IMPROVEMENT FOR LANDING ON SMALL-MEDIUM AIRPORTS USING FUTURE, AIRCRAFT-AUTONOMOUS GUIDANCE AIDS

G. Sachs*, F. Schuck*, F. Holzapfel*, J. Schaller**
*** Institute of Flight System Dynamics**
Technische Universität München, Boltzmannstr. 15, 85747 Garching, Germany
**** ESRI Geoinformatik GmbH, Ringstr. 7, 85402 Kranzberg, Germany**

Keywords: *Guidance aids, landing, small airport*

Abstract

Improvements are dealt with which are possible with an integrated presentation of guidance information and terrain in a 3-dimensional format for supporting the pilot in landing an aircraft. This is considered to enhance the accessibility of small to medium airports in demanding landing approach conditions as regards low visibility, adverse weather and/or a difficult terrain environment. The 3-dimensional guidance information displayed to the pilot comprises the command approach trajectory in the form of a tunnel, the aircraft position at an appropriately selected time ahead using a predictor, and an image of the terrain. The terrain image shows all elements of the outside world important for the control task of the pilot. It features a high-resolution replication of the airport and its surroundings as well as a graphical reproduction of obstacles. Furthermore, the 3-dimensional guidance information presented on the display offers the possibility to perform curved and steep approaches. Thus, the flexibility of approach and landing operations can be enhanced. Results from pilot-in-the-loop simulations show the performance which can be achieved with the guidance aids.

1 Introduction

Accessibility of airports is a significant issue for the mobility with aircraft. For this purpose, a high level needs to be maintained, independent of external influences and conditions. However, the accessibility of airports can be degraded due to various reasons with regard to which low visibility and adverse weather are important factors. This particularly holds for small airports which are not equipped with landing aids. Severe visibility or weather conditions can even lead to a stop in take-off and landing operations.

A further issue is a difficult terrain environment of the airport, like a mountainous area or a terrain showing obstacles in the surroundings of the landing site. This can aggravate the problems which arise from a deterioration in the visibility and/or the weather. Thus, the reachability of small airports may be further degraded.

For removing the restrictions in the accessibility of airports, various means are feasible. One possibility is to provide the aircraft with an autonomous capability for landing approaches and take-off as well as for the movement on the ground. Thus, there would be no necessity to install ground-based landing aids at the airport.

An autonomous capability for landing and take-off requires an appropriate equipment on board of the aircraft so that the pilot can independently follow the approach trajectory as well as perform a landing and take-off. For this purpose, the pilot has to be furnished with adequate guidance aids. Such guidance aids can be provided by a display presenting command and status information in an appropriate manner. A display type achieving this objective is a predictor-tunnel display which shows guidance information in a 3-dimensional format, with a terrain image included in an integrated form. The guidance information comprises, as main constituents, the approach trajectory presented in the form of a tunnel and the aircraft position at an appropriately selected time ahead using a predictor. Thus, command and status information is available. The terrain image comprises the airport and its surroundings as well as other elements which are important for the flight task of the pilot.

Research on cockpit displays presenting information of the described kind shows that improvements in the guidance and control of aircraft are possible (Refs. 1-11). A promising concept features a predictor-tunnel display (e.g. Refs. 1-3, 10, 11). The improvements possible with this display type are due to the command and status information, including preview, provided for the pilot. A further issue is the pictorial and descriptive manner in which the guidance information is displayed. It enables an intuitive access, yielding a reduction of the mental effort for reconstructing the spatial and temporal situation.

This paper is concerned with aircraft-autonomous aids supporting the pilot, provided by a predictor-tunnel display presenting guidance information and a terrain imagery in a 3-dimensional, integrated format. The purpose is to show the potential of this display type for precise approach trajectory control, independent of ground-based support. A further issue is that current computer and navigation technologies offer a low-cost solution for predictor-tunnel displays, using Commercial-off-the-Shelf hardware. This is an important point in the present context because the addressed on-board guidance aids may thus become affordable for small aircraft operating on small to medium airports.

2 Concept of Aircraft-Autonomous Guidance Aids

The conceptual approach for providing aircraft-autonomous guidance aids is graphically presented in Fig. 1. This Fig. shows a tunnel which represents the approach trajectory to the landing site. The approach trajectory is presented to the pilot as the command flight path on a display in the cockpit. The form of the tunnel shown in Fig. 1 suggests that not only a straight flight path but also more complex approach trajectories are possible. Thus, curved and steep approaches can be performed. Such a possibility yields an enhancement in the flexibility of approach and landing operations. It may be particularly beneficial for airports in a difficult terrain environment, offering approach directions which are otherwise not feasible.

More details of the 3-dimensional display is given in Fig. 2 which shows the guidance information presented to the pilot. The displayed information comprises, as main elements, the command approach trajectory and the predictor symbol indicating the aircraft position at an appropriately selected time ahead as well as an image of the terrain.

The aircraft-autonomous guidance aids are intended to support the pilot in all three stages during approach and landing, yielding the following phases:

- Approach phase in the wide area of the airport
- Approach phase in the vicinity of the airport
- Runway landing phase

The displayed terrain image is constructed using a 3-dimensional data base which comprises digital elevation and surface models as well as graphical replications of obstacles (buildings, power lines, etc.). Data from various origins are applied, like CAD data, topographical data or aerial photographs. Different data sources are used for the generation of the terrain image, depending on the distance from the runway, Fig. 3.

3 Tunnel Construction

The tunnel presented in the 3-dimensional display (Fig. 2) shows the approach trajectory, thus providing the pilot with command information. For constructing the tunnel, various aspects are taken into account. The course of the command trajectory which can show lateral and vertical changes in the case of curved and steep approaches should be such that it is easy to fly and does not impair passenger comfort. Furthermore, the command trajectory has to comply with local and general rules or guidelines. An important point relates to safety which is of particular concern in a difficult terrain environment. This means that the distance between the command trajectory and the terrain is always greater than a specified safety margin. Another point relates to noise sensitive areas. An appropriate construction of the command trajectory offers the possibility to alleviate or avoid this kind of exposure.

The process of the tunnel generation is schematically shown in Fig. 4. As a starting basis, reference is made to waypoints which are connected by straight lines. A refinement of this basic trajectory is effected accounting for flight mechanics issues, e.g. by introducing a curved segment adequate for a turn in the case of a lateral flight path change. The result is a preliminary form of the tunnel in terms of its center line. This is subject to verification steps. Here, a check is performed using a terrain model in order to examine whether or not the tunnel comes too close to the surroundings. After passing all checks, the final tunnel version is available which will be used as a plug-in for the visualization software.

A detailed description is given in the following for a representative case, concerning the tunnel configuration which was generated for the approach trajectory to Bolzano airport (Italy) where flight tests are planned. This airport in the Alps is located in a mountainous area, thus yielding a demanding terrain environment.

The starting basis for the approach trajectory to Bolzano airport is presented in Fig. 5. The original waypoints are connected to each other using straight lines, yielding an initial form of the approach trajectory. The next step is concerned with modifications related to flight mechanics issues. This is demonstrated considering the refinement in the initial trajectory form for a lateral change. As shown in Fig. 6, every second point on a laterally changing trajectory segment will not be overflown but passed along the inside of the curve. For such trajectory parts, a curve segment is constructed such that it complies with flight mechanics considerations for performing a turn. Then, all trajectory elements can be combined, with waypoints shifted towards the respective curve segment (Fig. 7). The next refinement is concerned with the transition from straight to curved segments and vice versa at the beginning and end of a turn. For these parts of a curve, clothoid segments are used (Fig. 8). The objective is to make control easier with regard to the transition phases.

An important aspect in generating the tunnel is safety. This holds particularly for approaches in a difficult terrain environment. The issue is graphically illustrated in Fig. 9 which shows how the problem can be solved. A circle around the tunnel center with radius R is introduced as a safety margin. Thus, a tube or safety corridor is generated such that an intersection with the terrain can be avoided. In order to determine possible intersections with the terrain, appropriate terrain data are used, like a digital terrain or a digital surface model.

The final outcome of the tunnel generation process is the command approach trajectory. A graphical presentation is given in Fig. 10 which provides a perspective view on the tunnel and the ground track of the trajectory. It also gives an impression of how the trajectory fits in the mountainous terrain.

4 Predictor Control Law

An important constituent of the guidance information presented in the 3-dimensional display is the predictor (Fig. 2). The predictor can be considered to have the following functions:

1) Indicator of aircraft position
   The predictor indicates the position of the aircraft at an appropriately selected time ahead.
2) Element of control system
   The predictor is an element of a control system which consists of the pilot, the predictor and the aircraft.

Concerning the first function, a mathematical model is required for describing the continuation of the flight path in order to determine the predictor position at the prediction time ahead which is denoted by T_{PR}. The model which has been developed to meet predictor function 1 is graphically given in Fig. 11. It yields the following relation for the deviation of the predicted position from the command trajectory

$$\Delta h_{PR} = \Delta h - h_C^* + VT_{PR}\Delta\gamma + K_{\dot{\gamma}}\Delta\dot{\gamma} \qquad (1)$$

The deviation from the command trajectory is indicated in the 3-dimensional display as an error e_{PR} which can be expressed as

$$e_{PR}(s) = K_{PR}\left(\frac{K_{\dot{\gamma}}}{V}s^2 + T_{PR}s + 1\right)\Delta h(s) \qquad (2)$$

The second function of the predictor relates to manual control of the flight path, in terms of a closed-loop system consisting of the pilot, the predictor and the aircraft. For this function, pilot-centered requirements are relevant which result from the presence of the human operator in the control loop. The objective is to develop a predictor control law yielding a controlled element (predictor-aircraft system) which requires minimum pilot compensation. This objective can be achieved when the controlled element approximates a pure integration over an adequately broad region centered around the pilot-predictor-aircraft crossover. The described objective yields the following relation

$$Y_{PR}Y_C = \frac{K}{s} \qquad (3)$$

where Y_{PR} and Y_C are the transfer functions of the predictor and the aircraft, respectively.

The predictor control law developed for achieving the objective described by Eq. (3) can be expressed as

$$Y_{PR} = \frac{e_{PR}(s)}{\Delta h(s)} = K_{PR}\left(\frac{K_{\dot{\gamma}}}{V}s^2 + T_{PR}s + 1\right) \qquad (4)$$

With a proper selection of the prediction time, T_{PR}, and the gain in the $\dot{\gamma}$ pathway, $K_{\dot{\gamma}}$, the following expressions are obtained for the zeros of Eq. (4)

$$T_1 \approx T_{PR}$$
$$T_2 \approx \frac{K_{\dot{\gamma}}}{VT_{PR}} \qquad (5)$$

Using these expressions, the predictor relation given in Eq. (4) may be rewritten to yield

$$Y_{PR} = \frac{e_{PR}(s)}{\Delta h(s)} = K_{PR}\left(s - \frac{1}{T_1}\right)\left(s - \frac{1}{T_2}\right) \qquad (6)$$

5 Test Results

5.1 Simulation Test Facility

The described guidance aids are subject of an experimental program consisting of pilot-in-the-loop simulation tests. The simulation tests are performed using the research flight simulator of the Institute of Flight System Dynamics of the Technische Universität München, Fig. 13. This is a fixed-base flight simulator with a two-pilot cockpit. It provides programmable, wide cockpit-displays, side sticks for operating the aerodynamic pitch and roll control devices and pedals for the rudder. Furthermore, the flight simulator is equipped with a computer generated visual scene system featuring a spherical screen of 150 °. For the visual scene system, a high-performance visualization software is available which contributes to the realism of the simulation. The simulated vehicle for which a realistic and elaborate six-degree-of-freedom dynamics model is used is a modern regional class aircraft with two jet engines.

5.2 Simulation Test Results

Results from a simulation run are shown in Figs. 14 to 17. They can be regarded as representative for the achievable performance.

Results on the deviations from the command fight path are presented in Figs. 14 and 15. As a main result, the deviations from the tunnel center line are rather small. This holds for the lateral as well as for the vertical deviations. The aircraft stays within the boundaries of the tunnel the width of which is 35 m and the height 30 m. The fact that the deviations are small does not only hold for the straight parts of the command flight path, but also for those segments where changes in the approach trajectory take place.

In Fig. 16 and 17, the deviations of the predictor position from center of the reference cross section of the tunnel are shown. These deviations are also small, both in the lateral as well as in the vertical directions.

To sum up, the results presented in Figs 15 to 18 suggest that the goal of achieving a precise trajectory following has been achieved.

6 Project Consortium

The on-board guidance aid system has been realized by a consortium which comprises 12 institutions and industry companies from 6 European Countries, including an aircraft manufacturer, two universities and three airports. The members of the consortium are:

1) Epsilon GIS Technologies SA, Greece, – *Project Coordinator*, www.epsilon.gr, www.epsilon-eu.eu.
2) Aerolabs AG, Germany, www.aerolabs.de.
3) Aeroservices SA, Greece, www.aeroservices.gr.
4) Airport Authority Lugano, Switzerland, www.lugano-airport.ch.
5) Aschenbrenner Elektronik GmbH, Germany, www.aschenbrenner-elektronik.de.
6) Delft University of Technology, The Netherlands, www.tudelft.nl.
7) Diamond Aircraft Industries SA, Austria, www.diamond-air.at.
8) ESRI GeoInformatik GmbH, Germany, www.esri-germany.de.
9) IABG mbH, Deutschland, www.iabg.org.
10) Institute of Flight System Dynamics, Technische Universität München, Germany, www.fsd.mw.tum.de.
11) Airport Authority of Bolzano, Italy.
12) TopoSys GmbH, Germany, www.toposys.de.

7 Conclusions

Guidance information displayed to the pilot in a 3-dimensional format is considered an aircraft-autonomous aid to enhance the accessibility of small-medium airports, particularly in low visibility, adverse weather and in a difficult terrain environment. The guidance information comprises a terrain image as well as the command flight path and a predictor for indicating the aircraft position. With reference to pilot-centered requirements, an appropriate control law is developed for the predictor. The terrain image presented in the display shows all pictorial elements important for the pilot. The construction of the command flight path presented in the 3-dimensional guidance display accounts for various aspects. An objective in constructing the command approach trajectory which can show lateral and vertical changes is that it is easy to fly and does not impair passenger comfort. Furthermore, the command flight path complies with local and general rules or guidelines. An important aspect is safety which is of particular concern for a difficult terrain environment.

References

[1] Theunissen, E. Integrated Design of a Man-Machine Interface for 4-D Navigation. PhD Dissertation, TU Delft, The Netherlands, 1997.

[2] Grunwald, A.J. Improved Tunnel Display for Curved Trajectory Following: Control Considerations. Journal of Guidance, Control, and Dynamics, 1996, Vol. 19, No. 2, pp. 370-377.

[3] Grunwald, A.J. Improved Tunnel Display for Curved Trajectory Following: Experimental Evaluation. Journal of Guidance, Control, and Dynamics, 1996, Vol. 19, No. 2, pp. 378-384.

[4] Haskell, I.D. and Wickens, C.D. Two- and Three-Dimensional Displays for Aviation: A Theoretical and Empirical Comparison. The International Journal of Aviation Psychology, 1993, 3(2), pp. 87-109.

[5] Helmetag, A., Mayer, U. and Kaufhold, R. Improvement of Perception and Cognition in Spatial Synthetic Environment. Proceedings of the 17th European Annual Conference on Human Decision Making and Manual Control, 1998, pp. 207-214.

[6] Lenhart, P.M., Purpus, M. and von Viehbahn, H. Flugerprobung von Cockpitdisplays mit synthetischer Aussensichtdarstellung. DGLR-JT98-060, 1998.

[7] Funabiki, K., Muraoka, K., Terui, Y., Harigae, M. and Ono, T. In-Flight Evaluation of Tunnel-in-the Sky Display and Curved Approach Pattern. AIAA Guidance, Navigation, and Control Conference Proceedings, 1999, pp. 108-114.

[8] Lam, T.M., Mulder, M., van Paassen, M.M. and Mulder, J.A. Comparison of Control and Display Augmentation for Perspective Flight-Path Displays. Journal of Guidance, Control, and Dynamics, 2006, Vol. 29, No. 3, pp. 564-578.

[9] Sachs, G. and Möller, H. Synthetic Vision Flight Tests for Precision Approach and Landing. AIAA

Guidance, Navigation and Control Conference Proceedings, 1995, pp. 1459-1466.

[10] Sachs, G., Dobler, K. and Theunissen, E. Pilot-Vehicle Control Issues for Predictive Flightpath Displays. AIAA Guidance, Navigation, and Control Conference Proceedings, 1999, pp. 574-582.

[11] Sachs, G. and Dobler, K. Perspective Predictor/Flight-Path Display for Longitudinal Manual Control Improvement. Journal of Guidance, Control, and Dynamics, 2002, Vol. 25, No. 3, pp. 494-501.

Copyright Statement

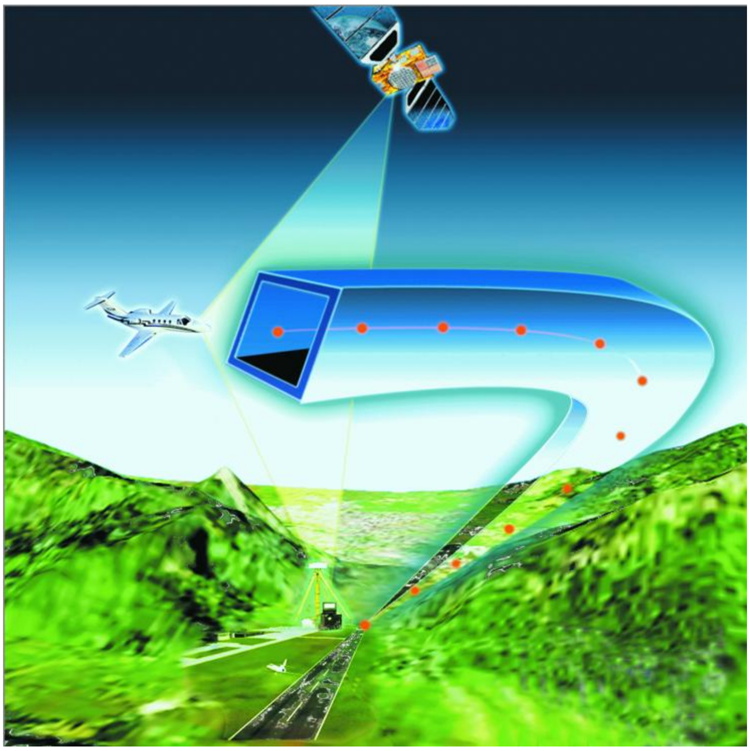

Fig. 1 Concept of aircraft-autonomous guidance aids

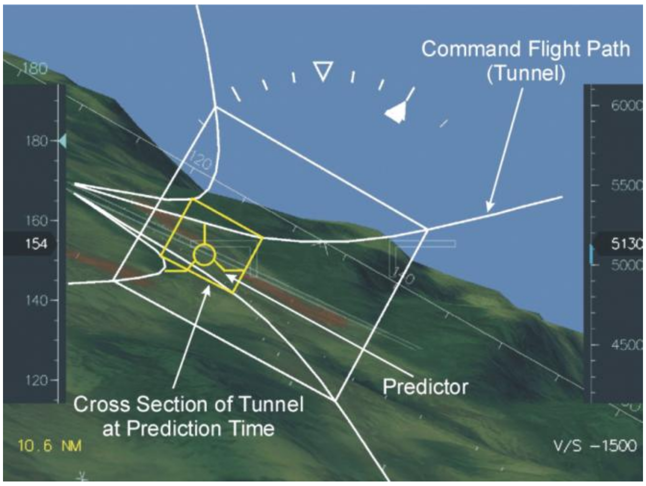

Fig. 2 Display presenting guidance information in 3-dimensional format

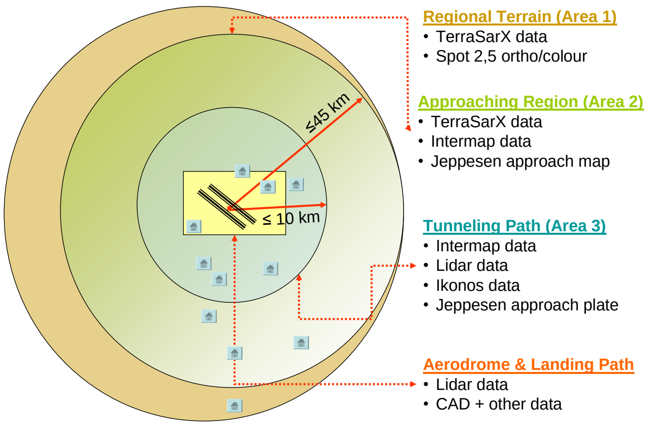

Fig. 3 GIS data sources used for areas with different distances to airport

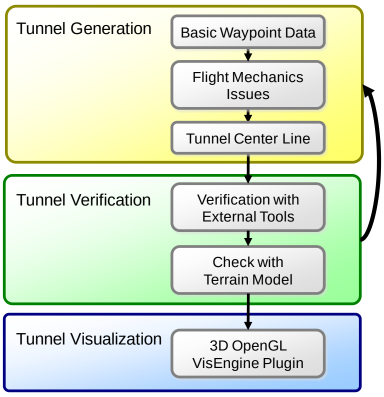

Fig. 4 Tunnel generation process

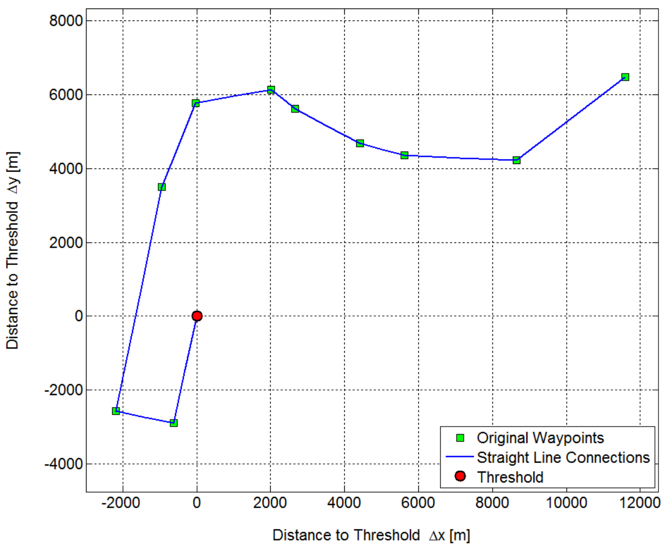

Fig. 5 Basic flight path with original waypoints connected by straight lines

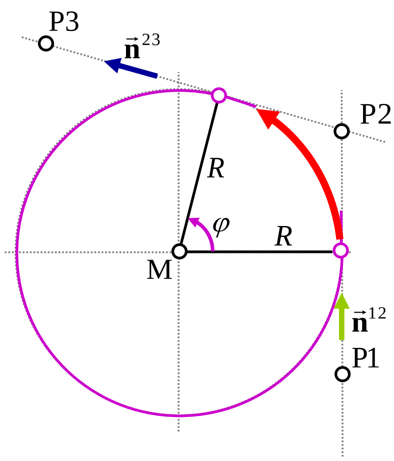

Fig. 6 Lateral change in approach trajectory

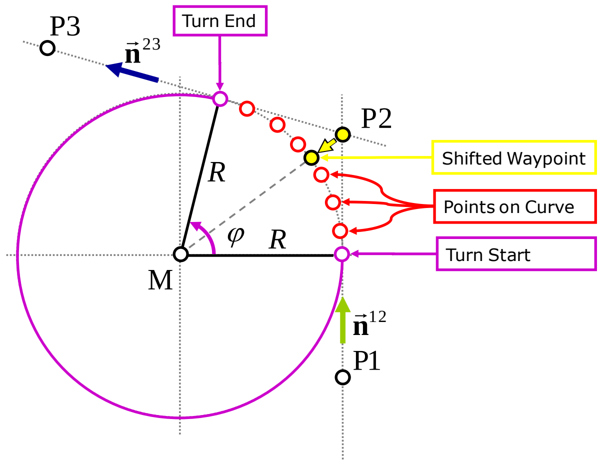

Fig. 7 Curved trajectory segment with shifted waypoint

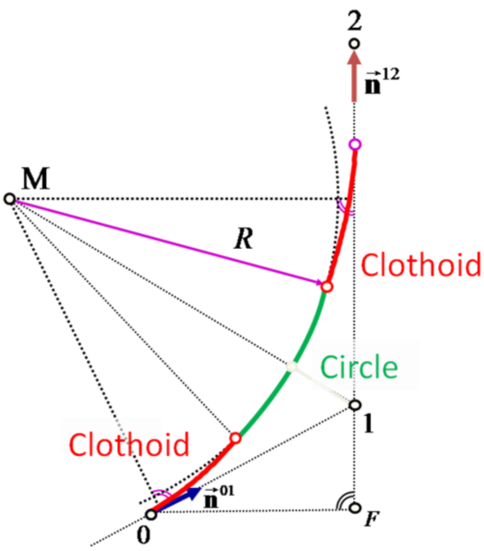

Fig. 8 Clothoid segments at beginning and end of a curve

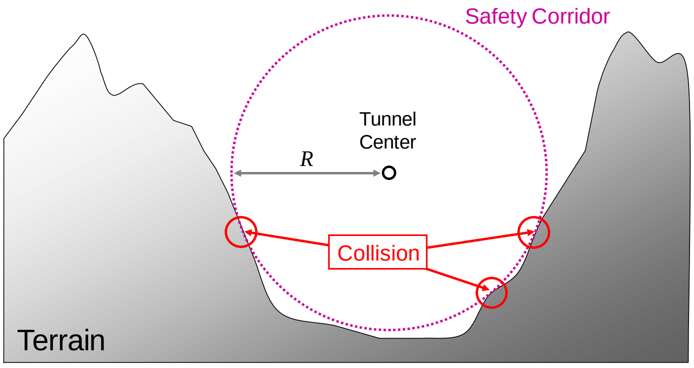

Fig. 9 Safety corridor

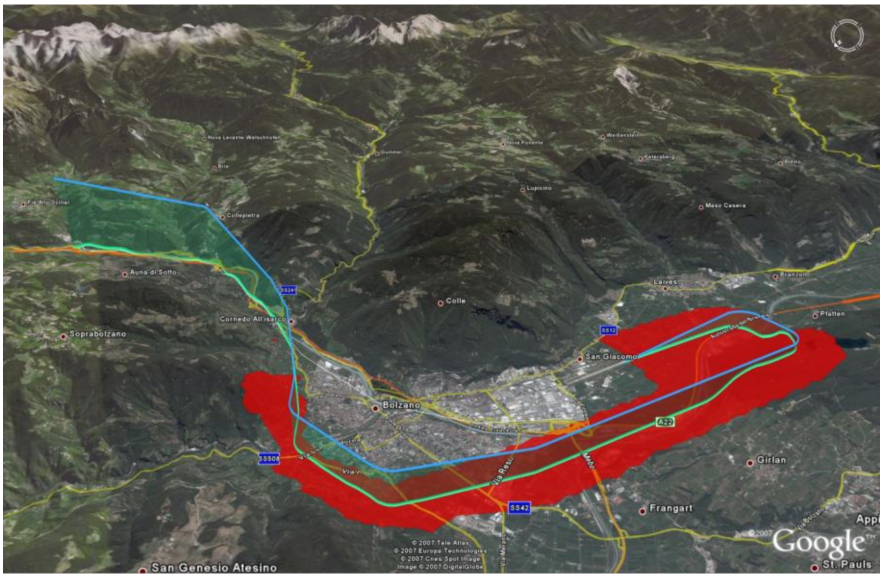

Fig. 10 Tunnel and ground track of approach trajectory to Bolzano airport

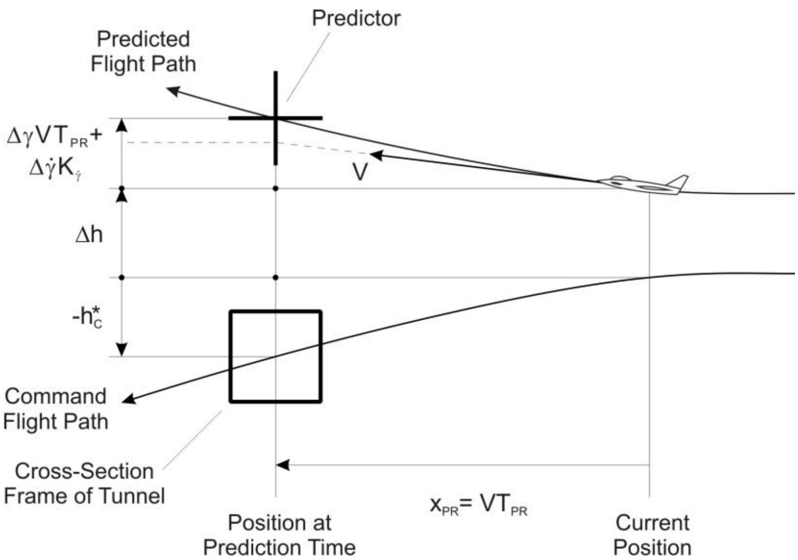

Fig. 11 Predictor and longitudinal flight path continuation

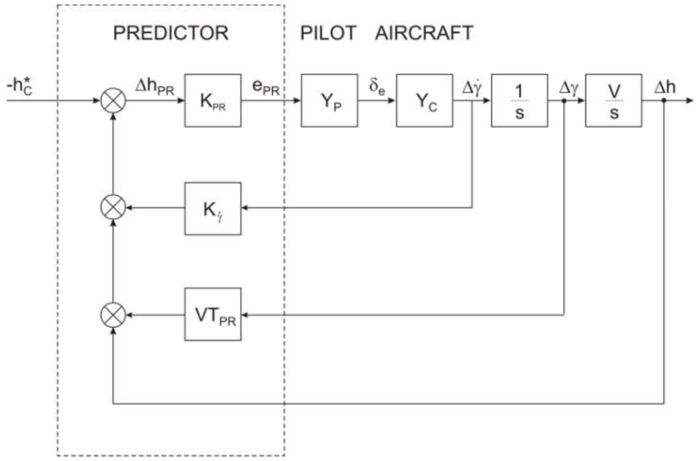

Fig. 12 Block diagram for longitudinal predictor

Fig. 13 Flight simulator of the Institute of Flight System Dynamics
of the Technische Universität München

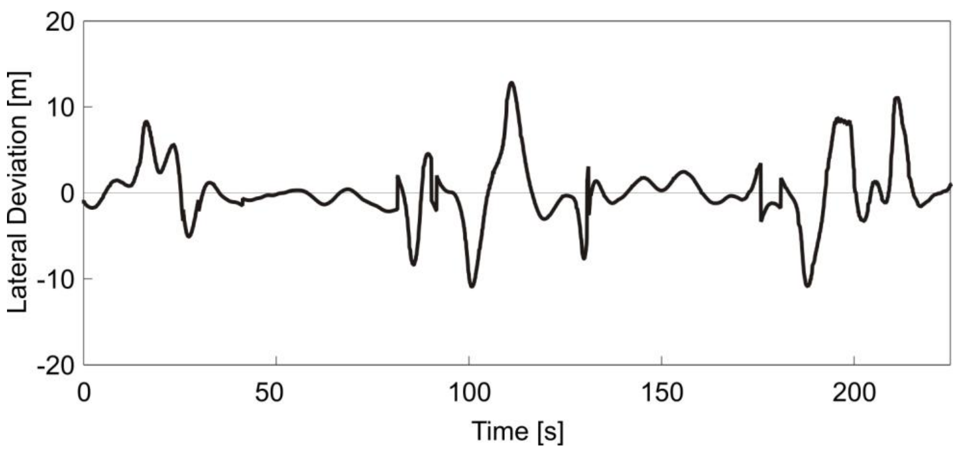

Fig. 14 Lateral deviation from command flight path

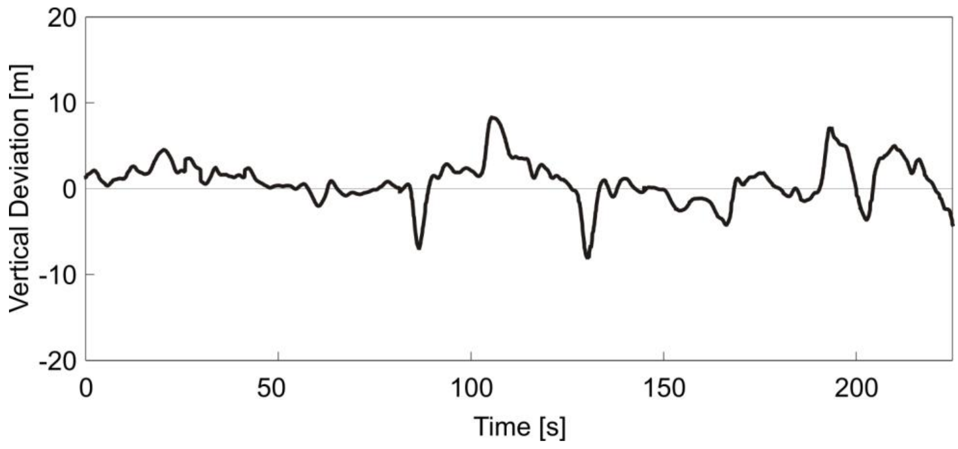

Fig. 15 Vertical deviation from command flight path

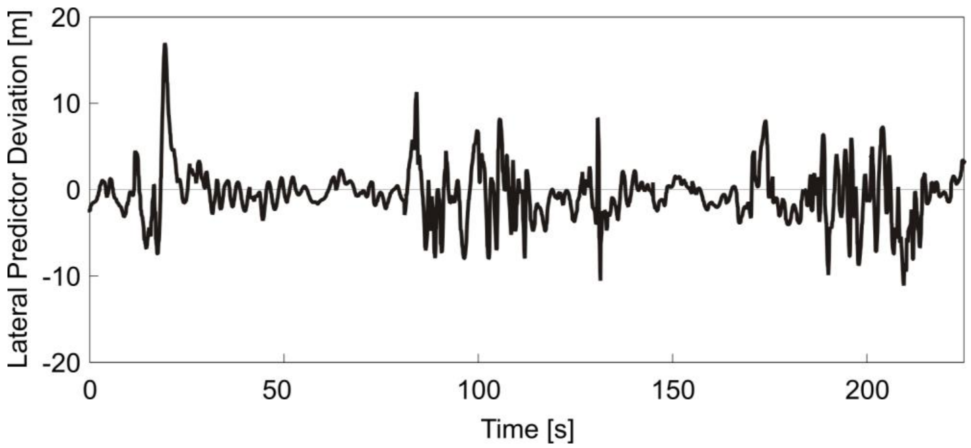

Fig. 16 Lateral predictor deviation from command flight path

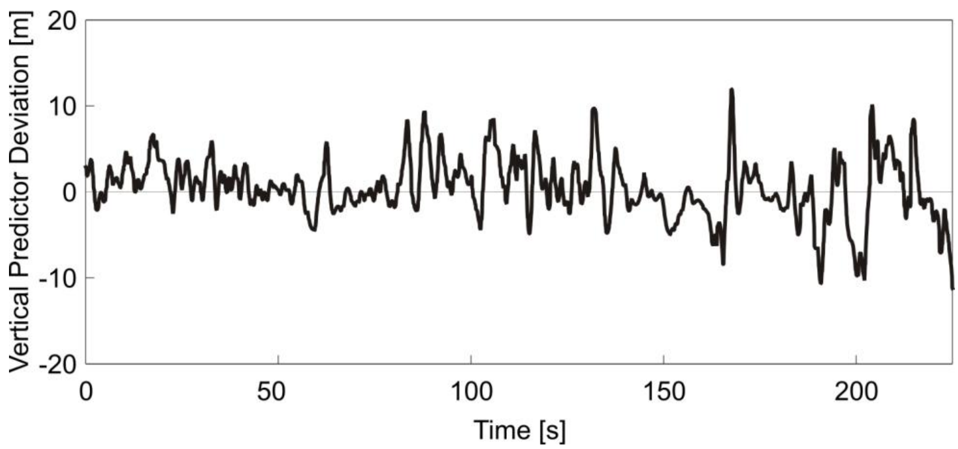

Fig. 17 Vertical predictor deviation from command flight path