Supporting Pilots in Recovering Trajectories with Tunnel-In-The-Sky Displays

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Tunnel-in-the-sky displays have shown great potential for reducing pilot workload and navigation error. Although it is a well-evaluated concept, only little research has been conducted on situations in which the pilot has (deliberately or not) flown outside of the tunnel. This paper describes the experimental evaluation of various alternatives to support pilots in recapturing their nominal trajectory. The concepts studied include the use of guiding arrows, path deviation indicators, a symbol representing the tunnel and a “return tunnel”. Results from a pilot-in-the-loop experiment indicate that a “return tunnel” performed best on situation awareness and workload aspects and that most pilots participating in the experiment had a general preference for this support concept.

Introduction

Tunnel displays may enable aircraft to closely follow intricate trajectories as a means for improving air traffic management efficiency, and for meeting noise abatement concerns (e.g. Grunwald, 1984, Mulder, 1999). While studies to date have demonstrated the potential benefits of tunnel displays, only little research has been conducted on situations in which the pilot has flown outside of the tunnel. The tasks of determining the aircraft's position in relation to the tunnel, creating a mental image of the situation, and generating a recovery path to intercept the original trajectory can be very demanding at times. Therefore, track-recovery support (TRS) is necessary to enable the pilot to reacquire the planned trajectory.

Several papers indeed state that TRS is an “issue” for TIS displays (Beringer, 1999, Theunissen, Rademaker & Etherington 2002, Newman, 2003, Newman & Mulder, 2003). Besides scenarios in which the original trajectory is abandoned for some reason, the TRS symbology is also applicable in a transition from a flight phase with low (or less) precision guidance to a flight phase with high (or more) precision guidance. In this case, the TRS symbology directs the pilot to the beginning of the precision path. Theunissen et al. addressed the transition from conventional navigation modes to guidance along a complex, tightly constrained path. They considered two path-intercept concepts: a flight path predictor with a reference marker (directional guidance) and a 3-D intercept-path towards the precision path. In an initial evaluation of the flight path predictor with target marker concept, they concluded that the task of the pilot using this display is similar to using a predictor reference box when flying on the fixed path. They did not test the 3-D intercept-path concept, arguing that there is no difference between flying a 3-D intercept-path or flying the original precision path. Williams (2000) tested how well pilots were able to acquire a pathway in the sky with several types of guidance. It was found that a follow-me airplane yielded best performance over a flight predictor and the no-guidance condition.

This work studies the return maneuver as a whole. The starting point is an aircraft that has strayed from the nominal trajectory: it has an arbitrary cross track error and track-angle, and visual contact with the tunnel may be lost. Four TRS concepts will be described that assist the pilot in finding and recapturing the precision path. These concepts were selected after a theoretical investigation of initially eight concepts (Verschragen, 2004). The results of an experimental evaluation in which these concepts are compared are described.

Approach & Preliminaries

The TRS concepts are intended for path finding as well as path intercepting support. Supporting pilots in recovering the tunnel can be done in two ways:
1. Provide the pilot with information on the status of the aircraft: i.e. the position and track in relation to the tunnel. The status information enhances the situation awareness of the pilot, enabling him to form a better recovery strategy.
2. Provide the pilot with guidance information; the pilot follows the guidance commands given to him by the display. This approach relieves the pilot of the task of forming a recovery strategy.
3. In case of guidance information, a recovery algorithm is needed that computes either a recovery path or, in case of directional guidance, a commanded track-angle. In case of status information, the pilot determines a recovery path himself. Either way, the information for track-recovery support has to be

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presented through display symbology. The next section discusses four TRS concepts. Each concept will be explained on the basis of the intelligence needed for the concept and the way the information is presented on the display. We assumed the following:

- The TRS elements are presented only on the Primary Flight Display.
- The Navigation Display is not considered, as it could hide differences between the concepts.
- The nominal trajectory is straight.
- Only the horizontal plane is considered.
- The aircraft velocity is constant.
- The effects of wind and turbulence are neglected.

**TRS Concepts**

Four TRS concepts will be discussed in this paper, for a more detailed analysis including other concepts the reader is referred to (Verschragen, 2004).

**Arrows Concept (AR)**

The arrows concept (AR) provides directional guidance: the pilot is instructed to fly in a certain direction (Newman, 2003). The pilot is presented with the track (and flight-path) angle error of the aircraft with respect to the desired track (flight path) angle, Figure 1. The size of the arrows is related to the magnitude of the errors represented by them. When the aircraft flies at the desired track (or flight path) angle, the arrows disappear.

The intelligence behind the arrows is in analogy with the procedure of flying to a VOR beacon. Three areas are defined (parallel to the tunnel), each with a different commanded track-angle. Figure 2 shows these three areas and the trajectory shape intended by the arrows.

**Tunnel Symbol Concept (TS)**

The tunnel symbol (TS) concept is a status information concept: it provides the pilot with the difference in track angle (and vertical off-set) with respect to the tunnel, Figure 3. As compared to the AR concept, no “error” is shown, but a difference in track-angle. A pilot derives his recovery strategy.

The intelligence behind the display derives the track-angle difference between aircraft and tunnel (and vertical off-set). No recovery path or direction is generated. Rather, the algorithm determines whether the aircraft is flying in the correct tunnel-direction and also whether it is flying towards or away from the tunnel. Then, the track-angle error is shown by a hatched plane that rotates about its vertical center axis, Figure 4. The vertical position deviation of the aircraft with respect to the tunnel is clarified by the vertical position of the tunnel symbol on the display. When a change in flying direction in relation to the original tunnel occurs, the tunnel symbol flips from the left to the right side (or vice versa). The cross-track error is shown qualitatively by the scaling of the tunnel symbol; at a certain size of the cross-track error, the symbol will not become smaller if the cross-track error becomes larger, this to keep the tunnel symbol readable. The symbol is shown in green if the direction of flight is within ±90 or -90 degrees of the tunnel-direction, otherwise it is shown in red. Furthermore, the symbol is fully drawn if the pilot is flying towards the tunnel and dotted if the pilot is flying away from the tunnel.

**Return Tunnel Concept (RT)**

The return tunnel (RT) concept is a path-based guidance display: a 3-D path leading back to the tunnel is presented to the pilot. For the RT concept implementation an elaborate algorithm was defined (Verschragen, 2004). The “return tunnel” only differs from the original tunnel by its green color, Figure 5. The return tunnel is generated when the pilot presses a button. It does not move along with the aircraft but remains a static object in the world and approaches the original tunnel with an intercept angle of 30°.

**Deviation Indicators Concept (DI)**

The deviation indicators (DI) concept offers only status information; the pilot is provided with the horizontal and vertical deviations from the planned path. Also the rate at which these deviations increase or decrease is given to the pilot, which indirectly informs the pilot about the difference in track between the aircraft and the tunnel.

The deviation indicators consist of one horizontal and one vertical scale that indicate the position of the aircraft in relation to the planned path, Figure 6. In analogy with the “follow-the-needle” principle, the deviation indicators scale centers represent the own aircraft. A moving square on the scale shows where the original path is located. The indicators are extended with a yellow trend vector that indicates the velocity at which the cross-track error changes. The scales are linear and show deviations from -1000m to +1000m between the tunnel and the aircraft for both dimensions, small lines indicating another 250m.
Experimental Evaluation

The goal of the experiment was to evaluate the effects of the four TRS concepts on pilot performance, workload and situation awareness.

Subjects and instructions. Nine experienced professional airline pilots participated in the experiment. They were instructed to capture the tunnel in the way they thought best.

Apparatus. The experiment was run on a desktop computer in a noise-free room. The pilot controlled the aircraft motion with a joystick. With the RT concept a button could be pressed to generate the return tunnel. The 17” computer screen showed a generic “tunnel-in-the-sky” Primary Flight Display extended with one of the experiment concepts.

The aircraft model. A linear model of a Cessna Citation 500 was used, trimmed for a speed of 77m/s. No wind or turbulence model was simulated.

Independent variables. Two independent variables were defined: the TRS concept (4 levels), and the experiment scenario (6 levels). The scenarios are shown in Figure 7. Scenarios 1 and 2 are considered more difficult than the others, because here the tunnel is not visible at the start of the runs. Vertical deviations from the nominal path are limited. Scenarios 3 and 4 have an initial vertical off-set compared to the tunnel of 100m (above the tunnel). In all other scenarios, no vertical off-set is used.

Experiment design and procedure. A full-factorial within-subjects design was used, yielding 24 conditions. The subjects first received instructions on how the TRS concepts worked and had a chance to fly them as many runs as needed to understand the concept. After the learning phase, the pilot flew the 24 conditions in a randomized order. After the experiment, a pilot questionnaire was handed out, querying pilots on performance, workload and situation awareness aspects of the TRS concepts.

Dependent Measures

The following dependent measures were defined:

- **First-turn errors:** maneuvering in the wrong direction at the start of the run. The RT return trajectory of is taken as the “correct” trajectory.
- **Spread of mean cross-track error:** a measure to determine the diversity of the return routes.
- **Number of stick inputs:** several counters were defined to separate the larger stick deflections from the smaller ones. The counted number of deflections per run is divided by the run time.
- **Total return time:** the time it took pilots to guide the aircraft back into the tunnel.
- **Maximum cross-track error:** the maximum distance to the reference path.
- **Constant track interval:** the longest “straight” segment (track-angle error smaller than -1°/+1°) is measured relative to the total run time.
- **Time to final atd:** the total time necessary to not only return to the original trajectory, but also to reach a certain atd at the original track.

The last performance measure is used to determine which concept allows the most time-efficient returns. To be able to compare different runs, the run with the farthest atd at the moment of intercept, atd_final, is selected. For all other runs of the same condition, the time necessary to reach this atd_final was calculated:

\[
T_{\text{to final atd}} = T + \frac{\text{atd}_{\text{final}} - \text{atd}_{\text{intercept}}}{V_{\text{intercept}}},
\]

where \( T \) stands for total return time, atd_intercept is the atd at intercept of the particular run and \( V_{\text{intercept}} \) is the velocity of the aircraft at the moment of intercept.

Experiment hypotheses. First, it was hypothesized that the amount of first-turn errors would be lowest with the RT and AR displays, and the spread in mean cross-track error would be smallest with the RT display. Second, it was hypothesized that RT and DI would yield in the lowest and highest workload, respectively. It was expected that the RT display would yield more control activity than the other displays, because the pilot would try to stay inside of the return tunnel. Third, as far as performance is concerned, it was hypothesized that the RT display leads to the longest return times. The RT algorithms create a return route with a small intercept angle, and therefore gradually reducing the cross track error. For the AR concept, the return times were expected to be smallest, because the pilot is directed perpendicularly to the original tunnel. With the other two concepts the return times are hypothesized to lie in-between.

Fourth, it was hypothesized that the RT concept would provide the most efficient returns; the RT algorithms were designed to minimize time-loss incurred by the out-of-tunnel incident. The maximum cross-track errors were expected to be largest for the RT display, because the RT algorithms create a return route that is not optimized for minimizing position errors, while with other concepts, the pilot can apply his own preference. Finally, it was hypothesized that RT leads to the longest sections of constant track-angle, again as it is inherent to the RT algorithm.
Results

A full-factorial ANOVA was conducted on most dependent measures. Some data were defined as “counters” (e.g., the number of f-t errors and the number of stick deflections), data that is not necessarily normally distributed. Here, the non-parametric Friedman test was used. If it revealed a significant effect, Wilcoxon tests were executed to compare each of the displays separately. Figure 8 shows the means and the 95% confidence limits of some of the main dependent variables, for one difficult (1) and one easy scenario (3 or 5).

**Table 1. Number of first-turn errors per condition.**

<table>
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<tr>
<th>Scenario</th>
<th>TS</th>
<th>AR</th>
<th>RT</th>
<th>DI</th>
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<td>3</td>
<td>6</td>
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</table>

*First turn errors.* The amount of first-turn errors was significantly influenced by the display type ($\chi^2=13.57$, $p<0.01$). Wilcoxon tests revealed that the TS concept leads to more first-turn errors than the other three concepts. Furthermore, with the RT concept, less first-turn errors are flown than with the DI concept (Table 1).

*Diversity return routes.* Figure 8 shows that for scenario 1 (considered difficult) the spread in the mean cross-track error is largest for the TS display followed by the DI display. The RT and AR displays show the smallest spread. Scenario 5, however (considered simple), shows equally large spreads in mean cross-track error for all concepts. Thus, in hard scenarios it becomes clear that RT and AR allow the pilot to fly a more precise route than the tunnel symbol and deviation indicators displays. In simple scenarios this effect is not (less) visible.

*Control activity.* The counters show a distinction between large and small aileron stick deflections. Only a marginal significant influence is found of the display format. Wilcoxon tests revealed that for large stick deflections TS is outperformed by the RT ($\alpha=0.05$, $p=0.0256$) and DI ($\alpha=0.05$, $p=0.0629$) concepts. For small deflections, Wilcoxon tests revealed that DI was outperformed by AR ($\alpha=0.05$, $p=0.0650$) and TS ($\alpha=0.05$, $p=0.0830$) concepts. The AR concept performs better than the RT concept ($\alpha=0.05$, $p=0.0830$). For small stick deflections the RT concept shows the highest control activity. These are due to the tracking of the return tunnel.

*Fastest return.* A significant effect on the total return time was found for both the display ($F_{3,21}=21.587$, $p<0.01$) and scenario ($F_{5,35}=42.950$, $p<0.01$) Furthermore, a significant 2-way interaction was found $F_{15,105}=5.947$ ($p<0.01$). A Post-Hoc analysis (SNK, $\alpha=0.05$) revealed that the RT display performed worse than the other three displays.

*Most efficient return.* The time to final atd was significantly influenced by the display type ($F_{3,21}=4.131$, $p=0.019$). The scenario significantly affected the time to final atd ($F_{5,35}=91.733$, $p<0.01$). A Post-Hoc analysis (SNK, $\alpha=0.05$) revealed that the RT display was outperformed by the AR display.

*Minimizing position errors.* The maximum cross-track error is significantly influenced by the display format ($F_{3,21}=13.462$, $p<0.01$) as well as scenario ($F_{5,35}=27.095$, $p<0.01$). The 2-way interaction was significant ($F_{15,105}=7.407$, $p<0.01$) as well. Post-Hoc analyses (SNK, $\alpha=0.05$) for display revealed three different groups. The TS concept leads to the smallest maximum cross-track errors, followed by the AR and DI concepts in the second group. The RT display yields the largest errors.

*Stable return maneuvering.* Display ($F_{3,21}=31.056$, $p<0.01$) and scenario ($F_{5,35}=11.367$, $p<0.01$) significantly affected the variability on the return maneuvers. Again the interaction was significant ($F_{15,105}=4.917$, $p<0.01$). Post-Hoc analysis (SNK, $\alpha=0.05$) for display revealed three groups. The RT concept performed best. A second group contains the TS and AR displays. The TS concept also forms a third group with the deviation indicators.

*Questionnaire.* The pilots indicated that the RT and AR concepts show which direction to steer to at the start of the maneuver in the most clear way. The size of the track-angle error is shown clearest with the RT and TS concepts, and the lateral position can be obtained easiest with the DI display. Pilots indicated that with the RT, their understanding of the flown trajectory after the run was best and that the RT display was the most intuitive. Subjects indicated that the RT concept improved situational awareness most.

Also, with the RT the capture maneuver costs least effort. It was considered the most comfortable and the DI concept the least comfortable display. Workload was found lowest for the RT concept, followed by the AR concept. Regarding performance, most pilots were of the opinion that the RT allows best performance in general. Overall, six of nine pilots preferred the RT concept.
Discussion

From the statistical and subjective results, it appears the RT display offers the best situational awareness; the amount of first-turn errors is smallest for RT display, indicating that the RT offers the clearest symbology. The diversity between the return routes were smallest for this display. Pilots indicated that the RT provided the most intuitive display and helped them best to understand the trajectory flown.

The RT display leads to the highest control activity for small stick deflections. This is caused by the tracking of the tunnel and not to intercepting the nominal trajectory. RT resulted in the lowest amount of large stick deflections, indicating that pilots felt comfortable with this display.

The AR display allows the most efficient return, while it was hypothesized that the RT display would perform better on this measure. This discrepancy is due to the design of the RT algorithm: with small deviations from and flying with large intercept angles towards the tunnel, the return trajectory will first cross the original tunnel before initiating a turn to final intercept of the planned path.

The TS display leads to the smallest position errors, but it also resulted in the steepest turns. This can be expected since if the aircraft is flying away from the tunnel initially, a steep turn (i.e. a smaller radius) will limit the maximum position errors.

The RT concept leads to the longest and least efficient returns with largest position errors, because the algorithms that produce these return tunnels were not designed to optimize these measures for performance. The return algorithms generate stable return trajectories that gradually approach the original path. Therefore, the RT display leads to longest intervals of constant track-angle. Furthermore, the pilots indicated that they felt they performed best with the RT display.

Conclusions

The objective of this work was to evaluate four track-recovery support concepts. It was found that the return tunnel concept (RT) offers the best situational awareness and the lowest control activity in terms of large stick deflections. It also led to the largest return times and position errors, but this is inherent to the algorithms that calculate the return tunnels. Obviously, because pilots relied on the tunnel guidance, it resulted in minimal variations in return maneuvers. And because pilots tried to accurately fly the tunnel return trajectory, the highest number of small stick deflections was found with this concept. The RT concept was preferred by most pilots. Performance with the RT can be enhanced by modifying the algorithms that calculate the return trajectories. Control activity can be reduced by optimizing the (return) tunnel dimensions.

For future research, some extensions should be made to the experiment design. First, the reference track should include one or more curved sections. This will imply a redesign of the return trajectory algorithms. Thrust settings should be incorporated as well, resulting in a variable speed and therefore a variable radius of turn. Most importantly, a navigation display should be taken along in the experiment, which contributes significantly to the situation awareness. The role for the track-recovery support display will then shift more to supporting the pilot in performing a smooth intercept with the reference trajectory.

It is recommended that future experiments include high-workload situations, in which the pilot has to divide his attention between different tasks. An intuitive display will pay off in these situations, because processing information will demand less of the pilot. It is hypothesized that the RT concept will outperform all others under these circumstances.

References


Figure 1. *The arrows concept AR (encircled).*

Figure 2. *The trajectory that is the result when following the arrows (AR) recovery concept.*

Figure 3. *The tunnel symbol concept TS (encircled).*

Figure 4. *Tunnel symbol color and line attributes.*

Figure 5. *The return tunnel (RT) concept.*

Figure 6. *The digital indicators (DI) concept.*

Figure 7. *Experiment scenarios definition.*
Figure 8. Means and 95% confidence limits for the main dependent measures.