall behavior of the prototype display could meet the demanding requirements for pilots to perform critical approach and landing performance evaluations. In addition, an artificial noise function to simulate poor weather conditions for both day and night operations with the noise generation coupled to the aircraft flying parameters to simulate varying weather conditions. The flights in the California area were conducted in low visibility conditions of marine fog. One approach into Santa Barbara is shown in Figure 4. Conditions varied from 100' ceilings to 500' ceilings and visibilities between $\frac{3}{4}$ mile and 2 miles. Pilots flew low approaches to 30 to 50 feet above the runway. The pilot flying responded with "lights" and the response time was recorded and compared to when the pilot not flying saw the lights looking out the window. The integration of the Kollsman EVS II image into the display worked well in the toughest marine fog conditions. The findings indicated a statistically significant average of 30 ft