3-D Perspective Displays for Guidance and Traffic Awareness

Chad Jennings, Keith W. Alter, Andrew K. Barrows, Per Enge, J. David Powell

Department of Aeronautics and Astronautics
Stanford University

Biographies

Chad Jennings is a Ph.D. candidate in the Department of Aeronautics and Astronautics. Mr. Jennings did his undergraduate work in Physics and Astronomy at Vassar College. Prior to coming to Stanford to complete his M.S. and Ph.D., Mr. Jennings taught physics, astronomy, and cosmology at Phillips Academy in Andover, MA.

Keith Alter is a Ph.D. candidate in the Department of Aeronautics and Astronautics. He is a certified flight instructor and received his B.S. and M.S. degrees from Stanford. Prior to returning for his Ph.D. Mr. Alter worked for five years in the Flight Deck Research group at Boeing Commercial Airlines Group.

Andrew Barrows is a Ph.D. candidate in the Department of Aeronautics and Astronautics. He received his S.B. and S.M. degrees from MIT, where his Master's thesis focused on real-time flight planning systems for light aircraft.

Per Enge is a professor in the Aeronautics and Astronautics department. He received his M.S. and Ph.D. from the University of Illinois at Champaign Urbana. He oversees the WAAS and LAAS research efforts at Stanford.

J. David Powell is a professor emeritus of Aeronautics and Astronautics. Dr. Powell has co-authored two textbooks on control systems. His research deals with precision navigation and control of land, air and space vehicles.

Abstract

In August 1999 the Stanford University GPS Lab performed a series of flight tests designed to explore the possibilities of dynamically updating tunnels, enhanced height-above-terrain awareness, and traffic awareness in a 3D perspective tunnel-in-the-sky display. Based on current accident reports from the NTSB specific experiments regarding CFIT (Controlled Flight Into Terrain) accidents and runway incursions were performed. The results are subjective in nature and point out that a properly researched display holds excellent potential for aviation. Future work in several disciplines is necessary before such a display could be utilized in common practice. All the same, a system that mixes precise positioning information from a sensor such as WAAS, attitude information, and eventually the position and intent of other aircraft from a sensor such as ADS-B into an intuitive image has exciting possibilities.

Introduction

Aircraft accidents continue to occur at steady rates despite technological advances in flight displays and aircraft instrumentation. A significant contributor to the problem is a lack of pilot situational awareness. Researchers at Stanford and other institutions continue investigate how to leverage the positioning benefits of WAAS and current graphics hardware to generate improved flight displays.

Several groups of have studied and developed the tunnel-in-the-sky concept, in which guidance is presented to pilots as a 3D pathway. The pathway can be depicted as a path with hoops or goalposts (Wiener and Nagel, 1988; Grunwald 1984) guiding the pilot to their destination. The work has shown, in extensive simulation, that a pathway can provide accurate guidance while reducing pilot workload (Regal and Whittington, 1995).

Prior Stanford work demonstrates the value in precision guidance and reduced workload of a tunnel-in-the-sky display when implemented in real-time in a light aircraft (A. Barrows et al. '95, '96). Flight tests flown in August 1998 show the viability of using precise and timely position and attitude information to power a display for use in the challenging mountainous terrain of Southeast Alaska (Alter et al. '98).

In August of 1999 the GPS Lab at Stanford University executed a series of flight tests to evaluate and explore arenas of tunnel-in-the-sky research. This paper describes the experiments to demonstrate: dynamically adapting tunnels for missed approaches, enhanced terrain rendering, and a runway incursion alerting system.

Motivation

Figure 1 depicts a Honeywell primary flight display and a Honeywell TCAS 2000 display. The primary flight display shows elements of aircraft state, roll, pitch, heading, airspeed, and altitude. The TCAS 2000 display shows a plan view of neighboring traffic as well as issuing a recommended rate of climb to maintain sufficient separation from the aircraft indicated by the aircraft at 12 o'clock (indicated in red). The intent tunnel-in-the-sky displays is to fuse the information presented on these two displays along with guidance and terrain information into one single intuitive image.

Figure 2 shows the Controlled Flight into Terrain (CFIT) Fatalities versus Year for the last ten years. One can see from Figure 2 that the trend of CFIT fatalities remains constant and that CFIT fatalities number approximately 400 each year. CFIT occurs when the pilot, through misunderstanding of his surroundings, flies the aircraft into the terrain. This type of accident is especially tragic since it only involves variables over which the operators have control. The difficulty is making sure that the pilots understand the geometry of the terrain and how they are positioned and oriented in those surroundings; this is often referred to as situational awareness.

The persistence of CFIT fatalities provides the motivation to investigate and develop improved flight displays (A. Barrows et. al '96 and K. Alter et al. '98, H. Moller et al. '94, E. Theunissen, '97)

Figure 1. A Honeywell Primary Flight Display and a TCAS 2000 display can be integrated into an intuitive graphical image.

Runway incursions also continue to be a lingering threat to air safety. A runway incursion is defined as more than one vehicle (aircraft, fuel truck, etc) occupying a runway at one time. The number of runway incursions per year has risen 75% from 186 in 1993 to 325 in 1998, and incursions are occurring this year at the same rate as 1998.

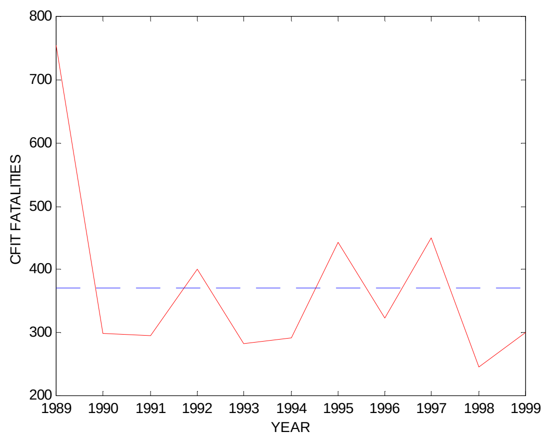

Figure 2. The Controlled Flight into Terrain Fatalities for the last ten years. The 1999 datum is extrapolated from 150 fatalities between January 1999 to July 1999. Data from the National Transportation Safety Board (NTSB). The blue horizontal line represents the mean of 360 fatalities/year

Two recent near misses underscore the pressing need for action on this issue:

- On 1 April, 1999 a Korean Air 747 departing O'Hare International Airport in Chicago, IL with 379 people aboard, passed 25 to 50 feet above an Air China 747 (8 crew aboard). The Air China 747 was erroneously taxiing across an active runway. (NTSB accident report DCA99SA054A)

- Another example from Cairo was taken from a concise but revealing accident report: *On May 12, 1998, Egypt Air A320 landed at Cairo airport and was clearing the runway when Ethiopian airline B767 departed and took the top 4 feet off Egypt Air's vertical stabilizer. Ethiopian air came back around and landed safely. No injuries reported. Investigation being conducted by Egyptian government.*
(NTSB accident report DCA98WA047A)

These incursions took place at large international airports. Runway incursions are a persistent problem for all sectors of aviation, civil air transport as well as general.

The CFIT and runway incursion statistics are but two motivations for Stanford University and other groups around the world to pursue enhanced tunnel-in-the-sky displays.

System Architecture

The system can be broken down into four components: flight hardware, sensors, display hardware, and display software (See Figure 3). To carry out the tests we outfitted a 1965 Beechcraft Model BE65-A80 Queen Air piston twin engine aircraft owned and operated by Sky Research Inc. of Ashland, OR.

The hardware within the Queen Air consisted of two racks of computers and sensors. Several GPS antennae have been mounted to the fuselage to support a variety of experiments. The flight test crew consisted of one pilot, one safety pilot, and between one and three engineers.

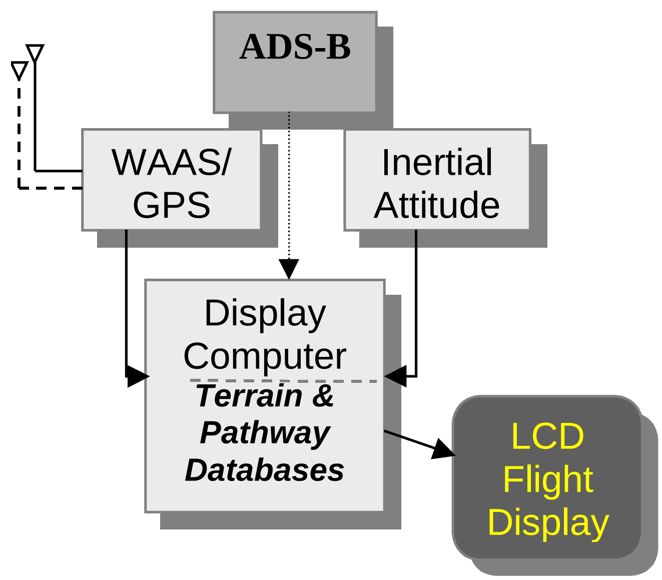

Figure 3. Schematic of display system architecture.

The flight display demands precise positioning information. Raw GPS position and velocity

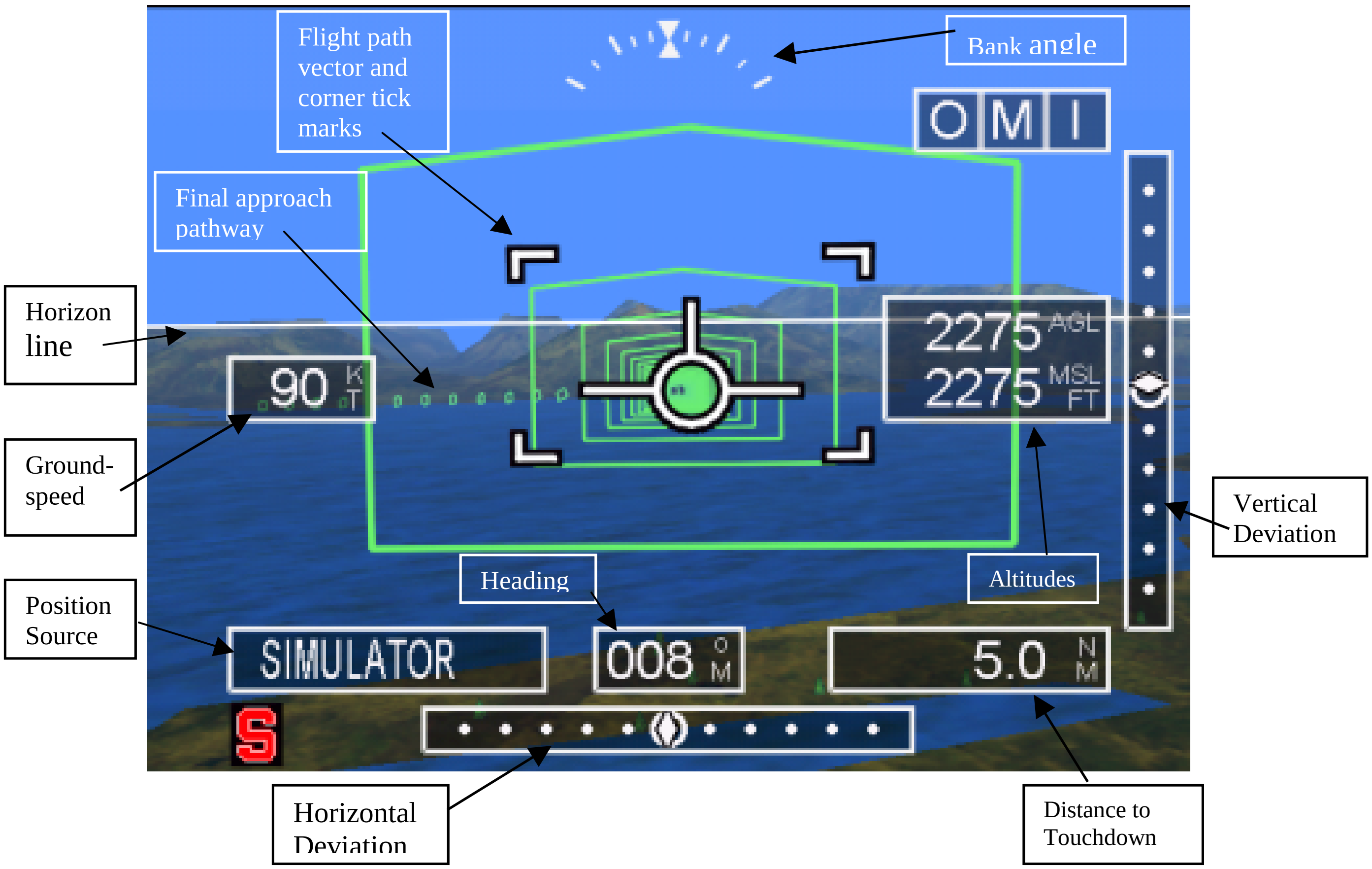

Figure 4. Tunnel-in-the-Sky Display

were provided by a NovAtel GPS card inside the P90 rack mountable computer. Differential corrections for the GPS equipment were received by a NovAtel Millennium GPS card, reading the WAAS GPS test signal currently under development by Raytheon. The WAAS user software was developed for the National Satellite Test Bed Prototype developed at Stanford University (R. Fuller et al. '99). Since Raytheon is still testing the signal, having a backup positioning system was prudent. The Coast Guard Differential Corrections were fed to a NovAtel GPS card within the display computer as a redundant position sensor.

The attitude information was fed to the display computer from a commercial grade Inertial Measuring Unit (IMU) from Honeywell Inc., through a CEI-100 ARINC interface card from Condor Engineering. Attitude data was also read into the display software at 10Hz.

In the near future the third sensor, ADS-B, will become available. ADS-B is a digital datalink between (air and/or land) vehicles, whereby each vehicle broadcasts its GPS derived position, ICAO aircraft identification number, whether the aircraft is climbing, descending, or turning and airspeed. This information can be used to position and orient the image of the traffic in the display in real-time.

Data from the two sensors (and soon from the third) are fed serially to the display computer. This computer is a Pentium II 333 MHz machine. The display is rendered on an Obsidian 2 graphics card from Quantum 3D, Inc. The display system has been designed with a goal of keeping the system inexpensive, for this reason all the components are off-the-shelf technology. However, with the continuing trend of cheaper and more powerful graphics hardware, this off-the-shelf system can still maintain a refresh rate of 20 to 30 Hz.

The final component in the display hardware is a 6.4 inch diagonal sunlight readable Active Matrix Liquid Crystal Display.

The code to generate the 3D perspective display was written in C; the graphics were driven by a Quantum3D software toolkit called OpenGVS.

With the enhancements added in the last year the display software consists of several modules. A description of the real time updating of position and attitude can be found in A. Barrows et al. ION-GPS '97. The details of the terrain generation can be found in K. Alter et al. ION-GPS '98. This paper will concentrate on describing the variable slope tunnels, terrain rendering enhancements, and the runway incursion alerting system.

Flight Study

In order to demonstrate and test the improvements we flew a series of flight tests at several locations in California: Moffett Field, the Santa Cruz Foothills, Truckee, and Lake Tahoe. Each of the enhancements mentioned above will be discussed in turn.

Variable Slope Missed Approach Tunnels: In most prior implementations of the tunnel-in-the-sky display symbology, including the Stanford University displays previously flown, the trajectory that the tunnel depicts, whether an approach, enroute segment, or missed approach, has been precomputed before flight and represents a fixed object in space. Creating the tunnel as a static object can be advantageous as 1) the tunnel vertices can be precomputed, and thus it is easier to animate the tunnel in a real-time graphics implementation, and 2) most flight paths and profiles flown should probably be certified in advance of flight to be clear of obstacles and terrain. However, during climb or missed approach the pilot is most often trying to achieve an optimal climb performance based on a particular power setting and airspeed. Variables such as airplane weight, winds, actual aerodynamic performance (i.e., poorer performance due to wing icing), and the actual point at which a missed approach is initiated can significantly influence the desired flight profile. Thus, for climbs and missed approaches, a new implementation was selected in which the vertical profile of the tunnel-in-the-sky varies in real-time to match the actual current climb profile of the airplane.

The variable-slope missed approach tunnel has a predetermined horizontal flight path that can include a combination of straight and curved segments. This path does not change in real-time, and could, for example, be designed to guide the airplane over a path that has the lowest maximum terrain altitude in the departure quadrant. The altitude of the tunnel at the current location of the airplane is adjusted in real-time to match the current altitude of the airplane. The climb gradient of the tunnel is smoothly adjusted to match the current climb gradient of the airplane, such that quick short-term changes in airplane climb gradient, due to turbulence or pilot action, do not cause the tunnel to move about excessively. A low-pass filter was used to generate the tunnel gradient from the current airplane gradient; a time constant of 5 seconds was determined to be a good intermediate value that allows the tunnel to move smoothly based on pilot action without excessive lag.

While the missed approach tunnel has a variable profile, the lower extent of the tunnel must be constrained to make certain that the pilot is never shown guidance symbology that would take the airplane below the minimum altitude for the climb or missed approach. For example, missed approaches are designed with a minimum climb gradient from the missed approach point; pilots flying at least this gradient are guaranteed to avoid obstacles and terrain. Thus, the missed approach tunnel described in this paper has been designed such that if the tunnel profile intersects the minimum climb gradient required, the tunnel profile will be adjusted to make certain that the tunnel guidance always shows a profile which is at or above the minimum requirement. The tunnel segments which are constrained are indicated on the display as amber-colored hoops (instead of the nominal magenta-colored hoops for the missed approach tunnel) to advise the pilot that he is approaching the minimum climb gradient required for the missed approach.

Improved terrain and terrain texturing: In 1998 Stanford University demonstrated a low-cost high resolution perspective terrain display which was integrated with the tunnel-in-the-sky display to provide pilots with greatly improved spatial awareness of terrain in their forward field of view. Terrain objects were created for the local areas in which the airplane was operated from USGS digital terrain databases and Land-Use-Land-Coverage (LULC) databases. While pilot feedback on the potential of the display was very positive, it was generally perceived that the display could be significantly improved in its capability to provide the pilot with height-above-terrain cues, especially when the airplane was close to the terrain. Specifically, the textures chosen for the ground and water were considered to be appropriate from distances of approx. 2000 ft. and above, but lacked definition and became "fuzzy" when the airplane approached to within a few hundred feet of the surface. Since perspective terrain displays become more important to the pilot the closer the airplane comes to the terrain, an effort was made in the newest implementation of the perspective display to improve the terrain object for intentional or unintentional operation within a few hundred feet of the terrain.

When approaching level or rugged terrain, the pilot utilizing a perspective 3-D display has an evident functional requirement to maneuver the airplane to avoid the terrain. While it might seem most appropriate to adjust the terrain surface to appear as realistic as possible, it should be recognized that making the terrain look more like it does in real life is not necessarily the best way to provide the cues required for terrain separation. Previous research and implementations of perspective terrain displays suggest the following features for improved pilot determination of distance to and height above ground when utilizing terrain displays:

- The terrain should be covered with a dense and random arrangement of common-sized textured objects (Kleiss '94). While trees are commonly used as appropriate objects, the objects do not necessarily have to be trees.
- Texture used on the terrain surface should be homogeneous and isotropic (i.e., the texture should look similar from any relative direction) (Stevens '95).
- Colorization of terrain by height can be used to provide cues as to where terrain is higher. This colorization scheme can improve ridgeline detail.
- Simulated atmospheric haze can be used to improve pilot recognition of terrain that is closer to the airplane from terrain that is farther from the airplane. Haze also improves contrast of ridgelines.

The newest perspective terrain display incorporates all of the features described above. A large pine tree was selected as an acceptable common-sized object. Through an iterative process, tree density was chosen to be approximately 150 trees per sq. mile, which was as dense as the display would allow without reducing the display update rate unacceptably. Tree height was chosen to be 100 ft.; shorter trees did not provide valuable cues until the pilot was already "too close" to the terrain. Pilots commented that knowing in advance that the trees were 100 ft. tall was valuable.

In addition to the features described above, a significantly denser and higher contrast texture was used on the terrain as compared to prior implementations. In addition, "detail texture" was utilized. With detail texture, a finer texture emphasizing the details of the surfaces is blended in with the regular texture progressively as the distance to the terrain object decreases. Detail texture not only provides additional visual cues as the airplane approaches terrain, but the onset of the appearance of detail texture on the terrain display indicates that the airplane is within approximately 1000 ft. of the terrain.

Runway Incursion Alerting: ADS-B is undergoing a continued set of flight trials sponsored by the FAA, the Cargo Airline Association among others. As a result the ADS-B air to air datalink is not yet readily available. Therefor, in this set of flight tests a virtual aircraft was rendered on the display. This virtual aircraft was programmed to take the runway as the real aircraft was on final approach. There was no actual aircraft broadcasting its position via ADS-B.

One of the fundamental issues involved in developing an airborne alerting code is to avoid overuse of the alert. To avoid falling into this trap the alerting software was designed to be simple and modular. A protected zone surrounds each runway. This zone is divided into three regions. Starting at the bottom of the runways in Figures 5 and 6 the regions are: Short Final, Position & Hold, and Rollout. The exact dimensions of each region were tailored to the dimensions of the runways at Moffett Field and then adjusted based on empirical observations during testing prior to the flight trials.

The logic that determines whether a caution or warning is issued, follows the these simple rules:

- When a vehicle shows intent to use or is using a runway all other vehicles are issued a caution on that runway.

- When two vehicles show intent to enter the same region, then issue warnings to both vehicles.
- Issue a warning if one vehicle shows intent to enter Position & Hold when another shows intent to enter Short Final on the same runway.

This concept of intent is designed to account for

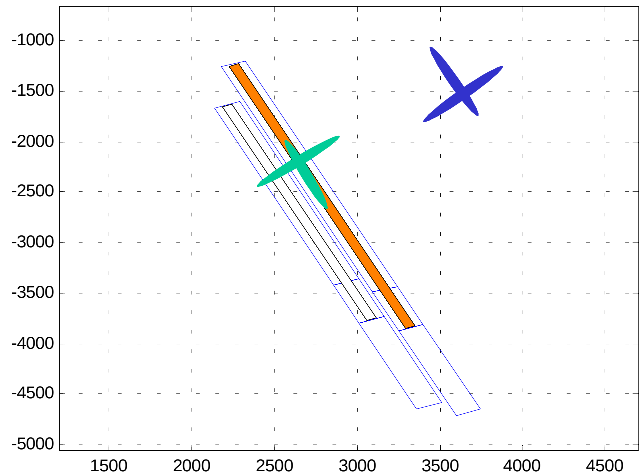

Figure 5. Caution on the right runway. The Safety Regions are outlines in blue.

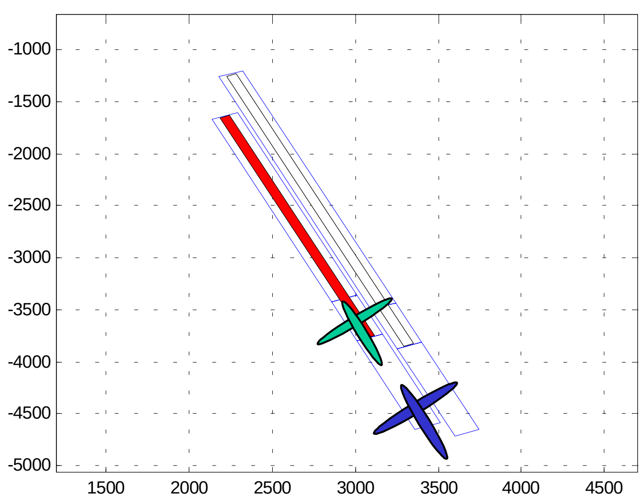

Figure 6: Warning on the left runway.

the velocity of a vehicle. A predicted point, $\vec{P}$, is the location of the vehicle in ΔT seconds based on the current position, $\vec{S}$, and velocity, $\vec{V}$. The predicted point is simply expressed by:

$$\vec{P} = \vec{S} + \vec{V} * \Delta T$$

If the predicted point for a vehicle lies within a region then it is assumed that that vehicle has intent to enter that region. Another way to describe intent is to say that the size of the safety regions scale linearly with velocity. This technique is analogous to adding lead compensation in a control system. The sole benefit is to give a reasonable and predictable amount of extra time for a pilot to react to an advisory.

ΔT is sized to ensure that a vehicle crossing an active runway will continue to generate a caution on that runway until it is impossible for the vehicle to start breaking and have any part of the vehicle lie within the runway boundaries when it halts. For our flight tests ΔT was set to eight seconds.

The "decision making" aspect of the software is a decision matrix, $\vec{D}$, where $\vec{D} \in R^{mxn}$. m,n = number of possible locations for aircraft 1 and 2, respectively. The elements of $\vec{D}$ are display options such as DisplayWarningOnLeftRunway or DisplayCautionOnRightRunway, etc. Thus $\vec{D}ij$ is the display option appropriate for vehicle 1 being in the ith region while vehicle 2 is in the jth region. In this implementation it is relatively easy to add more vehicles and it is trivial to add different display options.

The method of alerting the pilot is a non-trivial decision. Fortunately, the perspective nature of our display allows for a simple yet effective solution. When displaying a Caution on the Right, for example, the runway is displayed as orange rather than gray. When displaying a Warning the runway is rendered in red.

A short example: In Figure 5 an aircraft occupies the rollout region of the right runway, therefor a Caution is displayed on the right runway to all other aircraft. In Figure 6 that same aircraft is inside the Position & Hold region while another aircraft is in the Short Final region. This scenario is cause for a Warning on the left.

Results

In this series of flight tests we flew a total of 14 approaches, 5 missed approaches and 7 runway incursion approaches. We also flew a total of 4 hours to evaluate the enhanced terrain rendering for height-above-terrain awareness.

In flight testing, pilots found the missed approach tunnel to be easy to fly both horizontally and vertically. The most common suggestion received from the pilots who flew the display was that, unlike the static tunnel symbology which is easy to interpret with no explanation or training whatsoever, the missed approach tunnel requires pilot instruction on the functionality of the display and the symbology used.

The reaction to the changes in the terrain rendering was also favorable. Pilots felt they were better able to interpret their height above the terrain. Rendering an additional detailed texture below 1000 feet AGL (Above Ground Level) gave a perfectly intuitive visual cue for height-above-terrain. Also, the AGL altitude indication provides useful information that is part of every pilot's vocabulary, and thus easily understood. This feature is only realizable using a precise positioning sensor, such as WAAS, and accurate terrain databases. Leveraging these advancements could give pilots real-time AGL information at a significantly lower cost than a radar altimeter.

Lastly, the pilots found the runway incursion display very helpful. Since there was no other vehicle it is impossible to determine how much earlier a pilot could discern an aircraft on the runway with the display than without. Our pilots found the red indicator to be much more commanding than the orange. In the next generation the warning color will be changed to amber to better coordinate with display industry standards.

The results of our flight testing are anecdotal rather than numeric. We have not recorded sufficient data to claim statistical significance in any of our tests. The primary result of this paper is that each experiment points to an avenue of new and interesting research. The motivation described above points out that in addition to being solid research pursuits these activities can have real and measurable impact in the aviation industry.

Conclusions

This paper discusses three separate experiments flown by the GPS Group at Stanford University in August 1999. Each experiment serves illustrate ripe avenues of scientific research with significant industry applicability. The variable slope tunnel shows that it is feasible to generate guidance that responds to current aircraft conditions. Moreover these updating tunnels did so at a rate that did not generate resonances with pilot commands. In other words the pilot never had to chase or anticipate a tunnel that was changing too quickly or slowly, respectively. This success suggests that other forms of dynamically updating tunnels might be feasible. Examples could be tunnels that dynamically reroute conflicting traffic or tunnels that automatically update to avoid current weather. The improvements in the terrain rendering suggest that prudent inclusion of height cueing can generate intuitive situational awareness for low flight. The runway incursion experiments point out one possible arena of benefit of including traffic in a 3D perspective display. Other cases that might benefit from an intuitive traffic display are almost innumerable. From approach guidance for a 747 aircraft to taxi guidance for a single-engine tail dragger, providing pilots with a complete and intuitive picture of the surrounding traffic could help to reduce all manner of aviation accidents. Other cases such as visualization of CSPA (Closely Spaced Parallel Approach) scenarios might be well served with such a display.

It should be stated that this type of perspective display has shortcomings. The pilot only has awareness of the region in forward field of view, and is effectively blind to the side and rear. To address this issue 3D perspective displays are generally intended to accompany a top down or bird's-eye view to give pilots strategic as well at tactical information. (C. Wickens et al. '98)

The accuracy and integrity of the information it provides govern the effectiveness of a 3D perspective display. The position and attitude sensors must be accurate, have high bandwidth, and have high integrity. Using the WAAS and the Honeywell IMU yielded excellent input to the display.

From years of research by groups from all over the world, it is evident that tunnel-in-the-sky displays have the potential to give pilots excellent situational awareness in a variety of flight regimes. The flight test research described above points out three promising areas of future work. The accident statistics and reports from the NTSB support the urgency for pilot display research. Obviously there are many questions left to answer, in fields from human factors to sensor integration to system engineering. The goal of this paper is to illustrate that many groups have done excellent work and the opportunities for more excellent work exist in plenty.

Acknowledgements

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