DESIGN OF TUNNEL-IN-THE-SKY DISPLAY AND CURVED TRAJECTORY

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Abstract

The Japan Aerospace Exploration Agency (JAXA) has been researching a perspective display format called "Tunnel-in-the-Sky", which provides a pilot with navigation and guidance cues using a perspective image of a nominal trajectory. The proposed display and trajectory definition scheme were designed to minimize tracking error and workload while giving a high level of pilot situational awareness. Applications considered include as a guidance and situational awareness display as part of a future air traffic management system, helicopter operations, a tool for flight experiments, and enhancement of autopilot mode awareness.

1 Introduction

Since the concept of instrument flight was introduced a half century ago, a number of efforts have been conducted to develop a display which provides visual cues as intuitive as out-of-window visual cues. A perspective image of nominal flight trajectory is a typical concept for such a display. In spite of the fact several such displays have been developed with different terms, Channel (Canal)-, Corridor-, Highway-, Pathway- and Tunnel-in-the-Sky Display, these share the same basic idea and concept.

The advantages of the Tunnel-in-the-Sky over conventional 2D display formats are reported as (1) higher tracking performance in manual flight, (2) lower workload, (3) enhanced situation awareness, (4) greater suitability for curved trajectories. During the past 30 years, some prominent research activities have been conducted, and display design strategies have almost been established [1]–[4]. In particular, by the recent improvement in on-board graphics generation capability and the spread of satellite navigation systems, in-flight-evaluation of such displays became common, and a few commercial products for general aviation have appeared on the market. However, although the Tunnel-in-the-Sky has become a common image in near-future advanced cockpits, there are still several issues to be clarified before it plays a dominant role in the cockpit.

Since 1997, JAXA has conducted several flight simulations and flight tests to further improve the display format and to investigate the design parameters of curved approach trajectories using airplanes and helicopter [5]–[7]. These activities have not just been limited to developing an advanced display suitable for use in a future air traffic management system, but have also focused on the development of a flight experiment tool to assist pilots in following complex trajectories. This paper summarizes JAXA's recent activities on the design and application of Tunnel-in-the-Sky displays.

2 Display Design

2.1 Aircraft Control Task

The basic component of a Tunnel-in-the-Sky display is the perspective image of the tunnel. A pilot receives information from the tunnel regarding his position relative to it, its direction, and the required future flight path. The

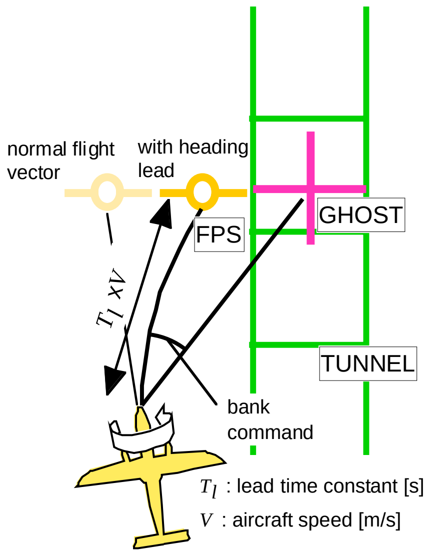


Fig. 1 Horizontal geometry of the display

Fig. 2 Basic symbology of the display

introduction of a Flight Path Predictor Symbol (FPS) facilitates the control task by showing the predicted position of the aircraft with respect to the tunnel. Because of the difference between longitudinal and lateral vehicle dynamics, the FPS's position is defined separately in the pitch and roll axes. In the pitch axis, the motion of the FPS should be quickened by pitch rate so that the pilot controls the FPS directly instead of pitch attitude. In the roll axis, the FPS includes not only the current flight path vector but also the heading change trend, which can be predicted from bank angle assuming a coordinated turn (see Fig. 1) or from lateral acceleration. Control becomes much easier when a ghost aircraft symbol (GHOST) is presented [8]. This symbol depicts the demanded future position of the aircraft, and moves along the tunnel. The difference between the positions of the FPS (predicted position) and the GHOST (commanded position) explicitly provides pitch and roll commands to the pilot, and the control task becomes similar to that with a flight director.

In Fig. 1, the time constant T_l represents the ratio between course error gain and heading error gain. In some previous JAXA studies the GHOST was not utilized, or if it was used the pilot was implicitly allowed to choose the time constant within a certain range . While this method allowed the pilot to choose the gain of the human-machine system by superimposing his own GHOST on the tunnel, the author did not adopt this method since the flight task should be simplified as much as possible and training costs and operational standardization must be taken into account. Based on flight simulation experiments, a value of 5 s was selected for T_l.

2.2 Symbology

The display symbology has been progressively evaluated and refined throughout the flight simulations and flight tests. Although some minor details still require attention, most of the algorithms and design parameters have been frozen. Fig. 2 depicts the display format customized for JAXA's MuPAL-α research airplane, which is based on a Dornier Do.228. The annotated features in the figure and some functions are described below:

(1) FPS
(2) GHOST

(3) Tunnel. The tunnel comprises a series of gates at 500 m longitudinal intervals connected by longitudinal segments. The width of the tunnel, 100 m, was set by reference to other studies and the results of flight simulation experiments. Parts of the tunnel more than 10 km ahead of the aircraft are not displayed; instead, a dotted line is shown following the tunnel center. The green tunnel represents the target flight path. Descent position (the point of change from level flight to descent) is indicated on the tunnel by an amber square. Bank entry position is indicated by an amber circle. Aural messages indicating descent timing have been found to be especially useful to pilots tracking complex trajectories with steep descent angles.
(4) Speed flag. Deviation from the reference airspeed is indicated by this yellow box with chevrons. When the deviation exceeds 10 kt, the box is filled with yellow.
(5) Flight Path Acceleration Symbol
(6) Airspeed tape
(7) Vertical speed
(8) Altitude. Normally, the altitude indication represents a GPS-referenced value, with reversion to pressure altitude in the case of GPS integrity degradation
(9) Heading arc
(10) Wind indication. The estimated wind speed and direction are presented experimentally.
(11) Distance indication. When the aircraft is within 200m of the center of the tunnel, the distance to the touchdown point along the target flight path is shown in green. Otherwise, straight-line distance to the runway is presented in yellow.
(12) Pitch angle indication. In order to reduce clutter, the pitch ladder is shown as separated left and right halves. Though attitude is not the prime parameter to be controlled, pilots sometimes complained of degraded attitude awareness. A "Gradation Background" was therefore introduced to enhance attitude awareness [9].
(13) Plan view. Current route and flight path angle are presented. In this figure, traffic information is also integrated.

2.3 Discussions

2.3.1 Bank angle of the tunnel

There is a continuing debate on whether the tunnel section should "bank" or not. In the proposed display, curved tunnel sections are banked according to the nominal speed and radius of the curve. During flight simulation evaluation of display design parameters, participating pilots preferred a banked tunnel over a non-banked one. A problem which came to light during these experiments was the discrepancy between the bank angle of the GHOST and the required bank angle. Since the GHOST symbol was also banked with the tunnel, the bank of the GHOST was perceived as a "roll cue" by the pilots and as a consequence, the aircraft tended to fly inside the intended curve during simulations and a first series of flight tests. In order to solve this problem, the start of the GHOST bank was displaced by a time interval T_l s along the tunnel. It is hypothesized that this "Bank Forward" modification may enable pilots to use the roll-axis motion of the GHOST as a roll-in and roll-out cue. This is the reason why the shape of GHOST is not square but circular. In flight tests, the banked tunnel was still preferred because the pilots were able to receive information about wind and speed error.

2.3.2 Guidance to the tunnel

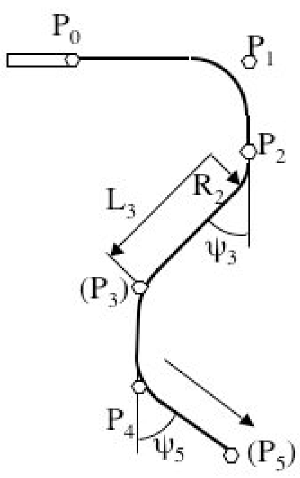
A major topic is how to guide the aircraft to the entrance of a tunnel (the initial point of a nominal trajectory), or how to guide the aircraft to return to the tunnel in case of large deviation from nominal trajectory. One solution could be to use a guidance tunnel which is not fixed in an inertial frame. In spite of several trials, it was concluded that the most robust and easy way in any condition is to use a plan view.

2.4 Trajectory Definition

Preliminary rules for approach path design, such as the minimum length of the final straight approach segment, the steepest permitted bank angle and the minimum length of the introductory leg before the final turn, have been selected on based on flight experiments using a Tunnel-in-the-Sky display.

In previous research into curved approaches conducted by JAXA, routes were initially described by series of waypoints. As the research progressed, however, it became clear that this waypoint type description had limitations for the precise definition of complex routes, and consequently, the concept of a "Path Object" [10] was introduced. An example of a Path Object route definition is shown in Fig. 3.

As the trajectory is fixed in inertial space, in strong winds significant deviation from the nominal route may occur when attempting to track it, and there is the risk that tracking the nominal route may require maneuvers close to the performance limits of the aircraft with a consequent danger of loss of control. The following trajectory generation and modification algorithm is considered to avoid such problems.



// Example of route file
X_0 Y_0 H_0 //Waypoint form
X_1 Y_1 H_1 //Waypoint form
X_2 Y_2 H_2 R_2 L_3 ψ_3 //Radius form
0 0 H_3 //continue
X_4 Y_4 H_4 //Waypoint form
L_5 ψ_5 H_5 //Arc-length form

Fig. 3 An example of route definition file

Following the basic concept of a Path Object, the horizontal trajectory is defined using connected straight legs and circular arcs. In order to reduce deviation and pilot workload when the route is flown, the aircraft's flight guidance system re-generates the trajectory from the definition as a higher-order function. Fast-time simulation is then conducted to generate a trajectory assuming a scheduled roll rate (for example, 3 deg/sec or 5 seconds to reach 15 degrees bank), and the second-order trajectory is replaced by the calculated trajectory. The point of initiating a turn is shifted along the preceding straight leg. When route modification is applied, the estimated wind is included in fast-time simulation [11], [12].

The original route and the route modified to compensate an estimated steady wind are shown in Fig. 4, along with corresponding time histories of bank angle from piloted flight simulations following the trajectories. The route modification successfully reduces the maximum achieved bank angle.

In the contrast to the horizontal trajectory, no smoothing is applied to the vertical trajectory, because it is important to provide information to allow the pilot to anticipate changes of flight path angle. Estimated wind is utilized to alter the flight path angle so that the aircraft

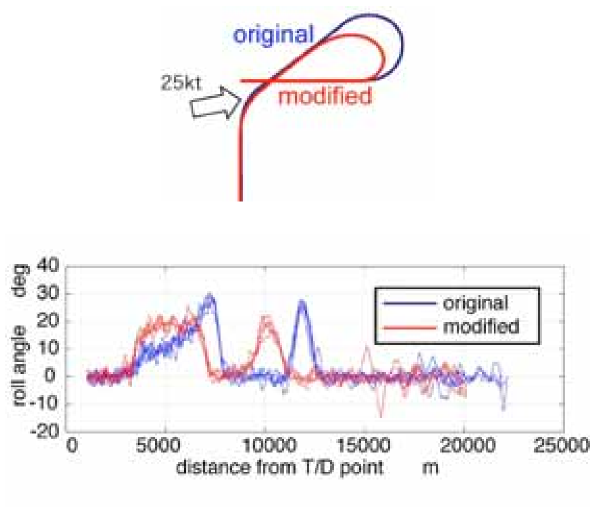


Fig. 4 Effect of route modification: time history of roll angle

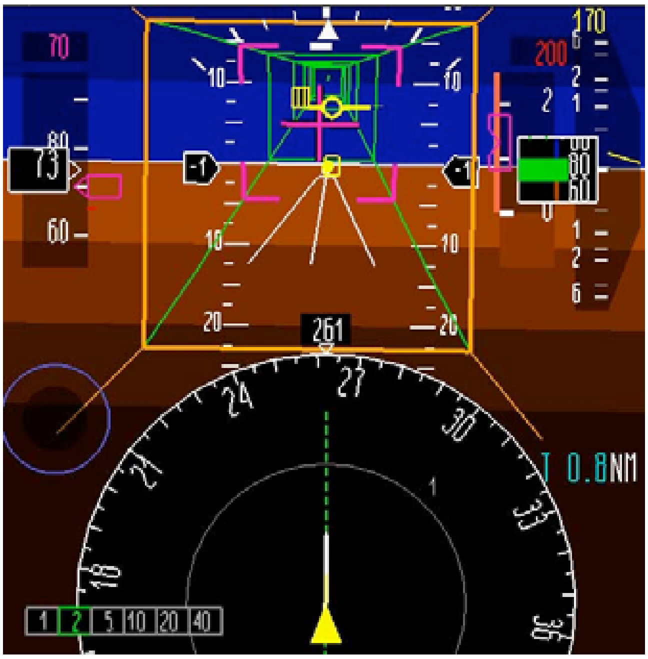


Fig. 5 Snapshot in noise measurement task

maintains a constant "flight path relative to air mass". Although theoretically possible, the flight path angle of the final straight leg not modified. Vertical path modification is applied after modification of the horizontal trajectory.

3 Applications

3.1 A Tool for Flight Experiments

In many kinds of flight experiment, pilots are required to follow a nominal trajectory as precisely as possible. If the shape of the trajectory is complex, workload is high and the quality of retrieved data might be degraded. Using a Tunnel-in-the-Sky display instead of a Flight Director (FD) or conventional horizontal map successfully supports such experiments by reducing pilot workload in the tracking task[13].

Fig. 5 depicts the snapshot of a display used for noise measurement of a helicopter [14]. The display provides the pilot with the nominal trajectory and timing for changing power setting. In this experiment, the size of the tunnel cross-section and FPS prediction time are smaller than for conventional operations to attain higher tracking performance.

3.2 Helicopters

Fig. 6 depicts a Tunnel-in-the-Sky display designed for a JAXA's MuPAL-ε research helicopter, which is based on a Mitsubishi MH2000A. The following were identified as key factors in the design of a Tunnel-in-the-Sky display for helicopters [6].

(1) Longitudinal cueing
Compared to conventional fixed-wing aircraft, power (collective pitch) plays a much greater role in the flight path control of helicopters. Helicopter pilots are instructed to control flight path using collective pitch and airspeed using pitch attitude (longitudinal cyclic pitch) as a basic technique ("speed on pitch"). On the other hand, while performing ILS (Instrumental Landing System) approaches, pitch attitude is frequently used to correct flight path error in order to avoid disturbances which might be caused by changing power settings. The results of a series of piloted flight simulations revealed that an FPS algorithm which adds prediction factors based on collective pitch motion to the algorithm for fixed-wing aircraft gives the best

Fig. 6 Display for helicopter

compatibility with both control techniques.

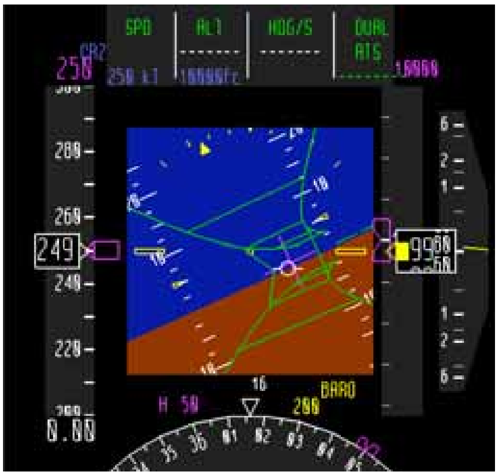
(2) Horizontal Field-of-View
During flight tests, it was sometimes reported that major Tunnel-in-the-Sky symbols, such as the flight path predictor and tunnel, overlapped altitude or airspeed instruments located at the edges of the display, or even disappeared from the display altogether in strong crosswind conditions.

Compared with a fixed-wing aircraft, the approach speed of a helicopter is lower and its rate of turn at a given bank angle is greater. In general, lower target speeds require a greater display horizontal field-of-view. For example, supposing a maximum bank angle of 25º, T=7s and a target speed of 70kt, the minimum required display horizontal field-of-view is 100º, whereas an airplane flying at 100kt requires 70º. However, because the physical size of the display is limited, especially in small aircraft, expanding the field-of-view may result in smaller display symbols and consequently poor readability. To avoid this, the authors devised a method to keep major symbols in the center of the display by automatically shifting its line-of-sight. This "Automatic Centralization Function" successfully avoids clutter while maintaining information readability in curved parts of the trajectory. On the other hand, in flight tests, it was recommended that the display line-of-sight be reset before the runway is in sight.

3.3 Autopilot Mode Awareness

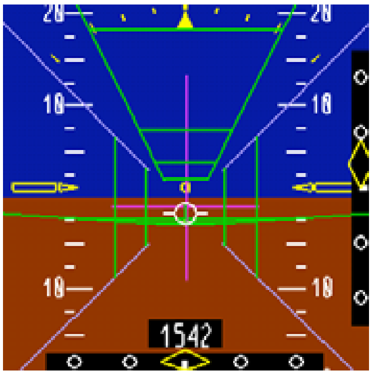
Cockpit automation in modern aircraft has drastically reduced pilot workload and enhanced flight safety. The US Federal Aviation Authority (FAA) conducted an extensive survey about the problems that occur between flightcrews and the automated flight deck, and made recommendations for further flight safety [15]. Among the issues reported, degradation of autopilot mode awareness, when the aircraft may behave in a way the crew does not expect, is considered as a threat to total safety during autoflight. As the complexity and variety of automatic flight modes seem to contribute to the degradation of mode awareness, a practical solution could be to improve the human-machine interface.

In modern cockpit, it is hypothesized that a pilot maintains situation awareness of the state



(a) ALT mode + LNAV

(b) Flight level change (Altitude Capture) + LNAV



(c) LOC track + GS capture

Fig. 7 Display for mode awareness enhancement of the automatic flight control system (AFCS) by the following steps:

- The pilot reads the indications of the Flight Mode Annunciator (FMA) display (the green text along the top of Fig. 7(a)), and interprets the various abbreviations as the names of the horizontal, lateral and autothrust modes.
- The pilot identifies the functions of current modes. He or she refers to his knowledge that is based on the flight manual, his training and experience.
- The pilot predicts the effect of the current mode on the flight path or course based on his knowledge about the mode.

Due to the complexity of these cognitive steps, the pilot may fail to correlate the AFCS's behavior with his intention, and may fall into "mode confusion".

As the nature of the Tunnel-in-the-Sky display, it can present demanded flight path, and help the pilot to comprehend the intention of AFCS and to predict future state. If the method of visual presentation by a tunnel can successfully represent the operation of the autopilot mode, it may contribute to enhance the autopilot mode awareness. The proposed Tunnel-in-the-Sky display format was integrated into an existing Primary Flight Display (PFD) in place of the FD, and basic sets of display formats were constructed corresponding to autopilot modes such as altitude hold, heading select, and approach. Flight simulations to evaluate the display system demonstrated the potential capability to prevent human error related to mode confusion [7].

4 Concluding Remarks

This paper summarizes recent activities on the design and application of Tunnel-in-the-Sky displays at JAXA. As the next stage, research will be focused on standardization and certification issues. Although the characteristics of human-machine systems in the display have become clear and the display design strategy has almost been established, we must be careful about the fact that the display and flight techniques used are different from conventional ones. Continuous effort must be paid to detect any problems in advanced concepts to enhance flight safety.

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