INTEGRATED DESIGN OF A PILOT VEHICLE INTERFACE FOR 4-D GUIDANCE AND NAVIGATION: FROM CONCEPT TO IN-FLIGHT DEMONSTRATION

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Abstract. To efficiently utilize the flexibility in data presentation offered by today's programmable display systems, an integrated approach to the design of the Man-Machine Interface is required, necessitating a seamless fusion of knowledge from the different disciplines involved in the design process. This paper describes the development of the DELPHINS Tunnel-in-the-Sky display, and shows how an integrated approach has been applied to answer many of the design questions.

Keywords. Integrated design, perspective displays, guidance, navigation, man-machine interface

1. INTRODUCTION

The introduction of digital datalinks between aircraft and Air Traffic Control (ATC) and the advent of highly accurate positioning systems, offers the possibility to increase airspace capacity by decreasing separations between aircraft. By using flexible curved approach procedures, ATC has more freedom in managing the traffic flow, resulting in a better utilization of airway and runway capacity. The resulting increase in requirements on position and velocity control of the aircraft and the fact that approach paths may contain curved segments, will certainly increase the pilot's workload and reduce his ability to maintain an adequate level of spatial and navigational awareness. This can be compensated for by providing the required data in such a way that the effort for interpretation, integration, and evaluation is reduced.

Conventional guidance displays employ a very simple presentation, e.g. a moving bar indicating a deviation to be zeroed. The design of algorithms driving the guidance display is a typical control engineering problem. The introduction of programmable display systems on the flightdeck offers almost unlimited flexibility in the presentation of guidance and navigation data, and as a result the possibility to improve the information transfer is available.

The development of advanced display formats requires consideration of perceptual and cognitive aspects. Due to the interdependency of requirements and constraints from the different disciplines involved, and the fact that margins exist, trade-offs are possible. The efficiency of the design process is largely determined by the ability to mediate requirements and constraints between the different disciplines, while the quality of the final product is significantly influenced by the trade-offs which have been made to satisfy the requirements within the constraints. As a result, it is very important that the consequences of trade-offs are clear for all disciplines involved in the design process. An approach is needed which allows potential concepts to be qualitatively evaluated against certain predefined criteria with respect to possibilities for interpretation, integration, and evaluation of the presented data.

In 1990 the Delft Program for Hybridized Instrumentation and Navigation Systems (DELPHINS) was initiated at the department of Telecommunication and Traffic Control Systems of the Faculty of Electrical Engineering. In the context of DELPHINS, research is performed into presentation methods for guidance and navigation data to improve the information transfer from machine to man. An example of a potential display concept for four-dimensional (4-D) navigation and guidance is the DELPHINS Tunnel-in-the-Sky display, which is characterized by a perspective presentation of the future flightpath.

This paper describes the design of perspective flightpath displays for aircraft guidance and navigation in a control-theoretical, cognitive, and perceptual context, while taking into account current and expected future technical possibilities and limitations.

2. GUIDANCE AND NAVIGATION

Navigation can be defined as "to direct and control the course of an aircraft". To fulfil the navigation task, guidance is required. This comprises control of elevator, aileron, rudder, and thrust. It can be performed manually, or automatically. In the latter case, since humans possess invaluable qualities in coping with unpredictable situations, the pilot functions as a supervisor. His role is to compensate for the limited flexibility and adaptability of automated systems in the event of an unforeseen circumstance for which the system was not designed. To exploit the flexibility and adaptability of the human operator, the system must be designed so that the pilot is able to quickly detect anomalies and to safely and rapidly take over full control of the aircraft. For the safe execution of the guidance and navigation task, it is important that the pilot is able to determine the relation between his Ego-centered Reference Frame (ERF) and the World Reference Frame (WRF), thus establishing an adequate level of spatial awareness. Furthermore, in order to be able to anticipate changes, it is important that the pilot is able to predict the future required ERF-WRF relation, which is determined by his navigational awareness.

The Navigation Error (NE) of an aircraft consists of a Positioning Error (PE) and a Flight Technical Error (FTE). The PE is the difference between the true position of the aircraft and the position reported by the positioning system. The FTE represents the difference between the desired position of the aircraft and the position reported by the positioning system. The pilot is only aware of the FTE, and a change in PE will be perceived as a change in FTE.

Today's aircraft displays mostly employ singular and sometimes dual dimensional data presentation methods for guidance and navigation data. The integration of the data which is required to obtain spatial and navigational awareness has to be performed by the pilot. This process involves mental rotation and scaling operations, which costs time and may introduce errors. With one-dimensional (1-D) and two-dimensional (2-D) guidance and navigation displays, position and orientation data is either presented separately, or combined into one parameter. The Navigation Display (ND) presents a plan view of the flightpath relative to the aircraft position (Figure 1).

As a result, it contains 2-D (lateral) position information, and 1-D orientation information (heading). Depending on the mode, a WRF (North Up) or an ERF is used (Track or Heading up). The Attitude Indicator (AI) presents the pitch and bank of the aircraft relative to a depiction of the horizon. In general a so-called inside-out frame-of-reference is used (fixed airplane symbol against a moving horizon), although Russian aircraft employ a hybrid solution, in which the aircraft symbol rolls but is fixed in the vertical direction, and the artificial horizon translates in the vertical direction to convey pitch information. By allowing the aircraft symbol to roll against a fixed background, the principle of control display motion compatibility (Johnson and Roscoe, 1972) is satisfied. The altimeter presents 1-D position information, and can also be used to indicate the desired altitude. The glideslope and localizer indicators present 1-D position error information, while a flight director presents guidance commands. Figure 2 presents an example of a conventional guidance display.

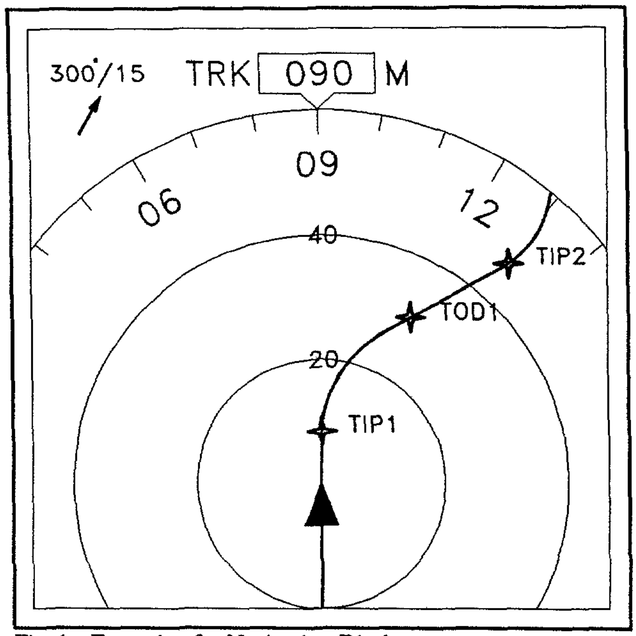

Fig. 1. Example of a Navigation Display

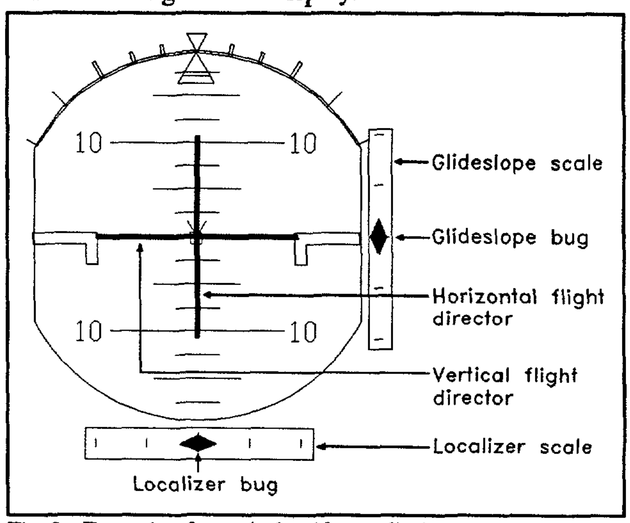

Fig. 2. Example of a typical guidance display

By integrating the information conveyed by the ND, the AI, and the altimeter the pilot is able to obtain a certain level of spatial and navigational awareness. Conventional flight directors are based on a weighted combination of position- and angular errors. In the horizontal dimension, Cross-Track Error (XTE) and Track-Angle Error (TAE) are used to calculate the deflection of the vertical flight director bar. In the vertical dimension, Flight path Angle Error (FPAE) and Vertical Error (VE) are used to calculate the deflection of the horizontal flight director bar. As a result of the integration of multiple parameters into a single dimension, the pilot is unable to extract information about the specific errors from the flight director display. Furthermore, since the error gains of the display are determined by the flight director algorithms, the possible bandwidth the pilot can apply for scanning and executing the flight director commands is rather limited. In situations where the required performance is less than the performance for which the gains have been determined, the pilot is forced to maintain the higher gain, and the possibility to neglect errors for a certain time is very limited. Finally, the flight director does not present the pilot with preview on the future desired trajectory which is required for anticipatory control. The ND presents the pilot with trajectory preview in the horizontal dimension, required for lateral navigational awareness. However, the resolution of this data is too low to be useful for anticipatory control. As a result, the pilot is forced to apply a continuous compensatory control strategy.

3. DESIGN QUESTIONS

The goal of the design process is to optimize the information transfer from machine to man. One of the most effective mechanisms for the simplification of complex visual scenes is the human perceptual system (Garner, 1970). This simplification mechanism is developed in humans through years of repeated confrontation with the rules of perspective scenes. With this system, the human is capable of rapid interpretation of otherwise complex visual scenes. To capture this simplification capability in man-machine systems requires the use of pictorially realistic information presentation (Jensen, 1978)
The advancements in the area of computer graphics make it technically and economically feasible to present an abstract, dimensionally and dynamically compatible analogy of the spatial environment in real-time. Such Computer Generated Imagery (CGI) can be used to emphasize important features in the outside world scene, de-emphasize or eliminate unimportant features, and introduce artificial cues.
To reduce the required effort for interpretation and evaluation, emergent features can be used to exploit certain cognitive abilities which are involved in the early stages of perceptual processing. The Proximity Compatibility Principle (PCP) predicts that tasks requiring the integration of information across sources benefit from more integrated displays (Wickens and Andre, 1990). By presenting the data so that the presentation is compatible with the user's expectation, semantic distance can be minimized (Norman, 1989). The spatial presentation of the imaginary flightpath in the 3-D environment can be used to alleviate the pilot from performing the mental integrations of the separately displayed position and orientation data into a spatially coherent picture.
For the design of a 3-D guidance and navigation displays, questions regarding the contents and representation of the real-world analog must be answered. The following first three questions address the contents, while the latter six address the representation.

- How to determine which objects in the visual environment contribute, and should be emphasized, and which objects mainly cause clutter?
- When to employ representations of imaginary elements?
- How to determine whether and when additional data presentation is necessary?
- How can the objects be represented and to what abstraction level can the representation be reduced?
- How to emphasize important objects?
- How to employ representations of imaginary elements?
- How to integrate additional data into the presentation?
- How to select the perspective design parameters and the frame of reference?
- How to select the presentation medium?

For the implementation and the integration in a target environment the following additional questions must be addressed:

- What are the system performance requirements in terms of memory, speed, and display resolution?
- What data is required?
- What are the requirements with respect to data latency, update-rate, accuracy, noise?

Addressing these questions requires a more detailed analysis of the specific properties of spatial data presentation in relation to the anticipated tasks to be performed. Such an analysis also allows the comparison with findings from other studies related to a specific aspect. Important questions which must be addressed are:

- What are the specific properties of spatially integrated environment and trajectory presentation, and what are the similarities and fundamental differences with 1-D and 2-D datapresentation?
- What are the consequences/possibilities of spatially integrated data presentation with respect to perception, interpretation, evaluation, and action?
- What are the consequences of a mismatch between the presented and perceived virtual space?
- What is the influence of data latency, limited update-rate, limited accuracy, noise?
- What is the influence of non-ideal operating conditions like turbulence, crosswind?
- What are the specific advantages and disadvantages of spatially integrated datapresentation?
- What are possibilities to compensate for deficiencies, limitations and disadvantages?

4. DESIGN

A perspective flightpath displays presents a spatially integrated view of the future 3-D trajectory on a 2-D display (Figure 3).

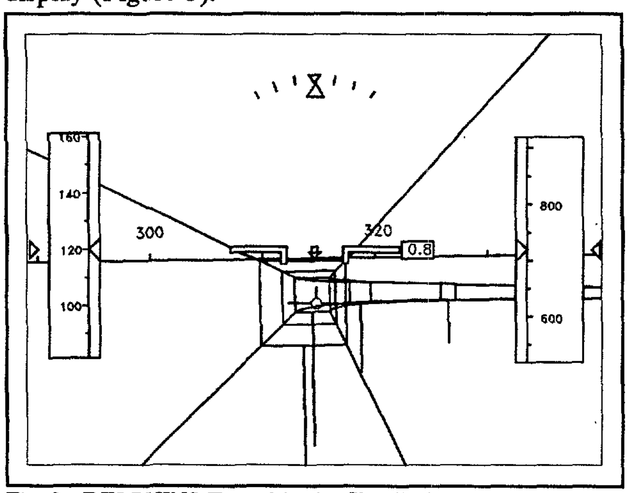

Fig. 3. DELPHINS Tunnel-in-the-Sky display

4.1. *Frame of reference*

Based on the frame of reference used for the projection, these displays can be divided into egocentric and exocentric ones. In an egocentric perspective flightpath display, the 3-D world is depicted as seen from the aircraft. In an exocentric display, the situation is viewed from another position. With an egocentric perspective projection, information about position and orientation errors is conveyed through a distortion of the natural symmetry of the presented trajectory. Since the detection of symmetry takes place in the early processing cycles of visual information, this feature can be exploited to reduce the required effort for interpretation and evaluation. Any other frame-of-reference than an ego-centered one cannot exploit this advantage, and will require additional mental processing. Therefore, an egocentric projection was selected.

4.2. *Design parameters*

Position and orientation errors distort the symmetry of the representation of the tunnel. It is the distortion of the symmetry that is perceived, and not separate position or orientation errors. Theunissen (1994b) describes the relation between the distortion of the symmetry and the position and orientation errors as a function of the design parameters of the perspective display.
The motion of the aircraft relative to the virtual tunnel allows the extraction of error rates and produces additional cues which are conveyed through the presentation of successive snapshot images of the situation. In Theunissen and Mulder (1995a) it is discussed how data about position errors, and rotation rates are present in the visual flow field. These dynamic cues give the pilot a sense of egospeed. Besides a cue for egospeed, pilots can extract temporal range information from the display. Temporal range judgements are based on global optical flow rate, which must exceed a certain threshold to allow accurate estimates to be made. Temporal range information is often used to determine the moment to initiate certain anticipatory control actions. Theunissen and Mulder (1994, 1995a) studied the relation between the moment an error-correcting control action is initiated and temporal range information in a perspective flightpath display. In Theunissen and Mulder (1995b), some requirements on the design parameters to generate adequate temporal range cues are discussed.

4.3. *Representation of the flightpath*

Just as with real-world objects, the meaning of an imaginary element should be intuitively apparent from the representation. Since the real-world 2-D counterpart of a 3-D trajectory is a road, the desired flightpath is often visualized as a 3-D road. Various representations have been tried in the past, resulting in designations such as Flightpath Channel (Wilckens and Schattenmann, 1968), Pathway-in-the-Sky (Hoover *et al.*, 1983) and Tunnel-in-the-Sky (Grunwald, 1984). In Theunissen (1994b), the representation of a flightpath is divided into a flightpath element, cross sections, and altitude poles based on the following three different functions:

- provide position and orientation information
- resolve ambiguities in the trajectory
- resolve ambiguities towards other objects

Position and orientation errors are provided by all elements of the flightpath. The ambiguity within the representation is resolved through the presentation of cross-section frames, which in combination with the observers expectation about the shape of the object provide a cue for resolving ambiguities. As a result of the apparent motion of the cross-section frames towards the observer, and the resulting optic flow field, the feeling of three-dimensionality increases, and ambiguities are further reduced. The ambiguity towards other objects, notably the ground, is resolved through the presentation of altitude poles. The altitude poles also provide a possibility to temporarily use a very high lateral error gain, which will be discussed later.
Various representations of the flightpath have been tried in the past. It must be realized that especially in the early period of research into perspective flightpath displays, the representation was dictated by the limitations of the available means to generate perspective images in real-time. Wilckens and Schattenmann (1968) used dots to indicate the corners of cross-section frames in his 'channel display'. Hoover *et al.* (1983) represented their 'pathway-in-the-sky' by means of tiles. Jensen (1978) used 'telephone poles' to visualize the desired trajectory. None of these formats did employ a continuous presentation of the flightpath, i.e. no interconnections existed between the references. In the absence of such interconnections, the error gains in the display are determined by the positions of these trajectory frames. Grunwald (1984) and Wickens *et al.* (1989a) both used interconnections, yielding a continuous presentation of the desired trajectory, and as a result of the error gains. As discussed previously, the height and width of the tunnel determine the position-error gain. Sometimes, it is desirable to also have a source of a very high position error gain which can be used for temporal fine-tuning. Reducing the tunnel size to obtain this high gain would force the pilot to continuously apply a high control gain, which reduces the flexibility. This problem can be solved by presenting references indicating the center of the tunnel sections. In this way, horizontal and vertical error gain can be used separately. In fact, the altitude poles already provide such information for lateral control. During experiments performed in the flight simulator of the Delft University of Technology, pilots mentioned that in the final approach they used the alignment of these poles for accurately positioning the aircraft on the centerline. An alternative might be to present a diamond shaped cross-section. This, however, introduces a number of drawbacks of which the discussion goes beyond the scope of this paper.

4.4. *Identification of objects to be presented*

The identification of objects which are to be displayed requires a method to identify which objects in the visual environment contribute to the tasks to be performed, and which objects mainly cause clutter. With respect to the guidance and navigation task, objects which function as an important reference for spatial orientation and/or navigation in the 3-D world are considered relevant. Examples are objects with a known geographical location, and objects with a familiar shape and/or size, allowing the observer to estimate his relative position. With respect to collision avoidance, the presentation of objects which might constitute a potential hazard is desired. The two most important objects of the latter category are terrain and other aircraft. An imaginary element is the position predictor, which depicts the future estimated position of the aircraft.

4.5. *Presentation of objects*

For the presentation of objects, the question regarding the level of detail of the representation must be addressed. In this context, the highest level of detail is considered a representation which is visually indistinguishable from the real-world analogy. Besides the fact that this would be a computational extremely expensive operation, in most cases such a high level of detail is likely to result in clutter, and hence not desirable. Thus, the question is: 'to what abstraction level can the object representation be reduced?'. However, the question is not complete yet, since an important constraint regarding the required effort for interpretation must still be specified. This constraint is formulated as: 'the real-world objects must be intuitively recognized from the abstract representation'. With the current version of the display, terrain is depicted as a 3-D mesh, in which the height of each point is determined by the maximum altitude within a predefined range. Color coding is used as an additional means to convey terrain altitude. Other traffic is presented as aircraft symbols, similar to the symbology used by Ellis *et al.* (1987) in their perspective Cockpit Display of Traffic Information (CDTI) studies. In certain situations it might be necessary for the pilot to focus his attention on a specific object, for example in case the object poses a potential hazard. Attributes such as color, intensity, blinking, and magnification can be used to emphasize such an object. Since the attention of the pilot is influenced by his expectations and motivation, features must be used that are strong enough to attract his attention regardless of a certain bias. With the current display format, two types of objects, representing two different types of threats (terrain and other aircraft), can be emphasized by a change in color and by blinking. To exploit the common population stereotype of red for danger, terrain which is below the aircraft altitude and aircraft which constitute a potential collision hazard are colored red. When the time to collision reaches a certain minimum threshold, the representation of the corresponding object(s) starts to blink. To present the future predicted position of the aircraft to the pilot, an abstract presentation of an aircraft is used. Position ambiguity is resolved by presenting the imaginary cross-section of the tunnel at the future position of the aircraft. This cross-section is transparently highlighted, which in turn avoids occlusion of other objects.

4.6. *Disadvantages and compensations*

A spatially integrated presentation is only beneficent when integration of information from the three spatial dimensions is required. With 1-D and 2-D datapresentation methods it is possible to use a constant scaling for the depiction of the desired data. With 3-D displays the accuracy with which a singular parameter can be determined is often a function of position, orientation, and velocity of the viewpoint. 3-D displays suffer several other limitations which must be taken into account. As a result of the integration of the third dimension, the resolution of the information along the viewing axis decreases with increasing distance from the viewpoint. Furthermore, due to the integration of multiple parameters into a single object, it is often harder to estimate the value of a parameter in a single dimension (Wickens *et al.*, 1989b). Also, angular distortion occurs, which makes it very hard to estimate angles in planes which are not perpendicular to the viewing direction (McGreevy and Ellis, 1986), and finally objects which are close to the observer might mask objects which are further away.
From the previous discussion, two drawbacks of perspectively projected spatially integrated data can be identified which might need to be compensated for: the lack of an angular reference in curved sections, and the reduced accuracy with which single spatial parameters can be estimated. The former problem can be compensated for by presenting a position or track prediction relative to the desired track. The latter problem, resulting from the perspective projection, can partly be compensated for by integrating virtual metrical aids, or by separately presenting the required data. The warping of virtual metrical references is equal to the warping of the other data, which reduces the errors resulting from this distortion.

4.7. *Integration of additional data*

As indicated in Section 4.6, a disadvantage of perspective data presentation is that the integration makes it harder to estimate singular parameters, and the fact that the accuracy is determined by the position, orientation, and velocity of the viewpoint. By analysing the information which is required for the tasks to be performed with respect to accuracy, and comparing this with the way this information is conveyed through the perspective presentation, assumptions can be made about the necessity of additional information. Examples are the presentation of airspeed, roll angle, and altitude. To maximize spatial and representational consistency with current displays, the additional data about altitude, airspeed, and roll angle is integrated in a way which is equivalent both in location and representation with today's PFD.

4.8. *Dealing with constraints*

A major difference between command displays such as the flight director, and perspective flightpath displays such as the Tunnel-in-the-Sky, is that the former is based on the presentation of a weighted sum of position and angular errors and error rates, whereas the latter presents an abstraction of the real world, and thus is based on position and attitude. To avoid information conflicts, visual stimuli obtained through the perspective flightpath display must be compatible with visual stimuli from the outside world and the motion cues obtained through the vestibular system. In order for the pilot to believe the flight director, the commands must have a certain degree of consistency with the other information available. The fact that a flight director command is not required to have a one-to-one relation with any other perceivable cue, allows for certain differences in the update-rate of the required data. The data which is required for the closure of the inner control loop (attitude) has to satisfy more

stringent requirements with respect to latency and update-rate as compared to the data required for the closure of the outer loop (position) (Hess, 1987). With a perspective flightpath display, the information is not combined into a single parameter. As a result, both position and attitude data must satisfy update-rate requirements which yield a smoothly animated display.
To achieve such a smoothly animated display, the data update-rate must exceed a certain threshold. Update-rates in the order of 20 to 30 Hz prove to be adequate. As a result of the limited bandwidth of the carrier tracking loop in GPS receivers (typically about 16 Hz), these receivers output position data at an update-rate below that required for smooth animation. In case it is impossible to oversample the position data, inter- or extrapolation techniques are needed to increase the position information update-rate. Interpolation introduces latency, which reduces the stability of the control loop due to a decrease in phase-margin. Thus, interpolation is only acceptable in case the position update-rate is sufficiently high. With extrapolation, the prediction, which is based on position data and models which use other elements of the state vector such as velocity, attitude, and heading is inevitably accompanied by a prediction error which is corrected at each new position update. These corrections, however, can be perceived as a sudden change in FTE, and introduce a noise component in the optical flow field with the same frequency as the position information update-rate, which can become very distracting. Therefore, the prediction algorithm must apply some form of error smoothing to avoid a distortion of the dynamic cues. An in-depth discussion of position prediction techniques is beyond the scope of the paper, however, more information about position prediction can be found in Mulder (1992). For the in-flight testing of the Tunnel-in-the-Sky display, a Kalman predictor with a circular-path message model was used.

5. RESULTS

In 1990, an initial concept for a perspective flightpath display was specified in the context of DELPHINS. In parallel, based on the anticipated system requirements, development of a display design system and target hardware for simulator and in-flight evaluation commenced (Theunissen 1994a). A first laboratory concept demonstration was given in the beginning of '91, and at the end of '91 the flight simulator at the Faculty of Aerospace Engineering was equipped with a programmable display system developed in the context of DELPHINS. Display format evaluations were performed in '91 and '92, and in '93 a study was performed into pilot closed-loop control behaviour (Theunissen, 1993). In 1994, open-loop control strategies were investigated (Theunissen and Mulder, 1994a). Furthermore, a concept for the integration of terrain and traffic information was developed and implemented. An in-flight concept demonstration with the laboratory aircraft of Delft University followed in december '94 (Theunissen, 1995). For this purpose, an airborne version of the display system and a simple experimental Flight Management System (XFMS) have been developed. The system is based on commercial of-the-shelf components. Position data is obtained from a GPS receiver, and through a datalink with a ground reference station, DGPS corrections are obtained, resulting in sub-meter accuracy. A simple XFMS and a database with the runway coordinates and the ILS approach path is used for the generation of the required trajectories. From the data of the XFMS and the actual position and attitude of the aircraft, the Display Electronics Unit (DEU) generates the perspective flightpath, which is presented on the Display Unit (DU). To execute a curved approach procedure, ATC vectors the aircraft towards an arbitrary point on the ILS path. The XFMS calculates a route from the current position of the aircraft to this point, and the DEU generates a perspective flightpath (Figure 4), allowing a smooth intercept of the final straight segment.

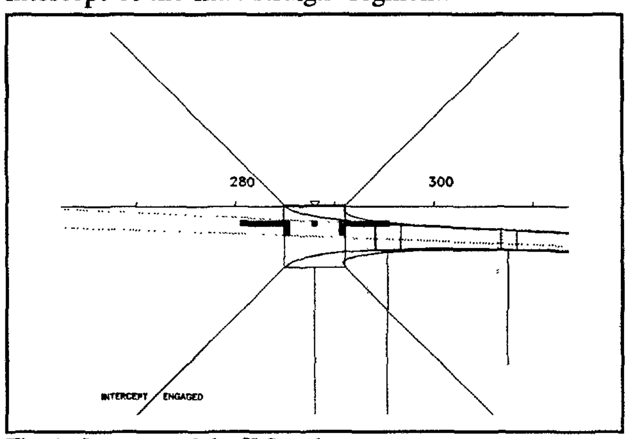

Fig. 4. Intercept of the ILS path

The radius of the curvature between the intercept segment and the ILS segment is determined by aircraft velocity and the desired bank angle.

6. CONCLUSION

As indicated in the introduction, the large degree of freedom resulting from the flexibility in data presentation with programmable displays poses the designer with new problems. An example is the design of a perspective flightpath display, which requires the specification of numerous parameters. An approach was needed which allows some kind of qualification of potential concepts with respect to the different domains involved in the design process. By means of a structured analysis of the specific properties of perspectively projected spatially integrated data, and by identifying the strengths and weaknesses, it is possible to:

- reduce the large number of degrees of freedom in the design,
- compare the possibilities with respect to interpretation, evaluation and action with conventional presentation methods,
- allow trade-offs to be made,
- compensate for deficiencies,
- define system requirements,
- justify design decisions.

The result of such an integrated approach is more than the sum of its parts.

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