Alaskan Flight Trials of a Synthetic Vision System for Instrument Landings of a Piston Twin Aircraft

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ABSTRACT

Stanford University has developed a low-cost prototype synthetic vision system and flight tested it onboard general aviation aircraft. The display aids pilots by providing an "out the window" view, making visualization of the desired flight path a simple task. Predictor symbology provides guidance on straight and curved paths presented in a "tunnel-in-the-sky" format. Based on commodity PC hardware to achieve low cost, the Tunnel Display system uses differential GPS (typically from Stanford prototype Wide Area Augmentation System hardware) for positioning and GPS-aided inertial sensors for attitude determination. The display has been flown onboard Piper Dakota and Beechcraft Queen Air aircraft at several different locations. This paper describes the system, its development, and flight trials culminating with tests in Alaska during the summer of 1998. Operational experience demonstrated the Tunnel Display's ability to increase flight-path following accuracy and situational awareness while easing the task instrument flying.

Keywords: synthetic vision, display, tunnel, highway, terrain, situational awareness, instrument approach

1. INTRODUCTION

Synthetic vision systems for aircraft have been investigated in a research setting for several decades. Despite promising accuracy and workload results, these systems have not found their way into the commercial realm. The numerous reasons are a result of the complexity inherent in aerospace systems. Inertial navigation systems remain too expensive for the general aviation community. The availability of flightworthy displays and inexpensive 3-D processing has been severely limited until only recently. Fielding a system for everyday use requires a level of integration typically found only on high-end transport aircraft. The resulting high cost of synthetic vision has hampered aviation operators in efforts to demonstrate real-world benefits of tunnel-in-the-sky displays. In 1994, work was begun at Stanford University to investigate avenues to lowering system cost while demonstrating operational benefits of cockpit synthetic vision systems. Several years of research under a *low-cost* and *operationally oriented* paradigm have yielded compelling results. Significant operational experience was gained with quantitative and qualitative results indicating significant benefits to be gained in accuracy, situational awareness, safety, and operational flexibility.

2. BACKGROUND

Instrument flying is a demanding activity during which the pilot must assess global aircraft status by systematically scanning the instrument panel. In light aircraft the cockpit contains a loosely integrated set of dials and indicators. Flying by instrument reference becomes especially difficult during changes in flight condition, such as intercepting a localizer or descending through clouds to a landing. Synthesis of this "big picture" is often referred to as "situational awareness" – a pilot's understanding of where the aircraft is relative to important features such as desired flight path, terrain, and traffic. A more natural, intuitive depiction of the world and desired flight path can be a powerful aid to increasing situational awareness

The challenge of maintaining situational awareness in this dynamic environment has led to the development of more intuitive primary flight displays. The concept that emerged involved a 3-D perspective display of the outside world along with a road or "tunnel" through which the pilot flies the airplane. This concept of a "tunnel-in-the-sky" display is not new; the work described here has its roots in the Army Navy Instrumentation Program directed by George Hoover beginning in 1952. This display concept has been carefully investigated in recent decades[7, 17, 12, 14, 16, 4]. However, most of this work has centered on laboratory simulation and expensive turbine test aircraft. The goal of the effort described here was to apply new enabling technologies to a system that addresses the operational, budget, power, and form-factor constraints of piston aircraft.

Situational awareness remains an issue even for the crews of large well-equipped transport aircraft. Controlled Flight Into Terrain (CFIT) incidents - in which a perfectly functional aircraft is flown into the ground by pilots unaware of its proximity to terrain – are a major reducible factor in airline accidents. Although this situation is being improved by the Enhanced Ground Proximity Warning System (EGPWS) [13], depiction of terrain on a forward perspective display can provide an additional tool for situational awareness.

Trajectories for use with tunnel-in-the-sky displays should be carefully designed so that flight through the tunnel satisfies all minimum height or distance requirements from terrain. Clearly, if the trajectory to be flown has been properly designated, a perspective display including only a tunnel should be adequate for safe flight so long as the pilot remains within the boundaries of the tunnel at all times. However, it is now economically feasible to add a 3-D depiction of local terrain to a tunnel-in-the-sky display if the graphics generator has a reasonable amount of processing power. When terrain is added to a tunnel-in-the-sky display, pilot spatial awareness with respect to aircraft position and proximity to hazardous terrain can be significantly improved. Since perspective terrain provides a depiction of the ground that is very similar to what the pilot sees in a visual flight environment (i.e., out the window on a clear day), perceptual workload to process this additional information is relatively minimal.

Digital terrain source data continues to become more readily available over time. Much of the currently available information is derived from declassified military digital terrain elevation data (DTED). Accurate terrain data for the United States can be acquired easily from the U.S. Geological Survey (USGS) in the form of Digital Elevation Model (DEM) data. Integrity of this data is a significant concern for those who require it for safety critical operations such as aircraft flight. The RTCA Special Committee 0193 and EUROCAE Working Group 44 are currently developing terrain and obstacle database standards for instrument flight operations. It is hoped that high-integrity terrain models will become more readily available in the next few years. The National Imagery and Mapping Agency and NASA are conducting the Shuttle Radar Topography Mission (STRM) scheduled for a September 1999 launch. The objective of this mission is to obtain the most complete high-resolution digital topographic database of the earth. If successful, much of the high-integrity terrain data should be available a year after the mission.

3. DISPLAY FORMAT

The display symbology and its use by the pilot are described here - hardware and software to generate the displays are described in the next section. Design of the displays was a compromise between including enough information for the pilot to perform the flying task and preventing excess clutter. This was especially difficult with the small displays used in the high-glare cockpits of the flight test aircraft used. The baseline display in Figure 1 presented an artificial horizon along with numerical readouts of altitude, heading, and groundspeed. (An air data computer would have allowed display of airspeed.) The field of view is 40 deg horizontal by 50 deg vertical. The approach and missed approach paths were depicted as a series of 100 m wide by 60 m tall “hoops” spaced at 200 m intervals. Trajectories were stored as sequences of segments with constant turn radius (including straight segments) and constant climb gradient (including constant-altitude flight or descents).

Predictor symbology similar to that used in Ref. 8 provided pilot guidance through the tunnel. A “predictor symbol” shaped like a circle with wings displayed the aircraft’s predicted position (based on current position, velocity, and lateral acceleration estimated from bank angle) 3.5 sec in the future. Another symbol, the “nominal path symbol,” was presented as four tick marks that represented the aircraft’s desired position in 3.5 sec if it were flying perfectly down the center of the tunnel. The predictor time of 3.5 sec was chosen to suit aircraft dynamics – longer times are suitable for larger aircraft with slower dynamics[8]. From the pilot’s point of view, the guidance task was simply to fly the predictor symbol into the center of the four tick marks. This task is very similar to flying with a flight director since the higher derivatives used to drive the predictor symbol provide lead compensation. Test pilots expressed a desire to see raw horizontal and vertical deviation information, so scales similar to the familiar localizer and glideslope needles were added.

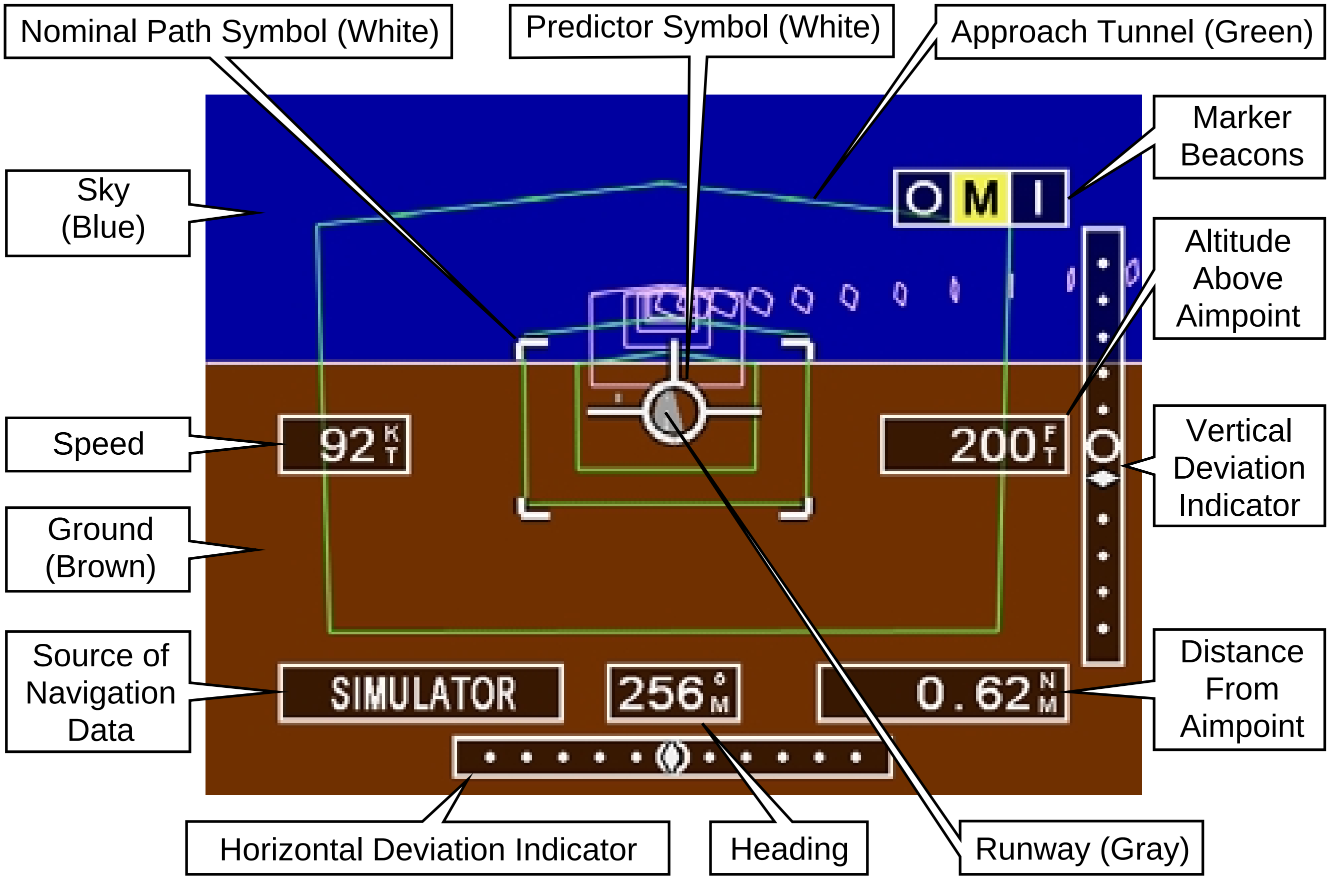

Figure 1. Baseline Tunnel Display with no terrain information.

For the flight trials in the mountainous terrain of Alaska described below, textured terrain was depicted instead of the brown and blue artificial horizon. The symbology described above was simply overlaid on top of the terrain as shown in Figure 2. The software used to generate the terrain is described in the next section.

4. SYSTEM DESIGN

Differential GPS (DGPS) was chosen as the position sensor to avoid expensive inertial instrumentation. DGPS data came primarily from Stanford's Wide Area Augmentation System (WAAS) prototype using the FAA National Satellite Test Bed network of reference receivers. This provided the display with 2 m 95% vertical accuracy[6]. The Tunnel Display has also been used with the carrier-phase DGPS Integrity Beacon Landing System invented at Stanford[5] and with DGPS corrections provided by the US Coast Guard.

Attitude data was supplied by a system based on complementary filtering of GPS attitude with inertial sensors[9]. This system used a small triangular array of three GPS antennas on top of the fuselage to provide carrier phase differential attitude measurements. To eliminate noise and dropouts in the GPS attitude signal, inexpensive quartz tuning fork rate gyros were integrated using a Kalman filtering scheme.

The synthetic vision system has undergone several implementations before maturing into the system used for the Alaskan flight trials. At all times commodity PC hardware was employed to keep costs down. The initial platform, first flown on a single piston-engine Piper Dakota in 1995, was an 80486-based laptop using DOS as the operating system. 3-D graphics software was custom written for this purpose because dedicated graphics hardware was still too expensive. Attitude information was inferred from DGPS velocity data. The right-seat pilot held the laptop computer up to the instrument panel.

The 9.5-inch diagonal display was transflective, so it was easy to read in the bright environment of a general aviation cockpit. However, it was limited to grayscale images.

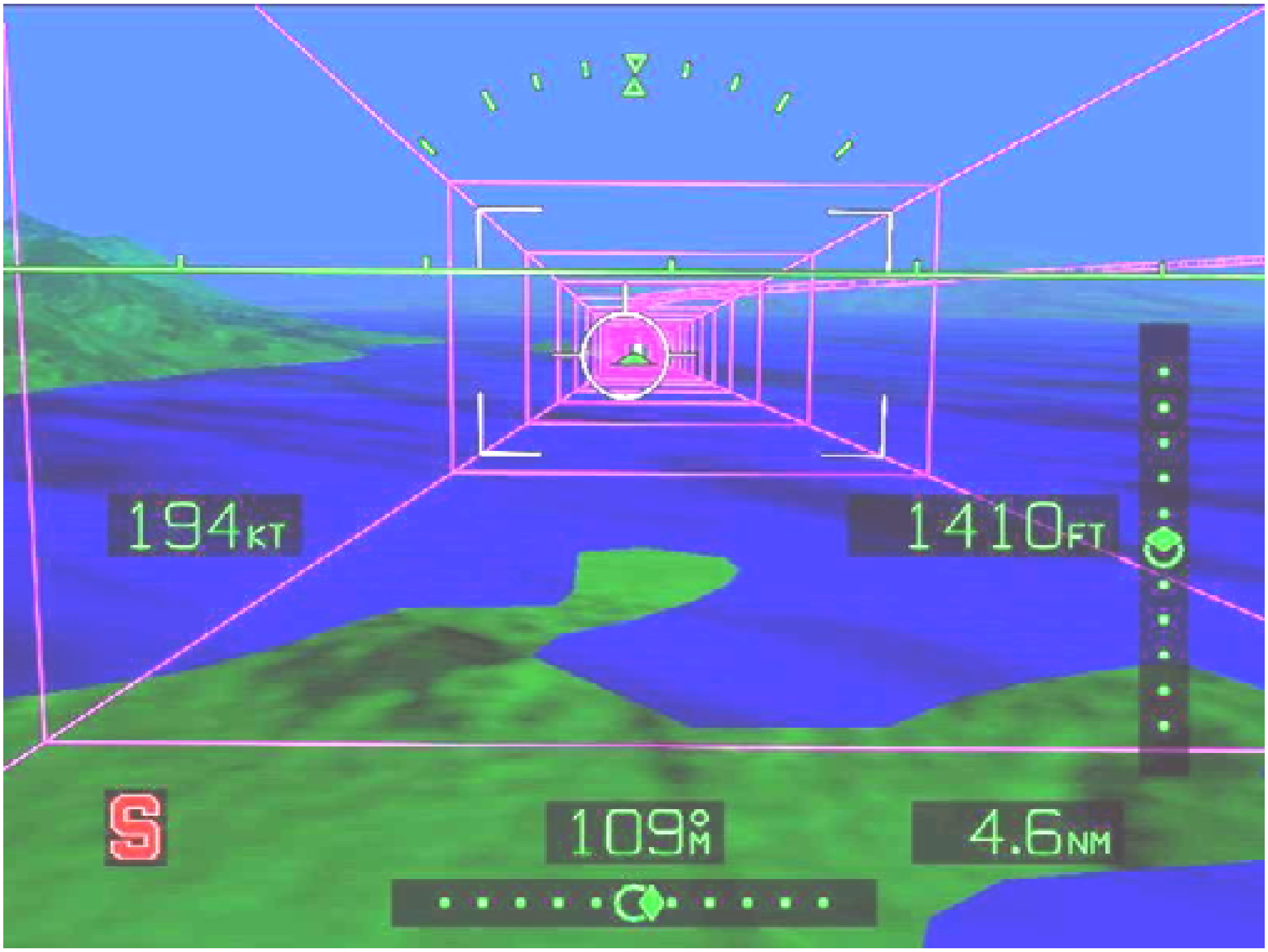

Figure 2. Tunnel Display with terrain

In 1996, the computer was upgraded to a ruggedized Pentium PC running at 90 MHz with Windows NT as the operating system. This change was made to take advantage of the emerging selection of low-cost 3-D graphics hardware that accelerates the OpenGL 3-D graphics library. Development of the GPS/inertial attitude system was also begun in that year. The 5.5-inch diagonal color Active Matrix Liquid Crystal Display (AMLCD) attached to the Piper Dakota's glareshield proved difficult to read in bright sunlight.

The flight test aircraft was changed to a twin piston-engine Beechcraft Queen Air in 1997, allowing approaches to be flown at speeds (120 – 140 kts) closer to those of airliners. The graphics hardware was also upgraded, reflecting the rapid development and price drops in this arena. A sunlight-readable 6.4-inch diagonal AMLCD was mounted in the instrument panel to the left of the heading indicator – close enough to the center of the pilot's scan to serve as the primary flight display.

In 1998, terrain information was added to the display necessitating another upgrade. A Pentium II processor running at 333 MHz was added along with an Obsidian2-based graphics board capable of drawing high speed textured polygons. While most of the display code was initially written in C at the lowest possible level, the complexity of handling terrain information prompted the addition of the OpenGVS hierarchical scene graph API from Quantum 3D, Inc.

Terrain and water databases were created from USGS DEM and Land-Use-Land-Coverage (LULC) information. Coastline data for Alaskan terrain came from the Alaska Department of Natural Resources. Since a terrain skin including all of the gridded elevation points in a DEM database would result in hundreds of thousands of polygons per frame, the terrain surface was rendered as a mesh calculated from a Delaunay triangulation using selected points in each database. The terrain skin was further optimized for graphics presentation by using multiple levels-of-detail in the terrain skin: terrain that was further away from the pilot was drawn in less detail. The reduced terrain surface had very little reduction in overall terrain accuracy, but resulted in the typical display frame (see Figure 3) containing 8,000-10,000 textured polygons. This allowed smooth animation of the display at 30 Hz.

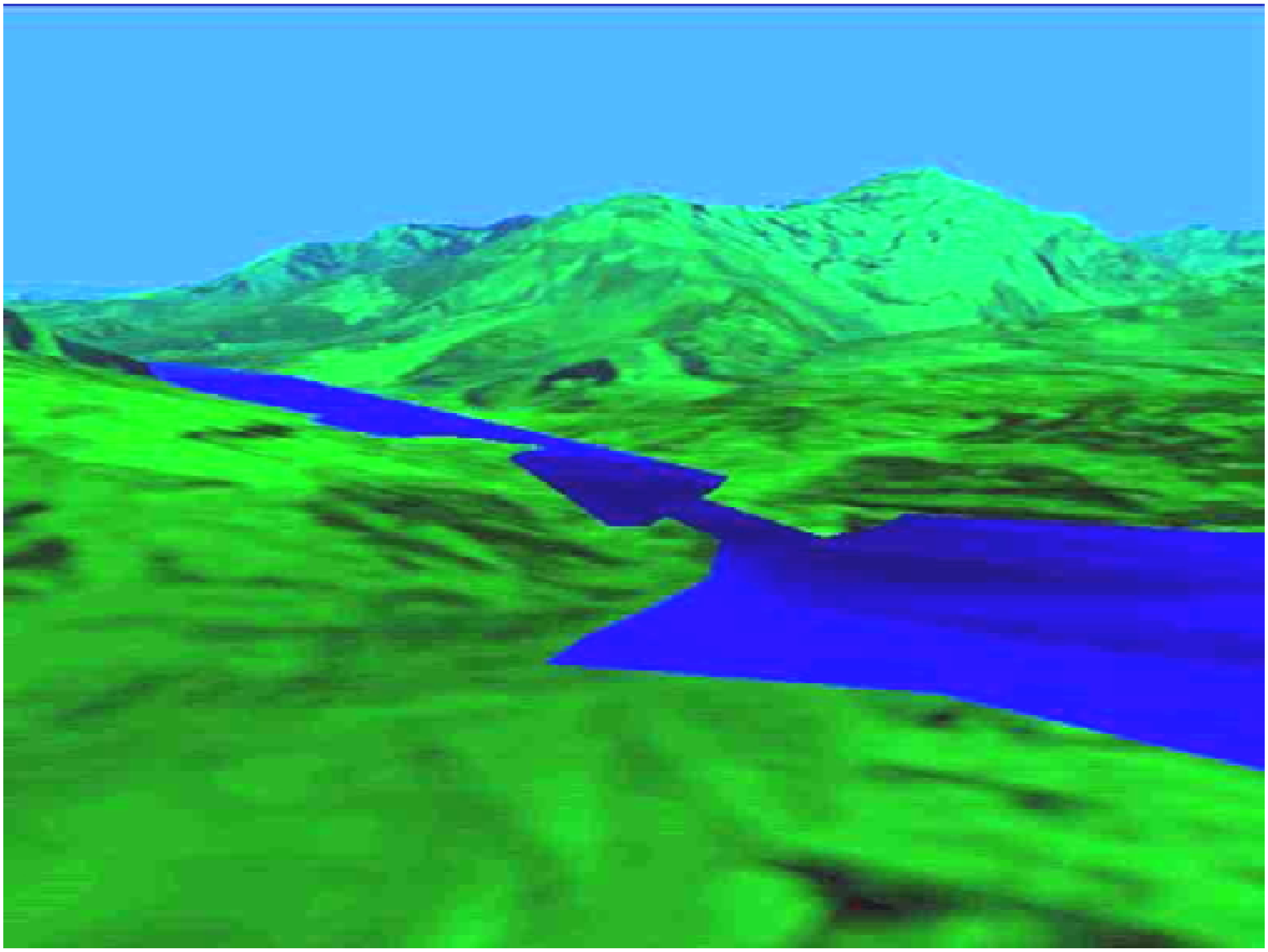

Figure 3. Terrain near Petersburg, Alaska.

5. DEVELOPMENTAL FLIGHT TRIALS

Developmental flight testing of the display and sensors took place during 1995 and 1996 at Palo Alto, Livermore, and Truckee, California[2]. The flight paths were mostly straight-in approaches and missed approaches. The level of path complexity was increased for tests at Moffett Federal Airfield, CA, chosen for its long parallel runways and lack of air traffic. These included the segmented and curved approaches described below and fully documented in Ref. 3. During these tests, the project test pilot did not look outside the cockpit, relying only on the Tunnel Display for flight path information. These experiments performed in visual flight conditions with a safety pilot in the right seat monitoring the pilot.

The segmented approaches shown in Figure 4 began just over 3 nm from the runway aimpoint on an extended left base leg. Descending with a flight path angle of 3 deg, a series of three 30 deg left turns brought the aircraft onto a 2 nm final approach. Low approaches were made at 120 kts airspeed with the aircraft making a left climbing turn to rejoin the downwind leg and tunnel. These approaches were flown with a high degree of accuracy: root mean square flight technical error (RMS FTE) was 52.7 ft laterally and 50.7 ft vertically. In fact, the horizontal flight track repeatability caused a number of noise complaints to the airfield operations office – the airplane was flying over the same houses each time! (Subsequent flight tests were planned to minimize noise exposure.)

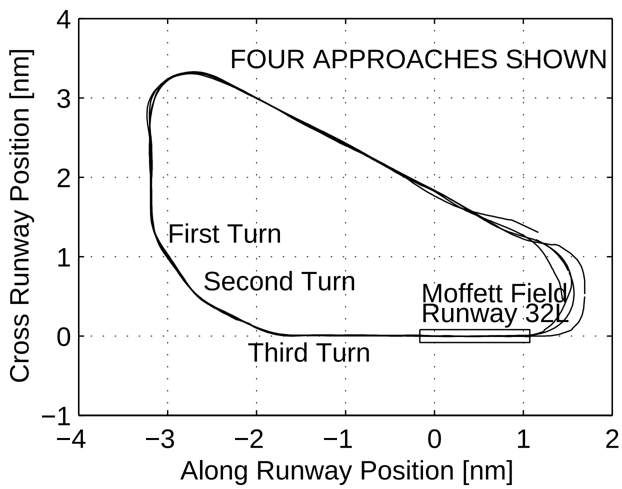

Figure 4: Segmented approaches at Moffett Field in Beechcraft Queen Air.
Repeatability of ground tracks actually resulted in noise complaints.

Shorter curved approaches were also flown with the aircraft turning onto final approach 1.5 nm from the runway. Figure 5 presents two of these test runs that were interrupted by traffic sequencing information from the control tower. In the first case, the tower commanded a left 360-deg turn to ensure separation from another aircraft. It was decided to continue this data run with the pilot flying the turn with reference to the display's artificial horizon. When the curved tunnel reappeared on the display after most of the turn was complete, the pilot smoothly merged into the tunnel and continued the approach. On another occasion, the tower instructed the pilot to cut short the turn from base leg to final approach. This required the pilot to leave the curved tunnel on base leg, "cut the corner," and the rejoin the approach less than a mile from the runway. Both of these deviations, the 360-deg turn and the shortened turn, were executed easily by the pilot indicating good 3-D situational awareness of the aircraft's position relative to the curving flight path. Although low-altitude maneuvers are not part of normal instrument flying, they illustrate the Tunnel Display's potential to enable new capabilities.

To quantify the achievable accuracy of this system in the Queen Air, a set of flight tracks was flown with controlled straight and curved segments. Turns of 30, 60, 90, and 180 deg were flown with radii ranging from 750 m to 3000 m. The tightest turn radii were smaller than in normal instrument flying practice (the 750 m turn in the Queen Air resulted in a bank angle of approximately 30 deg) but were included to explore the limits of system capability. These patterns were flown with the pilot wearing view-limiting glasses (to simulate instrument flight conditions) and a safety pilot in the right seat. The tests resulted in a database of over 75 min flying controlled straight lines and over 30 min in turning flight. On straight segments the horizontal and vertical RMS FTEs were 21.8 ft and 11.8 ft respectively. On curved segments the corresponding numbers were 38.2 ft and 15.8 ft. These results are better than the Instrument Landing System even at decision height[11].

Greater accuracy could likely be achieved with different symbology. Two obvious approaches would be to tighten the spacing of the four corner tick marks and further quickening of the predictor symbol. However, accuracy gains would be expected to raise pilot workload. These parameters must be carefully tuned to the type of flight operation involved.

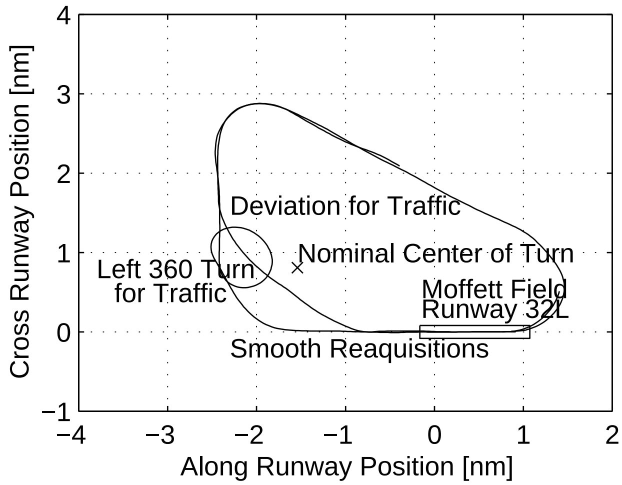

Figure 5: Curved approaches at Moffett Field in Beechcraft Queen Air.
Pilot was able to accommodate deviations for traffic and smoothly reenter the approach tunnel.

6. ALASKA FLIGHT TRIALS

To fully explore the benefits of the Tunnel Display in mountainous terrain, it was used for flight trials in Alaska in August 1998. This series of tests was fully documented in Ref. 1; some of the results are condensed here. Overlays to IFR approaches were flown at three Alaskan airports: Juneau, Sitka, and Petersburg. In addition, various visual arrival procedures were programmed and flown by instrument reference to demonstrate the operational flexibility of the Tunnel Display. Several arrivals into the Juneau runway 26 traffic pattern are depicted in Figure 6.

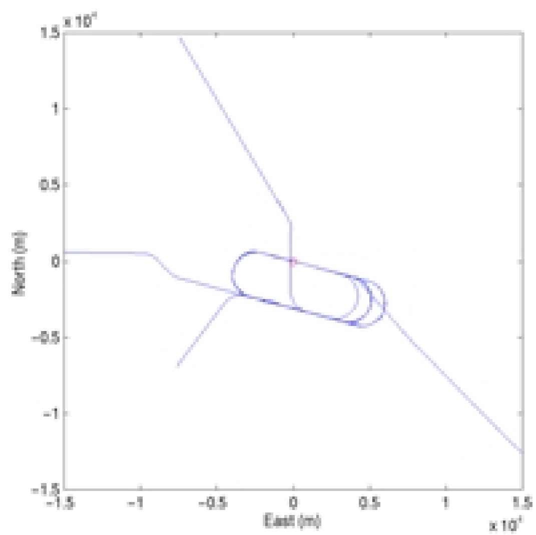

Figure 6. Arrivals flown into the Juneau runway 26 traffic pattern using the Tunnel Display

The nine pilots who flew with the display (including guest airline personnel) expressed satisfaction with its ease of use, even in light to moderate turbulence. In general, the pilots were able to fly the display well with virtually no training prior to the flight, save an explanation of the display symbology. The aggregate RMS FTE results were 77 ft horizontally and 36 ft vertically. These very precise FTE values were maintained even though pilots were only instructed to “fly through the tunnel." Presumably, these errors could have been smaller if the pilots had been instructed to "stay as close to the center of the tunnel" as possible. FTE when pilots were flying straight segments was 74.3 ft horizontally and 34.6 ft vertically, while FTE during curved tunnel segments was 82.1 ft horizontally and 38.8 ft vertically. This result suggests that with the Tunnel Display pilots are capable of flying real-world curved flight trajectories nearly as precisely as they can fly straight flight paths and profiles.

Pilots found the terrain on the display to be representative of the actual terrain outside of the airplane. Subjective results suggested that the terrain display in conjunction with the tunnel-in-the-sky provided very good local pilot spatial awareness, although most pilots expressed a desire for a navigation display for better overall situational awareness. A map display that answers the question "Where along the tunnel am I now?" would be the logical companion to a Tunnel Display in a complete glass cockpit.

7. FUTURE WORK

While the display provided good terrain awareness when the aircraft was a fair distance away from terrain, pilots' subjective estimates of height above terrain could be improved with better terrain texturing. Studies[15] suggest that an isotropic, homogeneous terrain texture with high spatial frequency components provides the best perceptual cues for pilots flying close to terrain. Adding common-sized surface objects such as trees greatly improves height above terrain cueing[10]. Work is underway to improve the perspective terrain's cueing properties when the aircraft is close to the terrain while maintaining realism when the aircraft is further away. This updated display should be flying within the next few months.

In addition to improved terrain texturing, work continues on adding real-time coloring of terrain to alert pilots of potential hazards[16]. Using current aircraft state and modeled aircraft dynamics, dangerous terrain would be shaded amber or red, informing the pilot of relative locations of potential risks.

8. CONCLUSIONS

Extensive operational experience with the Tunnel Display at Stanford (37 hours, 162 landing approaches, 9 pilots, 2 aircraft, 6 different airports) has demonstrated that:

1. A Tunnel Display can be implemented using low-cost technologies and flown on inexpensive piston aircraft.

2. This low-cost approach resulted in a simple system that allowed for rapid development of display improvements and new flight procedures.

3. The Tunnel Display allowed for greater path-following accuracy than conventional instruments while reducing subjective pilot workload.

4. Pilots learned to fly the Tunnel Display with almost no training. Student pilots were soon able to fly instrument approaches better than most instrument-rated pilots.

5. Situational awareness of the aircraft's position relative to the flight path was improved. Pilots could make tactical deviations to instrument approaches and still rejoin the tunnel approach before landing.

6. Subjective results suggested that the terrain display in conjunction with the tunnel-in-the-sky provided very good local pilot spatial awareness.

7. Ongoing operational experience and pilot evaluation has been very valuable in continuous improvement of the display format.

In summary, the Tunnel Display shows promise for increasing the safety and utility of instrument flying. Increased situational awareness can reduce accident rates across the entire spectrum of aviation, from light aircraft to large transports. Increased accuracy and flight path flexibility are a natural match for future ATC systems that will use airspace, fuel, and time more efficiently. Synthetic vision technology may prove very useful for wake vortex and traffic visualization, especially on closely spaced parallel approaches. Finally, niche applications poised to benefit from this precision guidance technology include forest fire fighting, aerial application, remote sensing, and search and rescue.

ACKNOWLEDGMENTS

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