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Combined Vision Systems Literature Review

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16. Abstract

Improving safety during low-visibility operations is one of the most critical challenges in aviation. Toward this end, the aviation community has been working to develop flight deck display technologies that improve the pilot's ability to acquire visual information in situations where natural vision is compromised. The Combined Vision System (CVS) is one such technology. CVSs utilize data taken from imaging sensors onboard the aircraft (e.g., millimeter wave radar, forward-looking infrared), as well as terrain and obstacle databases, combine them, and present them in a superimposed fashion on a flight deck display. Some of the operational benefits of CVSs include improved tracking performance, reduced flight-path error, and reduced workload. Future research should address pilot performance with a CVS in specific operational constructs (e.g., head-down vs. head-up displays), the effects of CVS display minification on pilot performance, and head-down to head-up transitions while using a CVS.

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Introduction

For decades, the aviation community has been looking for comprehensive solutions to low-visibility conditions to enhance operational capabilities independent of airport infrastructure. To incorporate the advancing technology and capabilities, the Federal Aviation Administration (FAA) and the 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.

Various landing aids have been developed to assist the crew in approach and landing tasks. Instrument landing system (ILS) has been a standard landing system for more than 50 years now, and many airports are already equipped with different categories (CAT I, CAT II, CAT III) of this system. In particular, CAT III auto-land facilities are used worldwide and clear economic benefits for airlines rise from such auto-landing capability; in particular, the reduction of en-route diversions in degraded visual conditions. Nevertheless, such systems are still expensive and not all airports are equipped with the necessary infrastructure. Pilots use this type of guidance until a predefined minimum altitude—called decision height (DH)—at which visual contact with references of the runway such as approach lights, runway threshold, etc. should be established. The visibility and a decision altitude (DA), decision height (DH), or minimum descent altitude (MDA) for an instrument approach procedure is established based on the approach type, supporting ground infrastructure, and other approach design requirements. For example, the MDA for a nonprecision approach might be 300ft, whereas it may be as low as 100ft for a CAT II approach. Unless visual contact has been established to a reference such as approach lights, the threshold environment (its surface, markings, or lights), the touchdown zone environment (its surface, markings, or lights), the runway environment (its surface, markings, or lights), or other visual references required by the FAA regulations, a pilot may not continue the approach below DA/DH or MDA. If visual contact with a required visual reference cannot be established before descending below DA/DH or MDA, the pilot must initiate a go-around, execute another approach, or divert to another destination.

In recent years, apart from ground based landing aids such as ILS, the aviation community has been working on the development of several new display technologies. These technologies aim to improve the ability of a pilot to acquire visual cues from the runway environment including Synthetic Vision Systems (SVSs) and Enhanced Vision Systems (EVSs), and a combination of EVS and SVS – termed Combined Vision System (CVS)[1]. Any of these systems can be displayed on a head-up display (HUD) or a head-down display (HDD). Their intended function may include operations (regardless of the environmental conditions) where

- Little to no ground infrastructure exists;
- Elements of the runway environment can be detected early; and
- The runway can be tracked in a continuous manner down to flare, touchdown, and rollout.

Furthermore, one of the proposed Next Generation Air Transportation System (NextGen) essential capabilities is the concept of equivalent visual operations (EVO). EVO is the capability to attain an equal level of safety to current-day Visual Flight Rules (VFR) operations and maintain the operational flow of VFR regardless of the weather and visibility conditions. One research challenge for EVO is the definition of required on-board equipment and on-ground infrastructure. With today's regulations,

[1] The use of the terms EVS and SVS in this context are broad terms that encompass EVS, EFVS, SVS, and SVGS.

significant investment is required for “all-weather” landing capability. Advanced vision systems such as SVS, Synthetic Vision Guidance System (SVGS), EVS, EFVS, and CVS offer a means of providing EVO capability without significant airport infrastructure investment while potentially improving operational efficiency during low visibility operations.

The development of the CVS concept is deeply rooted in both EVS and SVS technologies; therefore, there are dedicated sections for each of these three technologies. The definitions and assumptions used herein are based on the following FAA documents:

- AC 20-167A Airworthiness Approval of Enhanced Vision System, Synthetic Vision System, Combined Vision System, and Enhanced Flight Vision System Equipment Vision System Equipment
- AC 25-11B Electronic Flight Displays
- AC 120-29A - Criteria for Approval of Category I and Category II Weather Minima for Approach (Operational criteria from AC 120-28D is being moved to AC 120-XLS, Criteria for Approval/Authorization of All Weather Operations (AWO) for Takeoff, Landing, and Rollout)
- AC 120-28D - Criteria for Approval of Category III Weather Minima for Takeoff, Landing, and Rollout (Operational criteria from AC 120-28D is being moved to AC 120-XLS, Criteria for Approval/Authorization of All Weather Operations (AWO) for Takeoff, Landing, and Rollout)
- FAA-S-8081-4D Instrument Rating practical test standards
- RTCA DO-315C Minimum Aviation System Performance Standards (MASPS) for Enhanced Vision Systems, Synthetic Vision Systems, Combined Vision Systems, and Enhanced Flight Vision Systems
- RTCA DO-359, Minimum Aviation System Performance Standards (MASPS) for Synthetic Vision Guidance Systems
- AC 120-71A Standard Operating Procedures for flight deck crewmembers
- AC 90-106A, Enhanced Flight Vision Systems
- AC 20-185, Airworthiness Approval of Synthetic Vision Guidance System

Definitions and Assumptions

To account for the diverse set of definitions of advanced vision systems including EVS, EFVS, SVS, SVGS, and CVS used in the research literature, regulatory documents, and industry publications, this document is structured based on the following assumptions:

- Table 1 contains the definitions for each of the systems addressed in this literature review
- The placement of a particular publication summarized herein within one of the three literature review sections of this document was based on both technical terminology and technical content used in research reporting. For example, if a system under examination was named “enhanced vision system” or “synthetic vision system” but the content indicated that it technically included a combination of the two, it was placed under the heading “CVS literature review”.
- The subsections are ordered to reflect that the research and development of the EVS and SVS concepts chronologically precede the concept of CVS.

- Research conducted in the domain of rotorcraft and unmanned aerial systems *is not* included.
- This literature review *does not* include research conducted on EVS, SVS, or CVS for head-mounted or head-worn displays.

Table 1

Definitions

Enhanced Vision System	An EVS is an electronic means of providing a display of the forward external scene topography through the use of imaging sensors, such as forward looking infrared (FLIR), millimeter wave (MMW) radiometry, MMW radar, low-light-level image intensifying, etc. EVS does not necessarily provide the additional flight information/symbology on a HUD (or equivalent display) required for operational credit. It also does not have to be integrated with a flight guidance system as it is required for EFVS. The elements of an EVS include • EVS sensor system • Sensor display processor • EVS display • Pilot controls/interface
Synthetic Vision System	Synthetic vision is a computer-generated image of the external scene topography from the perspective of the flight deck, derived from aircraft attitude, high-precision navigation solution, and database of terrain, obstacles, and relevant cultural features. SVS is an electronic means to display a synthetic vision depiction of the external scene topography to the flight crew. Synthetic vision creates an image relative to terrain and airport within the limits of the navigation source capabilities (position, altitude, heading, track, and the database limitations). SVS can provide situational awareness, but no operational credit. The application of SVS is through a primary flight display (PFD) from the perspective of the flight deck (egocentric), or through a secondary flight display from the perspective correlating to outside the aircraft (exocentric, like a "bird's eye" view of a moving map display). The components of an SVS include • Display • Terrain and obstacle database • Position, altitude, attitude, heading and track sources
Combined Vision System	A CVS may include database-driven synthetic vision images combined with real-time sensor images superimposed and correlated on the same display (e.g., HUD, HDD). This includes selective blending of the two technologies based on the intended function of the system. CVSs can provide situational awareness, but whether or not a CVS qualifies for operational credit depends on how it is configured and whether it meets the regulatory requirements for EFVS or SVGS operational credit. For the purposes of this document, CVSs are considered as incorporating both EVS and SVS. Each EVS or SVS may comprise of multiple real-time sensors or multiple databases, respectively.

SVS literature review

Beringer (2016) conducted an evaluation of general aviation pilot performance while using SVS compared to performance without SVS. Objective measures of flight performance (glide slope RMS error, localizer error, and frequency of missed approach), subjective mental workload, and pilots' opinions on the displays were compared between two display locations (HDD vs. HUD), with presence or absence of SVS, and two visibility conditions (1200 vs. 1400 ft. RVR). Flight performance did not differ significantly between runs with and without SVS, pilots uniformly preferred SVS over the non-SVS display, reporting that they felt more confident while using it and that they believed that they could operate safely to lower minima with it. These findings suggest that, while objective performance may not improve among general aviation pilots using SVS, it is worth noting the preference for it as well as the increased confidence while using it.

Barrows, Alter, Jennings, and Powell (1999) described the development and validation of a prototype synthetic vision system that was feasible for low-cost implementation in piston aircraft. In addition to synthetic terrain, the system presented a "tunnel-in-the-sky" guidance on straight and curved approach paths. In order to produce the synthetic image, a combination of GPS data, attitude sensors on the aircraft, and terrain and water databases were used. The paper described the system development and flight testing in Alaska during the summer of 1998. The operational experience demonstrated the "tunnel-in-the-sky" ability to increase flight-path following accuracy and situational awareness while easing the task of instrument flying. The results also indicated that the pilots were generally satisfied with its operation and that such a system could feasibly be implemented in piston aircraft.

Bolton and Bass (2001) reported an experiment evaluating spatial biases in head-down synthetic vision systems (SVS) displays by examining how pilots' spatial judgments differ between the terrain texture and geometric field of view of the display. The experiment was part of a larger study aimed at evaluating judgment-based measures of spatial awareness in synthetic vision systems. In the experiment, seven levels of terrain texture and either 60 degree or 30 degree geometric field of view (GFOV) were varied in a within-subjects design, along with two levels each of relative angle, relative distance, and relative height of the terrain point. Participants' estimates of relative angle, distance, height, and abeam time were compared against the actual values. The researchers observed that (a) participants underestimated relative height, angle, and distance more with a 60 degree GFOV than with a 30 degree GFOV; (b) participants underestimated angles more for far distances than for near distances; (c) participants overestimated angles more for points below the aircraft than for points above the aircraft. There were a number of human factors considerations highlighted by this research, including (a) training for SVS systems should be incorporated to minimize potential perceptual biases, and (b) SVS design could account for potential perceptual biases by compressing the relative distance of terrain close to the aircraft.

Williams et al. (2001) described a concept of operations for synthetic vision systems for commercial and business aircraft. The authors proposed a synthetic vision system for commercial aviation that uses an enhanced view of the flight environment, hazard and obstacle detection, and precision navigation guidance. The system would be active during all phases of flight (i.e., ground operations, departure, en-route, and arrival). According to the authors, the primary safety benefit of implementing this system would be preventing controlled-flight-into-terrain (CFIT) accidents and runway incursions. In addition, the system would provide operational benefits through improved ground operations in low-visibility conditions.

Comstock Jr, Lou, Lance, and Dawn (2001) reported on human perceptual issues such as display size and Field-of-View (FOV) and their impact on pilot performance in the context of the design and implementation of SVS type of displays. The authors suggested that the issue of display size was driven largely by the need for displays compatible in size with older aircraft displays, current generation displays, and potential next generation larger display surfaces. Head-Up Display technology was outside the scope of the paper. The primary research questions were centered on the efficacy of using small displays for presentation of forward-looking perspective view terrain information with overlaid "HUD-like" symbology. Three display sizes were evaluated: (1) Size "A/B" representing the size of the Electronic Attitude Director Indicator (EADI) found on Boeing 757 aircraft, (2) Size "D" representing the size of the Primary Flight Display (PFD) on the Boeing 747-400 or 777, and (3) Size "X" representing a larger advanced display. An important issue when displaying visual scene information is the scale factor to be used. Each display could be shown in a format analogous to an electronic "window" of that size at the front of the aircraft, or the scene can be minified permitting additional angle to be shown on the display. A question this study was trying to answer was whether there was an optimal Field-of-View (FOV) for each display size. More specifically, the focus was on evaluating the impact of different FOVs on each of the three display sizes for approach and landing tasks. Both performance and subjective response data were collected. The results showed none of the display and FOV combinations were detrimental to maintaining horizontal or vertical path. Small display sizes, while not the preferred size, may be utilized without positional performance penalties when raw horizontal and vertical guidance information was present. A number of valuable comments were received from the participants as follows:

- Small FOVs may make one "seasick" in turbulent conditions, unlike in the smooth air of this fixed-base test environment.
- Participants suggested that they would use a wide FOV at higher altitudes in order to spot traffic more easily, or to see areas they may be turning toward, and would like the ability to narrow the FOV prior to landing, at which point the runway would be the primary object of interest.

An FOV issue noted, but not examined, was when cross-winds would drive the flightpath vector off-screen on the smaller display sizes with small FOVs. The authors recommended that careful consideration should be given with respect to this issue when specifying the operational concept and requirements for SVS primary flight displays. Furthermore, they proposed that the relationship between pitch ladder (scaling), FOV, and display should be examined in a future research study especially during unusual attitude recovery. Other SVS perceptual issues identified by the researchers as topics for future research included evaluations of how pilots handle discrepant information given how potentially compelling the pictorial SVS presentations could be.

Prinzel et al. (2002) reported findings from a study that evaluated pilots' situational awareness while using a synthetic vision system in a flight simulator. The system used an onboard database to present terrain, obstacle, and airport information. A within-subjects design with three display types (Size "A" HDD, Size "X" HDD, HUD), two terrain textures (generic, photo), and two landing scenarios (high workload, low workload) was used. While a variety of performance data were collected during the flights, only lateral path error was reported in the paper. Post-hoc questionnaires and semi-structured interviews evaluated pilots' subjective appraisals of the three display types and two terrain types and explored general attitudes toward the synthetic vision system. Results of the performance data indicated no significant main or interaction effects of display type or terrain type on lateral path RMS error, but indicate lower lateral path error compared to baseline runs using only the electronic attitude direction indicator (EADI). This was especially the case during the higher-workload segment, which involved a circling maneuver prior to the final approach, where lateral error was 853 ft greater with EADI than with SVS. Questionnaire and interview data also indicated a preference for photo terrain over generic terrain and a preference for the larger Size “X” display. Pilots also reported a subjective improvement in situational awareness while using the SVS over a standard display. While no performance gains were reported in the research, the findings point to a preference for SVS displays among pilots in general. The results indicated that SVS displays in the flight deck may improve subjective measures of satisfaction and situational awareness.

Prinzel et al. (2003) examined the effectiveness of a synthetic vision system for preventing controlled-flight-into-terrain accidents with two experiments. The first experiment tested the system in a general aviation aircraft simulator while the second tested it in a commercial aircraft simulator. In the first experiment, an altimeter error (i.e., incorrect barometric altimeter setting) was introduced prior to the pilot performing maneuvers with continuously deteriorating natural visibility and being asked to descend to an altitude that would potentially cause a collision. Physiological data (i.e., electromyography, heart rate, and skin temperature) were recorded. Results showed a non-significant physiological response before the potential collision condition, indicating that the synthetic vision system made the pilots aware of it. In the second experiment, commercial pilots were asked to fly a circling approach in low-visibility conditions and then fly the aircraft between two mountain peaks. Pilots who performed the tasks with no synthetic vision system made more pitch adjustments than those using the synthetic vision system. While no pilots using the system collided with the terrain, three of the four pilots not using the system experienced a collision. Pilots using the synthetic vision system also exhibited lower workload, self-reported less difficulty, and better situational awareness. These observations provided support for the notion that synthetic vision systems have the potential for improving safety of flight in low-visibility conditions.

Arthur, Prinzel, Kramer, Bailey, and Parrish (2003) reported an experiment evaluating the degree to which a synthetic vision system retrofitted into an existing HDD improved pilots’ ability to detect a potential CFIT—the most common type of aviation accident—and compared flight performance, usability, and acceptability between display types and terrain detail. In a simulated Boeing 757, pilots conducted circling visual approaches to a runway surrounded by mountains using only the synthetic vision system. Pilots flew using three display types (HUD, Size “A” HDD, Size “X” HDD) and two terrain types (generic texture, photo-realistic texture). Additionally, four pilots flew using a navigation display with no synthetic vision. Path and speed error were monitored during the runs. To introduce a potential CFIT, the departure path on the final run was altered to direct the airplane toward a mountain peak. Situational awareness was assessed based on whether or not the pilot adjusted the flight path to avoid the peak. The findings revealed that all pilots using the baseline display experienced a CFIT while none did who used the SVS. Comparing among display types, RMS lateral path error was significantly lower with the HUD (M = 61 ft) than with Size “A” HDD (M = 82 ft) and Size “X” HDD (M = 80 ft but did not differ significantly between SVS display types and terrain texture. Post-run questionnaires and interviews assessed differences in pilots’ subjective workload and situational awareness between display and terrain texture types. Photo texturing was judged to provide better situational awareness than generic texturing, and the Size X and HUD displays were judged to provide better situational awareness than the Size A and generic displays. The results demonstrated that synthetic vision improved pilots’ ability to detect potential conditions for CFIT collision over the standard navigation display and provided support for the notion that SVS can be feasibly retrofitted into existing flight decks.

For the purposes of this document, the results, and pilot feedback from the SVS and EVSs demonstrated during the evaluations reported by Tuttle, Imrich, Etherington, and Theunissen (2003) are summarized in sections "SVS literature review" and "EVS literature review", respectively. The authors reported on a demonstration that was a part of Boeing's Technology Demonstrator (BTD) program and included two enhanced vision systems and a synthetic vision system. The systems were demonstrated in operational context, the perceived benefits of integrating these technologies are discussed, and subjective data from participants are summarized. While evaluation of emergent technologies was in the original statement of work, the BTD program was not initiated as a research activity. The program's focus was to show the connection between airplane capabilities and operational aspects of safety, efficiency, and capacity. The goal was to demonstrate this capability in a transport category airplane and focus on benefits associated with commercial operations.

Nine technologies were demonstrated aboard the airplane: Quiet Climb System, Vertical Situation Display, Navigation Performance Scales (NPS), Integrated Approach Navigation (IAN), GNSS Landing System (GLS), Head-Up Display (HUD), Surface Guidance System (SGS) 1, 2, Synthetic Vision System (SVS), and Enhanced Vision System (EVS). Participants' feedback and lessons learned from implementation are discussed.

The demonstration flights were conducted at several airports in a variety of weather conditions including good weather, rain, snow, icing, and fog as well as in daylight, dusk, and night. Weather included stable and convective weather. Airports used for the demonstration were Seattle's Boeing Field (KBFI), Moses Lake (KMWH), FAA's Technical Center facility in Atlantic City, NJ, and Reagan National Airport in Washington, D.C. The pilot evaluators flying the tests or demonstrations included experimental and production test pilots from Boeing, airline pilots, and pilots from regulatory authorities. Experience of demonstration pilots ranged from high technical familiarity and test or military experience with similar systems to general awareness of the concepts from limited briefings. Some pilots had considerable operational military experience with NVGs (Night Vision Goggles) or other IR or TV based systems.

A typical flight departed with a demonstration of taxi-related features that included EVS and SVS, as well as other onboard features. En-route operations were conducted over a wide variety of terrain types. Terrain, lake, and large body of water depictions were shown in a wide range of weather conditions, at various sun angles, and with varying night lighting characteristics. A similar profile was used as for taxi-in and taxi out. Additionally, on some flights, cooperative vehicles (e.g., an airport van) were moved ahead of the aircraft to show differences in IR sensing capability compared to the visible spectrum, with and without landing or taxi lights. In other instances, targets of opportunity such as aircraft taking off or landing on adjacent or crossing runways were pointed out to pilots and observers prior to those targets passing through the field of view of the IR sensors.

Below, is a summary of the SVS evaluation results, and feedback provided by the pilot evaluators who participated in the demonstration program:

- There was a mostly positive reaction to SVS displayed on PFD and ND;
- There was a mixed reaction to the "tunnel" concept (en-route and approach), varying from positive to expressions of concern for the amount of exposure (training) that may be needed to use the concept operationally. Workload appeared to be quite high, at least at first. Previous experience with the "tunnel" format indicated that workload diminishes as pilots become accustomed to the mechanics of the flight path vector and predictor symbology. Some evaluators adapted readily to flying the tunnel, while others had difficulty capturing and remaining within the tunnel. Most pilots

agreed that the "tunnel" would in some way need to be appropriately related to an applicable level of RNP.

- Special Use Airspace (SUA) presentations were useful and generally well received. Difficulty was noted in judging distance from such areas. SUA limit altitudes presented a confusing picture at times. Crosscheck of analogous information on the ND would be needed to support this task.
- SVS taxi displays (all formats) were generally well-liked and thought most useful.
    - The top-down and exocentric formats seemed to be selected more often due to personal preference than due to any inherent advantage or capability difference.
- Errors in data sources identifying taxiway edges, ramps, holding points or other features were dramatic and of interest to the pilot evaluators.
- The feedback about SVS PFD and ND depictions was positive as a situational awareness tool. Reaction to the tunnel concept was mixed. The authors noted that the concept may require more exposure. No training on the display concepts was conducted prior to the flight other than the static briefing.

SVS was reported to have the potential to improve pilot awareness of surrounding conditions, to include terrain and topographical features. Although previous research indicated that use of tunnel formats could reduce pilot workload while increasing performance and pilot situational awareness, this conclusion was not supported during the BTD program. The authors suggested that these results may highlight a need for training and familiarization with the tunnel concept prior to use, or a need for further research into individual differences in the use of such displays.

For surface operations, SVS was reported to have the potential to improve awareness of aircraft location, movement, and surrounding features, thus reducing the likelihood of clearance violations or runway incursions. In the long term, the authors suggested that SVSs are likely to serve as a foundation for other features such as display of nearby traffic and cleared taxi routes.

Alexander, Wickens, and Hardy (2005) investigated the effects of varying guidance symbology ("tunnel in the sky" vs. "follow-me" aircraft [FMA]), display size (small vs. large), and geometric field of view (GFOV) of the primary flight display, as well as flight path (straight vs. curved), on measures on flight path tracking performance, control activity, situational awareness, and subjective mental workload. Using a high-fidelity flight simulator, pilots flew step-down runway approaches using only the primary flight display. In the first experiment, pilots flew with highlighted tunnel, lowlighted tunnel, and FMA guidance symbology. The researchers observed that vertical control was best with the lowlighted tunnel, whereas lateral control was equal between the FMA and lowlighted tunnel and worse with the highlighted tunnel. While the lowlighted tunnel and FMA afforded better traffic awareness than the highlighted tunnel, subjective mental workload was lowest when using the highlighted tunnel and highest with the FMA. In the second experiment, pilots flew in instrument meteorological conditions with a small display (8 x 6.5 inches) and large display (10 x 8 inches), as well as narrow (30 degrees) and wide GFOV (60 degrees). While vertical deviation between conditions were not significantly different, they were higher in the FMA condition than in both tunnel conditions, with deviations of 5.5 and 5.19 meters in straight and curved legs, respectively, compared to 4.27 and 4.17 meters in straight and curved legs, respectively, with the lowlighted tunnel and 4.37 and 4.01 meters in straight and curved legs, respectively, with the highlighted tunnel. Lateral deviations were smaller with the 60 degree GFOV (M = 6.89 m) compared to the 30 degree GFOV (M = 9.58 m), and a display size x GFOV interaction suggested that the benefit of increasing GFOV was augmented with a larger display. Overall, the results indicated that a lowlighted tunnel in the sky, combined with a wide GFOV and large display, would afford improved pilot performance during approaches in low- to no-visibility conditions.

Wickens and Alexander (2009) investigated attentional tunneling--the allocation of attention to a particular channel of information for longer than optimal--as one of the causes for task breakdown in the flight deck. The authors described the observations of seven experiments testing the effect of a synthetic vision system (SVS) incorporating a highway in the sky (i.e., visual markers indicating the desired flight path). Ab-nominal events such as blimps, offset runways, weather change, and low visibility were incorporated across the seven experiments. Across all experiments, use of SVS with the highway in the sky increased the likelihood of detecting an off-nominal event compared to use of SVS without a highway in the sky, suggesting that attentional tunneling did not take place. The results suggest that incorporating a highway in the sky in a synthetic vision system can provide benefits in the flight deck in the form of reduced risk of attentional tunneling and improved safety.

Kramer et al. (2011) conducted an experiment comparing SVS and EFVS for aiding pilots during approach, landing, and ground maneuvering in low visibility. The objective was to determine if SVS could meet the performance standards of EFVS in these operations. In a simulator, 24 pilots flew straight-in instrumented landings in three visibility conditions (1000, 1400, and 1800 feet RVR), with two display types (HUD and HDD), and three vision system conditions (no vision system, SVS, and EFVS). Decision height was 150 feet in the condition with 1800 RVR, no vision system, and HDD and 200 feet in all other conditions. Presence or absence of touchdown zone and centerline lights was varied between runs. During each run, path error, landing performance (i.e., sink rate, speed at touchdown, distance fore or aft of touchdown zone, and distance left or right of centerline), and control input was measured. After the runs, subjective workload was assessed via a questionnaire. Results revealed no difference in landing performance between display types of vision system type, with frequency of landing meeting high performance standards not differing appreciably between display conditions. However, presence of touchdown zone and centerline lights improved landing performance. Workload for the SVS and EFVS systems did not differ and was ranked as moderate. The findings suggest that SVS may enable lower decision height.

Kramer et al. (2013) conducted a fixed-base pilot-in-the-loop simulation evaluation at NASA Langley Research Center on the use of SVS/EFVS in NextGen low visibility approach and landing operations. Twelve crews flew approach and landing operations in a simulated Chicago O'Hare environment. Various scenarios tested the potential for using EFVS to conduct approach, landing, and roll-out operations in visibility as low as 1000 feet runway visual range (RVR). SVS was tested to evaluate the potential for lowering decision heights (DH) on certain instrument approach procedures.

Results of objective and subjective measures showed that using SVS on a HUD to enable lower decision heights and/or lower OTW visibility than are currently flown was feasible. Regardless of OTW visibility level or the absence/presence of TDZ/CL lights, all SVS HUD approaches were within the landing box (i.e., between 200ft to 2700ft longitudinal distance from threshold and within 58 ft lateral distance of centerline) defined in existing performance-based auto-land standards for touchdown longitudinal position and lateral position from centerline. However, OTW visibility affected the go-around rate with the SVS HUD concepts, with nearly twice as many go-arounds being performed in 1000ft RVR than being performed in 1400ft RVR. SVS HUD operations in visibilities as low as 1400ft RVR (with a 150ft DH) were deemed feasible. The observed SVS HUD go-around rates and post-test pilot commentary indicated that HUD SVS presentation must be carefully designed to avoid obscuring required natural vision landing references.

OTW visibility level or the presence /absence of TDZ/CL lights notwithstanding, all evaluated SVS HDD concepts met the desired lateral touchdown criteria established for this test. However, OTW visibility did impact the go-around rate for the SVS HDD concepts, with four times as many go-arounds being performed in 1400ft RVR than being performed in 1800ft RVR. SVS HDD operations in 1800ft RVR with a 150ft DH appeared promising if TDZ/CL lights were present.

The existence of large, un-annunciated lateral and vertical navigation system errors (+/- 131 ft lateral error; +/- 115 ft vertical error) did not affect pilot touchdown position or sink rate performance while flying with the SVS HDD concepts. The tendency to go-around was less pronounced with the large lateral navigation system error runs (one go-around out of 12 possible approaches) than it was with the large vertical navigation system error runs (three go-arounds out of 12 possible approaches).
Results of Pilot Flying (PF) visual behavior under the SVS operational concepts showed significant increase in head up time and reduced number of head up and head down transitions between HUD and HDD vision system locations respectively for all segments of flight, including flare and landing rollout. During the visual segment of the approach, the SVS HDD condition eye tracking results indicated pilot visual attention remains inside the flight deck 25% of the time. Pilot visual attention continued to transition between the OTW scene and flight instruments and guidance available on the HDD. Relative to the Conventional HDD condition, this is a 10% increase in head up time when using SVS during the visual segment. There were no significant effects in PF visual behavior observed when contrasting SVS and Conventional vision systems on the HUD.

In summary, having TDZ/CL lights appeared to have assisted the pilots in landing closer to the touchdown aim point (1000ft past the runway threshold). Pilots reported significant gains in overall situational and traffic awareness when they had cockpit display of traffic information (CDTI). However, an unexpected runway incursion was not detected when a crew was flying with FLIR imagery on the HUD and CDTI head-down.

Summary

Based on the review of SVS literature, summaries of the operational benefits of the SVS and challenges to SVS operations are provided below:

Table 2

Summary of SVS operational benefits and challenges

SVS Ops Benefits	**SVS Ops Challenges**

• When combined with flight guidance symbology, improves awareness of
    o Terrain/topography
    o Obstacles, etc.
• Improves flight-path following accuracy
• Eases the task of instrument flying
• Improved ground/surface operations
• User (Pilot) Satisfaction
• Performance does not degrade with minification (when flight guidance symbology is present)
• Potential for improving safety by helping pilots *detect* potential conditions for
• CFIT collisions
• RWY incursions
• Reduction of subjective cognitive WL
• Lowlighted "tunnel in the sky" + wide FOV + large display may afford improved pilot performance in low- to no-visibility conditions
• Potential for reduced attention tunneling (SVS + "highway in the sky")
• Potential for enabling lower decision height
	• May lead to perceptual biases such as:
	    o Underestimation of height, angle, distance (with larger FOVs)
	    o Underestimation of angles more for far distances than for near distances
	    o Overestimation of angles more for points below the aircraft than for points above the aircraft
	• Symbology behavior in high cross-winds
	• Increased lateral path error during the high-workload landing
	• Mixed perception and no clear performance advantage with the use of "tunnel in the sky" concept
	• Perceptual issues with judging distance to SUA
	• Legibility under direct sunlight
	• Terrain depiction illusions
	• Generic vs. photorealistic display of terrain
	• Database integrity

EVS Literature review

Kramer et al. (2013) evaluated the use of SVS/EFVS in NextGen low-visibility approach and landing operations. The evaluation was comprised of various scenarios that tested the potential for using EFVS to conduct approach, landing, and roll-out operations in visibility as low as 1000 feet runway visual range (RVR). Results from the objective measures indicated that expanding the portion of the visual segment for which EFVS can be used -from decision height (DH) to the runway - in visibilities as low as 1000ft RVR was viable as longitudinal and lateral touchdown performance were excellent. Possibly more important than the landing performance results was that the go-around rate was 0% when flying the EFVS concept, regardless of the out-the-window (OTW) visibility level (1000 or 1400ft RVR) or if touchdown zone/center line (TDZ/CL) lights were present or not. The enhanced flight visibility was held at approximately 2400ft.

Results from the subjective results also supported the expanded use of EFVS from DH to the runway. This concept was rated as having less workload and was ranked as the crew's preferred display concept (over the Conventional and SVS concepts tested) to fly with in low visibility conditions. RVR affected lateral touchdown performance in the presence of an EFVS failure (i.e., no HUD or Forward Looking Infrared (FLIR) imagery available), but not touchdown longitudinal position or sink rate performance. All lateral touchdown positions were within 19 feet of centerline in the presence of an EFVS failure.

Results of pilot flying visual behavior under the EFVS operational concepts showed significant increase in head-up time and reduced number of head-up and head-down transitions between HUD and Head-Down Display (HDD) vision system locations respectively for all in-flight segments of the approach. Particular significance was observed in the visual segment, indicating that pilots flying the conventional HDD condition remained head down 35% of the time even after visual acquisition of the approach lighting system, continuing to check guidance and instruments available on the HDD.

In another study, Kramer et al. (2011) compared SVS to EFVS for aiding pilots during approach, landing, and ground maneuvering in low visibility conditions. Twenty-four pilots flew simulated straight-in instrumented landings in three visibility conditions (1000, 1400, and 1800 ft RVR), with two display types (HUD and HDD), and three vision system conditions (no vision system, SVS, and EFVS). Presence or absence of touchdown zone and centerline lights was varied between runs. During each run, path error, landing performance, and control input was measured. Subjective mental workload was assessed after each run. Results revealed that pilots maintained good objective performance while using EFVS even when visibility was as low as 1000 RVR. Moreover, the go-around rate was 0% when pilots used the EFVS, regardless of visibility conditions, whereas go-arounds occurred in 17% of approaches in the SVS condition. Pilots reported lower mental workload when using the EFVS compared to the baseline and SVS displays as well. Overall, these findings speak to the benefits that EFVS offer, especially in low-visibility conditions.

Hellemann and Zachai (1999) described the current state of mm-wave (MMW) sensors and their capabilities for use in enhanced vision systems. While alternatives to an MMW sensor for such an application at the time the paper was published included infrared sensors and pulse radar, MMW offered benefits over these methods, including high-speed scanning ability, improved weather penetration, and increased cost-effectiveness. The cost-effectiveness of MMW sensors made those good candidates for use in general aviation aircraft. Ultimately, the sensor system described by the authors and termed HiVision was determined to be appropriate for implementation in enhanced vision systems and showed potential for aiding the pilots in less-than-ideal visibility conditions.

Nguyen, Harrah, and Jones (2002) evaluated an experimental enhanced vision system that incorporated a suite of imaging sensors (including CCD, short-wave IR, and long-wave IR) with a flight test at dusk using the NASA 757, the purpose of which being to compare the three sensor types in visual range and quality of visual information. The evaluation consisted of three taxis, two take-offs, and eight approaches with two landings. Subjective observations of video data revealed that the IR sensors offered improved situational awareness over the CCD as ambient luminance decreased. The short-wave IR sensor provided the best image clarity and ease of detecting runway lights. This initial test of IR imaging for enhanced vision provided useful information for further development of enhanced vision systems on the flight deck.

Hines, Rahman, Jobson, and Woodell (2002) examined the ability of an enhanced vision system that utilized the fusion of multiple image sensors to improve situational awareness in pilots flying in low-visibility conditions. The system fused data from three forward-facing, onboard image sensors: 1) color CCD camera, 2) short-wave IR camera, 3) long-wave IR camera. This was accomplished through image registration, which aligned images taken at different times, from different sensors, and from different viewpoints so that all corresponding image points match via geometric transformation. The researchers compared the ability to register sensor data between two algorithms: multiple linear regression (MLR) and sensor specifications (SS) during runway approaches. Still images taken during a runway approach from each sensor were registered, and the registration accuracy of the fused images was visually compared between the two algorithms. The researchers observed that the MLR algorithm was superior to the SS algorithm at registering the images. This discrepancy was due to the sensors not being bore-sighted and aligned prior to testing, demonstrating the importance of performing this procedure. Nevertheless, the MLR algorithm was able to accurately register the images despite sensor misalignment.

Tuttle, Imrich, Etherington, and Theunissen (2003) reported on a flight demonstration that was a part of Boeing's Technology Demonstrator (BTD) program and included two enhanced vision systems and a synthetic vision system. For the purposes of this document, the review of the flight demonstration program, results, and pilot feedback from the SVS are summarized in the "SVS Literature Review" section. What follows is a summary of the results from the EVS evaluation and participants' feedback. Specifically, the results showed EVS on the HDD provided benefits in detection and awareness of traffic during taxi operations when the IR sensors performed well. In general, EVS improved pilots' awareness during night operations, and in marginal VMC (Visual Meteorological Conditions), dust, and haze. Yet, crew training on image interpretation was necessary in all cases. The results of the demonstration program indicated that the level of airplane integration of EVS can greatly influence its usability. The authors suggested that a higher level of EVS system integration would result in superior EVS performance and that the controls of EVS imagery, location, and protection of EVS sensor windows need to be carefully considered. The two EVSs were most effective at night, in moderate rain, and light drizzle. They were also effective in haze and smog during daylight operations. Operations in clouds and fog resulted in a significant decrease in capability. A single taxi operation in snow also resulted in a significant reduction in EVS utility.

The EVS observations made by program pilots, invited demonstration pilots, or observers during the demonstration are summarized below:

- IR imagery alone appears to be usable when presented either on a HUD or HDD.
    - On HDD, the EVS was not subject to many of the constraints, limitations, or concerns that apply to its display head up.
    - HDD presentations afforded easier management of display brightness and contrast and were viewable by any crewmember at any time.
    - Unique issues associated with HUD presentation included two issues that have been found to potentially adversely affect perceived usability of see-through enhanced and synthetic vision systems.

- It was noted that HUD display of EVS can be effective in showing EVS imagery relative to aircraft flight path: a useful feature for judging projected vertical or lateral clearance from turbulent cloud formations ahead when flying at night.
- On HUD, the EVS field of view was limited to that of the HUD and locked directly forward.
- On HDD, EVS was effective in seeing aircraft, vehicles, and personnel on ramps, taxiways, or runways in some combinations of night lighting conditions, background lighting conditions, and visibility (other than fog).
- As installed on the BTD, contrast, and brightness of EVS imagery usually needed to be set at such a level that visibility through the HUD was greatly diminished.

- Positioning errors of the IR image on the order of 0.5 nautical miles were noted during approach.
- On the ground, the crossover point ahead of the aircraft where the optical visual scene and sensor input correlated was about 600 feet ahead of the aircraft due to IR camera vertical displacement from the design eye point. The authors suggested that such misalignment would need to be greatly reduced in a production system.
- Objects of interest were often not within the field of view or entered the field of view with insufficient time for pilot response.
- Provisions need to be made to keep the lens or camera window free from in-flight icing, a significant issue in the BTD installation.
- The quality and interpretation of the IR imagery varied significantly as a function of target temperature, lighting conditions, sun state, cloud cover, background lighting, sensor spectrum, fusion methods, and factors affecting thermal contrast.
- Image quality ranged from excellent in some conditions to no useful picture.
- The spectral sensitivity of the sensors (IR) limited their ability to penetrate clouds and fog, but useful information was provided in haze at night with limited precipitation, and in some precipitation conditions not involving fog. Various image aberrations can occur with optical systems regardless of the frequency range used. Cases were noted of potentially misleading depth cues, figure-ground reversal (e.g., hills appearing as valleys or vice versa), and distortion of self-motion cues, leading to uncertain perception of speed.
- Pilots found it difficult to determine altitude from the IR imagery alone even when picture quality was high. Head-up imagery was effective only at close range and only when the object of interest was within the HUD field of view.
- Pilots noted that objects visible optically often did not paint in IR and vice versa.
- It was possible for IR imagery to effectively mask the scene behind the HUD. Visibility in the IR and in the visual spectrum can differ significantly; if the pilot was otherwise unaware that an object ahead could be detected visually the object could remain undetected. Pilots had difficulty knowing if or when to de-clutter the IR image from the HUD based on the IR image alone.
- HUD raster brightness and contrast adjustments required extensive attention.
- Training and experience were necessary to learn how to adjust the system and to keep them adjusted in changing conditions.

- Evaluators expressed concerns about the raster imagery blocking or diminishing the view through the HUD, violating the HUD's primary purpose. This concern was so great that a few pilots turned off HUD EVS imagery and declined any further opportunity to turn it on again.
- Several evaluators expressed an opinion that EVS would, could, or should play a significant role in decreasing takeoff or landing minima.

Improved pilot situational awareness appeared to be the most direct benefit from the EVS system as installed in the demonstrator. Based on the pilot evaluators' feedback, the authors recommended that if EVS were to be fielded, crew training and operational experience should be an essential element of its implementation. Pilots must be able to correctly interpret the imagery and if operational credit were sought with EVS, it would require additional operational experience prior to implementation in the transport category environment. Importantly, when presenting EVS imagery on a HUD blocking the external view should be avoided. Experience with EVS during the demonstration program was reported as consistent with prior research on absorption and transmission of the IR spectrum in fog. Infrared sensor imagery can be effective in spotting other aircraft, vehicles, or personnel on the airport surface. It was particularly useful near the gate area for seeing maintenance personnel and equipment around the aircraft at night. Use of EVS/HUD in commercial transport category aircraft was generally viewed as a long-term possibility (5+ years), requiring significant flight deck crew training, operational experience, and regulatory changes to realize benefits in this area. Interpretation of depth cues in the EVS imagery was a concern, especially during ground operations. Pilot evaluators' feedback indicated that these systems should not be fielded on a HUD without a much better management of brightness and contrast, including a select/deselect switch on the wheel.

Summary

Based on the review of EVS literature, summaries of the operational benefits of the EVS and challenges to EVS operations are provided below:

Table 3

Summary of EVS/EFVS operational benefits and challenges

EVS/EFVS Ops Benefits	EVS/EFVS Ops Challenges
• Improves awareness of o Traffic o Terrain/topography o Obstacles o Hazards o RWY environment o Taxiway environment, etc. *in low-visibility conditions* • Permits EFVS to be used for operational credit in accordance with 14 CFR Parts 91, 121, 125, and 135 • Effective in showing imagery relative to aircraft flight path • Improves judgment of projected vertical or lateral clearance from turbulent cloud formations ahead during night flying	• Sensor fusion/blending o Registration without misalignment • Parallax (e.g., vertical displacement between DEP and location of camera) • Insufficient FOV • Image interpretation could be impacted by o Target temperature, lighting conditions, Sun state, sensor sensitivity spectrum • Potentially misleading depth cues • With IR image alone, difficulty in judging altitude and speed • Sensor accuracy and reliability • HUD vs. HDD

CVS Literature Review

Foyle, Ahumada, Larimer, and Sweet (1992) reviewed human factors research studies related to the design, development, and usage of Enhanced and Synthetic Vision Systems and specifically addressing field of view (FOV), interpretability of infrared (IR) imagery, head-up display (HUD) symbology, HUD advanced concept designs, sensor fusion, and sensor-database fusion and evaluation. The authors pointed out that it is essential to determine the extent to which the Enhanced/Synthetic Vision Systems accurately "transduce" or present the visual cues that impact pilotage in all phases of flight. If required visual cues are not accurately or reliably represented to the pilot, the total system performance may be hindered and safety could be compromised. The key challenge has been and still is to design visual displays that preserve the most useful and unambiguous visual cues pilots naturally use. This can be achieved through augmentation of those visual cues such that the pilot can use them under reduced-visibility conditions and in place of the missing or degraded cues that are available under better visual conditions. The results from the FOV studies indicated that the effects of FOV size on control can be very understated and suggested that one way this issue can be overcome in the design of SVS was to inset, using sensor fusion techniques, a narrow FOV sensor image, effectively increasing the system FOV.

In summary, the review of the work conducted at the Aerospace Human Factors Research Division of NASA Ames Research Center concluded that out-the-window viewing in low-visibility weather or viewing sensor imagery with limited display characteristics may result in the degradation of the visual cues usually available. To offset such degradation, advanced displays in which the out-the-window scene is enhanced or augmented were proposed. Such enhancements were suggested as a way of adding the necessary visual cues, which were removed or made unreliable by the degraded visual conditions, back to the scene.

Hecker and Doehler (1998) provided an overview of the German Aerospace Center's (DLR) enhanced vision concept and research approach, which included synthetic vision in combination with sensor data. Data fusion was introduced as an integrated concept from sensor to man-machine interface. The research platform was a fixed base flight simulator supplemented with real-time simulations of imaging sensors (imaging radar and infrared). Data fusion algorithms were generated to combine different levels of information, such as terrain model data, processed images acquired by sensors, aircraft state vectors, and data transmitted via datalink. Furthermore, methods for enhancing radar images by fusion with a terrain database were developed and applied. Position and attitude, given by the vehicle's navigation system, were used to transform elements of a 3D terrain model into a scene description. Fundamentally, the EVS concept was what the authors called "vision fusion." This meant a coupling of the already preprocessed, sensed multichannel image data with synthetic image data. The coupling enabled the system to detect known objects by comparison between the data from the synthetic model and the data from the real sensor image. The purpose of this coupling was twofold: (a) Integrity monitoring of the whole system and (b) approach configuration was deemed essential for the successful future validation of the concept.

Korn and Hecker (2002a) described an effort by the German Aerospace Center to develop pilot assistance systems that use a combination of MMW radar sensor data, terrain data, and navigation sensor data and present findings from 51 flight tests on the system's ability to extract information necessary for successful landing (i.e., runway lights, runway stripe, and approach light system). Additionally, as distance to the runway decreased, the accuracy of the system in localizing extracted information increased. In all flight tests, the CVS was able to extract information early enough to present it on a display in the flight deck before reaching the minimum runway visual range. The observations herein validated the German Aerospace Center's prototype CVS and provided support for such a system being a useful and performance-improving tool for pilots in reduced-visibility landings. While the results did not extrapolate to real-world improvements in pilot performance, they provided evidence for a combined vision system having potential benefits on the flight deck.

Korn and Hecker (2002b) review the benefits of enhanced vision systems and synthetic vision systems for pilots' situational awareness. They proposed a system that, when integrated with a pilot assistant system (i.e., combination of all assistance functions into a single interface), increases the visual range of pilots during, runway approach, landing, and taxiing in low-visibility conditions. The described system used geolocation and an onboard terrain database to create a synthetic visual representation of the environment and combined it with visual information captured using HiVision radar to produce a combined visual representation. In validation testing of over 50 runway approaches, the combined vision system extracted information necessary for successful landing.

Harrah, Jones, Erickson, and White (2002) discussed the current state of NASA research on synthetic vision systems, as well as research milestones leading up to that point. Data from a CCD camera[2], short- and long-wave infrared cameras, and X-band radar were combined and used to create an enhanced vision system for the pilot. The system was tested in landings, take-offs, and taxiing.

[2] CCD cameras use a small, rectangular piece of silicon called a Charge-Coupled Device (CCD) to gather and imprint the incoming light. The silicon chip is a solid-state electronic component composed of light-sensitive cells.

Observations indicated that the system was able to reliably capture information necessary for operation in low-visibility conditions. The authors concluded that the system had the potential for improving pilots' situational awareness in low-visibility operation during landing, takeoff, and taxiing.

The research conducted by Bailey, Parrish, Kramer, Harrah, and Arthur (2002) was included in the CVS section herein for the reason that while the concept was named "Synthetic Vision Systems," it included real-time detection sensors. The authors provided an overview of the technical challenges encountered in the Synthetic Vision Systems Project under NASA's Aviation Safety Program. The motivation behind developing such a concept was rooted in the relationship between limited visibility as a contributing factor and CFIT accidents, general aviation accidents, and airspace capacity limitations. The SVS concept incorporated worldwide terrain, obstacles, airport databases, navigation information, and detection sensors to produce a real-time, unobscured view and could potentially be retrofitted into existing flight decks. Initial testing indicated that the system was well received by pilots and provided situational awareness benefits. However, some limitations included legibility under direct sunlight and terrain depiction illusions. To account for these deficiencies, continued development focused on expanding the luminance capabilities, setting guidelines for display contrast, and refining the terrain display. These new developments further improved system performance and pilots' situational awareness. One challenge regarding terrain depiction was identified as being rooted in providing adequate computational processing power for rendering onboard terrain databases in detail. While this could have been addressed by presenting a generic terrain display as opposed to a photo-realistic display, pilots tended to prefer the photo-realistic display. Quantified pilot performance, however, did not differ between the two displays. Several benefit analyses were conducted, from which the researchers observed an initial distrust in the system due to its novelty, indicating the need for a training program. Additional challenges were identified due to the need for airworthiness certification. Obtaining certification requires assuring the integrity of onboard terrain databases and accuracy and reliability of enhanced vision system sensors (e.g., radar and infrared sensors). In conclusion, while there have been numerous challenges regarding the development and implementation of advanced vision systems, their implementation provides human factors benefits in the form of reduced accident risk and situational awareness.

Theunissen et al. (2004, 2005) presented an overview of the SVS concept history, development, and concept of operation as well as how this technology could contribute to an increase in safety by compensating for the loss of information caused by reduced visibility conditions. According to the authors, the SVS concept can provide the pilots with continuous awareness of (a) separation between planned flight path and terrain, (b) deviation of the aircraft from the flight path, and (c) current and expected separation between aircraft and terrain. The SVS concept aims to increase the access to airports by a combination of these safety benefits with increased operational capabilities, which allow the crews to manually fly complex trajectories in an obstacle-rich and/or terrain-challenged environment and continue to lower visual minima. The overall system integrity was identified by the authors as a critical factor, which could determine the extent to which operational minima could be reduced in order to increase operational capabilities. Important issues were also identified, including the quality of terrain, flight path, airport, obstacle, and position databases, as well as the ability to detect errors in a timely manner. SVS-enabled operations need to guarantee an equivalent level of safety. Thus, an on-time detection of hazardous discrepancies between the real environment and the "synthetic" (generated from the database) environment must be assured. According to the authors, one way to deal with situations in which either SVS database errors or lack of information regarding obstacles or bad weather can reduce safety is the integration of real-time imaging data, a sensor-based depiction of the environment to augment the normal vision, that is, EVS. Such an approach draws on the human ability to detect inconsistencies between two overlapping images. The use of a particular sensor depends on the concept of operation and the criticality of the SVS for the given operation. Spatial and temporal multi-resolution image fusion has been a common approach to combining sensor and synthetic data. In the resulting presentation, none of the original sources is clearly distinguishable. The authors pointed out that although it may be desirable to compensate for some sensor deficiencies, integrity monitoring of the synthetic data is better supported when certain specific elements or features from the synthetic world are clearly identifiable as such. In order to achieve this, the data used to generate the synthetic environment is divided into a number of layers and the imaging sensor data is treated as one of the layers. Layer depiction and a predefined priority scheme can be used to control the visibility of the data specifically required to support an operational task. While several methods are available to integrate the EVS image into an SVS scene, the optimal way of integration depends on tasks to be performed and intended use of the information as well as phase of flight and visibility conditions.

Schnell, Ellis, and Etherington (2005) tested a technological framework for integrating Synthetic Vision Information System (SVIS) with Enhanced Vision System (EVS) in low-level terrain following and terrain avoidance missions. In a simulator, military pilots flew at 600 feet AGL at 240 knots. Between eight runs, pilots flew with a HUD and HDD, with and without synthetic vision terrain, with and without forward-looking infrared, and with a guidance pathway or a flight director. To measure how well the pilot maintained the assigned ground track and flight path, lateral and vertical flight technical errors were recorded during each run. After the runs, subjective workload and situational awareness were assessed. Results indicated that presence of synthetic vision terrain improved certain measures of flight tracking performance (i.e., lateral tracking, cross track error, and track angle error) and presence of the HUD improved vertical tracking. Adding terrain improved both workload and situational awareness, as did using the HDD instead of HUD. There were no objective performance differences associated with presence or absence of forward-looking infrared, but pilots reported increased display clutter, workload, and decreased situational awareness when it was present. These results support the notion that terrain detail afforded by synthetic vision can improve objective and subjective measures of pilot performance during low-altitude flying. However, it is important to minimize display clutter, which may increase workload and reduce situational awareness.

Bailey, Kramer, & Prinzel (2006) reported an experiment that evaluated the fusion of synthetic and enhanced vision systems, testing the usability, acceptability, and utility of the fused system during simulated landing in two-crew commercial and business aircraft. An enhanced vision display was incorporated with or without fused synthetic vision and with or without pathway guidance and a runway outline. Pilots used the system as a head-up display and as an auxiliary display. In the experiment, each pilot flew 40 runway approaches in varying wind and weather and with some runs including runway incursions and compromised database integrity (i.e., lateral navigation error of 50 or 75 feet). During each run, path control performance was assessed. After the runs, the experimenters assessed qualitative and quantitative measures of mental workload, situational awareness, display preferences, and display clutter. It was observed that lateral path error was lower by 14 feet with pathway guidance and runway outline, and subjective path control performance was improved by synthetic vision. Post-experiment workload assessments and situational awareness revealed that pathway guidance and runway outline reduced workload and increased situational awareness, and that fused synthetic vision improved situational awareness. Subjective assessment of display preference and display clutter revealed that fused synthetic and enhanced vision display that incorporated tunnel guidance and runway outline was the most preferred when presented on both-head up and auxiliary displays, with the head-up display preferred over the auxiliary display. These findings provide evidence that fused enhanced and synthetic vision can improve performance and situational awareness and reduce workload, especially when combined with tunnel guidance and runway outline and presented on a head-up display.

Parrish et al. (2009) review the NASA SVS project, the goal of which is to improve pilot awareness by providing a synthetic view of the external environment through the integration of on-board geospatial databases, navigational information, and onboard imaging sensors. In order to truly improve situational awareness, the vision system, in addition to a terrain view, must include independent, redundant sources of visual information that augment synthetic vision with real-time measurement of surrounding terrain, air and ground traffic, and other information not included in an on-board database. Regarding best practices, the authors recommended that terrain databases incorporate detailed texturing, coloring, and shading in order to convey terrain and elevation information while providing sufficient computational memory and processing power. Other important considerations included flight operations symbology that provided useful information without adding clutter or distraction, and presentations of synthetic vision system on a large HDD with variable field of view. If presented on a HUD, it was recommended to maximize symbology legibility in direct sunlight, as illegible renderings reduce situational awareness. Because the majority of research on this topic targets transport and business aircraft, future investigations were suggested in order to identify best practices for implementing synthetic vision systems in general aviation aircraft.

Gulec and Koktas (2012) presented a CVS method that consisted of image processing and tracking algorithms, which utilized information from navigation systems and databases along with images from daylight and infrared cameras, for the recognition and tracking of the designated runway through the approach and landing operations. Video data simulating the straight-in approach of an aircraft from an altitude of 5000ft down to 100ft in a set of atmospheric conditions such as fog and low light levels were synthetically generated. Correct detection and false alarm rates were used as the primary performance metrics.

The method described by the authors included a variety of information sources from onboard databases to real-time imaging sensors. These sources were utilized through multi-sensor data fusion algorithm, which was described as a synergistic use of information provided by multiple sensors to support the accomplishment of a given task. Specifically, the system described in this work was a CVS runway detection system to support approach and landing operations in degraded visual environments. The system blended database and real-time sensor information data fusion techniques that utilize information from a daylight camera, a long-wave infrared (LWIR) camera, onboard databases, and navigation systems. The algorithm performance was evaluated by means of detection rate and false alarm rate. The results were presented across altitude in order to show the continuous and reliable nature of the outputs throughout each scenario. The performance of the proposed CVS was superior to the use of onboard databases and navigation solution used in current SVS systems and specifically at low altitudes where the tasks and errors are more critical due to less error recovery time before touchdown. According to the authors, the study made a significant contribution to the CVS body of knowledge by presenting objective measures of CVS performance (i.e., detection rates and false alarm rates) and clear and unambiguous presentation of the runway borders. therefore requiring less cognitive load to resolve the image as in classical EVS displays where the sensor imagery is directly displayed to the pilot. The reported performance metrics reached up to 98% for correct detection rates and down to 5% for false alarm rates, depending on the visual environment and the video source.

Cheng, Li, Wu, and Feng (2013) reported findings from a preliminary investigation into the fusion of synthetic vision systems and combined vision systems in general aviation aircraft. The system investigated herein used an infrared sensor and a visible band camera to acquire data for the enhanced vision system and GPS antennae, a gyro sensor, flight symbology, and a terrain database to create synthetic vision. The SVS and EVS were fused using a pyramidal approach (i.e., algorithmic comparison of both data sources). Test approaches and landings were performed using a Cessna 172 with fog at varying times of the day. Subjective observations by the pilots revealed that the fused system enhanced contrast and brightness over independent SVS or EVS and provided an effective "view" of the environment in low-visibility conditions.

Kumar, Kashyap, Naidu, and Gopalratnam (2013) reported on the development of indigenous Integrated Enhanced and Synthetic Vision System (IESVS) at the National Aerospace Laboratories in Bangalore, India. Indigenous IESVS was expected to get into operation by 2014 and provide aircraft with the capability of operation from all Indian regional airports with minimal infrastructure and instrumentation facilities under adverse weather conditions including day, night, rain, fog, smoke, and other low visibility conditions. The system was projected to provide CATI landing capabilities at all airports within India and achieve CAT II and possibly CAT IIIA approach and landing without any additional infrastructure facilities. The initial work included technology analysis, requirement specification, and a roadmap for the technology. IESVS was described as a functional combination of EVS and SVS where (a) the EVS generates real-time images from combination of weather penetrating multispectral infrared (IR) imaging sensors like short wave infrared (SWIR), medium wave infrared (MWIR), long wave infrared (LWIR) and millimeter wave radar (MMWR); and (b) SVS generates a rendered image of the external scene topography from the perspective of the flight deck derived from aircraft attitude and high precision navigation data using onboard database of terrain, obstacles, and relevant cultural features. The weather penetrating imaging sensors provide separate thread integrity monitor and "enhanced vision" to the pilot. The system was planned to be developed in phases with human factor studies on a research simulator and integration into an avionics suite for transport aircraft applications.

Lebedev et al. (2014) provided an overview of a visualization concept in which an enhanced image from a camera sensor onboard an aircraft is combined with a synthetic, 3D image based on navigation data and onboard databases of terrain, objects, and textures. The presented approach was novel in that it provided for the fusion of the sensor and synthetic image based on a photogrammetric method. With this method, the geospatial coordinates of the aircraft and runway were used as reference points for presenting the synthetic image. To orient the camera, reference points of each of the four corners of the runway were aligned with the four corners as identified by the camera. However, the system was deemed limited in that the sensor did not reliably identify the runway reference points in low-visibility conditions. According to the researchers, the presented algorithm held promise as a method for integrating a combined vision system in the flight deck and the potential for providing human factors benefits in the form of reduced accident risk and optimized pilot workload.

Zheltov, Vizilter, and Vygolov (2014) described a research and development project of a prototype EVS and SVS system and reported results from an experiment testing the ability to integrate the two systems. The EVS fused an array of sensor data, including medium wave infrared, long-wave infrared, and a TV image, which was then combined with synthetic vision image created using terrain, obstacle, texture, and airport databases to produce fused synthetic and enhanced vision. Observations from a simulated flight test reveal that the SVS and EVS can be combined successfully to produce a robust CVS. Kramer et al. (2017) investigated the use of advanced vision system technologies, such as EFVS and SVS, as technologies supporting future all-weather operations as well as to determine if equivalent visual operations were feasible. The objectives were to evaluate the operational feasibility, pilot workload, and pilot acceptability of conducting straight-in instrument approaches with published vertical guidance to landing, touchdown, and rollout to a safe taxi speed in visibility as low as a 300ft runway visual range (RVR) using vision system technologies on a head-up display (HUD). Two methods of combining dual-sensor (millimeter wave radar and forward-looking infrared) EFVS imagery on a dual-HUD installation were evaluated by pilot crews as they conducted approaches to runways with and without touchdown zone and centerline lights. Additionally, the effects of adding synthetic-vision (SV) imagery to the dual-sensor EFVS imagery on crew flight performance, workload, and situational awareness during extremely low-visibility approach and landing operations, as well as the impact of HUD failure, were assessed. The results showed that all EFVS concepts flown resulted in excellent approach path tracking, touchdown performance, and centerline tracking during rollout, without any negative impact on pilot workload. Adding SV imagery to EFVS concepts provided situational awareness improvements but no improvements in flight-path maintenance were observed. The HUD failures occurred randomly throughout the trials and had no effect on pilot performance.

Objective measures results indicated that approaches with a dual-sensor EFVS HUD, with or without synthetic vision, in visibilities as low as 300 ft RVR seemed feasible. Regardless of the out-the-window visibility level or airport lighting configuration tested, all flown EFVS HUD approaches had a) equivalent ILS tracking during the instrument segment, b) were within the lateral confines of the runway with acceptable sink rates during the visual segment of the approach, c) resulted in touchdowns within auto-land tolerances, and d) had excellent tracking of the centerline during rollout. The participants unanimously affirmed that the EFVS provided all the visual cues required in the visual segment at or before the decision height to continue for a landing. No operationally relevant path maintenance differences were found due to the absence or presence of SV imagery combined with the EFVS imagery on HUDs. Pilots preferred having SV with the EFVS imagery on the HUD for low-visibility terminal operations. The dual-sensor EFVS (FLIR+ MMWR) on the HUD enabled successful approaches, without negative impact on workload, in visibility as low as 300ft RVR in this simulation experiment.

Summary

Based on the review of CVS literature, summaries of the operational benefits of the CVS and challenges to CVS operations are provided below:

Table 4

Summary of CVS operational benefits and challenges

CVS Ops Benefits	CVS Ops Challenges

• Combination of all EVS and SVS operationally beneficial functions into a single interface may
  o Further expand the ops benefits of EVS and SVS
  o Help resolve the EVS and SVS ops challenges
• When on HUD, improved tracking performance (i.e., lateral tracking, cross track error, and track angle error)**)**
• Lower lateral path error with pathway guidance and runway outline
• Potential for reduced subjective WL
• Potential for superior performance to both EVS and SVS (when outline of RWY presented)
• Improved integrity of navigation solution
	• Preserve the most useful and unambiguous visual cues pilots naturally use
	  o Augment missing or degraded visual cues under reduced-visibility conditions
	    ▪ Without adding visual clutter
	• Visual clutter
	• HUD vs. HDD
	• (HUD + HDD) vs. (HUD - HDD) vs. (HDD - HUD)
	  o HUD/HDD symbology consistency and continuity
	    ▪ Impact on performance and WL

Research "gap" analysis

Based on the results from the review of related literature, follow-on research areas were identified in order to ensure that the operational criteria that are developed for conducting CVS operations are a) based on data, not on opinion; b) support CVS operations to be conducted, and c) the criteria are applied in a consistent and standardized manner.

Pilot Performance Using CVS in Specific Operational Constructs

Characterizing pilot performance will enable the FAA to develop operational concepts using CVS that are appropriate for the operating conditions and contribute to safety when low visibility is a limiting factor. Developing these new and optimized operational concepts will enable low visibility operations on more types of instrument approach procedures (IAPs) and contribute to increased efficiency and throughput in the NAS.

Currently, FAA regulations permit a CVS to be used to conduct EFVS operations under 14 CFR § 91.176 if the CVS is certified to conduct EFVS operations and the operator is approved to conduct the operations. To be certified to conduct EFVS operations, the CVS must meet all of the requirements for an EFVS specified in 91.176 and the pilot compartment view vision system requirements of 23.773, 25.773, 27.773, or 29.773, as appropriate (see AC 90-106A and AC 20-167A). In accordance with the regulatory requirements for conducting EFVS operations, use of a CVS for such operations could only be conducted using a head-up presentation.

Use of a CVS display, however, might be possible for operational credit in other than an EFVS operational construct. Research is needed to

1. Identify specific operational constructs for which a CVS could be used for operational credit – head down or head up (other than EFVS operations). One example might be to use the EVS sensor imagery on a CVS HDD to independently verify aircraft position (act as an integrity monitor) in lower than standard visibility conditions and to lower than standard decision heights than are currently permitted on certain IAPs.
2. Characterize pilot performance (flight technical error, stabilized approach, and other performance parameters) using a CVS in specific operational constructs. Identify operational and human factors considerations and evaluate whether the CVS adequately supports the pilot's tasks.
3. Evaluate whether the head down presentation of EVS sensor imagery permits timely verification of aircraft position before descending below DA/DH or MDA?

Display Minification

Minification is a term that is defined by the angle represented on an SVS display (e.g., a traditional ADI pitch ladder display illustrates a compression ratio of approximately 7.7 in vertical direction when the display is located at 32in from design eye point) divided by the angle subtended by that representation at the design eye point (DEP). On a HUD, the angle depicted and the angle subtended at the DEP are the same so the minification ratio would be 1.0 (i.e., no minification). On HDD, the angular representations may be compressed horizontally and vertically because of limited display area.

Display minification may affect pilot performance in tasks that require accurate interpretation of angle referenced display symbology, distance, altitude, and angular displacement judgments. Excessive minification may affect the utility of displayed guidance symbology during approach and landing, especially in relation to other information used on the display. The minification ratio needs to be such that prominent topographical features are easily identified and correlated with the actual external scene. Furthermore, the crew should be able to accurately perceive relative distances to prominent topographical features. The following list of research questions have not been adequately addressed in the research literature:

1. How does CVS display minification on an HDD affect a pilot's ability to use CVS in specific low visibility operational constructs?
2. Does CVS display minification on an HDD affect a pilot's ability to use EVS sensor imagery to independently verify aircraft position before descending below DA/DH or MDA on a low visibility approach?

To address these research questions adequately, the research should be conducted with a sample of the **end user population** (not only test pilots), where a robust research methodology is used, and where different levels of minimization in both horizontal and vertical direction are examined.

Head down to head up transition

Another topic that has not been sufficiently addressed in the research literature is the head-down to head-up transition and acquisition of visual references and the runway environment during CVS operations. More specifically, a key point for the FAA is understanding how it affects, or if it does affect, pilot performance during low visibility operations. Does the CVS guide visual search in a way that facilitates more efficient acquisition of visual references and the runway environment? Whether operational credit is given for certain operations could pivot on this one point. Objective data, not just pilot opinion, is needed over a spectrum of experimental conditions of interest that address real-life operational scenarios including low visibility, night operations, etc. Here again, the research should be conducted with a sample of the **end user population**, where a robust research methodology is used, and where different levels of visibility and lighting, as well as failure conditions (e.g., loss of HUD or HDD) should be examined.

Conclusion

Combined vision systems technology has the potential to be a comprehensive solution to low-visibility conditions and to enhancing operational capabilities independent of airport infrastructure. However, further research is needed to support the notion of CVS having the capabilities to provide acceptable operational performance in very low visibility conditions. That is, the system may not yet have the accuracy and integrity necessary for guidance to touchdown in extremely low visibility. Efforts are underway to utilize the EVS component as an integrity monitor, and thus, correct/eliminate the errors which may be resident in the SVS database. This would provide an HDD, and/or HUD synthetic image that is exactly aligned with the real world, including the depiction of transient obstructions in the aircraft's path and enable approach to landing through touchdown, rollout, and taxi to the ramp in zero-zero conditions.

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