

*SYNTHETIC VISION
INFORMATION SYSTEM*

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ABSTRACT

Data from the Flight Safety Foundation (FSF) shows that the hull-loss accident rate for commercial jet transports during the last two decades has essentially remained constant at around 1.5 accidents per million departures. If the air traffic volume doubles as expected in the next decade, the absolute number of accidents will increase, even if the current low accident rate remains low. Public perception of flight safety is generally based on the absolute number of accidents and not accident rates. Therefore reduction of the accident rate such that the actual number of accidents decreases must be a primary goal; otherwise the predicted costs and loss of life are not likely to be tolerable by the industry or traveling public. This paper details Rockwell Collins efforts in the NASA Synthetic Vision Information System Program to address these accidents. The improvement in situational awareness and reduction in pilot workload resulting from these synthetic vision displays should allow aircrews to avoid landing short, flying too close to terrain, or blundering onto an active runway. These systems can also aid aircrews in re-planning en route and in the crucial final approach segment, by providing intuitive guidance cues to reduce pilot workload and improve performance. Furthermore, these guidance cues allow pilots to compensate for mistakes made at the strategic level.

PROJECT DESCRIPTION

Capitalizing on extensive prior studies and demonstrations, Rockwell Collins has assembled a world class team consisting of American Airlines, Boeing, Embry-Riddle Aeronautical University, Flight Dynamics, Jeppesen, NASA, FAA and the Technical University of Delft in The Netherlands. This team will prototype and validate a computer generated, database derived visualization system called the Synthetic Vision Information System (SVIS).

The prototype formats and the system functionality to support SVIS will be extensively validated through an exhaustive set of trade studies and analyses. The primary focus of these studies will be on human factors considerations. We feel that the primary challenges lie in this area rather than in the rapidly maturing avionics hardware and software technology. However, 3-D graphics, storage technology and database issues will be addressed to ensure that the prototype system will readily transition to product development.

We propose a tactical, pathway display with underlying proximate terrain displayed on a PFD. An accompanying MFD provides strategic display of the 3-D flight plan overlaying terrain over the entire flight plan area. For retrofit applications that preclude the use of these formats on existing cockpit instruments, simplified formats suitable

for use on a HUD will be developed. Taxi and surface maps will improve surface operations, safety and efficiency.

FORMAT DESCRIPTION

Recent research and safety analyses[7] indicate a need to improve vertical position awareness, automation awareness, and situational awareness in the cockpit. Conventional FMS displays do not intuitively portray both lateral and vertical flight profile. Current technology requires the pilot to assimilate large amounts of textual data to properly interpret the current and anticipated (future) aircraft situation. A 3-D map presentation, see Figure 1, which graphically depicts the flight plan and predicted vertical trajectory of the aircraft in the context of surrounding terrain, will present navigation data in an easily understandable format.

The 3D map has, in addition to the traditional map controls of range and map center, angle of view controls that allow for rotation of the map presentation about two axes. The two axes of rotation are a horizontal line through the map center (which allows for various vertical viewing perspectives) and a line through the map center which is perpendicular to the map center lateral plane (which allows for various lateral viewing perspectives).

The 3D map provides predicted flight path views that are referenced from the ground (same as a vertical profile view), referenced directly above a map center position (same as a plan map view) or referenced from an intermediate point in between.

A traditional FMS plan map format served as the baseline for the 3D map format. The three-dimensional information was added to the existing lateral information of a plan map. The lateral viewing angle of the 3D map can be adjusted to any value ranging from 0° to 360° which is different from the fixed north-up presentation of the traditional plan map. The lateral viewing angle is adjustable independently from the desired vertical viewing angle, which can be varied from 0° to 90°.

For the tactical display[8], see Figure 2, the desired trajectory is visualized by the tunnel. A number of spatial awareness aids have been integrated. The semi-transparent window shows the cross-section of the tunnel and the predicted position in 5 seconds. The spatially integrated presentation of terrain data is often referred to as Synthetic Vision. Besides the depiction of the future flight path and terrain it is also possible to include other traffic and weather.

Reising[2] compared a traditional head-up display with a pathway head-up display for flying a curved instrument

approach. Their results suggest that a pathway format provides the information needed for better flight performance in this task. They report that pilots describe the major benefit of this technique as being “instant situation awareness.” This assessment is also solidly confirmed through Collins’ internal research.[3,4,5]

The head-up display (HUD), see Figure 3, consists of standard HUD symbology with the addition of limited path visualization and a wire-frame terrain underlay.



Figure 2. Tactical Pathway Display



Figure 1. Strategic 3D Map Display



Figure 3. HUD Terrain Display

ACCIDENT STATISTICS

Data[6] from the Flight Safety Foundation (FSF) show that the hull-loss accident rate for commercial jet transports during the last two decades has essentially remained constant at around 1.5 accidents per million departures. If air traffic volume doubles as expected in the next decade, the absolute number of accidents will increase even if the current accident rate remains low. Public perception of flight safety is generally based on absolute number of accidents and not accident rates. Therefore reduction of the accident rate such that the actual number of accidents decreases must be a primary goal—the currently predicted costs and loss of life are not likely to be tolerated by the industry or traveling public.

FSF data show that almost 60% of all commercial accidents occurred during the approach and landing phases of flight. These accidents account for half of all accident fatalities. It is also known that CFIT is the dominant accident type and is responsible for more than half of all commercial aviation fatalities to date. Recent data clearly show that loss of control in flight is now emerging as a primary accident type, occurring with almost the same frequency as CFIT accidents. The data indicate that neither of these accident types is limited to the approach and landing phases.

The following factors are associated with past CFIT accidents:

- Air taxi and regional operators have higher accident rate than air transport operators
- Non-precision approaches are five times riskier than precision approaches
- 25% of CFIT accidents occurred to aircraft equipped with a GPWS
- Lack of flight crew situational awareness of terrain and aircraft position is a contributing factor
- 20% occur during enroute phase (most are single-pilot operations); 10% during takeoff
- Generally occur in rugged terrain, but significant numbers are in flat areas
- Almost 90% involve IMC or darkness
- Some due to visual illusions leading to incorrect altitude perception
- Moderate risk increase if there is an absence of charted arrival procedures
- Many due to lack of visual approach guidance and terminal approach radar

Loss of control accidents have been attributed to numerous factors including:

- VFR flight into IMC leading to disorientation and incorrect attitude perception
- Rushed approaches leading to poorly managed high-energy conditions
- Poor management and awareness of systems status
- Poor aircraft handling during asymmetric thrust conditions
- Conditions involving adverse winds
- Excessive banking during approaches with low circling minimums or go-around
- Lack of vigilance and crew coordination during high workload conditions

The impact of CFIT accidents is staggering in the Air Force as well, with nearly 200 fatalities, and 100 aircraft valued at \$2B lost over the last 10 years alone. The mission profiles for Air Force CFIT mishaps from 1980 through January 1994 show that the more aggressive and difficult flight profiles account for the majority of mishaps. Not surprisingly, a low-level flight profile is a major contributing factor in CFIT mishaps for all aircraft types. Additionally, the pattern for heavy transports is very similar to

commercial aviation and points to the flight profile that is linked to commercial CFIT accidents as well. These flight profiles take place during high task load on the operator and, in the fighter/attack case, high physiological load as well. It is not surprising that over 50% of CFIT mishaps have situational awareness components listed as contributing factors.[1]

Clearly it is the overall lack of the crew's understanding of where they are and where they are going in three-dimensional space[9] that enables CFIT accidents to occur. The operational forces are moving towards flying more precisely on more complex approaches in all visibility conditions. The addition of pathway guidance cues and terrain awareness to head-up display systems is a key to providing the pilot with more complete situational awareness for hazard avoidance.

Besides addressing the problems of controlled flight into terrain and loss of control accidents, Rockwell Collins will apply its experience in cockpit display formats and technology to reduce the risk of runway incursion accidents. Runway incursion accidents have been attributed to reduced visibility, complex airport layouts, and lack of vigilance on the part of flight crews and air traffic controllers.

While the aviation safety record is very good, improved pilot situational awareness through intuitive and up-to-date traffic, weather, and terrain awareness systems will make accidents even more rare.

BUSINESS CASE

We expect SVIS to provide both operational and safety benefits. While these two topics have overlaps, they will be separated here in order to set a historical perspective. Cost/benefit analyses of potential upgrades to improved avionics systems have historically been centered on gaining operational benefits to offset the investment cost of the system. However, increasing public awareness of air traffic safety, aided by recent findings of the Flight Safety Foundation, is causing airlines to consider safety improvement as a necessary factor for future avionics.

The SVIS offered by the Rockwell Collins team will provide operational and safety benefits to airlines beyond those provided by TAWS. Airlines currently lose millions of dollars each year due to cancelled, delayed and rerouted airline flights due to weather. By adding curved path guidance for arrivals and departures and missed-approach guidance, the SVIS will allow operations at decreased takeoff and arrival minimums in poor weather. The SVIS will also greatly enhance the safety margin in airline

operations. This enhancement can be expected to result in lower accident rates and reduced insurance costs.

SAFETY AND OPERATION BENEFITS

Analyses of CFIT, loss of control, and runway incursion safety data were used to generate the following top-level requirements[9]. In general terms, improved awareness is needed for terrain, obstacles, traffic, and weather. The proposed multi-function display (MFD) is conceived to meet these requirements. It lends itself well to flight planning and procedure rehearsals. The close coupling with the Flight Management System (FMS) allows route planning with terrain clearance protection. The Primary Flight Display (PFD), with integrated flight path, pathway, and terrain presentations is designed to meet the predictive, guidance, and crew decision-making requirements.

Synthetic vision benefits may be grouped as safety-related (as listed above) and as operational benefits. Safety does sell, and the industry and the flying public both want improved safety. But operational improvements give an economic justification for the installation of new equipment and the requisite training.

Safety Requirements	
Improved Situational Awareness	<ul style="list-style-type: none"> • Terrain and obstacle (manmade and natural) awareness • Aircraft position in the air, particularly vertical path awareness
	<ul style="list-style-type: none"> • Aircraft position on airport (relative to runways and taxiways) • Aircraft energy awareness and approach path stability • Traffic awareness both in the air and on the ground • Weather awareness including real-time weather reporting • Special Use Airspace status • Aircraft systems status
Improved Real-Time Guidance	<ul style="list-style-type: none"> • Conflict resolution guidance for terrain conflicts, traffic and obstacles (on the ground and in the air) • Vertical guidance for approaches at all airfields • Real-time taxi guidance capability
Improved Predictive Alerting	<ul style="list-style-type: none"> • Predictive alerting of potential landing short • Predictive aircraft energy decay alerting
Improved Crew Decision – Making	<ul style="list-style-type: none"> • Improved go-around decision making • Emergency procedures support
Improved Flight Planning (Pre-flight and In-flight)	<ul style="list-style-type: none"> • Operational adaptability due to weather • Airport and approach familiarization tools • Terrain proximity check for all FMS planned routes • Electronic charts incorporating terrain and obstacle data
Provide Rehearsal Capability	<ul style="list-style-type: none"> • Especially useful for complex/unfamiliar procedures • Used during low workload times like preflight and enroute

Clear operational benefits (summarized below), in addition to the safety benefits, will speed the adoption of the new technology.

Operational Requirements
<ul style="list-style-type: none"> • Lower takeoff and approach minimums • More efficient surface operations • Approach path flexibility (curved, segmented, etc.) • Improved missed approach guidance • Greater use of airspace

CANDIDATE SYSTEM

Consideration of the desired safety and operational benefits discussed above leads to the candidate system functional diagram shown in Figure 4. The functions are allocated to the FMS, display and navigation systems. Intuitive pictorial representations are an important aspect of this approach. Another important aspect is database storage, retrieval and processing. The envisioned functions in the candidate system raise a number of system issues, which are discussed below.

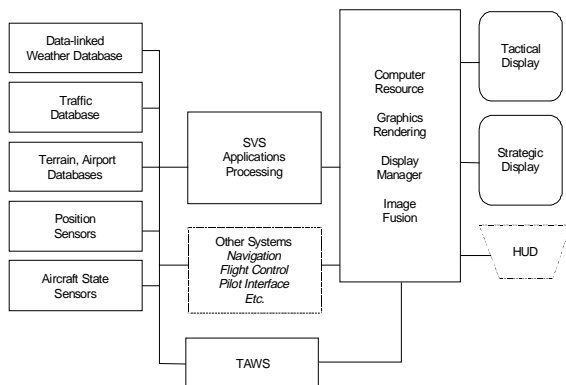


Figure 4. Candidate System

SYSTEM ISSUES

CERTIFICATION

Use of terrain and obstacle data on primary displays can be compelling information to pilots for use in routine and abnormal operations. The regulatory agencies have not been presented with a system to approve at this time. Until this happens and firm compliance policies are in place, the certification processes present a risk. The risk primarily involves cost to complete certification approval. This risk may be with regard to the resources to get approval and/or schedule delays due to the certification activity. The following items are specific risk areas that may be encountered during the process of obtaining approval for the use of terrain and obstacle databases.

- There are uncertainties in the certification criteria and administrative policy.
- The number of laboratory tests, demonstrations, flight tests, etc. is unknown.
- Human factors evaluation criteria are yet to be finalized.
- Coordination will be required with other world regulatory agencies.

Many of the areas listed above are being investigated at this time with the regulatory agencies. Considerable activity will be necessary to define policy, guidance, and responsibility within the agencies.

RETROFIT

Approximately 65% of the fleet currently have electromechanical (EM) display systems, and about 35% have EFIS display systems[6]. Of the EFIS systems, approximately half were made by Collins. This fact implies that there is a significant portion of the fleet that can be upgraded to SVIS technology by upgrading the Collins EFIS systems. If cost-effective display upgrades can be developed, then Collins will offer the SVIS technology to the EFIS-equipped airplanes.

For airplanes equipped with electromechanical displays, the addition of SVIS technology is more complicated.

Display and navigation capabilities may not be adequate for SVIS. EFIS-equipped systems already have serial busses and an information-rich display environment. EM display systems typically receive analog signals from federated subsystems, and the integration of information required for Synthetic Vision is not easy. Further, airplane owners have historically been reluctant to upgrade the EM systems to EFIS systems due to lack of adequate investment payback potential, as shown by the large number of air transport carriers (DC-9, MD-80, 737, etc.) equipped with EM displays.

There are two routes possible for SVIS upgrade of the EM systems. The first assumes that upgrade to a complete EFIS cannot be justified and that a low-cost upgrade is necessary. In this case, Collins would investigate the creation of an SVIS-capable multi-function display that would be placed in the HSI location. This versatile display would be capable of the usual HSI functions and would also be able to display the terrain features required to enhance lateral and vertical awareness. Another relatively low cost system that has great additional benefit would be a head-up display. The HUD could provide much of the operational benefit and capability at the expense of the situational awareness benefits. If brought to the marketplace, this HUD system would offer an alternative

for those owners who do not want to change the basic display system.

If the additional safety and operational benefits provided by the SVIS technology cause the cost tradeoff to favor a display system upgrade, then Collins will consider the development of SVIS-capable display systems suitable for retrofit into the older aircraft. There is reason to believe that, due to increasing costs of accidents, airlines will invest in new avionics that increase safety levels. In this model, the cost of the avionics investment is traded off against the expected cost of an accident rather than cost savings created by operational benefits.

TRADE STUDIES AND ANALYSIS

We will conduct trade studies in human factors, graphical methods, and database issues.

HUMAN FACTORS STUDIES

INTEGRATION

The ability of synthetic vision displays to integrate information from multiple sources of data, some primary to the task at hand, and some useful, but secondary, invites designers to provide a great deal of information on a single display surface. The density of the displayed information

and its effect on the ability of crewmembers to extract relevant information from the display become key issues.

2-D VS. 3-D DISPLAYS

Recently, more attention has been given to alternative methods of displaying information that may be more intuitive for the pilot. Three-dimensional displays of terrain, weather and traffic present information in a manner more consistent with the pilot's mental model of the real world. For example, a pilot may take the 2-D flight path and the readout from a digital altitude indicator, and then have to do some mental calculations to formulate the data in a usable way. A 3-D display of altitude and flight path could decrease the number of mental steps a pilot must go through before arriving at usable information. Furthermore, it has been argued that 3-D flight guidance displays have the potential to depict environmental data and mission critical information to pilots in order to increase situational awareness, including the reduction of the Controlled Flight Into Terrain accidents.

However, 3-D displays do have some potential problems that might lead to performance decrements. Studies have shown that they may lead to problems identifying absolute distances and depth dimensions. These effects will be studied by comparing the 3-D display, with varying levels

of realism, with a co-planar display. If distance recognition and depth are identified as critical tasks, augmentation to the 3-D presentations similar to range rings for map displays will be pursued.

REALISM

The issue of required realism for the synthetic vision information systems is an issue open for debate. Three-dimensional displays require a certain minimum level of realism in order to circumvent errors in display interpretation. In particular, depth cues are very important. But what other types of information are important to be displayed with a high degree of realism? Is it ever necessary to provide a "photo-realistic" representation of the world?

The types of formats that are being suggested might also be called Augmented Reality, in which the natural feedback to the operator is enhanced with simulated cues. In this case, absolute realism of the display representation is not expected to be necessary. This is because we are not expecting to be providing a re-creation of the outside world, but only a representation of certain dimensions of the outside world.

The higher the required realism of the display, the higher the potential costs for the customers. Moreover, technical limitations may exist as to the level of realism that is

achievable given the architecture in the cockpit. Therefore, compromises must be made between level of realism and the costs/benefits to the customer.

WIREFRAME VS. TEXTURE

Since many existing avionics displays are stroke written rather than raster scanned, it is important to ascertain the effectiveness of wireframe representations of terrain. If such a representation is effective, it will facilitate a lower cost retrofit solution.

GRAPHICS RENDERING CONSIDERATION

The proposed prototype and product displays employ classic 3D graphics characterized by transforming polygons, filling triangular surface patches with shaded texture, and removing hidden surfaces with the aid of a z buffer. Required rendering performance can be estimated by assuming a 1024x768 LCD filled with terrain. As is typical, a depth complexity of 3 can be assumed, so that every visible pixel occludes 2 others of greater depth. Then $(1024 \times 768) \times 3 = 2.4\text{M}$ pixels must be rendered every frame. For a 20 Hz frame rate as is generally employed in avionics, the required rate becomes 48M pixels/sec. This is well within the capabilities of the latest-generation of 3D rendering chips.

More difficult to quantify is the number of triangles per second required to be processed. The fastest-available chips are specified at 3M to 15M triangles/sec, but these are for triangle strips in which each successive vertex defines a triangle in conjunction with the previous 2 vertices. For independent, isolated triangles, a performance divisor of 3 is typically required.

Assuming a 60-degree field of view and a 20-mile range, a total area of 209 square miles may be in view. Using DTED data, such a view has 71.7K elevation samples at 100 meter spacing, or 5.3M samples at 10-meter spacing. At the assumed 20 Hz frame rate, and noting that each sample defines 2 triangles, processing rates of about 2M and 200M triangles/sec, respectively, are required. The lower bound of 2M triangles/sec may be directly achievable, but the upper bound is far beyond current capabilities. Techniques to reduce the required computation and storage requirements will be addressed. One candidate approach is data reduction in the form of a triangulated irregular network (TIN) that approximates the sampled terrain with the fewest number of surface patches that meet some prescribed error tolerance. Depending on the tolerances and ruggedness of the terrain, reductions well beyond 90% are often achieved. Another common approach is level of detail (LOD) reduction methods that employ fewer triangles in the surface approximation as the distance from the viewer increases (along with reduced

texture detail). Use of off-line data reduction and LOD methods would appear to reduce the processing burden to within the capabilities of the proposed graphics hardware.

DATABASE ISSUES

Drawing on the team's database expertise, techniques will be developed to address the issues below.

Database Integration and Layering – SVIS applications will likely need to integrate a variety of digital database products from a range of vendors. These must comply with data integrity standards set forth by the FAA, NOAA, and other organizations, and must correlate with each other. They also will contain a number of thematic data layers including terrain, obstacle, cultural feature, airport, and imagery data products. These differ in their life cycles, or rate of change. Requirements will also vary with phase of flight.

Terrain, Obstacle and Airport Database Requirements – The earlier study identified SVIS resolution and accuracy requirements for database information. This information is grouped by flight phase. On the airport surface, resolution and accuracy required are 1 meter. For takeoff and landing 6 arc-second resolution is required. For terminal area operations and enroute, 30 arc-second resolution is desired.

SVIS Database Availability Summary – The earlier study also identified numerous issues associated with the availability and quality of SVIS databases. Terrain data for the most part are available to support applications in enroute and approach/departure phases of flight. The NASA Shuttle Radar Topography Mission will provide cost-effective terrain data to support takeoff/landing operations. For airport operations, detailed surveys of the airport using photogrammetry and Geographical Information Systems (GIS) technology are required for each airport. Obstacle data availability and reliability are severely lacking, particularly outside the US.

Airports must be surveyed for all obstacles before conducting high-integrity SVIS-based applications and operations. The National Geodetic Survey (NGS) within NOAA provides accurate surveys of obstacles for the FAA at major airports. These surveys continue at this time, but it will take significant additional effort to map most airports for obstacles.

For surface operations, an accurate database of the airport layout is required for terrain, obstacles, and runway, taxi, and ramp areas. Again, photogrammetry and GIS are required. Expected enhancements in technology will greatly improve the development and cost of providing this type of data. Database issues are considerable, especially concerning integrity for use in critical applications.

Rockwell Collins and Jeppesen have been involved in and will continue to work these issues in industry committees, such as RTCA SC-193/EUROCAE WG 44, and with certification authorities to lead efforts to provide database standards.

PROVISION FOR TRAFFIC AND WEATHER

Work underway at Rockwell Collins on ADS-B applications to display traffic during approaches to closely spaced parallel runways will be demonstrated during the surface operations demonstrations.

Through our participation in AWINS contracts, we are developing strategic and tactical display concepts for uplinked weather products. Strategic weather information includes uplinked precipitation products such as NEXRAD, winter precip products, icing and turbulence indicators, surface conditions such as a graphical depiction of METARS information, and graphical AIRMET and SIGMET products. These datasets are georeferenced, and will be overlaid on a display. The strategic display will be used to show vertically resolved weather information, such as icing and turbulence, directly by means of icons and outlines along the 3-dimensional flight path.

FLIGHT TESTS

Flight testing and formal evaluations will be conducted aboard the NASA 757 ARIES aircraft.

Flight testing at Eagle, Colorado is designed to operationally test terrain features of the proposed display formats. The airport is situated in a valley with high terrain on all sides. The location makes siting a precision approach system next to impossible. Neither the existing localizer nor GPS approaches are aligned with the extended runway centerline and the existing minimums are quite high, even for non-precision approaches. Lower minimums can only be achieved by using curved approach techniques and positive missed approach and takeoff guidance with full time vertical cues.

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For more information contact:

ROCKWELL COLLINS

400 Collins Road NE

Cedar Rapids, Iowa 52498

319.295.4085

Fax: 319.295.2297

Web site: www.rockwellcollins.com

**Rockwell
Collins**