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A Description of the “Crow’s Foot” Tunnel Concept

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Symbols and Abbreviations

AFL	Above Field Level
AGATE	Advanced General Aviation Transportation Experiment
ARIES	Airborne Research Integrated Experimental System
ASDE	Airport Surface Detection Equipment
CAMI	Civil Aerospace Medical Institute
DoD	Department of Defense
EVS	Enhanced Vision Systems
GUI	Graphical User Interface
HGS	Head-up Guidance System
HSCT	High-Speed Civil Transport
HSR	High-Speed Research
HUD	Head-Up Display
IFR	Instrument Flight Rules
ILS	Instrument Landing System
in	inches
LaRC	Langley Research Center
nm	nautical mile
SVS	Synthetic Vision Systems
TCAS	Traffic Alert and Collision Avoidance System
TIFS	Total In-Flight Simulator
TOGA	Take-Off / Go-Around
USAF	United States Air Force
USN	United States Navy
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
XVS	eXternal Visibility System

Abstract

NASA Langley Research Center has actively pursued the development and the use of pictorial or three-dimensional perspective displays of tunnel-, pathway- or highway-in-the-sky concepts for presenting flight path information to pilots in all aircraft categories (e.g., transports, General Aviation, rotorcraft) since the late 1970s. Prominent among these efforts has been the development of the “crow’s foot” tunnel concept. The “crow’s foot” tunnel concept emerged as the consensus pathway concept from a series of interactive workshops that brought together government and industry display designers, test pilots, and airline pilots to iteratively design, debate, and fly various pathway concepts. Over years of use in many simulation and flight test activities at NASA and elsewhere, modifications have refined and adapted the tunnel concept for different applications and aircraft categories (i.e., conventional transports, High Speed Civil Transport, General Aviation). A description of those refinements follows the definition of the original tunnel concept.

Summary

NASA Langley Research Center has actively pursued the development and the use of pictorial or three-dimensional perspective displays of tunnel-, pathway- or highway-in-the-sky concepts for presenting flight path information to pilots in all aircraft categories (e.g., transports, General Aviation, rotorcraft) since the late 1970s. Numerous research studies have shown that a 3 dimensional presentation of the intended flight path on a tactical display is highly intuitive resulting in higher situation awareness and lower workload. Prominent among these efforts has been the “crow’s foot” tunnel concept, which originated in a series of interactive workshops that brought together government and industry display designers, test pilots, and airline pilots to iteratively design, debate, and fly various pathway-in-the-sky concepts.

The “crow’s foot” tunnel concept emerged as the consensus pathway concept from a September 1996 workshop as an improvement to the traditional connected-rectangle tunnel. The connected rectangle tunnel was truncated to short segments, creating a “crow’s foot” at each corner of every rectangle which thereby minimized display clutter and obscuration. The pathway itself was not considered to represent primary guidance information to the pilot, but rather, to provide a pictorial representation of the flight path, fixed in space (earth-referenced), defining the desired flight path; the piloting task was to fly down the tunnel using a velocity vector. Flight director guidance and symbology was added to reduce the pilot’s workload in conducting this task. Today, the “crow’s foot” tunnel has been significantly modified to provide real time feedback regarding the ownship position relative to the intended path. This tunnel concept, know as the dynamic tunnel, is an intuitive presentation of the path error to the pilot.

The “crow’s foot” tunnel concept has been used ever since in simulation and flight test activities of NASA’s High-Speed Research (HSR) eXternal Visibility System (XVS), Advanced General Aviation Transportation Experiment (AGATE), and the Aviation Safety Synthetic Vision Systems programs. Other pathway concepts have been influenced from its development and the accompanying workshop discussions. Among the direct users of the Langley-developed workshop software were Boeing-Seattle, Boeing Helicopter-Philadelphia, the FAA-Civil Aerospace Medical Institute (CAMI), the

Research Triangle Institute, Wright-Patterson Air Force Base, and Rockwell-Collins.

Over years of use within simulation and flight test activities at Langley, many modifications have accumulated to refine and adapt the tunnel concept for different applications and different aircraft categories (i.e., conventional transports, High Speed Civil Transport, General Aviation). A description of those refinements follows the detailed definition of the original tunnel concept.

Introduction

NASA Langley Research Center has actively pursued the development and the use of pictorial or three-dimensional perspective displays of tunnel-, pathway- or highway-in-the-sky concepts for presenting flight path information to pilots for all aircraft categories (e.g., transports, General Aviation, rotorcraft) since the late 1970s (References 1-38). The concepts have also been of intense interest to other researchers in the flight display community (References 39-136).

Prominent among these efforts has been the NASA Langley Research Center “crow’s foot” tunnel concept, which originated in a series of interactive workshops (Reference 30) that met at about six month intervals through September 1996, to investigate tunnel-, pathway- or highway-in-the-sky concepts. These workshops brought together government and industry display designers, test pilots, and airline pilots to iteratively design, debate, and evaluate various pathway-in-the-sky concepts.

The first two workshops were focused on the subject of advanced pictorial displays, regardless of the specific application. The most prominent feature of these advanced flight displays, being enabled by rapid advances in computer graphics, was the "tunnel" element – a variation on the Naval Air Development Center "tile" pathway. These tunnel or highway formats were being evaluated at various flight display research laboratories, including NASA Langley Research Center (LaRC). These pictorial displays had been shown, in both Department of Defense (DoD) and NASA research, to enable highly-precise flight path control, especially for vehicles required to execute complex curved flight paths, such as those that may be utilized for landing approaches to closely-spaced parallel runways. These "real-world", three-dimensional displays had been successfully tested in simulation showing significant gains in pilots' situation awareness, pilot/vehicle performance, and aircraft safety, without increases in pilot workload and with potential for significant operational benefits (References 31-38).

The primary emphasis of these first two workshops focused on the utility, acceptability and usability of pathways and the various features available. While the specific application was unstated, the prevailing assumption was the pathway would be utilized within a Synthetic Vision-like system. Synthetic Vision Systems (SVS) are characterized by their ability to represent, in an intuitive manner, the visual information and cues that a flight crew would have in daylight, Visual Meteorological Conditions (VMC). The view of the outside world is provided by melding computer-generated topography (terrain), obstacle, and airport depictions from on-board databases and flight display symbologies. Additional, supplemental information derived from weather-penetrating sensors may be shown directly as insets or fused to the database imagery or these data may be processed for information extraction and iconic insertion to the database presentation (e.g., sensor processing to identify runway edges or detect objects). The visual information and cues are depicted based on precise navigation (position) information for proper alignment and registration of the onboard terrain database to the real-world. The SVS also includes traffic information from surveillance sources (such as Traffic Alert and Collision Avoidance System (TCAS), Airport Surface Detection Equipment (ASDE), etc.) and other hazard information (such as wind shear).

In contrast to SVS, Enhanced Vision Systems (EVS) use imaging sensors to penetrate poor lighting conditions or weather phenomena such as fog, haze, rain, and/or snow, to improve the pilot’s vision

outside the flight deck. EVS technology, unlike SVS, is not reliant upon navigational accuracy or a database. However, one of the principal problems with EVS applications is the requirement to train the pilot to interpret and understand the visual artifacts that may occur in sensor images and the potential that EVS technology may not penetrate in all weather phenomena.

The second two workshops were focused on the specific application of those pathway formats to the eXternal Visibility System (XVS) of the NASA High-Speed Research (HSR) Flight Deck Systems Program. The XVS element was concerned with replacement of the forward windows in a High-Speed Civil Transport (HSCT) with electronic display media and a suite of imaging sensors (i.e., an eXternal Visibility System). The purpose of the XVS was to enable a “No-Droop” configuration of the HSCT. The “No-Droop” mission of the XVS was defined as that system which, in a HSCT, would support routine airline operations in environmental conditions and at facilities equivalent to current subsonic transport capabilities, without the requirement to articulate the forebody geometry for ground operations, takeoff, approach and landing. The XVS primary flight display relied on high resolution video camera imagery of the outside scene, with overlaid symbology. The presentation was somewhat analogous to that of an EVS, except the imaging sensor (a visual spectrum camera) was not weather-penetrating and it was intended to replicate, not necessarily enhance the pilot’s outside visual cues. The display was similar in many respects to a Head-Up Display; however, it was significantly different from a HUD in that the image and symbology were not collimated and the resulting XVS display (combined symbology and sensor) did not have a “real-world” background for comparison and contrast. The purpose of the pathway formats within the XVS display was to enable highly-precise flight path control.

The primary symbology concerns in the XVS application were the prevention of display clutter and the obscuration of hazards with a mixed sensor and symbology image. The camera image in Visual Flight Rules (VFR) operations was the primary means of hazard avoidance and traffic separation making the occlusion of sensor image components by symbology a primary issue. These concerns were not so prominent in the first set of workshops, as they assumed hazard locations (traffic and obstacles) would be known within the constraints of an SVS (from surveillance sources), and therefore, obscuration would not be an issue.

The consensus pathway concept (namely, the crow’s foot concept) that resulted from the September 1996 workshop was used extensively in simulation and flight test activities of NASA’s HSR XVS program. Under this program, four flight tests were conducted to resolve XVS issues, including the demonstrated effectiveness of the pathway concept. The first two flight tests used the NASA LaRC B737-100 aircraft, while the last two used the United States Air Force (USAF) Total In-Flight Simulator (TIFS) Convair 580 in an HSCT configuration. More recent simulation and flight test research using the pathway concept has been conducted with NASA’s SVS Project under the Aviation Safety Program. The flight activities were conducted aboard LaRC’s Airborne Research Integrated Experimental System (ARIES) B757-200 aircraft and a Gulfstream G-V aircraft, owned, modified and operated by the Gulfstream Aerospace Corporation.

In the next section, a description of the original tunnel concept is given. Following this description, a summary of the modifications to the original concept is given, including a review of the motivation behind each change.

The Original “Crow’s Foot” Concept

The tactical presentation of a tunnel naturally results in a rectangular tube geometry, depicting a vertical and lateral flight path trajectory. The most common rendering of this tube tunnel is via a wire-frame (connecting a series of rectangles as shown in Figure 1). This wire-frame tunnel has the

advantage of reducing display obscuration (compared to a solid tube) while sufficiently portraying the intended flight path.

The “Crow’s Foot” pathway concept evolved from the traditional wire-frame rectangle tunnel (Figure 1). The principal motivation for the “Crow’s Foot” and principal reason for its acceptance is to further minimize clutter and obscuration, using truncated short segments, at each corner of every rectangle, thereby, creating a “crow’s foot” (Figure 2).

A single corner element - a “crow’s foot” - consists of three joined lines, two of which were parts of the original rectangle and the other was a remnant of the line connecting the corresponding corner of the next successive rectangle along the flight path. A tunnel or pathway segment, defined by the original rectangle and now by four “crows’ feet” each, was drawn to indicate the upper, lower, left, and right edges of the path, defining the lateral and vertical extent of the desired flight path trajectory.

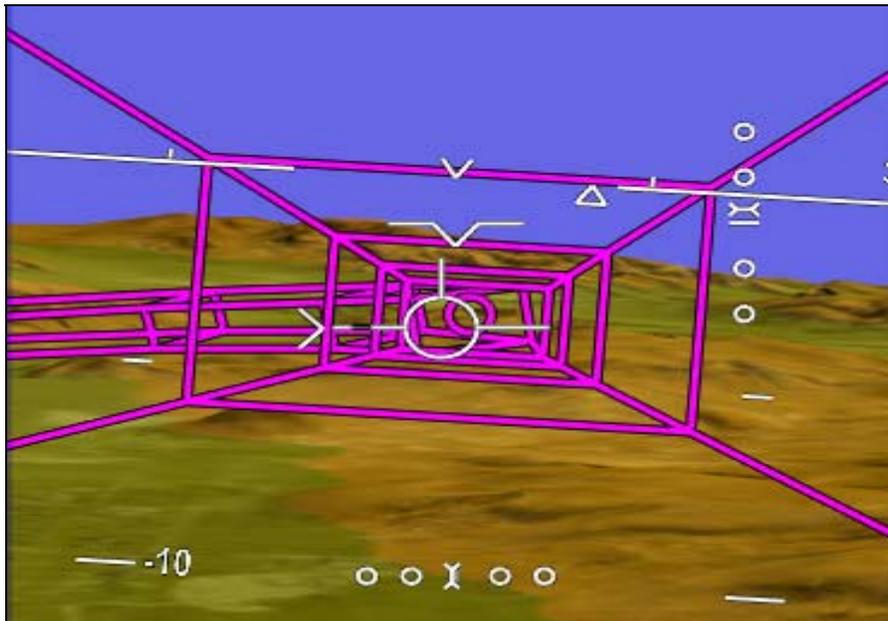


Figure 1. Conventional connected-rectangle tunnel.

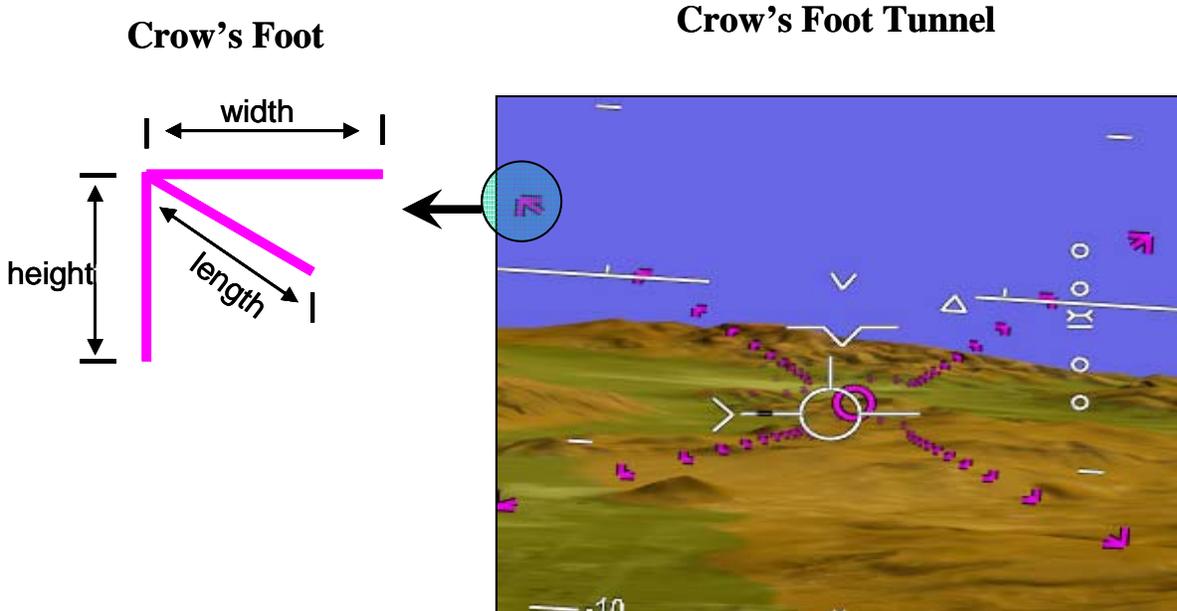


Figure 2. "Crow's foot" tunnel.

The tunnel is fixed in space (earth-referenced) defining the desired flight path, and the piloting task is to fly down the tunnel using the aircraft velocity vector symbol. The pathway itself does not present primary guidance information to the pilot, but rather, it creates a pictorial representation of the flight path relative to ownship (raw data, in the vernacular of the aviation community). The pathway concept, however, does include flight director guidance and flight director guidance symbology (to be discussed later), since all the aircraft state information necessary to provide a pathway also enabled the provision of guidance.

The horizontal tunnel size was scaled to be approximately equivalent to $\pm 1/2$ angular dot localizer deviation centered around the localizer course (where 1 dot angular deviation equals 175 ft of lateral displacement at the runway threshold) with a 600 foot (+/- 300 ft) maximum width. The vertical tunnel size was scaled to be approximately equivalent to ± 1 angular dot glideslope deviation (where 1 dot equals 0.35 degrees angular deviation) centered along the glideslope path with a 350 foot (+/- 175 ft) maximum height and a 50 foot (+/- 25 ft) minimum height. Thus, the tunnel narrows both vertically and laterally as it approaches the runway threshold.

Recent research has shown that the tunnel should be removed at approximately 500 feet Above Field Level (AFL) for fixed-wing approach and landing operations. By this altitude, stabilized approach procedures should be in effect so flight path tracking performance and awareness for the remainder of the approach would not be significantly improved with a tunnel. At this altitude, the entire tunnel symbology is removed (i.e., "decluttered"); however, the guidance symbology remains to complete the approach and execute a flare to touchdown.

Glideslope and Localizer Course Deviation Indicators were adapted to show "equivalent" dot error indications of tunnel centerline deviations. (Actual ILS course deviation data, if available, are also presented on the same scales.)

The original tunnel concept consisted of segments that were spaced at 0.2 nautical miles (nm) intervals. Every 5th segment, or every nautical mile, the segment contained a post that was drawn from the bottom of the segment to the ground (Figure 3). This was done to give a relative height cue.

An 'X' was drawn where the post touched the ground. Also, these 'post' segments had a line that connected the bottom two corner “crow’s feet”. In addition, at each mile post segment, a digital readout of the distance along path (in nautical miles) was displayed as a billboard sign. The distance displayed in the sign was the distance from that segment until touchdown. The digital readout above the sign was the ownship distance to the sign. Thus, the addition of the two numbers resulted in the ownship distance to touchdown.

Both the billboard signs and segment posts were dropped from the latest instantiations of the crow’s foot tunnel concept as they were found to provide more clutter than benefit, especially for XVS and HUD displays.

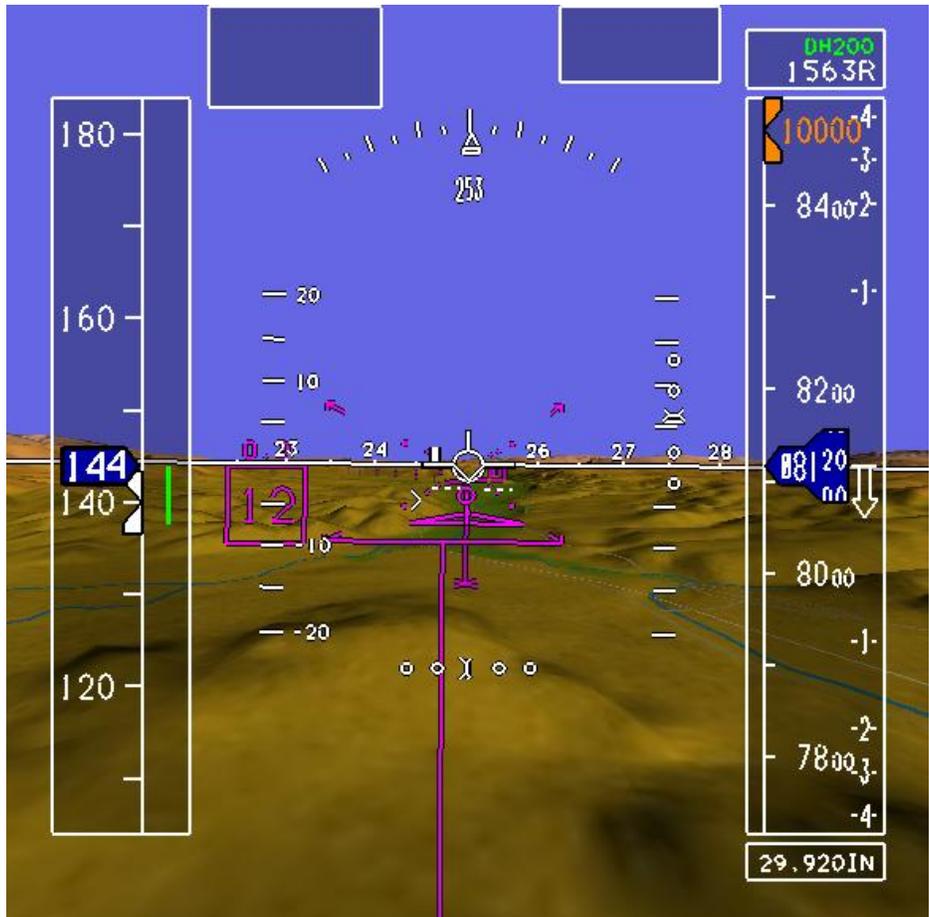


Figure 3. Tunnel with post segments and distance along path billboard signs on a SVS enhanced tactical display.

Modifications

Over years of use in simulation and flight test activities at LaRC, many modifications have been made to refine and adapt the tunnel concept to different applications and different aircraft categories (i.e., conventional transports, High Speed Civil Transport, General Aviation). Perhaps one of the least noticed but more significant changes was to parameterize the software in almost every facet of the concept to allow significant control of the tunnel visual attributes and other parameters via graphical user interface (GUI). Another modification, not directly related to the tunnel concept, was to provide

control of symbology sizes (e.g., flight path marker, guidance symbol) to compensate for control/display gain changes when using different physical display sizes (e.g., when using an ARINC Size A 6" wide by 5.5" tall display versus an ARINC Size D 8" wide by 8" tall display).

Other tunnel modifications significantly influenced the functionality of the tunnel and are described below.

Inside/Outside Tunnel Rendering

When flying within the tunnel, the “crow’s foot” tunnel is very effective in reducing clutter while maintaining the perception of a 3-dimensional pathway. However, when outside the tunnel, the “crow’s foot” symbology is somewhat difficult to interpret as the intended path, since the “crow’s foot” symbology does not provide adequate context to determine the tunnel shape and direction. Therefore, the tunnel was modified to allow for different rendering based on whether the ownship position was inside or outside of the tunnel. When inside the tunnel, the tunnel is rendered in “Crow’s Foot” symbology. When outside the tunnel, the tunnel is rendered as a traditional wire-frame with the near-side removed. This creates a “trough” geometry (see Figure 4) which is an intuitive means to guide the crew in reacquisition of the tunnel.

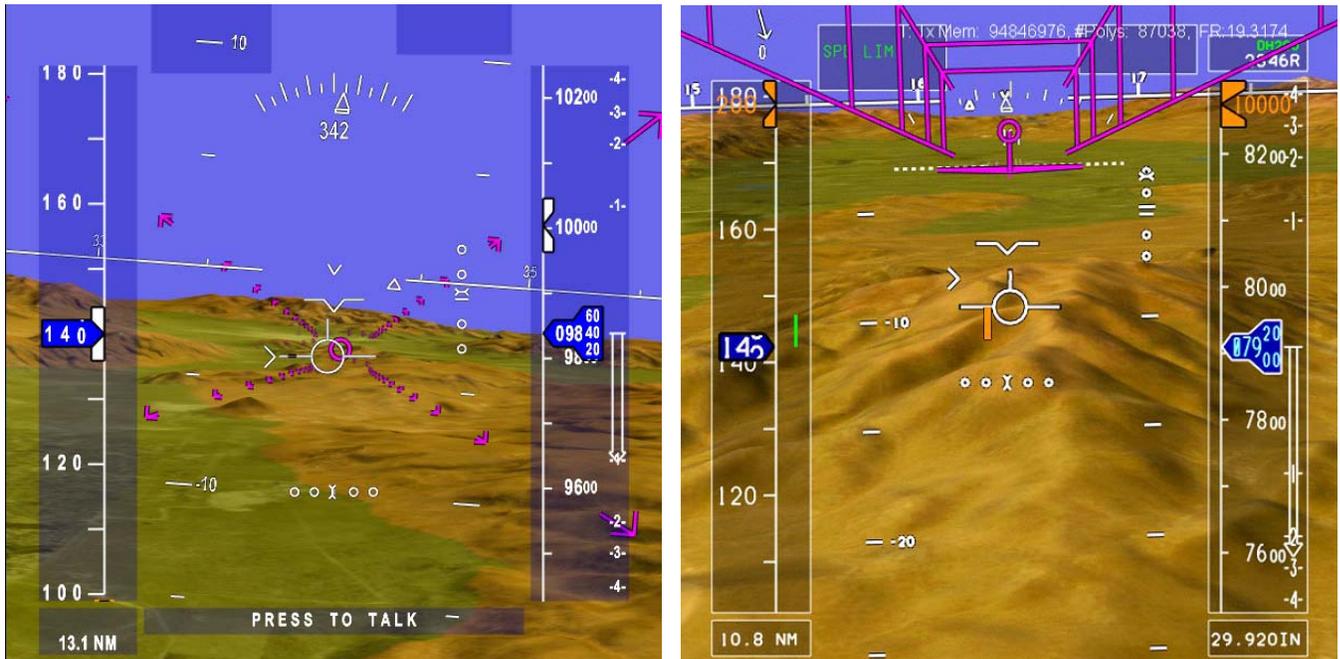


Figure 4. Inside the tunnel renders as Crow’s Feet (left) and outside the tunnel renders as trough geometry (right).

Fade brightness with distance

Tunnel fading (Figure 5) is the reduction in the brightness of the tunnel segments as a function of the distance from the ownship position. The fading function was implemented only while inside the tunnel to help reduce clutter and enhance depth cueing of the tunnel. Outside the tunnel, the fade function was turned off to ensure that the tunnel was set to its maximum brightness to enhance visibility for reentry.

Fading was implemented as a linear function from 100 percent brightness beginning at x nm from

ownership and reaching a y percent brightness at $x+1$ nm, where x and y are user-selected values. Brightness was then held constant at y percent beyond the $x+1$ nm distance. This function was implemented as a GUI control with an on/off box and a static distance control parameter (x) and a y percent brightness parameter. Nominally, x and y have been set to 3 nm and 5 percent, respectively.

Additional logic was added to eliminate fading for non-straight segments of the tunnel. Logic for heading and/or glideslope changes was implemented as follows:

- a. If a path heading change was to occur within u nm (where u is a new static parameter on GUI panel), $(u + 1)$ was added to the original static distance control parameter.
- b. If a path glideslope change was to occur within v nm (where v is a new static parameter on GUI panel), $(v + 1)$ was added to the original static distance control parameter.

Nominally, u and v have both been set at 0 nm.

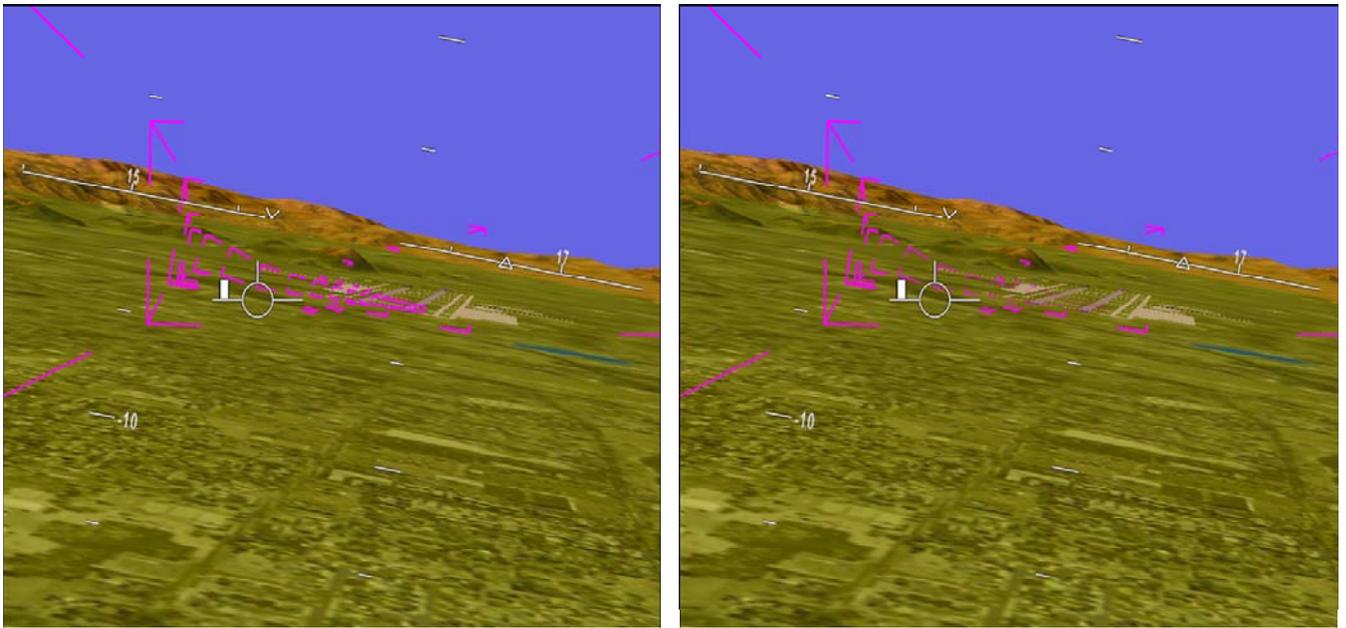


Figure 5. Non-faded (left) and Faded (right) tunnel.

Distance four rail to two rail switching

When inside the tunnel, the “Distance four rail to two rail switching” function allows the user to eliminate the two vertical crow’s feet of each tunnel segment beginning at a user-defined distance from ownship (Figure 6). The motivation for this modification was clutter reduction.

If a tunnel segment was within x nm (where x is a user-defined constant), then the segment's corners were drawn with all four nominal “crow’s feet”. If a segment was farther away than the x nm, then only the bottom two “crow’s feet” were drawn. This function was implemented with GUI control of an on/off box and the static distance control parameter (x). The rail switching feature was disabled when outside the tunnel (Figure 6). Nominally, x has been set at 1 nm.

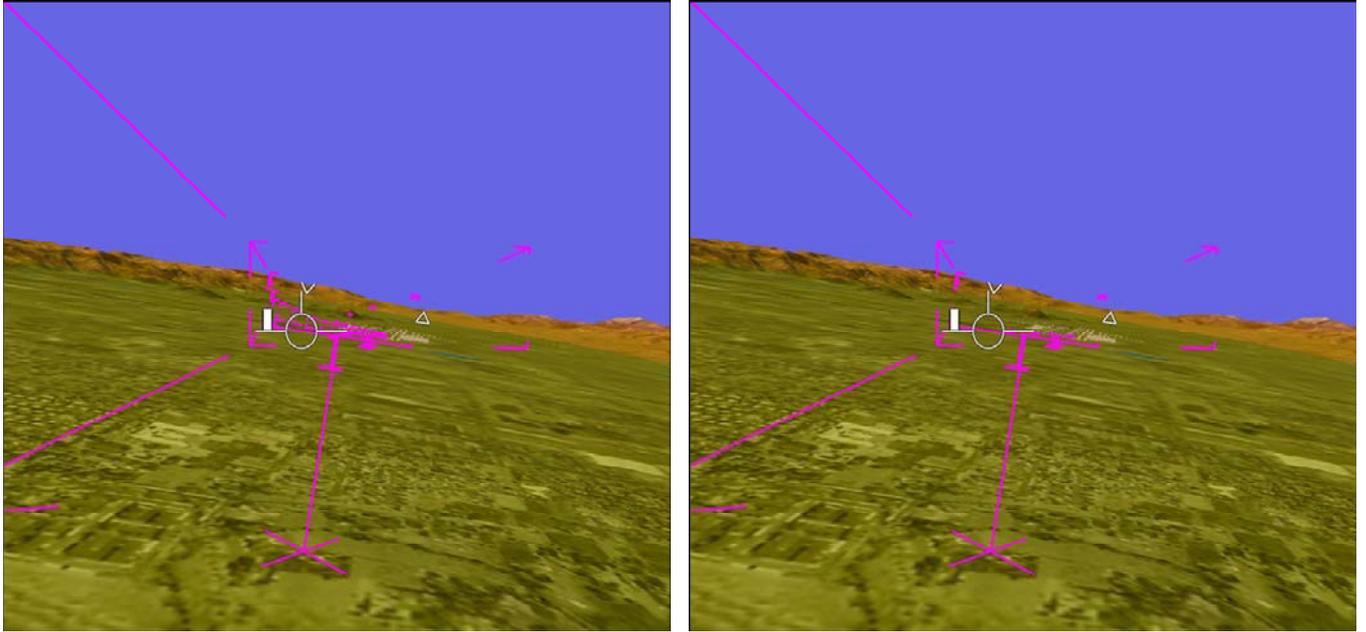


Figure 6. The 4-rail (left) and 2-rail (right) tunnel concepts.

Path guidance symbologies

Guidance symbology has been found in simulation and flight test to be a desirable addition to tunnel concepts. Three guidance symbol types have been evaluated with the “crow’s foot” tunnel:

- a ghost airplane (also known as a “Follow-me” Aircraft)
- an integrated cue circle analogous to that used in conventional HUD flight directors.
- a ‘tadpole’ guidance symbol, a variation of the integrated cue circle, as discussed below in the HUD guidance symbols section.

The ghost aircraft depiction (Figure 7) uses a modified pursuit guidance control law developed by Merrick, et al (References 91 – 93). While this form of guidance may not be optimal, it is sufficient for most applications considered, particularly as it augments the flight path data represented by the tunnel rather than being self-sufficient. The ghost airplane symbol (positioned about the ghost airplane tail-light) was located x seconds (where x is a GUI-controlled parameter) ahead of ownship on the centerline of the tunnel. The x -second lead parameter could be decremented from that value with decreasing range to the runway threshold to a minimum value y , (a GUI controlled-parameter) at threshold distance parameter z (a GUI controlled-parameter).

The lead time, x , for the modified pursuit control law can be loosely thought of as being the “gain” in the guidance control law. A smaller lead time corresponds to higher performance (i.e., tighter path tracking), albeit with more pilot effort to closely follow. For fixed-wing landing and approach tasks, the lead time has typically been set between 30 and 5 seconds, with a nominal value generally being about 5.5 seconds on final (see References 114-117).

The ghost aircraft symbol is used only when there are explicit vertical and lateral flight path definitions. Yaw, pitch and roll attitude of the ghost reflected the track and flight path angles of the path at that lead position. On final approach, the ghost airplane transitioned to the integrated circle symbol (i.e., just the tail-light) at 500 feet AGL for declutter purposes.

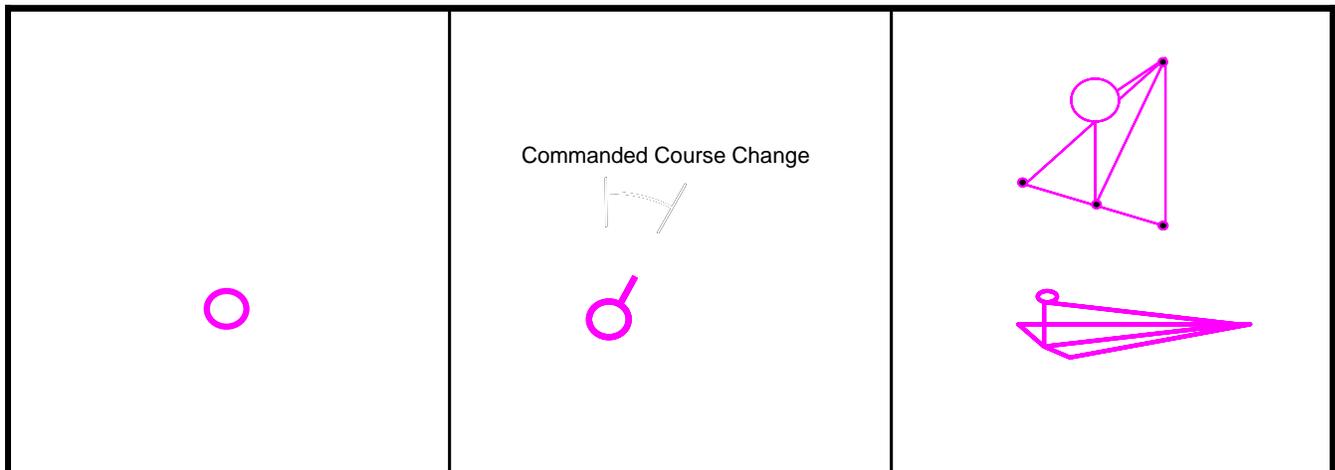


Figure 7. Guidance symbols: Integrated cue (left), “Tadpole” (center) and Ghost aircraft (two perspectives, at right).

The integrated cue circle symbol has been used with various control laws for positioning dependent upon the piloting task and experiment requirements. The integrated cue circle symbol has been driven solely from pitch and roll flight director commands, solely from the pitch and roll ghost-aircraft “tail-light” control law, and from hybrid flight director/ghost-aircraft control laws. In the hybrid case, the integrated cue circle symbol was positioned as follows:

1. The lateral position of the circle was determined by the existing ghost airplane lateral command equations (References 91 - 93).
2. The vertical position of the circle was dependent on flight phase (approach or departure).
 - a. For approach, the vertical position of the circle was determined by the existing ghost airplane vertical command equations (References 91 - 93).
 - b. For departure, the vertical position of the circle was determined by a “speed on gamma/pitch” control law (such as that shown in Figure 8).

A “tadpole” symbol has also been used. The tadpole symbol closely resembles the integrated cue circle but includes a “tail” on the top of the symbol. The pitch and roll positioning of the tadpole is driven identically as the integrated cue circle. The tail of the tadpole turns to indicate the magnitude and direction of an impending tunnel turn (i.e., the tadpole points left indicating a left tunnel turn). The tadpole symbol is analogous to that used in numerous USAF/USN fighter aircraft HUDs.

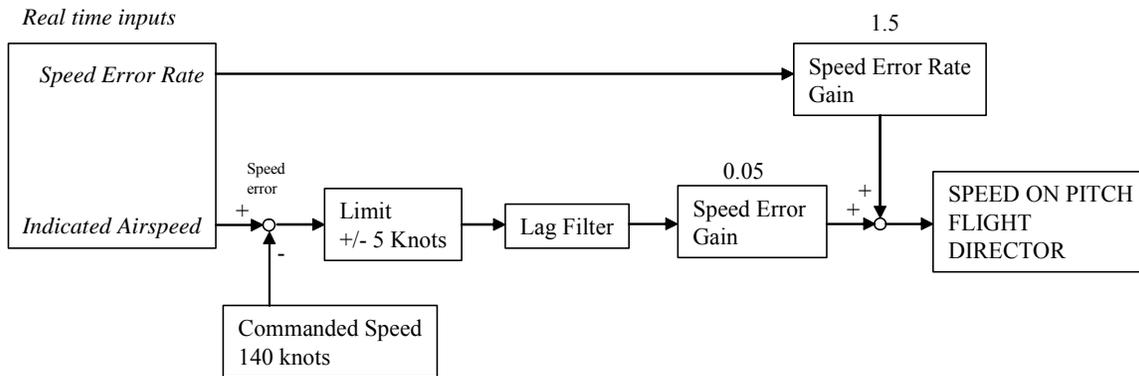


Figure 8. Block diagram of “speed on gamma/pitch” control law.

Dynamic tunnel

The dynamic tunnel concept was a boundary alerting modification to the “crow’s foot” tunnel concept that, in real time, alerts the pilot of an impending boundary (top, bottom, left-side, or right-side) requiring correction maneuvers. In other words, the rendering was developed to enhance the visibility of the “crow’s foot” tunnel by dynamically modulating the “crows’ feet” as a function of path error. The concept provides the pilot with feedback as to where they are in the tunnel or if they have flown outside the tunnel based upon the “size” or depiction of the crow’s foot tunnel (Reference 35).

The premise of the dynamic tunnel was that when the pilot is flying in the center of the tunnel, there should be the smallest amount of tunnel/symbology clutter. However, as path error increases to appreciable levels, the tunnel walls would “grow” to help the pilot gauge where the boundaries of the tunnel are. This helps to overcome a criticism of “low clutter” tunnels. Similarly, the “low-clutter” crow’s foot tunnel presents a more challenging visual perception than the connected-rectangle tunnel for recognition and reentry when outside of the tunnel path. The dynamic tunnel code allows flexibility to tailor the “crow’s foot” tunnel in this scenario as well.

The dynamic tunnel concept was developed so the “crow’s foot” elements were dependent on path error, with a unity length indicating a “full boundary” condition. Figures 9 and 10 show the lateral and vertical path error curves (respectively) which define the tunnel segment lengths for the dynamic tunnel concept. This function was implemented with two control parameter table look-ups on GUI panels that related boundary length of each of the three segments (height, width, and length) of a crow’s foot element (see Figure 2) to the appropriate path dot error. These two tables (one for lateral error control of the lengths of the two sides and one for vertical error control of the lengths of the top and bottom) were used whenever the aircraft was within the tunnel, causing the “InTheTunnel” logic to be true and enabling the function. Interpolation between column distances was provided within the graphic programming so that segment growth was smooth across dot error variations.

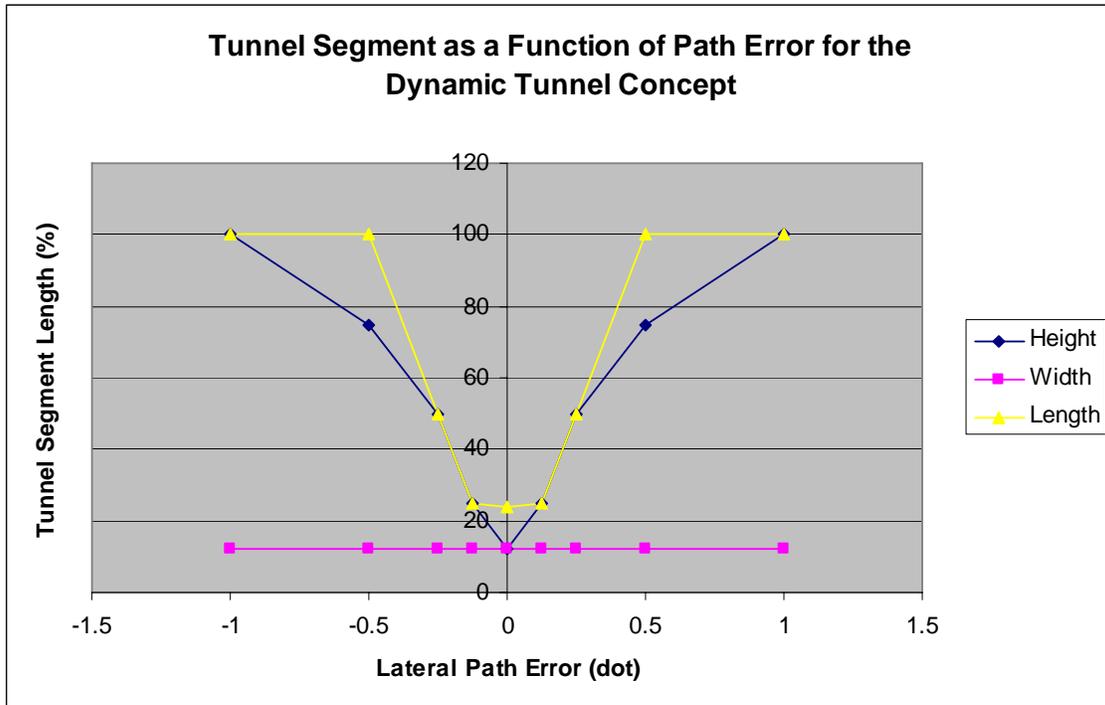


Figure 9. The lateral path error curve defined for the dynamic tunnel concept.

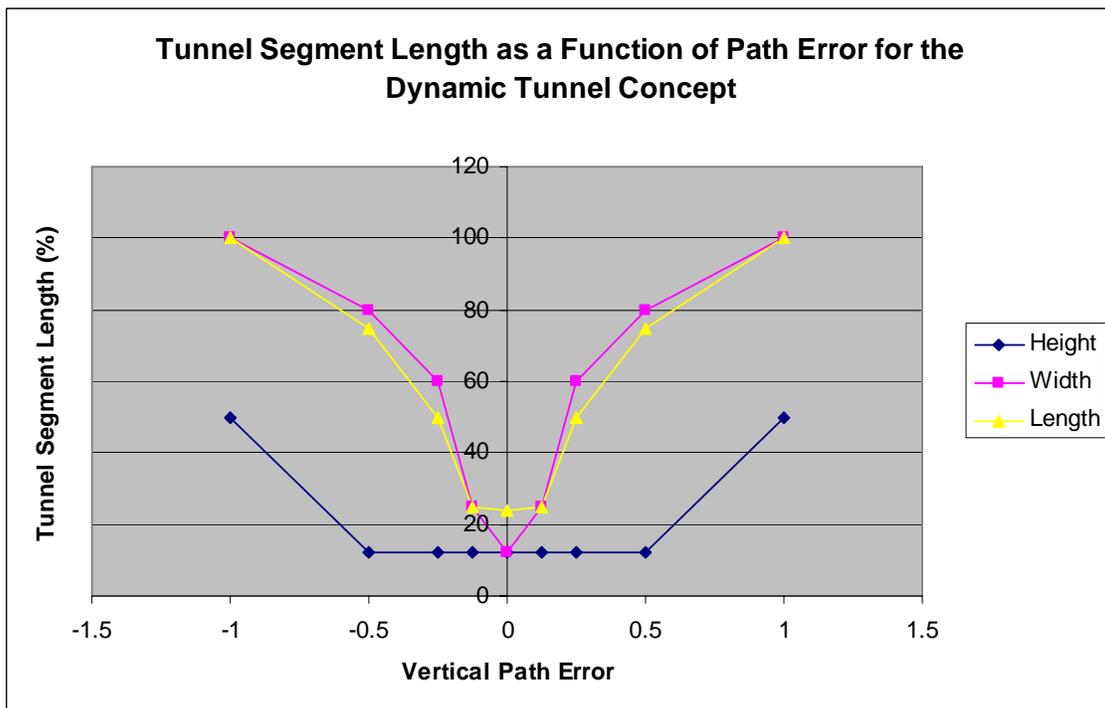


Figure 10. The vertical path error curve defined for the dynamic tunnel concept.

As an example, Figure 11 presents the dynamic tunnel as it would appear with ownship near the center position of the tunnel (the unmodified “crow’s foot” tunnel). The tables could be set such that with a +0.25 dot vertical error, the bottom of the tunnel would fill in from both the left and the right bottom corners with quarter-tunnel width segments, with a gap equal to half the width of the tunnel (see Figure 11).

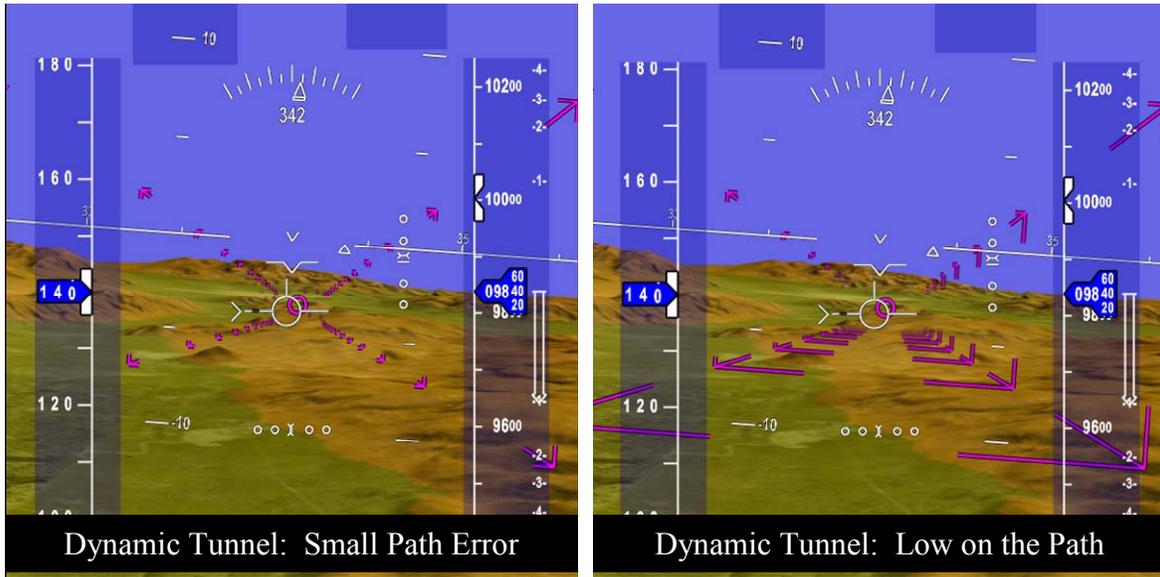


Figure 11. Dynamic tunnel with ownship near tunnel center (left) and with ownship approaching bottom boundary (right).



Figure 12. Dynamic tunnel with ownship outside of and below the tunnel.

HUD Stroke Symbolologies

Pathway research also included the development of tunnel concepts for typical monochromatic stroke-on-raster HUDs (Reference 36). All of the tunnel-related symbology was included as a stroke symbology option within the Rockwell Collins Flight Dynamics Head-up Guidance System (HGS) 4000 Computer for flight test evaluations. This modification was made to ensure that the tunnel was clearly visible and distinct during daylight conditions and from the raster synthetic vision background. Further, as stroke symbology, the brightness of the tunnel could be independently modulated by the pilot separate from the raster background.

In addition to the tunnel drawing routines, the HGS-4000 stroke symbology was modified to include Vertical “Raw Data” and Lateral “Raw Data” Indicators. The nominal HGS-4000 raw data symbology was modified to include path deviation indication in addition to the nominal angular (Instrument Landing System) deviation indicators. The raw data symbology included a deviation scale, showing “on path” and +/- 2 dots deviation (see Figure 13, using the vertical raw data indicator as an example). The triangular symbol showed Glideslope angular deviation as is nominally displayed on the HGS-4000 when properly configured. A path deviation indicator (“Dogbone”) was added to show linear deviation from the tunnel path.

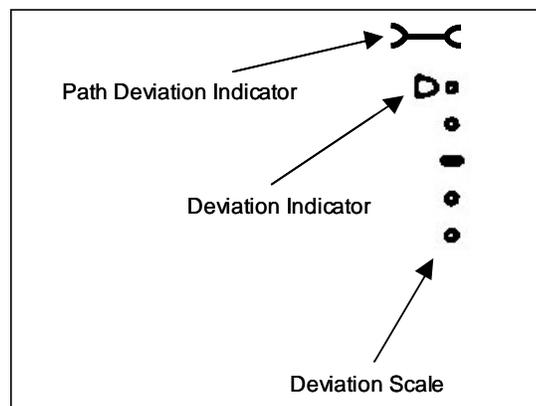


Figure 13. Vertical deviation “Raw Data” indicator.

The “dual” raw data indicators provide a compact and efficient method of conveying navigation performance indication to the pilot. The glideslope and localizer information are “ground-based” and represent an independent data source by which to cross-check the accuracy and validity of the “aircraft-based” tunnel guidance. As shown in the example in Figure 14, if a curved arrival is programmed to converge to an ILS final approach course, the “dogbones” show linear deviation along the curved path. As the curved path intercepts the final ILS approach course, the pilot can use the localizer raw data to verify the final approach course and, thus, validate the accuracy and integrity of the aircraft navigation solution generating the magenta path.

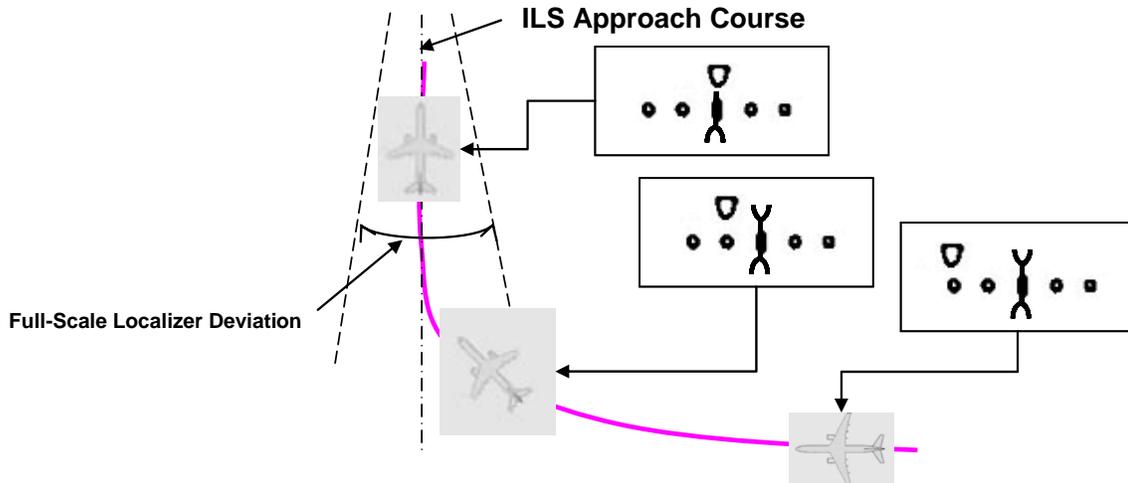


Figure 14. Lateral deviation “Raw Data” indicator functionality.

The stroke symbology changes are available for display when the HGS-4000 is operated in "Research" mode. The positioning and logic associated with each symbol was controlled by ARINC 429 data bus communications protocol between the HGS-4000 and on-board research computers.

Departure Tunnel

The majority of tunnel applications address only the approach phase of flight, since the research to date indicates the benefits of tunnel concepts are primarily found for earth-fixed procedures involving complex turning, descending flight path trajectories.

An initial departure tunnel concept was developed but never advanced beyond the proof of concept phase. Departure procedures are not often “earth-reference” so adaptation of tunnel concepts to the departure are not straight-forward. When departure procedures do include earth-references, they typically only involve lateral path definitions without vertical climb components. The designer must be concerned that a tunnel which shows vertical path elements, may imply vertical path “constraints”. These “constraints” might inappropriately imply or assume a climb profile when none exists. This situation might potentially present hazardously misleading information if the actual aircraft climb performance is not included in the tunnel and guidance design. For instance, the tunnel should never command a climb gradient that could not be attained by the aircraft. Further, the tunnel should never command a climb gradient less than that nominally possible, unless desired by the pilot, when a vertical trajectory limit is not in effect. This ensures that maximum altitude and potential energy is reached, as quickly as possible, to mitigate the effects of a potential engine failure. Simulation evaluations also suggested that the display clutter caused by the departure tunnel perhaps outweighed any potential benefits of situation awareness, particularly for HUD applications.

The departure tunnel was based on the “crow’s foot” concept of only using the corners of a wire-frame tunnel. For departures and go-arounds, the flight path is constrained laterally but not vertically. Thus, the “crow’s foot” height (refer to Figure 2) is extended upwards to signify there is no top constraint and the width portion of the “crow’s foot” is removed. The resulting shape is a sideways “T”, where the bottom of the “T” points in the direction of the path. A further description of the Departure Tunnel concept is included in the Appendix.

Concluding Remarks

The key feature of the Crow's Foot tunnel concept is its minimal clutter rendition while still enabling pathway information to be effectively conveyed to the pilot and thus, appropriately used for aircraft control. The longevity and proliferation of the NASA Langley Research Center "crow's foot" tunnel concept is testament to the original consensus concept as envisioned by the participants in the pathway workshop series. Likewise, the contributions of many individuals are embedded in the many modifications that have since accumulated to adapt the tunnel concept to different applications, different phases of flight and different aircraft categories.

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Appendix

Departure Tunnel Description

A departure tunnel was conceived with the following characteristics, as presented directly from a programming task statement:

1. Because of the lack of vertical path constraints during this phase of flight, the basic tunnel element is no longer the 3-D crow's-foot or angle-iron symbol used during the approach phase of flight. The basic tunnel element is a 2-D "T" rotated 90 degrees (Figure A1) so the base of the "T" is pointed in the direction of the departure route (the desired track angle). Each whole line segment of the "T" is 0.025 nm long (GUI-controlled parameter).



Figure A1. The basic 'T' element of the departure tunnel.

2. A tunnel section, instead of being formed by four crow's-foot or angle-iron symbols to form a box, is now formed of six rotated-T elements, three to a side (Figure A2). A GUI option to select reduction to four elements, two to a side, should also be provided.

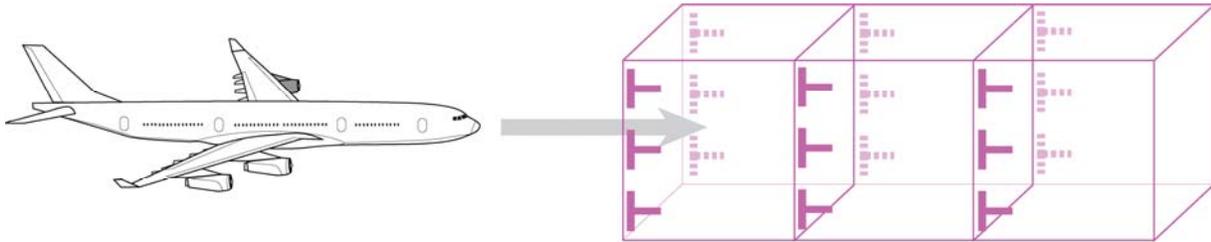


Figure A2. Side view of ownship and the departure tunnel.

3. A tunnel section is 0.1 Nmi wide (GUI-controlled parameter), and the rotated-T elements of each side are spaced 200 feet apart vertically (GUI-controlled parameter).
4. Tunnel sections are spaced 0.2 Nmi apart (GUI-controlled parameter) along the departure route (Figure A3).

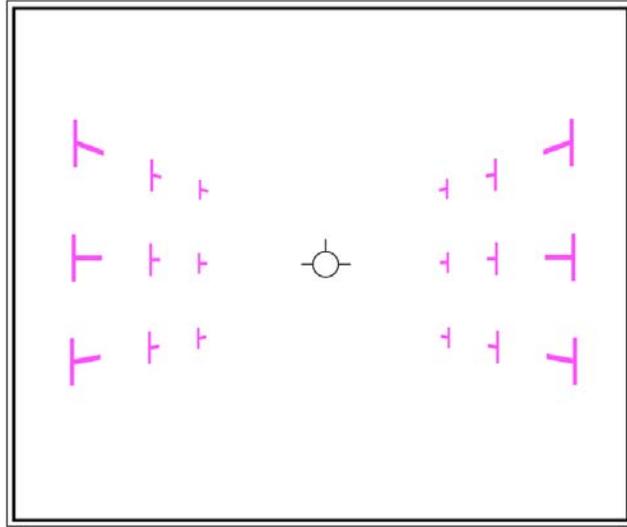


Figure A3. Departure tunnel.

5. The vertical structure of the tunnel is dependent on a predicted vertical path (climb / descend / level) of the ownship, such that the three-to-a-side rotated-T elements are aligned about the predicted vertical path.
 - a. Each “T” in the three-to-a-side element is positioned in altitude along the path track in multiples of 200 feet (e.g., one each at 2400, 2600, 2800 for an ownship level at 2501 feet; at 2200, 2400, 2600 for an ownship level at 2500 feet). The 200 foot parameter should be GUI-controlled.
 - b. The predicted vertical path of the ownship is calculated based on ownship altitude and a first order low pass (first order time delay) filtered value of ownship gamma. The parameter of the first order low pass filter should be a GUI-controlled constant.
6. A “Fade brightness with distance ahead” function, as available for the approach tunnel, shall be available with GUI-controlled parameters (on/off, distance, %) and enabled with within/without tunnel switching logic, as well as the path heading change logic (glideslope change logic is not necessary, as no vertical path exists).
7. When the ownship is laterally outside the tunnel (it is not possible to be outside of the tunnel vertically, as the tunnel is always aligned vertically along the velocity vector), an adaptation of the adaptive crow’s foot control parameter table on a GUI panel used for the approach tunnel (dynamic tunnel) shall be available such that near-side tunnel elements (the three-to-a-side rotated-T elements) should be able to grow in size to exaggerate the perspective size difference between the near- and far-side tunnel elements. The base of the rotated-T elements on the far side tunnel elements should grow to connect with the next tunnel segment (forming an outside wall of symbols). The columns of the control parameter table should be based on 0.1 Nmi distances rather than based on fractions of lateral dot error. Interpolation between column distances (as done with the adaptive crow’s foot implementation) should be provided. The three left side elements shall be dimensioned by two parameters (top of the “T” and base of the “T”), and the three right side elements shall be dimensioned by two similar parameters (top & base designators are similar to the present approach tunnel upper and lower corner designators).
8. When the ownship is laterally inside the tunnel, an adaptation of the path heading change logic

for the “Fade brightness with distance ahead” function should identify whether the path heading change ahead has the far side to the right or the left. This determination is used as an input to an adaptation of the inside-the-tunnel adaptive crow’s foot control parameter table on a GUI panel used for the approach tunnel. This table functionality shall be available such that far-side tunnel elements (the three-to-a-side rotated-T elements) should be able to grow the base of the rotated-T elements to connect with the next tunnel segment (were they at the same altitude). Thus the far side of the turn assumes a wall-like appearance.

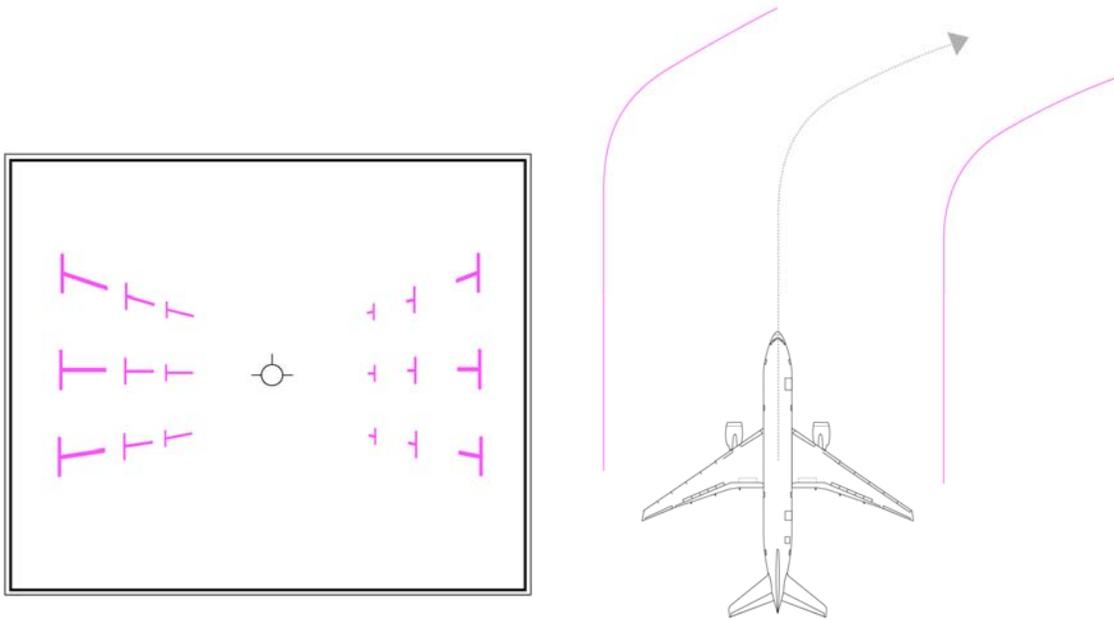


Figure A4. Pilot view (left) of the departure tunnel and top view (right) of ownship and the departure tunnel when executing a right turn.

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14. ABSTRACT NASA Langley Research Center has actively pursued the development and the use of pictorial or three-dimensional perspective displays of tunnel-, pathway-, or highway-in-the-sky concepts for presenting flight path information to pilots in all aircraft categories (e.g., transports, General Aviation, rotorcraft) since the late 1970s. Prominent among these efforts has been the development of the "crow's foot" tunnel concept. The "crow's foot" tunnel concept emerged as the consensus pathway concept from a series of interactive workshops that brought together government and industry display designers, test pilots, and airline pilots to iteratively design, debate, and fly various pathway concepts. Over years of use in many simulation and flight test activities at NASA and elsewhere, modifications have refined and adapted the tunnel concept for different applications and aircraft categories (i.e., conventional transports, High Speed Civil Transport, General Aviation). A description of those refinements follows the definition of the original tunnel concept.					
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