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Flying Curved Approaches and Missed Approaches: 3-D Display Trials Onboard a Light Aircraft

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BIOGRAPHIES

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ABSTRACT

Cockpit displays that enhance situational awareness in light aircraft are becoming feasible through the rapid development of enabling technologies including differential GPS, inexpensive computers, and ruggedized color LCD panels. A prototype glass cockpit system was developed and used to explore implementation and operational issues through flight testing. The display provided an "out the window" three-dimensional (3-D) perspective view of the world, making the horizon, runway, and desired flight path visible to the pilot even in instrument flight conditions. The desired flight path was depicted as a tunnel through which the pilot flew the airplane. Predictor symbology was added in response to pilot requests for better guidance and presentation of path-following errors.

Piloted simulations and flight tests on a four-seat Piper Dakota demonstrated enhanced accuracy and capability on a variety of trajectory types. These included curved approaches with one constant-radius turn, segmented approaches, and complex missed approaches with multiple curved segments, climbs, and descents. Flight technical error and position histories document system performance. Hardware, sensors, and computational issues specific to the problem of practical 3-D perspective flight displays are discussed. The results demonstrate that an intuitive display can allow precise navigation on complex flight paths and increase safety through improved situational awareness. In addition to enhancing typical passenger aircraft operations, such systems would be valuable for applications requiring precise path following in low-visibility situations

INTRODUCTION

The instrumentation in typical light aircraft is based on 50-year-old technology manifested as a loosely-integrated set of dials, gauges, and indicators. New opportunities for making flying safer and easier are offered by the accurate three-dimensional (3-D) positioning (down to meter and even centimeter accuracy levels) possible with differential GPS. However, commercial avionics have not yet taken full advantage of the capabilities of GPS, presenting navigation information in conventional bearing/distance formats, or at best with a small moving map. A display that fully utilizes this 3-D information was developed that allowed the pilot to see a perspective picture of the outside world, including the desired flight path and runway environment, even in low visibility conditions. This display was tested in piloted simulations and flight trials, and offers significant benefits over conventional displays.

BACKGROUND

Current Instrumentation

Flying in bad weather with reference solely to instruments is one of the most difficult challenges a pilot faces. The pilot must integrate information from many sources (artificial horizon, airspeed indicator, altimeter, vertical speed indicator, and navigation instruments) to form a mental picture of where the aircraft is and where it should be going. Even the Instrument Landing System (ILS), the most accurate landing system normally used, uses a cockpit display that requires interpretation of position information from two needles. These needles indicate lateral and vertical angular deviations from the straight-in approach path (normally having a slope of 3 deg) down to the runway. A significant amount of training and skill is required to smoothly fly an ILS approach by hand.

The information required to fly an ILS approach is printed on a paper approach plate that lists relevant frequencies, altitudes, distances, and headings. This information is printed in small type along with instructions for the missed approach procedure, which is designed to maneuver the aircraft back into position to make another approach. Because the missed approach leads the aircraft away from the ILS radio signal, the pilot is without positive course guidance during one of the most critical phases of the flight. It is not difficult to lose awareness of where the aircraft is relative to where it should be when flying with current light aircraft instrumentation. Situational awareness is critical in a demanding phase of flight such as instrument approach, motivating the need for better display technologies.

Three-Dimensional Displays

Much of the work on providing pilots with increased situational awareness has involved depicting a 3-D perspective view of the outside world. Integrating this 3-D view with the many data sources needed for flight results in a single display from which the pilot can obtain all primary flight data. The desired flight path may be naturally depicted as a "highway-in-the-sky", "pathway-in-the-sky", or "tunnel" through which the aircraft is flown. The pilot can intuitively infer where the aircraft is relative to the desired flight path and what action needs to be taken to stay on this trajectory. Being able to see the path ahead gives a "preview" of the trajectory forcing function. Most of the work on 3-D perspective displays has centered on laboratory simulation involving large aircraft models [1-4]. The limited amount of flight test work done has used large turbine-engined research aircraft with expensive inertial navigation systems. [5, 6].

SYSTEM DESCRIPTION

Additional work is needed before 3-D cockpit displays can be made practical for all classes of aircraft. Flight testing is needed to assess operational issues involved with perspective displays, especially those related to general aviation. A tunnel display system was developed that addresses the budget, power, and form-factor constraints of light aircraft. The system described below was tested onboard a four-seat Piper Dakota test aircraft and also in a ground simulator configuration.

Display Screen

The tunnel information was presented on a flat-panel display on the right side of the instrument panel, providing a central position in the pilot's instrument scan. The avionics-qualified 640x480 pixel 6.4 inch diagonal active-matrix liquid crystal display (AMLCD) was driven by a personal computer running the graphics software. Unlike the screens used on laptop computers, aviation AMLCDs are ruggedized and fitted with powerful backlights to make them visible in the high ambient lighting of an aircraft cockpit in daytime.

Display Symbology

The tunnel display, shown in Figure 1, was made simple to enhance ease of use for the typical general aviation pilot. The background consisted of the ground in brown, the sky in blue, and a white horizon line to provide the information found on a standard artificial horizon. The field of view was 40 deg vertical by 50 deg horizontal and included the runway and control tower. Terrain could also have been presented, but with an increased computational burden. The approach path was depicted as a series of green "hoops" and the missed approach path as a series of magenta hoops whose pentagonal shape gave an up/down cue to the pilot. The hoops were 100 m wide with a spacing of 200 m. To reduce computational complexity, the straight segments of the missed approach used a hoop spacing of 500 m. Altitude, heading, and speed were shown, as well as tapes at the bottom and right of the display that imitated standard ILS needles. The display is shown in a climbing right turn in Figure 2.

Previous tests of this display [7] depicted a triangular "own aircraft" symbol fixed at the center of the image. In describing the tracking strategy used, pilots said they attempted to "fly" this symbol through one of the next hoops in the tunnel. Test subjects commented that it was difficult to assess small deviations from the desired flight path, especially in the vertical direction. There was also ambiguity as to which of the next few hoops the pilot should try to fly through. In response to this feedback, predictor symbology similar to that described in [1] was added. Instead of a symbol fixed at the center of the display, these experiments depicted a white predictor symbol that moved to represent the aircraft's position 3.5 sec in the future. This future position was based on the current aircraft state and included the effect of lateral acceleration determined from bank angle. Another symbol, the "nominal path symbol," was presented as four white tick marks that represented the aircraft's desired

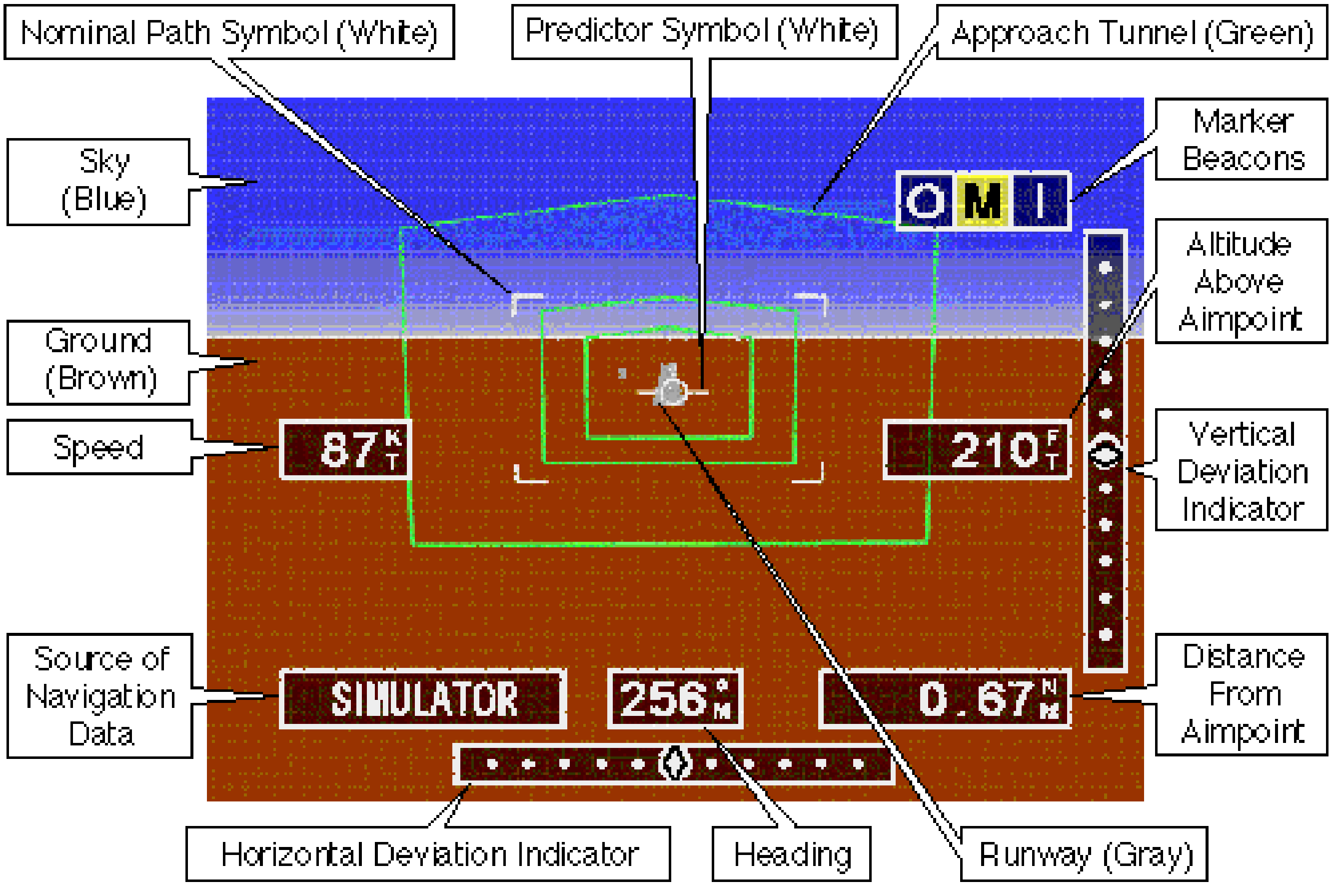

Figure 1: Tunnel Display on Final Approach

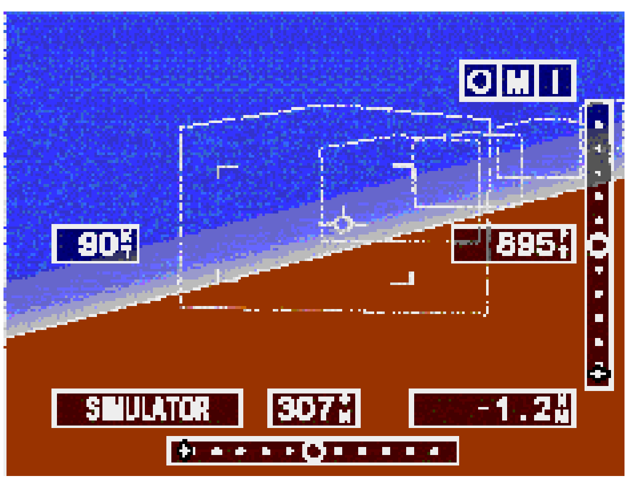

Figure 2: Tunnel Display in Climbing Right Turn

position in 3.5 sec if it were flying perfectly down the center of the tunnel. The tick marks were referenced to the point on the tunnel closest to the 3-D position of the predictor symbol. The time of 3.5 sec was "tuned" empirically to give acceptable performance with small aircraft. As described in [8], longer prediction times are more suitable for large aircraft with slower dynamic response. Since the information used to determine the predictor symbol position included higher derivatives of position (velocity and lateral acceleration), the display effectively provided lead compensation. This allowed the display to serve the function of a flight director, but presented in a more intuitive format. From the pilot's perspective, the flying task was made very simple: "fly" the predictor symbol into the middle of the nominal path tick marks. Ambiguity about which hoop to fly through was eliminated.

Computer Hardware

A ruggedized 90 MHz Pentium personal computer was used to perform sensor fusion, tunnel predictor calculations, and graphics rendering functions. Some of the 3-D graphics functions were accelerated by a video board that implemented parts of the rendering pipeline in hardware. To prevent "jaggedness," all lines on the display were drawn with antialiasing, a standard feature of commercial glass cockpit avionics. The increasing capabilities and dropping prices of personal computer hardware make it an enabling technology for practical low-cost avionics.

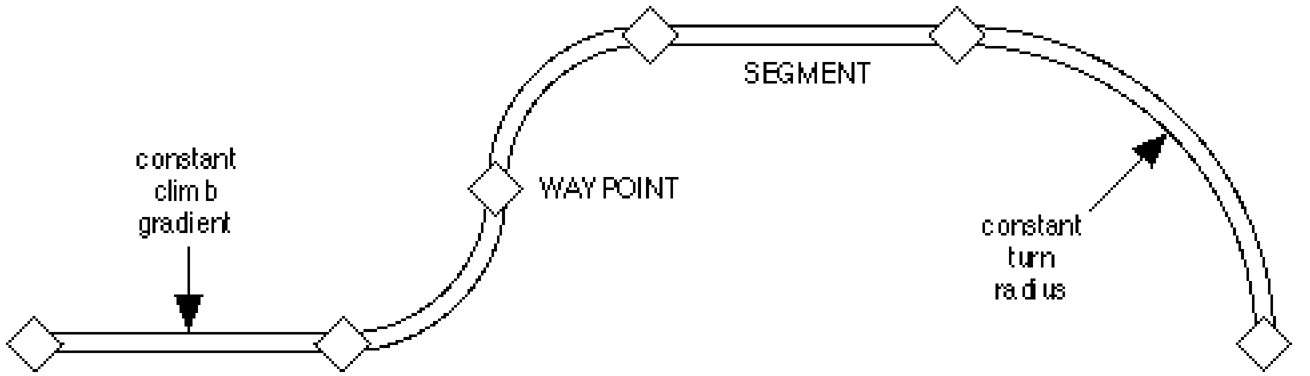

Figure 3: Segmented Flight Path Description

Sensors

Positioning data was provided in flight by the Stanford University's Wide Area Differential GPS Testbed [9]. The system had a 2 m 95% vertical accuracy [10] and was precise enough that a scene reconstructed from a 3-D database closely matched the actual view out the cockpit windshield. Attitude information was derived by combining GPS attitude with angular rate data using complimentary filtering techniques [11]. Rate gyroscopes were employed to measure high-frequency information since current GPS attitude receivers are limited to 10 measurements/sec.

The display was interfaced to a high-quality personal IFR procedures simulator for ground-based testing and rapid prototyping. The simulator ran on an IBM-compatible personal computer and was modified to produce serial output in a packet format identical to that of the GPS equipment used in flight testing. A control yoke and console were used to control power, trim, flaps, and landing gear, making keyboard use unnecessary. The flight dynamics emulated those of a high-performance single-engine aircraft. Since the runway database used by the simulator was constructed from real-world information in Jeppesen-Sanderson's NavData database, the display looked and functioned exactly as it did in flight using GPS data.

Path Representation and Computational Issues

Typical flight management computers represent the flight plan as a series of waypoints. The aircraft flies from one waypoint to another, turning toward the next waypoint as each waypoint is passed. Sophisticated systems have "turn anticipation" that allows the aircraft to smoothly transition from one active waypoint to the next with minimal overshoot at the turns. Transients during which the aircraft is turning are not explicitly represented in the flight plan.

A fundamentally different, explicit method for representing all straight and turning portions of the flight path was used for the tunnel display. This explicit definition was needed for efficient realtime retrieval of tunnel information used to generate the continuous predictor symbology. The flight path and tunnel were described as a series of path segments that could be linked together by waypoints to form an arbitrarily complex trajectory. These segments were curved with a constant turn radius and changed altitude with a constant climb or descent gradient. (Note that straight and level segments were simply a special case of the general segment type.) An example path is shown in Figure 3. Data describing the waypoints between segments was also stored to provide backward compatibility with conventional approach procedures. This explicit method of path description allowed flying on much tighter and more compact paths (on the order of a typical airport traffic pattern) than is possible with conventional instruments.

It is common in simulation to assume that the earth is a "flat plate," greatly simplifying navigational computations and the description of flight paths curving through three dimensions. A Cartesian system can be attached to the earth at a convenient spot, typically the landing aimpoint, to create a runway coordinate system. However, altitudes referenced to this "flat plate" diverge from barometric altitudes away from the aimpoint because conventional altimeters are referenced to the curved earth geoid. For example, 10 mi away from the aimpoint these altitudes will be approximately 100 ft apart. This would be noticeable to a pilot with a tunnel display and barometric altimeter in the same panel. To be compatible with current air traffic control operations, a practical tunnel display must use flight paths that use an accurate model of the earth's surface. Since the display system was to be used in the real world, all path computations were performed in geodetic coordinates. Drawing the 3-D graphical elements required efficient transformations between geodetic and earth-centered, earth-fixed (ECEF) coordinates. A large amount of transformation data was precomputed and stored on a segment by segment basis for fast retrieval.

SIMULATOR TESTS

Two pilots flew the simulator described above using the tunnel display. Pilot A was a student pilot with only

1.5 hours (one lesson) of flight time - literally as inexperienced as a test subject could be and still be a pilot. Pilot B was an instrument-rated private pilot with 210 hours of flight time.

Procedures

The simulator pilots flew curved and segmented approaches, both of which included missed approach procedures designed to bring the aircraft back to the start of the approach. Both pilots flew both procedures with four different wind conditions (down the runway at 15 kt, 90 deg right crosswind at 15 kt, 90 deg left crosswind at 15 kt, and no wind) for a total of eight approaches per pilot. The order of approach type and wind condition was randomized to mitigate systematic learning effects. The landing gear of the simulator was left down to emulate operation of the fixed-gear Piper Dakota flight test aircraft. Power was adjusted to produce an airspeed of 90 kt at all times. A "light" turbulence setting was used, although experienced pilots have commented that this setting feels more like "moderate" turbulence from their flight experience. A one-hour training session was given on the use of the simulator and tunnel display.

The curved approach, shown as the pilots flew it in Figure 4, began with the aircraft on a wide base leg at a 90 deg angle to the runway. After a short straight segment, the pilot made a 90 deg right turn with an 800 m (0.43 nm) radius and finally rolled out onto a straight final approach. The segmented approach, shown as the pilots flew it in Figure 7, also began on a wide base leg. A series of three 30 deg right turns (800 m radius) brought the aircraft onto final approach. Both approaches began approximately 1000 ft above the runway and continuously descendedat 3 deg. Approximately 200 ft above the runway, the pilots were told that a landing would not be possible and that a missed approach should be executed. Power was applied and the pilot transitioned from flying through the green approach tunnel to following the magenta missed approach tunnel. The missed approach climbed straight ahead and then made two right turns separated by straight segments to bring the aircraft back to the approach path. The missed approach leveled out 1000 ft above the runway.

Both approaches along with their missed approach trajectories were extremely compact compared to approach procedures in current use. For example, the straight final approach segments were both about 2 km long, compared with 8-12 km for a typical procedure. The procedures were deliberately made small to fit into the airspace used at the flight test airport during visual conditions. Following these paths with reference to conventional light aircraft instruments would have been virtually impossible due to the number of flight path changes required in a short period of time.

Results

Figure 4 shows a bird's eye view of the curved approaches and missed approaches flown by both pilots. The figure contains eight traces, from both pilots flying with four wind conditions each. All eight ground tracks lie very close to each other, forming a thick trace on the graph despite the varying wind conditions. Each trace begins at the "Start Approach" label, continues clockwise to the runway, onto the missed approach, and then back to the beginning of the approach.

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Figure 4: Bird's Eye View of Curved Approach and Missed Approach (Simulator, Pilots A and B)

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Figure 5: FTE on Curved Approach (Simulator, Pilot A)

Figure 5 shows flight technical error (FTE: the difference between sensed position and desired position) both laterally and vertically for pilot A on the curved approach with the four wind conditions. The curved approach is “flattened out” onto the paper so that the abscissa is distance from the start of the approach with the aircraft moving from left to right. The beginning and end of the turn are indicated. RMS FTE values for pilot A were 6.6 m laterally and 4.7 m vertically. Maximum errors were less than 20 m in both dimensions. (The upturn in vertical FTE at the end is a pullup to the missed approach.) Figure 6 presents the same information for pilot B. RMS FTE values for pilot B were 11.8 m laterally and 6.7 m vertically. Pilot B’s errors just after the turn initiation tended towards the inside of the turn.

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Figure 6: FTE on Curved Approach (Simulator, Pilot B)

Figure 7 shows a bird’s eye view of the segmented approaches and missed approaches flown by both pilots. Again, all eight ground tracks lie very close to each other, except for a small deviation noticeable at the first turn on one of the tracks.

Figure 8 shows FTE for pilot A on the segmented approach with the four wind conditions. Again, the segmented approach is “flattened out” onto the paper with the beginnings of the three turns indicated. RMS FTE values for pilot A were 6.5 m laterally and 4.2 m vertically. Maximum errors were less than 20 m in both dimensions. Figure 9 presents the same information for pilot B. RMS FTE values for pilot B were 13.2 m laterally and 9.8 m vertically. One event at the first turn produced errors of approximately 70 m to the right (inside of turn) and approximately 50 m below the desired path.

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Figure 7: Bird’s Eye View of Segmented Approach and Missed Approach (Simulator, Pilots A and B)

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Figure 8: FTE on Segmented Approach (Simulator, Pilot A)

Discussion

FTE for pilot A was consistently smaller than FTE for pilot B, an unexpected result since pilot B had more flight hours and an instrument rating. Pilot B’s increased experience with the dynamics of real aircraft may have actually made it more difficult to adapt to the dynamics of the simulated aircraft. Learning effects or fundamental physiological factors may also account for the difference. It should be remembered, however, that the path-following errors for both pilots were relatively small compared to

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Figure 9: FTE on Segmented Approach (Simulator, Pilot B)

typical values using conventional instruments [12]. It should also be emphasized that minimizing FTE is not an end in itself. The tunnel display appeared to give the pilots the situational awareness they needed to accomplish these complex flight paths. Both pilots were able to follow the intended trajectories with acceptable accuracy with none of the "hunting" for the correct path typically seen when using a conventional ILS display in varying wind conditions. Most of the vertical FTE exhibits oscillatory behavior possibly related to the phugoid mode of the aircraft.

Neither pilot complained of lack of vertical situational awareness as had been noted without the predictor symbology. FTE values using the new predictor symbology were reduced from values for the tunnel display without the predictor symbol. The values seen here are reduced by a factor of two or three compared with those in [7] which used a different pilot flying the same simulator.

Both pilots produced repeatable ground tracks despite varying wind conditions. It was demonstrated in [7] that missed approaches flown in the conventional manner show scatter due to different wind conditions. This uncertainty requires approach designers to specify large obstacle clearance areas when setting up conventional missed approach procedures [13]. The tunnel display, with its ability to produce repeatable ground tracks, could allow lower minimums and increased utility at some airports.

Additional Simulator Trials

Several other simulator experiments were performed with pilot A to explore new pilots' ease of learning to fly with the tunnel display. In the first test, pilot A was given a half-hour of instruction in the use of a conventional ILS needle display and in flying (straight-in) ILS approaches. The pilot then flew 6 nm straight in approaches with a 3 deg glideslope and no wind. Four approaches were flown, two with the tunnel display and two with the ILS needle display. Using the tunnel display, the pilot was able to bring the aircraft into position for a safe landing at the 200 ft decision height. FTE was similar to pilot A's performance flying curved and segmented approaches. Flying the ILS gave less satisfactory results. On one of the approaches the aircraft passed through the decision height so quickly that it crashed into the ground. The aircraft had also drifted so far off course laterally that it was displaced 0.8 nm from the runway centerline. On the other ILS needle approach, 600 m vertical FTE values were observed. It should be noted that asking a low-time pilot to learn to fly an ILS approach in only a half an hour is an impossible request. It typically takes many hours of flying before this can be done safely. In contrast, however, the tunnel display allowed this low-time pilot to quickly become proficient at flying the procedure, with successful results the very first time.

Another test was performed to determine the ability of the tunnel display to guide a pilot along extremely complicated curved flight paths. The pilot was shown a path with a series of left and right turns with bank angles up to 45 deg. The entire procedure, which did not include any climbs or descents, took about 7 min to fly at a speed of 90 kt. The ground track that resulted is shown in Figure 10. If the aircraft is imagined as a skywriter with a smoke system, it is evident that pilot A spelled "GPS" in the sky solely by instrument reference! Accurate flight path control was therefore demonstrated by a new pilot on a path far more complex than any conventional instrument flight procedure.

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Figure 10: Skywriting With GPS

FLIGHT TESTS

Pilot B, the 210 hour instrument pilot, flew the Piper Dakota test aircraft on a series of test flights at the Palo Alto, California airport to verify the display performance described above.

Procedures

All approaches were flown in visual meteorological conditions to runway 30 with a right traffic pattern in use. A safety pilot flew in the left seat and handed yoke control to the test pilot during test runs. The test pilot's primary reference to the approach path was the tunnel display. An instrument training hood was not worn due to the high level of traffic at the airport. The goal was to fly the aircraft on the curved and segmented approach procedures used in simulator testing. In practice, it proved extremely difficult to combine our flight test procedures with the normal flow of traffic at Palo Alto.

The base leg of the curved approach (see Figure 4) was too far from the runway to allow flying of the complete procedure. Typically, the control tower would command the pilot to turn base earlier than desired. The test pilot did the best job under the circumstances to intercept the curved approach path and follow it through final approach. The segmented approach procedure (see Figure 7), with its base leg slightly farther from the runway, could only be authorized once by the control tower. All other attempts put the aircraft so close in on the base leg that only the straight-in final approach segment could be intercepted using the tunnel display. The missed approach segments were also too large for the control tower authorize them; doing so would have disrupted the normal traffic flow. Due to these difficulties, the flight data presented here includes only the approach segments near the runway. Four curved approaches and four segmented approaches are documented.

Results

Figure 11 shows a bird's eye view of four curved approaches. The aircraft moves from left to right on the plot, and the turn center is indicated. (The constant-radius turn is distorted by the unequal scales on the graph.) While there is a spread between the various ground tracks, the pilot was able to successfully fly the curved approaches using the tunnel display.

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Figure 11: Bird's Eye View of Curved Approaches (Aircraft, Pilot B)

Figure 12 shows a bird's eye view of four segmented approaches moving from left to right. The ground tracks were not repeatable since local traffic prevented the pilot from flying through the segmented tunnel. The tunnel display was only used to intercept the straight-in final approach segment.

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Figure 12: Bird's Eye View of Segmented Approaches (Aircraft, Pilot B)

Discussion

The pilot was able to fly abbreviated curved approaches using the tunnel display. Although lateral errors exceeded 50 m, the results are encouraging because they demonstrate the capability to maneuver an aircraft on a relatively tightly curved path with reference to a practical tunnel display. The display appeared to facilitate situational awareness of the aircraft's relationship to the desired flight path, even though the pilot was not always authorized by the control tower to fly on that path.

The segmented approach data demonstrates the need for an adequate flight location for initial development of cockpit instrumentation. The pilot spent more time trying to get to the tunnel to intercept it than actually flying in the tunnel by reference to the display. Since the instrument flight procedures likely to be flown cover more geographical area than normal VFR flight operations, Palo Alto airport may not be suitable for developmental flight testing. One option for testing alongside VFR airport operations may be to overlay standard instrument approach procedures with tunnel display flight path descriptions. In this way, practice IFR approaches could be requested from the control tower and flown with few interruptions.

CONCLUSION

The results of piloted simulation and flight testing may be summarized as follows:

1. In piloted simulation, the tunnel display allowed pilots to closely follow curved approaches, segmented approaches, and missed approaches with better accuracy than conventional instruments.

2. There were no reports of difficulty perceiving and controlling small flight path deviations. This suggests that the addition of predictor symbology to the display was valuable from a guidance standpoint.

3. Display use was learned very quickly, even by the 1.5 hr student pilot.

4. Future flight testing requires careful site selection and planning to avoid conflicts with other air traffic.

The tunnel display shows promise as a practical aid to pilot situational awareness and increased safety. Aircraft utility may also be enhanced by allowing accurate navigation along flight paths more complex than are used today. In addition to enhancing typical passenger aircraft operations, such systems could be valuable in markets such as airborne remote sensing, medical evacuation, forest fire control, and search and rescue. Training and proficiency requirements will also benefit from the ease of use of the system. Rising performance/price levels of the enabling technologies promise to make a commercial system feasible in the near future.

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