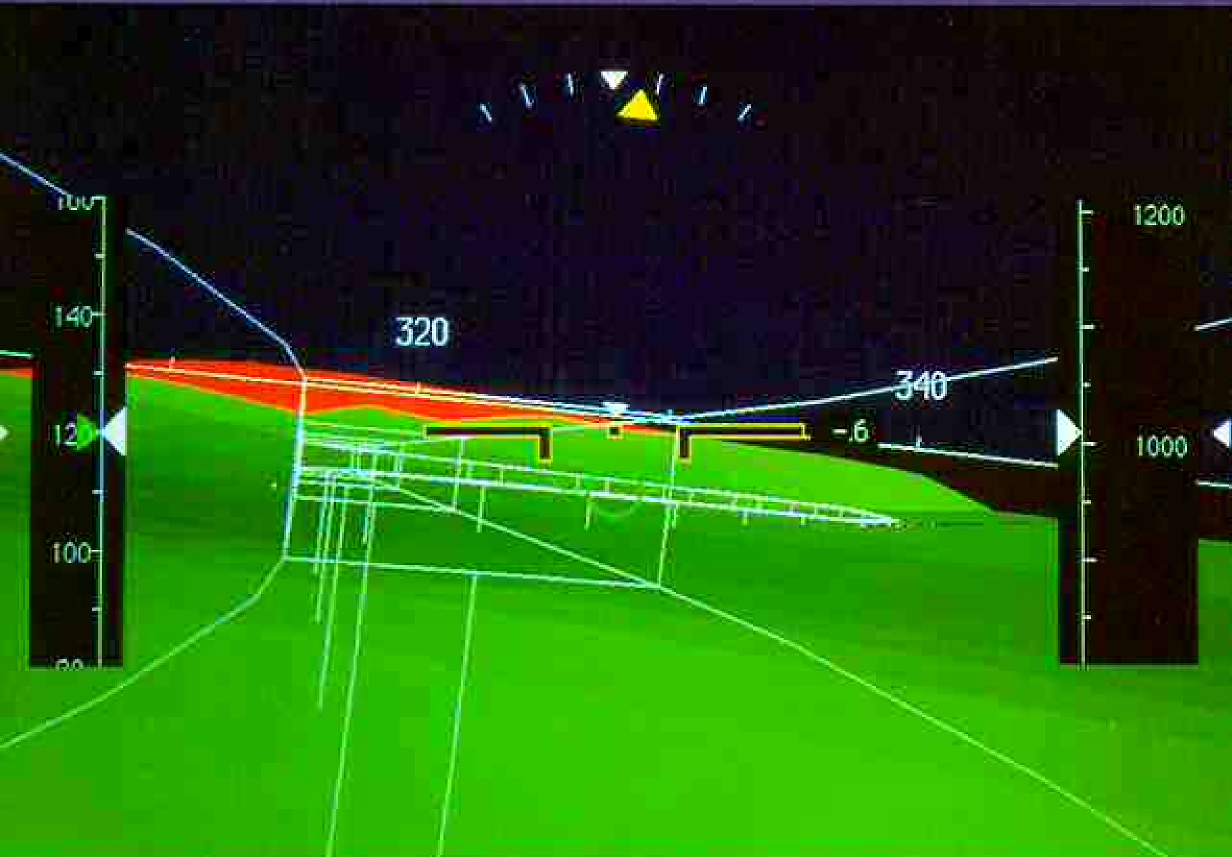
Integrated Design of a Man-Machine Interface for 4-D Navigation



Eric Theunissen

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On the front cover: A perspective flightpath display with integrated terrain information showing a curved approach to the runway. The specific symbology used in this picture is discussed in Ch. 6 of this thesis.
On the back cover: Photo taken during the first in-flight test of the DELPHINS Tunnel-in-the-Sky display on December 19, 1994. The pilot flying is prof. dr. ir. J.A. Mulder.

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PROEFSCHRIFT

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Eric THEUNISSEN

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Henk Stassen enlarged my field of view by pointing out many similarities between the questions and problems discussed in this thesis and those in other disciplines. Furthermore, Henk's detailed comments contributed significantly to the end result.

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SUMMARY

Due to the ever increasing number of aircraft passengers and the resulting increase in aircraft, bottlenecks in airspace capacity are beginning to emerge. Once the number of aircraft has reached a certain threshold, any further increase will cause unacceptable delays. Since the bottlenecks mainly occur in the vicinity of airports, this is were a solution should start. The basic idea behind improvements is to abandon today's straight-in approaches and allow aircraft to intercept the final straight glidepath at predetermined locations. This provides air traffic control with more possibilities to manage the traffic flow, creating the opportunity to increase capacity. An additional advantage is that it becomes possible to avoid noise sensitive areas by using noise abatement procedures. This concept, however, increases the task demanding load of the pilot. In contrast to the current straight-in approach, he will have to fly more complex curved approaches. Due to the more frequent changes in direction, it becomes harder to maintain an adequate level of spatial awareness. As a result, the pilot will have to scan the navigation display more frequently. Because of the already high workload during the approach, an introduction of more complex approach trajectories is likely to reduce safety. By providing the pilot with the information he needs to more easily or just as easy accomplish his task as before, while maintaining spatial awareness without the need to scan additional displays, it becomes possible to fly more complex approaches without a reduction in safety.

The goal of the research described in this thesis was to increase safety. An analysis of possibilities to reduce task demanding load for aircraft navigation by improving data presentation has been performed. The results of this analysis and the results of previous research both showed that displays providing a spatial presentation of the future trajectory have advantages relative to current non-spatial displays. These advantages result from the fact that the pilot has to perform less integration of information and the fact that the more natural presentation requires less effort for interpretation and evaluation. Furthermore, it became apparent that hardly any detailed guidelines to the design of these types of displays exist which take specific human capabilities in the areas of perception, cognition, and control into account. For the designer this causes many questions regarding *how* and *why* with respect to the specification of a display format for navigation and guidance. Furthermore, it becomes very difficult to maintain an overview of all the design aspects and their relations with the task requirements, which increases the danger that certain undesired effects are overlooked.

To change this situation, the question on how to utilize the existing knowledge in the areas of perception, cognitive science, and control theory, has been addressed. It was decided to translate specific design questions to the previous domains. To accomplish this, the information content of the presentation is described by deriving a relation between the position and orientation errors of the aircraft and the resulting changes in the position and orientation of the perspectively presented trajectory. Next, it was investigated how the various design aspects influence this relation, what the consequences are for the translation of the data into useful information, and how useful the information is with respect to the ability to apply a certain control strategy. This analysis served to derive guidelines for the design aspects. To be able to investigate certain design questions in more detail, the concept has been implemented in a way which allows the manipulation of the design aspects. This implementation has been used to obtain feedback from professional pilots, to perform pilot-in-the-loop studies in a flight simulator, and to test the concept in real flight.

1 INTRODUCTION

1.1 Navigation, communication and air traffic management

The increasing number of aircraft delays is a clear indication that the capacity of the existing air traffic system is approaching its limits. When extrapolating the current air transport growth of approximately five percent a year, it will have doubled by the year 2010. Similar to transport by road, the relation between traffic density and the amount of delays is far from linear and once a certain limit has been reached, a small increase in traffic density causes a tremendous increase in delays. Besides the fact that at some point this becomes economically unacceptable, it also increases pollution from aircraft forced to fly holding patterns until they are allowed to land, making it environmentally unacceptable. Finally, and most importantly, even in case the accident rate remains constant, the growth of air transport will be accompanied by an increase in absolute numbers of accidents.

The generally accepted solution to this problem is to develop new approaches for air traffic management which utilize the available airspace more efficiently. The main difference with current air traffic control is that no longer only a number of fixed airways similar to railroads or highways are considered. With the advent of satellite based positioning systems and powerful onboard computers, the technical limitations which necessitated the fixed airway system have disappeared. There is no question that abandoning the system of fixed airways will pose a significant challenge to air traffic control to efficiently utilize the increase in flexibility. Advances in the area of satellite based positioning and communication will significantly influence future *air traffic management* (ATM). The direct information exchange between the flight management system (FMS) computers and ground based ATM computers through a *data link* is seen as the cornerstone of future ATM. The future air navigation system (FANS) of the International Civil Aviation Organization (ICAO) will provide integration of satellite based communication, navigation, and surveillance (CNS) with ground based ATM. The advent of accurate positioning systems such as the global positioning system (GPS) allows the positioning error to be reduced. One of the FANS elements is *automatic dependent surveillance* (ADS) that encompasses the automatic transmission of position reports from aircraft to controllers. The world's first demonstration of full ADS utilizing GPS derived positions took place on Oct. 21 1991 during a Northwest Airlines Boeing 747-400 flight from

Detroit to Tokyo (AW&ST, 1991). In a future *four-dimensional* (4-D)[1] environment, aircraft are required to remain inside a so-called aircraft performance shell. This shell is a limited volume of airspace that moves as a function of time. The volume of airspace is sometimes referred to as a *bubble-in-the-sky*. It is anticipated that this will allow for reduced separations between aircraft, thus increasing airspace capacity. A potential concept for future ATM became known as *free flight*. The concept of free flight allows pilots to select their own flightpaths in real-time, with controllers intervening only to prevent problems. Free flight is a concept encompassing a real time air traffic management triad: People, Procedures, and Technologies. An element of free flight which will enable the pilot to electronically see and avoid other aircraft in a largely passive mode is *air-to-air automatic dependent surveillance-broadcast* (ADS-B). ADS-B is a Data Link application in which equipped aircraft automatically broadcast their position to any listeners in the local vicinity. The data link broadcast may be received and processed by other aircraft or ground systems. This data can be used to provide the pilot with a picture of the surrounding traffic.

It is generally agreed that in a future free flight environment the human is the most critical element in the use of new technologies, equipment, and procedures.

With the advent of the microwave landing system (MLS) and GPS, a variety of new approach procedures also becomes possible. Whereas the simplest form of them will be similar to the ones employed with the current instrument landing system (ILS), advanced procedures should allow for steep-angle and curved approaches to be flown. The introduction of a data link makes it possible to uplink approach procedures into the flight management system (FMS), allowing flexible curved approaches. These developments provide air traffic control (ATC) with more freedom in managing the traffic flow, allow aircraft to fly shorter straight final segments and more efficiently use parallel runways, and thus result in a better utilization of airway and runway capacity. Furthermore, ATC is provided with an increased opportunity to vector aircraft around populated and other noise sensitive areas.

The use of technologies such as GPS and data link, allows new concepts for air traffic management to be pursued. An example is free flight which aims at providing aircraft the opportunity to fly optimized routes. Since the human is the most critical element in such a future scenario, it is of uttermost importance that communication between humans and computers is optimized, both on the ground and on board the aircraft.

The last fifteen years have demonstrated an enormous increase in the performance of onboard computers. The Boeing 747-400, which received its FAA type certificate on January 10, 1989, is equipped with an FMS with a processing capacity of 2.8 MIPS and 32 MB of memory. It contains

[1] 4-D refers to the fact that waypoints are specified in the three spatial dimension as a function of an extra dimension: Time. Hence the fourth dimension.

approximately 1.1 MB of software. The airplane information management system (AIMS) of the Boeing 777, which made its first flight on June 12, 1994, has a computing capacity of 144 MIPS and a memory of 256 MB. It contains approximately 10.6 MB software comprising 440K lines of source code (Johnson, 1993). The avionics architecture for the MD-95 jet, is reported to have 38 times the processing power of it's predecessor (Smith, 1995). In the military community, even more powerful computer system are being introduced. The computer hardware of the F-22 is reported to have a performance exceeding that of seven Cray computers (Rich and Janos, 1994). Software is expected to contain approximately 1.6 million lines of code, and software integration is expected to be the largest challenge (Proctor, 1996). The final version of the software is expected to be delivered in August 2000! (Hughes, 1996). Wilkie et al. (1995) describe the situation as follows: '*The speed limit on future vehicle development cycles will not be in the domain of hardware, but in the software that must be developed to implement increasingly complex algorithms and provide connectivity to the various vehicle subsystems'*.

Similar to the situation with the fixed airways, the instruments in the cockpit of commercial aircraft have not changed much over the past forty years. Until approximately fifteen years ago, almost all instruments were electromechanical and as a result the presentation was determined by mechanical constraints. Although in the early eighties programmable electronic displays were introduced, the opportunity to exploit the tremendous increase in flexibility in order to improve the man-machine interface was hardly utilized. In many cases the electronic displays merely emulated the presentation of the electromechanical instruments they replaced. It goes without saying that this reduced certification time and cost, and allowed an early introduction of electronic displays. Therefore, it may certainly have been the right decision at that time. This does not mean, however, that we should not consider to make a more radical change somewhere in the future. New developments in display devices are also fundamental to the potential MMI concepts which can be applied. Most of the current display devices utilize cathode ray tubes (CRT). Image generation is performed by means of a hybrid raster/stroke method to combine calligraphic capability and high intensity (stroke mode) with the possibility to present solid areas (raster mode). A trade-off exists between refresh rate, the size and intensity of the solid areas, and the amount of symbology presented in stroke mode. Requirements with respect to minimum refresh rate and intensity limit the size of the display area which can display solid shapes. Active matrix liquid crystal displays (AMLCD) which are fully raster based and in which intensity is determined by the backlighting do not suffer from this trade-off. Fortunately, in many new airplanes (Boeing 777, 737 -700, -800 and -600, Lockheed Martin C-130J) and upgrades (F16), AMLCDs are used instead of CRTs, and as a result do not impose a bottleneck on potential MMI concepts.

Today's computer and display systems offer almost unlimited flexibility in the implementation of functionality and the presentation of data and finally allow the implementation of concepts which have been discussed for over forty years but could not be implemented due to technical constraints.

With respect to operational behavior, current systems suffer from problems in the area of reliability, integrity, and correctness caused by errors in the implementation (IATA, 1994a & 1994b). These are either caused by unforeseen system states or coding errors. Software updates take considerable time, in most cases longer than a year, and require the airlines to come up with procedures to patch the problems (IATA, 1994b).

The bottleneck in the development of Man-Machine Interfaces has shifted from the hardware to the process of creating software.

The increased performance of onboard computer systems and the increased flexibility in data presentation poses three challenges to the design and implementation process:

- What to implement;
- how to implement it;
- how to validate it.

The first challenge comprises the development of methods to truly integrate human factors in the design process and will significantly influence the operational aspects of the system. The second challenge comprises the development of efficient approaches to implement and update the desired functionality. The approach taken to implement the desired functionality determines the maintainability, upgradability, reusability, and adaptability and thus influences total life cycle cost. To be able to efficiently validate the implementations, integration of verification and validation methods into the design process is needed, i.e. design for testability.

An up-front investment is required to reduce cost in the later life cycle phases. Adequate lead time for specifying, designing, and implementing an integrated system is required.

1.2 Do we still need pilots?

In the military community, the concept of future unmanned fighter aircraft is being explored (Fulghum, 1996a,b,c). Unmanned aerial vehicles (UAVs) are among the most rapidly expanding military aerospace sectors. The main reasons are the great weight and cost savings which can be achieved by removing the cockpit, the associated environmental and safety equipment, and the displays, input devices and associated computers from the aircraft. Such an aircraft would be remotely controlled and an on-board automated system returns the aircraft to base in case of a data link failure. To avoid complex autonomous software, the X-36 drone, which has been developed to test agility of a tailless design, is manually piloted from a ground control station. In contrast, the Tier 3- (Darkstar), a new reconnaissance drone, is fully autonomous. Unfortunately, Darkstar crashed shortly after lift-off on its second flight. The program manager commented: *'We try to* *dream up every possibility, but there's always one that gets away. The pilot would have known to chop the throttle when the airplane got into its funnies. In the flight test phase, the man is so important'*. Although it is sometimes speculated that in the far future commercial aircraft will also be remotely or completely automatically controlled, most of the reasons why the pilot might be removed from the fighter cockpit do not apply to civil aviation. Wickens (1984) summarizes the advantages of having a pilot in the control loop as: *'Humans can respond perceptually to a changing environment and to relations in the environment. They can go beyond the information immediately given, respond to low-probability occurrences, and adopt alternative strategies and alternate modes of performance when necessary. In short, humans are flexible'*. Unfortunately there are also disadvantages beyond the additional weight and volume taken up by the pilots. Wickens (1984) summarizes these as: *'Humans are also variable (they produce errors), and they may become creative in changing their responses when it is not optimal to do so'*.

For the near future, the advantages of having a pilot on board the aircraft are considered to outweigh the disadvantages. As a result, the limitations of the human operator have to be taken into account when developing new aircraft systems in order to safely operate in a future ATC environment.

1.3 Implications

The resulting increase in requirements on position and velocity control of the aircraft, and the increase in complexity of approach procedures, will certainly increase task demanding load and reduce the pilot's ability to maintain an adequate level of spatial and navigational awareness.

In several cases, a lack of situation awareness has been identified as a major factor in the chain of events resulting in controlled flight into terrain[2] (CFIT). An example is the crash of an Airbus A320 near Strasbourg in 1992 (Sparaco, 1994). This aircraft which was in a perfect technical condition, flew into a hill as a result of a wrong setting of the desired vertical flightpath. It is very likely that in case the displays had supported the pilot with maintaining an adequate level of situation awareness, the error might have been detected and the accident prevented.

The earlier mentioned advantages of a future ATC environment can only be realized if the systems onboard the aircraft allow the pilot to fly these more complex procedures in a safe way.

One potential solution is to fly these complex approaches on autopilot, but even in this scenario, adequate displays are needed to keep the pilot in the loop, so he can intervene in case an

[2] A CFIT accident is defined as the inadvertent flight into the ground or water of a perfectly serviceable aircraft, controlled by a qualified pilot, with no prior awareness on the part of the crew of the impending crash.

unexpected event happens for which the automation was not designed. Without adequate displays, unique human capabilities such as the high degree of flexibility and adaptability, the possibility to recognize and exploit advantageous opportunities, and the possibility to integrate perceived data with other information to resolve ambiguities and contradictions, are not utilized. As a result, an intervention of the pilot may necessitate a go-around. Since the approach is potentially a very dynamic situation, it is important that the man-machine interface (MMI) supports an efficient interaction between the pilot and the guidance and navigation system of the aircraft. In this way, the pilot can compensate for the limited flexibility and adaptability of automated systems. Jensen (1981) proposes that cockpit displays for curved approach tasks should present preview information. To maintain adequate spatial and navigational awareness, data must be presented which allows the pilot to determine the position of the aircraft relative to the desired trajectory in three dimensions.

Conventional electromechanically instrumented aircraft will at best be able to fly basic curved approaches which are specified in approach charts, but can never utilize the flexibility offered by data links to the full extent.

Given that during times of intense task demanding load the pilot's attention is exclusively devoted to high priority tasks, it is questionable whether the conventional data presentation methods suffice to provide the pilot with enough information to maintain the required spatial and navigational awareness and at the same time execute or monitor the safety and conduct of the approach. Knox (1986) conducted a piloted simulation study to examine the requirements for using electromechanical flight instrumentation to provide guidance for manually controlled flight along complex, curved approach paths, and concluded that flight director guidance is required. Information needed to maintain navigational awareness had to be obtained from an approach chart combined with along track distance data presented by a distance measuring equipment (DME) indicator and an advanced track angle arrow on the horizontal situation indicator (HSI) which showed the pilot where he was going in the turn. Thus, to maintain an adequate level of navigational awareness, the pilots were required to scan several displays and mentally construct the total picture. Erkelens and Dronkelaar (1990) performed a flight simulator evaluation of the flyability of curved MLS approaches with wide-body aircraft. The primary flight display (PFD) included a flight director display to present steering commands, and a second display presented an HSI in rose mode providing a plan view of the approach. They conclude that *'within certain constraints, i.e. adequate approach minima, turn radius and glide path intercept position, curved path procedures are flyable in appropriately equipped wide-body aircraft'*. They also conclude that *'based on subjective crew responses and on statistical flight performance data, crews are able to accurately fly curved path procedures with only minimal familiarization'*.

The fact that previous research indicates that it is possible to fly curved approaches with conventional command displays should not be a motivation for not trying to improve the MMI for curved approach procedures in order to increase safety.

1.4 Data presentation

In aircraft equipped with an electronic flight instrument system (EFIS), a possible approach is to enhance the conventional data presentation displays. The PFD can present the required guidance data, and the navigation display the trajectory in a plan view, allowing the pilot to maintain a certain level of lateral navigation awareness. Vertical navigation awareness can be achieved by integrating data into the navigation display, e.g. a numerical presentation of the altitudes at the waypoints or by introducing a vertical situation display (VSD) (Baty, 1976; Houck et al., 1986; Fadden et al, 1987) which presents a side-view of the situation. However, a significant part the data format of the current EFIS is based on an emulation of the electromechanical instruments they replaced. These instruments required a trade-off between the desired presentation and inherent mechanical limitations, which is still reflected in the electronic display formats.

It is highly unlikely that with all future developments, safety can be increased by extrapolating current concepts. New functionality and new technology cannot simply be layered onto previous design concepts, because the current system complexities are already too high. Better MMI's require a fundamentally new approach.

Bennet and Flach (1994) argue against what they refer to as the classic goal of designing idiot-proof systems. They claim that such an approach is profoundly wrong since one can never anticipate and design away the exigencies, misunderstandings, and problems that will arise in people's use of systems. Instead, one should include information about the constraints so the pilot is aware of the total space in which solutions can be achieved. They conclude that the use of dynamic, graphics representations holds great promise for increasing the capability of the human to deal with unanticipated variability.

A potential concept for a navigation and guidance display which increases spatial and navigational awareness is the presentation of spatially integrated data.

When a display presents a spatial presentation of the future desired trajectory, it is often referred to as 3-D or a perspective flightpath display.

The fundamental advantage of a perspective flightpath display relative to the conventional flight director is that it continuously provides the pilot with information about the spatial constraints rather than commands to minimize an error independent of the actual constraints.

1.5 Vision Systems

Besides developments in the area of radio-positioning systems, advances in the area of sensors and computer graphics technology have resulted in the development of so-called enhanced- and synthetic vision systems (SVS), respectively.

The driving factor behind the development of an enhanced vision system (EVS) is the desire for autonomous operation under all visibility conditions in order to reduce revenue losses caused by weather.

The current approach with EVSs is the combination of sensor data for the depiction of the outside world with computer generated symbology for the presentation of additional guidance data (Burgess and Hayes, 1993). In case of a head-up display (HUD), this information is overlaid on the visual scene. EVS is seen as a key component for the autonomous aircraft. Patterson (1993) describes an EVS as *'a system which includes sensors capable of supporting the means for safe operation in a low visibility (i.e. fog) environment'*. Based on the fact that no single sensory input is as important to the pilot as his vision, and to exploit the human's unique pattern recognition abilities which still far exceed those of any computer, the ideal system should provide displays representing the essential outside scene information. This allows the pilot to operate at a level similar as under visual meteorological conditions (VMC). Even in case an EVS is not enough for a completely autonomous aircraft, the easy transfer from the EVS image to the real runway compared to the transfer of instruments to reality would allow decision minima to be reduced, and a major goal is to allow EVS equipped aircraft to land on a Cat I[3] equipped runway under Cat IIIa[4] conditions (Patterson, 1993). Furthermore, since an EVS is based on visual information, it provides an independent means for monitoring the integrity of the positioning system during approach, landing, and taxiing. To obtain an easy transfer between the real world and the enhanced image, it is likely that EVS data and its symbology will be presented on a head-up display (HUD).

As sensor technology is the basis for all vision enhancement efforts, the maximum improvement which can be achieved is determined by the limitations of the available sensor technology. Patterson identifies the following EVS sensor technology candidates: Low-light level (LLL) optical sensors, laser, infrared (IR) sensors, millimeter wave (MMW) sensors and X-band radar. Since an EVS should provide a visual based guidance capability under reduced visibility conditions, the cues required for the guidance task which are present in the visual environment should also be provided by the EVS system. However, due to limitations inherent with EVS (e.g. the limited field

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[3]On a Cat I equipped runway the minimum height at which the runway must be visible is 200 ft and the minimum runway visual range 2400 ft.

[4]Under Cat IIIa conditions the minimum height at which the runway must be visible is 50ft and the required runway visual range is 700 ft.

of view and the resulting absence of peripheral cues), not all required cues are available, which necessitates some form of display augmentation. With current EVS concepts, typical HUD guidance symbology such as the flightpath vector (FPV) and a perspective runway symbol is used. However, this kind of display augmentation is only useful for straight-in approaches. When using an EVS in a curved approach procedure, additional information to maintain navigational awareness is required. Because it takes some time for the human eye to refocus when switching between near-infinity and the close-by head down displays, a transition between the head-up presented EVS and guidance data and the head-down navigation display may be unacceptable. As a result, the information required to maintain navigational awareness must be presented on the HUD.

A synthetic vision system (SVS) is based on the computer generated image of the outside world as seen from the pilot's or another selectable viewpoint. The data needed for this approach comes from a massive on-board database containing digitized terrain and manmade feature data. The position of the viewpoint and the viewing direction must be calculated from the onboard positioning and attitude determination systems. The introduction of SVS further increases the possibility to improve the information transfer from aircraft to pilot. This can be achieved by combining the essential information which is currently obtained from the outside world view with the additionally required information.

Computer generated images can be used to emphasize important features in the outside world scene, de-emphasize or eliminate unimportant features, and include artificial guidance cues, e.g. cues which are not present in the real-world, but contribute to better pilot performance/system safety.

One argument for the depiction of artificial terrain is to increase the pilot's terrain awareness in order to avoid controlled flight into terrain. It is important to recognize that the data presented by a SVS is determined by a database, which is susceptible to omissions and errors, and as a result it can give the pilot a false sense of safety. Important data, not in the database, must be recognized using EVS and integrated into the display. But even when database integrity requirements are not met, using a stored terrain database to provide warnings in case of an potential conflict can be used to improve safety, and recently systems based on this concept have been demonstrated. Allied Signal, for example, has developed error-tolerant algorithms which consider aircraft position, track, absolute altitude and flightpath in relation to stored terrain data to determine if the projected flightpath conflicts with terrain ahead of the aircraft. This feature has been coined *look ahead* alerting, and offers a significant improvement in advance alerting times for flight into very precipitous terrain (Aerospace, February 1995).

The spatial presentation of EVS and SVS data makes the integration of perspective guidance data an ideal candidate to present dimensionally compatible data which at the same time provides the pilot with the required navigational awareness.

1.6 Designing and introducing a new MMI

If you truly want to understand something, try to change it (Kurt Lewin).

MMI design addresses both representational aspects and functionality. Task and design requirements can be specified at different levels of detail. Initial design requirements are far from complete and lack the details required for a complete implementation. These details must be obtained through an iterative process involving domain experts and end-users. This process is illustrated in Fig. 1.1, which shows a general representation of the design process of a Man-Machine Interface.

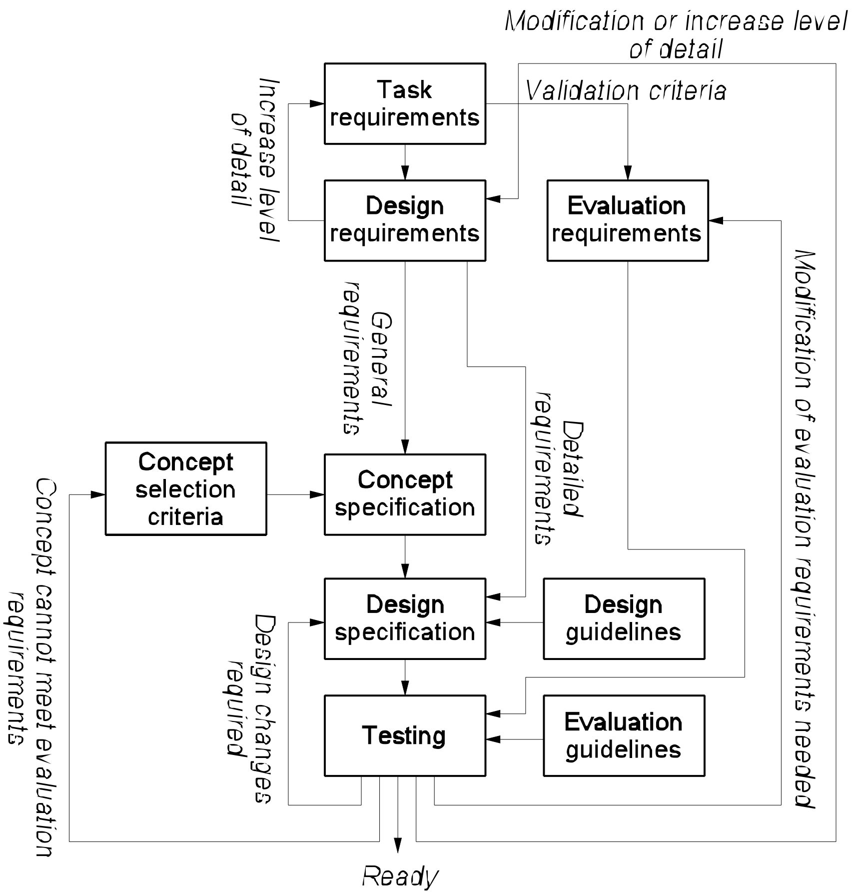


Fig. 1.1. *General representation of the design process of a Man-Machine Interface.*

Based on the general design requirements and concept selection criteria, a certain concept is selected. More detailed design requirements and design guidelines yield an initial design specification. This specification is translated into an implementation which is tested against certain evaluation criteria which must guarantee that the implementation satisfies the task requirements. In case the results of the testing show that not all requirements are met, the results should be used to determine whether it is likely that the requirements can be met by a change in the design specification or that a change in concept is needed. In the process of refining design requirements, technical limitations with respect to potential implementations must be taken into account constraining the number of possible approaches to satisfy the design requirements.

One should always consider that every existing implementation is a trade-off which resulted from the technical limitations of the time. Therefore, it is important to understand why a certain design was selected and why others were rejected.

1.6.1 MMI for navigation

To safely accomplish the navigation task, pilots need to be aware of the aircraft position and orientation relative to the desired trajectory. The current navigation display provides the pilot with a planar picture of the aircraft's position and heading relative to the flightpath. It significantly lacks in the ability to provide navigational awareness in all three spatial dimensions. Other displays provide information about the vertical dimensions. Achieving an adequate level of navigational awareness in all three spatial dimensions necessitates a lot of scanning and mental integration, increasing task demanding load as a result of non-optimal displays.

The idea behind current guidance displays is to treat the pilot as a servo-mechanism which operates over certain bandwidth. This is an enormous waste of the unique capabilities of the human operator.

Rather than spending the major part of his resources to behave like a good servo, the unique capabilities of the human operator with respect to his ability to deal with unexpected events, should be exploited to compensate for the limited flexibility of the automated systems. The anticipated increase in traffic density and the desire for flexible, curved approach paths will further increase task demanding load, especially in situations where it is already very high.

To avoid that future developments impair safety, better navigation and guidance displays must be developed which require less effort from the pilot to stay on top and ahead of the situation.
To reduce the sudden built-up of task demanding load, displays should provide information which enables pilots to operate in an open-loop mode allowing anticipation of future events.

1.6.2 The future

Future navigation and guidance displays should provide the information the pilot needs to monitor and anticipate the situation as it develops, and intervene with maximum efficiency when necessary.

The elements of the display which provide guidance should not force the pilot to apply a continuous compensatory control strategy. Rather than commanding the pilot what to do, or at best showing only the error with respect to the desired trajectory, guidance and navigation displays should provide information about the margins within which the pilot is allowed to operate. Only in this way can human flexibility be exploited. This is a fundamental difference with current command displays.

Well designed displays providing information about the constraints within which the pilot is permitted to operate, allow a trade-off to be made between workload and performance. For the control task this implies that the display should provide information which the pilot needs to apply anticipatory and error-neglecting control strategies.

Several research programs have demonstrated significant advantages of 3-D displays (Parrish et al, 1994; Regal and Whittington, 1995), whereas avionics developers indicate that 3-D is not only feasible, but perhaps critically important for near-term terminal-area operation (Reinhart, 1992). In the context of the development of an enhanced situation awareness system (ESAS), which is defined as *'a system solution to achieve conflict-free navigation while executing the best performance flight plan moderated by passenger comfort'* (Taylor, 1994), new methods for the determination and presentation of guidance data are needed. Furthermore, the application of perspective flightpath displays is certainly not limited to large commercial aircraft. The application of improved MMI's such as the *Highway in the Sky* display is one of the elements of NASA's blueprint for a general aviation renaissance (Ethell, 1994).

Although perspective flightpath displays have been discussed for over forty years, the flight director command display is still the only instrument used for precision manual flight. Until about a decade ago, technology was the limiting factor for the implementation of perspective flightpath displays. Now, this is no longer the case, and the reasons for employing less sophisticated displays which were necessitated as a result of the technical limitations of forty years ago, must be revisited. Fadden et al. (1987) state that *'while the promise of spatial displays is great, the cost of their development will be correspondingly large. The knowledge and skills which must be coordinated to ensure successful results is unprecedented. From the viewpoint of the designer, basic knowledge of how human beings perceive and process complex displays appears fragmented and largely unquantified'*. This is one of the most used arguments against perspective flightpath displays and it stresses the need for a structured approach to the design. Only then it will become possible to develop a certification approach.

1.6.3 Systems overview

To be able to pursue a structured approach, an overview of the systems involved in the presentation of navigation data is needed. Preferably, such an overview should be representative for both current and potential future concepts. To create this overview, a distinction will be made between the data generation-, data transformation-, and data presentation processes. Since the goal of this thesis is to developed a structured approach to the specification of the data presentation process for spatial navigation displays, the level of detail of this overview is further increased. The process of data presentation can be described as a set of rules which determine how the data is represented, e.g. alphanumerically or by means of symbols, and a set of rules which determine the attributes of the representation such as position, orientation, size, and color. This approach has been applied for the analysis and description of the systems involved in the presentation of navigation data and resulted in Fig. 1.2. This system overview will be used as a frame of reference in this thesis.

The goal of this figure is to show the relation between the different sources of data and the different elements of the MMI which must be specified. By making a clear distinction between the specification of format and functionality, it is possible to pursue of structured approach to the implementation. The specification of the format has been subdivided into *static synthetic data*, *symbology*, and *dynamic synthetic data*. The specification of functionality has been subdivided into the categories *selection rules* and *transform rules*. The following discussion briefly describes how the different types of data are transformed into a picture.

In Fig. 1.2, three different types of elements are used: Data stores, data transforms, and inputs to data stores and transforms. The upper part of Fig. 1.2 shows the different inputs which provide navigation related data. The category *spatial sensors* represents systems which measure multi-dimensional arrays of parameters. Examples are radar and IR imaging systems. The category *data link* represents systems which can transmit data to the aircraft whereas *loader* refers to on-board systems which can be used to load data from a physical medium. A distinction is made between three different categories of data: *Weather*, *traffic*, and *flightplan*. For the manual inputs, a distinction is made between two different systems, the *control display unit (CDU)* and the *mode control panel (MCP)*. The CDU allows access to the navigation data through alphanumeric commands, whereas the MCP can be used to select certain navigation objectives through a number of pre-defined one-dimensional commands with selectable parameters. Examples are capturing and tracking a selectable vertical speed, heading, and altitude. Depending on the mode of operation, either the flightplan or the inputs from the MCP are used to generate a *forcing function* which defines the trajectory the aircraft has to track. The data which can be presented is divided into four different categories: *Raw sensor data* represents the category which directly represents the data as measured by the sensors. The values of the data are mapped onto a certain color or intensity distribution. Data from the spatial sensors can also be used to estimate specific parameters (Sridhar and Phatak, 1992). Such a process typically comprises a pattern recognition stage and a parameter estimation stage.

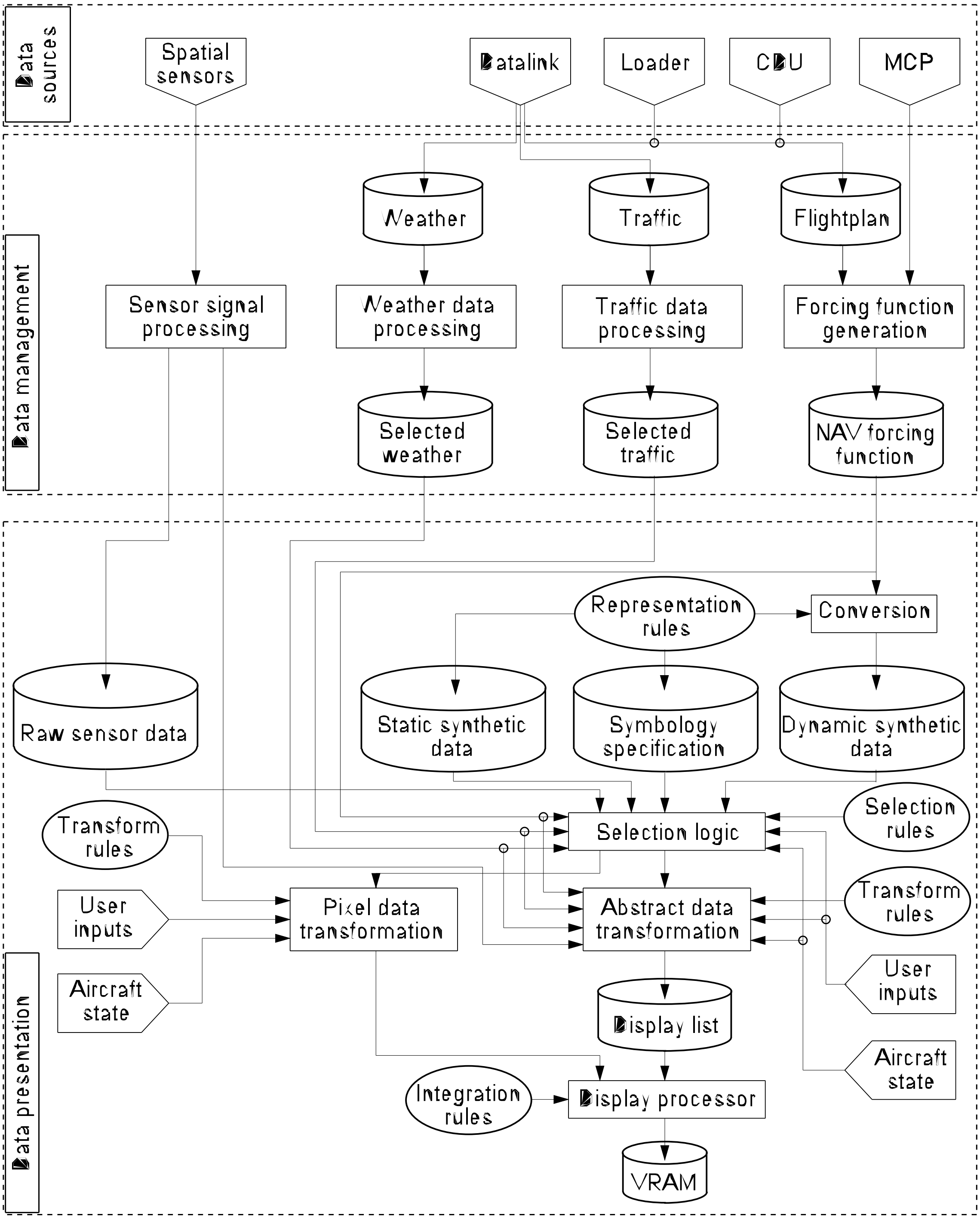


Fig. 1.2. *Overview of the systems involved in the presentation of navigation data.*

Static Synthetic Data refers to data which describes abstractions of real-world objects. An example is terrain data. *Symbology specification* refers to data describing symbology which due to their specific representation have a particular meaning. Properties of the symbology such as position, orientation, color, and size can be used to convey information. Examples are conventional instruments. *Dynamic Synthetic Data* refers to data which describes the geometry of objects according to a set of *representation rules* and a *forcing function*. An example is the representation of the flightplan. Based on the *selection rules*, the *selection logic* controls which data is to be presented. The *transform rules* determine the dynamic properties of the objects to be presented such as position, orientation, color, and style. The *data transformation* applies the transform rules. A distinction is made between transformations which are applied on abstract data types and transformations which are applied on pixel data. The abstract data types are stored in a display list and transformed into pixels by the *display processor*. The display processor combines this data with the pixel data from the *pixel data transformation* according the *integration rules*. The result is stored in video random access memory *(VRAM)*, which in turn is translated into an image.

Representational aspects comprise the *symbology specification*, the *static synthetic data specification*, the *representation rules* for dynamic synthetic data, and the integration with sensor data. Functionality comprises data *selection rules* and data *transformation rules*.

1.6.4 Integrated systems engineering

Based on a review of human engineering activities in ten major acquisition projects, Beevis (1987) concludes that *'an approach which combines the interaction of hardware, software and human functions is made especially necessary by the impact of advanced technology on the roles of human operators and maintainers, on the man-machine interface, and on the system development process itself'*.

Johannsen (1994) defines integrated systems engineering as: *'Integrated systems engineering is concerned with the systematic development of large-scale systems by means of using integrative knowledge across several disciplines'*. It is, however, not limited to large scale systems. The systems development process can be divided into a number of stages. Sage (1992) identifies the following:

- Requirements and specifications;
- preliminary conceptual design;
- logical design and architectural specifications;
- detailed design and testing;
- operational implementation;
- evaluation and modification;
- operational deployment.

The fact that these are successive stages with little or no overlap is the reason this approach is referred to as the waterfall model. Johannsen (1994) argues that in reality these system life-cycle approaches are elaborated further with several iterative loops with possible feedback to earlier stages to reformulate goals, perform a partial redesign, or increase the level of detail. He argues that the pure top-down approach suggested by the waterfall model requires a full overview of all the possible goals and means by the whole development team from the beginning on and that the participation of end-users is not well supported. The design process of an MMI as represented in Fig. 1.1 shows the feedback loops which enable the iterative process. Theunissen (1994c) indicates that one of the problems which hampers the efficient design of systems is the fact that in many cases end-users are initially unable to specify complete requirements. Johannsen (1994) indicates that prototyping and participative design approaches are more recent alternatives which may be combined with the more strict systems life-cycle approaches. *'The idea of prototyping is to arrive, as soon as possible, at final design solutions in a still preliminary or approximate version'* (Johannsen, 1994). A method with which prototypes of display format and functionality can be automatically generated from a specification is discussed by Theunissen (1994c).

1.6.5 Human Factors

Designing machines that accommodate the limits and advantages of the human operator is the concern of a field referred to as human factors. Human factors is closely related to engineering psychology. With respect to the design of displays, Wickens (1984) emphasizes this relation as follows: *'One important goal of engineering psychology should be to obtain data banks representing these trade-offs between display variables, so that the system designer can select beforehand the display parameters that may be sacrificed or shortchanged in the interest of economy with minimum cost to system performance'*. Thus, it is the job of the system designer to integrate technical and human factors aspects. To prevent a too limited applicability, engineering psychology does not focus on specific design problems. For the system designer this means that to successfully integrate human factors knowledge into the design process, an approach is needed which allows the translation of specific design questions into a more general context.

Studies performed in the field of experimental psychology have provided an enormous amount of knowledge about perception, cognitive processing and control behavior with spatial displays. The challenge lies in the translation of specific design questions into a more general context and to use findings from engineering psychology and human factors research to provide answers or guidelines on how to obtain answers.

1.6.6 An integrated approach

The main characteristic of the MMI discussed in this thesis is the spatially integrated presentation of the future trajectory and other objects in the 3-D environment which are relevant to the navigation task. Fig. 1.2 presented an overview of the systems involved in the presentation of navigation data. It was pointed out that the process of data presentation requires the specification of representation rules, selection rules, and transformation rules. The specification of these rules raises many questions, and for each category of the rules a few examples of the questions which are typical for a spatial display are provided.

Design questions with respect to the representation rules:

- 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?

Design questions with respect to the selection rules:

- 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?

Design questions with respect to the transformation rules:

- How to select the perspective design parameters?
- How to select the frame of reference?

It is evident that to answer these questions, knowledge about how humans perceive and use the data presented by spatial displays is needed. As pointed out in the previous section, to benefit from the existing knowledge in this area, specific design questions must be translated into a more general context.

Besides representational aspects, implementation questions must be addressed. Examples are:

- 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?

A main goal of this thesis is to build bridges between the different disciplines involved in the design process of a display for 4-D navigation as to allow a truly integrated design. To be able to evaluate different design options and potential trade-offs, the underlying relations must be addressed. This is only possible when the design concept and design parameters can be related to the task requirements and task performance. Task requirements determine the data which must be observable. The specific representation determines the observability which depends on the cognitive work needed to extract meaning from the available data. Thus, in order to be able to translate the previous design and implementation oriented questions into a more general context, more fundamental questions such as the following must be answered:

- What are the specific properties of spatially integrated data presentation, and what are the similarities and fundamental differences with 1-D and 2-D data presentation?
- What are the consequences/possibilities of spatially integrated data presentation with respect to 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?
- What are the specific advantages and disadvantages of spatially integrated data presentation?
- What are possibilities to compensate for deficiencies, limitations and disadvantages?

Whereas the development of a flight director command display is mainly a control engineering problem for which structured approaches to the design exist, the previous discussion illustrates that a perspective flightpath display requires consideration of control theoretical, perceptual and cognitive aspects. As indicated earlier, a major argument against the perspective flightpath display is the apparent complexity of the concept as compared to a simple command display. In contrast to guidelines for flight director design, no detailed design guidelines for perspective flightpath displays exist.

For an efficient design process of an MMI based on the presentation of spatially integrated data, a framework integrating technical, control-theoretical, perceptual, and cognitive aspects is needed.

With this approach, it should become possible to relate changes in the design and the design parameters to the available visual cues, the span of potential control strategies, and the resulting changes in performance. Such a framework also allows one to determine plausible causes for problems and can serve as a guide towards solutions. When making modifications or proposing new designs, it is of crucial importance to understand the motivations which resulted in the current and past ones and the reasons which caused other approaches to be abandoned. Research into various aspects of perspective flightpath displays dates back to the early fifties. The numerous options for the representational aspects and the selection of values for the design parameters yield an enormous variety in perspective flightpath display formats. Without a design framework which relates these aspects to the type, magnitude and dynamic behavior of task related visual cues, the different concepts which have originated over the past forty years can only be compared with each other in terms of design parameters. By combining this data with empirically determined relations between the influence of changes in design parameters and task performance, qualitative predictions about relative task performance can be made when comparing different designs. As a result of possible interactions between the effects of changes in the design parameters, such an approach is only likely to succeed when comparing quite similar designs.

As the number of studies into perspective flightpath displays increases, the need to compare different concepts on the basis of task related variables arises. A conceptual framework is needed, which allows a comparison between different designs in terms of task-related visual cues.

Fig. 1.1 presented a general representation of the design process of an MMI. This thesis discusses the development of an integrated design framework, and this process is illustrated in Fig. 1.3.

The initial basis of the design guidelines for a certain concept is obtained through an integration of application domain specific knowledge and cognitive ergonomic knowledge. To benefit from the research into perception and control of self motion, the visual cues conveyed by the display must be described as properties of the optic flow pattern.

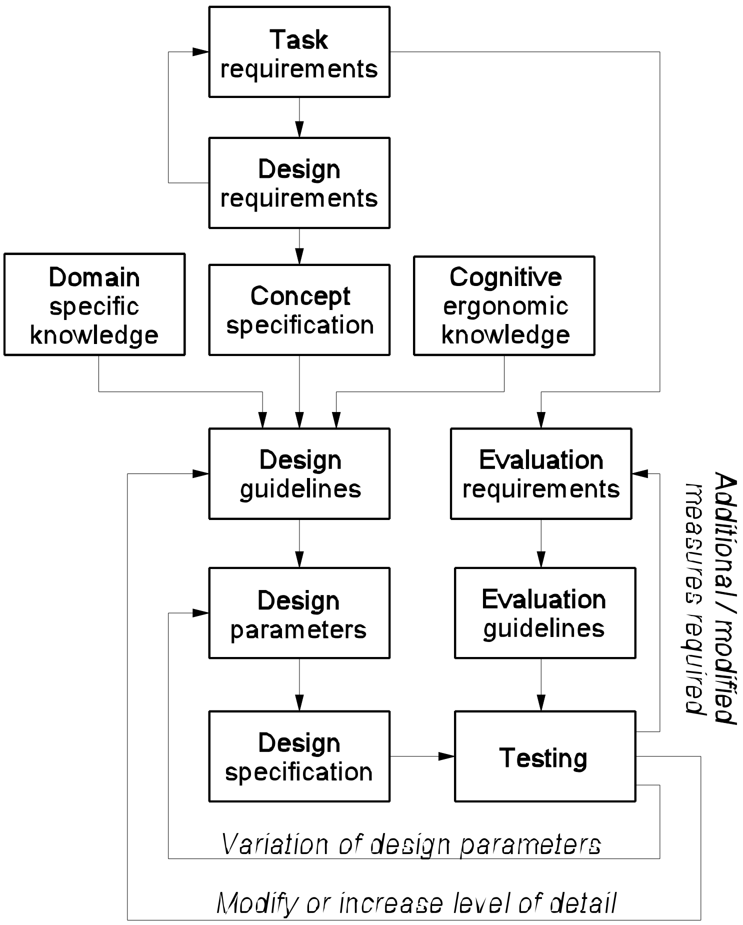


Fig. 1.3. *Specifying and refining design and evaluation guidelines.*

In this thesis, the display format is divided into elementary visual cues such as rotations and translations of certain elements. This makes it possible to describe the magnitude of these cues as a function of the design parameters. The level of detail of the design guidelines is increased in an iterative process, in which hypothesis about the relation between visual cues and the resulting task strategies and performance are made and evaluated.

1.7 Summary and structure of this thesis

The first part of this chapter discussed new developments in the area of positioning and communication systems which are the enabling technologies for future air traffic management. It was concluded that:

- For the near future, the advantages of having a pilot on board the aircraft are considered to outweigh the disadvantages. As a result, the capabilities and limitations of the human operator have to be taken into account when developing new aircraft systems in order to safely operate in a future ATC environment.
- The resulting increase in requirements on position and velocity control of the aircraft, and the increase in complexity of approach procedures, will certainly increase task demanding load and reduce the pilot's ability to maintain an adequate level of spatial and navigational awareness.
- The earlier-mentioned advantages of a future ATC environment can only be realized if the systems onboard the aircraft allow the pilot to fly these more complex procedures in a safe way.
- Conventional electro-mechanically instrumented aircraft will at best be able to fly basic curved approaches which are specified in approach charts, but can never utilize the flexibility offered by data links to the full extent.
- The fact that previous research indicates that it is possible to fly curved approaches with conventional command displays should not be a motivation for not trying to improve the MMI for curved approach procedures.
- It is highly unlikely that with all future developments, safety can be increased by extrapolating current concepts. New functionality and new technology cannot simply be layered onto previous design concepts, because the current system complexities are already too high. Better MMI's require a fundamentally new approach.
- A potential concept for a navigation and guidance display which increases spatial and navigational awareness is the presentation of spatially integrated data.
- Computer graphics images can be used to emphasize important features in the outside world scene, de-emphasize or eliminate unimportant features, and include artificial guidance cues, e.g. cues which are not present in the real world, but contribute to better pilot performance/system safety.

The second part of this chapter focused on the design process of a man-machine interface. It was concluded that:

- For an efficient design process of an MMI based on the presentation of spatially integrated data, a framework integrating technical, control-theoretical, perceptual, and cognitive aspects is needed.

- The challenge lies in the translation of specific design questions into a more general context and use findings from engineering psychology and human factors research to provide answers or guidelines on how to obtain answers.

The research described in thesis focuses on the development of an integrated design approach for an MMI based on the presentation of spatially integrated data. This research was performed in the context of the Delft program for hybridized instrumentation and navigation systems (DELPHINS).

The goal of this thesis is to identify, structure and place into context the technical, control-theoretical, perceptual, and cognitive aspects involved in the design process of an MMI for 4-D navigation based on the presentation of spatially integrated data. The goal is not the detailed design of a specific MMI.

The rest of this thesis is divided into two parts. The first part discusses the relations between navigation/guidance task requirements, design concept, task performance, and design parameters in a perceptual, cognitive, and control-theoretical context. It represents the upper part of the process of generating design guidelines presented in Fig. 1.3. The discussion serves as the basis for the design, implementation and evaluation presented in the second part. To answer the previous questions, the first part of this thesis focuses on the following subjects:

- Identification of navigation and guidance task requirements;
- identification of potential task strategies;
- identification of required data (controllability);
- analysis of data processing methods (availability);
- identification of static and dynamic visual cues (observability);
- investigation into potential use of these cues.

Ch. 2 discusses the navigation task in more detail. Based on navigation task requirements, display requirements for the manual and supervisory control task are presented. To determine how safety can be increased, the factors which might cause a navigation accident are analyzed. The relations between the different factors are presented by means of a risk tree. The risk tree visualizes how a number of events can result in a navigation accident and provides more insight into the data which must be presented to increase the likelihood of detection of particular events. A general requirement is that the pilot must always be aware of the position of the aircraft relative to the current and future three-dimensional trajectory, which is referred to as navigational awareness. Current guidance and navigation displays are analyzed in the context of navigational awareness and compared to a perspective flightpath display.

From the previous discussion it follows that there is a need to relate the representation and design parameters to the task related variables. To relate the design parameters to task related variables, the relation between visual cues and potential control strategies which are possible to satisfy task requirements is needed. To do this, the visual cues are expressed as properties of the optic flow pattern. Based on research into perception and control of self motion (Owen, 1990) and the resulting organizational framework in which parameters of an optical flow pattern are related to control actions, it is possible to relate the design parameters to task related variables, which is discussed in Ch. 3. The control oriented visual cues in a perspective flightpath display which are available from a single snapshot and a dynamic presentation are analyzed. A distinction is made between directional, velocity, and temporal range cues. The transformation of aircraft state information into visual cues is presented as a function of the design parameters of the perspective flightpath display, and compared to conventional flight director algorithms. The distortion of the symmetry caused by position and orientation errors is divided into a component conveying position error cues and a component conveying orientation error cues.

Ch. 4 discusses the implications resulting from the multitude of control oriented visual cues for pilot control strategies. A significant feature is that other control strategies than continuous compensatory control become possible. The relations between the available visual cues and intermittent open and closed-loop control, anticipatory control, and error-neglecting control strategies are discussed.

The relations between task requirements, design parameters, visual cues, and task requirements discussed in the first part serve as the basis for the specification of design guidelines and the implementation and evaluation of a specific MMI to validate previously made assumptions. This is discussed in the second part of the thesis.

The representation determines the perceptual and cognitive effort which is needed to translate the perceived image into relevant information. The discussion in Chs 3 and 4 serves as the basis for the specification of design guidelines in a perceptual, cognitive, and control-theoretical context. Ch. 5 discusses the design aspects such as the selection of the viewing volume and the frame of reference, the representation of the flightpath, the integration of additional symbology and the position data filters. Design options are discussed in the context of the resulting visual cues (Ch. 3) and potential control strategies (Ch. 4).

Until Ch. 6, the design aspects have been discussed. To validate certain assumptions and increase the level of detail of design guidelines, end-users must be involved and experiments are needed, thus requiring an implementation of the concept. As indicated by Johannsen (1994), prototyping can support and facilitate the process of user participation by supplying the appropriate tools for the interaction between user and designer. To gain experience with this new type of MMI, it was decided that first the basic format and functionality would be established in an early prototype, which is later expanded, integrated and refined. The basic functionality has been used for early operational demonstrations and experiments in order to elicit feedback from domain experts in the early development phase. Ch. 6 focuses on the specification and implementation of a perspective flightpath display format and functionality. The choices made regarding the design of the

DELPHINS Tunnel-in-the-Sky display format and functionality are discussed in the context of the navigation task presented in Ch. 2 and the design guidelines presented in Ch. 5.

Ch. 7 discusses the evaluations and experiments which have been performed to increase the level of detail of the design guidelines. The evaluations served to gain feedback on the display format. The experiments were performed to gain insight into more detailed design aspects. The first experiment was performed to gain more insight into the combined influence of error gain (Ch. 3) and display augmentation (Ch. 5). The second experiment was conducted to gain more insight in the relations between the visual cues resulting from the dynamic trajectory preview and the pilot's ability to use certain cues for error-neglecting control (Ch. 4). The third experiment served to investigate the differences between attitude and velocity vector aligned frames of reference (Ch. 3 and 5). Ch. 8 presents conclusions and recommendations.

2 NAVIGATION

The science by which geometry, astronomy, radar etc. are used to determine the position of a ship or aircraft and to direct its course (Webster's).

2.1 Introduction

The goal of aircraft operations is the safe and efficient transportation of people and/or cargo by air. The airlines want to fly the most economic routes and meet their schedules, which may result in conflicting requirements between airlines with respect to the use of a particular piece of airspace at a particular moment in time. It is the job of air traffic control (ATC) to make sure that the requirements with respect to airspace are satisfied in a safe way for all airlines. This means that in case of conflicting requirements, ATC should resolve the conflict in such a way that on the average the overall costs are minimized and no specific airline is penalized. To do this efficiently, flight plans are negotiated in advance which contain the route to the desired destination, a departure time-slot indicating the time window within which the aircraft is allowed to leave, and an estimated arrival time. To reach their destination, aircraft have to follow the route specified in their flight plan. Due to several reasons, the pilots may request to deviate from the assigned flight plan requiring tactical intervention from ATC. For the economical execution of the navigation task, airspeed must be maintained at an optimum value. To remain within the 4-D constraints of the flight plan, which is necessarily earth-referenced, ground speed must be maintained within certain constraints. In general, the position constraints as a function of time are calculated by determining the optimum airspeed and from this ground speed is calculated based on assumptions regarding wind velocity. The uncertainty in these assumptions is used to define a certain margin which in turn can be translated to spatial constraints. If during the execution of the navigation task the difference between the actual wind velocity and the predicted velocity exceeds the threshold used in the predictions, a conflict between optimum airspeed and ground speed requirements can occur at some point, and pilots might request a change in the flight plan. Also, ATC may initiate changes by assigning new flight levels and/or velocities. The current air traffic system suffers from a problem which affects both ATC and the airlines. The lack of detail in the flight plan with respect to the desired position as a function of time causes a relatively high number of tactical interventions to maintain adequate separation. This makes it difficult for ATC to optimize airspace capacity and often prevents the airlines to fly the assigned route with the optimum airspeed. Several future scenarios to solve this problem are being investigated and two quite different ones will be briefly discussed. The first one, which is being investigated in the context of the program for harmonized air traffic management in Eurocontrol (PHARE) is characterized by an increasing level of detail with respect to the desired position as a function of time. It is anticipated that through more detailed planning, the number of tactical interventions can be reduced. To preserve airspace capacity, ATC will issue a clearance for a limited volume of airspace by defining a set of position constraints as function of time. The dependence of these spatial constraints on time is the reason the route is often referred to as being 4-D. This concept is not new. Jones et al. (1950) discuss an ATC control system based on *'moving blocks wherein reserved air spaces constantly move in accordance with the intended motion of the aircraft'*. The pictorial situation display which was implemented in a C-47 cockpit showed a planar view of the situation including the moving blocks. They report that *'about 100 pilots have flown this variable-speed, curved-path, moving-block method in a teleran Link trainer'*. Thus, the basic concept for 4-D air traffic management was developed, implemented and evaluated almost half a century ago! Another concept, which is mainly pursued in the U.S. is *free flight*. With free flight, pilots would be permitted to select their own flightpaths in real-time, while controllers intervene only to prevent problems.

Free flight: A safe and efficient flight operating capability under instrument flight rules (IFR) in which operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move toward free flight. (From: Final Report of RTCA Task Force 3 on Free Flight Implementation)

Williams and Green (1991) performed a simulation experiment to investigate a scenario in which some aircraft fly an FMS generated profile which is negotiated with ATC and other aircraft fly an ATC generated profile. They conclude that *'dissimilarities between airborne and ATC-generated speed strategies were found to be a problem under moderate traffic conditions when most of the traffic remained on established routes. The different cruise speeds of the Transport Systems Research Vehicle (TSRV) flying FMS generated speeds and the other traffic flying ATC generated speeds produced potential in-trail conflicts that required controller intervention'*. Another option, in which 4-D equipped aircraft fly an offset-route scenario was also investigated. Both scenarios resulted in significant fuel penalties, and Williams and Green conclude that under moderate traffic conditions *'it therefore appears more efficient for 4-D equipped aircraft to fly trajectories with similar, though less fuel-efficient, speeds which conform to ATC strategy when traffic conditions require speed control by ATC'*. Under conditions of heavy traffic, they obtain different results.

When time-delays forced off-route path stretching, pilots were able to consistently fly controller vectors to absorb time delays while using there 4-D FMS capability to determine the optimum moment to turn back on course yielding an operational benefit.

There is still no consensus about which future scenario can provide the most benefits to the airlines, while allowing ATC to safely manage the traffic flow. However, it is almost certain that the system of using only fixed airways will be abandoned.

To improve airport capacity, multiple glidepath approaches are being investigated as a means to reduce inter-arrival separation while avoiding wake vortices. To allow for a practical implementation of *reduced-separation, multiple glidepath approaches*, Abbot (1985) investigated a display concept which provides the pilot with the information required to be responsible for self-separation under IFR. Abbott (1991) describes the development and evaluation of a time-based closed-loop algorithm to diminish the effects of approach speed reduction prior to landing for the trailing aircraft as well as the dispersion of the inter-arrival times. He reports that the closed-loop algorithm yielded a 6-percent increase in runway throughput as compared to an open-loop algorithm.

For the airlines, the ability to calculate a 4-D route which is optimized both with respect to fuel consumption and time is fundamental to the concept of 4-D navigation. Mallet (1993) presents a bibliographical study about the different ways to generate optimized 4-D trajectories satisfying a set of pre-determined constraints. For the execution of the flight plan, a 4-D navigation capability is needed. A basic requirement is the ability to determine the position of the aircraft. For the safe execution of the navigation task, the pilot must be able to answer the following questions:

1. Where am I and where am I going?
2. Where should I be and where should I be going ?
3. How do I get there?

To answer the first question, the pilot must be able to establish the relation between the ego-centered reference frame (ERF) and the world reference frame (WRF).

The ego-centered reference frame (ERF) corresponds to the pilot's forward view of the world and the world-centered reference frame (WRF) corresponds to a north-up geographic map (Aretz, 1990).

The second question requires knowledge about the 4-D route specified in the flight plan, and relates to a set of desired (3-D) positions as a function of time. The third question addresses the required guidance and control of the aircraft.

Guidance is the determination of a trajectory from a current position and velocity to a desired position and velocity, satisfying specified costs and constraints. Control is the determination of the commands to the vehicle actuators to implement the trajectory, preserving a stable feedback loop.

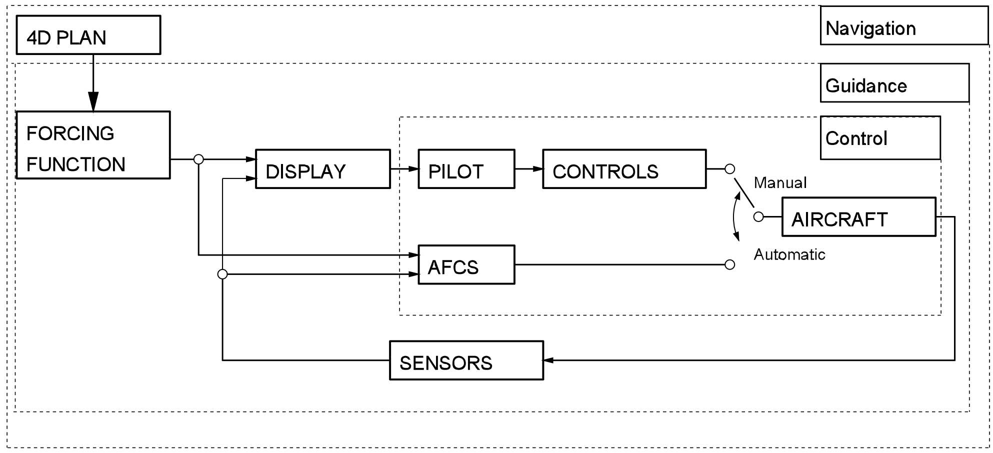


Fig. 2.1. *Overview of the relation between navigation, guidance, and control.*

Fig. 2.1 shows the elements in the navigation, guidance, and control loop. In the navigation loop the flightplan, which is represented by a number of 3-D positions, is converted into a number of straight and curved segments, which together represent the trajectory the aircraft has to fly. In the guidance loop, the deviation from the desired trajectory is used to generate a forcing function representing the short-term trajectory the aircraft has to track. The guidance loop provides the control loop with the desired position as a function of time. During manual control the pilot has to track the forcing function generated in the guidance loop. During automatic control, the automatic flight control system (AFCS) uses the difference between the position estimated by the positioning system and the desired position provided by the guidance loop, to determine the required deflections of the control surfaces. The previous discussion illustrates that in all three loops certain processes are automated. It is a fact that automation has increased safety by reducing certain types of errors, but also that new types of errors have been introduced. Although this thesis is not about automation, it is necessary to discuss some specific aspects which are related to navigation and guidance. A problem with many automated systems is the high degree of coupling, i.e. the many interactions between different systems. Woods (1994) points out that *'changes in automation, through increased coupling, make systems more vulnerable to the latent failure type of system breakdown where multiple contributors come together in surprising ways'*. Furthermore, he states that *'the signature of failure in tightly coupled systems is often misperceived and labeled as simple another case of human error'*. This characterizes many of the problems encountered with today's automation. As a result of the evolutionary approach, the functionality of the flight management system has gradually increased. Since new functionality often has been implemented on top of existing layers, the total possible number of states has increased far beyond what is necessary to achieve the original objectives. This makes the system more complex and more difficult to understand, resulting in questions such as *'what is it doing and why is it doing that'*. More specific information about the problems introduced by automation can be found in the report of Curry (1985) for the first generation of automated systems (Boeing 767, Airbus A310), and for the second generation (Airbus A320) in Sarter and Woods (1995).

2.2 Manual control

The type of control task, and as a result the data which must be presented by the displays, is determined by the flight control system. With conventional flight control systems (FCS), the pilot's manual control task can be divided into two types of control functions: Those which are needed to establish an equilibrium state of aircraft motion and stabilize aircraft motion after disturbances (stabilization), and the maneuvering function which requires the pilot to guide the aircraft along the desired trajectory (guidance). Flightpath tracking may be viewed as an outer-loop control function where the pilot corrects for low-frequency flightpath errors by adjusting commands to the high-frequency attitude control loop. The inner-loop stabilization task has high bandwidth requirements and results in considerable task demanding load. The task itself only uses the capability of the pilot to function as an error-correcting servo-mechanism. With the introduction of fly-by-wire (FBW) technology, the direct mechanical link between the control column and the control surfaces has disappeared. The introduction of an FCS, which processes the pilots rudder and stick or control column inputs and calculates the desired deflections of the control surfaces based on a set of predefined control laws, has made it possible to provide stabilization through the complete flight-envelope. This allows the function of aircraft stabilization to be shifted from the pilot to the closed-loop FCS, thus yielding a significant reduction in task demanding load. As a result, more resources are available for tasks in which the unique human capabilities are more needed. Furthermore, since the FCS can operate over a larger range of frequencies, it allows aircraft to be designed with relaxed static stability yielding the possibility to improve aircraft efficiency. The basic control function of the pilot is to maneuver the aircraft along the desired trajectory. With a FCS, several concepts are possible to translate control inputs to control surface deflections in order to obtain the desired system state. Two different concepts which will be mentioned here are *pitch rate command/pitch-angle hold* and *flightpath-angle rate command/flightpath-angle hold*. The first term in these descriptions refers to the variable the pilot controls through longitudinal stick or column inputs. The second term refers to the state of the system once the input is removed. With a pitch rate command system, the pilot controls pitch rate through longitudinal stick or control column movements and once the desired pitch angle is obtained the stick is returned to its neutral position. In this concept, engine thrust is controlled by means of the thrust levers. To change either the velocity or the flightpath angle (FPA) while keeping the other constant, control of both pitch and thrust is required. Thus, due to the coupling between attitude and airspeed, the pilot has to make multiple inputs to independently control a single output of the system. With a flightpath-angle rate command system both the deflections of the control surfaces and the required change in thrust are controlled by the FCS to match the actual FPA with the commanded FPA while keeping velocity constant. When extending the concept to *integrated flightpath and propulsion control* (IFPC), the FCS also manages engine thrust to match the actual velocity with the commanded velocity while keeping FPA constant. Thus, it is possible to directly control flightpath angle with longitudinal stick movements and velocity with the thrust levers, yielding a more task-oriented control concept. Since the parameters of interest are now controlled as single-input single-output systems, complexity, and as a result task demanding load is reduced. Since the FPA is identical to the vertical direction of the inertial velocity vector, the concept is also referred to as longitudinal velocity vector control-wheel steering (Lambregts and Cannor, 1979). With an approach based on the total energy control system (TECS), the structured design of an IFPC system is possible (Lambregts, 1983a, 1983b). Lambregts and Cannor (1979) discuss the development and evaluation of a longitudinal velocity vector control-wheel steering mode to reduce task demanding load and improve efficiency and safety. Their findings indicate that such a radical change in control concept also necessitates a change in the displays to maintain good control-display compatibility. These changes relate to the symbology representing the parameters under control. In a later study (Steinmetz, 1986), a change in the frame of reference for the attitude indicator is evaluated to make the primary cues presented by the display more compatible with the control inputs. Lambregts (1995) proposes that in a future flight control system, manual and automatic modes share a full-time inner-loop control augmentation algorithm that provides the desired aircraft control dynamics over the entire envelope. He argues that since numerous studies have shown that flightpath angle based control yields the most effective, lowest task demanding load and safest manual control concept, vertical and horizontal flightpath angle should be chosen as the reference control variables for manual control.

Although a task-oriented control and display system would be the ideal situation, even in the absence of a task-oriented control system, a task-oriented display can already reduce task demanding load.

2.3 Supervisory control

Almost all large commercial aircraft are equipped with an autopilot. Since the certification of the successful fail-passive dissimilar design of the flight control computers (FCC) for the Boeing 737-300 in 1984, most of the FCC's use the approach of dissimilar redundancy. Lachmann and McKinstry (1975) discuss an automatic guidance and control system for accurate position control of an aircraft along a curved four-dimensional path. Kaminer and O'Shaughnessy (1989) describe an approach in which the total energy control system (TECS) concept is adapted for 4-D navigation.

> The technology needed to automatically fly four-dimensional curved approaches exists for more than ten years. It is very likely that this capability will soon be introduced in commercial aircraft.

During supervisory control the pilot monitors the system state and the actions of the autopilot.

> The role of the pilot is to compensate for the limited flexibility of automated systems in the event of an unforeseen circumstance for which the system was not designed. To exploit the flexibility of the human operator, the system must be designed so that the pilot is able to safely and rapidly respond to unexpected events.

For effective supervisory control, it is crucial that the pilot has the ability to inspect and verify the goals of the autopilot system. Based on these goals, he uses the information about the desired state and the actual state to make an assumption about the future actions of the autopilot, which requires an understanding of the autopilot. This understanding is expressed as the pilot's *internal representation* (Stassen et al., 1990) of the autopilot system. It is apparent that the quality of the internal representation which the pilot uses to predict the future system state is directly related to the probability with which the pilot makes the correct assumptions. Dangerous situations arise when there is a mismatch between the perceived and the actual system state or between the perceived and the actual goals of the autopilot. Bailey (1982) stressed this by stating that: *'If the automated system does not support the maintenance of an accurate internal representation, the operator may not recognize the relevance of new information to information stored in long-term memory'*.

> The displays should present the information in such a way, that it enables the pilot to continuously and accurately update his internal representation.

A difference between the pilot's predicted actions and the actual actions of the autopilot will result in a decrease in his confidence level. If this level exceeds a certain threshold, he will intervene. The variety of different modes in which the automation can operate in combination with the absence of visual feedback indicating the underlying hierarchy often results in an incomplete internal representation. This makes it hard to keep up with the automation and can cause so-called *automation surprises*; situations in which the automated systems act in some way outside of the expectations of their human supervisors. Sarter and Woods (1995) investigated the properties of advanced cockpit automation and their impact on human-automation interaction. They distinguish between three different categories of automation surprises: Situations where the automation fails to take an expected action, situations where the automation carries out an action that was not explicitly commanded by the pilot, and surprises related to system failures that do not involve salient system indications to alert the pilot to the problem.

Displays must unambiguously convey the goals of the autopilot, for example by presenting the future forcing function in combination with the planned control actions.

Another problem often encountered when automation replaces certain functions which sometimes still must be performed manually is out-of-the-loop performance. The out-of-the-loop performance problem refers to situations in which operators of automated systems are handicapped in their ability to take over manually in case of an automation failure.

As a sudden take over of the pilot mostly occurs in case of a problem, displays should be designed so that the automation deficit is minimized.

Wilckens and Schattenmann (1968) already stressed the importance of adequate displays for supervisory control by stating that *'the human pilot will have to monitor the safe operation of the autopilot and should still be able to take over and complete the landing safely. This should be possible in spite of the probably lower training level, reduced by the extended automatic operation'*. Out-of-the-loop performance can be linked to two major issues associated with the implementation of automation: Loss of manual skills and loss of awareness of the state and processes of the system (Endsley and Kiris, 1994). With respect to loss of proficiency, Wiener and Curry (1980) mention that *'although there has been no specific accident or incident in which loss of flying proficiency has been cited as a contributing factor, individuals involved with pilot training have noted perceptible skill losses in pilots who use automatic equipment extensively'*. It is also mentioned that *'many crew members seem to have discovered the loss of proficiency on their own and regularly turn off the autopilot, in order to retain their manual flying skills'*. Similar comments are made by pilots who participated in a later study (Curry, 1985).

Displays should present the guidance data in such a way that they support pilots in retaining their manual flying skills.

2.4 Safety

The only certainty is that the unexpected will happen (unknown).

2.4.1 Introduction

In the chains of events which might ultimately result in an accident, the function of the pilot is to timely detect deviations and factors which might cause deviations from normal conditions and deal with them in a maximally efficient way. The possibility of detecting abnormal situations and accurately recognizing their significance is determined by the pilot's ability to perceive data containing relevant information and integrate it with already available information. The detection of events is determined by the detection threshold. The optimal threshold has to result from a trade-off between the false-alarm rate and the probability of a missed detection. This process is very similar to the integrity monitoring performed in for example GPS receivers. Here too, a context dependent detection threshold can improve performance relative to a fixed detection threshold. This smart behavior is something, humans are very good at. Based on information in working memory regarding the current situation and experience (long term memory), human operators have the capability to anticipate, focus attention and dynamically adapt their detection threshold. Their unique pattern matching capabilities allow operation with rather poor signal to noise ratios. Furthermore, humans are excellent in their ability to integrate perceived information with already existing information. These properties make them hard to approach by automation for the detection and qualification of events in complex situations. With respect to achieving a solution when confronted with unexpected and previously unencountered situations, humans have the ability to resort to knowledge-based behavior. Furthermore, they excel in their ability to deal with ambiguity, once recognized, by requesting more information through the appropriate channels. An important factor influencing the ability to deal with unexpected situations is knowledge about the constraints. This knowledge determines the domain space in which a solution can be generated. Because the constraints generally increase with increasing time, the ability to achieve a solution decreases with an increase in detection time.

For the design of an MMI which increases safety, the fundamental question is how the unique capabilities of the human operator can be exploited in order to achieve this. The pilot must be aware of the danger, aware of the cause, and aware of the options.

A term which is closely related to the pilot's ability to detect and cope with unexpected events and will therefore be discussed in the next section, is situation awareness.

2.4.2 Situation Awareness

Many accidents and incidents caused by pilot error, or in which the pilot was an essential component in the chain of events, are contributed to a lack of what is referred to as *situation awareness*. This raises the question of what is meant by situation awareness. The term *awareness* suggests conscious knowledge. Various definitions of situation awareness have been proposed since it was introduced. Sarter and Woods (1991) define situation awareness as *'accessibility of a comprehensive and coherent situation representation which is continuously being updated in accordance with the results of recurrent situation assessments'*. Vidulich (1992) defines situation awareness as *'the capability to appropriately assess yourself, your system, and your environment in order to make the right decision at the right time'*. Endsley (1988) defines situation awareness as *'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'*. The problem with the concept of situation awareness is that the term itself is so general that it leaves room for all kind of different interpretations. This raises for example the question whether situation awareness should be regarded as specific ability or as a criterium against which different designs can be compared. Wickens (1995) approaches the definition of situation awareness from two directions, one based on the formal definition of its components, the other through the consensus definition which has emerged from the community of researchers and pilots which have been most concerned with the concept. To obtain a consensus definition which represents the format one he proposes: *'Situation awareness is the continuous extraction of environmental information about a system or environment, the integration of the information with previous knowledge to form a coherent mental picture, and the use of that picture in directing further perception, anticipating and responding to future events'*.

In an attack on the concept of situation awareness, Flach (1994) argues that it *'if we have a theory that provides a comprehensive and coherent situation representation, then we have a basis for designing effective displays and training programs and explaining likely errors; and no inferred mental constructs such as situation awareness will be required'*. However, there is a consensus definition and situation awareness is often used as a reference in experiments in which pilots rate a certain design in terms of situation awareness. As a result, we cannot simply ignore the concept of situation awareness. To further complicate the situation, misleading/ambiguous information may lead to false awareness which is perhaps even worse than a lack of good awareness. When an operator realizes that he lacks needed information he is likely to actively search for it. In contrast, if he thinks he is aware, he might be less motivated both to search for and accept new information contradicting his current 'awareness' due to confirmation bias. An example of such a situation is cited by Wickens (1995) with respect to the Strasbourg A320 accident: *'It appears that the pilots were unaware that they were unaware'*.

Summarizing, although situation awareness is still a widely debated concept there seems to be a general consensus about what it represents. Since the concept of situation awareness is used to derive design guidelines (Endsley, 1995) and as a measure to evaluate designs (Prevett and Wickens, 1994; Parrish et al., 1994; Regal, 1995), it is important to understand what is meant by it in the specific context. This raises the following two questions: How to deal with situation awareness when examining previous research and how to deal with it when justifying design decisions.

To deal with situation awareness when examining previous research, the exact meaning of it in the specific context in which it was used must be recovered. To increase the level of detail of Endsley's (1988) definition, Pew (1994) proposes the following description for situation: *'A situation is a set of environmental conditions and system states with which the participant is interacting that can be characterized uniquely by its priority goals and response options'*. Fortunately, in many cases the term situation has been replaced by more task specific indications.

Examples are spatial awareness (Parrish et al., 1994), navigational awareness (Aretz, 1990), global awareness (Prevett and Wickens, 1994), terrain situational awareness (Kuchar and Hansman, 1993), and mode awareness (Sarter and Woods, 1995). With respect to navigation and guidance display research, situation awareness mostly refers to the knowledge of the pilot regarding the position and orientation of his airplane relative to the environment and the elements in this environment which have relevance for the navigation task. Aretz (1990) discusses the concept of navigational awareness which he defines as *'the pilot's knowledge of the aircraft's current location and heading in the ego-centered reference frame relative to the desired course in the world-centered reference frame'*. If the pilot is successful in relating the ego-centered reference frame to the world-centered reference frame, navigational awareness will be achieved. Otherwise, disorientation will result. Prevett and Wickens (1994) refer to global awareness as *'knowing where things are in three-dimensional space, both with respect to one's momentary position, and with respect to a more stabilized coordinate system'*. To make a clear distinction between spatial, navigational and global awareness, a slightly different definition of navigational awareness is used in this thesis.

Spatial awareness is the ability to determine the relation between the ego-centered reference frame and the world-centered reference frame. Navigational awareness is spatial awareness with the ability to predict the future relation between the desired ego-centered reference frame and the world-centered reference frame.

Spatial awareness involves knowledge about position, attitude, and heading. Several components can be relative, for example: The position is known relative to a certain reference point, or the current heading is known relative to the desired one. Relative information about altitude can be obtained from the distortion of the vertical symmetry of the flightpath. For safe operation, absolute knowledge about attitude and altitude is required, and thus a reference is needed. Such a reference can be integrated in the perspective flightpath, or presented separately. One of the first studies into the ability of pilots to obtain a certain level of spatial awareness was performed by Eisele et al. (1976), although the term spatial awareness was not coined yet. Their research addressed the isolation of minimum sets of visual cues sufficient for spatial orientation in ground referenced aircraft landing approaches. Subjects were presented with a static perspective image of a scene containing a number of cues, from which they had to estimate their position errors. Four contact analog elements, the runway outline, the runway centerline, the touchdown zone, and a texture grid were used to provide real-world cues. Synthetic guidance data was included by means of T-shaped poles representing the desired flightpath. Eisele et al. (1976) concluded that *'the accuracy and speed of judgements are enhanced more by the presence of synthetic guidance information than they are by the perspective projection of any combination of four contact analog elements representing the real-world visual scene on approach to the airport'*.

Navigational awareness can be considered as the part of global awareness which concerns the trajectory. Similar to spatial awareness, navigational and global awareness can also be relative or absolute. Relative navigational awareness comprises knowledge about future changes in heading and flightpath angle of the desired trajectory. The minimum level can be defined as the fact that knowledge about such a change is present, whereas a higher level can be related to the level of detail of this knowledge. Such detail can comprise the time and distance to the change, the rate of change, and the magnitude of the change. Therefore, navigational awareness is divided into detection, qualification, and quantification of elements and their properties. In the context of Endsley's definition of situation awareness, detection refers to the perception of the elements, while qualification and quantification refer to both the process of comprehension and projection into the future. The need for qualitative or quantitative awareness should be addressed by specific task demands. The question: "How accurate is the pilot able to estimate a change in the direction of the future flightpath?" addresses relative quantitative navigational awareness. The question "How accurate is the pilot able to estimate the future desired heading?" requires the pilot to establish the relation between his ERF and the WRF, and addresses absolute quantitative navigational awareness. Relative navigational awareness can be obtained through the geometry of the flightpath. However, absolute navigational awareness requires a reference, for example a heading tape. Information about the time and distance to a change in the trajectory may influence the timing of the pilot's other tasks, and determine the possibility of anticipatory control. The ability to obtain knowledge about the rate of change will influence the magnitude of the pilot's anticipatory control action, whereas knowledge about the magnitude of the change can be used to anticipate the future stabilized ERF-WRF relation.

The justification of design decisions in the context of situation awareness requires a way to indicate the contribution of the design to the pilot's ability to achieve and maintain an adequate level of situation awareness. When a human operator has to perform a certain task, the information needed for the task can be divided into elements which are of immediate importance and elements which allow the operator to anticipate future task requirements. The knowledge resulting from the process of acquiring the needed information through perception, interpretation, and extrapolation into the future is nicely captured by Endsley's (1988) and Wickens's (1995) definition. Based on the task dictated information requirements, a method for data presentation must be developed which minimizes the effort for perception, interpretation and evaluation. If an MMI satisfies these requirement and maximizes the possibility that the operator translates the data into the required information, adequate situation awareness should result. As such, designing for situation awareness is nothing new. It is just a compact way of summarizing the many requirements which must be satisfied to maximize the possibility that the abilities and limitations of the human operator are adequately considered in the design process. In this context, Flach's (1994) attack on the concept of situation awareness becomes very understandable. Many guidelines exist on how to present information, once it has been identified as necessary. The major bottleneck in this process is the identification of all task requirements and the resulting identification of all required information and the relative priorities and then finding the appropriate guidelines with a satisfactory level of detail.

2.5 Problem analysis and requirements definition

The basic reason for having a human operator in the navigation loop is the flexibility to cope with events for which the automation was not designed. The MMI should present the pilot with current and future task requirements, provide him with the information needed to perform these tasks, keep him aware of events which threaten safety, and provide information about the constraints within which the pilot can operate. The format of the presentation should aim to minimize the cognitive effort required to extract a meaning from the presented data. To determine whether and how MMI improvements can increase the safety of aircraft navigation, the potential causes of incidents and accidents must be identified. Next, all chains of events leading to these causes must be investigated, and the possibilities of the human operator to detect indications and to respond in a way which maximizes the possibility of returning to safe operational conditions. This analysis should be used to investigate how current MMI's provide the human operator with the information required to maintain safety and where improvements are possible, either through enhancements or new approaches. In Fig. 2.1 the relation between navigation, guidance, and control was illustrated. Both errors in the control loop and errors in the guidance loop can cause a navigation accident. To show how a certain combination of events can result in a navigation accident, a risk tree was created. The potential threats which can cause a navigation related accident are divided into those which originate in the control loop, thus affecting aircraft stability, and those which originate in the guidance loop, causing a collision. A guidance error can only cause an accident if the aircraft is guided to a location where a safety hazard is present and this safety hazard is not detected in time to avoid it. Three different types of safety hazards, namely *fixed objects*, *moving objects* and *adverse weather*, have been used to further classify navigation accidents caused by a guidance error. This classification serves as the basis for the risk tree presented in Fig. 2.2.

As can be seen from Fig. 2.2, the nature of the accident has been divided into *loss of control*, *collision with fixed object*, *collision with moving object* and *accident due to weather*. The *and* gates below these four categories show the required contributing factors. The guidance error is further subdivided into a *forcing function error* and a *position error*. The only external cause which is considered is weather. Other external causes such as terrorist attack or surface to air missiles are not included in this discussion. Fig. 2.2 shows that a navigation accident caused by a guidance error can be prevented through timely detection of the error itself or the safety hazard. Thus, guidance displays should contain features which maximize the probability that the pilot detects these events. In the following sections, the four categories which have been introduced to classify the nature of the navigation accident will be discussed in more detail.

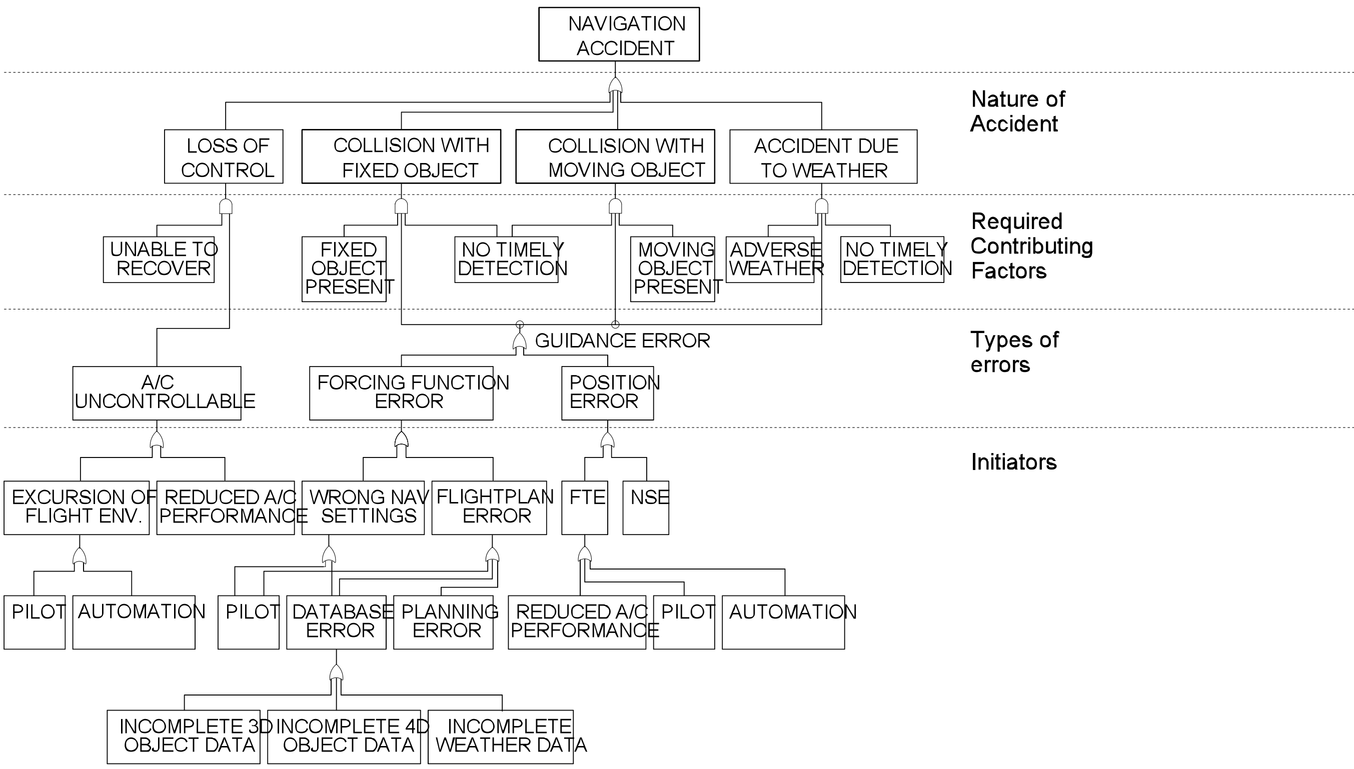


Fig. 2.2. *Risk-tree showing the events which can result in a navigation accident.*

2.5.1 Loss of control

With respect to the excursion of the flight envelope, this can be caused by pilot action, automation, and combinations of both. Several incidents and accidents have occurred due to a combination of a pilot's misinterpretation of the automation's goals and authority problems between pilot and automation. Examples are the Airbus A300-600 accident in Nagoya (Mecham, 1994), the Airbus A330 accident in Toulouse (30/6/94) and the Airbus A310-300 incident in Orly (24/9/94). In the Nagoya accident, the take-off/go-around levers were inadvertently activated. As a result, autothrust and flight director reverted to go-around mode. The aircraft deviated from the glide slope and the crew applied a nose-down input. The attempt to recapture the glide slope failed, and the autopilot was engaged. The resulting struggle between the pilot and the autopilot ultimately resulted in a stall from which the aircraft could not be recovered. In the Toulouse A330 accident, the autopilot was set for altitude capture at 2000 ft. In the *autopilot altitude acquire mode*, pitch limit protection is not engaged. Immediately after take-off with thrust set in take-off go-around mode, the left engine throttle was reduced to idle as part of a test. The autopilot tried to capture the preset altitude and aircraft pitch rapidly increased to 29 degrees. The alpha floor (angle of attack) protection feature increased power on the left engine, but the pilot reduced thrust on the right engine to easy asymmetric thrust conditions which interrupted the alpha floor function. These actions got the aircraft in an uncontrollable stall and it crashed approximately 45 seconds after liftoff. These are only a few examples of accidents in which an important contributing factor was the pilot's unawareness of the actual goals of the autopilot.

A potential improvement in safety can be achieved through a better presentation of the goals of the autopilot system and the constraints.

2.5.2 Collision with fixed object

The category *forcing function error* has been introduced to cope with the different methods in which a reference trajectory is specified for either manual guidance or automatic flight. The possibilities range from 1-D settings such as altitude capture, altitude hold, speed hold, and heading hold to the use of a 4-D flight plan (Fig. 1.1). Errors can result from the planning process, erroneous MCP settings, or ATC. An example of a wrong MCP mode setting is the 3300 ft/min vertical speed instead of 3.3 degrees flightpath angle resulting in the Strasbourg accident with the A320 (20/1/92). An incident with an A320 at Gatwick (3/7/88) which almost landed three miles short (Hughes and Dornheim, 1995) was also caused by this mistake. Johnson and Pritchett (1995) performed an experimental simulator study to test pilot detection of an error in autopilot mode selection. They reported that most pilots showed a lack of awareness of the commanded descent mode and were confused by the resulting aircraft states, and that 10 of the 12 pilots involved did not act prior to significant glidepath deviations. A presentation of the aircraft's position and orientation relative to the current and future forcing function (trajectory preview) provides cues which can be used to early detect abnormal situations. This feedback allows the pilot to identify wrong navigation settings or flight plan errors.

By integrating trajectory preview with data about constraints, settings which do not satisfy the constraints can be detected.

Hansman et al. (1992) discuss two experiments in which pilots sometimes received ATC vectors into terrain. They report a hazard recognition rate of 3% with current paper charts. In a comparison between the effectiveness of spot elevation symbols versus smoothed contour depiction, they report hazard recognition rates of approximately 22% for the situation in which pilots assumed that ATC was providing terrain clearance. To increase the pilot's terrain awareness, terrain contour information is being added on new approach charts (Steenblik, 1994). Hansman et al. (1992) also report an increase in recognition rate to 78% once pilots recognized that sometimes erroneous vectors were issued. These results illustrate that although terrain depiction increases hazard recognition rate, methods to reduce the confirmation bias are needed. Such methods must attract the pilots attention and motivate him to recheck his assumptions. Database errors, however, still go undetected and the integrity of current terrain databases is several order lower than required.

Due to insufficient integrity of current terrain data bases, integration of terrain data may be used to increase the pilot's awareness but not for actively maintaining separation from the terrain.

Since the 4-D flight plan promises a conflict-free route, this poses high integrity requirements on the data used to generate the flight plan. In the discussion concerning the reference path definition with the global positioning system landing system (GLS) it is stated that (Boeing, 1995) *'a key decision yet to be finalized is whether or not the final approach path definition will be stored on-board in a high-integrity database or will be uplinked by the ground station'*. It is generally believed that uplinking the path points will greatly reduce airline logistics concerns and will result in the highest integrity system possible. To increase the integrity of the flightpath database, Kelly and Davis (1994) propose the addition of a third independent point between the final approach fix (FAF) and the glidepath intercept point (GPIP) to verify the straight line defined by the FAF and the GPIP. Both traffic management and database integrity are fundamental to safety and thus extremely important. They are, however, not unique for the MMI discussed in this thesis but apply to all potential guidance concepts requiring information about their environment for navigation purposes. As a result, it is not considered a factor which might hamper the application of a certain MMI in favor of another one.

Due to system limitations, errors result. The total system error (TSE) of an aircraft consists of a navigation system error (NSE) and a flight technical error (FTE). The NSE is the difference between the true position of the aircraft and the position as estimated by the positioning system. It results from the inherent limitations with respect to the accuracy of the positioning system. The FTE represents the difference between the desired position of the aircraft and the position reported by the positioning system. In the absence of additional references, a change in NSE cannot be distinguished from a change in FTE and causes the navigation displays to show the same change in position as a change in FTE would. As a result, it is likely that a change in NSE will be perceived as a change in FTE. Thus, in general an NSE cannot be identified as such by the pilot. It results from the inherent limited accuracy of the positioning system. A FTE results from imperfect tracking by the pilot or the automation. It can also occur when due to reduced aircraft performance it is no longer possible to track the predefined forcing function. An example of an accident in which the automation stopped to perform the tracking function and the pilots remained unaware of this is the crash of an Eastern Airlines L-1011 into the Everglades in December 1972 (NTSB, 1973). This example stresses the importance of adequate displays for the supervisory control task.

The displays should indicate the performance of the automation relative to the current and future requirements in a compelling way.

To cope with the limited accuracy of positioning systems and the occurrence of flight technical errors, separation standards have been introduced. When an aircraft leaves the area defined by the separation standards, the possibility of a collision arises of which the occurrence is uncertain. The only satisfactory description of uncertainty is probability (Lindley, 1987). Not considering a probabilistic approach leads to standards based upon worst-case analysis, which is economically inefficient. At present, regulating authorities require mandatory carriage of specific equipment for air navigation, thus constraining the optimum application and implementation of modern airborne equipment. A potential solution is the application of the required navigation performance (RNP) concept, which was first proposed by Davis at the Air Transport Association (ATA) Operation Forum in San Diego in 1991 (Kelly and Davis, 1994). The RNP defines an aircraft containment surface about the nominal flightpath, called a tunnel, which specifies the allowed approach and landing flightpath limits. This tunnel is specified by four RNP parameters: Accuracy, integrity, availability, and continuity. In the RNP concept, 95% of the distribution of the TSE must be within the inner tunnel. Thus, the accuracy parameters define a TSE surface around the aircraft. The big advantage of the RNP concept is that it is an airspace system function and not a navigation sensor function, and thus allows airspace requirements to be satisfied independently of the methods by which they are achieved. Kelly and Davis (1994) present an in-depth discussion of the RNP concept including a methodology to determine the RNP for aircraft precision approach and landing under IMC.

2.5.3 Collision with moving object and adverse weather

In general, the pilot has no possibility to detect an error in the 4-D object data or in the weather data until he can perceive cues about the impeding event itself. The likelihood of detection can be improved by using onboard sensors to detect these phenomena at a greater distance and display them to the pilot to increase his awareness of these potential threats. Examples of systems to detect adverse weather phenomena are weather radar and windshear detection. An example of a system to detect other aircraft which might impose a safety threat is the traffic collision avoidance system (TCAS).

To provide pilot's with a picture of the surrounding traffic, the so-called cockpit display of traffic information was developed (Palmer et al., 1981). Ellis and McGreevy (1983) compared plan-view projections with perspective projections of cockpit displays of traffic information (CDTI). They report that pilot maneuvered somewhat earlier with the perspective format and more often maneuvered in the vertical dimension. They conclude that with the plan-view display the tendency to maneuver horizontally results from the poorer presentation of the vertical dimension. In the context of free flight, this CDTI concept has recently received new attention.

Besides midair collisions, aircraft collisions on runways occur due to runway incursions. In 1990, 281 runway incursions (0.43 events per 100.000 airport operations) were reported of which two resulted in incidents. In 1993 the number of events declined to 0.30 per 100.000 operations and in 1994 it was 0.33 (Phillips, 1995). Runway incursions can be reduced by providing better guidance and the number collisions can be avoided by providing systems which allow earlier detection of intruders, especially under poor visibility.

By providing the pilots with information about other traffic, they can take a more active role in maintaining adequate separation.

A data link can be used to uplink information about traffic and weather. In 1991, NASA Langley performed a series of in-flight evaluations in which a data link was used to transmit ATC instructions and weather information (Phillips, 1992). Pilots commented that they wished they had the cockpit weather information needs (CWIN) system today (Phillips, 1993). In 1992, NASA demonstrated the feasibility of receiving weather data directly from weather satellites during flight (AW&ST, 1992). A particularly dangerous phenomenon is windshear. If a sustained energy-reducing windshear (decreasing headwind, down draft, or increasing tailwind) takes away aircraft energy faster than engine thrust can add it back, a flight safety hazard exists. Since 1964 windshear has been a causal factor in at least 26 U.S. air carrier accidents, resulting in more than 500 fatalities and 200 injuries. To detect the presence of a windshear in advance, sensors are required. In 1986, NASA and the FAA initiated a joint program to investigate the feasibility of remote airborne windshear detection. Both radar and lidar (light detection and ranging) are used as sensors to detect the presence of windshear (Lewis, 1993). When microburst conditions are accompanied by moderate to heavy rains (*wet micro bursts*), a radar has a highly visible target to measure. However, micro bursts and other forms of windshear may contain little or no rain at low altitude (*dry microburst*). The wavelength of a laser signal is much smaller than that of the radar and reflects from aerosol particles carried in the atmosphere at low altitude. As a result, lidars can measure wind velocities in clear, dry air. Lewis (1993) reports that preliminary observations show the airborne radar detection performance to be excellent over a wide range of meteorological conditions, the lidar showed acceptable detection performance in dry micro bursts, and that a significant advance warning of up to a minute or more was provided. After a three-year certification process, the first commercial carrier use of a predictive windshear system occurred on November 30, 1994 (Finneran, 1995).

Recent developments allow the timely detection of windshear. One should, however, also design for the possibility that a windshear is encountered.

Besides presenting preview on future events, the displays should allow the pilot to be maximally effective under adverse weather conditions. Oliver (1986) indicates that to successfully cope with windshear, a pilot primarily requires two things: The earliest possible recognition of its presence and the ability to optimize aircraft performance thereafter. Piloted simulation tests have shown that as few as 20 sec of warning allow a pilot to add engine power and fly through even very strong windshear conditions with minimum altitude or airspeed loss. With respect to optimizing performance during a windshear encounter, Oliver (1986) states that *'for optimizing performance* *in severe shear conditions, the pilot needs an instrument display that includes a direct representation of the flightpath: The pilot needs to know where the aircraft is going, not merely where it is pointing'.* Whereas in more stable conditions, the flightpath can be assessed and controlled with sufficient precision and timeliness by reference to an attitude display, in violent and dynamic conditions associated with a microburst, this capability breaks down.

To be effective in windshear, a display must portray the aircraft's actual flightpath integrated with an efficient, confusion-free display of airspeed and angle of attack, and the altitude above terrain (Oliver, 1986).

2.5.4 Conclusion

The analysis of the different factors which can cause a navigation accident have provided a number of guidelines which must be taken into account when specifying format and functionality of an MMI for 4-D navigation. These guidelines will be used for the specification of an initial implementation, which will be discussed in Ch. 6.

2.6 Displays

2.6.1 Introduction

To be able to determine whether and how future improvements are possible, one must understand why and how tasks were performed in the past. When flying in visual meteorological conditions (VMC), most of the information needed for guidance and navigation can be obtained from cues present in the outside-world view. Lateral position and heading can be estimated by comparing landmarks in the visual scene with landmarks on a map. This of course requires some mental processing, but results in a fairly good spatial awareness. The accuracy and resolution with which estimates of the position and velocity of the aircraft can be made from the view through the windshield depend on altitude. In reduced visibility, the required features in the 3-D environment may not be perceivable. Furthermore, the environment might present misleading cues. This necessitates the presentation of data by means of instrument displays.

2.6.2 Navigation and guidance instruments

The displays presenting the information used to be electro-mechanical. Often, the limitations of these instruments determined the method of information presentation, and as a result man has to adapt to the machine. In the eighties, the electronic flight instrument system (EFIS) was introduced on the flightdeck of commercial aircraft. The main reason for the introduction of the EFIS was the possibility to present multiple instruments on a single display and to present only the necessary information at a certain moment, thus offering the possibility to reduce the total number of instruments in the cockpit. The formats used to present the information often were imitations of the electro-mechanical instruments they replaced. The potential for improvement in the information transfer from machine to man, made possible by the flexibility of programmable display systems, was certainly not used to the full extent. Today's guidance and navigation displays employ singular and sometimes dual dimensional data presentation methods. 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 effort, time, and may introduce errors.

Conventionally instrumented aircraft are equipped with an attitude director indicator (ADI) and a horizontal situation indicator (HSI) for the presentation of guidance and navigation data. The ADI can present guidance commands by means of a flight director. The HSI presents heading and lateral displacement data. In aircraft which are equipped with an EFIS, guidance data is presented on the primary flight display (PFD), whereas navigation data is presented on the navigation display (ND). A typical PFD format contains an ADI, velocity and altitude tapes, and mode annunciators. A typical navigation display can present an HSI combined with a depiction of the desired route and waypoints. Furthermore, data regarding true airspeed, ground speed, wind velocity and direction, vertical deviation from the desired flightpath, distance and time to waypoints, and the navigation sensors used is often depicted. Fig. 2.3 presents an example of a display format for a navigation display which is representative for current aircraft equipped with an electronic flight instrument system.

Several methods to present guidance data exist. Guidance displays can be divided into a category presenting status data and a category presenting commands. Furthermore, several dimensions of data can be integrated into one guidance display. Table 2.1 gives an overview of the possibilities.

Table 2.1 *Categories of guidance displays*

	Status	Command
1-D	Glideslope, localizer	Flight director bars
2-D	Flightpath vector	Single cue flight director
3-D	Flightpath	Lead plane

The localizer and the glide slope indicators are examples of one-dimensional (1-D) status displays for guidance. They present the pilot with an indication of the angular deviation from the approach path. The horizontal and vertical flight director needles are examples of 1-D command displays, and the single-cue flight director is an example of a two-dimensional (2-D) command display.

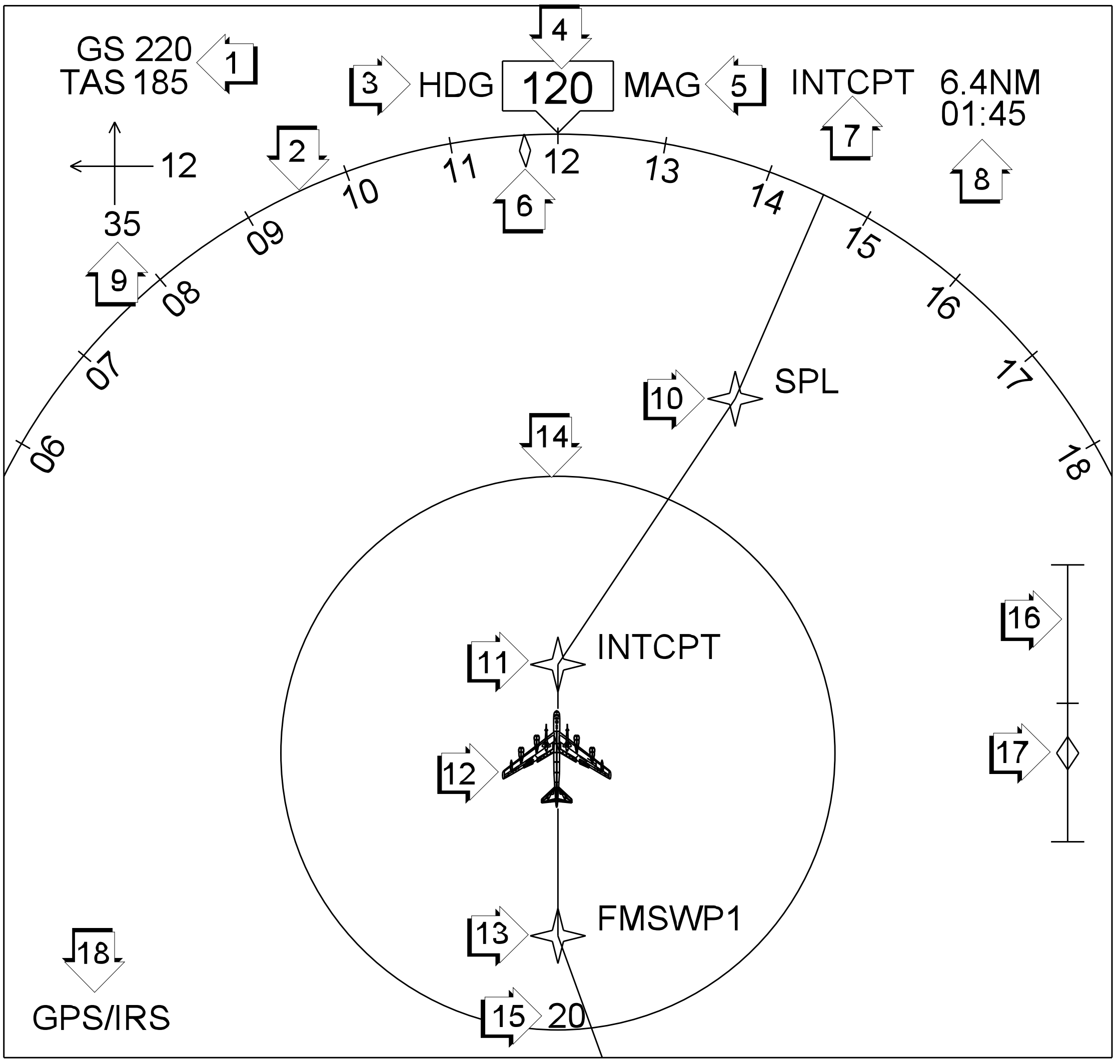


Fig. 2.3. *Typical navigation display format.*

1. *Indicators for ground speed (GS) and true airspeed (TAS).*
2. *Heading/track scale.*
3. *Indicator whether display is heading up (HDG) or track up (TRK).*
4. *Digital heading/track indicator.*
5. *Indicator whether heading is magnetic (MAG) or true (TRUE).*
6. *Aircraft track.*
7. *Name of next waypoint.*
8. *Distance and time to next waypoint.*
9. *Wind display (35 kts tailwind and 12 kts crosswind).*
10. *Waypoint.*
11. *Position of next waypoint.*
12. *Aircraft symbol indicating current location.*
13. *Location of previous waypoint.*
14. *Range circle.*
15. *Indicator for radius of range circle.*
16. *Vertical deviation scale.*
17. *Symbol indicating vertical deviation.*
18. *Indication of navigation sensors used.*

Fig. 2.4 presents an example of a conventional guidance display with command and status data.

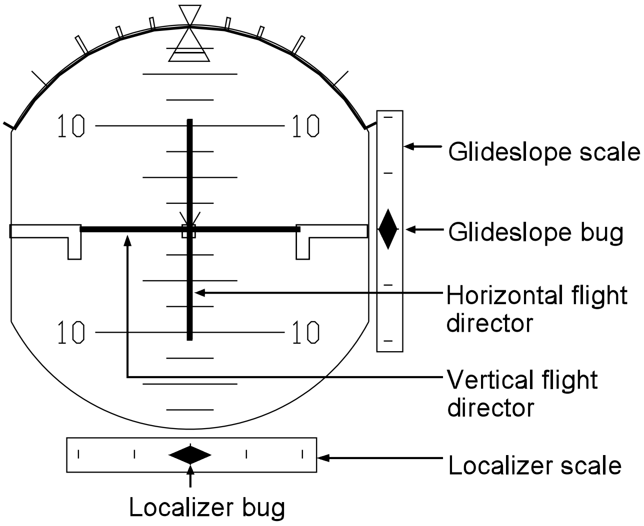


Fig. 2.4. *Conventional guidance display. The flight director bars present steering commands. The glideslope and localizer bug indicate the angular deviations from the desired path.*

The glide slope/localizer and the flight director display originated as electro-mechanical instruments, and since the introduction of the EFIS, they have been presented on the PFD. During an approach, pilots have to estimate the flightpath angle (FPA) of the aircraft. The flightpath vector, a 2-D status display, indicates the direction of travel (velocity vector) of the aircraft, and thus presents the pilot with the FPA. A *tunnel-in-the-sky* display is an example of 3-D status data, whereas a perspective lead-plane is an example of a 3-D command display.

2.6.3 The flight director display

The conventional instrument for the guidance task is the flight director display that presents steering commands. It originated in a time when the flexibility in data presentation was determined by the limitations of the electromechanical instruments, and the method of data presentation has not changed since. Optimization of the MMI was a single domain approach. Flight director commands are based on a weighted combination of position and angular errors, presented in one dimension. The design of flight director control laws is a typical control engineering problem, based on an analysis of the closed-loop behavior of the system, which requires a model of the pilot's control behavior. Several design methods have been developed (McRuer et al., 1971; Curry et al., 1977; Hess, 1977). The commonality between the different methods is that they all model the pilot as a servo-mechanism with some inherent limitations. The methods differ on complexity of the pilot model. The two most widely used are the cross-over model (COM) (McRuer and Jex, 1967) and the optimal control model (OCM) (Kleinman et al. 1970). Both methods have successfully been applied to the development of flight director displays. Although with a flight director a high tracking performance can be achieved, a flight director does not contribute at all to the pilot's navigation awareness.

As a result of the integration of multiple variables into a single dimension, the pilot is unable to extract information about the specific guidance errors from the flight director display.

The error-gains of the display are determined by the flight director algorithms. Since the deviation indicated by the flight director has no physically interpretable meaning, the pilot has no way of knowing how ‘wrong’ a certain deviation is. As a result, the pilot’s possibility to make a trade-off between the effort spent on tracking the commands and the resulting performance is very limited. In situations where the required performance is less than the performance for which the gains have been determined, the pilot is forced to spend more effort than needed to keep the aircraft within the constraints. Finally, the flight director does not present the pilot with preview on the future desired trajectory and future constraints, which is needed for anticipatory and error-neglecting control. The navigation display 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, with conventional displays the pilot is forced to apply a continuous closed-loop compensatory control strategy with the inherent workload. An increase in resolution of the navigation display yields a reduction in the range of the displayed information, which in turn reduces the amount of trajectory preview. By applying a non-linear scaling, it might be possible to combine the required resolution with an adequate amount of trajectory preview. However, a non-linear scaling in one dimension will increase the required effort for integration of the data into a spatially coherent picture.

2.6.4 The need for more information

Future procedures such as curved and steep angle approaches increase the frequency of changes in orientation between the ERF and the WRF. This will make the pilot’s task more difficult, and reduces the ability to maintain an adequate level of navigational awareness. Trajectory preview provides the pilot with the information necessary to maintain navigational awareness and allows the anticipation and verification of flight director commands and the actions of the autopilot. In an instrument landings system (ILS) approach, it is quite easy to determine the ERF-WRF relation, since only the deviations to a straight reference line must be taken into account. Due to the simplicity of the approach path, it is easy to mentally generate trajectory preview, and maintain navigational awareness. Therefore, the conventional 1-D and 2-D guidance displays suffice. For more complex approaches, trajectory preview can be obtained from the flight plan on the navigation display, but this increases the load on working memory. Also, the navigation display only presents a top view of the trajectory and no side view, and as a result the pilot has to generate his own mental representation of the vertical profile. The introduction of a so-called vertical profile display (VPD) could alleviate the pilot from this task (Fig. 2.5).

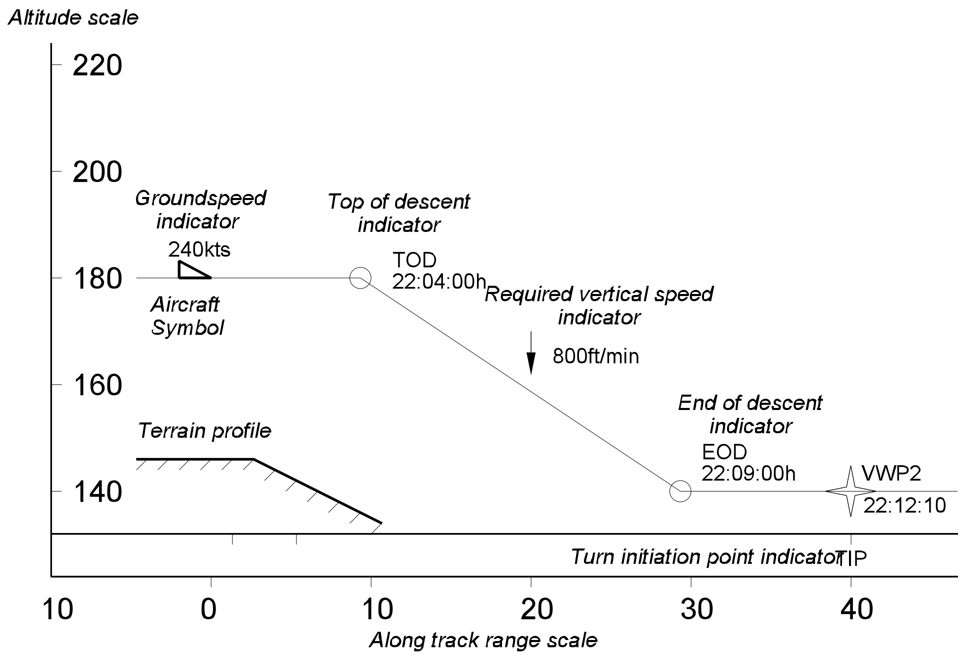


Fig. 2.5. *Example of a vertical profile display.*

Baty, (1976), Houck et al. (1986) and Vakil et al. (1995) discuss the application of the VPD or vertical situation display (VSD). Since the late 1980s, a VPD is provided in the Gulfstream IV cockpit. Although McDonnell Douglas experimented with VPDs for presentation on the lower half of the PFD, the concept was not mature at the time of the MD-11 design freeze. At the moment, no large commercial aircraft is equipped with a VPD.

2.6.5 Gathering the required information

To obtain all required information, the pilot has to regularly scan the instruments. A change in task is likely to necessitate a change in scanning strategy. Endsley and Bolstad (1992) claim that *'attention, working memory and long term memory are believed to be critical limits of situation awareness at each of its three levels: Perception, comprehension and projection'*. Due to the increased complexity of the trajectory to be flown, attention must be divided among multiple displays. Harris et al. (1981) assessed the effect of curved approaches and advanced displays on pilot scan behavior. They report that pilots use very similar scanning patterns in both conventional and advanced cockpits. For curved approaches, however, a shift of attention towards the electronic horizontal situation display (EHSD) is reported. This indicates the increased requirement for positional information as a result of the higher frequency of required changes in the orientation of the ERF relative to the WRF. The switching of visual attention between the different displays is guided by the pilot's internal representation and unfortunately human sampling strategies are not optimal due to several causes (Wickens, 1984). An improvement can be achieved by providing preview on upcoming events, thus guiding the sampling by an *external model* (Wickens, 1984).

Because the pilot has to deal with an increased number of changes in the trajectory and to perform more mental rotations, requirements on working memory also increase.

2.6.6 Conclusion

Today's guidance and navigation displays employ singular and sometimes dual dimensional data presentation methods. They require the pilot to scan multiple sources of information and mentally integrate the data which is required to obtain navigational awareness. This process involves mental rotation and scaling operations, which costs time and may introduce errors. Furthermore, a graphical depiction of the vertical flight profile as depicted in Fig. 2.5 is still lacking on the current electronic flight instrument system (EFIS) displays of large commercial aircraft. Although it has been demonstrated that it is possible to use conventional command displays for the guidance task along a complex four-dimensional curved trajectory, safety may be impaired, since the increase in complexity is likely to cause a reduction in navigational awareness, thus reducing the pilot's ability to adequately deal with unexpected events. Therefore, navigation and guidance displays which reduce task demanding load and increase navigational awareness are needed.

2.7 Potential improvements

2.7.1 Better automation

For quite some time, the use of artificial intelligence (AI) such as expert systems, is being investigated as a means of improving situation awareness. The idea is to reduce the task demanding load by using adaptive aiding systems which provide context dependent assistance. Rouse (1994) presents a very nice example of probably one of the first adaptive aiding systems which resulted in a demo-mishap as a result of *conflicting intelligence*. A major research program which investigated the possibility to apply cooperative knowledge-based systems and advanced computing technologies to the cockpits of advanced tactical fighters was the Pilot's Associate (PA) program. The PA program began in 1986 and was sponsored by the Defense Advanced Research Projects Agency (DARPA) and the U.S. Air Force. It's objective was to improve combat effectiveness and survivability of future fighter aircraft. The PA should be a trusted associate or assistant for the pilot, not a system capable of autonomous operation. The PA should be capable of enhancing the pilot's situation awareness, interpreting the pilot's intent and responding to pilot directives. One of the main challenges was the fact that the PA planning systems must operate in an extremely dynamic environment in which many events cannot be accurately predicted or modeled. In the context of the PA program, Rouse et al. (1990) describe an approach in which an interpretation of pilot activity serves as a basis for applying expert-system recommendations. LaPuma and Marlin (1993) describe some of the results which have been achieved.

With adaptive automation, the flexibility on the automated side is increased relative to conventional automation to provide context dependent aiding to the operator. Verfurth et al. (1991) discuss an experiment in which an intent inferencer was tested to predict the pilot's goals based on his actions and the state of the aircraft. The experiment was conducted for the cruise, cruise descent transition, descent, descent approach transition, and the approach phase of a B-727 aircraft. They conclude that *'an interface which allows effective pilot control of the aircraft and at the same time facilitates intent inferencing, is the key to the development of intelligent cockpit aids'*. The potential danger which this increase in flexibility introduces is the misunderstanding of the operators intents and vice versa, resulting in the conflicting intelligence mentioned earlier (Rouse, 1994). The potential for catastrophy in such a situation is determined by the degree of authority and autonomy of the automation. Billings and Woods (1994) state that *'as long as pilots remain fully responsible for the safety of their operations, they must have the authority to remain at the locus of control of the operation, regardless of the amount or type of automation used to exercise that control'*. They stress that automation must be predictable in systems in which the human is responsible for mission safety. As pointed out by Sarter and Woods (1994), although an automated system is deterministic and predictable, those who monitor or interact with the system in context may perceive the system very differently. This is caused by the fact that increasing complexity of automation reduces the possibility to develop a veridical internal representation of the system. Since adaptive automation increases the complexity of system behavior, Billings and Woods (1994) conclude that to insure that humans are able to understand, predict the behavior of, and remain in command of the automation, civil aviation automation should be adaptable but not adaptive. As indicated in the introduction, *the main reason to include a human in a system is that the human functions as the flexible, adaptive component of the total system in order to cope with events for which the automation was not designed*. Given the fundamental limit that the human is unpredictable, one might argue that perhaps there is no in-between. Either, the human is responsible and is supported with a system which is easy to predict, or the system must be designed so that it includes flexibility similar to that of a human operator, making the human operator really superfluous. A potential application of the use of a so-called associate which does not suffer from the predictability problem is in a monitoring role rather than at some level in the chain of command. The associate continuously tries to predict the future required actions of the pilot and compares them with the actual actions. In case the mismatch becomes too large, the associate could attract the pilot's attention and provide information regarding the source of the conflict. Note that this is in fact a description of a smart alarm system which aims at motivating the pilot to re-assess the situation. As such, it could reduce the effects of confirmation bias, the tendency of humans to seek information that confirms the chosen hypothesis, and avoid information which could disconfirm it. The adaptability of the system should provide a low false alarm rate.

Summarizing, there is a trend to combat the increasing complexity with support through enhanced automation such as context dependent aiding. Situations can be identified where this is the optimum solution (military, future electronic battlefield, increasing number of threats, etc.). The viability and advantages have been demonstrated for certain military applications. In civil aviation, however, the environment is different, and so are the priorities. Today's problems with much less sophisticated automatic systems already indicate the enormous number of potential pitfalls and it can be concluded that the application of artificial intelligence is not a near-term solution.

2.7.2 Better data presentation

Solving a problem simply means representing it so as to make the solution transparent (Simon, 1969).

Navigation, guidance, and control are not three independent tasks. To maintain a high degree of cognitive coupling between these tasks, displays should reflect the relations between them. With a flight director display, however, the control task is isolated. Endsley and Bolstad (1994) state *'probably the first thing that can be done to help pilots achieve situation awareness in a demanding environment is to improve the pilot-vehicle interface so that the required information can be gleaned with a minimum amount of workload'*. Thus, rather than reducing task load demands by using AI techniques to present *the right information at the right time*, one can aim at developing display formats which reduce the cognitive effort needed to turn the perceived data into useful information. This leaves the authority to decide what is needed and when with the pilot.

One of the most effective mechanisms for the simplification of complex visual scenes is the human perceptual system (Garner, 1970).

The simplification mechanism of the human perceptual system is developed through years of repeated confrontation with the rules of perspective scenes and as a result, humans are capable of rapid interpretation of otherwise complex visual scenes.

By replacing symbology (which by definition represents another thing) by a direct visualization of the needed information, the effort for interpretation can be reduced. To capture this simplification capability in man-machine systems the use of pictorially realistic data presentation is required (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 and thus make the stimuli of the representation compatible with the stimuli from real-world cues. 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[5] 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, the mental effort needed to translate the perceived data into meaningful information can be minimized.

To exploit the simplification mechanism of the human perceptual system which is developed through years of repeated confrontation with the rules of perspective scenes and therefore allows rapid interpretation of otherwise complex visual scenes, the required flightpath must be presented as it would be seen when it was actually painted in the sky.

2.7.3 The perspective flightpath display

A potential alternative to the flight director which is based on this concept is the perspective flightpath display. Instead of presenting control commands, a perspective flightpath display makes control intuitive through direct visualization of the guidance requirements.

A perspective flightpath display presents a spatially integrated view of the desired trajectory on a two-dimensional display

Perspective flightpath displays visualize an imaginary trajectory in an intuitive way. A perspective flightpath display can benefit from the fact that an integrated presentation of the data in a suitable frame of reference minimizes required mental integrations and rotations. This 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. As a result of the trajectory preview, guidance and short-term navigation information are available from a single display format. Thus, by making control intuitive from the presentation of guidance requirements, the advantage is that the data required for aircraft guidance also contains the information needed to maintain a certain level of spatial and navigational awareness. The perspective presentation of the desired future trajectory results in a non-linear scaling of the position information as a function of distance along the line-of-sight, yielding both a high resolution for manual control and an adequate amount of preview. In the absence of position and attitude errors, the desired trajectory is displayed as a symmetrical shape. Position and attitude errors result in a distortion of this symmetry. Since people are used to live in a 3-D world and the displayed image is a direct representation of this world, the distortions can be used to evoke natural responses for their correction. In other words, the display format conveys physically interpretable information in a way which requires minimum mental effort for interpretation and evaluation. The direct visual feedback allows the pilot to identify the system

[5] Emergent features are specific attributes of an object which are instantaneously recognized.

under control, resulting in a good internal representation. Furthermore, since the perspective flightpath display presents status information, the concept can be used both for manual and supervisory control. Due to the compatibility of the interface between supervisory and manual control, it is possible to reduce the automation deficit.

A flight director display does not present any information which contributes to the pilot's navigational awareness. To maintain an adequate level of awareness, the pilot has to scan the navigation display. Due to the difference in bandwidth requirements between the guidance task and the navigation task, the required frequency of scanning the navigation display is much lower. People learn to sample channels with higher events rates more frequently and lower rates less frequently. As a result, the pilot has to store the information conveyed by the navigation display in his working memory. Because of limits in memory people may forget to sample a particular display source. Furthermore, under stress the focus of attention is more restricted and fewer cues are sampled (Wickens, 1984). If in such a case a certain event triggers the pilot to scan the navigation display, he will not instantaneously have sufficient situation awareness since it takes a certain amount of time to orient oneself to the situation. The trajectory preview presented by a perspective flightpath display allows the pilot to continuously refresh important information contributing to navigational awareness and thus reduces the demands on working memory. The integrated trajectory preview relieves the pilot from continuously having to scan the navigation display and using this information to predict and/or verify changes in guidance information or commands.

Trajectory preview in the primary flight display allows the sampling of information on the navigation display to become more optimal since it is not determined by the limitations of working memory.

Besides the trajectory itself, other navigational data such as geographic data and other aircraft can be integrated in the perspective flightpath display. A consistent representation between the navigation display and the perspective flightpath display is required to maintain a high degree of cognitive coupling between the two presentations.

Summarizing, the spatial integration of trajectory preview reduces the need to scan several instruments and mentally integrate this data into the required information. Also, it reduces the load on working memory to maintain an adequate level of navigational awareness. The reduction of the required effort for interpretation, integration, and evaluation in combination with a reduction on the load on working memory enables the pilot to safely cope with more complex situations.

2.7.4 Differences with a flight director and resulting implications

A flight director employs a very simple presentation, e.g. a moving bar indicating a deviation to be zeroed. Since the pilot has no preview on future requirements, his control action must be a direct response to the displayed command. Thus, the pilot functions as an error-zeroing servo-mechanism, applying a closed-loop compensatory control strategy. Due to the spatially integrated trajectory preview, perspective flightpath displays present navigation and guidance data in a way which is fundamentally different from conventional planar data formats used today. The presence of preview about future requirements and constraints allows pilots to apply a much wider variety of control strategies, making a better utilization of their resources possible. As indicated by Haskell and Wickens (1993), '*the way in which a task is performed differs as a function of the displays employed'*. They point out that *'when making empirical comparisons between different display types, researchers must evaluate measures other than performance on only one type of task; they must go beyond performance in any case and examine task performance strategies'*. With a perspective flightpath display, several control strategies can be applied to perform the guidance task. Closed-loop control can be used to minimize position and directional errors. By taking the future desired state into account, anticipatory control can be used to reduce the required closed-loop gain. The possibility of applying a certain control strategy is determined by the data presentation. Flight director displays are compared by using measures which indicate how well the pilot is able to track a certain forcing function. These measures provide no indication of the pilot's ability to apply other control strategies such as error-neglecting control, which provide an opportunity to trade-off between workload and performance. To allow a fair comparison of different display concepts for aircraft guidance, measures should be used which allow an evaluation of the full range of potential control strategies to satisfy task requirements. Maximizing tracking performance is one limiting case, maximum error-neglecting control is the other.

Besides comparing display concepts in terms of tracking performance and control activity, there is a need for measures which indicate the pilot's ability to apply other control strategies than continuous compensatory control.

The large variety in possible control strategies with a perspective flightpath display makes it much harder to approximate the control behavior of the human operator with a control theoretical model. Currently no validated models exist which can be used to describe the range of possible control strategies with a perspective flightpath display. Mulder (1995) describes research into methods to model the pilot's control behavior taking into account both anticipatory and compensatory actions.

2.7.5 Data processing

An argument which is sometimes used against perspective flightpath displays is that they do not present raw data as with the conventional ILS glideslope and localizer deviation indicators, and thus do not provide the pilot with the opportunity to monitor system integrity based on unprocessed[6] sensor data. However, the mere existence of useful raw data is the result of the single radio-path generated by the ILS glide slope and localizer stations. Any deviation from this path results in a difference in depth of modulation (DDM) of the received signals. The DDM is directly used to drive the glide slope and localizer indicators, hence the classification as raw data. Both candidates for ILS replacement, MLS and GPS aim at providing multiple approach paths by presenting the pilot with accurate data about his current position, instead of deviations from a path predefined by the setup of a localizer and glide slope antenna. The fact that the guidance data changes from relative to absolute necessitates some form of processing on board the aircraft. Even for the presentation of glide slope and localizer deviations, the difference between the actual position and the desired position must be computed.

With an approach system other than the current ILS, it is a false assumption to think that the glide slope and localizer indicators present raw data. As a result, with MLS and GPS, the argument that glideslope and localizer indicators allow the pilot to monitor system integrity based on unprocessed sensor data is no longer valid.

A possibility to compensate for the absence of raw data would be the integration of visual data obtained from onboard cameras and sensors.

2.7.6 Limitations

Besides many advantages, perspective flightpath displays have certain limitations which must be taken into account. Due to the integration of multiple variables into a single object, it is often harder to estimate the value of a variable in a single dimension (Wickens et al, 1990). Barnett and Wickens, 1988 showed that certain exceptions exist, e.g. a configuration as a rectangle may facilitate integration without harming focused attention, but 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. Thus, the nature of the perspective projection inherently reduces the accuracy with which a variable which is mapped to distance along the line of sight can be estimated. 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,

[6] There is always some form of processing, e.g. amplification. In this context, unprocessed refers to data which directly gives an indication of the deviation from a reference without having to calculate the difference between the current position and the reference. Therefore, this is only possible with relative positioning systems such as ILS.

objects which are close to the observer might mask objects which are further away. These facts must be considered in the context that as long as no perceptual conflicts occur, perspective flightpath displays need not necessarily have to result in complete veridical perception of the 3-D world, but should rather be an effective guide to actions. For the guidance task, the fact that information further away from the viewpoint suffers a reduction in resolution is not considered a problem, since this information is of less importance at the moment. In fact, as a result of the perspective projection, the important information (near in time) in the 3-D world is emphasized. Accurate information about heading and attitude can be provided by means of separate indicators, fully integrated into the display.

To allow a fair comparison of different concepts, specific limitations should always be considered in the light of task requirements and not on an absolute basis.

2.8 History of perspective flightpath displays

The more original a discovery, the more obvious it seems afterwards (Arthur Koester).

The concept of the 3-D flightpath display for aircraft guidance dates back to the US Army Navy Instrumentation Program (ANIP) in the 1952-1963 period. ANIP's goal was to define and develop improved man machine interfaces (MMIs) for aircraft. The ANIP was organized and, until his retirement in 1959, directed by George W. Hoover of the Office of Naval Research. The ANIP led into the Joint Army-Navy Aircraft Instrumentation Program (JANAIR) in the 1960's. At that time, the prevailing limitations in computer technology frustrated implementation of the flightpath display and many of the display formats proposed in the context of the ANIP and JANAIR have never flown. Quinn (1982) presents an overview of pictorial display formats proposed between 1950 and 1982. One of the first perspective flightpath displays is the Farrand *Path-in-the-Sky* HUD. This display dates from 1960, and shows a path extending from the aircraft towards the runway. Wilckens (1968) investigated whether it was possible to use a perspective flightpath display for accurate ILS guidance. He demonstrated the relation between the dimensions of the tunnel and pilot performance and control behavior for a basic perspective guidance display. In early 1975, Northrop aircraft corporation initiated action under its independent research and development (IR&D) program to extend the earlier work on flightpath displays. A feasibility demonstration of the *maneuvering flightpath display* (MFPD) was performed in 1977 (Wattler and Mulley, 1977). During part of this program, G.W. Hoover served as a consultant on the project. In the eighties, the pictorial format program in the U.S. addressed many issues of perspective flightpath displays. In May of 1980, a contract was awarded to McDonnell Aircraft Corporation (MCAIR) to develop the initial pictorial format concepts. Boeing Military Airplane Company was the winner of the evaluation phase of the program. Wattler and Logan (1981) discuss a so-called *transition path* feature which must ensure that during deviations from the flight plan, the most effective means of returning to the original flightpath is presented. Jauer and Quinn (1982) describe the development of pictorial formats for primary flight, tactical situation assessment, stores management, system status, engine status, and emergency procedures. They discuss a *flight channel* as an alternative to the flight director and propose graphic terrain to extend the flight display to allow IFR operation similar to VFR operation (more than 10 years before the term *synthetic vision* was coined). Jauer and Mitori (1982) describe software, processing, and storage requirements for implementing advanced pictorial display formats including a perspective flightpath display. Jauer and Quinn (1982) discuss a so called *command path* to transition the aircraft from some known location to a sky-track or other predetermined location. In 1983 the total in-flight simulator (TIFS) from Calspan was equipped with a pathway-in-the-sky display, called the *command flightpath display* (CFPD). The format of the CFPD is nearly identical to Northrop's MFPD. On February 9, 1983, G.W. Hoover was the first to fly the CFPD. A total of 90 hours of ground simulation and 20 hours of in flight operation demonstrated that the CFPD provides the pilot with adequate information to execute take-off, climb, cruise/navigation, approach and landing, without reference to conventional parametric displays or the real world (Filarsky and Hoover, 1983). Based on the results of the flight trials with the command flightpath display (CFPD), Hoover et al. (1983) conclude that *'the concept of continuous command information is perhaps one of the most significant innovations that the CFPD format provides to man-machine systems displays. By having this information available, the necessity for memorizing each segment of the mission flight plan, or even referring to a navigation chart, is eliminated'*. Thus, the interface serves as external memory, reducing the load on working memory. Hoover et al. (1983) indicate the operational advantages by stating that *'each pilot, while flying the symbology format, had to be coached by a second pilot with regard to each upcoming event of the flight plan'* and *'no coaching relative to the flight plan was necessary when the evaluation pilot was flying the CFPD'*. With respect to navigational awareness, they report that while flying the CFPD format, the majority of the pilots stated that *'there was never any question as to where they were, what they were doing, or what they should be doing'*. In contrast, they report that with the symbolic format several of the evaluation pilots reported experiencing vertigo (a sensation of whirling in which one tends to lose one's equilibrium) during some of the flight maneuvers.

Swenson et al. (1993) discuss the design, simulator, and in-flight evaluation of a *computer aided low-altitude helicopter flight* (CALAHF) guidance system. They report a significant improvement in pilot situational awareness, and mission effectiveness as well as a decrease in training and proficiency time required for a near terrain, nighttime, adverse weather system. Möller and Sachs (1994) discuss a synthetic vision system which includes a curved flightpath in the form of a tunnel. Parrish et al. (1994) and Regal and Whittington (1995) performed simulator studies which have demonstrated the advantages of perspective flightpath displays with respect to performance, workload, and situation awareness.

Besides development and concept demonstration of flightpath displays, research has been performed into the various specific aspects of these displays and methods to augment them. Jensen (1978) discusses the effects of prediction, quickening, frequency separation, and percentage of pursuit in perspective displays. Grunwald (1981) investigated the effectiveness of superimposed predictor symbology for 3-D helicopter approaches. In a later study (1984) he describes a tunnel display for 4-D approaches. The fourth dimension is integrated into the display by the presentation of the predicted and the commanded 3-D vehicle position. Adams (1982) evaluated a pictorial display consisting of boxes which either moved along the desired trajectory, or were fixed at designated way points. He reports that the display is easy to learn and easy to use, but lacks accurate information on pitch, roll, and heading angles. Reising et al. (1989) evaluated the effectiveness of the pathway format versus a HUD format, when flying preprogrammed routes of various levels of difficulty. A second purpose of their study was to compare a 3-D stereo version of the pathway to a 2-D version. They report that pilots performed significantly better with the pathway display, but found no significant difference between 3-D stereo and 2-D. Wickens et al. (1989) examined the effects of frame of reference in a dynamic 3-D display with position prediction and trajectory preview. They report an advantage for the predictor/preview configuration which was greatest with the inside-out perspective.

Lintern et al. (1990) compared a perspective flightpath display format with a symbolic display to determine the effects on pilot training and transfer. They report that a moderately detailed pictorial display offers a considerable advantage for training in landing approaches. Busquets et al. (1991) investigated the effect of short-term exposure to a stereoscopic flightpath display on real-world depth perception. They report no differences with non-stereo displays, but indicates that depth perception effects based on size and distance judgements and on long-term exposure remain issues to be investigated. Dorighi et al. (1993) investigated whether a tunnel-in-the-sky display improved situational awareness compared to a conventional electronic attitude director indicator. Grunwald (1996a, 1996b) developed and evaluated a new predictor guidance scheme based on an actively driven predictor reference window. He reports superior performance as compared to a nonactive reference window.

2.9 Summary

As indicated in Sect. 2.4, a common factor in many incidents and accidents attributed to a lack of situation awareness is, that although the required data was available, it was not used. The out-of-the-loop performance problem, which can occur when the pilot suddenly has to take over from the automation, was indicated in Sect. 2.3. Ballas et al. (1991) refer to this problem as *automation deficit*. An MMI should allow supervisory control and minimize automation deficit. A problem which was also mentioned and which is related to out-of-the-loop performance is loss of proficiency. Under conditions of stress, pilot scanning is likely to become less optimal, thus increasing the possibility that important data is missed. It was pointed out that to be able to capitalize on the unique human capabilities regarding the detection of events and the recognition of their relevance, and to maximize the ability to efficiently deal with new situations, an adequate level of situation awareness is needed. For the navigation task, an adequate level of navigational awareness is needed to provide the possibility of detecting and interpreting events which influence the safety of navigation. Thus, the MMI should present the data required to maintain navigational awareness, allow rapid detection of deviations, factors which might cause deviations, and events which might threaten safety. Furthermore, the MMI should allow the pilot to be maximally effective under adverse conditions resulting from these events. Examples are a degradation of automation reducing handling qualities or external influences such as windshear. Navigational awareness allows the pilot to anticipate changes in the trajectory and as a result changes in the desired aircraft state. It presents an opportunity to increase performance during manual control, but perhaps even more important, it allows the pilot to anticipate and verify actions of the automatic flight control system (AFCS) when the autopilot is engaged. In other words, it allows the pilot to stay ahead of the automation. Furthermore, better awareness increases the possibility to successfully cope with unexpected events, which is one of the main reasons the pilot is still in the cockpit. With respect to navigation such events can range from a re-route proposal of ATC to an in-flight emergency which affects aircraft performance. Some problems may require only a number of procedural actions, resulting in mostly rule-based behavior. For new types of problems, which go beyond those which can be solved by rule-based behavior, the pilot has to resort to knowledge-based behavior. Both situations require that the information about the actual situation resides in the pilot's working memory.

For the safe execution of complex 4-D navigation procedures, a MMI is needed which can be used both for supervisory and manual control while achieving desired task performance in a way which minimizes cognitive load and maximizes navigational awareness.

When the displays for the guidance task are based on commands, they cannot support the build-up of task relevant information (awareness) needed to successfully switch to knowledge-based behavior. The current flight director is an example of a display which has been optimized for tracking performance but does not contribute at all to navigational awareness.

To maintain navigational awareness pilots have to frequently scan the navigation display and store the relevant information in working memory. In contrast, guidance displays presenting trajectory preview have the potential to continuously support the maintenance of navigational awareness and reduce the load on working memory. This increases the capacity to cope with unexpected events which interfere with the task at hand and which require some sort of action.

The presentation of spatially integrated trajectory preview has the potential to improve the MMI for navigation and guidance.

This claim is supported by the results of various research programs. The basic technology for the generation and successful integration of such an MMI exists, although improvements in for example the data update-rate and resolution may be needed. However, it is not only a technical problem, one also has to consider human limitations. Fadden et al. (1987) state that *'while the promise of spatial displays is great, the cost of their development will be correspondingly large. The knowledge and skills which must be coordinated to ensure successful results is unprecedented. From the viewpoint of the designer, basic knowledge of how human beings perceive and process complex displays appears fragmented and largely unquantified'*. Due to the trade-off which is required between generalizability and level of detail, existing guidelines to man-machine interface design are too general to be of direct use for a detailed design. On the other hand, several concepts from engineering psychology can be used to provide more insight into design questions and to serve as a foundation for a design framework.

An approach is needed which supports a structured design process for perspective flightpath displays in which technical possibilities and human factors are truly integrated.

3 VISUAL CUES

An integrated presentation conveys more information than the sum of its parts.

3.1 Introduction

To structure the discussion about the different aspects of the MMI for guidance and navigation, the model of human information processing as presented by Wickens (1984) is used. This model distinguishes between *perceptual encoding*, *decision and response selection*, and *response execution*. This chapter focuses on the perceptual encoding, whereas the next chapter deals with decision and response selection. The first part of this chapter discusses the information contents of the visual cues conveyed by a perspective flightpath display and relates this to the required perceptual encoding. Wickens (1984) states that *'at any level of perceptual processing it should be apparent that the accuracy and speed of recognition will be greatest if the displayed stimuli are presented in a physical format that is maximally compatible with the visual representation of the unit in memory'*. An important feature of humans is that certain compatibility relations, such as the spatial correspondence between stimulus and response seem to be intrinsically related to the hard wiring of the nervous system (Wickens, 1984). If such features can be exploited, the cognitive load can be minimized. The second part of this chapter discusses the contribution of the visual cues conveyed by the display to the build-up and maintenance of navigational awareness.

The ideal display format is one in which the visual stimuli convey the required information so that the processing for perceptual encoding is minimized. Each level of stimulus dimension may be referred to as a feature (Wickens, 1984). A perspective flightpath display can be described as a set of components, in most cases line segments, each having specific features such as length, orientation, thickness, and color. Together these components form an object, the tunnel, which itself also has features, one of which is symmetry. To bypass the feature analyzers on the component level, the flightpath should be presented in such a way that it evokes holistic perception. The term holistic describes a mode of information processing in which the whole is perceived directly rather than as a consequence of the separate perceptual analysis of its constituent elements (Wickens, 1984). The three general characteristics which allow an object to be perceived holistically are the *surrounding contours*, *the correlated attributes*, and *a potential familiarity* (Wickens, 1984). The pilot has not to decompose the object into features which are relevant for the task. Rather, the emergent features of the object are directly perceived, horizontal and vertical distortions are processed in parallel and can be used to initiate natural multi-dimensional control responses.

To reduce cognitive processing, the representation should evoke holistic perception.

To describe how position and orientation errors determine the magnitude of the visual cues as a function of the design parameters, the cues have to be expressed as properties of the optic flow field. In this chapter, the object representing the flightpath is therefore decomposed into more elementary features.

3.2 Background

Visual cues are those stimuli which are responsible for the information transfer from display to observer. Several cues containing task relevant information may be available. This raises the question about the relevance of each cue for the specific tasks. Furthermore, some cues convey ambiguous information which can only be resolved with additional information. Sometimes this additional information is not explicitly available and assumptions about the structure of the environment are used. In case of an erroneous assumption, misperception results. To prevent errors resulting from misperception, it is important to understand its causes. When dealing with potentially misleading visual cues in the real world, adequate training can be used to compensate. In contrast to the real world, the designer of a perspective flightpath display has absolute control over the structure of the virtual environment which conveys the visual cues, and as a result has more possibilities to prevent misperception through adequate design. Most aircraft related research into visual cues addresses the naturally available cues. Since accurate position cues are only dominantly available during the landing phase or low-level flight, these are the two major areas covered by this research. At higher altitudes, only rotations can be perceived with a high enough resolution. The visual cues conveyed by a perspective flightpath display are not naturally available in the aircraft environment, and the required computer performance for artificially generating them was prohibitive until the early eighties. As a result, research on this specific topic is relatively scarce in the aerospace community. In contrast, with car driving these cues are continuously available. Ample research has been performed on the subject and the established framework with respect to the perception and processing of this information and the resulting control can be translated to the aircraft situation and used to predict pilot usage of these cues. Furthermore, results from research into perception and control of self-motion are of interest since many of the identified task specific functional variables can be related to position and velocity control with a perspective flightpath display. Various descriptive terms are in use to describe phenomena related to the perception of visual cues from the optical flow field. Owen (1990a) presents a lexicon of terms for the perception and control of self-motion and orientation. In his discussion of an organizational framework to relate perceiving and acting to variables of stimulation, Owen distinguishes between two classes of event variables influencing sensitivity to changes in self motion, indicated by *functional* and *contextual* variables. He defines a functional variable as *'a parameter of an optical flow pattern used to select and guide a control action'*. An example of such a parameter is the orientation of the borders and the centerline of a road, which provide essential information for position control during car driving. Contextual variables are defined as *'those optical properties which influence sensitivity to functional variables'* (Owen, 1990b). Based on result of research into perception and control of changes in self-motion, Owen (1990b) states that *'results to date indicate that functional variables are of an order high enough to be completely relative, e.g., not specific to either absolute event or optical variables'*. For a perspective flightpath display this implies that in case the visual cues comprise the task relevant functional variables, pilots do not have to know absolute size, distance, speed, or flow rate to apply the correct control actions. Furthermore, results suggest that *'functional variables have an effect on performance which is asymptotic. Equal-ratio increments in the variable produce equal-interval improvements in performance, at least in the middle range of sensitivity. Ceiling and floor effects may bend this function into a cubic form. In contrast, contextual variables reveal an optimum level of performance, hence, they have a quadratic form'* (Owen 1990b). The magnitude and the dynamic behavior of the visual cues conveyed by a perspective flightpath display are a function of the field of view, the dimensions of the flight corridor, and the frame of reference. Suitable values for these parameters depend on task specific requirements with respect to range and resolution of the displayed data and the required magnitude of the visual cues. The latter requirements follow from the properties of the human operator with respect to perception, interpretation, and evaluation of information. Owen (1990b) indicates that *'the nature of the quadratic effect shown by contextual variables suggests that they are related to the operating characteristics of the sensory system supporting sensitivity to functional variables, since they parallel effects found in sensory psychophysics'*. This implies that for the design parameters of display features conveying visual cues which function as contextual variables optimum values exist. A proper selection of the design parameters requires an understanding of their relation with the magnitude of the various cues conveyed by the display. In this chapter, a potential approach which allows a comparison between different designs in terms of task-related visual cues described as functional variables is presented. It is based on the research into perception and control of changes in self motion (Warren and Wertheim, 1990), and the research into perspective flightpath displays performed in the context of the Delft program for hybridized instrumentation and navigation systems (DELPHINS) between 1990 and 1995. In the following sections, the control oriented visual cues in a perspective flightpath display are discussed. Sect. 3.3 presents a brief overview of research into the perception of directional cues from a visual scene. Sect. 3.4 discusses the transformation of position and orientation errors into a perspective presentation, and makes a comparison with conventional flight director algorithms. The cues conveyed by single snapshot are discussed in Sect. 3.5 and it is indicated how certain visual cues can be characterized as functional and contextual variables for position control. The functional and contextual variables are described as a function of task related variables and display design parameters, enabling a comparison between different designs in terms of the magnitude of the resulting visual cues. The cues resulting from a dynamic presentation and the resulting perception of relative velocity are analyzed in Sect. 3.6. It is also discussed how the visual cues resulting from transitions can be used for the timing of anticipatory actions. Furthermore, the influence of the frame of reference on the dominant visual cues is discussed.

3.3 Preview and perception of directional cues

> The most direct, and in a sense the most important, problem which our conscious knowledge of Nature should enable us to solve, is the anticipation of future events (Heinrich Hertz).

An important difference between conventional guidance displays and a perspective flightpath display is the presence of trajectory preview in the latter one. This preview conveys information about future position and orientation requirements and allows the pilot to anticipate changes in the trajectory.

> The presence of preview on the future trajectory and its constraints provide the pilot with the opportunity to anticipate changes in requirements, and thus allows him to stay ahead of the situation.

For the guidance task, directional information is needed. Various researchers addressed the question of which features in a three-dimensional scene are used to extract the required information. Gibson (1950) hypothesizes that the focus of expansion is used in car driving by keeping it in the direction the vehicle must go. Gordon (1966) discusses the principles applying to the perception of positional, velocity, and acceleration fields under rectilinear and curvilinear motion. He states that since experimental evidence suggests that drivers guide themselves by reference to the road edges and the center stripe, the often quoted statement that the focus of radial outflow is the cue for the direction of sensed locomotion is challenged. Although the direction of vehicle motion is related to the focus of expansion, the focus itself is not an effective cue. He further motivates this by arguing that the focus of expansion of a flat horizontal plane lies at the vanishing point in the sky or will occupy points on trees or buildings if the road is curved. Generally, it is difficult, if not impossible, for the driver to locate the focus of expansion, and contrary to Gibson (1955), the borders and lane markings are used in vehicular guidance. When the vehicle is aligned with a straight or regularly curved highway, the road assumes a steady state appearance. The borders and lane markers remain almost stationary in the driver’s field of view. A road of constant curvature assumes a steady state appearance up to the break in curvature. Lateral guidance could consequently be considered to involve the maintenance, through visual feedback, of an acceptable steady state condition and zeroing the deviations from it (Gordon, 1966). If the moving vehicle is misaligned laterally with the road, the entire field of view moves as a unit. Riemersma (1982) investigated the optical cues in the dynamic visual field which are related to the movements of the vehicle. He distinguishes between two components for the control of lateral position: Lateral motion and heading rate. The heading rate reflects itself in an optical translation of all points of the visual field. The lateral motion becomes optically manifest as rotations of the optical images of the edge lines, without a change in position of the optical vanishing point. The extent of lateral misalignment is indicated by the rate of extent of slewing and side-slipping of the road borders and lane markers. Various studies addressed the perception of guidance information from a perspective runway image, e.g. Wempe and Palmer (1970). The general conclusion was that such an image allows adequate lateral control but lacks cues for accurate vertical control. This can be explained from the fact that for lateral control a symmetrical conditions exists which functions as a visual reference. For vertical control, such a reference is not available. To extract the flightpath angle error, the pilot must compare the perspective shape of the runway to some internal representation build up on the basis of experience. The low sensitivity to angular changes increases the difficulty to accurately estimate the error. Morrelo et al. (1977) added a perspective runway and an extended centerline to an electronic attitude and director indicator (EADI). They report that pilots comments indicated that the integrated display format on the EADI eliminated the need to scan the EHSI during the approach. The runway and relative track information enable the pilot to better understand his position and trajectory relative to the extended runway centerline. With the Tunnel-in-the-Sky, lateral directional cues follow from the track angle error (TAE) and cross-track error (XTE) rate. This information is conveyed by the lines parallel to the desired trajectory. In the section about design, a direct indication of the inertial vehicle motion will be discussed.

3.4 Transformation of information

Before the visual cues conveyed by a perspective flightpath display are discussed in more detail, a comparison between the transformation of task related data into visual cues for a flight director and a perspective flightpath display is presented. Conventional flight directors are based on a weighted combination of position- and angular errors and error rates. In the horizontal dimension, XTE and TAE are used to calculate the deflection of the vertical flight director bar. In the vertical dimension, flightpath angle error (FPAE) and vertical track error (VTE) are used to calculate the deflection of the horizontal flight director bar. In Sect. 2.6 the drawbacks of the flight director were discussed. The fact that the data processing methods for a flight director and a perspective flightpath display are completely different, has important consequences for the availability of information. Furthermore, besides obtaining information from the data which is displayed explicitly, additional cues are generated depending on the way the data is transformed. These cues can increase the information conveyed by the presentation, and may result in performance differences between display formats which cannot be explained from the proximity compatibility principle (Wickens and Andre, 1990) alone. An example is the introduction of temporal range cues, resulting from a dynamic perspective presentation. To understand the origin and contribution of such cues, an analysis of the data transformations is required. An important factor influencing these data transformations is the frame of reference used for projecting 3-D data onto a 2-D display. The different frames of reference can be divided into egocentric and exocentric ones.

In an egocentric perspective flightpath display, the three-dimensional world is depicted as seen from the aircraft. In an exocentric display, the situation is viewed from another position.

In order to be able to compare the guidance data presented by a perspective flightpath display with the data presented by a flight director, a description is needed indicating how the actual position and orientation errors are transformed into the data presented on the display device as a function of the design parameters. Fig. 3.1 presents the data processing for a typical flight director, and Fig. 3.2 for a perspective flightpath display for lateral guidance.

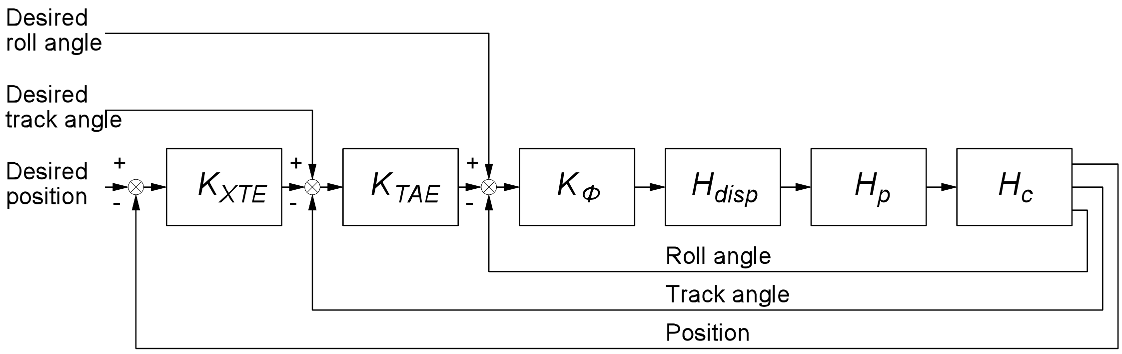


Fig. 3.1. *Typical data processing of a lateral flight director display. Errors are weighted and combined into a single variable. This prevents the observer from extracting position or orientation errors from the display.*

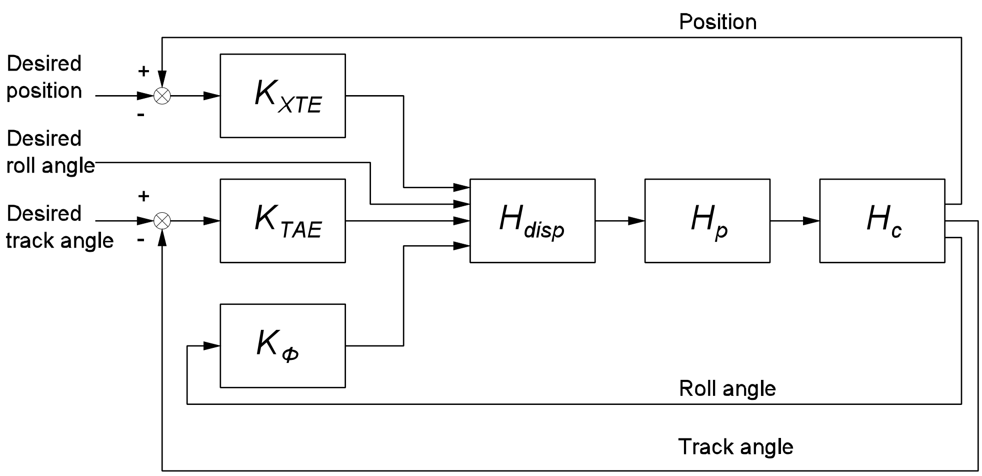


Fig. 3.2. *Data processing with a perspective flightpath display. Position and orientation errors influence different aspects of the presentation which allows the observer to extract information about these errors.*

In Fig. 3.1, position, track angle, and bank angle errors are integrated into one dimension, and presented by the deviation of a single element with one degree of freedom. In Fig. 3.2, position and angular errors determine the spatial presentation of the three-dimensional trajectory. In both figures, H_{disp}, H_p, and H_c represent the transfer function of the display, the pilot, and the aircraft, respectively. The roll angle, track angle, and lateral position error gains are represented by K_φ, K_{TAE}, and K_{XTE}, respectively. McRuer et al. (1971) describe an analytical approach for the design of a flight director which yields values for the error gains to satisfy both pilot-centered, and guidance and control requirements.

Wilckens (1973) indicated that a perspective presentation of the flightpath contains information which is comparable to a flight director command display for a manual compensatory tracking task by showing that the presentation contains data proportional to the first- and second-order derivatives of position error (for this derivation he inherently assumed an ERF). Grunwald and Merhav (1978) illustrated that with a dynamic perspective image of a future circular vehicle path the error ε(t) to be zeroed can be approximated by Eq. (3.1):

$$\varepsilon(t) = \frac{1}{2}\frac{d}{V(t)^2}\ddot{\eta}(t) + \frac{1}{V(t)}\dot{\eta}(t) + \frac{1}{d}\eta(t), \qquad \textbf{(3.1)}$$

with d the looking distance, η(t) the current cross track error, and $V(t)$ representing vehicle velocity. This form of equation is often referred to as a quickened display (Stokes et al, 1990) of the variable η, which is comparable to the algorithm driving a flight director in which the cross track error has to be zeroed. When taking into account only one looking distance d, the information presented is basically the same.

An essential difference between a flight director and a perspective flightpath display is that a perspective presentation of the flightpath allows the extraction of position and orientation errors, which is impossible from a flight director display.

Since the spatial presentation requires the specification of variables for its six degrees of freedom, this allows the integration of a total of six dimensions of data. Two degrees of freedom are used to convey lateral and vertical position errors, and two degrees are used to convey track and flightpath angle errors. In an ERF, the desired trajectory is displayed as a symmetrical shape with a certain orientation and at a certain distance from the viewpoint in case all errors are equal to zero.

The natural symmetry of the object allows for a stationary condition. Any other frame of reference than an ego-centered one cannot exploit this advantage, and will require additional mental processing.

The orientation of the object can be used to convey a bank reference. For the final spatial dimension (distance along the line of sight) no stationary condition exists, which inhibits the direct use of this dimension. The integration of these dimensions onto a two-dimensional display causes ambiguity. This ambiguity is resolved through assumptions about the geometry of the three-dimensional object, and through the presence of visual motion cues. With a perspective flightpath display, the distortion of the symmetry can be related to position and angular errors through the gains K_{TAE} and K_{XTE}, which are a function of the perspective design parameters. In the next section it will be described how position and orientation errors cause a distortion in the symmetry of the perspective presentation of a flightpath in an ERF, and how the magnitude of this displayed distortion can be influenced by the design parameters, such as geometric field of view, tunnel size, and minimum preview distance.

3.5 Static information

Emergent features (e.g. symmetry) may be directly registered by specialized feature detectors at an early stage of perceptual processing (Triesman).

3.5.1 Introduction

The perspective flightpath display presents a virtual Tunnel-in-the-Sky which, in the absence of position and angular errors, is displayed as a symmetrical shape (Fig. 3.3). Both lateral and vertical position and orientation errors result in a distortion of the natural symmetry of the perspective representation of the flightpath (Fig. 3.4), and as a result a snapshot representation of the tunnel can provide the pilot with information about these errors.

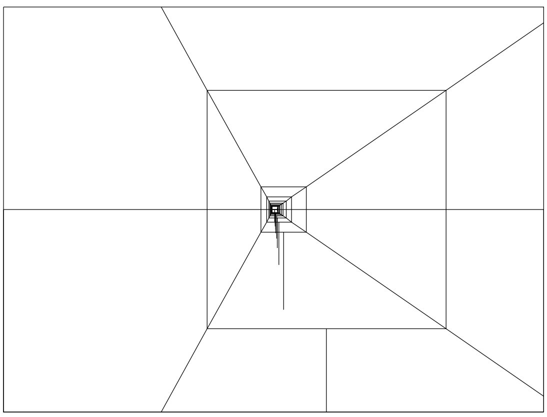


Fig. 3.3. *Influence of a cross-track error on the symmetrical reference condition. The viewpoint is located to the left of the central tunnel axis, which yields a distortion of the symmetrical reference shape.*

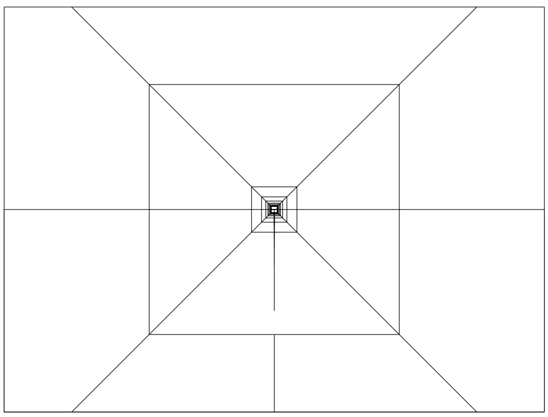


Fig. 3.4. *Symmetrical reference condition. The viewpoint is located exactly in the center of the tunnel, and the viewing direction is aligned with the central axis of the tunnel. Any deviation from this shape is easily detected*

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.

3.5.2 Symmetry and design parameters

To describe the relation between the distortion of the symmetrical shape caused by position and orientation errors as a function of the design parameters, an analysis of how the projection method transforms the 3-D flightpath into a 2-D representation is required. Fig. 3.5 shows an exocentric view of two aircraft inside a tunnel segment. Aircraft *1* is exactly on course and exactly in the center. Aircraft *2* has a cross track error *XTE*, a track angle error *TAE*, a vertical track error *VTE* and a flightpath angle error *FPAE*.

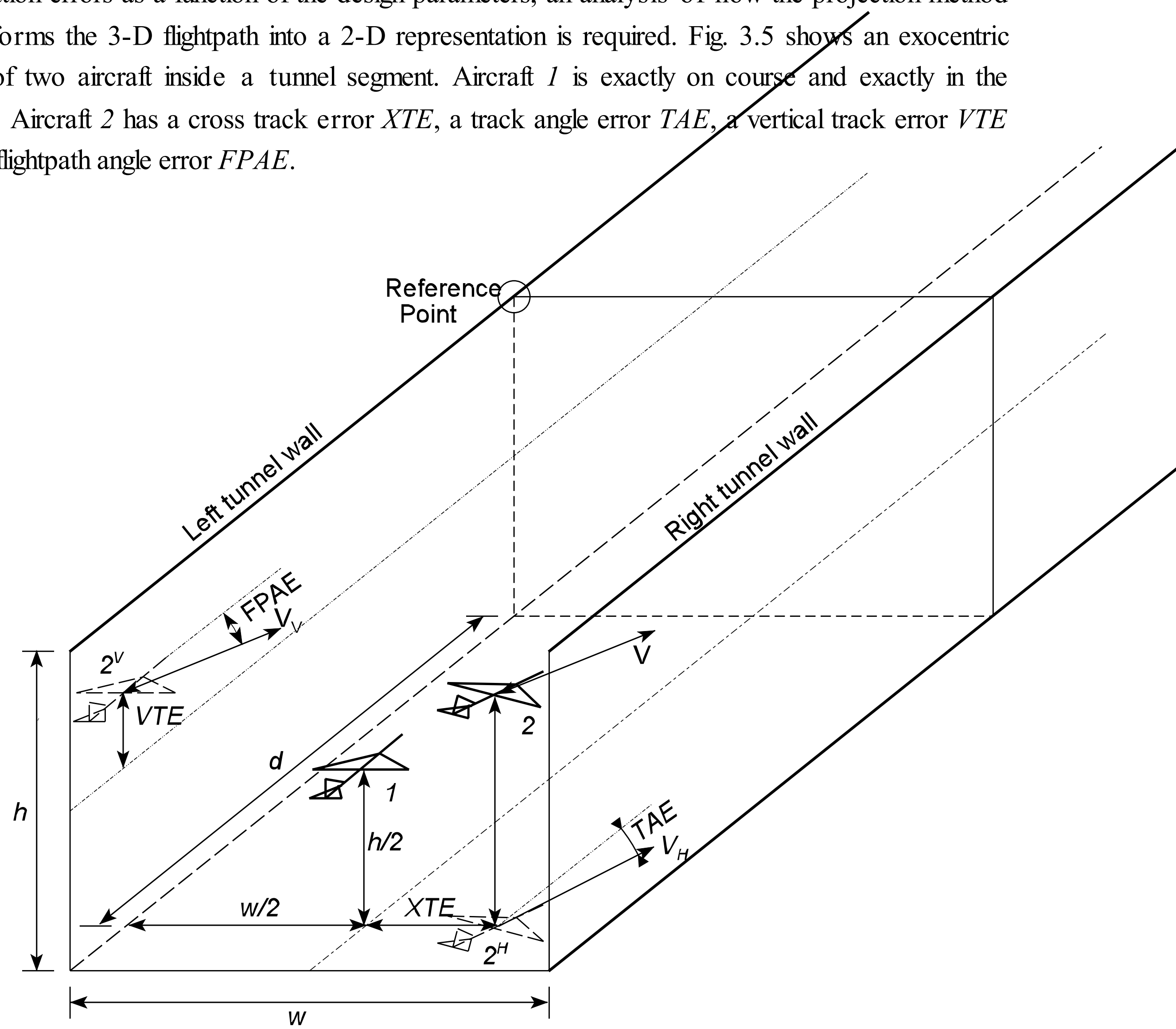


Fig. 3.5. *Specification of the cross track error XTE, track angle error TAE, vertical track error VTE and flightpath angle error FPAE. Aircraft 1 flies exactly on the centerline of the tunnel. Aircraft 2 has both lateral and vertical position and orientation errors. The cross track error and track angle error are indicated relative to the shadow 2^H of Aircraft 2, whereas the vertical track error and the flightpath angle error are indicated relative to the shadow 2^V of Aircraft 2. In this figure w represents the tunnel width, h the tunnel height, and d the distance between the aircraft and a cross-section of the tunnel in which a reference point lies.*

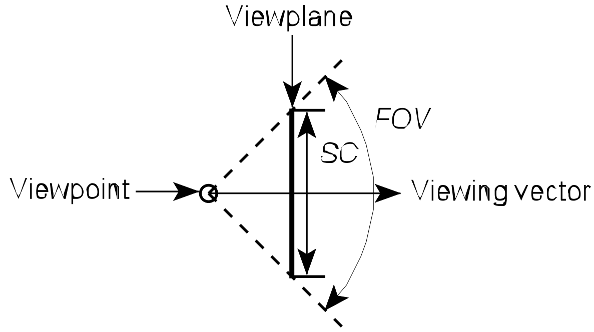


Fig. 3.6. *Basic mechanism of a computer graphics camera. The viewplane represents the screen-area on which the visible 3-D world must be depicted. Every point within the field of view is projected on the viewplane at the location where an imaginary line between this point and the viewpoint intersects the viewplane. The viewing vector indicates the central display axis.*

With a perspective projection, all visible points within a certain 3-D viewing space are projected onto a 2-D *viewplane*. This process is similar to a camera taking a picture. With computer graphics, this is generally performed through a series of matrix multiplications, and a detailed discussion can be found in numerous books about computer graphics, e.g. Hearn and Baker (1986). Since the projection is orthogonal, for an analysis of the projection method it suffices to consider a two dimensional projection. Fig. 3.6 presents the basic mechanism of a computer graphics camera.In Fig. 3.6, *FOV* indicates the field of view and *SC* the screen size. To obtain a description of the distortion of the symmetry caused by position and orientation errors as a function of the design parameters, the camera is positioned at the locations of Aircraft *1* and Aircraft *2* in Fig. 3.5. A top view of this situation in which the Aircraft *2* has no track angle error yet is presented in Fig. 3.7.

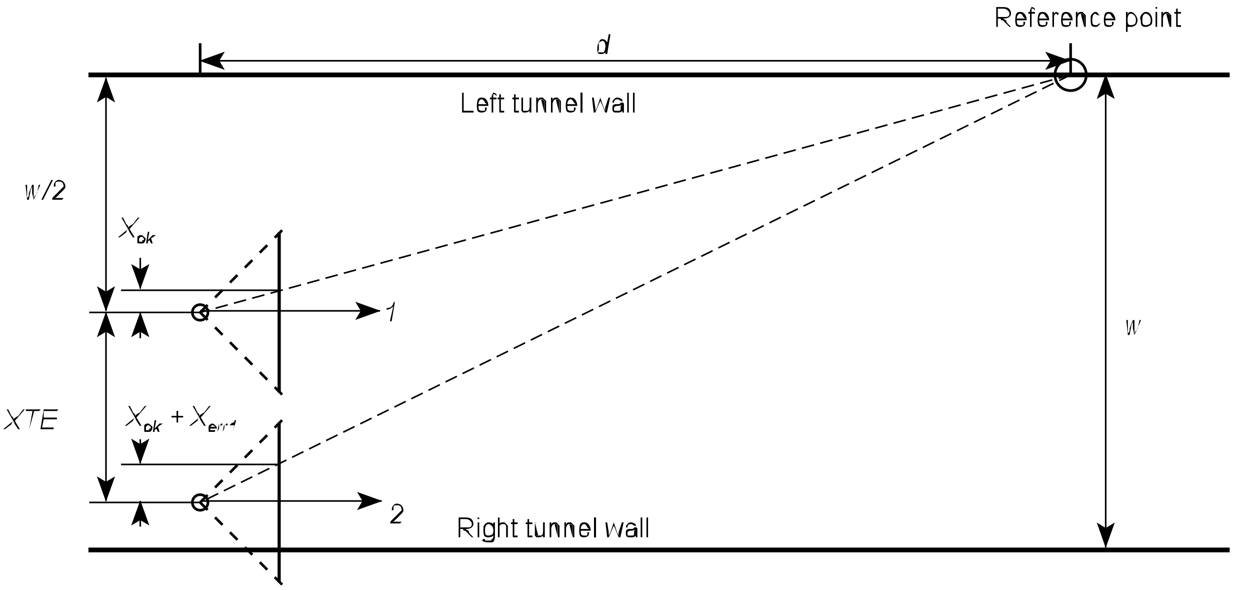


Fig. 3.7. *Top view of a tunnel section with viewpoint 1 in the center and viewpoint 2 displaced of a distance XTE. The intersection of the dashed lines with the viewplane determine the location where the reference point is projected on the viewplane.*

Viewpoint *1* is exactly in the middle at a distance *w/2* from each tunnel wall. The second viewpoint is displaced over a distance *XTE* relative to the first one. An object in 3-D space such as the tunnel can be described by a number of reference points which are connected by lines. For a basic perspective projection it suffices to map these reference points to 2-D space and to connect them in the same way as in 3-D space. To map a reference point onto the viewplane, a line between this point and the viewpoint is intersected with the viewplane. Fig. 3.7 shows such lines for an arbitrary reference point at a distance *d* from the viewplane to both locations of the viewpoint. The location of the intersection determines the location of the reference point in 2-D space. To avoid misperception, the ambiguity which is introduced with this process must be resolved. This will be discussed in Sect. 5.2. Fig. 3.8 presents a top view of the situation in which the second viewpoint also has a different orientation. The angular difference is the track-angle error *TAE*. Similar to a top view, a side view can be constructed. Tunnel width *w* must be replaced by tunnel height *h*, the cross-track error *XTE* is replaced by the vertical track error *VTE* and the track-angle error *TAE* by the flightpath angle error *FPAE*. Basic geometry can be used to describe the relation between the distortion of the symmetrical shape caused by position and orientation errors as a function of the design parameters.

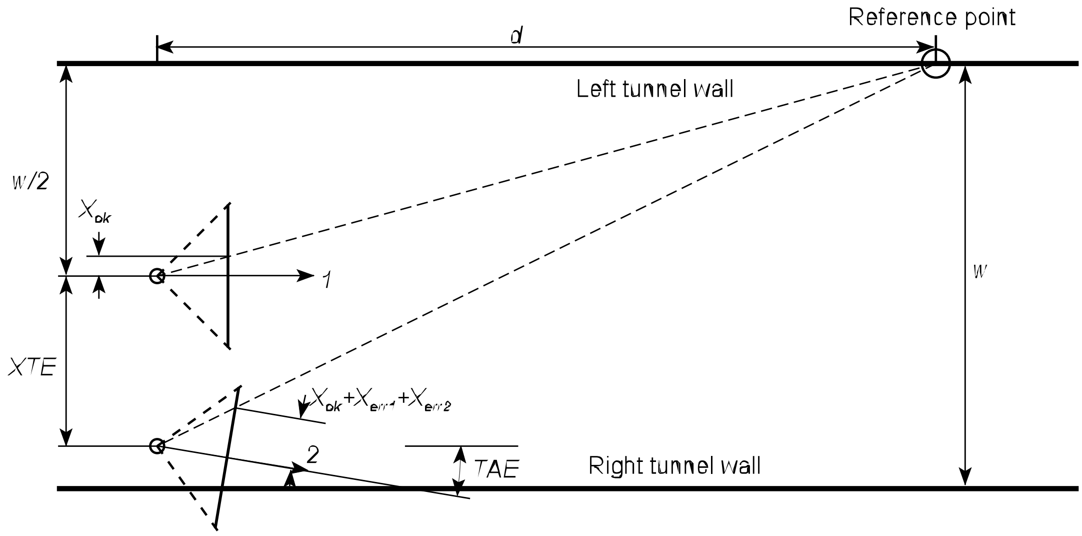


Fig. 3.8. *Similar situation to Fig. 3.7, only now the second viewpoint is also rotated over an angle TAE.*

The horizontal deviation from the symmetrical reference condition can be divided into a part x_{err1} which is only caused by the cross track error *XTE*, and a part x_{err2} which is caused by the orientation error but which is also a function of position error. Eq. (3.2) expresses the relation between the cross track error *XTE* and x_{err1} as a function of screen size *SC* [m], the geometric field of view *FOV* used for projecting the 3-D world onto a 2-D viewplane, and the distance *d* [m] towards the reference point. Eq. (3.3) presents the combined contribution of cross track error *XTE* [m] and track angle error *TAE* on x_{err2} as a function of screen size *SC* [m], field of view *FOV*, tunnel width *w* [m], and the distance *d* [m] towards the reference point.

$$x_{err1}=\frac{SC}{2\cdot\tan(FOV/2)}\cdot\frac{XTE}{d};\tag{3.2}$$

$$x_{err2}=\frac{SC}{2\cdot\tan(FOV/2)}\cdot\left(\tan\left(\arctan\left(\frac{w/2+XTE}{d}\right)+TAE\right)-\frac{w/2+XTE}{d}\right).\tag{3.3}$$

The factor *SC/2tan(FOV/2)* is equal to the distance between the viewplane and the viewpoint used for projection. Since the screen size and the geometric field of view can both be varied and yield a certain magnification, this representation is used throughout the discussion rather than the distance. Note that from Eq. (3.3) it follows that the contribution of the track angle error on x_{err2} depends on the current cross track error, and becomes negligible for large values of d which makes it possible to simplify Eq. (3.3) into Eq. (3.4), yielding:

$$\lim_{d\to\infty} x_{err2}=\frac{SC}{2\cdot\tan(FOV/2)}\cdot\tan(TAE).\tag{3.4}$$

This discussion illustrates that an observer can use the section of the tunnel at a large distance from the viewpoint to estimate the track angle error, and the nearby section for the cross track error. When *XTE* is replaced with *VTE*, and *TAE* with *FPAE*, the equations present the relations for the vertical dimension in a velocity-vector aligned reference frame. It must be stressed that the goal of presenting these equations is not to indicate how the observer processes the information from the display, but only that the information is present and due to the familiarity of the observer with the 3-D world probably will be processed in a way which allows him to make separate estimates of *XTE*, *TAE*, *VTE*, and *FPAE*. As a result of this ability, the pilot will be able to update his internal representation of the dynamics of the system under control, which is not possible with a flight director display. It is important to notice that the gain and the maximum resolution of the cross track error cues are inversely proportional to the size of the tunnel. The gain of the track angle error cues is not a function of tunnel size, but of geometric field of view.

3.5.3 Orientation of the viewing vector

For navigation through the three-dimensional space, the direction of travel is determined by ground-track and flightpath angle. With a perspective flightpath display, the presentation of all world-referenced navigation information is determined by the frame of reference. Fig. 3.3 showed a perspective presentation of the flightpath which was completely symmetrical. When the direction of the viewing vector is coupled to the aircraft body axis, a certain asymmetry will be present when the aircraft flies correctly through the tunnel. This is caused by the fact that there exists a difference between the direction in which the aircraft is pointing and the direction in which the aircraft is flying. Fig. 3.9 illustrates this in more detail.

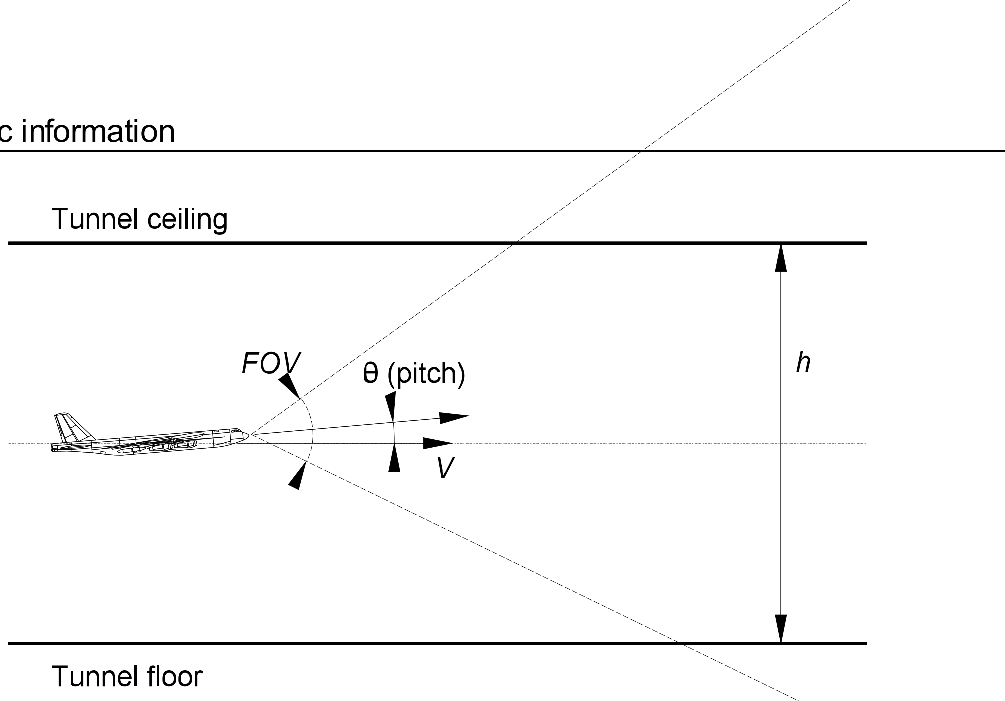


Fig. 3.9. *Side view of an aircraft flying exactly in the center of the tunnel. To maintain level flight, the pitch angle is larger than zero. As a result, the tunnel the pilot sees in this situation is asymmetrical in the vertical dimension.*

To illustrate how this misalignment influences the presentation of the flightpath, Fig. 3.10 shows a nearby section of the tunnel which the pilot would see in the situation of Fig. 3.9, and Fig. 3.11 shows a section of the tunnel at a large viewing distance. This distinction is made to allow the different features to be discussed separately. A similar problem exists in the horizontal dimension when crosswind is present. Fig. 3.12 illustrates this situation.

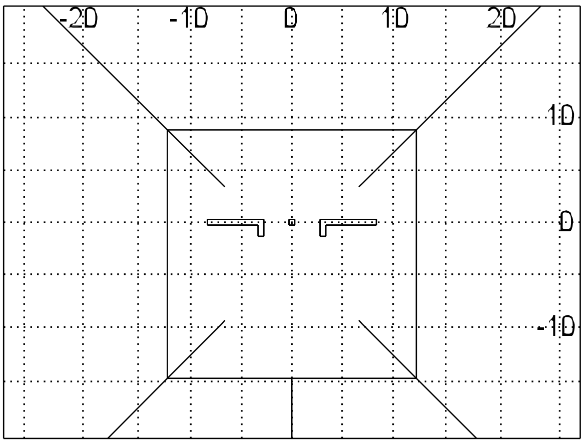


Fig. 3.10. *Nearby trajectory in the absence of position and orientation errors for the situation depicted in Fig. 3.9. The bottom lines of the tunnel intersect the boundary of the display closer to the central axis.*

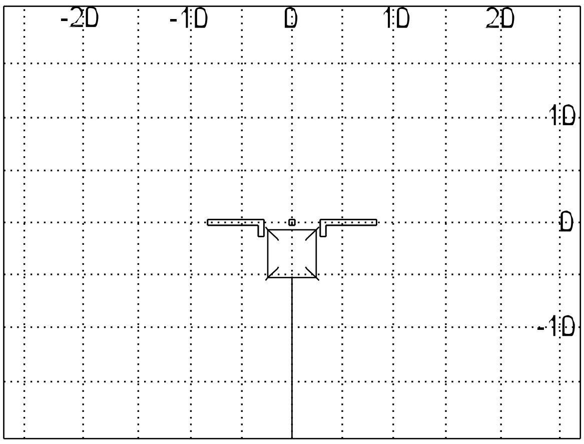


Fig. 3.11. *Distant trajectory in the absence of position and orientation errors for the situation depicted in Fig. 3.9.*

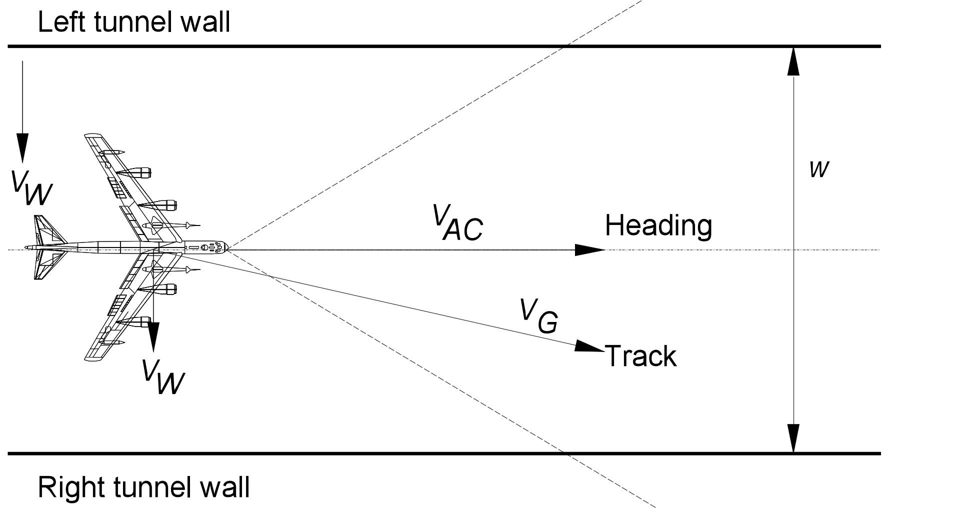


Fig. 3.12. *Aircraft in the center of the tunnel with its heading in the direction of the tunnel. Due to the crosswind V_W, the groundspeed V_G of the aircraft is different from the velocity V_{AC} relative to the air. The ground track is in the direction of the right tunnel wall.*

Due to the crosswind, the aircraft in Fig. 3.12 has a track angle error. To remain inside the tunnel, the aircraft has to change its heading so the track is aligned with the direction of the tunnel. This situation is depicted in Fig. 3.13.

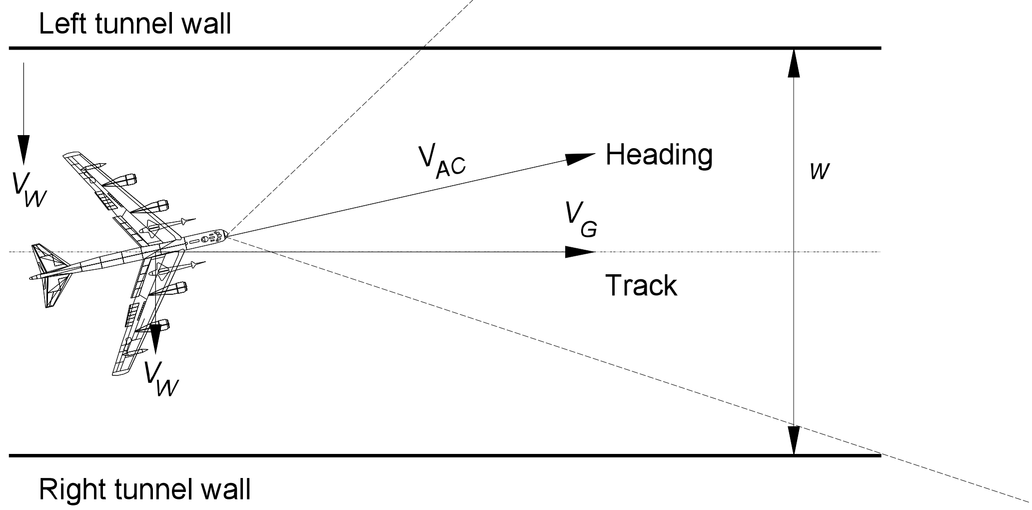


Fig. 3.13. *Aircraft flying straight down the tunnel in the presence of a crosswind V_W. As a result of the required crab angle, the horizontal symmetry with respect to the center of the display will be lost.*

Note that the dashed lines which indicate the field of view now intersect the tunnel walls at different distances from the aircraft. This will yield a picture like Fig. 3.14.

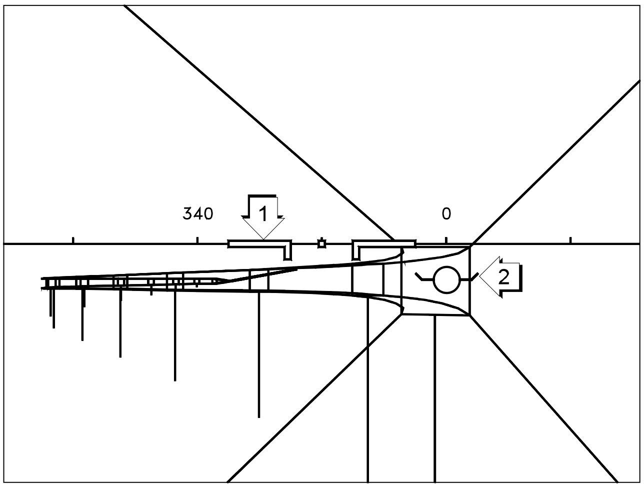


Fig. 3.14. *Attitude aligned perspective flightpath display in the presence of crosswind representing a situation as depicted in Fig. 3.13. The aircraft attitude symbol (1) is fixed in the center of the display. The velocity vector symbol (2) indicates the earth-referenced direction of flight.*

A potential solution which yields a fully symmetrical presentation in the absence of position and orientation errors, is to align the frame of reference with the aircraft direction of flight. This yields a so-called velocity-vector aligned frame of reference.

Attitude aligned displays are centered around the direction in which the aircraft is pointing. Velocity-vector aligned displays are centered around the direction in which the aircraft is going.

Fig 3.15 shows a top view of a situation in which the frame of reference is aligned with the direction of flight, and Fig. 3.16 shows how this the situation would be depicted on the display.

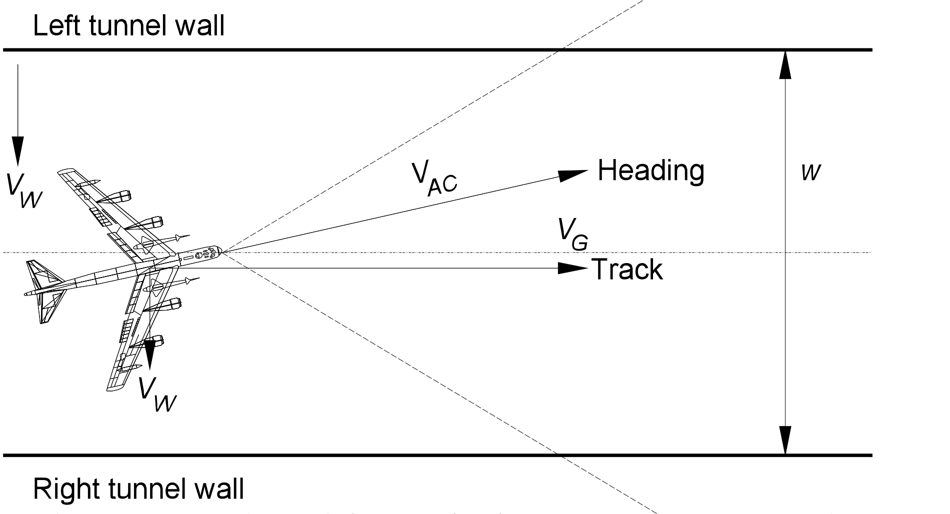


Fig. 3.15. *Velocity-vector aligned frame of reference. In this situation the viewing vector is aligned with the direction of where the aircraft is going rather than where it is pointing. Note that since in this situation the viewpoint is located in the cockpit, maintaining a symmetrical reference condition on the display will cause the center of gravity to be displaced relative to the centerline of the tunnel.*

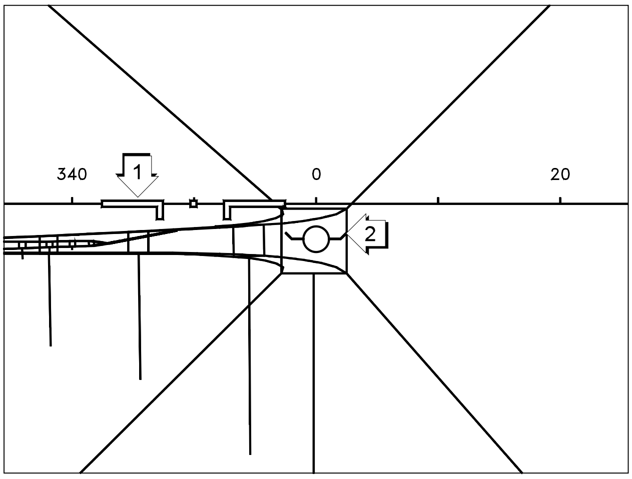


Fig. 3.16. *Velocity-vector aligned perspective flightpath display in the presence of crosswind. The aircraft reference symbol (1) points in the direction of the aircraft heading. The velocity vector (2) is fixed in the center of the display.*

From the previous discussion, it follows that when the frame of reference is coupled to the aircraft body axis, besides position and orientation errors, angular differences between the direction in which the aircraft is pointing and the actual earth-referenced direction of flight cause a distortion of the symmetry of the shape of the tunnel. The following discussion illustrates how position and orientation errors influence the symmetry of the presentation. Fig. 3.17 presents a top view of a situation in which the aircraft has a position error which is equal to 25% of the tunnel width but no orientation error. Fig. 3.18 presents a top view of a situation in which the aircraft has an orientation error but no position error.

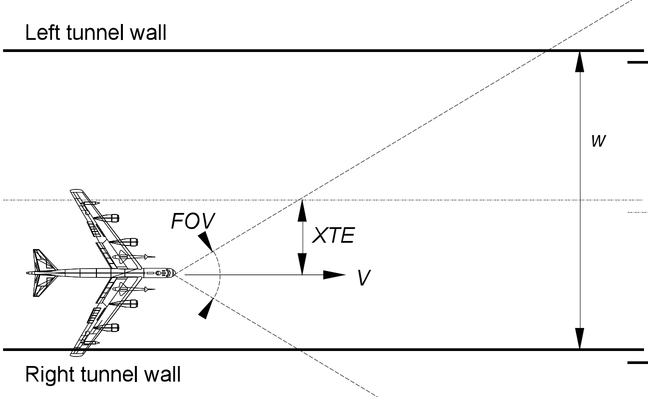


Fig. 3.17. *The aircraft has a cross track error XTE which is equal to 25% of the tunnel width w.*

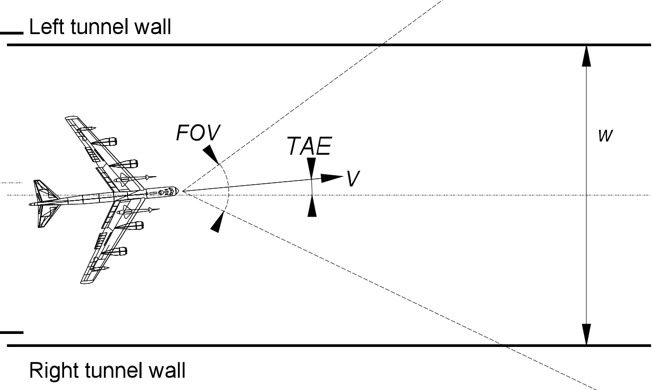


Fig. 3.18. *The aircraft has a track angle error but no cross track error.*

To illustrate how the contribution of a cross track error influences the horizontal symmetry of the situation depicted in Figs 3.10 and 3.11, Fig 3.19 shows a nearby section of the tunnel which the pilot would see in the situation of Fig. 3.17, and Fig. 3.20 shows a section of the tunnel at a large viewing distance. The situations presented in Figs 3.10 and 3.11 are indicated by the dashed tunnels. Grid lines have been added to allow the specification of display translations in terms of the azimuth and elevation.

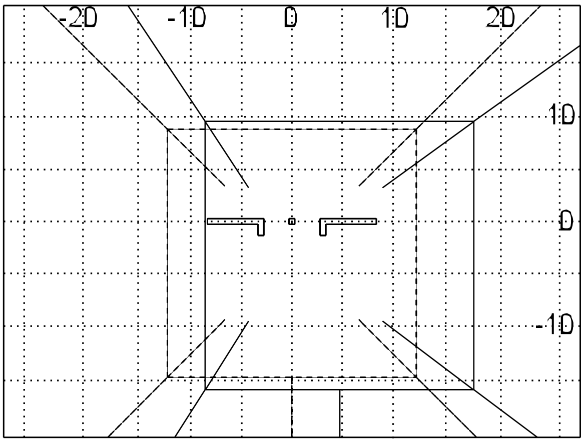


Fig. 3.19. *Effect of a cross track error on the nearby trajectory. The dashed tunnel is the reference condition presented in Fig. 3.10. Note the rotation of the tunnel lines.*

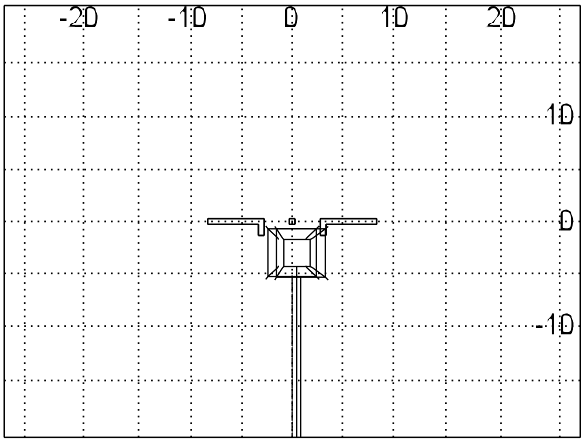


Fig. 3.20. *Effect of a cross track error on the trajectory at a larger distance from the viewpoint. Note that there is hardly any difference with the reference condition.*

As can be seen from Fig. 3.20 the endpoint remains almost in the same location. When looking at the tunnel lines in Fig. 3.19, it can be seen that a position error mainly causes a rotation of the tunnel lines around the endpoint. As a result of this rotation, the cross section frame is displaced to the right. In the next section, the magnitude of this rotation will be expressed as a function of position error and tunnel size.

To illustrate how the contribution of a track angle error influences the horizontal symmetry of the situation depicted in Figs 3.10 and 3.11, Fig 3.21 shows a nearby section of the tunnel which the pilot would see in the situation of Fig. 3.18 with a track angle error of 5 degrees. Fig. 3.22 shows a section of the tunnel at a larger viewing distance. Here too, the reference conditions presented in Figs 3.10 and 3.11 and an azimuth-elevation grid have been included. As can be seen from Figs. 3.21 and 3.22, the tunnel is translated over an angle which is equal to the orientation error. In contrast to Fig. 3.19, which presented the change in shape for a cross track error, the tunnel lines in Fig. 3.21 are all at approximately the same angle as depicted in Fig. 3.10 which showed the tunnel in the absence of position and orientation errors.

Summarizing, position errors mainly cause a rotation of the tunnel lines and as a result a translation of the tunnel cross-sections which is inversely proportional to the distance from the viewpoint. Orientation errors mainly cause a translation of the whole tunnel.

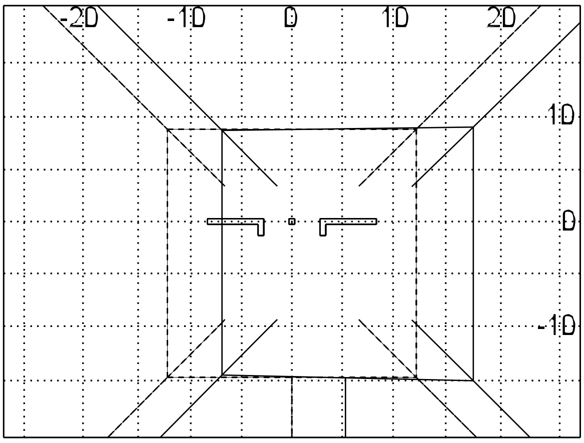


Fig. 3.21. *Effect of a track angle error of 5 degrees on the nearby trajectory. The scene appears to have translated approximately 5 degrees to the right.*

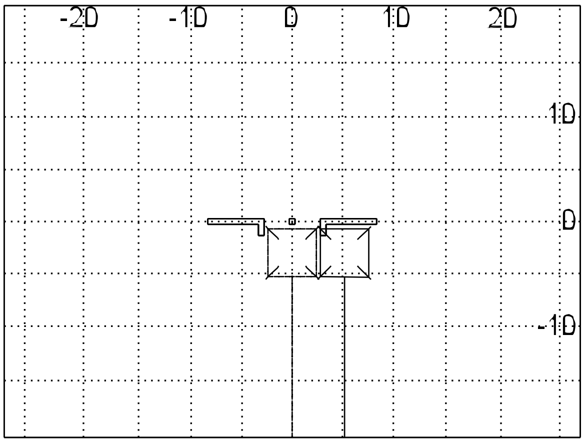


Fig. 3.22. *Effect of a track angle error of 5 degrees on the distant trajectory. Similar to the nearby trajectory, the main effect is a translation of the scene of approximately 5 degrees to the right.*

From these examples it may seem that with an attitude aligned frame of reference, a lateral orientation error yields the same visual cues as those which would be obtained when flying straight down a tunnel with a certain crab angle to compensate for crosswind. This, however, only applies to a single snapshot of the situation. The dynamic cues which result from the successive presentation of snapshots contain information about the direction of motion. When flying straight down the tunnel with a certain crab angle to compensate for crosswind, as depicted in Fig. 3.13, the center of optic outflow, which indicates the direction of motion, coincides with the vanishing point of the tunnel. In contrast, when a certain orientation error is present, the center of optic outflow differs from the location of the vanishing point of the tunnel. The additional information contained in the dynamic cues will be discussed in Sect. 3.6.

In an attitude aligned frame of reference, the cues resulting from a single snapshot of the situation provide not enough information to zero the orientation errors. Additional information, contained in the dynamic cues resulting from the presentation of successive images, is needed to extract the direction of travel from the center of optic outflow. To correctly fly down the tunnel with an attitude aligned frame of reference in the presence of crosswind, the pilot has to estimate the center of optic outflow. Since the location of the symmetrical reference condition varies as a function of crosswind, this necessitates additional symbology to directly indicate the direction of travel.

3.5.4 Functional variables

To better understand the contribution of the visual cues to task performance, a description of the functional variables for the specific task(s) is needed. The parameters in the equations expressing the distortion of symmetry are directly related to the 3-D world. For every element of the tunnel which is presented on the 2-D display, distance to the viewpoint must be known to calculate the distortion of the symmetry caused by that specific element. Although the previous equations are useful to provide more insight in the contribution to position and orientation cues of elements at a certain spatial location, the third dimension in these equations is not useful for relating the perceived visual cues to the control actions. Since the emergent feature (distortion of symmetry) is a 2-D phenomenon, i.e. the magnitude of the distortion does not vary along the viewing axis, an expression relating the distortion to position and orientation errors as a function of tunnel size and field of view without including the third dimension is desirable. In order to relate control actions to the available visual cues in terms of the optic flow pattern, such an expression should directly relate the position and orientation of the elements in the 2-D representation to the position and orientation errors. An additional advantage of expressing the effects of spatial position and orientation errors as 2-D cues is that perceptual thresholds can be related to minimal perceivable differences in spatial position and orientation errors. This allows the designer to specify minimum display size and resolution. As shown earlier, the distortion of the symmetry of a straight segment of the flightpath provides position and orientation cues. In the previous section, it was pointed out that for position errors which are small compared to the tunnel size, the distortion of the symmetrical reference condition can be approximated by a rotation of the tunnel lines. It was also indicated that the effect of small orientation errors can be approximated by a translation of the tunnel image over a distance which is equal to the ratio of the orientation error and the field of view. Wolpert et al. (1983) refer to the angle between the tunnel lines and the line perpendicular to the horizon as the *splay angle*. Fig. 3.23 illustrates the concept of splay angle S_0 for the situation of a cross track error, which causes the tunnel lines 1 to 4 to rotate over an angle ΔS_1 to ΔS_4, respectively.

With a perspective flightpath display presenting a tunnel with a width w and a height h, the splay angle S_0 of the tunnel lines in the absence of position errors is equal to:

$$S_0 = \arctan\left(\frac{w}{h}\right). \qquad \textbf{(3.5)}$$

Horizontal and vertical translations of the viewpoint result in changes in the splay angle. For a cross track error, the change is splay angle ΔS_1 is equal to $-\Delta S_3$ and ΔS_2 is equal to $-\Delta S_4$. When the cross track error is small relative to the size of the tunnel, ΔS_1 is approximately equal to ΔS_2, and ΔS_3 is approximately equal to ΔS_4. In the absence of a vertical path error, and when defining a clockwise rotation as positive, ΔS_1 can be approximated by $-XTE \cdot K_{wh}/w$. The constant K_{wh} is determined by the ratio of tunnel width and tunnel height.

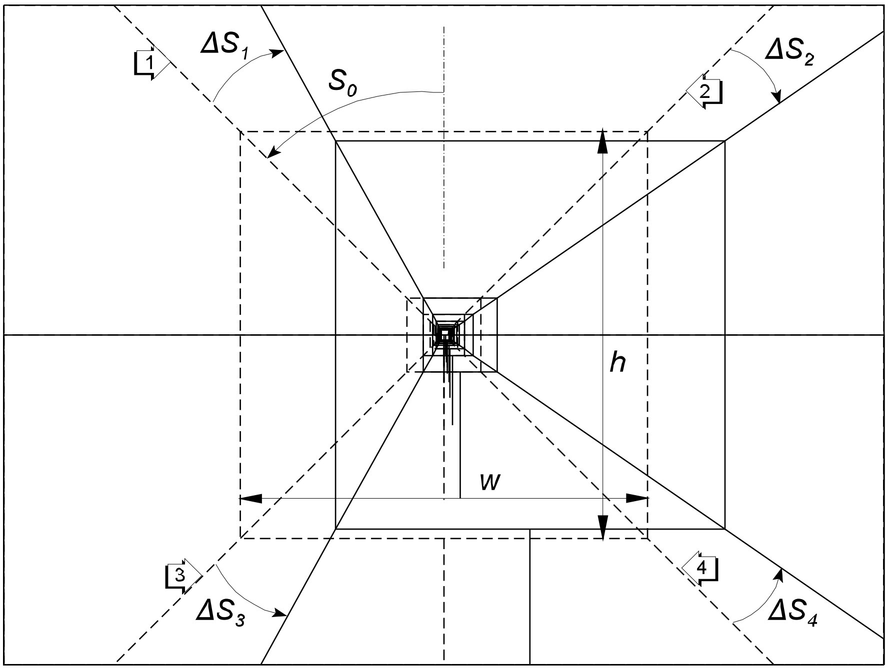


Fig. 3.23. *Influence of a cross-track error on splay angle S_0. The dashed tunnel indicates the symmetrical reference condition and the solid tunnel is seen when the viewpoint is displaced to the left yielding a cross track error. Tunnel lines 1 to 4 rotate around the vanishing point as a result of the cross-track error. The change is splay angle is referred to as ΔS_i, in which the index i is used to identify the tunnel line. As can be seen, the upper tunnel lines rotate clockwise and the lower tunnel lines counter clockwise around the vanishing point.*

For a vertical track error, ΔS_1 is equal to $-\Delta S_2$ and ΔS_3 is equal to $-\Delta S_4$. In the absence of a cross track error, ΔS_1 can be approximated by $-VTE \cdot K_{hw}/h$. The constant K_{hw} is determined by the ratio of tunnel width and tunnel height. In App. A it is illustrated how K_{wh} and K_{hw} can be calculated from the ratio between tunnel width and tunnel height. Also, the error resulting from this approximation, is discussed. In the presence of both a cross track error and a vertical track error, ΔS_1 to ΔS_4 follow from the sum of the rotations caused by a cross track error and the rotations cause by the vertical track error.

Summarizing, when the position errors are small compared to the tunnel size, the absolute ratios K_{XTE} and K_{VTE} between the change in splay angle and the absolute position error can be approximated by Eq. (3.6) for lateral position errors, and Eq. (3.7) for vertical position errors, respectively.

$$K_{XTE} = \frac{K_{wh}}{w} \ [Rad/m]; \tag{3.6}$$

$$K_{VTE} = \frac{K_{hw}}{h} \ [Rad/m]. \tag{3.7}$$

Cross track error rate can be approximated by the product of velocity and track angle error expressed in radians. Furthermore, vertical track error rate can be approximated by the product of velocity and flightpath angle error. Using these relations, the rate of change of splay angles, S_{XTE} and S_{VTE} can be approximated with Eq. (3.8) for lateral orientation errors and Eq. (3.9) for vertical orientation errors, respectively.

$$\dot{S}_{XTE} = \frac{K_{wh} \cdot V}{w} \cdot TAE \ [Rad/s], \tag{3.8}$$

$$\dot{S}_{VTE} = \frac{K_{hw} \cdot V}{h} \cdot FPAE \ [Rad/s], \tag{3.9}$$

Owen et al. (1984) have shown that all splay angles within the visual field vary proportionally with the changes in position, yielding splay rate to be called a global optical variable. Owen (1990) describes several studies which all indicate that splay rate is the functional variable for altitude control. A symmetrical object such as the tunnel provides splay rate cues both for vertical and horizontal position control. It is therefore assumed that with a perspective flightpath display, splay rate is the functional variable for position control. Based on Owen's organizational framework (1990), in the middle range of sensitivity an equal-ratio increment in splay rate gain should provide an equal-interval improvement in performance. Sect. 7.3 addresses this hypothesis for the perspective flightpath display.

As pointed out in the previous section, orientation errors mainly cause a translation of the tunnel. The amount of translation is proportional to the ratio of the orientation error and the field of view. When expressing the amount of translation as a percentage of the total display size, the lateral displacement can be approximated by Eq. (3.10) and the vertical displacement by Eq. (3.11). In these equations, T_x presents the lateral displacement and T_y the vertical displacement, both in percentage of the total display size. *HFOV* and *VFOV* represent the horizontal and vertical field of view, respectively.

$$T_x = \frac{TAE}{HFOV} \cdot 100\%; \tag{3.10}$$

$$T_y = \frac{FPAE}{VFOV} \cdot 100\%. \tag{3.11}$$

Since cross track error rate is proportional to the track angle errror, there are two cues for orientation errors. The gain of the splay rate cue is proportional to vehicle velocity and inversely proportional to tunnel size. The gain of the direct cue (image translation) is inversely proportional to field of view. It is important to notice that the gain of the rate cue is determined by both the design parameters and an element of the state-vector.

For control, the basic requirement is that the pilot is able to extract splay angle, splay rate, and amount of translation of the tunnel from the presentation.

By expressing the control oriented visual cues as a distortion of the symmetry, they can be described as properties of the optic flow pattern. Whereas previously, different designs could only be compared with each other in terms of the values of the design parameters, with this approach it is possible to compare different designs of perspective flightpath displays in terms of gains for the task related visual cues. Table 3.1 presents a summary of the cues which have been discussed in this section for an attitude aligned frame of reference, and Table 3.2 for a velocity vector aligned frame of reference.

Table 3.1. *Summary of the cues for position and orientation errors in an attitude aligned frame of reference.*

Functional variable	Gain	Dimension	Cue
XTE	K_{wh}/w	Rad/m	horizontal splay angle
VTE	K_{hw}/h	Rad/m	vertical splay angle
heading	*100/HFOV*	%/degree	horizontal image translation
TAE	$K_{wh} \cdot V/w$	1/s	horizontal splay rate
pitch	*100/VFOV*	%/degree	vertical image translation
FPAE	$K_{hw} \cdot V/w$	1/s	vertical splay rate

Table 3.2. *Summary of the cues for position and orientation errors in a velocity vector aligned frame of reference.*

Functional variable	Gain	Dimension	Cue
XTE	K_{wh}/w	Rad/m	horizontal splay angle
VTE	K_{hw}/h	Rad/m	vertical splay angle
TAE	*100/HFOV*	%/degree	horizontal image translation
TAE	$K_{wh} \cdot V/w$	1/s	horizontal splay rate
FPAE	*100/VFOV*	%/degree	vertical image translation
FPAE	$K_{hw} \cdot V/w$	1/s	vertical splay rate

3.5.5 Preview on changes in the trajectory

Besides information about position and orientation errors, the display contains information about changes in the direction of the future trajectory. A single snapshot provides information about the presence and the magnitude, whereas the dynamic presentation also conveys temporal range information. This latter aspect will be discussed in Sect. 3.6.4. For a circular segment, a change in the trajectory can be characterized by its magnitude and its rate of change. The magnitude determines the ability to predict the future ERF-WRF relation, which is important for navigational awareness. The rate of change influences the magnitude of the control actions required. In order to be useful, the display should allow the pilot to accurately extract unambiguous information about the curvature. Therefore, cues which vary as a function of the design parameters, but are needed to convey consistent (quantitative) information are not useful. Fig. 3.24 illustrates a situation for two different curves with radius R_1 and R_2. On each curve a point is located at the same angle ψ, yielding P_1 and P_2. The dashed lines connect P_1 and P_2 with the viewpoint, and the distance between the intersection and the center of the viewplane is indicated by x_1 and x_2, respectively.

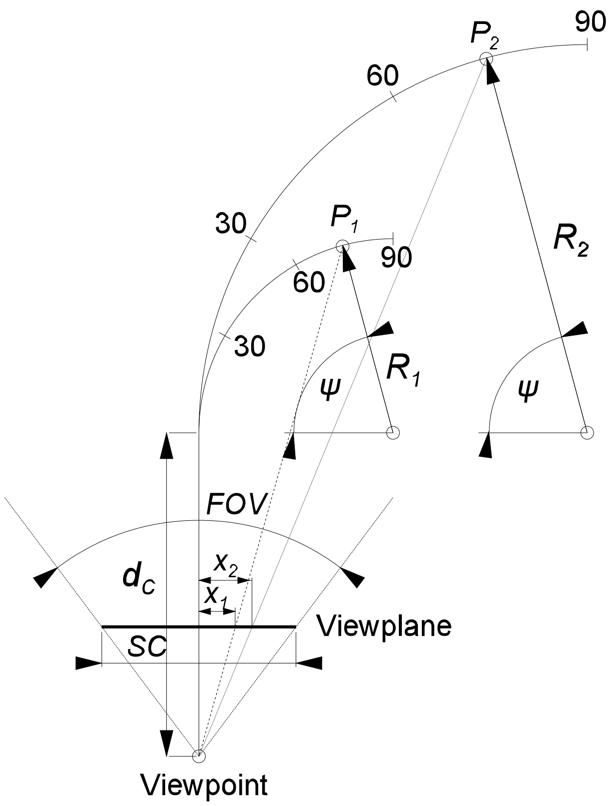


Fig. 3.24. *Top-view of a viewpoint located at a distance d_C before two different curves. The location of a reference point P in the curve is indicated by the angle ψ. The distance x_1 represents the location of the projection of P_1 on the viewplane, and x_2 the location of P_2. The difference between x_1 and x_2 is caused by a change in radius from R_1 to R_2.*

When defining the sensitivity of the curvature cues as the ratio of the change in display location and the change in curvature, the sensitivity G_s can be expressed as:

$$G_s = \frac{1}{2 \cdot \tan(FOV/2)} \cdot \frac{d_C \cdot (1-\cos(\psi))}{(d_C + R \cdot \sin(\psi))^2}. \qquad \textbf{(3.12)}$$

In Eq. (3.12), d_C represents the distance [m] remaining to the curvature, R the radius [m], and ψ the location of the point in the curved segment [rad], specified by the relative change in track. Fig. 3.25 shows the relation between the sensitivity and the ratio of d and R for different locations in the curve (ψ=10,30,50,70,90 degrees)

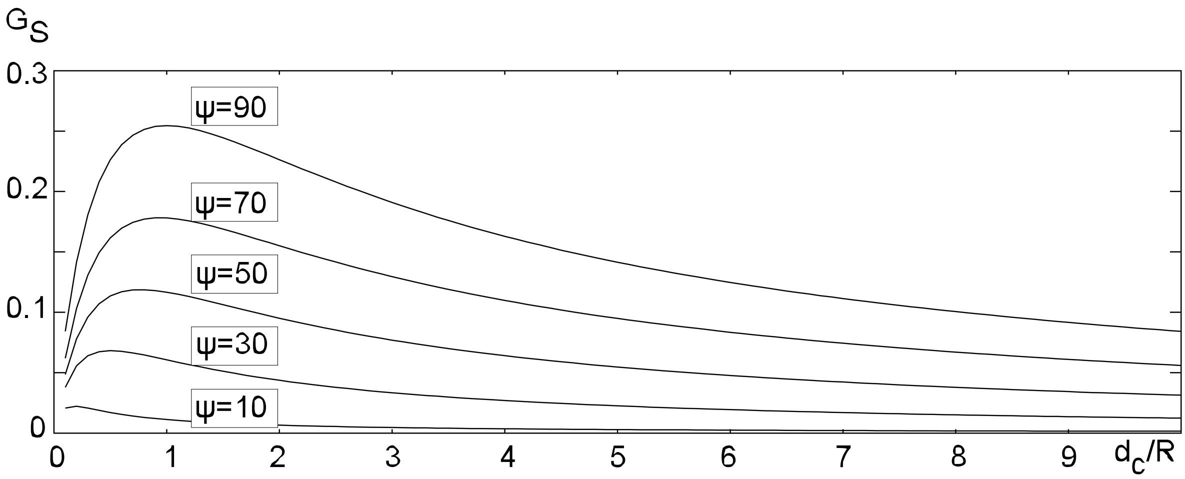


Fig. 3.25. *Gain G_s of the cues indicating a change in curvature as a function of the ratio of the distance d_c to the start of the curve and curve radius R. G_s represents the ratio of a change in display location of a reference point P_n at a location specified by the angle ψ and a change in curve radius R (see also the previous figure). As can be seen from this figure, the location of points further along the curve (larger ψ) varies more when the radius is changed than points in the beginning of the curve.*

As can be seen from Fig. 3.25, the sensitivity increases with decreasing distance towards the curved segment until a certain minimum distance is reached. Furthermore, the sensitivity increases with increasing distance along the segment. Finally, it is important to realize that the maximum sensitivity which can be used is also determined by the moment the initiation of the anticipatory action is required.

3.6 Dynamic information

3.6.1 Introduction

Research into the perception of self-motion from the optical flow field provides a good basis for understanding the velocity cues conveyed by a perspective flightpath display. Gibson et al. (1955) provided the first mathematical description of the optical flow pattern during self motion. Owen

(1990b) gives an overview of the important contributions of Gibson to the research into self-motion perception. Gordon (1966) discusses three mechanisms for the perception of motion. At slow rates, motion is inferred from a change in position, at more rapid rates motion is directly perceived, and at still more rapid rates, motion appears as blur. When the data update-rate of the display exceeds a certain threshold, the successive snapshot images of the situation yield a smoothly animated display, conveying an illusion of continuous motion. This threshold lies at approximately 10 Hz, although higher update rates yield a more smoothly animated display. The motion of the aircraft relative to the virtual tunnel allows the extraction of error rates and produces additional cues. These dynamic cues provide the pilot with a sense of egospeed and three-dimensionality, convey directional information, and allow him to extract temporal range information. The following sections discuss each of these cues in more detail.

3.6.2 Perception of velocity

Two important velocity cues available in the 3-D world are optical edge rate and global optical flow rate. Optical edge rate is defined as *'the speed at which texture elements pass a given point in the subject's field of view'* (Warren, 1982). As indicated by Larish and Flach (1987), the term edge rate is misleading as the actual information appears to be local average texture flow rate as noted in Warren's (1982) definition, rather than actual edges. Local optical flow rate of texture elements within the visual field scales with ratio of velocity over distance to the plane in which the surface lies. Gordon (1966) indicated this relationship by stating that *'distance to the surface must be specified to permit a judgement to be made of the speed of motion'*. Warren (1982) partitioned the expression for local optical flow rate into two factors: One factor depending on location and the other only on the ratio of path speed and altitude. He named the V/h ratio global optical flow rate, and hypothesized that the perception of egospeed would scale with global optical flow rate. Based on experiments investigating the information for decelerating self motion, Owen (1990b) concludes that *'fractional loss in speed is clearly the functional event variable for visual perception of one's own speed, even when stopping is not related to any particular place on the ground surface and no surface is approached so that time to collision is not a relevant factor as it is with descent'*.

For rectilinear flight over a flat surface, edge rate is completely determined by the speed of the observer and the spacing of the edges on the surface. Edge rate is independent of altitude, and therefore remains proportional to ground velocity when altitude varies, but not when ground texture varies. Global optical flow rate is defined as the rate of expansion of the visual field, which is a ratio of forward velocity and altitude. Therefore, flow rate is proportional to ground velocity only under the condition of constant altitude. Larish and Flach (1987) examined the relative contribution of optical edge rate and global optical flow rate to the perception of egospeed under viewing conditions in which the degree of three-dimensional cuing was varied. In the uncontrolled condition, subjects monitored a conventional display with a perspective representation of a moving 3-D scene. In controlled viewing conditions, stronger 3-D cues where presented through the use of a binocular device. They report that optical edge rate appears to be an important variable in the perception of egospeed under all conditions. Optical edge rate was the dominant source of information used in the uncontrolled conditions, with global optical flow failing to contribute significantly. Under controlled viewing conditions, a much greater effect of global optical flow rate was reported. Larish and Flach hypothesized that the result is due to the ability to perceive depth in the controlled viewing conditions. The effect of global optical flow rate might become even more pronounced if stronger 3-D information is provided. The results suggest that the cues used in the judgement of egospeed change as a function of the availability of conflicting 2-D depth cues. Experiments into the contribution of edge rate and flow rate to the sensitivity to acceleration (Warren et al., 1982; Owen et al., 1984) revealed that the sensitivity to edge rate and flow rate varies among individuals. They conclude that *'the findings indicate that the human visual system has two types of sensitivity for detecting increase in speed of self motion, and that the two types are unequally distributed over individuals'*. Johnson and Awe (1993) conducted an experiment to determine the ability to control ground speed in the presence of relevant and irrelevant variations in edge and flow rates. They tested whether more experienced pilots would be better able to ignore irrelevant variations in edge rate, and whether pilots would show a bias toward using edge rate relative to global optical flow rate for the control of ground velocity. They report that *'no evidence was found that people are more intrinsically sensitive to edge rate variation, nor that pilots may be biased toward using edge rate to control ground speed'*. Since the center of optic outflow indicates the direction of travel, it is likely that vehicle path estimation accuracy is also related to the magnitude of the flow rate. Based on their research into visual cues in nap-of-the-earth helicopter flight, Grunwald and Kohn (1993) conclude that *'the vehicle path estimation accuracy and head yaw rate activity generally increase with the V/h ratio. Due to larger "local expansion" the far viewing distances yield more accurate estimates than close distances. However, due to blurring effects, close distance estimates no longer improve with V/h'*.

3.6.3 Velocity cues with a perspective flightpath display

With a perspective flightpath display, velocity cues are conveyed by the motion of the cross section frames toward the observer. Optical edge rate is determined by the distance between the successive frames. When this distance varies while the observer is unaware of it, the cues provide by edge rate can cause a misperception of relative velocity. Global optical flow rate is determined by the geometric field of view and the tunnel size. If the tunnel size varies while the observer is unaware of it, global optical flow rate can cause a misperception of relative velocity. Thus, a tapered segment of the perspective flightpath which might be needed to gradually increase the position constraints also increases global optical flow rate and can potentially yield a misperception of velocity. Furthermore, all velocity cues are relative and inertially referenced.

Since the velocity cues resulting from the dynamic presentation of the flightpath cannot be considered reliable indicators for either absolute or relative velocity and are inertially referenced, additional data about the velocity relative to the airmass must be presented, for example by means of a separate airspeed indicator.

To describe the effects of the successive presentation of images, the velocity gain G_v is introduced.

Velocity gain is the ratio of the velocity of an element on the display and the relative velocity between the observer and the element which is caused by a displacement between the observer and the element.

An equation for the velocity gain G_v can be easily derived from the geometric relations and yields:

$$G_v = \frac{x \cdot SC}{2d^2 \cdot \tan(\frac{FOV}{2})} \qquad \textbf{(3.13)}$$

The parameter d represents the distance from the viewpoint to the plane perpendicular to the viewing vector in which the element lies, x indicates the distance between the central display axis and the element, FOV the geometric field of view which is used for the perspective projection, and SC the size of the screen (Fig. 3.6). The parameter SC can be expressed in actual dimension of the screen, the resolution of the display pixels, or the observer field of view. When relating the gain to pixels, the displayed resolution of the data can be obtained. When expressing the screen size relative to the observer field of view, it can be related to a minimum perceivable angular difference. Because velocity cuing is obtained through the movement of the tunnel frames, x can be substituted by $w/2\text{-}XTE$, which yields:

$$G_v = \frac{SC \cdot (\frac{w}{2} - XTE)}{2d^2 \cdot \tan(\frac{FOV}{2})} \qquad \textbf{(3.14)}$$

In this equation w represents the width of the tunnel [m] and XTE the cross-track error [m]. With Eq. (3.14) the magnitude of the horizontal and vertical velocity gain can be calculated for an arbitrary element of the flightpath. From Eq. (3.14) it follows that the magnitude of the velocity gain is inversely proportional to the square of the distance from the viewpoint. The change in the magnitude of the velocity streamers as they are closer to the viewpoint, increases the feeling of three-dimensionality. Velocity cues are generated by the cross-section frames. Thus, the spacing between these frames influences the amount of cuing which conveys a feeling of three-dimensionality, and the tunnel size influences the magnitude of the cues. Frame spacing will be further discussed in Sect. 5.6.2.

By combining the horizontal and vertical components of the velocity gain in a vector, a streamer pattern can be plotted, which gives an indication of the flow of the tunnel elements. This makes it possible to visualize how position and orientation errors and differences between the aircraft body-axis and the earth-referenced direction of flight influence the dynamic aspects of the presentation. To illustrate the effect of a cross track error on the dynamic data, Fig. 3.26 presents the velocity field in the absence of position and orientation errors and Fig. 3.27 for the situation of a cross track error, both for the situation of rectilinear motion.

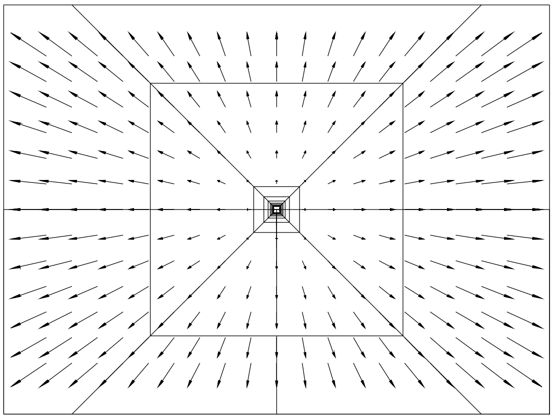


Fig. 3.26. *Velocity streamers in the absence of position and orientation errors.*

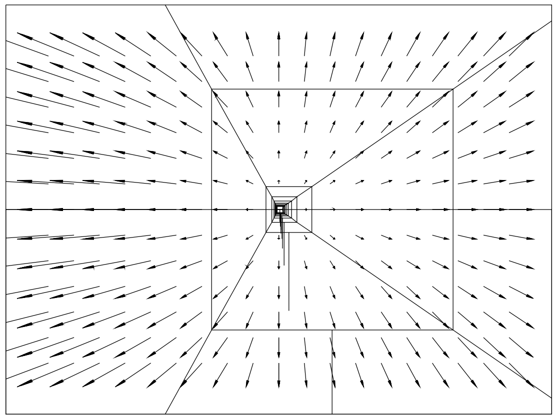


Fig. 3.27. *Velocity streamers in the presence of a cross-track error.*

In Sect. 3.6.3 it was indicated that the dynamic cues contain information which allow the pilot to extract the direction of motion, and hence allow him to distinguish between the situation in which there is a difference between orientation errors and the situation in which there is a difference between the orientation of aircraft body-axis and the earth-reference direction of flight. To illustrate the difference in dynamic cues, Fig. 3.28 shows the velocity field for the situation depicted in Fig. 3.13 and Fig 3.29 the velocity field for the situation in Fig. 3.18. Both in Fig. 3.13 and Fig. 3.18 the aircraft body axis are not aligned with the central axis of the tunnel. In case the track angle error in Fig. 3.18 is equal to the crab angle in Fig. 3.13, a single snapshot of the tunnel will show no difference. When looking at the dynamic cues by visualizing the velocity streamers, Fig. 3.28 shows that the center of optic outflow for the situation in Fig. 3.13 coincides with the vanishing point of the tunnel. From Fig. 3.29 it can be seen that in case of a track angle error, the center of optic outflow, however, no longer coincides with the vanishing point. As indicated in the definition of velocity gain, only the displacement of an element on the display which is caused by a displacement between the observer and the element is taken into account. Since a change in orientation also causes a change in position of the displayed elements, an angular velocity gain is introduced. This gain is defined as the ratio of the velocity of an element on the display caused by a change in orientation of the viewpoint, and the rate of change in orientation.

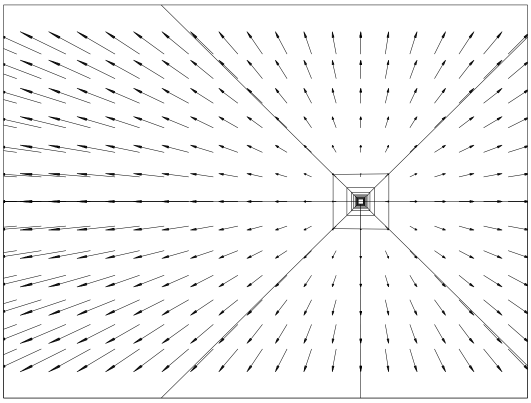


Fig. 3.28. *Velocity streamer pattern for the situation in which the track of the aircraft is aligned with the tunnel axis and the aircraft flies with a crab angle of 10 degrees due to crosswind. The direction of flight can be perceived from the location of the center of optic outflow.*

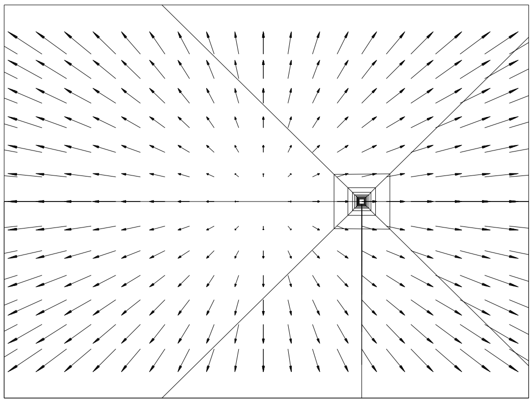


Fig. 3.29. *Velocity streamer pattern for the situation in which the aircraft has a track angle error of 10 degrees. Note that the static image of the tunnel is the same as in the previous figure, but the center of optic outflow is in a different location.*

For the horizontal plane, yaw gain G_{yaw} can be expressed as:

$$G_{yaw} = \frac{SC}{FOV}. \tag{3.15}$$

From Eq. (3.15) it follows that in case of a change in orientation of the viewpoint, a component is added to all vectors. This component is equal for all elements of the display. Fig. 3.30 presents an example in which such a yaw component is present.

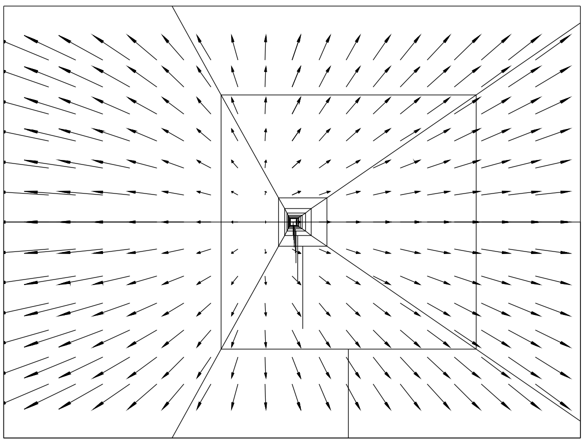


Fig. 3.30. *Velocity streamers in the presence of a cross-track error and a yaw component.*

The difference with Fig. 3.27 is that the center of optic outflow no longer coincides with the vanishing point of the tunnel. The difference with the streamer pattern in Fig. 3.29 is that due to the yaw component the streamer pattern is no longer symmetrical with respect to the vertical axis through the center of optic outflow.

Summarizing, in Sect. 3.5.3 it was concluded that '*in an attitude aligned frame of reference, the cues resulting from a single snapshot of the situation provide not enough information to zero the orientation errors. Additional information, contained in the dynamic cues resulting from the presentation of successive images, allows the pilot to extract the direction of travel from the center of optic outflow*'. In this section the dynamic cues were discussed which contain the information the pilot needs to match the direction of flight with the direction indicated by the tunnel.

3.6.4 Perception of temporal range information

When the preview contains information about changes in the future trajectory, the dynamic presentation of this preview conveys so-called temporal range information. This temporal range information can be used for the timing of anticipatory control actions, e.g. the moment to initiate a control action to enter a curve. In the situation of recti-linear motion, the dynamic perspective presentation of the trajectory allows the pilot to estimate the time until the center of projection reaches a certain reference point without knowing tunnel dimension or vehicle velocity. Owen (1990b) indicates that the availability of an optical specification of time to collision was already acknowledged by Gibson in 1958. This important phenomenon has been referred to as time-to-contact (TTC) (Lee, 1976) and time-to-passage (TTP) (Kaiser and Mowafy, 1993). Owen (1990b) reports on research investigating the influence of flow acceleration on descent detection. The results showed that flow acceleration only had a minor effect, but that the inverse of the fractional loss in distance to a surface (representing the time to contact), might be useful for control of both sink rate and the onset of flare. The fact that information about TTC and TTP are present in the optical flow field can be demonstrated by describing the position of a three-dimensional point after mapping on a 2-D surface by two spatial angles. For small angles, i.e. when the tangent of the angles can be approximated by the angle itself, Eq. (3.16) expresses the *TTP* as the ratio of the spatial angle ξ and its rate of change $d\xi/dt$.

$$TTP = \frac{\xi}{\frac{d\xi}{dt}}. \tag{3.16}$$

In general, the eye reference point will not lie in the center of projection, which introduces image compression or expansion. However, since both the spatial angle and its rate are compressed by the same factor, this does not affect the estimate of the TTP. With increasing tunnel size, the maximum angular rate of change decreases, which increases the minimum TTP which can be perceived. For anticipatory control, it is important that within a certain time window an accurate estimate can be made of the time until a specific event. When this minimum TTP exceeds the maximum threshold of the useful time-window, its contribution to anticipatory control will become useless. Eq. (3.17) presents the minimum average value of TTP which can directly be perceived, as a function of velocity, tunnel size, and field of view.

$$TTP_{min} = \frac{tunnelsize}{V \cdot FOV} \qquad \textbf{(3.17)}$$

In this equation, *tunnelsize* represents the size of the tunnel in [m], *V* the vehicle velocity [m/s], and *FOV* the field of view [rad]. The reason why the size of the tunnel is used rather than width or height, is that the horizontal field of view may differ from the vertical field of view and the width of the tunnel may differ from the height. As a result, it may take longer for either the sides or the top and bottom of the tunnel to reach the boundaries of the viewplane. Kaiser and Mowafy (1993) performed a series of studies in which they examined the ability of an observer to infer temporal range information from objects which are not on a collision course but leave the observer field of view before they pass them. The observer had to indicate the moment a target (which had left his field of view) would pass. The targets were between 1 and 3 seconds from passage when they exited the field of view. Kaiser and Mowafy (1993) report that the estimates showed a non-veridical temporal scaling effect. Shorter TTP's were overestimated and longer TTP's underestimated.

The previous discussion assumed the absence of a rotational component. In the presence of such a component, the optic flow field is obtained by adding a constant vector to all vectors of Fig. 3.27, resulting in a shift of the optic center. Fig. 3.30 illustrated an example. The rotational component changes the angular rate of the points projected onto the 2-D viewplane, which in turn makes it impossible to estimate the TTP of a single point. However, when looking at the constructs in 3-D space defined by interconnections between a set of points, the size of these constructs is not affected by a yaw component, and the TTC can be perceived from the size and its rate of change.

The studies into temporal range information performed by Lee (1976) and Kaiser and Mowafy (1993) dealt with objects with a relative motion directly toward the observer. The walls of the tunnel, however, run almost parallel to the direction of motion. Crossing a tunnel wall will mostly occur at a relatively small angle between the direction of motion and the direction of the wall. In Sect. 3.5.4 it was illustrated how splay angle conveys information about position errors. The visual cues resulting from the dynamic presentation contain temporal range information with respect to the time a tunnel wall is crossed. This temporal range will be referred to as time-to-wall crossing (TWC). If the pilot is able to extract temporal range information with respect to the walls of the tunnel, a fundamental question is the order of the model which best approximates the pilot's estimate of the TWC. The assumption for a first-order model is, that the pilot does not use the aircraft's yaw rate in his estimate, and consequently assumes a future trajectory that is straight. The visual flow field contains information about rotations and translations, and under the assumption of a constant velocity and a constant rate of rotation, the future vehicle path is circular. If the observer is capable of extracting this information from the visual flow field, a second-order approximation of the TWC might be possible. Fig. 3.31 illustrates a top view of the situation in which both a straight and circular future vehicle path are indicated. The straight path intersects the tunnel wall at location *1* and the circular path at location *2*. The angle at which the aircraft will leave the tunnel in location 1 is equal to the current track angle error *TAE*. In location *2*, the angle will have increased by the amount ΔTAE to TAE_X. With a circular vehicle path, ΔTAE is equal to the product of the TWC and the yaw rate *r*.

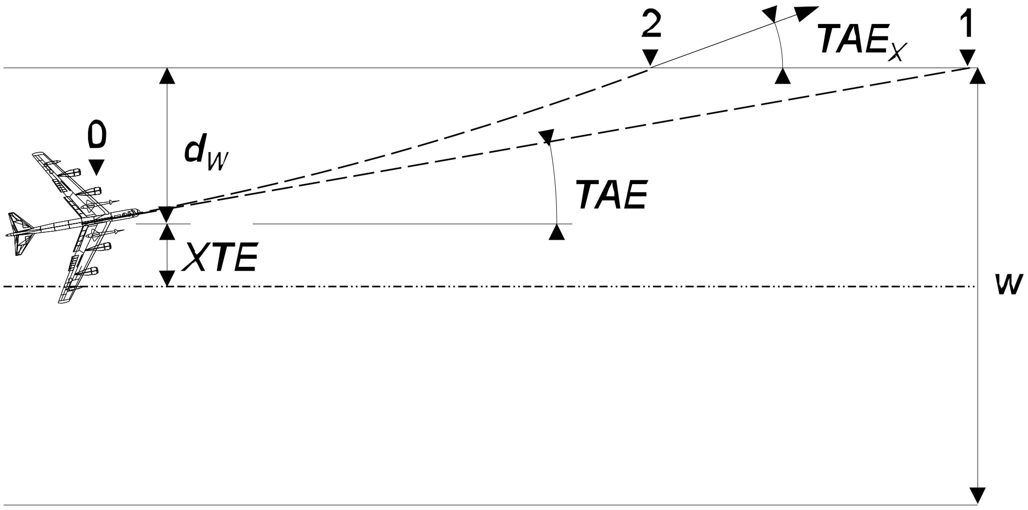


Fig. 3.31. *First and second-order prediction of the intersection of the future trajectory with the tunnel wall. At present, the aircraft is at location 0. The first-order prediction intersects the tunnel in location 1 and the second-order prediction in location 2. XTE represents the current cross track error, TAE the current track angle error,* d_w *the current distance towards the tunnel wall which will be crossed, and* TAE_X *the angle at which the circular trajectory crosses the tunnel wall.*

Eq. (3.18) presents the TWC based on a first-order model, and Eq. (3.19) for a second-order model, both for the horizontal plane.

$$TWC = \frac{d_W}{V \cdot \sin(TAE)}; \qquad \textbf{(3.18)}$$

$$TWC = \frac{1}{r}(TAE + \arccos(\cos(TAE) - \frac{r \cdot d_W}{V})). \qquad \textbf{(3.19)}$$

In these equations d_w represents the perpendicular distance from the aircraft to the tunnel wall [m], *TAE* the current track angle error [rad], *V* the velocity [m/s] and *r* the yaw rate [rad/s].

Fig 3.32 illustrates both the shape of the tunnel the pilot would see in the current situation and the shape at the moment the aircraft crosses the wall at location 2.

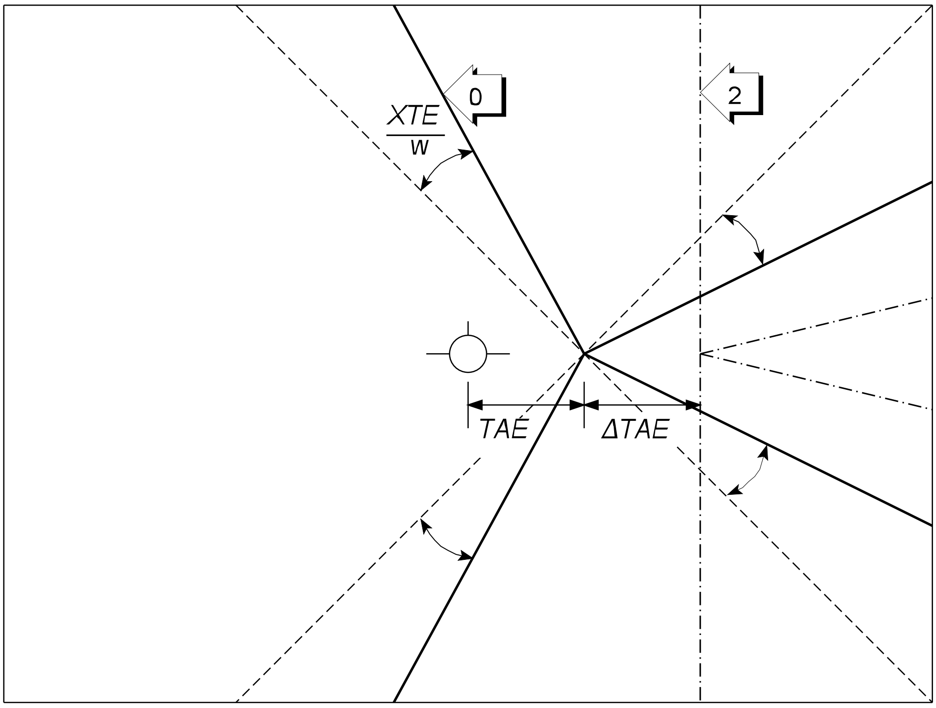


Fig. 3.32. *Shape of the tunnel at location 0 and location 2 in Fig. 3.29. In location 0 the tunnel is already displaced by the amount TAE and the tunnel lines have rotated over approximately XTE/w radians. In location 2, the tunnel lines indicating the left wall will run vertical and the track angle error TAE has increased by the amount ΔTAE to* TAE_X.

The dynamic change in shape contains information which provides an indication of the TWC. At the moment the aircraft crosses a tunnel wall, the lines representing the wall will run vertical. The horizontal displacement of these lines from the center of the screen indicates the track angle error at the moment the tunnel wall is crossed. In App. A it is illustrated that for position errors which are small compared to the tunnel size, splay rate is proportional to cross track error rate. Eq. (3.8) showed that in this situation, splay rate is proportional to track angle error. When assuming velocity V constant and track angle error rate equal to yaw rate r, differentiating Eq. (3.8) and substituting r for track angle error rate yields that yaw rate is proportional to the acceleration of the splay angle, and the relation can be expressed as Eq. (3.20).

$$\ddot{S} = \frac{V \cdot r}{w}. \tag{3.20}$$

When referring to the time the error-correcting control actions is initiated as t_0 and the time the aircraft crosses the tunnel wall as t_{TWC}, Eq. (3.21) shows the relation between the splay angle (S), splay angle rate and splay angle acceleration:

$$S(t_0)+\dot{S}(t_0)\cdot TWC+\frac{1}{2}\ddot{S}(t_0)\cdot TWC^2=S(t_{TWC})=0. \quad (3.21)$$

The first term in Eq. (3.21) represents the contribution of the existing position error. The second term represents the contribution of an orientation error. Together with the first term it represents a first-order relation between splay angle and TWC. The presence of a yaw component is represented by the second derivative of the splay angle. Yaw is conveyed through the horizontal translation of the visual scene. If the pilot would base his estimate of the TWC only on splay rate, the TWC would follow from the ratio of the current splay angle and splay rate, yielding a first-order approximation. As illustrated previously, the components required to make a second-order estimate of the TWC are available. An observer might learn to exploit the relation presented in Eq. (3.20) and use the rate of the horizontal translation of the image as an indication for the magnitude of the acceleration and might make a better than a first-order estimate of the TWC. The relation presented in Eq. (3.20) contains both velocity and tunnel size, and from this one might conclude that the observer needs to know both parameters. However, the observer only needs to perceive a cue indicating the ratio between velocity and tunnel size, and the magnitude of this cue is proportional to global optic flow rate. The change in track angle error between the time the TWC is estimated and the time the aircraft crosses the tunnel wall was referred to as ΔTAE (Fig. 3.32). When yaw rate is constant, Eq. (3.20) can be changed into Eq. (3.22):

$$\ddot{S}(t_0)\cdot TWC=\frac{V\cdot \Delta TAE}{w}. \quad (3.22)$$

Eq. (3.23) shows how the 2nd order estimate TWC_{S2} could be extracted from the available cues:

$$TWC_{s2}=-\frac{S(t_0)}{\dot{S}(t_0)+0.5\cdot\ddot{S}(t_0)\cdot TWC_{s2}}. \quad (3.23)$$

As indicated previously, the assumption that splay acceleration is proportional to yaw rate, is an approximation. Fig. 3.33 shows the true TWC for a circular path, an estimate based on the use of splay angle, splay angle rate and splay angle acceleration, and a first-order estimate. As can be seen from this figure, if the pilot would make a first-order estimate at t=0, he would perceive a reduction in TWC of approximately 20 seconds when making a new estimate at t=1. This clearly provides information that the estimate is too high. It is not the goal of the research described in this thesis to determine how an observer extracts the TWC. Such a question should be addressed by researchers in the field of experimental psychology. The reason why the question has been addressed and discussed is to illustrate that the presentation contains information which allows a better than a first-order estimate to be made.

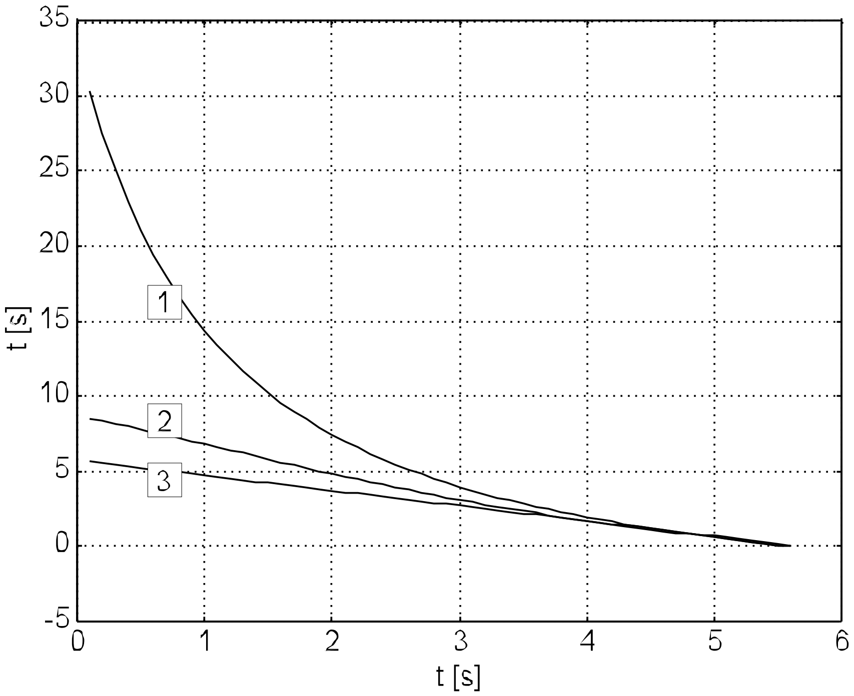


Fig. 3.33. *Different estimates of the TWC.*

1. *First-order estimate*
2. *Second order estimate based on splay angle and scene translation*
3. *True TWC*

It is expected that with adequate training, pilots will be able to make better than first-order estimates of the TWC.

Summarizing, the dynamic trajectory preview conveys cues which allow the extraction of temporal range information. Time-to-passage cues provide information with respect to transitions in the trajectory and time-to-wall crossing cues provide information about the temporal range to the constraints indicated by the walls.

3.6.5 Influence of the frame of reference

With a perspective flightpath display, the dominant visual cues are those cues which are conveyed through the motion of the whole image. Rotation about the three axis of the frame of reference yields three dominant cues: Horizontal image translation, vertical image translation and image rotation. The frame of reference determines which variables are presented as dominant visual cues. With an attitude aligned frame of reference, horizontal translation is coupled to heading, vertical translation to pitch θ, and rotation to roll. With a velocity-vector aligned frame of reference, horizontal translation is coupled to track, vertical translation to flightpath angle γ, and rotation to roll around the velocity-vector.

Control task requirements should be taken into account since the frame of reference determines whether the dominant visual cues convey orientation or directional information

Between θ and γ a significant difference in the dynamics exists which is likely to influence pilot control behavior. Eq. (3.24) presents the relation between a change in θ and γ.

$$\Delta\gamma = \Delta\theta - \Delta\alpha. \quad \textbf{(3.24)}$$

In this equation, Δα represents the change in angle of attack. Fig. 3.33 shows a typical elevator impulse response of θ and γ.

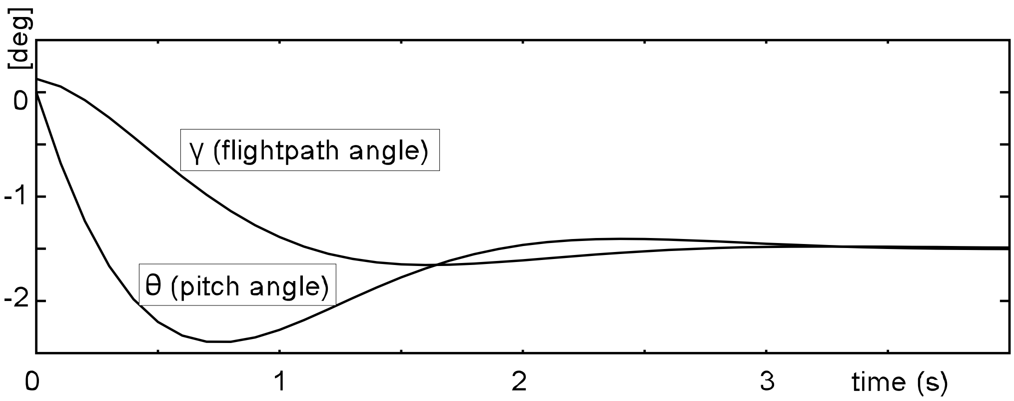


Fig. 3.34. *Typical elevator impulse response of pitch and flightpath angle.*

As can be seen from this figure, there is a considerable difference. The response of γ shows an increase in rise time and damping. The response lag of γ typically makes it unsuitable for the inner-loop stabilization task, in which the short period and angular motion resulting from external disturbances have to be suppressed.

A velocity-vector aligned frame of reference is only advisable when the flight control system takes care of the inner-loop stabilization.

In Sect. 5.3.3, the impact of the differences in dynamic behavior of the dominant visual cues on the selection of the frame of reference will be discussed in the context of control task requirements.

4 CONTROL

4.1 Introduction

In Sect. 2.1 guidance was defined as *'the determination of a trajectory from a current position and velocity to a desired position and velocity, satisfying specified costs and constraints'*, and control as *'the determination of the commands to the vehicle actuators to implement the trajectory, preserving a stable feedback loop'*. Disturbances on the system and changes in the forcing function cause differences between the desired and the actual system state. Control comprises the actions required to keep the error between the desired system state and the actual system state within predefined constraints. As indicated by Haskell and Wickens (1993), the way in which a task is performed differs as a function of the displays employed. As said before, they point out that *'when making empirical comparisons between different display types, researchers must evaluate measures other than performance on only one type of task; they must go beyond performance in any case and examine task performance strategies'*.

When preview on changes in the desired system state and an internal representation of the system dynamics are available, open-loop control can be used to reduce the effects of these changes and the required gain for closed-loop control can be reduced. Conventional guidance displays such as the flight director and the localizer and glide slope indicators do not present preview and force the pilot to employ a continuous compensatory closed-loop control strategy. In the previous section, the control oriented visual cues have been discussed and it was illustrated that similar to a flight director, a perspective presentation of the flightpath contains information about first and second-order derivatives of the variables to be controlled. However, a significant feature of the perspective flightpath display is that the multitude of control oriented visual cues resulting from the dynamic trajectory preview allow other control strategies than continuous compensatory control. Examples are intermittent open- and closed-loop control, anticipatory control, and error-neglecting control.

Ample research has been performed on human control behavior in compensatory tracking tasks (Kleinman et al., 1970; McRuer et al., 1965, 1967, 1971). In contrast, research into pilot control behavior when presented with the information typical for perspective flightpath display formats is relatively scarce. An extensive literature review about the modeling of pilot control behavior with spatial displays is presented by Mulder (1994). With a perspective flightpath display, the nature of the control task (boundary control), and the visual cues have certain similarities with car driving. In the latter area, various concepts have been proposed concerning the use of visual cues with respect to the control task and various models have been proposed to describe the driver's control behavior in relation with the visual environment.

To understand and appreciate the advantages of a perspective flightpath display relative to a flight director with respect to the control task, this chapter discusses potential control strategies which can be applied to satisfy the navigation task requirement of maintaining the position error within certain predefined constraints. The first part of this chapter presents a brief overview of research into human control behavior which is relevant for the discussion regarding perspective flightpath displays. The second part discusses how specific cues conveyed by a perspective flightpath display allow a certain control strategy to be applied. Since cue requirements can be translated into design parameters requirements, this allows the designer to make trade-offs once cue requirements are known. In general, research into control strategies and tracking performance addresses the behavior of a well-trained operator. The last part of this chapter briefly addresses potential advantages of perspective flightpath displays with respect to the acquisition of flying skills.

4.2 Preview

The feature of a perspective flightpath display which provides the possibility to use a range of control strategies, is the trajectory preview presenting data about future position constraints. In the discussion throughout this chapter, a difference is made between the contribution of the preview to the extraction of position and orientation information which allows the pilot to track a non-changing trajectory, and the contribution of preview to the extraction of temporal range information which allows the pilot to anticipate a change in the trajectory and time the initiation of open-loop actions.

4.2.1 Preview providing position and orientation information

Gordon (1966) states that *'the behavior involved in steering an automobile, for instance, has usually been misunderstood. It is less a matter of aligning the car with the road than it is a matter of keeping the focus of expansion in the direction one must go'*. The velocity field provides information on the speed and direction of the vehicle's forward motion. The driver may become aware of the misalignment of the car by slewing shifts in direction, and by side-slipping sidewise movements which exceed the human visual position and movement thresholds. The driver's perceptual response is based upon an integration of these and other information. On the basis of human perception theory, it is difficult to determine which of the four combinations of slew, sideslip, rate, and amplitude the driver perceives. The driver responds to a total situation, not to isolated or ranked cues. To investigate whether a single variable can be found to describe and predict driver control responses, Godthelp (1984) proposed the so-called time-to-line crossing (TLC) concept. The TLC concept is based on the assumption that there is a relation between the remaining time the vehicle under control is within a certain boundary, and the moment a control action is initiated.

4.2.2 Scanning trajectory preview

Gordon (1966) poses that *'perceptual anticipation is of central importance to the driving task. The driver must anticipate at least one reaction time ahead if he is to meet the current situation'*. The driver's visual fixation distance has been related to anticipation requirements. Wohl (1961) believes that fixation distance D may be predicted by $D=\tau\cdot V$, where τ is the driver's response lag and V vehicle velocity. If the driver would not look at least this far ahead, he could not respond appropriately. However, it is generally accepted (Gordon, 1966; Grunwald and Merhav, 1978; Godthelp, 1984) that the driver does not view a fixed distance ahead, and this model is too much of a simplification. Gordon (1966) describes the typical scanning behavior of a driver as follows: *'He looks far ahead, returns to a middle distance, and seemingly in disregard of anticipation requirements, he may check his alignment with the road and nearby vehicles'*. Since the trajectory preview contains conveys both cues needed for the extraction of position and orientation information and cues needed for timing of actions, and elements generating these cues are located at different preview distances, a well-trained operator would be expected to scan the range distances containing useful data.

4.3 Control strategies

In their research into driver control behavior, McRuer et al. (1977) discuss the effects of the preview obtained from the road. As a result of this preview, a certain amount of open-loop control can be applied, and the gain for feedback control can be reduced. McRuer et al. (1977) present an approach in which they distinguish between compensatory, pursuit and dual mode control behavior. With compensatory control, the driver uses lateral position and heading errors. With pursuit control the driver takes advantage of the trajectory preview to initiate an open-loop control action to follow the desired path, i.e. the driver applies feedforward control. With dual mode behavior, the driver initiates an open-loop control action which is succeeded by closed-loop compensatory control. Most of the available vehicle control models are based on the fundamental assumption that drivers control their vehicle with permanent visual feedback. However, as it is commonly accepted, visual feedback is sometimes interrupted. Godthelp (1984) investigated the potential role of visually open-loop strategies and error neglection in vehicle control. He assumed that the time available for a driver to control his vehicle in an open-loop mode largely depends on the accuracy of the open-loop generated steering-wheel action and the time available for error neglection. Godthelp (1984) conducted several car-driving experiments in which he evaluated the concept of the TLC. His results indicated that:

- Drivers are very capable to estimate the required amount of open-loop control to initiate a curve,
- the accuracy of an open-loop control action to initiate a curve decreases with increasing curvature,
- the necessity for compensatory control increases with increasing curvature, and,
- the TLC after the initiation of the open-loop control action decreases with increasing curvature.

To gain more insight in the control behavior of drivers in the temporary absence of visual information, Godthelp (1984) studied the occlusion strategies adopted by drivers. His results indicated that the occlusion time, i.e. the time the driver is *willing* to control his vehicle in the absence of visual information, is approximately 40% of the total TLC. When drivers were told to *ignore* position and heading errors, and only apply control at the moment they think is necessary in order to remain on the road, drivers adopted a strategy with a fixed TLC. From this, Godthelp (1984) concluded that the control strategy is strongly determined by the degree of uncertainty about the future vehicle trajectory.

4.4 Control strategies with perspective flightpath displays

In Ch. 3, the cues conveying position, orientation, and temporal range information have been discussed. To model pilot control behavior for a closed-loop compensatory control task with a perspective flightpath display, one might assume that the magnitude of the control action is a weighted combination of position and orientation errors and their rates. The magnitude of the weighting factors is determined by the design parameters of the perspective display. Research to model pilot control behavior with this kind of data presentation is performed by Mulder (1995). At the moment, however, no accurate model is available which allows tracking performance to be predicted as a function of the display design parameters and the dynamics of the system under control. In the absence of a validated model, a more heuristic approach combined with empirical studies is needed to gain more insight into the influence of the design parameters on pilot performance and control behavior. For closed-loop compensatory control, only the difference between the actual and the desired system state is needed. For anticipatory control, information about the actual state and the future desired state as a function of time (forcing function) is needed. For error-neglecting control, not only the forcing function, but also the constraints must be presented. In Ch. 3 it was demonstrated that the perspective flightpath display contains all required information. For the discussion of control strategies with a perspective flightpath display, a distinction is made between the tracking of straight segments, the tracking of curved segments, and the transition between these two types of segments.

4.4.1 Straight segments

In Sect. 3.5.3 it was demonstrated that information about position errors can be inferred from the rotation of the tunnel lines, and information about orientation errors from scene translation relative to a reference position. The resolution of splay angle increases with decreasing distance to the viewpoint. The effect of scene translation is most apparent at the location where the four lines representing the tunnel converge, thus at a large distance from the viewpoint. When flying a straight segment, the pilot can use the section of the tunnel at a large distance from the viewpoint to most accurately estimate the track angle error and the flightpath angle error, and the nearby section for the most accurate estimate of the cross track error and vertical track error. The future cross track error is a function of the current cross track error and the track angle error. If the current cross track error is acceptable, the magnitude of the track angle error determines when the pilot will initiate a control action to prevent the aircraft from leaving the tunnel.

With compensatory control the pilot tries to minimize the actual position error. When the pilot's task is to minimize lateral position errors, he will try to zero the future cross track error by correcting for every cross track error and track angle error. Since the gain of the cross track error is inversely proportional to tunnel size, it seems logical that a decrease in tunnel size yields an increase in tracking performance and an increase in control activity. This was first discussed and confirmed by Wilckens (1973), who performed a simulator experiment in which pilots flew ILS approaches with the aid of a perspective flightpath display. The experiment to be discussed in Sect. 7.3 also investigates the relation between error gain, tracking performance and control behavior for a situation in which pilots were instructed to maximize tracking performance.

The trajectory preview in combination with boundaries indicated by the virtual tunnel walls, allows the pilot to willingly ignore position and orientation errors for a certain period of time. This control strategy is referred to as error-neglecting control (Theunissen and Mulder, 1994). The similarity with car driving in terms of control task (boundary control) and the type of visual cues (spatially presented constraints) together with the results of the TLC experiments performed by Godthelp, suggest that with error-neglecting control the pilot might base the moment of an error-correcting action on an estimate of the remaining time before the aircraft crosses one of the imaginary tunnel walls, the so-called time-to-wall crossing (TWC). If this is indeed the case, a main question is the order of the model which the pilot uses to determine the timing of the control action. In Sect. 3.6.4 it was indicated that the dynamic visual scene conveys cues which contain the information which is needed to make a better than first-order estimate. The experiment to be discussed in Sect. 7.4, was performed to gain more insight into which cues pilots use to decide to initiate a corrective action when applying an error neglecting control strategy.

4.4.2 Curved segments

When flying a curved segment, no stationary reference for the correct track angle is available from the perspective flightpath. As a result, it is impossible to directly determine the track angle error. Furthermore, no symmetrical reference for determining the condition of zero cross track error is available, which may cause a bias. A possible control strategy is to keep the intersection of the tunnel walls with the screen boundary at a constant position. In this way, the pilot zeros the trend in the cross track error, which in turn is identical to zeroing the track angle error. Consequently visual attention will probably shift away from the center when entering a curve, to monitor the cross track error rate with the highest gain. Another strategy is to allow a certain trend in the cross track error. Intervention will take place when either the cross track error or its rate exceed a certain threshold. Here too, it is hypothesized that when the pilot is instructed to fly as accurate as possible, he will try to maintain zero cross track error and zero cross track error rate. As a result, tunnel size will influence tracking performance and control behavior. From their research into visual cues in nap-of-the-earth (very close to the ground) helicopter flight, Grunwald and Kohn (1993) conclude that *'the flightpath for curved motion is considerably more difficult to estimate than for straight motion, since it relies on the entire streamer pattern rather than on local field estimates. Since in curved flight the near as well as the far field is used, the estimates are less accurate and improve less with increasing V/h ratio'*. The velocity V over height h ratio is the global optical flow rate which was discussed in Sect. 3.6.2. The trajectory used in the experiment to be discussed in Sect. 7.3 included both straight and curved segments to investigate the differences in performance between the two types of segments.

4.4.3 Transitions, anticipatory control, timing and magnitude

Due to the similarities between the visual cues present with car driving and perspective flightpath displays, both with respect to the control task and the visual cues, it is anticipated that trajectory preview allows pilots to anticipate changes in the trajectory and can be used to reduce their closed-loop gain. As indicated in the previous section, the dynamic nature of the trajectory preview allows the extraction of temporal range information. In Sect. 3.6.4 it was indicated that the temporal range cues conveying the time-to-passage (TTP) do not require a conformal presentation of the flightpath. Since the magnitude of these cues increases with decreasing distance from the viewpoint, and the fact that temporal range information is not really useful beyond a certain limit, the pilot will mostly use the nearby trajectory preview for the extraction of temporal range information. To make the transition between a straight and a curved segment, the pilot is required to make a certain control input. For the accurate initiation of an anticipatory control action, the pilot has to be able to estimate the time until a certain reference point, for example a cross section frame, is passed. When flying towards such a reference, the TTP cues convey the required information. As indicated in Sect. 3.6.4, this poses certain requirements on the design parameters.

Eq. (3.17) showed that TTP_{min} is proportional to tunnel size and inversely proportional to the geometric field of view. If TTP_{min} is too large, the pilot is unable to accurately time the moment an initiation is required. Furthermore, the pilot must estimate the required magnitude of the control action, which is related to the curvature of the circle segment and vehicle velocity. The situation would be ideal if the magnitude of the visual cues is approximately proportional to the desired magnitude of the control input. As indicated in the Sect. 3.5.5, the required cues from the perspective flightpath are a function of viewing distance and relative orientation, which makes the task quite difficult. The presentation of a bank reference or bank command can be used to aid the pilot in generating the required control action for initiating a turn at the right time. This can be achieved by presenting a reference angle on the roll scale, or by banking the representation of the tunnel itself. The latter option has been investigated by Grunwald (1984), who reports that this did not contribute much to performance, and who found that it was confusing in transitions to curved sections, since setting the bank angle at the commanded value did not necessarily bring the lateral deviation to zero. In a later design, Grunwald (1996a) included transition sections with a gradually increasing reference bank angle to provide more accurate guidance. Another method to aid the pilot in anticipating a curve, is the presentation of a flightpath predictor, which will be discussed later. Time histories of aircraft bank angle resulting from the experiment which will be discussed in Sect. 7.3 show that the pilot anticipates the curve and that timing and magnitude of the control action are more homogeneous when a position predictor is presented.

4.5 Training and transfer

The previous discussion regarding control strategies assumed a well-trained operator. Two important aspects of training are learning how to process the stimuli and to build-up an internal representation of the system under control. Learning how to process the stimuli may be optimized by designing the MMI is such a way that features are used which stimulate automatic processing. Although it is not exactly known what functions are hard-wired in the nervous system, it is very likely that the presentation of an object like the tunnel evokes holistic perception and thus allows the bypassing of the features analysis level of the components by which the object is constructed. This should contribute to minimizing the time which is needed to train an operator in how to process the visual stimuli. The fact that perspective flightpath displays present position and orientation information in a natural way but with an accuracy which is higher than mostly encountered in the visual environment, might have merit for a quick build-up of the internal representation.

Several studies indicate that perspective flightpath displays have certain features which might reduce the training time needed to acquire basic flying skills.

Adams (1982) reports that pilot comments suggest that the display is *easy to learn* and *easy to use*, that it *provides good situation awareness*, and that it could *improve the safety of flight*. Filarsky and Hoover (1983) report that *'the command flightpath display requires minimal training time both initially and for maintaining flight proficiency as compared to performance utilizing standard symbolic display'*. The reported training time prior to actual flight in the total-in-flight simulator (TIFS) was one half hour. Research performed at NASA Langley using people who had never flown showed that 90 % were able to take off, fly a pattern, and land in instrument conditions the very first time when using a perspective flightpath display (Ethell, 1994). The experiments performed in the context of the research described in this thesis, also showed that for qualified pilots the training time required to achieve a constant level of high tracking performance with the perspective flightpath display was less than an hour.

During training, students must obtain an accurate internal representation of the dynamics of the aircraft. When presented with a conventional out-of-the-windshield visual scene, accurate observations of orientation can be made. Only when very close to reference objects, for example during the landing, accurate observations of relative position are possible. With the addition of a perspective flightpath display, the student pilot is continuously able to extract both accurate position and orientation information from the visual scene. As a result, the student pilot has the possibility to make a better observation of the state-vector, which in turn allows him to better identify the dynamics of the system under control.

Lintern et al. (1990) studied the effects of perspective flightpath displays on training and transfer. They report that the presentation of the desired future trajectory has a positive effect on transfer. They also evaluated the presence of disturbances such as crosswind on transfer, and report that with a perspective flightpath students were better able to compensate for such disturbances. In a control-theoretical context, the disturbances yield a reduction in the signal to noise ratio of the observed state-vector. This results in a longer time required to construct the correct internal representation. However, a useful internal representation also requires knowledge about the statistics of disturbances. Thus, for training purposes, maximum transfer might be obtained by first using the display in the absence of disturbances to correctly identify the system dynamics, and then introduce disturbances to allow the student to identify the model in the presence of disturbances. This conclusion is also drawn by Lintern et al. (1990), on the basis of their experimental results.

4.6 Conclusions

Conventional guidance displays, such as the flight director and the localizer and glide slope indicators, do not present preview and force the pilot to employ a continuous compensatory closed-loop control strategy. A significant feature of the perspective flightpath display is that the multitude of control oriented visual cues resulting from the dynamic trajectory preview allow other control strategies than continuous compensatory control. Although for the sake of discussion, the contribution of preview to the extraction of position and orientation information has been separated from the discussion about the extraction of temporal range information, both result from the same perception. The scan pattern of the pilot might provide more insight into the specific use. Looking far ahead (in the center of the display) would indicate the process of estimating the track angle error and gaining information about the necessity to anticipate changes in the trajectory which require future action, looking at an intermediate distance to determine a possible excursion of the constraints and anticipate changes in the trajectory which require almost immediate action, and looking very nearby to estimate the current cross track error with a high resolution.

The presence of a range of error gains allows the operator to select his own weighting function, and choose to neglect errors and error rates within certain constraints.

Thus, the availability of trajectory preview indicating spatial constraints combined with temporal range cues allows an error neglecting control strategy or a certain amount of anticipatory control to be applied. Rather than a continuous closed-loop compensatory or pursuit control strategy, the pilot can apply a strategy of intermittent closed-loop compensatory, anticipatory, and error-neglecting control.

The freedom in timing to switch between the different strategies allows the pilot to better distribute his resources.

Both anticipatory control and error-neglecting control require the presence of temporal range information. Thus, in order for the display to be useful for anticipatory and error-neglecting control, the display design parameters must be selected in such a way that it is possible to extract the required temporal range information from the display. It is important to notice that these temporal range cues are only available in an ERF. Therefore, efficient anticipatory and error-neglecting control is only possible with an ego-centered perspective flightpath display.

5 DESIGN ASPECTS

5.1 Introduction

Fig. 1.2 in Ch. 1 presented an overview of the systems involved in the presentation of navigation data. It was concluded that '*for an efficient design process of an MMI based on the presentation of spatially integrated data, a framework integrating technical, control-theoretical, perceptual, and cognitive aspects is needed*'. It was also concluded that '*the challenge lies in the translation of specific design questions into a more general context and to use findings from engineering psychology and human factors research to provide answers or guidelines on how to obtain answers'*. In Ch. 2, the aircraft navigation task was discussed. A risk-tree showing how certain combinations of events can result in a navigation accident was developed, and improvements to increase safety were identified. It was concluded that '*the presentation of spatially integrated trajectory preview has the potential to improve the MMI for navigation and guidance*'. To allow a translation of specific design questions into a more general context, Ch. 3 discussed the visual cues conveyed by a perspective flightpath display in terms of properties of the optic flow pattern. In this way, it became possible to describe the magnitude of the specific visual cues as a function of the design parameters. Furthermore, representation requirements were identified to minimize the cognitive effort which is needed to turn the perceived image into useful information. In Ch. 4 the different control strategies which are possible with a perspective flightpath display were discussed. It was concluded that '*the presence of a range of error gains allows the operator to select his own weighting function, and choose to neglect errors and error rates within certain constraints'* and that '*the freedom in timing to switch between the different strategies allows the pilot to better distribute his resources'*. In this chapter, the relations between the navigation and guidance task discussed in Ch. 2, the available visual cues discussed in Ch. 3, and the potential control strategies discussed in Ch. 4, will be used to derive guidelines on how to answer specific design questions.

When using the overview presented in Fig. 1.2 as a reference, Fig. 5.1 presents the part of the data presentation which is of importance to the rest of this chapter.

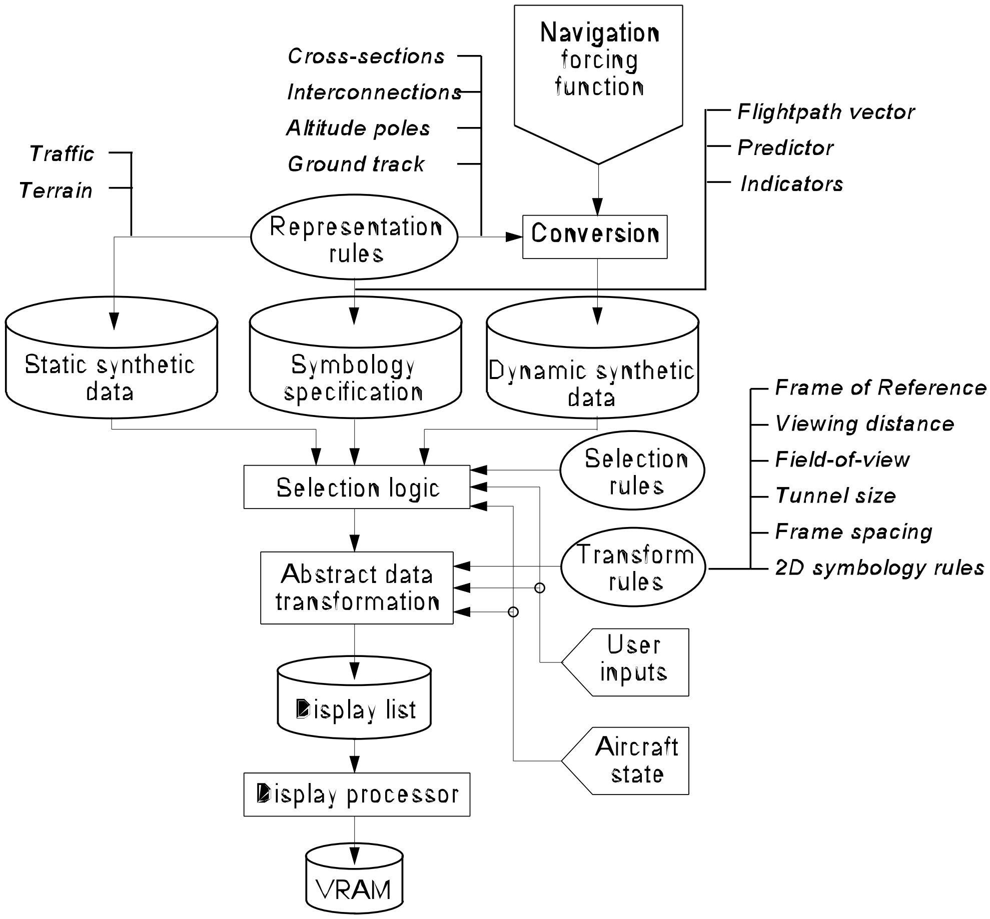


Fig. 5.1. *Transformation of the forcing function into an image which is stored in video ram (VRAM).*

The information presented in this chapter aids in the specification of the following items:

- Conversion of the dynamic synthetic data into a visible object (*transform rules*), determined by the *frame of reference* (Sect. 5.3), *viewing volume*, (Sect. 5.4), and *display algorithms* (Sect. 5.7).
- Conversion of the navigation forcing function into an object which can be visualized (dynamics synthetic data), determined by the *representation rules* (Sect. 5.5) and the design parameters influencing the *transform rules* (Sect. 5.6).
- The specification of additional pre-defined 3-D objects (*representation rules* for static synthetic data) which must be integrated in the presentation (Sect. 5.8).
- The specification of symbology (*representation rules*) and dynamics (*transform rules*) for display augmentation (Sect. 5.9).

The viewing volume determines the boundaries between the visible and the invisible part of the 3-D world. The choice of the design parameters depends upon task requirements with respect to range, resolution and dynamics of the required information, the properties of the positioning and attitude determination system, and the properties of the human operator with respect to perception, interpretation, and evaluation of information. A general guideline for display design is that the information which is most frequently needed should require the least effort for perception, interpretation, and evaluation. This can be accomplished, for example, by using dominant visual cues and emergent features to exploit specific cognitive abilities which are involved in the early stages of perceptual processing. The integration of a third dimension onto a 2-D display causes ambiguity which must be resolved by using features that provide the observer with a feeling of three-dimensionality. This chapter discusses methods to suggest 3-D, an approach to select the frame of reference and the viewing volume, and the representation of the flightpath and other objects. Furthermore, display augmentation concepts and the requirements on position and orientation data are presented.

5.2 Suggesting 3-D

As indicated in Sect. 3.4.2, the integration of the third dimension (distance along the line-of-sight) causes ambiguity. This ambiguity can be resolved by including cues which provide the observer with information about distance along the line-of-sight. Several methods can be used to suggest depth in a 3-D display. Stereoscopy can be used to give the observer a feeling of three-dimensionality. Turner and Hellbaum (1986) present a review of a number of stereoscopic display technologies from the standpoint of their suitability for the crew station environment. Besides stereoscopy, alternatives can be used to convey the required depth cues to the viewer. One of the most effective depth cues is *motion perspective* which occurs when the observer moves relative to the environment (Wickens et al., 1990). Motion perspective allows the perception of relative distances, velocities and locations. Kim et al. (1987) claim that though stereoscopic displays generally permit superior tracking performance, monoscopic displays can allow equivalent performance when they are defined with optimal perspective parameters and provided with adequate visual enhancements. Nataupsky and Crittenden (1988) compared response times to a path offset for stereo 3-D and non-stereo presentations for different path representations. They report a significant improvement in reaction time with the stereo display, and an interaction between the use of stereo and pathway representation. They report that with the non-stereo display the effects of pathway representation on reaction time were much greater, and they conclude that as a result the choice of representation in a non-stereo display is more critical. They also give another interpretation of their results, namely that stereo 3-D cues do not greatly enhance a well designed display. This might explain the findings of Reising et al. (1989), who compared 2-D presentation of pathway information to a 3-D stereo version and report that performance with the 3-D version was not significantly better. The fact that the type of presentation can compensate for depth cues provided by stereopsis is further discussed in Sect. 5.5. A potential problem with stereo-displays is the exposure effect on real world acuity. Parrish and Williams (1990) investigated stereopsis cuing effects on hover-in-turbulence performance. They report a significant improvement in performance with the stereo display. A possible factor contributing to this difference is the fact that the hover condition was investigated, and as a result the contribution of optic flow cues to three-dimensionality is minimal. This indicates that for implementation of flightpath displays in helicopters, stereo displays might be needed to compensate for the lack of longitudinal motion induced 3-D cues, a problem which is not present in conventional aircraft. Busquets et al. (1991) studied the effect of short-term exposure to stereoscopic three-dimensional flight displays on real-world depth perception and report that no significant short-term effects were found, but that effects of long-term exposure remains an issue to be investigated.

In Sect. 3.6.3 it was pointed out that the change in the magnitude of the velocity streamers as they are closer to the viewpoint increases the feeling of three-dimensionality, and that with a perspective flightpath display the spacing between the cross section frames influences the amount of 3-D cuing whereas the tunnel size influences the magnitude of the cues.

Results from previous research and from the evaluations which will be discussed in Sect. 7.2 indicate, that with an egocentric perspective flightpath display the cues resulting from the velocity streamers provide adequate information to resolve ambiguities in the representation of the flightpath. Results from other research into pathway displays suggests that tracking performance cannot significantly be improved through a stereo presentation.

5.3 Frame of reference

Many of the truths we cling to depend greatly on our own point of view (Obi-Wan Kenobi) and frame of reference.

Fig. 3.6 illustrated the concept of the computer graphics camera. The specification of the camera include the viewpoint, viewplane-normal and view-up vector, which together specify the frame of reference. The specification of the frame of reference is one of the most significant design questions for spatial displays, since it determines from where the situation is depicted and which variables are presented as dominant cues.

When a task involves some kind of spatial control, a spatially integrated presentation of the data in a suitable frame of reference can be used to minimize required mental integrations and rotations.

5.3.1 Egocentric and exocentric

The different frames of reference can be divided into egocentric and exocentric ones. In a study on manual three-dimensional pursuit tracking with exocentric display formats, Ellis et al. (1991)

report that human subjects can simultaneously adapt to a variety of display control misalignments. This suggests that exocentric perspective flightpath displays could also be used for aircraft guidance. With an egocentric perspective projection, information about position and orientation errors is conveyed through a distortion of the natural symmetry of the presented trajectory. With an exocentric frame of reference, however, the natural symmetry of the presentation in a stationary condition is no longer present. In Sect. 3.5 it was pointed out that 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. Furthermore, depending on the orientation of the viewing vector, mental rotations are required, which increases reaction time and can lead to control reversals. Recent studies into the frame of reference (Prevett and Wickens, 1994) confirm that egocentric perspective displays support better tracking performance than either planar or exocentric perspective displays.

> While exocentric reference frames are more beneficial for threat-detection and traffic avoidance tasks (Ellis et al., 1987), egocentric reference frames appear to be better for the aircraft guidance task.

The ability of a pilot to obtain and maintain a certain level of navigational awareness is influenced by the design parameters of the perspective flightpath display, and the frame of reference used for projection. The ability to detect and qualify a change in the future trajectory poses no problem, since this change generally emanates from the center of the screen. The ability to estimate the magnitude of the change (quantification) requires that the future trajectory (beyond the transition) is visible on the display. In case the change in direction exceeds half of the geometric field of view, a point will exist where the trajectory will exit the viewing volume. In case this point lies in the transition segment, it is impossible to estimate the future required direction.

> In an egocentric frame of reference, the limited field of view of a perspective flightpath display always imposes restrictions on the amount of visible data required for navigational awareness.

To support the pilot in maintaining a cognitive link between the two displays, methods must be used to create adequate visual momentum. Aretz (1990) demonstrated the feasibility of such an approach by presenting the ERF of the guidance display, in the form of a perceptual wedge, in a world-referenced navigation display.

Clearly there exists a conflict in information requirements between the local guidance and the global awareness task. Whereas the local guidance task is best served by the presentation of flightpath errors in an ERF, navigational and global awareness require more world-referenced information, and thus are best served by an exocentric frame of reference. This presents the designer with two options: Try to design a single display format in which trade-offs have been made between guidance and navigational/global awareness requirements or design two display formats, one optimized for the guidance task, the other for navigational/global awareness.

As indicated by Prevett and Wickens (1994), a moderate degree of exocentrism might yield adequate performance with respect to both guidance and global awareness, which in turn allows the use of a single display. The reduction in tracking accuracy, the increase in task demanding load, the increase in the possibility of control reversals as a result of the required mental rotations, and the absence of useful temporal range information are drawbacks which must be taken into account when considering the option of a single exocentric display format to meet both guidance and global awareness requirements. Since the limited field of view poses restrictions on the availability, and the egocentrism severely limits the accuracy of the quantification, egocentric perspective flightpath displays can only provide qualitative, relative navigational awareness.

When using an egocentric display for the guidance task, a satisfactory level of global and navigational awareness calls for the use of an additional, exocentric view of the situation.

5.3.2 Inside-out and outside-in

It is important to note that ego- and exocentric refer to the position of the viewing vector. Another distinction which is often used are so-called inside-out and outside-in displays.

Inside-out refers to a presentation of the world related information as it would be observed from within the aircraft. Outside-in refers to a viewpoint which is stabilized in a world-referenced system.

Stokes et al. (1990) present three principles that should influence the choice:

- The principle of the moving part;
- constancy of reference frames;
- the principle of frequency separation.

The principle of the moving part assumes that people have certain expectations about what actually moves in a system. The element that moves on the display should be the same and move in the same direction as the operator’s expectation of motion. The principle of constancy of reference frames is based on the fact that humans have a difficult time rapidly reorienting between different frames of reference. When an instrument represents an abstraction of the real world and the user is required to switch between the instrument and the real world, different frames of reference can result in control blunders. This is caused by the fact that to compensate for a given display movement, the required direction of the control action may be opposite between the two frames of reference. In case of an artificial presentation of the outside world, the principle of the constancy of reference frames leads to the conclusion that, to maintain static compatibility with the outside world view, an inside-out frame of reference should be used. However, the principle of the moving part suggests, that to maintain dynamic compatibility, the movement of the display should be consistent with the pilot's mental representation that the aircraft moves, and hence an outside-in frame of reference is required (Johnson and Roscoe, 1972). The attitude direction indicator (ADI) 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). With an outside-in frame-of reference, the horizon is fixed and the aircraft rolls right and left and pitches up and down. To prevent the aircraft symbol from going off the scale, the complete pitch range must be visible, posing quite a design challenge since the combined range and resolution requirements can result in a rather large display. 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. When regarding an attitude indicator as a display of which the error must be zeroed, control reversals can results. Therefore, an inside-out frame of reference must convey the illusion that the aircraft is moving. Kovalenko (1991) discusses an experiment which compared the contribution of inside-out and outside-in frames of reference to the pilot's ability to obtain spatial orientation. He concludes that *'the manufacture of the face of a view-from-the-aircraft indicator which would give the pilot quickly and simply the effect that the aircraft silhouette is mobile, requires delicate technology, unique colors and design studies of the highest level. All these matters are in practice not as pressing for the view-from-the-ground attitude indicator'.* When a conformal presentation is required, for example with a HUD in which the perspective presentation of the flightpath is overlaid on the visual scene, a mismatch in alignment or field of view exceeding a certain threshold results in conflicting information. With a HDD, however, the absence of direct visual information from the outside world in the display presents some freedom in the selection of the field of view and the viewing vector, and sometimes one or more of the variables describing the viewing vector are coupled to another reference frame. Examples are the outside-in representations of perspective displays, in which the view-up vector is coupled to the WRF, and the roll angle is indicated by a rotation of the aircraft symbol itself. Egocentric inside-out perspective flightpath displays have been used to present guidance information which enables pilots to fly a pre-defined three-dimensional trajectory with high positional accuracy (Wilckens, 1968; Grunwald et al., 1980, Filarsky and Hoover, 1983; Wickens et al., 1989; Theunissen, 1993). Grunwald (1984) and Wickens et al. (1989) also evaluated egocentric perspective flightpath displays with an outside-in frame of reference. Grunwald reports that the roll-stabilized version (outside-in) yielded generally larger lateral deviations and roll activity than the roll-version (inside-out). Wickens et al. (1989b) report better lateral tracking performance and better tracking of commanded velocity with the inside-out frame of reference and no significant difference in vertical tracking performance and workload. They conclude that *'although the inside-out frame of reference was favored, it is possible that the advantage shown by that perspective over the outside-in view might have resulted from the greater information that the inside-out display provided rather than from the frame of reference per se'*.

A full outside-in frame of reference requires the complete pitch attitude range to be visible, and thus necessitates a field of view of 180 degrees. Since the required visible pitch attitude range at a certain moment is much less, typically about 40 degrees, presenting the full scale is a waste of available display space. An outside-in frame of reference with respect to only the roll axis of the aircraft does not suffer from this disadvantage. Research into this type of reference frame shows some slight disadvantages with respect to tracking performance as compared to the inside-out version. However, these disadvantages may also originate from the increased experience of pilots who are used to an inside-out presentation of the attitude information.

Harwood (1989) investigated the influence of several spatial relationships to support navigation problem solving in helicopter flight. She concluded that *'the pattern of map-task dependencies revealed in this study suggests that no single map configuration is beneficial across all navigational tasks or modes of helicopter flight'*. With respect to the position of the viewpoint, it was concluded in Sect. 5.3.1 that '*when using an egocentric display for the guidance task, a satisfactory level of global and navigational awareness calls for the use of an additional, exocentric view of the situation*'.

Research results indicate that to satisfy both guidance and navigation requirements, two displays are needed. For the lateral direction of the viewing vector, the display for the guidance and short term navigation task should utilize an inside-out frame of reference. When the navigation task requires relative navigational awareness, an inside-out frame of reference should be used. Absolute navigational awareness is best obtained with an outside-in frame of reference.

5.3.3 Attitude and velocity vector aligned

The previous discussion differentiated between aircraft referenced and world referenced alignment of the viewing vector. With an aircraft referenced alignment, in most cases the frame of reference is aligned with aircraft body axis. In this situation, the viewing vector is aligned with the direction in which the aircraft is pointing. As indicated in Sect. 3.6, an angular difference between the aircraft body axis and the earth-referenced direction of flight changes the location of the symmetrical reference condition. This is illustrated in Fig. 5.2.

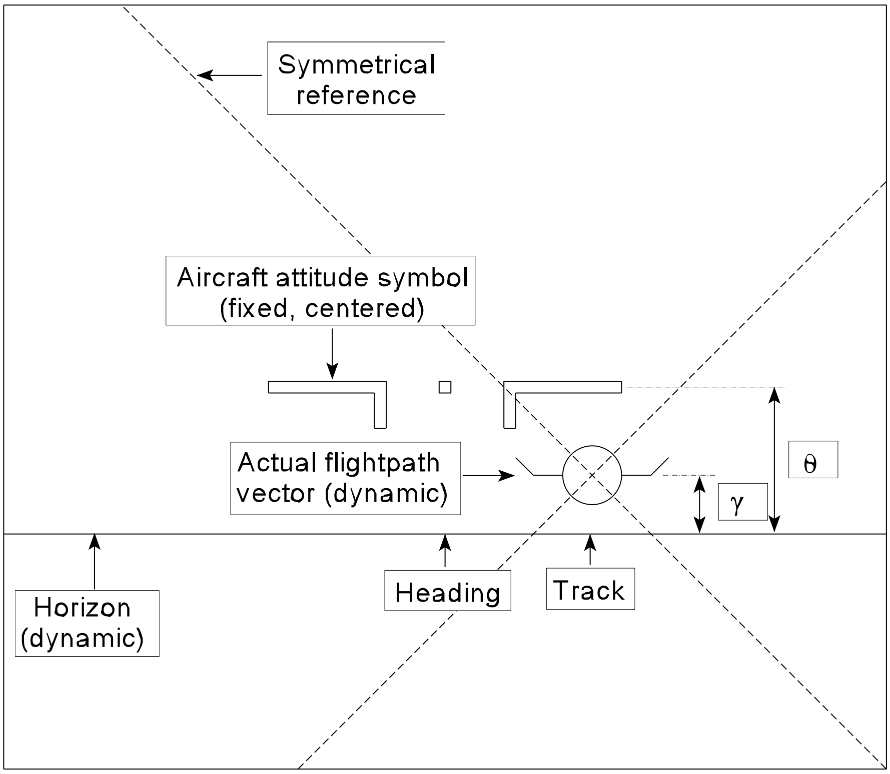


Fig. 5.2. *Attitude aligned frame of reference. The central display axis is coupled to the direction in which the aircraft is pointing, and as a result the aircraft attitude symbol is fixed in the center of the screen. The direction of the inertial velocity is indicated by the flightpath vector symbol. As discussed in Sect. 3.5.3, the location of the symmetrical reference condition varies as a function of crosswind and angle of attack. The dashed lines indicate the location were the tunnel would be if flying exactly in the center of it. The vertical motion of the horizon is coupled to pitch angle (θ).*

Another option for the direction of the viewplane normal is the direction of the earth-referenced velocity vector of the aircraft. This situation is illustrated in Fig. 5.3.

As indicated in Sect. 2.2, the type of control task should be taken into account when selecting between an attitude and velocity vector aligned frame of reference. The type of control task is determined by the flight control system (FCS). With a conventional FCS, an attitude aligned frame of reference presents the pilot with the dominant visual cues required for inner-loop closure. With a closed-loop FCS, the high bandwidth inner-loop stabilization task has no longer to be performed by the pilot and the primary task is that of maneuvering the aircraft along the desired trajectory. For navigation through three-dimensional space, the direction of travel is determined by ground-track and flightpath angle, thus for this task, the pilot needs information about track and flightpath angle. As the flightpath is earth-referenced, the center of the optic flow resulting from the motion of the viewpoint relative to the flightpath, is identical to the location where the earth-referenced velocity vector points. With an attitude aligned frame of reference, task-oriented symbology must be included to provide the pilot with a direct indication of the direction of travel in the three-dimensional world. Both the presentation of the future trajectory and the symbology indicating the direction of travel move, providing the pilot with a pursuit task.

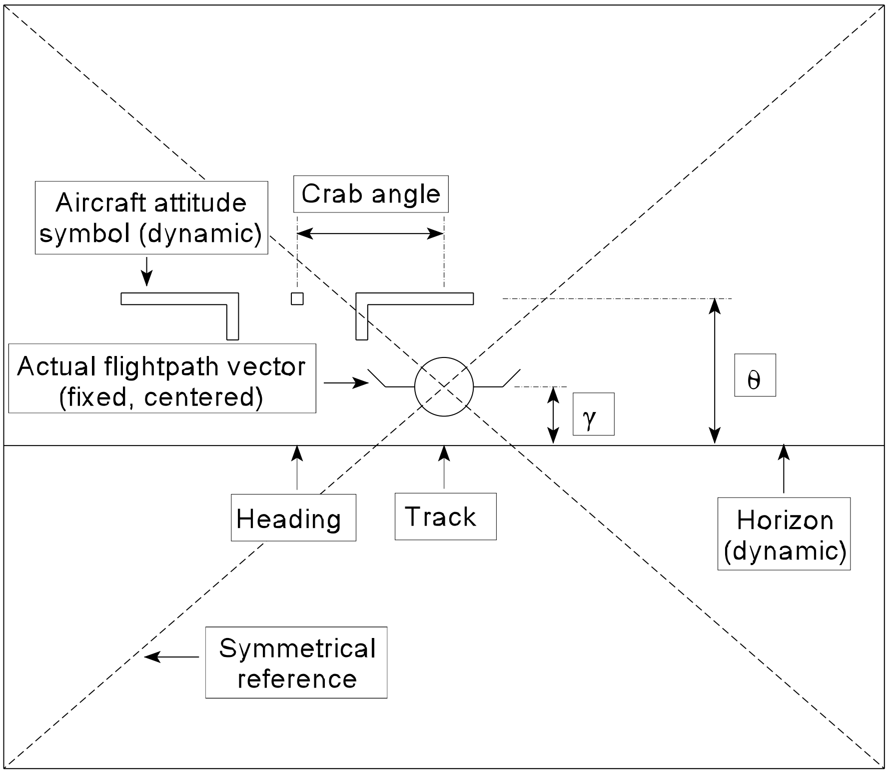


Fig. 5.3. *Velocity vector aligned frame of reference. In contrast to Fig. 5.2 which showed a situation in which the display is centered around the direction in which the aircraft is pointing, this display is centered around the direction in which the aircraft is going. The earth-referenced direction of flight is indicated by the actual flightpath vector, which, as a result of the velocity vector aligned frame of reference, is always positioned in the center of the display. As indicated in Sect. 3.5.3, with a velocity vector aligned frame of reference, the symmetrical reference condition is always in the center of the display. In this fig. the reference condition is indicated by the dashed lines. The vertical motion of the horizon is now coupled to flightpath angle (γ).*

In a velocity vector aligned frame of reference, the center of the display points in the direction of travel. Changes in the direction of travel are proportional to horizontal and vertical display translations, yielding dominant cues. Therefore, this is considered a more task-oriented approach.

Lambregts et al. (1979) describe the development of a velocity vector control wheel steering mode. Their evaluation showed that pilots had difficulty controlling flightpath angle due to the lag between control wheel input and flightpath angle response. This problem was solved by presenting both actual and commanded flightpath angle. Steinmetz (1986) hypothesized that with the velocity control wheel steering mode developed by Lambregts et al. (1979), the maneuvering task might be better served by a velocity vector aligned frame of reference and compared pilot performance and pilot opinion for a velocity vector aligned attitude indicator with a conventional version. He reports that although statistical analysis of performance measures did not show a significant improvement, pilots preferred the velocity vector aligned display format.

In Sect. 3.5.3, the influence of the frame of reference on the location of the symmetrical reference condition was discussed. It was concluded that *'since the location of the symmetrical reference condition varies as a function of crosswind, this necessitates additional symbology to directly indicate the direction of travel'.* In Sect. 3.6.5 the influence of the frame of reference on the display dynamics and the resulting dominant visual cues were discussed. It was demonstrated that for aircraft control, a significant difference in the vertical display dynamics between the two frames of reference exists. It was concluded that *'a velocity vector aligned format is only advisable when the FCS takes care of the inner-loop stabilization'.*

Sect. 7.5 will discuss some of the effects of the differences between attitude and velocity vector aligned perspective flightpath displays.

5.4 Viewing volume

The viewing volume is determined by the horizontal and vertical field of view, and the minimum and maximum viewing distance. The ratio between the horizontal field of view and the vertical field of view is determined by the aspect ratio of the screen. When this relation between horizontal field of view and vertical field of view is not used, different scaling is applied to the horizontal and vertical dimension. In case of a rotation of the view-up vector, this results in a shearing of the objects. When integrating angular based 2-D symbology like a pitch tape or a flightpath vector, angular range compatibility must be maintained to avoid cue conflicts. To avoid distortions between the perspective presentation of the 3-D flightpath and the attitude presentation, the visible pitch attitude range must correspond to the geometric vertical field of view. The vertical field of view determines the visible pitch attitude range, and the horizontal field of view determines the visible heading range. Therefore, requirements regarding the minimum visible pitch attitude range determine the minimum vertical field of view. Furthermore, the field of view determines magnitude of the perspective distortion, which influences the shape of objects. The relation between field of view and maximum perspective distortion will be discussed in Sect. 5.4.1. Finally, the observer field of view should be taken into account. Differences between the geometric- and the observer field of view cause a magnification or minification of the displayed objects. This will be discussed in Sect. 5.4.2.

5.4.1 Perspective distortion

Perspective distortion causes an apparent magnification of the size of an object when the viewpoint is rotated so that the object moves from the center of the display to an the edge, whereas the viewing distance to the object remains the same. Since the perspective distortion varies as a function of display location, the shape of the object is affected too.

Perspective distortion is defined as the ratio of the apparent size of an object at a certain location on the screen, divided by the size of the object at the center of the screen.

The effect of perspective distortion can be visualized by projecting a grid consisting of equally spaced azimuth and elevation lines onto a viewplane. Fig. 5.4 shows the effect.

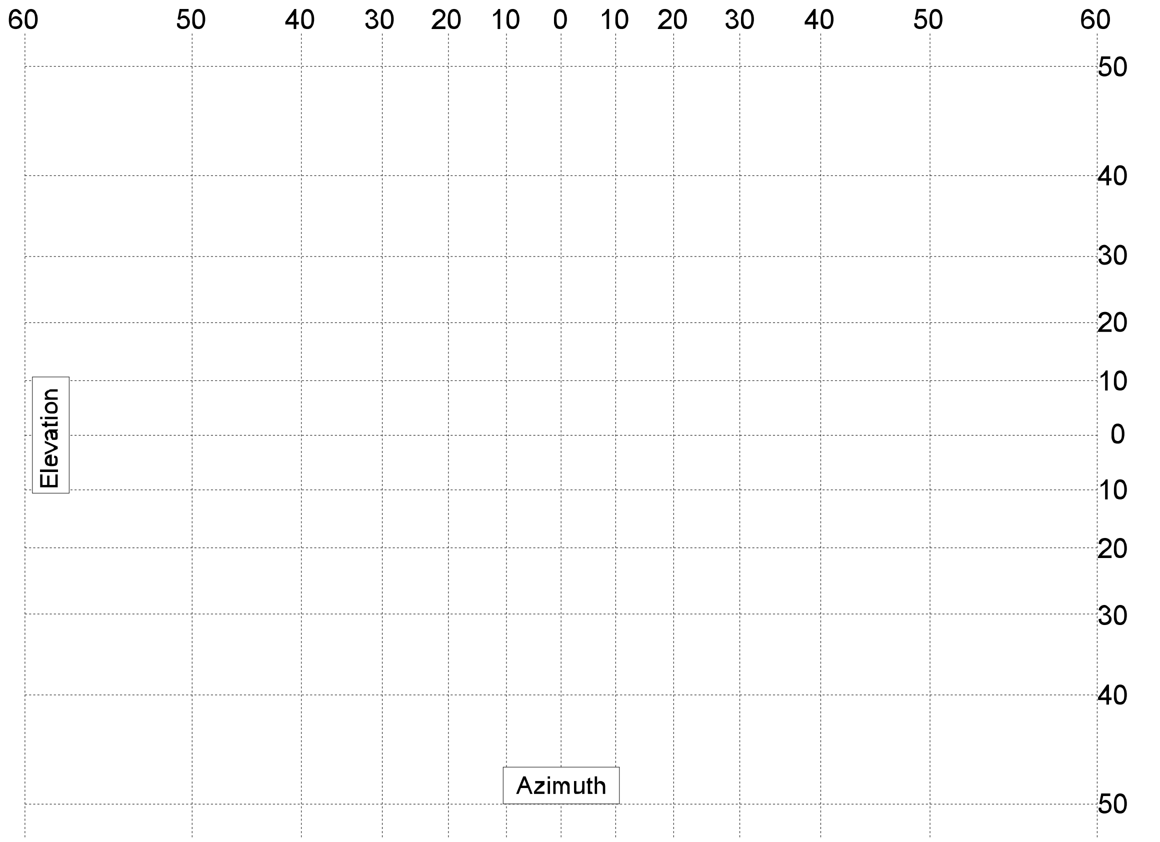


Fig. 5.4. *Grid showing how lines which are equidistantly spaced in azimuth and elevation are mapped onto a 2-D viewplane.*

As can be seen from Fig. 5.4, the spacing between the projected lines increases with increasing distance from the center of the screen. The magnitude of the distortion is inversely proportional to the cosine of the display location expressed as spatial angles. The maximum perspective distortion occurs at the edges of the screen. Eq. (5.1) presents the expression for the perspective distortion D_{persp}. In this equation, ξ represents the angular display location.

$$D_{persp} = \frac{1}{\cos(\xi)}. \quad \textbf{(5.1)}$$

By substituting *FOV/2* for ξ, Eq. (5.1) can be used to determine the upper limit for the geometric field of view as a function of the maximum allowable perspective distortion.

5.4.2 Geometric and observer field of view

The geometric field of view is the visual angle of a scene as measured from the center of projection. The observer field of view is the visual angle of a scene as measured from the observers eye-point.

If the observer field of view is smaller than the geometric field of view, the information is compressed. To quantify the amount of compression, the angular compression factor R_c, representing the ratio of the geometric field of view and the observer field of view, is introduced. When presenting spatially integrated data on a head-up display (HUD), the observer field of view must be equal to the geometric field of view yielding an angular compression factor of 1. Otherwise stimuli from the outside visual scene conflict with the perspective presentation of the flightpath. Thus, with a HUD the selection of the geometric field of view is determined by the observer field of view. A mismatch between the geometrical field of view and the observer field of view causes direction judgement errors. McGreevy and Ellis (1986) investigated the influence of a mismatch between the geometric and the observer field of view on the accuracy with which people can estimate the direction towards objects in a virtual 3-D world when using a perspective display. Although the systematic nature of the errors suggests that it is possible to compensate for at least part of them by applying some non-linear scaling, one must consider the relevance to the tasks at hand and the potential problems this might introduce. In case awareness is sufficient and none of the tasks requires absolute judgements about the direction to objects, corrections are not needed. In case such information is needed, alternatives exist, e.g. by means of integrating additional metrical aids as suggested by McGreevy and Ellis (1986). The observer field of view is determined by the size of the displayed image and the distance between the display and the eye-point of the observer. These two design parameters will be discussed in Sect. 5.7.

5.4.3 Effects of a limited field of view

One of the fundamental differences between the available visual information with car driving and the information with perspective guidance displays is the rather limited field of view of the latter ones. To compensate for the resulting missing peripheral cues, a variety of display augmentation concepts are possible. Grunwald and Merhav (1978) investigated the effectiveness of three different basic display augmentation concepts for guidance of low flying remotely piloted vehicles (RPVs). Their results show a strong dependence of the effectiveness of the display aids on vehicle dynamics and the spectrum of disturbances.

In his research into perspective display formats for the presentation of guidance information, Grunwald (1981) indicates that the lack of cues which results from the narrow field of view can yield an undamped system. He proposes the use of predictive display symbology to compensate for these missing cues, which is discussed in Sect. 5.10. Another reason to present the pilot with predictive symbology is to allow him to better determine the moment an anticipatory control action is required for curve initiation. In this way, the required closed-loop control behavior after the open-loop action is reduced and performance is increased. As discussed in Sect. 3.6.4, the field of view also influences the average value of TTP_{min}, the time between the moment an element with a relative velocity component towards the viewpoint leaves the viewing volume and the time it passes the viewpoint; and as indicated in Sect. 4.4.3 this influences the pilot's ability to successfully apply anticipatory control actions.

When using spatially integrated data presentation, one should distinguish between the need for veridical perception of the spatial layout and the goal of reducing the required effort for integration and interpretation of the displayed data. The latter requirement is much easier to satisfy than the former one and allows much more trade-offs to be made.
For a head down display, the selection of the field of view is not constrained by conformality requirements. As a result, it can be selected based on requirements with respect to the track angle error gain and constraints with respect to requirements concerning the minimum visible pitch attitude range and the maximum allowable perspective distortion. In case accurate judgements of location in terms of azimuth and elevation are required, additional metrical aids can be integrated to compensate for the effect of angular compression. If, as a result of a too limited field of view no adequate damping cues are available, predictive symbology can be used to restore these cues.

5.4.4 Preview distance

In Ch. 3 it was indicated that the trajectory preview provides the following information:

- Position and orientation information in a single snapshot, which influenced the compensatory control strategy;
- information about upcoming changes in the direction of the trajectory and temporal range information towards these changes, allowing anticipatory control;
- information about future position constraints, allowing error-neglecting control;
- information about the world-referenced trajectory in an egocentric reference frame providing a basic level of navigational awareness.

The amount of trajectory preview is determined by the minimum and maximum viewing distance. Furthermore, the minimum viewing distance can be used to control the maximum error resolution of the display. The absolute displacement of the endpoints of lines which rotate as a result of a change in splay angle, is inversely proportional to the minimum viewing distance. Results of several psychophysical studies into accuracy with which a change in stimulus can be detected, indicate that the accuracy is a function of the relative change in the stimulus. Therefore, the minimum and maximum viewing distances should be selected in such a way that the splay angle conveyed by the tunnel lines can be adequately perceived. Eq. (3.13) showed that the minimum viewing distance also influences velocity gain, which in turn influences the cues providing a sense of three-dimensionality. Hence, one should be very careful when increasing the minimum viewing distance as this can seriously reduce the compellingness of the third dimension. The ratio of the minimum viewing distance and the velocity V equals the minimum temporal distance which can be perceived and thus influences the pilot's ability to exercise anticipatory control. The maximum viewing distance determines the amount of trajectory preview, and in this way has a similar function as the range scaling with a navigation display. Since the resolution of the data is inversely proportional to the viewing distance, the maximum viewing distance should be based on the potential contribution of the displayed data to the required level of navigation awareness.

5.5 Representation of the flightpath

5.5.1 Introduction

The representation of the flightpath determines the cognitive effort which is needed to turn the perceived image into useful information. The elements of the flightpath provide the observer with the cues to determine position and orientation errors and exercise control to keep the errors within predefined constraints. In Sect. 3.5 it was concluded that '*for control the basic requirement is, that the pilot is able to extract splay angle and amount of translation of the tunnel from the presentation*'. Thus, there is a possibility to vary the representation of the flightpath to make a trade-off between the amount of elements and the available cues.

In Sect. 3.1 it was indicated that *'to reduce cognitive processing, the representation should evoke holistic perception'*. As indicated by Wickens (1984), this requires the presence of visual cues defining the shape of the object. Even in case the contours are not physically complete, our perceptual mechanism completes the contours through top-down processing. This presents the designer with some freedom which can be used to trade-off between the available computing power, amount of detail, and potential display clutter. For the design of perspective flightpath displays this was recognized by Wilckens (1973) who stated that *'when enough cues are available, the human observer completes the rest of the picture'*. In other words, the level of realism of an object must exceed a certain threshold after which it does not significantly contribute to control performance. Furthermore, as indicated in Sect. 5.2, the representation of the flightpath influences the cues which provide the observer with the information required to resolve ambiguities. Sect. 5.5.2 will discuss the basic elements of the representation, and how these elements convey the required information. Sect. 5.5.3 will discuss the integration of additional elements to provide 4-D cues. From the discussion on how the perceptual, cognitive, and control theoretical requirements influence the representational requirements, a set of guidelines is derived, which is presented in

Sect. 5.5.4. In Sect. 5.5.5, an overview of the representations used in other research into perspective flightpath displays is provided.

5.5.2 Basic elements

For the representation of the flightpath several possibilities exist. In general, the flightpath can be divided into a channel or tunnel indicating the desired trajectory, cross section frames to provide motion cues and cues to resolve ambiguities by exploiting the observers expectations about the shape of the 3-D object, and altitude poles and a ground track to resolve position ambiguities by relating the flightpath to a ground plane. The altitude poles also provide a possibility to temporarily use a very high lateral error gain, which will be discussed later in this section. 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. Such cuing is not available with a monorail display as used by Nataupsky and Crittenden (1988), which might explain the interaction they report between the use of stereo and non-stereo flightpath representation. By using dashed lines rather than solid lines to indicate the interconnections between the boxes velocity cuing can be increased. A fundamental requirement is that the spacing between the dashed lines in the 3-D world is correctly transformed to the 2-D presentation. Just connecting the boxes with dashed lines with equal 2-D spacing generates a constant edge flow pattern, but conveys conflicting global optical flow cues.

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. In general, the representation of a flightpath can be 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.

Fig. 5.5 gives an overview of different types of elements which have been used to represent the channel. Fig. 5.6 shows the different combinations of two elements with altitude poles, interconnections between the elements, and a ground track.

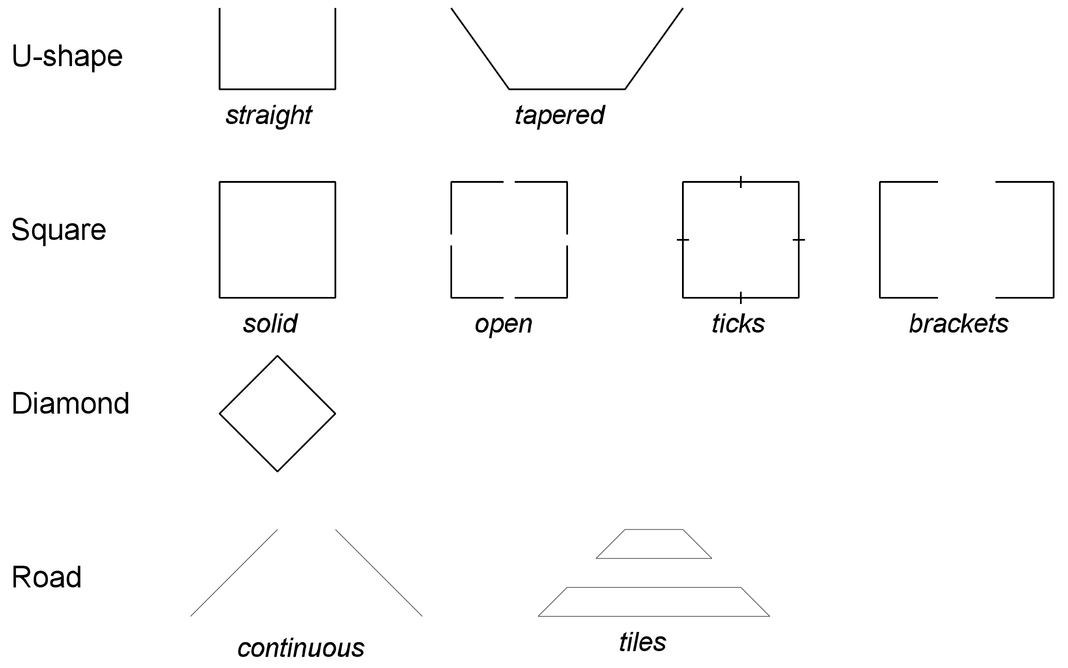


Fig. 5.5. *Typical elements to represent the flightpath.*

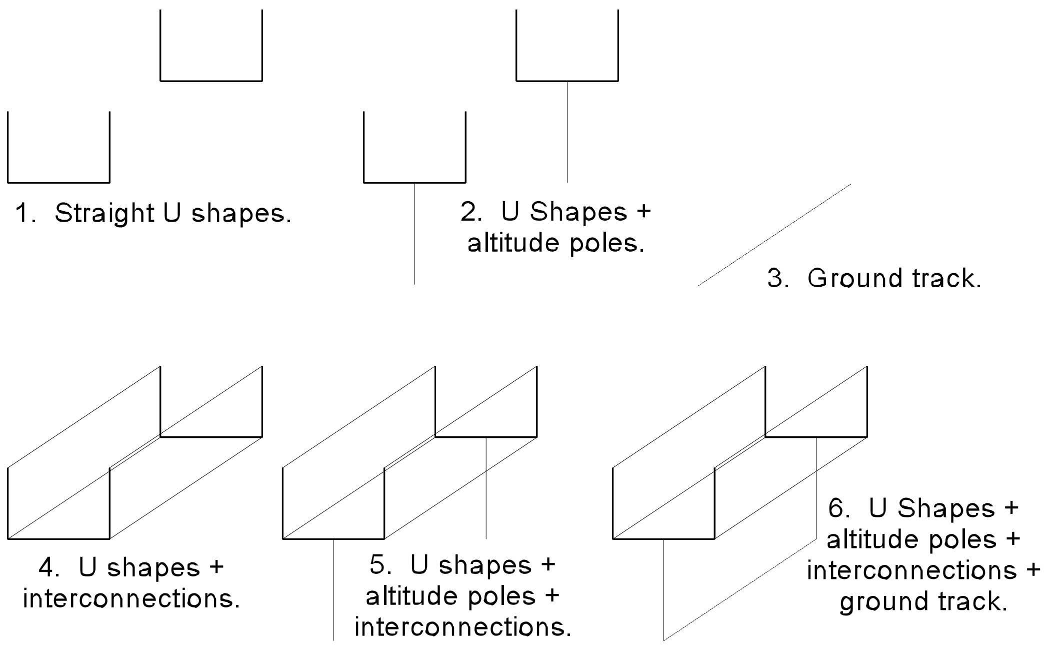


Fig. 5.6. *Different combinations of cross section, ground-track, altitude-poles, and interconnections.*

As discussed in Sect. 3.5, the height and width of the tunnel determine the position-error gain. Sometimes, it is desirable to have also a source of a very high position error gain which can be used for temporary 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. The *open* and *ticks* variant of the square in Fig. 5.5 are examples. In fact, the altitude poles already provide such information for lateral control. During experiments which will be discussed in Sect. 7.2, subjects 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. An advantage of rectangular elements is that judgement of horizontalness and verticalness is something people are very good at. The lines of rectangular cross sections are horizontal and vertical in the reference condition. With diamond shaped cross sections, this has to be inferred from the position of the four corners.

Representations employing the *continuous* or *tiled* road as depicted in Fig. 5.5 lack symmetry in the vertical dimension. Hence they do not provide altitude error cues through a distortion in symmetry. As a result, additional symbology is needed to provide the pilot with these cues. Often this is performed by the integration of a lead plane flying at the commanded altitude.

The orientation of the tunnel can be used to provide the pilot with roll commands. Grunwald (1996a) describes a method which can be used to generate a tunnel in which the elements are banked in curves, where the bank angle matches the one required for carrying out a coordinated turn at a given velocity.

5.5.3 Integration of 4-D cues

Desired/commanded velocity can be presented in the spatial domain by presenting a desired position as a function of time or by means of fast-slow indicators. The first option has been used by Grunwald (1984), who presented a moving window at the commanded future position, and by Filarsky and Hoover (1983), who presented a lead plane flying at the commanded velocity. The latter option has been used in several concepts developed in the context of the Army-Navy Instrumentation Program (ANIP). Besides the commanded velocity, the pilot must know the actual airspeed. In Sect. 3.6.3 it was indicated that the dynamic cues provided by the tunnel, do not convey information which is required to stay in a safe flight envelope, and that therefore the integration of an additional airspeed indicator is required. As a result, another option to present commanded velocity is to integrate it as a reference on the airspeed indicator. In this way, it can be combined with the presentation of actual airspeed, allowing the pilot to determine whether the commanded velocity does not cause any unsafe situations.

5.5.4 Summary of guidelines

Based on the analysis of the visual cues in Ch. 3 and the discussion in this section, the following guidelines for the specification of the representation of the flightpath are proposed:

- The representation should be designed so, that it is perceived as an object, not as a collection of elements.
- To exploit symmetry as an emergent feature, the representation should be symmetrical about the horizontal and vertical axis.
- To provide cues for resolving ambiguity and allowing the perception of temporal range information, cross section frames should be included. Since the magnitude of the cues reduces with increasing distance from the viewpoint, cross section frames are no longer needed beyond a certain viewing distance.
- To exploit the capability of humans to accurately judge horizontalness and verticalness, the cross section should contain horizontal and vertical elements.
- To allow the direct perception of perspective splay angle, interconnections between the cross sections should be used.
- To provide cues which allow the temporary use of an error gain which is independent of tunnel size, the cross sections should contain an indication of their center.
- To increase velocity cuing, these interconnections can consist of line segments which must be equally spaced in 3-D space to yield correct edge rate and flow rate cues.

5.5.5 Overview of existing representations

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 their *channel display*. The Northrop maneuvering flightpath display (MFPD) was represented by means of tiles. Hoover et al. (1983) represented their command flightpath display (CFPD) also by means of tiles. Jensen (1978) used *telephone poles* to visualize the desired trajectory. Similar to the MFPD and the CFPD, Reising et al. (1989) used tiles and added a centerline. Formats using a continuous road or tiles to indicate the pathway lack accurate altitude cues. Both with the MFPD and the CFPD a command plane was used to present altitude and velocity cues. None of these formats employed a continuous presentation of the flightpath, i.e. no interconnections existed between the references. In the absence of such interconnections, splay angle must be inferred from the relative position of the successive cross sections. This decreases the accuracy with which this variable can be perceived. 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. Dorighi et al. (1992) presented two cross sections at a fixed distance of 3.5 and 7 seconds ahead. Their tunnel is represented by dashed lines, with segment lengths of 200 ft spaced 200 ft apart. The movement of these lines present the velocity cues which in other tunnels are conveyed through the motion of the cross section frames.

5.6 Flightpath parameters

5.6.1 Tunnel width and height

The elements representing the flightpath can be scaled in their geometric dimensions, and thus determine splay-gain (Sect. 3.5). Based on the organizational framework discussed by Owen (1990b), it is hypothesized that in a certain range of sensitivity, equal ratio increments in splay gain yield approximately equal interval improvements in tracking performance.

Since the size of the tunnel is the parameter with which the gain of the functional variable for position control is determined, the selection of the dimensions of the tunnel should be based on requirements with respect to the maximum allowable flight technical error.

The dimensions of the tunnel are not necessarily constrained to physically relevant values. For example, a lateral error gain of 10 degrees/m would require a tunnel width of 5.7 m. Although such a high gain might be required for certain purposes, obviously, most aircraft will not fit in the physical tunnel defined by these constraints. As indicated by Eq. (3.17), the tunnel size is proportional to the average value of TTP_{min}. Therefore, when the size of the tunnel exceeds a certain threshold, no useful cues for anticipatory control are available. Wilckens (1973) reports that *'the acceptance for high deviation sensitivity allows the use of channel dimensions as meaningful tolerance limit indications even in the - generally most critical - landing phase. It was shown by test results that optimum tracking precision can be achieved with a channel calibrated for standard runway width'*.

Since at present no validated pilot models for use with a perspective flightpath display are available, the relation between splay gain and tracking performance must be obtained through pilot-in-the-loop experiments. To reduce the number of pilot-in-the-loop studies which are needed to determine the values of tunnel width and tunnel height in order to meet the performance requirements, models describing pilot control behavior when using a perspective flightpath display for the tracking of curved and straight segments must be developed.

5.6.2 Frame spacing

Information about the relative motion between the flightpath and the observer is mostly obtained through the cross section frames and the altitude poles. In Sect. 5.5.2 it was also indicated that dashed interconnections between the cross section frames provide velocity cues. The mechanisms which are responsible for this effect have been discussed in Sect. 3.6.2 and were identified as edge-rate and global optical flow-rate. It was indicated that edge-rate is determined by the spacing between the cross section frames. Too many frames will result in a cluttered display whereas too few frames will result in a lack of cuing. The time between the passing of successive frames determines edge-rate, and thus for optimal cuing the required distance between the different frames will be proportional to the relative velocity between the observer and the flightpath. Frame-spacing determines the display area which is occupied by each frame. The visual effect of a certain frame spacing depends on the tunnel size and the field of view. Therefore, frame spacing itself is not useful as a measure to compare different designs. A parameter is needed which indicates the visual effect caused by a certain combination of frame spacing, tunnel size and field of view. The ratio between the size of two successive cross section frames is such a parameter. If the ratio for cross sections near to the observer is close to 1 this will yield a cluttered display. To derive an expression for the ratio of two successive cross section frames, Fig. 5.7 shows a top view of a situation in which cross section frames of width w and spaced at a distance l are projected onto a viewplane. The parameter d_{min} represents the distance to the viewpoint at which the left and right border of a cross section frame touch the lines indicating the field of view.

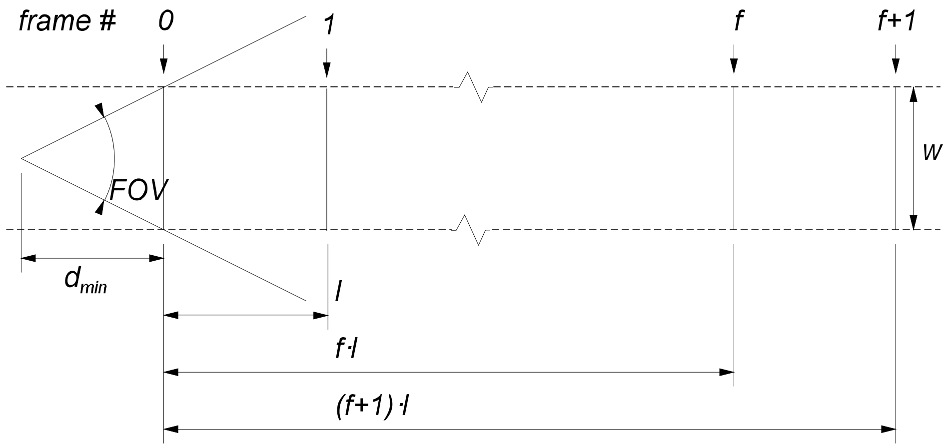


Fig. 5.7. *Top view of the projection of cross section frames numbered from 0 to f+1. The parameter w represents the width of the cross section frames, and l represents the spacing between them. The parameter d_{min} represents the distance between the viewpoint and the cross section which just touches the lines indicating the field of view.*

The ratio R_f of the size of the projected image of frame f and $f+1$ is equal to the ratio of the distance from frame $f+1$ to the viewpoint and the distance from frame f to the viewpoint. Eq. (5.2) expresses R_f as a function of d_{min}, f, w, and l.

$$R_f = \frac{d_{\min} + (f+1) \cdot l}{d_{\min} + f l} \quad \textbf{(5.2)}$$

The distance d_{min} is related to tunnel width w and field of view FOV in the following way:

$$d_{\min} = \frac{w}{2 \cdot \tan(FOV/2)} \quad \textbf{(5.3)}$$

By substituting Eq. (5.3) into Eq. (5.2), and expressing frame-spacing l in units of tunnel size w, Eq. (5.2) can be written as:

$$R_f = \frac{1 + 2 \cdot \tan(FOV/2) \cdot (f+1) \cdot n}{1 + 2 \cdot \tan(FOV/2) \cdot f n} \quad \textbf{(5.4)}$$

In this equation, the absolute dimensions of the tunnel have disappeared, and the dimensionless ratio n between frame-spacing and tunnel size can be used to determine the ratio of the size of the projected image between two successive cross section frames for a certain geometric field of view (FOV) and distance to the viewplane (d_{min}). Eq. (5.4) shows that only at distances close to the viewplane the ratio R_f between successive frames can be controlled over a large range by selecting the ratio between frame-spacing and tunnel size. When R_f approaches one, there is no need to display more cross sections. Thus, this equation can also be used as a criterium to determine the amount of spatial data which must be transformed.

5.7 Display size

For a given distance between the viewpoint of the observer and the display device, the size of the area on the display device on which the perspective scene is presented, determines the observer field of view. In Sect. 5.4.2 the angular compression factor was specified as the ratio between the geometric field of view and the observer field of view. The angular compression can be used to compare cues resulting from a translation of display elements, for example the cues required for pitch stabilization.

Cross and Bittner (1969) investigated the accuracy with which judgements about altitude, roll angle, and pitch angle can be made as a function of display size. For the roll angle experiments display size was varied between 8", 14" and 17" yielding a horizontal observer field of view of 12,21 and 25 degrees, respectively. They report that no effect of display size on the accuracy of roll angle judgements was found. For tasks relying on cues resulting from a rotation of display elements, the fact that the accuracy with which a change in stimulus can be detected is a function of the relative change in the stimulus, suggests that once the display size is large enough to convey the cues so that the perceptual thresholds are exceeded, display size no longer influences performance. However, besides using the rotational component, a pilot might also use the linear translation of the endpoint of the line at the intersection with the screen boundary. The magnitude of this translation is proportional to display size. With a perspective flightpath display, position error gain is proportional to splay gain, and error resolution to the linear excursion. As indicated in Sect. 4.4.2, a situation in which both error gain and error resolution influence the pilot's control behavior is the tracking of a curved segment.

In Sect. 3.5 it was discussed how a change in horizontal or vertical orientation of the viewing vector causes a translation of the displayed scene. When a task requires the perception of absolute displacement, angular compression influences task performance. An example is the influence of the size of the attitude indicator on the pilot's ability to achieve inner-loop pitch stabilization and vertical tracking performance (Honaker and Anderson, 1994). For a perspective flightpath display this implies that cues conveying information about position error and roll are less influenced by display size than cues conveying information about orientation errors. Since it is likely that as a result of the holistic perception the pilot uses a weighted combination of position and orientation errors, display size will influence pilot control behavior. Table 5.1 presents these parameters for several studies into perspective flightpath displays.

Table 5.1. *Overview of the observer field of view (OFOV), the display size, distance d_v between the eye-reference point of the observer and the display, and the compression ratio R_c which indicates how many degrees of spatial information are compressed into one degree of visual angle as seen from the eye-reference point.*

Ref.	OFOV [deg]	size [cm]	d_v [cm]	R_c [degs/deg]
Grunwald et al., 1980	17.6	23.3x23.3	75	5.1
Grunwald, 1984	25.7	34.1x34.1	75	3.5
Grunwald, 1984	11	14.4x14.4	75	8.2
Barfield and Rosenberg, 1992	75	259x198	170	0.6, 0.8, 1
Dorighi et al., 1992	8.5		100	10.6
Theunissen, 1993	21	28x21	75	2.5
Theunissen, 1995	21	22x16.5	60	2.5

As can be seen from Table 5.1, the values for the angular compression ratio R_c vary between 0.6 (representing a magnification of 1.67) and 10.6 for studies into perspective flightpath displays. Such a fact should be taken into account when comparing different studies. Grunwald (1984) reports excessively large variations in vertical path-angle during an experiment with a perspective flightpath displays. He contributes this both to the fact that the path-angle is not displayed explicitly and to the fact that the vertical visual angle is too large for accurate vertical control. Indeed the angular compression for that particular display was quite high (8.2). In another study (Dorighi et al., 1992) an even higher angular compression was used. In that design, however, a position predictor was integrated. Since the predictor depicted the future position of the aircraft, an excellent cue for minimizing variations in flightpath angle was available. With the Tunnel-in-the-Sky display discussed by Theunissen (1993), vertical path angle is explicitly displayed by means of the flightpath vector symbol, with a scaling which is conformal to the geometric field of view of the display. The display used in the study performed by Theunissen (1993) utilizes an angular compression ratio R_c which is a factor 3.3 smaller than in the display used by Grunwald (1984). The higher resolution of the angular cues may have contributed to the fact that in the study performed by Theunissen (1993) no large variations in path angle were found.

For the specification of the display size, the angular compression should be used as a criterium. The maximum allowable angular compression follows from stability and guidance requirements, which dictate thresholds with respect to the minimum perceivable display motion. When the physical limitations in display size dictate an angular compression which exceeds the maximum allowable angular compression, presentation of predictive data can be used to compensate for the reduction in stability.

5.8 Display algorithms

The representation of the flightpath is not only determined by it's geometric specification, but also by the algorithms used to transform the 3-D world space to 2-D device coordinates. For a wire-frame representation of the flightpath, the points in the 3-D world-space must be converted to 2-D display space, after which they are connected by means of lines. The algorithms to calculate a 2-D perspective wire-frame presentation of a 3-D object such as the flightpath for a certain viewpoint, viewing volume, and frame of reference, are trivial. They comprise a number of matrix multiplications and are described in many books about computer graphics, e.g. Hearn and Baker (1986). For a completely correct representation of the tunnel, the thickness of the lines should be inversely proportional to the distance from the viewpoint. However, with conventional wire-frame representations, the dependency between distance from the viewpoint and line width is not taken into account since the interconnections take place in 2-D space. As a result, the part of the tunnel which is further away from the viewpoint relatively contains too many pixels. When the intensity of the lines representing the tunnel is higher than the intensity of the background, the local intensity at that specific part of the tunnel is higher, causing distraction. The available spatial resolution of the display poses severe limitations on the different line-widths which can be used. The solution to this problem is similar to the one used to achieve anti-aliasing. With anti-aliasing, the fraction of a pixel which is covered by a line-segment is used to calculate an intensity level for the pixel (Hearn and Baker, 1986). Because the perspective mapping of a line of constant width results in a decrease in the total area of pixels covered by the line with increasing distance from the viewpoint, intensity control of the pixels can be used.

5.9 Presentation of objects

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. In Sect. 2.5, the depiction of terrain and other aircraft was identified as a means to increase the pilot's awareness of such threats. The location, orientation, and relative motion of these objects contribute to awareness which in turn guides potential actions. Here too, emergent features such as symmetry can be used to exploit cognitive abilities which are involved in the early stages of perceptual processing.

To minimize cognitive processing, objects indicating obstacles and/or threats should be presented in such a way that the presentation elicits spontaneous recognition. Therefore, the presentation should be compatible with the pilot's expectation. For a compatible presentation, 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 goal is to make the real-world objects intuitively recognizable from the abstract representation, resulting in the question: *'To what abstraction level can the object representation be reduced while still allowing spontaneous recognition?'*.

Research on this topic is performed in the context of the required realism of computer image generators (CIGs) for flight simulators. To achieve the desired performance in terms of update-rate, a trade-off between the number of objects in a scene and the level of detail of these objects is required. Kleiss et al. (1988) evaluated whether the apparent size of more detailed and familiar appearing objects serves as an additional cue for altitude control in simulated low-level flight. Results showed no difference between abstract objects and familiar objects. However, performance did improve with increasing object density. Their results suggest that CIG processing capacity may be most effectively utilized by increasing the object density rather than individual object detail. Wickens (1984) claims that *'there is emerging evidence that texture can be represented by a* *relatively small number of spatial features and may, in fact, be perceived analytically in terms of these spatial features, because the high degree of redundancy in texture allows much of its information contents to be captured by just a few levels of spatial frequency'*. Owen (1990b) discusses the existence of an optimal texture density for task performance. He hypothesizes on the reason for the existence of an optimal density but indicates that *'the finding of optimal texture density may temper the current drive toward greater detail realism'*. These findings justify a rather basic representation of the future desired flightpath, terrain, and the runway. When developing more advanced 3-D display formats to obtain a synthetic vision system (SVS), this fact should also be taken into account.

In Sect. 5.3.1 it was concluded that '*when using an egocentric display for the guidance task, a satisfactory level of global and navigational awareness calls for the use of an additional, exocentric view of the situation*'. Since it is likely that such a display will also include a depiction of objects representing geographic features and traffic, it is important to use a consistent representation between the display formats to support a high degree of cognitive coupling.

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.

The level of detail of the representation of objects should be high enough to allow spontaneous recognition. The representation should be consistent between different display formats, and allow the manipulation of certain attributes to attract the pilot's attention.

5.10 Display augmentation

In case the information from the perspective flightpath is not adequate, augmented symbology can be used. In this context, augmented symbology only refers to elements which have a specific relation with the displayed flightpath and does not refer to additionally integrated instruments such as an altimeter or a speed indicator.

Additional data can be included to aid the pilot with the guidance task. This data has been divided into three levels: Unprocessed status data, processed status data, and command data.

Unprocessed status data refers to physically interpretable data which is directly representative of the actual system state. Processed status data refers to physically interpretable data which is representative of a system state other than the actual one.

5.10.1 Unprocessed status data

In Sect. 3.5.3 it was concluded for an attitude aligned frame of reference that *'since the location of the symmetrical reference condition varies as a function of crosswind, this necessitates additional symbology to directly indicate the direction of travel'*. The direction of travel can be presented relative to the aircraft attitude symbol by using the difference between heading and track to determine the azimuth and the difference between pitch and flightpath angle to determine the elevation. The symbol indicating the direction of travel is usually referred to as a flightpath vector (FPV) symbol. The FPV is classified as unprocessed status data, since it directly represents the current direction of the aircraft velocity.

Problems with the FPV can occur when it is derived from the ratio of barometric altitude rate to airspeed. Since airspeed differs from ground speed by the amount of wind velocity, the FPV obtained this way does not indicate the true FPA. In case of headwind, the indicated FPA is smaller than the true FPA, and in case of tailwind, the indicated FPA is larger than the true FPA. An inertial reference system (IRS) or absolute radio navigation system can be used to determine the ground speed of the aircraft and obtain a true indication of the FPA.

A possible cue for glide slope control during landing is the angle between the aimpoint and the horizon, sometimes referred to as the H-angle. Lintern and Liu (1991) showed that distortion of this angle by simulation of up-sloping or down-sloping terrain beyond the runway influenced glide-slope control in a predictable way. They propose the use of texture lines parallel to the runway centerline to allow the pilot to estimate the real horizon, and thus obtain an accurate estimate of the H-angle. An alternative is to directly present the true horizon.

The results of the in-flight experiment which will be discussed in Sect. 7.6, indicated the need for an increased resolution of the pitch angle information to better stabilize the inner-loop. Since the evaluation which will be discussed in Sect. 7.2, showed that an integration of a conventional pitch tape can easily clutter the display, alternatives must be explored. One potential alternative is the integration of symbology which presents the pilot with better cues to stabilize the inner-loop. Another alternative is to divide the horizon into bands of a different intensity. The effectiveness of both options has not yet been determined.

5.10.2 Processed status data.

An example of processed status data is predictive data. Kelley (1962) stated that *'if a human operator knows what a system is going to do in the future then he can do a better control job'*. Kelley (1962) proposed the use of predictive displays to relieve the human operator from the task of performing predictions about the future system state and to increase operator performance. The predictive data is based on a fast-time model[7] of the system. When calculating the future system state, assumptions must be made about the operator's control inputs during the prediction time span. Commonly used options are to assume a constant control input during the time span, a constant input which returns to its neutral value after a certain period which is shorter than the prediction time span, or an input which exponentially returns to its neutral value. Factors which should be considered when making an assumption are the length of the time-span, the dynamics of the system under control and the nature of the control task. McLane and Wolf (1965) describe a perspective display for submersibles. In this display a pathway indicates the desired trajectory and a quickened tracking symbol is used as the element which must be guided along the pathway. Since the quickened tracking symbol is based on a weighted combination of current position, velocity and acceleration in such a way that it presents physically interpretable data, it is equivalent to a position predictor. In a review of predictive displays, Warner (1969) mentions several advantages of predictive displays which are relevant with respect to the aircraft guidance task:

- Manual control can approach optimal control with respect to a specified performance criterion;
- control of non-linear systems and of linear systems with pure time delays and other non-minimum phase characteristics can be improved;
- information processing requirements on the human operator can be reduced, especially in multi-dimensional control tasks.

A predictive display element is not the same as a quickened display element. A predictive display element provides information about the estimated future system state referenced to the current system state. The prediction is often performed by adding higher derivatives to the current state, in which the relative weighting is determined by the prediction time t for the first derivative and $0.5t^2$ for the second-order derivative. Quickening is achieved by adding the higher order derivatives of an error onto the actual error with some weighting, but with a quickened display the weighting factors can be selected independent of each other. As a result, a quickened display element does not necessarily present physically interpretable information such as the future error. Thus, the main difference is that a predictive element presents physically interpretable information relative to the current system state which allows the future error between desired and actual state to be controlled, whereas a quickened display element presents a signal which can be used to reduce the future system error but does not necessarily have any physically interpretable meaning. To illustrate the difference, Fig. 5.8 presents the structure of a predictive display, and Fig. 5.9 that of a quickened display.

[7]A fast-time model utilizes a repetitive computer solution of the vehicle or system equations of motion which runs faster than real-time, to generate a predicted response of the system based on certain assumptions about future control inputs and disturbances.

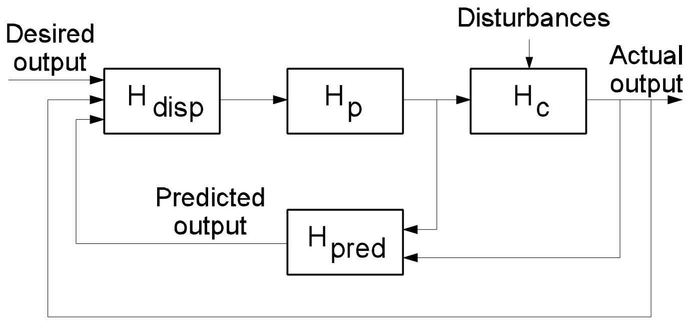


Fig. 5.8. *Structure of a predictive display. Both the actual and the predicted future system output are presented either relative to the desired output or in combination with the desired output.*

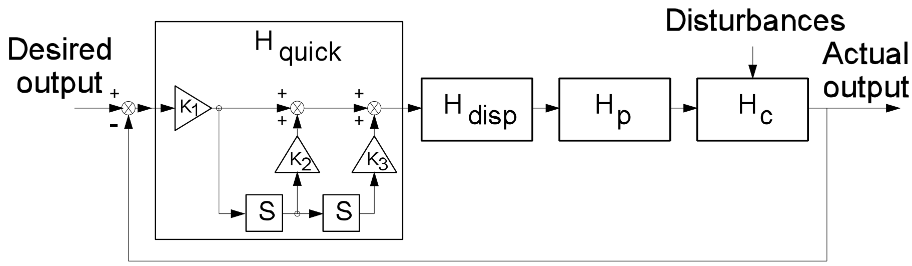


Fig. 5.9. *Structure of a quickened display. The difference between the actual and the desired output is used to calculate a command signal which has to be zeroed.*

5.10.3 Flightpath predictors

An airplane is a higher order dynamic system, and the pilot has to determine his multi-dimensional control actions by predicting the future system state as a result of his actions. Roscoe et al. (1975) describe a perspective display which presents the pilot with three predictor symbols, indicating the future position in 7, 14, and 21 seconds. Baty (1976) evaluated a track predictor for the navigation display. His results demonstrated an overall improvement in tracking performance, more homogeneous performance between pilots and between conditions, and reduced control activity. At present, track predictors are implemented in navigation displays of several types of aircraft, e.g. the Boeing 747-400 and the McDonnell Douglas MD-11. Grunwald and Merhav (1978) demonstrated that when using a camera image to control a remotely piloted vehicle (RPV), a correctly tuned flightpath predictor can compensate for the lack of peripheral visual cues which results from a limited field of view and provide adequate damping cues. With a perspective flightpath display, a predictor can also be used to compensate for a limited field of view. Furthermore, it can compensate for the lack of an adequate future track reference in curves by presenting a future position reference. Jensen (1978), Grunwald (1981, 1984) and Wickens et al. (1989) describe perspective flightpath displays with position prediction for the presentation of guidance information. A general conclusion is that the addition of a predictor symbol increases tracking performance. Thus, besides splay rate (position error) gain, position prediction can be used to increase tracking performance. The influence of both position error gain and position prediction including possible interactions will be discussed in Sect. 7.3. Grunwald et al. (1980) evaluated a second-order position predictor and report that with the optimum prediction time span lying between 4 and 7 seconds, the gain for the actual vertical acceleration had to be reduced to 20% to yield the best pilot performance. A potential cause for this problem is the validity of the assumption regarding the control inputs. It illustrates a problem with multidimensional predictive displays. In case the dynamics of the system under control differ between spatial dimensions, the optimum time spans for the prediction are also different between these dimensions. Whereas for a certain dimension a simplified assumption about constant control inputs may be valid, this may not be the case for the other dimensions. In a later experiment, Grunwald (1984) used a second-order (circular path) model to predict the future aircraft position. The reported results show that such a circular path model proves to be very satisfactory given the fact that the simplified assumption about zero control inputs is compensated for by a reduced gain of the actual vertical acceleration. A second-order predictor uses current position, velocity, and acceleration, and thus the structure is similar to that of a flight director. With the predictor, the way in which position, velocity, and acceleration are added, is determined by a fixed relation with time as the parameter which can be varied. Fig. 3.1 presented the structure which is representative for a flight director control loop. Fig. 5.10 presents the structure with the parameters for a second-order horizontal position predictor.

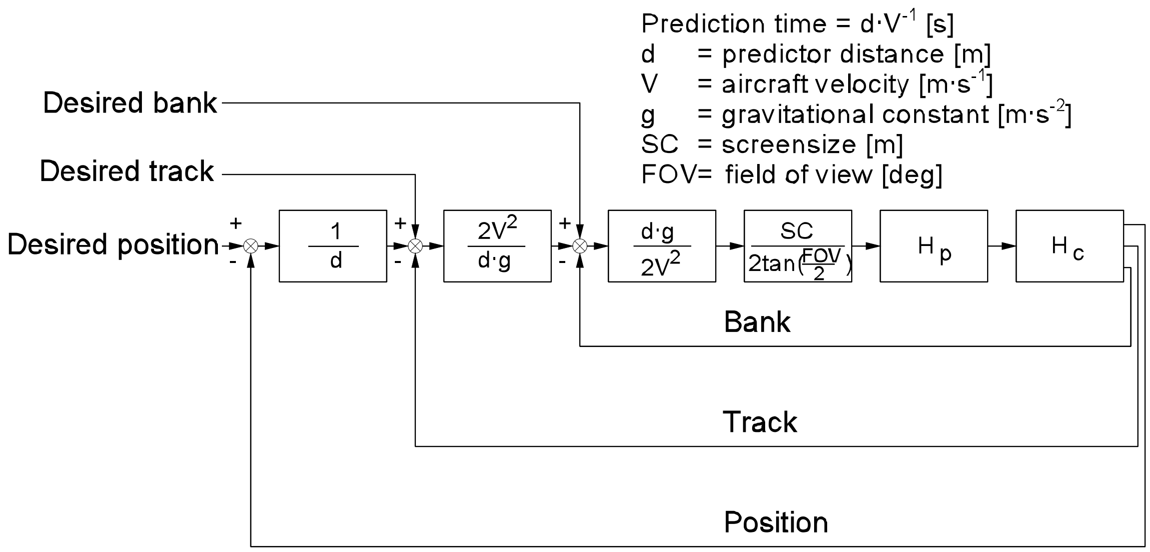


Fig. 5.10. *Structure of a lateral control-loop based on a second-order position predictor.*

Grunwald (1996a, 1996b) describes the development and evaluation of a new predictor guidance scheme based on an actively driven predictor reference window. He reports that for larger prediction times the new guidance scheme yields a superior performance as compared to the original configuration, in which a nonactive predictor reference window was used.

5.10.4 Trajectory prediction

In the conventional civil guidance and navigation situation, the aircraft has to follow a pre-defined trajectory. A different situation exists in air-to-air engagements, where the pilot is interested in obtaining the most advantageous position relative to his opponent. Viken and Burley (1992) discuss the development of a flightpath display which presents a prediction of the future (2-3 sec.) trajectory, allowing the pilot to see how his current control inputs affect the aircraft's future position and orientation. They performed an experiment in which pilots had to maneuver their aircraft behind a target aircraft and report that the addition of a trajectory predictor significantly reduced the time required to complete this task.

5.10.5 Other predictors

As discussed in Sect. 3.6.5, it is quite difficult to accurately estimate the curvature of a circular segment, and the type of augmentation to compensate for this drawback depends on the specific tasks to be performed. In military applications, e.g. terrain-following, perspective flightpath displays have been discussed to present the pilot with the three-dimensional route with maximal survival probability. Drake and Rothstein (1988) propose the use of a pathway-in-the-sky (PITS) display to present the pilot with guidance to execute evasive maneuvers, i.e. maneuvers to minimize exposure to a certain threat. They identify the need for accurate directional and timing information. They distinguish between early and mid-course maneuvers which can be specified by a desired heading and a g-level through the turn, and end-game maneuvers, which are much more dynamic and can be characterized by maneuver initiation time, g-level, and certain directional data. Coupled with these maneuver data are countermeasures data describing time and type of countermeasure. Following such a trajectory may require aggressive vertical transitions. The pilot needs to be able to estimate the amount of g-forces which will be experienced, in order to decide whether to roll inverted. With a perspective flightpath display, such an estimate will be based on the vertical curvature of the trajectory, which is difficult to determine from the perspective projection in an ego-centered reference frame. As a result, presentation of additional data might be required, e.g. a direct indication of the predicted g-forces, based on velocity and curvature.

5.10.6 Other display augmentation

Besides for describing displays which present the future system state based on an extrapolation of the current system state and assumptions about the control inputs, Breedveld (1995) uses the term predictive display to describe a display which shows the future system state based solely on the value of the control inputs. With this display, the control inputs provide rate commands which are used to generate set points for the future system state. An additional control system is needed to make the system under control to satisfy the future position and orientation requirements. This approach is similar to the one discussed by Lambregts (1978) regarding the development of a pitch velocity control wheel steering control law and display system. With this system, stick deflection is proportional to flightpath angle rate. The display shows the pilot the commanded flightpath angle based on the rate commands, and the flight control system is designed to match the future flightpath angle with the one commanded by the pilot. The difference with the previously discussed predictors is that the human operator does not directly control the system itself but provides commands to a control system. This control system operates in a separate closed-loop with the system and must ensure that the system reaches the state commanded by the operator. Thus, rather than presenting the operator with a system of which the order has virtually been reduced through the presentation of predictive information based on the system output and its higher order derivatives, the operator now controls a system which typically has first-order dynamics. Fig. 5.11 illustrates this situation for the flight control system discussed by Lambregts (1978).

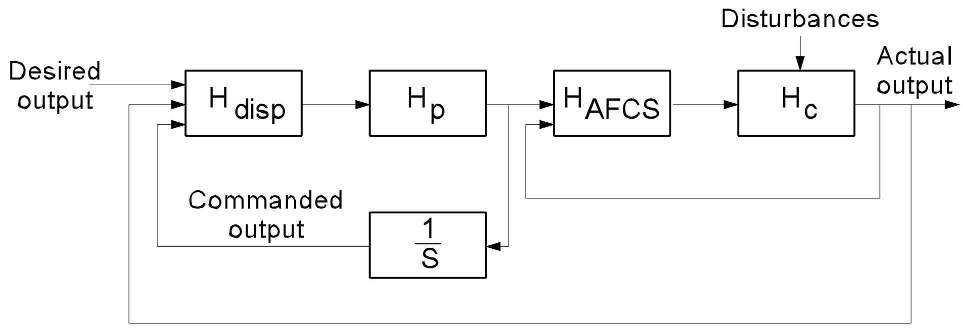


Fig. 5.11. *Prediction based on the integration of rate-commands. The pilot directly control the desired rate of the output. The automatic flight control system represented by H_{AFCS} uses the rate commands to compute the required control inputs to the system represented by H_c. To compensate for the response latency of the output, the result of the integrated rate commands, the commanded system state output is presented. Ddisturbances act on the system to be controlled.*

The findings of Lambregts and Cannor (1979) indicate that such a radical change in control concept necessitates the presentation of the commanded flightpath angle to maintain good control-display compatibility.

> When using a perspective flightpath display in combination with a flight control system which allows the pilot to directly control flightpath angle rate, the presentation of the commanded flightpath angle might be required.

It is important to consider that when the prediction is solely based on the commanded input and no feedback of the actual system state is presented, a malfunction of the control system needed to put the system in the commanded state may cause a disaster. An example of such a catastrophe is the display for the pressure relief valve in the Three Mile Island nuclear power plant. This display was designed to indicate what the valve was commanded to do rather than what it actually did. Although the display indicated that the valve was closed, the valve remained open due to a malfunction. This was one factor in the chain of events which led to the Three Mile Island incident.

5.10.7 Command information

Instead of presenting status information to aid the pilot in controlling the aircraft, command information can be presented, e.g. by means of a flight-director. Although often mathematically similar to a predictive display, a command display does not present physically interpretable information. The mechanism driving a command display is often that of a quickened display.

5.11 Requirements on position and orientation data

5.11.1 Introduction

The presentation of a perspective flightpath requires three-dimensional position and orientation data. The update-rate of this data determines the time between the successively presented images. To convey the illusion of continuous motion, the update-rate of the presented data must exceed approximately 10 Hz. Higher update-rates yield a more smoothly animated picture. This can be achieved by artificially increasing the update rate without using new data observations. Since processing delays caused by the transformation of sensor-supplied data into visual cues are unavoidable, a certain display latency will be present. Display latency is the time delay between aircraft response and the corresponding response of the cockpit displays. The effect of time delays on flying qualities is common knowledge in the flying qualities community. Time delays reduce closed-loop system stability, thereby increasing task demanding load and degrading task performance. Perceptual requirements can dictate a certain amount of filtering to obtain a smoothly animated picture. This specific problem is also present with applications such as distributed interactive simulation (DIS) which often suffer from a too limited bandwidth between systems providing position and orientation data and the display systems. Here too, methods to extrapolate the data (dead-reckoning) and methods to smooth the data are being investigated (Lin et al, 1995). Filtering introduces latencies which can influence system stability. To gain more insight into potential trade-offs between perceptual and control-theoretical requirements, a closer analysis of the different control loops is needed.

5.11.2 Perceptual requirements

Perceptual requirements address the apparent motion of the displayed elements. This is determined by the resolution and update-rate of the data driving the display. To obtain a smoothly animated picture, inter- or extrapolation can be used to increase the update-rate of the position and orientation data, and filtering to reduce the effects of noise. Whereas the minimum update-rate requirements for the position and orientation data follow from stability requirements, the perceptual requirements can be met by running an inter- or extrapolation loop at the required frequency, but do not necessarily require new observations of the data. The resolution of the data must be high enough to prevent visual artefacts which destroy the illusion of continuous motion, e.g. stepping effects. In case the accuracy is lower than the required resolution filtering may be needed.

A major difference between the conventional flight director and a perspective flightpath display 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 directly contains position and attitude data. In order for the pilot to maintain confidence in the flight director, the commands must have a certain degree of consistency with the other information available. In contrast, to avoid information conflicts, the cues obtained from a perspective flightpath display must be directly compatible with visual stimuli from the outside world and the motion cues obtained through the vestibular system. Thus, with a perspective flightpath display the perceptual requirements are more closely related to the position and attitude data. Furthermore, the dynamic presentation of spatially integrated trajectory preview provides temporal range cues. Eq. (3.17) showed that the average value of TTP_{min} is proportional to tunnel size. To be able to use the temporal range cues for anticipatory control, a high position error gain is needed, which in turn increases the requirements on the accuracy of the position data.

It is not known how much latency is perceptually acceptable, i.e. does not cause conflicts in the perception of the different visual cues. Filarsky and Hoover (1993) indicate that during the simulation phase of the CFPD experiments a data latency of 200 to 300 milliseconds was present, and some pilots indicated that the lag was very noticeable when flying the symbology, but not apparent when flying the CFPD. Since both display formats were driven by the same data processing system they conclude that *'lag time in displays are amplified when discrete symbols are utilized, but minimized with integrated real world visual cue displays'*. Findings from an experiment performed at Delft University of Technology indicate that a certain margin exists in which differences in latency between position and orientation data are not noticed, which will be further discussed in Sect. 7.5. In the absence of other cues, the pilot cannot distinguish between a display latency and a latency in the system dynamics and is likely to interpret a change in display latency as a change in system dynamics. Other experimental evidence also suggest that humans do not recognize latencies as such, although they certainly influence their control behavior (King, 1993). This will be discussed in more detail in Sect. 5.11.3.

5.11.3 Stability requirements

Since the closed-loop system also involves the control system, the display latency effects depend on the latency of the control system. Although specifications exist in which the relationship between maximum control system delays and associated flying qualities levels are documented, there currently is no explicit specification for allowable display latency to ensure acceptable aircraft handling qualities in instrument flight conditions (King, 1993; Funk et al., 1993). Research has shown that handling qualities ratings are best correlated with the stability characteristics of the inner control loop for the most difficult control axis (McRuer and Jex, 1967; McRuer and Krendel, 1974).

King (1993) examined handling qualities effects of display latencies between 70 and 400 milliseconds for precision instrument flight task. He reports that the results showed no discernable trends relating tracking performance to latency for test points between 70 ms and 300 ms, and only a slight reduction in tracking accuracy at 400 ms. Pilot ratings indicated that below 140 ms display latency, no significant quantifiable differences in handling qualities were observable, but between 140 ms and 300 ms a control degradation occurred. He further reports that pilots commented that they were perceptually unaware of latency changes between configurations, but that they acquired different control techniques due to *'slight changes in aircraft response characteristics'*. This shows that pilots interpreted the change in display latency as a change in system dynamics, and that the increase in latency forced the pilots to increase their effort in order to maintain constant performance.

To analytically determine the allowable latency from stability requirements, a closed-loop analysis is required. To do this, both a model representing the system dynamics and a model representing pilot control behavior are needed. In Sect. 3.2 it was pointed out that '*an important difference between conventional guidance displays and a perspective flightpath display is the presence of the trajectory preview in the latter one*'. As a result, methods which take this anticipation into account are required for adequate pilot modeling. Various preview/prediction models have been proposed (Sheridan, 1966; Reid and Drewell, 1972). It is important to notice that this applies to tracking tasks which are characterized by changes in the forcing function. To describe the visual cues for a compensatory tracking task in the presence of trajectory preview, but in the absence of changes, less complex models should suffice. For such a task, the effect of the trajectory preview is that a single snapshot of the presentation contains information about both position and orientation errors. Since the latter ones are proportional to position error-rate, the preview integrates position and position-rate information into a single snapshot.

Grunwald (1978) showed that the velocity field resulting from the relative motion between the viewpoint and the 3-D environment contains information about the future position error. For closed-loop stability analysis, he assumed that the pilot's control actions are proportional to the perceived future position error. This approach requires an assumption to be made about the part of the future which is used by the observer. Grunwald used a *two-distance model* to include the effect of a span of viewing distances. Whereas the basic assumption underlying Grunwald's approach is that the pilot extracts his future position error from the velocity field and uses this error to determine his control action, in Sect. 3.5 it was proposed that the basic cues the pilot uses are the distortion of the natural symmetry of the tunnel and the rotation of the image. It can be shown that mathematically the two approaches are very similar, since they both yield second-order models. When using a representation of the tunnel with dashed lines representing the position constraints (Grunwald, 1996a), adequate velocity field cues are present. When solid lines are used to indicate these constraints, as is the case with many implementations of perspective flightpath displays, the only velocity field cues are conveyed through the motion of cross section frames towards the observer, and as a result velocity cues are significantly reduced. Both Grunwald's approach and the approach discussed in Sect. 3.5 can be used for a closed-loop analysis in which the assumption is made that the pilot's control action is based on a prediction of the future position error which he tries to minimize by closing the control loop in such a way that a certain performance criterium is met and a stable system is obtained.

A possible approach to derive a simple pilot model is to assume that the control strategy is continuous closed-loop compensatory control in which the pilot uses the distortion in symmetry to minimize position errors. For continuous compensatory tracking tasks the cross-over model (COM) can be used to describe the pilot's control behavior. The COM states that a sufficiently trained pilot linearly relates a control input to a tracking error such that the open-loop pilot-aircraft system provides the following frequency domain characteristics:

- Sufficient bandwidth for task tracking and disturbance rejection;
- adequate stability margins (phase margin > 45 degrees);
- an integrator-like response at the crossover frequency.

A potential approach to relate the pilot's control actions to the visual cues is to assume that the aileron control action is based on a combination of image rotation representing roll, lateral tunnel translation indicating the track angle error and the difference between right and left splay angles indicating cross track error. For vertical control, image translation provides pitch cues needed for system stabilization, vertical tunnel translation indicating flightpath angle error, and differences between top and bottom splay angle to indicate vertical track error.

Aileron deflections (δ_a) can be expressed as:

$$\delta_a = K_1 \cdot (\varphi - \varphi_{nom}) + K_2 \cdot TAE + K_3 \cdot XTE, \qquad \textbf{(5.5)}$$

and elevator deflections (δ_e) as:

$$\delta_e = K_4 \cdot (\theta - \theta_{nom}) + K_5 \cdot FPAE + K_6 \cdot VTE. \qquad \textbf{(5.6)}$$

In these equations, K_1 to K_6 represent the weighing factors the pilot applies to the different cues. Based on these assumptions, a model for the numerical evaluation of display latency has been implemented by Kedde (1996). By expressing position and orientation errors as changes in splay angle and image translation, the influence of changes in the design parameters can be analyzed once a validated pilot model is available. Kedde (1996) demonstrated that under the assumption that the pilot maintains K_1 to K_6 constant, a reduction in tunnel size yields an increase in performance and an increase in control activity. The development and validation of more sophisticated models to describe pilot control behavior with spatially integrated trajectory preview is being pursued by Mulder (1994).

5.11.4 Analyzing latency effects

Since all latencies are lumped together in the inner-loop, the latency requirements which follow are always based on the stability requirements for the inner control loop. The bandwidth which is required to close the position loop, however, is less than the bandwidth required to close the attitude loop. Therefore, as long as outer-loop variables are not used to calculate inner-loop variables (e.g. through differentiation), the requirements on the latency of the position data should be less stringent than those regarding the attitude loop. Based on the approach discussed by Hess (1987), this multi-loop closure can be represented as a single loop. The outer loop has less stringent bandwidth requirements, and as a result a lower data update-rate is possible. Hess (1987) mentions a bandwidth reduction factor between 2 and 3 for each successive loop, yielding a potential reduction factor between 4 and 9 for the update-rate of the position data. Given, for example, a maximum allowable latency of 100 ms for the stabilization loop, a latency of 400 ms in the position data should not present any problems from a control-theoretical point of view. This provides the designer of the algorithms to increase the update-rate with more freedom to trade-off between latency and perceptual requirements as would be result from an approach in which all latencies are lumped into the inner-loop for closed-loop analysis.

5.11.5 Impact of position data latency and position data errors

Any latency of the position data influences the temporal range cues. The ability to exercise a certain amount of anticipatory open-loop control requires that the pilot has acquired an internal representation of the system under control. In case the data latency is different than during training, the pilot will probably perceive this as a change in handling qualities.

A position data latency relative to orientation or direction data can yield a perceptual conflict. When a change in orientation is conveyed through a lateral and/or vertical translation of the displayed information, the streamer pattern is the sum of a pattern resulting from the displacement of viewpoint similar to that presented in Fig. 3.20 and a pattern containing only equally sized velocity streamers resulting from the rotation of the viewpoint. Based on the rotation cues conveyed by the total pattern, the observer has certain expectations about the change in position of the viewpoint which must be confirmed by the cues resulting from the first streamer pattern. When the mismatch between the actual pattern and the expected pattern exceeds a certain threshold, a perceptual conflict will occur.

In Sect. 2.5, the navigation system error (NSE) was defined as '*the difference between the true position of the aircraft and the position as estimated by the positioning system*', and the flight technical error (FTE) as '*the difference between the desired position of the aircraft and the position reported by the positioning system*'. It was indicated that in the absence of additional references, a change in FTE cannot be distinguished from a change in NSE. Such references include information based on the pilot's internal representation of the aircraft dynamics, information from the outside world view, and information from the vestibular system. In case an error in the position data or data latency causes a perceived mismatch between the information resulting from any of the other sources, this can yield a number of effects. First of all, it can yield a reduction in confidence. Depending on the type of error, this may be desirable in a situation where it reduces a potential confirmation bias, but undesirable when a pilot makes an faulty assumption on which information to trust and which to ignore.

The impact of errors in the position and attitude data depends on the frequency spectrum of these errors. The component of the error vector which is perpendicular to the track yields a change in splay angle. The along track component yields a change in the magnitude of the velocity streamers. For frequencies which exceed the spectrum in which the position of the aircraft can vary, the pilot can identify the additional rotations and disturbances of the streamer pattern as noise and choose to ignore them. With respect to errors in the position data, such a situation is also likely to occur when there is a sudden stepwise change in the error.

When part of the spectrum of the position errors lies below the threshold were it can be identified as noise, it enters the control loop. As a result, the pilot is likely to try to compensate for virtual position errors, thus unnecessarily increasing control activity.

From research into flight simulation and virtual environments it is known that latencies between the cues conveyed by the visual and the vestibular system can cause motion sickness. This suggests that position data latency and position data errors might produce a similar effect with perspective flightpath displays. However, the goal of both the visual system of a flight simulator and the display media used to present a virtual environment is to closely approximate a real world scene and convey a sensation of complete immersion. Therefore, the image is conformal in azimuth and elevation and presented for a large observer field of view, up to 180 degrees or more. In contrast, the observer field of view with a perspective flightpath display presented head down on a typical display unit in a commercial aircraft will be much smaller, typically about 15 to 20 degrees. The display is an instrument, and the degree of immersion is much less. Therefore, it is likely that the effects of position data errors and latency will be less than with flight simulators and virtual environment systems.

5.11.6 Conclusion

Different approaches to position determination exist. For automatic flight control systems, the specification of accuracy, update-rate, and latency of the position and orientation data follow from stability requirements. When the pilot is in the control loop, the type of display also influences the data update-rate, latency and accuracy requirements. Displays which present steering commands instead of physically interpretable data, provide the designer with more freedom in applying methods to meet perceptual requirements. At the moment, not enough data is available to provide detailed guidelines for the development of position data predictors and filters to meet perceptual requirements. A worst case approach would be to apply the same criteria as used for the inner-loop stabilization task, but this might result in overkill. The fact that margins exist would also allow a better optimization in case there is a limited communication bandwidth between the system which determines the position and orientation and the display system. This is for example the case with distributed interactive simulation (DIS) applications.

5.12 Presentation media

The current generation of commercial aircraft is equipped with programmable head down displays. Implementation of a perspective flightpath display is mostly a matter of changing the software. Most of the research which investigated certain aspects of perspective flightpath displays used head down displays. Since pilots have to switch their attention between the outside world and the instrument panel to obtain all necessary information, the question arises whether it is possible to combine the information presented by the instruments with the information from the visual scene. This has resulted in head-up displays (HUDs) which overlay information about velocity, altitude, attitude, heading and flightpath on the visual scene. Only few commercial aircraft are currently equipped with HUDs, but it is important to consider whether it is possible to use a perspective flightpath display on a HUD. As indicated in Sect. 5.7, conformality with the outside visual scene is required, thus limiting the choice of the geometric field of view to the observer field of view. Besides the conformality requirement, HUDs should presented the data so that it is perceived together with the outside visual scene. This process imposes additional requirements with respect to the representation of data, since the danger of occlusion of outside world data exists. A simulated color HUD was used in the pictorial format display evaluation, and Hawkins et al. (1983) report that pilots did not like the color HUD during the part of the mission when outside vision was required since the solid areas tended to obscure the outside view.

Helmet mounted displays (HMD) also provide the possibility to present information overlaid on the visual scene. Whereas with a HUD the limiting factor was the relatively narrow observer field of view, a line-of-sight slaving system with an HMD removes this limitation. Experiments show that pilots have encountered considerable difficulties in controlling the aircraft by HMD devices. Part of the problem is that the viewpoint of the camera is displaced with respect to the actual eye position. Since a perspective flightpath is artificial, this problem can be removed by using the position of the pilot's eye as the viewpoint. Grunwald and Kohn (1993) demonstrated that another part of the difficulties with HMDs can be attributed to head/camera slaving system phase lags and errors. They report that *'in the presence of voluntary head rotation, these slaving system imperfections are shown to impair the Control-Oriented Visual Field Information vital in vehicular control, such as the perception of the anticipated flightpath or the vehicle yaw rate. Since, in the presence of slaving system imperfection, the pilot will tend to minimize head rotation, the full wide-angle field of regard of the line-of-sight slaved HMD, is not always fully utilized'*.

Both HUDs and HMDs use collimation techniques to project the information at optical infinity. Ample evidence from experiments is available that the eyes do not automatically focus at optical infinity when viewing collimated virtual images, but at a much shorter distance. (Roscoe, 1991). The perceptual consequence is that the whole visual scene shrinks in apparent angular size, yielding a so called *perceptual minification*. Roscoe (1991) states that *'because of the adverse effects of virtual images on eye accommodation, as well as the optical minification and poor image quality typically associated with sensor-generated displays, our judgements of spatial relations are simply not good enough to support complex flight missions as safely or effectively as we need'*. One might try to compensate for the perceptual minification, but the large individual differences limit the overall gain which can be achieved. On the other hand, the inability of complete veridical perception of the spatial layout of the environment from synthetically presented data does not mean that the concept of spatial data presentation for the navigation task is not to be pursued. As discussed earlier, the presentation of spatially integrated data has many advantages. The arguments presented by Roscoe (1991) emphasize the need to distinguish between task elements which require true veridical perception of the synthetically presented environment, and task elements which benefit from a spatial presentation but do not require complete veridical perception. In Sect. 5.4.3 it was pointed out that '*when using spatially integrated data presentation one should distinguish between the need for veridical perception of the spatial layout and the goal of reducing the required effort for integration and interpretation of the displayed data. The latter requirement is much easier to satisfy than the former one and allows much more trade-offs to be made*'.

The previous discussion illustrates that display media such as a HUD or a HMD impose additional requirements. When implementing a perspective flightpath display format which performed well on a head down display (HDD) for presentation on a HUD or a HMD, it is important to understand the potential causes for problems.

Thus, the question whether a perspective flightpath display can be presented on a HUD should be changed into the question *whether*, and if so, *how much* the design constraints imposed by the display medium influence the possibility of a display format to satisfy the task requirements which governed its design.

5.13 Summary

In Fig. 1.2, an overview of the systems involved in the presentation of navigation data was presented. For the presentation of a perspective flightpath, the desired format and functionality must be specified. In this chapter, the specification of these rules has been discussed in the context of the task requirements presented in Ch. 2, the properties of the visual cues presented in Ch.3, and the potential control strategies presented in Ch. 4. In this section, the important conclusions from this chapter are summarized to provide the designer with a set of guidelines to the specification of the representation, selection, and transform rules.

General:

- When using spatially integrated data presentation, one should distinguish between the need for veridical perception of the spatial layout and the goal of reducing the required effort for integration and interpretation of the displayed data. The latter requirement is much easier to satisfy than the former one and allows much more trade-offs to be made.
- Results from previous research and from the evaluations which will be discussed in Sect. 7.2 indicate, that with an egocentric perspective flightpath display the cues resulting from the velocity streamers provide adequate information to resolve ambiguities in the representation of the flightpath. Results from other research into pathway displays suggest that tracking performance cannot significantly be improved through a stereo presentation.
- For the specification of the display size, the angular compression should be used as a criterium. The maximum allowable angular compression follows from stability and guidance requirements, which dictate thresholds with respect to the minimum perceivable display motion. When the physical limitations in display size dictate an angular compression which exceeds the maximum allowable angular compression, presentation of predictive data can be used to compensate for the reduction in stability.

Frame of reference:

- When a task involves some kind of spatial control, a spatially integrated presentation of the data in a suitable frame of reference can be used to minimize required mental integrations and rotations.
- While exocentric reference frames are more beneficial for threat-detection and traffic avoidance

tasks (Ellis et al., 1987), egocentric reference frames appear to be better for the aircraft guidance task.

- To exploit the symmetry of the flightpath as an emergent feature, an egocentric frame of reference must be selected.
- To present aircraft orientation as dominant cues, an egocentric inside-out frame of reference is needed.
- When using an egocentric display for the guidance task, a satisfactory level of global and navigational awareness calls for the use of an additional, exocentric view of the situation.
- A velocity vector aligned format is only advisable when the flight control system takes care of the inner-loop stabilization

Field of view:

- For a head down display, the selection of the field of view is not constrained by conformality requirements. As a result, it can be selected based on requirements with respect to the track angle error gain and constraints with respect to requirements concerning the minimum visible pitch attitude range and the maximum allowable perspective distortion.
- In case accurate judgements of location in terms of azimuth and elevation are required, additional metrical aids can be integrated to compensate for the effect of angular compression. If, as a result of a too limited field of view no adequate damping cues are available, predictive symbology can be used to restore these cues.

Representation:

- The representation should be designed so, that it is perceived as an object, not as a collection of elements.
- To exploit symmetry as an emergent feature, the representation should be symmetrical about the horizontal and vertical axis.
- To provide cues for resolving ambiguity and allowing the perception of temporal range information, cross section frames should be included. Since the magnitude of the cues reduces with increasing distance from the viewpoint, cross section frames are no longer needed beyond a certain viewing distance.
- To exploit the capability of humans to accurately judge horizontalness and verticalness, the cross section should contain horizontal and vertical elements.
- To allow the direct perception of perspective splay angle, interconnections between the cross sections should be used.

- To provide cues which allow the temporary use of an error gain which is independent of tunnel size, the cross sections should contain an indication of their center.
- To increase velocity cuing, these interconnections can consist of line segments which must be equally spaced in 3-D to yield correct edge rate and flow rate cues.
- The level of detail of the representation of objects should be high enough to allow spontaneous recognition. The representation should be consistent between different displays, and allow the manipulation of certain attributes to attract the pilot's attention.

Design parameters:

- The selection of the dimensions of the tunnel should be based on requirements with respect to the maximum allowable flight technical error.
- When using solid tunnel lines, the frame spacing must be selected so that sufficient velocity cues are conveyed. The frame spacing ratio can be used to compare between different design options.

Augmentation:

- In an attitude aligned frame of reference, a direct indication of the direction of travel should be included.
- A presentation of the predicted future position can be used to increase tracking performance.
- When using a perspective flightpath display in combination with a flight control system which allows the pilot to directly control flightpath angle rate, the presentation of the commanded flightpath angle might be required.

Data requirements:

- In case the data from the position and attitude determination systems do not meet the update-rate requirements needed to produce a smoothly animated picture, extrapolation might be used to artificially increase the update-rate. At the moment, not enough data is available to provide detailed guidelines for the development of position data predictors and filters to meet perceptual requirements. A worst case approach would be to apply the same criteria as used for the inner-loop stabilization task, but this might result in overkill.

This chapter discussed the design decisions that must be made. In the previous chapter the potential control strategies which are possible with a perspective flightpath display were discussed. It is evident that the possibility to successfully apply a certain control strategy depends on the specific design of the display format and the magnitude of the design parameters.

As a result of the enormous freedom in the design and the resulting control strategies which can be applied, a comparison between a certain flight director and a certain perspective flightpath display in terms of tracking performance can not produce any generalizable results.

In the next chapter, an implementation will be discussed. This implementation will provide the opportunity to vary many of the design aspects discussed in this chapter and allow an evaluation of the different options. Not all design aspects can be varied, however, and therefore certain choices must be made. These choices will be discussed in the context of the guidelines developed in this chapter.

6 IMPLEMENTATION

There are no perfect designs, only perfect critics.

6.1 Introduction

By taking into account the aspects discussed in Chs 3 and 4, a more structured approach to the initial specification of design guidelines for a man-machine interface (MMI) for 4-D navigation based on the concept of spatially integrated trajectory preview is possible. Ch. 5 discussed specific design aspects in the context of task requirements, available visual cues and potential control strategies. To validate assumptions made in the previous chapters and to increase the level of detail of the design guidelines, pilot-in-the-loop experiments must be conducted. This requires an implementation of the MMI. The level of detail of the implementation must be careful selected in order not to drastically limit the generalizability of the results. The implementation should contain the essential features which have previously been identified as requirements to improve safety. It was decided that first the basic format and functionality would be established in an early prototype, which is later expanded, integrated and refined. The basic functionality was to be used for early operational demonstrations and experiments in order to elicit feedback from domain experts in the early development phase. Rather than presenting the design process in a veridical sequence yielding a description of several stages of modifications and evaluations, this chapter discusses the design decisions and their justification regarding format and functionality, whereas the next chapter discusses the evaluations and experiments which were performed.

A fundamental requirement to succeed in a rather limited time frame, is the ability to provide rapid feedback of the effects of changes in the design specification. To maximize flexibility throughout the research program, the concept had to be implemented in such a way that almost all features of the format can be modified in a very convenient way. This comprises the frame of reference, the viewing volume, the representation of the flightpath, the display augmentation symbology, and the presence and representation of additional instruments for velocity, altitude, vertical speed, heading and roll angle. Due to the overall complexity, incomplete initial specification of the requirements, and the potentially high frequency of changes in design requirements, software development, integration, and maintenance can pose a serious bottleneck. For efficient integrated system design these problems must be recognized and dealt with. Rapid prototyping was used to speed up the process of acquiring complete initial specifications. To be able to smoothly proceed beyond the prototyping phase, computer support was used at all design phases, allowing the transitions between these phases to be computer mediated. Hardware dependent and hardware independent mechanisms were separated, and a hardware dependent rule-base was used for optimization. For more detailed information about the approach which was used to translate specifications of format and functionality into an implementation, the reader is referred to Theunissen (1993, 1994b, 1994c). In this chapter, the design goals will be presented and the format and functionality which have been specified and implemented to meet these goals will be discussed.

6.2 Goals and approach

The requirement which has been presented in Sect. 2.9 and resulted in the selection of the concept of the perspective flightpath display was:

> For the safe execution of complex 4-D navigation procedures, a MMI is needed which can be used both for supervisory and manual control, while achieving desired task performance in a way which minimizes cognitive load and maximizes navigational awareness.

Based on the design guidelines for a perspective flightpath display which were developed in Ch. 5, Sect. 6.3 discusses the elements in the display format which provide the required information to satisfy this goal. Sect. 6.3.8 discusses the integration of traffic and terrain data. With respect to mode errors, it was indicated in Sect. 2.5 that safety can be increased by improving the feedback on the forcing function used by the automatic flight control system (AFCS). This allows a better detection of erroneous settings on the mode control panel (MCP). In Sect. 6.4 an application will be discussed in which the feedback from settings on the MCP is provided by depicting the resulting forcing function as a perspective flightpath.

6.3 Basic display

In this section, the basic display format will be discussed. Each subsection focuses on a particular design aspect.

6.3.1 Frame of reference

In Sect. 3.5.1 it was pointed out that '*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*'. In Sect. 3.4 it was pointed out that '*any other frame of reference* *than an egocentric one cannot exploit this advantage, and will require additional mental processing'*. In Ch. 4 intermittent control strategies comprising closed-loop, anticipatory and error-neglecting control were identified as alternatives to continuous closed-loop compensatory. It was concluded that the variety of control strategies which can be applied allows the pilot to better distribute his resources. Furthermore, it was concluded that *'efficient anticipatory and error-neglecting control is only possible with an egocentric perspective flightpath display'*. Due to the advantages of an egocentric frame of reference, it was decided to pursue an approach in which the PFD presents an egocentric perspective flightpath. As indicated in Sect. 2.7, the integrated trajectory preview with which the pilot is continuously confronted should allow him to better optimize his scan pattern. In Sect. 5.3.1 it was concluded that *'when using an egocentric frame of reference, a satisfactory level of global and navigational awareness calls for the use of an additional, exocentric view of the situation*'. It was also indicated that in order to place detected events in a global context, the pilot is required to maintain a cognitive link between the PFD and the navigation display. The integrated presentation of the trajectory on the PFD increases the possibility to maintain a high degree of cognitive coupling between the PFD and the navigation display.

In Sec. 5.3.2 the differences between an inside-out and an outside-in frame of reference were discussed. Both options can be selected, and to illustrate the typical difference between them, snapshots of the display are included (Figs. 6.19 to 6.22). These snapshots were taken in a situation in which the aircraft rolls and in a situation in which the aircraft has a rather high pitch angle.

In Secs 3.5 and 3.6 the differences in the static and dynamic aspects of the visual cues between an attitude aligned and a velocity vector aligned frame of reference were discussed. It was pointed out that *'control task requirements should be taken into account since the frame of reference determines whether the dominant visual cues convey orientation or directional information'*. The concept was implemented so that the frame of reference could be selected. In Sect. 7.5 an experiment, which was performed to gain more insight into these differences, will be discussed.

6.3.2 Representation of the flightpath

The first design decision is the representation of the flightpath. As discussed in Sect. 3.1, the basic requirement of the presentation is that it evokes holistic perception. In Sect. 5.5 various options to satisfy this requirement were discussed, and to evaluate different options it was decided that the implementation should support the variation of cross section shape, altitude poles, interconnections and ground track. The basic representation uses squares to indicate the cross sections, which are interconnected by continuous lines. In this way, all spatial constraints are represented. In Sect. 7.2 the evaluation, which resulted in a representation of the tunnel by interconnected boxes on altitude poles, will be discussed.

The representation is also determined by frame spacing, tunnel size, and field of view. As indicated in Sect. 3.6.3, frame spacing determines the amount of edge-rate cues and provides an increased feeling of three-dimensionality due to the apparent acceleration towards the observer. Eq. (5.4) presented the relative size of the tunnel frames as a function of the ratio between frame-spacing and tunnel size, the distance from the viewplane, and the geometric field of view. With a geometric field of view of 52.3 degrees, the term *2· tan(FOV/2)* is approximately equal to 1 and Eq. (5.4) changes into:

$$R_f = \frac{1+(f+1)\cdot n}{1+fn}. \qquad \textbf{(6.1)}$$

In this equation, n represents the ratio of frame-spacing and tunnel size, and f refers to the frame number. Figs 6.1 to 6.3 present tunnels for n=5, 10, and 20, respectively.

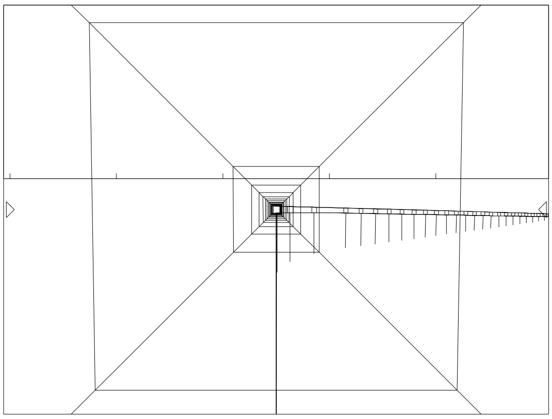


Fig. 6.1. *Frame-spacing based on length to width ratio of 5.*

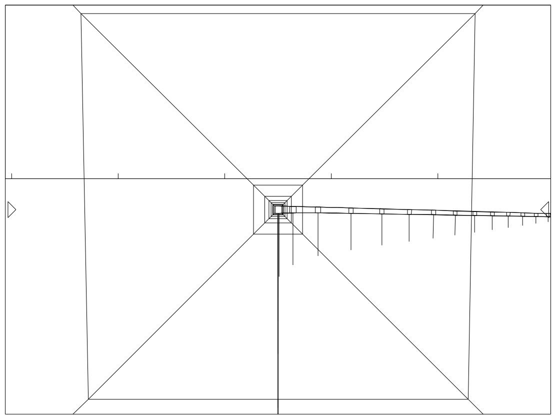


Fig. 6.2. *Frame-spacing based on length to width ratio of 10.*

For the basic implementation, a value of 10 was selected for n, yielding a spacing of 450 m. Tunnel size is inversely proportional to splay rate gain, and field of view is inversely proportional to the gain with which orientation errors are presented. As discussed in Sect. 5.4, the range over which the field of view can be varied is quite limited due to constraints following from angular range and resolution, and perspective distortion. Tunnel size on the other hand is not related to these requirements. In Sect. 5.6.1 it was pointed out that since it is assumed that splay rate is the functional variable for

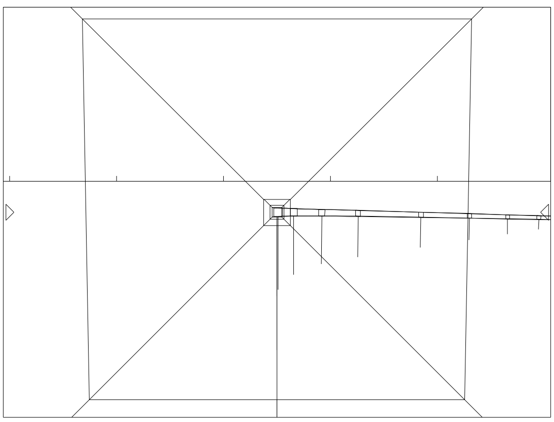


Fig. 6.3. *Frame-spacing based on length to width ratio of 20.*

position control, a range of values for tunnel size should exist in which an equal-ratio improvement in splay rate gain produces an equal-interval improvement in performance. An important factor influencing this range are the aircraft dynamics. The argument that meaningful tolerance indications provide adequate guidance cues for precision control resulted in a selection of a basic tunnel width of 45 m being equal to the runway width. It was decided that this would be the reference condition in an experiment in which tunnel size was going to be varied to study the influence on tracking performance and control behavior. A vertical field of view of 40 degrees was selected to provide the pilot with a pitch attitude range similar to most PFD formats. The relative screen dimensions dictated a horizontal field of view of 4/3 times the vertical field of view, yielding a maximum perspective distortion (Sect. 5.4.1) of 1.1. With a velocity of 120 kts this combination of tunnel size, and field of view yields an average value for TTP_{min} of 0.74 seconds. During flight the velocity will be at least 120 kts, and thus in most cases the average value of TTP_{min} is smaller than 0.74 seconds. Based on the findings of Kaiser and Mowafy (1993) it is expected that this is adequate for anticipatory control.

Due to memory and processing limitations of the graphics hardware, no continuous intensity modulation of the tunnel lines is used (Sect. 5.8). Instead, the intensity of the tunnel lines is reduced beyond a certain viewing distance.

6.3.3 Spatial awareness aids

To increase the ability of the pilot to obtain a certain level of quantitative spatial awareness, additional metrical aids have been integrated. A horizon line with a numerical heading scale (Fig. 6.4) allows the pilot to establish an absolute relation between his ERF and the WRF (Sect. 2.4.2). The heading tape is positioned on the real horizon, so the H-angle (Sect. 5.10.1) is directly visible.

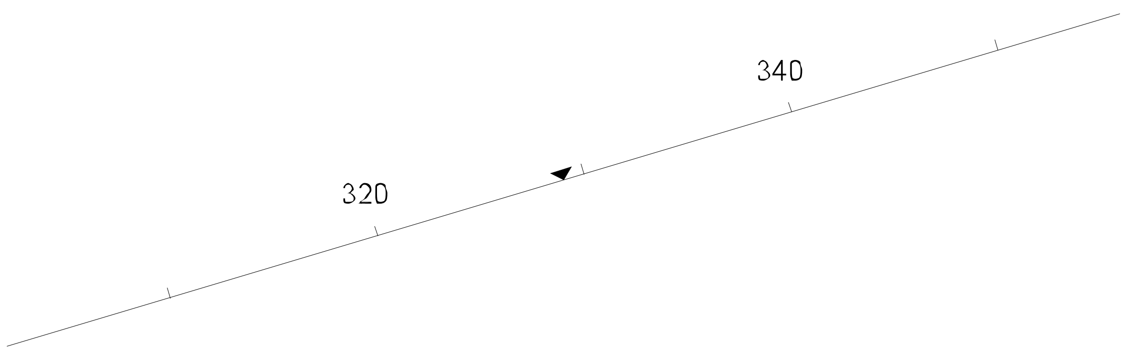
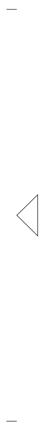


Fig. 6.4. *Artificial horizon with a numerical heading scale. The triangle points at the actual heading.*

To increase the accuracy with which the roll angle can be estimated, a roll pointer and scale (Fig. 6.5) are presented at the top of the display. Furthermore, a digital representation of pitch angle is



indicators with electronically generated representations which were integrated into an advanced flight display via moving-tape formats. They report that pilots preferred the presentation of information with the moving-tape formats, but that a higher workload was noted. They hypothesize that this was caused by the increase in resolution with which the data was presented, causing pilots to correct for smaller errors. They also investigated the addition of trend information and report that although performance data shows an increase in performance, subject opinion did not reflect this result. Konicke (1988) presents the development process of the 747-400 PFD display format in which the option of round dial instruments was investigated but rejected in favor of vertical tape displays. One of the conclusions which followed from the evaluation of the different representations was that *'the results of the 747-400 PFD development cycle suggest that the actual design of individual instruments has a larger impact on its utility than does the physical shape of the instrument. In addition, the actual designer of a cluster of instruments and their relationship to one another has a larger impact on the utility of the entire cluster than does the shape of the individual instruments within the cluster'*. Investigating the influence of the representation was not a goal of the current research program and both vertical tape displays and round dial instruments have been implemented for demonstration purposes.

6.3.5 Additional guidance symbology

Oliver (1986) argues that a direct indication of flightpath integrated with airspeed and altitude enhances the pilot's ability to judiciously trade between airspeed and altitude in order to achieve the optimal flightpath when confronted with windshear. He states that *'by their very design, the conventional instruments mounted in commercial cockpits today are incapable of providing the information necessary to enable a pilot to recognize the onset of a microburst early enough or to fly an optimum flightpath thereafter'*. To aid the pilot in determining vehicle direction, a flightpath vector (FPV) can be presented. The symbol consists of a circle with wings and surfaces at the end of the wings (Fig. 6.11).

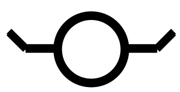
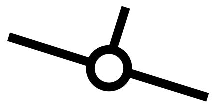


Fig. 6.11. *Flightpath vector symbol.*

This symbol indicates the current direction of the velocity vector of the aircraft relative to the aircraft attitude symbol. As a result, the center of optic outflow has not to be determined from the dynamic scene. Because a flightpath vector presents raw data, it is classified as unprocessed status information. During the evaluation of the FPV, some pilots acted as though the FPV indicated a future position rather than the direction of flight, which resulted in shortcutting the curves. Some pilots commented that the FPV should take lateral acceleration into account to prevent this problem. To do this, however, it is necessary to apply a certain weighting to the acceleration component which is equal to selecting an integration time and yields a second-order position predictor.



6.3.7 4-D cuing

In Sect. 2.1 it was indicated that for the safe and economical execution of the navigation task, airspeed must be maintained at an optimum value. To remain within the 4-D constraints of the flight plan, which is necessarily earth-referenced, ground speed must be maintained within certain constraints. Additional cues are needed to provide the pilot with information about his performance with respect to both airspeed and ground speed requirements. Preview is needed to allow the pilot to anticipate situations in which a conflict between these two requirements occurs. Thus, the control function is to maintain airspeed at the optimum value and use information about the performance in the fourth dimension to determine whether changing requirements can be met by changes in airspeed or require a partial replanning. In Sect. 5.5.3, two different approaches were described to integrate a reference velocity. Several implementations of perspective flightpath displays employed a so-called lead-plane with which the pilot had to stay in formation. This metaphor is more typical for military than for commercial applications. In Sect. 6.3.3 the reasons for including an airspeed indicator were discussed. Since the scale of this indicator serves as the reference, the commanded speed is also integrated on the scale and presented by means of a bug (Fig. 6.13, #3). The position constraints following from the fourth dimension can be spatially integrated. Due to the egocentric presentation, not all constraints are visible, and a depiction on an exocentric presentation is needed to provide the complete picture. The combination of an indication of the optimal airspeed and the temporal position constraints should provide the pilot with the information needed to determine whether some kind of action is required. Such an action can vary from deviating from the optimal airspeed to satisfy 4-D constraints to a renegotiation of the spatial/temporal constraints. Additional functionality is needed to translate different options into resulting cost, thus aiding the pilot with decision making.

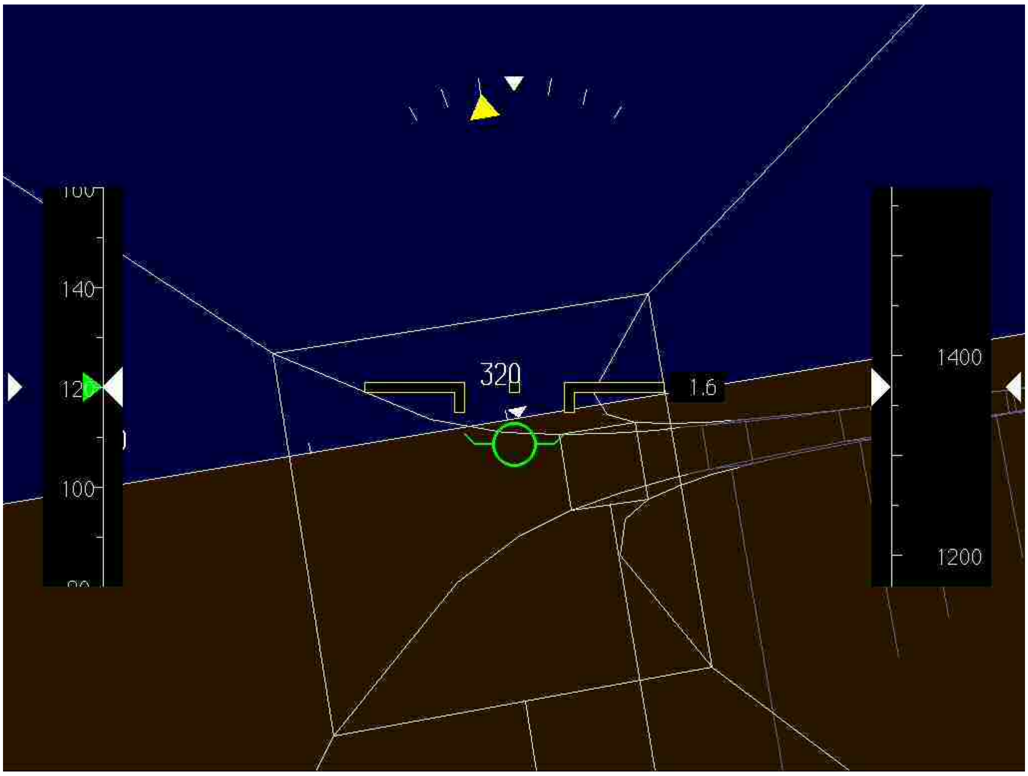


Fig. 6.14. *Basic display format in the flightpath vector configuration with tape instruments for the presentation of altitude and velocity. The symbology is explained in Fig. 6.13.*

Fig. 6.15. *Basic display format in the flightpath vector configuration with dial instruments for the presentation of altitude and velocity.*

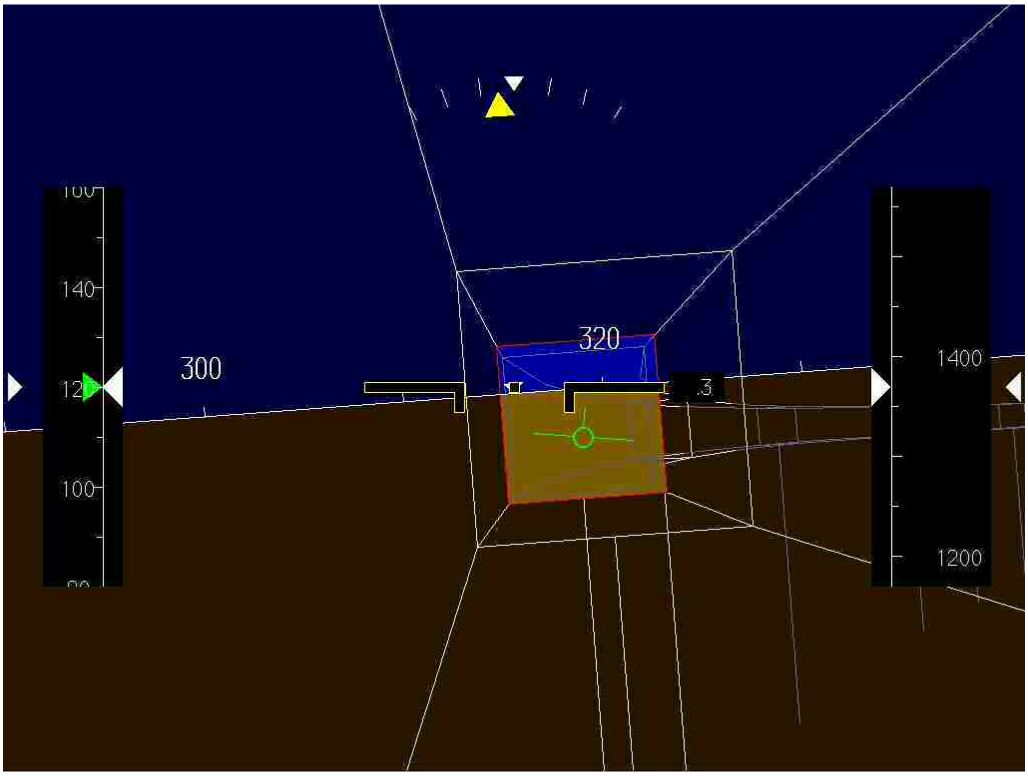


Fig. 6.16. *Perspective flightpath display with a position predictor. The predictor symbology is explained in Fig. 6.17.*

To illustrate the typical differences between an inside-out and an outside-in frame of reference, Fig. 6.19 shows an inside-out version of the display format for a situation in which the roll angle is approximately 17 degrees and Fig. 6.20 shows this situation for an outside-in frame of reference. Fig. 6.21 shows an inside-out version when the pitch angle is 10 degrees, and Fig. 6.22 shows the same situation for an outside-in frame of reference. Note that with the inside-out frame of reference, only the position and attitude of the horizon relative to the display is needed to extract attitude information. With the outside-in frame of reference, the position and orientation of the aircraft symbol must be used.

6.3.8 Depiction of traffic and terrain

In Sect. 2.5.2 it was indicated that by integrating trajectory preview with data about constraints, errors resulting from the planning process which do not satisfy the constraints can be detected. By presenting terrain information, errors in the forcing function which yield an intersection with terrain either caused by erroneous MCP settings or erroneous ATC vectors, can be detected. 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. In Sect. 2.5.3 it was indicated that spatial presentation of other traffic reduced reaction time and increased the use of the vertical dimension to execute avoidance maneuvers. A depiction of traffic can be selected. It is presented by aircraft symbols, similar to the symbology used by Ellis et al. (1987) in their perspective cockpit display of traffic information (CDTI) studies. Each aircraft is displayed on top of a color coded altitude pole. To attract the pilot’s attention in case of an imminent threat, 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 above 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.

6.3.9 Navigation display for global awareness

The use of a navigation display to maintain global awareness introduces the question whether this display should employ planar or spatial data presentation. A plan view display of the situation, with metrical aids to quantify distance and angle, presents the information in such a way that no ambiguities are introduced, and the resolution of the information is equal for the complete trajectory. To increase navigation awareness in the vertical dimension, a vertical profile display (Fig. 2.5) can be used. With an exocentric perspective display the resolution of the information suffers from the integration of more than two dimensions, but may still be enough to supply the pilot with the information required to achieve and maintain an adequate level of navigational awareness. To establish more accurate values of spatial awareness related variables, metrical aids such as a heading tape or an altitude tape can be integrated. Way et al. (1984) discuss the development and evaluation of an exocentric perspective flightpath display, referred to as a vertical situation display (VSD), in which the viewpoint is located 6000 feet behind and 1000 feet above the aircraft. This display format included terrain information and other potential threats. Prevett and Wickens (1994) also evaluated various exocentric presentations. In Way's approach an egocentric presentation of the future trajectory was presented on the HUD for aircraft guidance and the VSD served to provide global awareness. Prevett and Wickens tried to find an exocentric frame of reference which satisfies both guidance and global awareness requirements. With the exocentric perspective presentation, the absence of compelling dynamic perspective cues reduces the three-dimensionality, which might necessitate some form of compensation to resolve ambiguities. An example of a 2-D navigation display was presented in Sect. 2.6. Fig. 6.18 presents an example of an exocentric perspective flightpath display. Both presentation methods have their advantages and disadvantages, and further research is needed to determine which concept is best suited for achieving the required level of global awareness in all spatial dimensions.

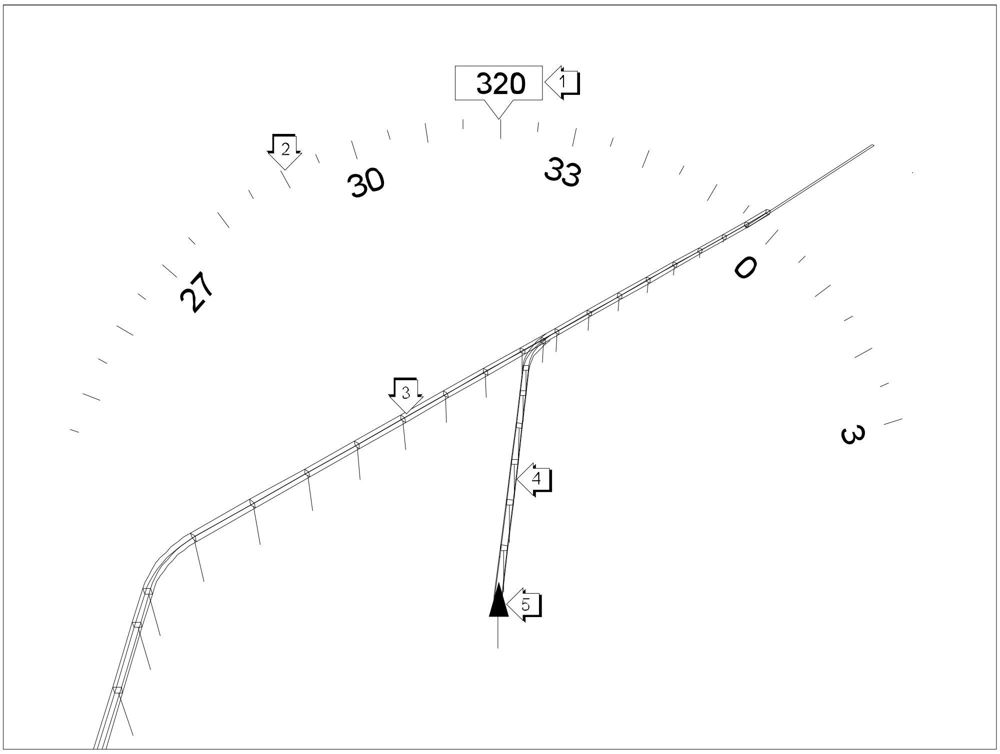


Fig. 6.18. *Example of an exocentric view to better support navigation awareness.*

1. *Actual heading indicator.*
2. *Moving heading scale.*
3. *Standard approach path.*
4. *Intercept tunnel.*
5. *Symbol indicating current position of the aircraft .*

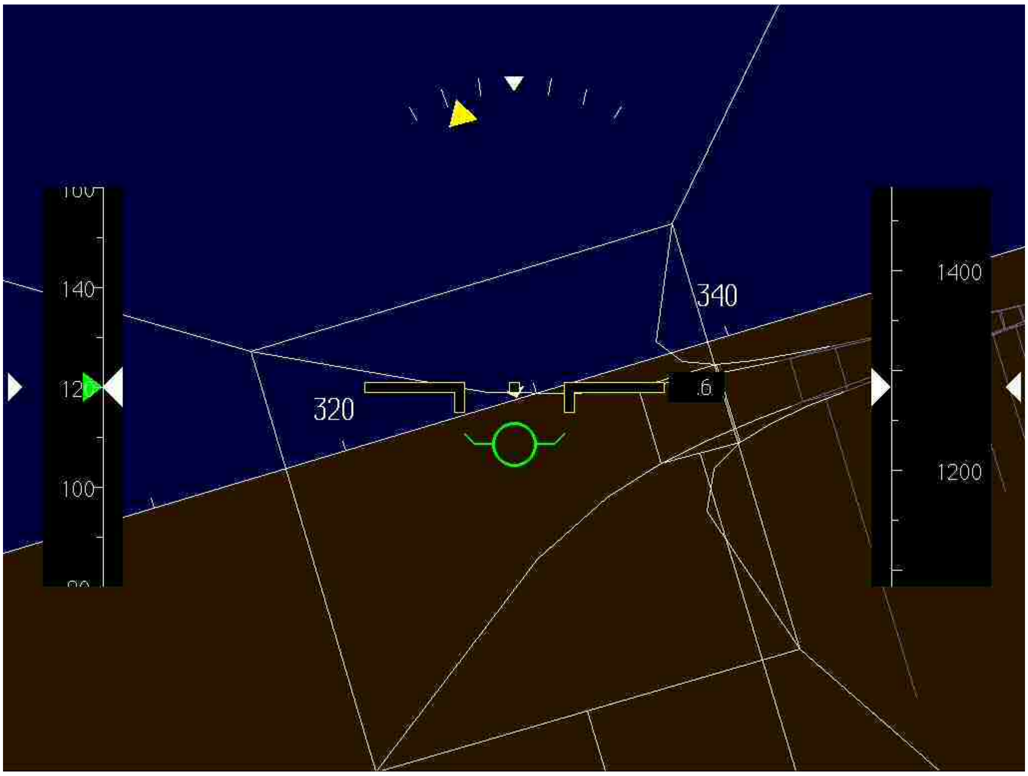


Fig. 6.19. *Inside-out version of the display format presented in Fig. 6.14 for a situation in which the roll angle is approximately 17 degrees.*

Fig. 6.20. *Outside-in version of the display format presented in Fig. 6.14 for a situation in which the roll angle is approximately 17 degrees.*

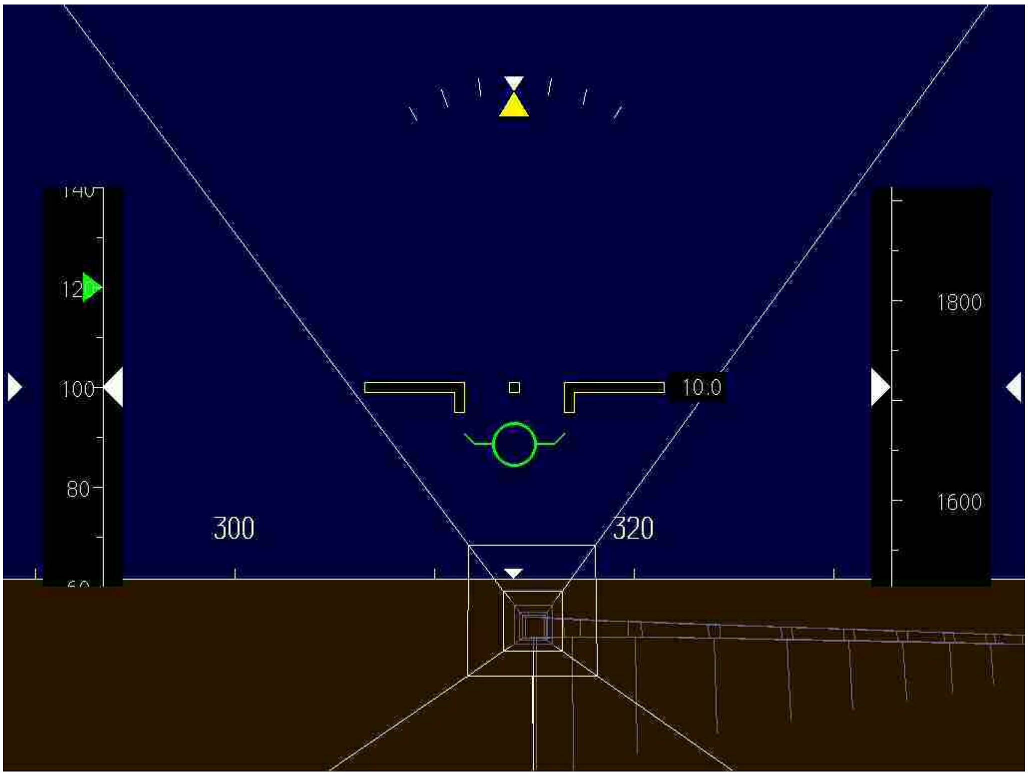


Fig. 6.21. *Inside-out version of the display format presented in Fig. 6.14 for a situation in which the pitch angle is 10 degrees.*

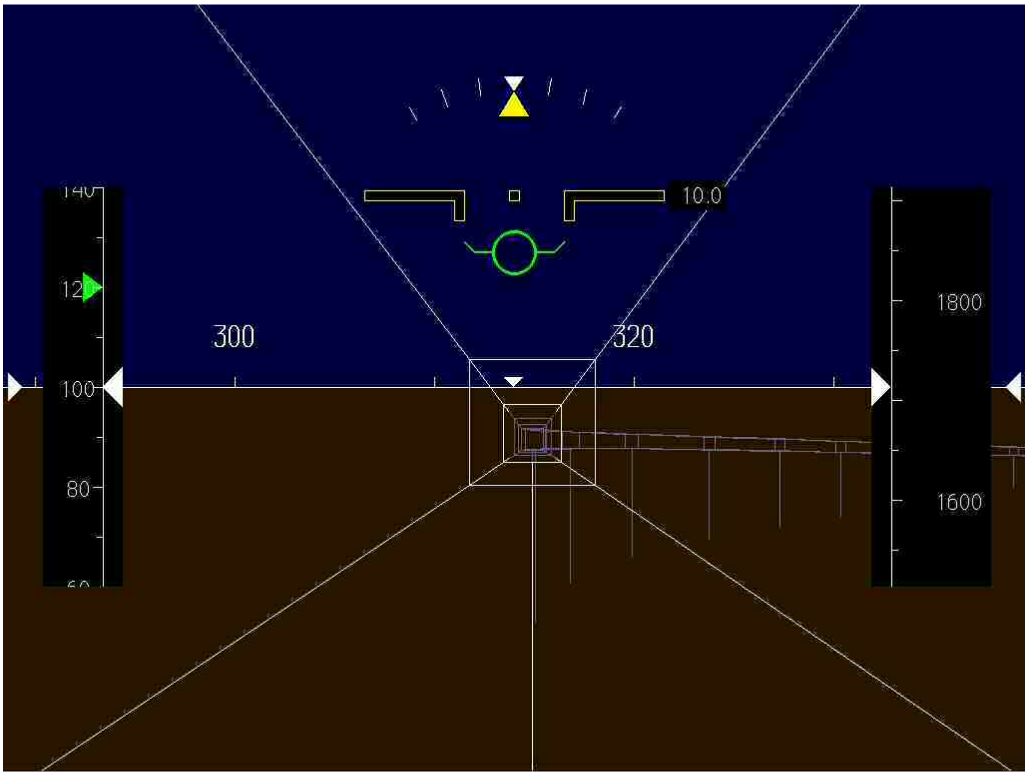


Fig. 6.22. *Outside-in version of the display format presented in Fig. 6.14 for a situation in which the pitch angle is 10 degrees.*

6.4 Adding functionality

6.4.1 Introduction

Whereas the previous design aspects focused on skill-based manual control and supervisory control, the presentation of spatially integrated trajectory preview also has merit for other tasks in which communication between the navigation system and the pilot is needed. Fig. 2.2 presented a risk tree showing the different factors which can cause a navigation accident. It was concluded that a potential improvement to increase safety can be achieved through a better presentation of the autopilot's goals and constraints. By presenting the forcing function which will be used by the autopilot, the possibility to detect errors in the forcing function increases. Furthermore, when generating a forcing function through the mode-control panel, an easy-to-comprehend representation of the forcing function reduces task demanding load. Fig. 1.2 presented an overview of the systems involved in the presentation of navigation data. This figure distinguished between systems involved in data management and systems involved in data presentation. Until now, the focus had been on the different aspects of data presentation based on an existing forcing function. In this section, the focus lies on the generation of the forcing function. In Secs 1.1 and 2.1 the concept of free flight, which permits pilots to select their own flightpaths in real-time was discussed. A fundamental requirement to increase flexibility is that the pilot is able to efficiently communicate his intents/goals both to the navigation system and to ATC.

6.4.2 Generating a forcing function

In the current situation, ATC provides the pilot with 2-D and 1-D vectoring by presenting desired heading, velocity and flight level. The pilot has two ways to communicate his intents to the navigation system. He can either enter a set of desired waypoints through the CDU, or use the MCP to select a desired state. The former method is quite time-consuming and can hardly be used in the terminal area. The MCP allows the pilot to separately enter a number of goals which together must yield the desired future system state. Examples of these goals are capturing and maintaining a pilot-selected heading, altitude or vertical speed. A fundamental requirement for safe operation is the ability to inspect and verify the goals as perceived by the navigation system and to verify the viability of the strategy to achieve these goals. In Secs 2.5.1 and 2.5.2 it was indicated that there is an opportunity to increase safety by improving feedback on the forcing function used by the AFCS. The lack of direct spatial feedback about the consequence of a set of combined actions makes it very hard to utilize the MCP to achieve a desired result like intercepting a certain point in 3-D space. On current flight decks no adequate feedback is available which allows the pilot to communicate his (three-dimensional) goals in a more intuitive way. An improvement in the interaction between the pilot and the guidance and navigation system can be achieved by improving the feedback on the result of the MCP settings and introducing functionality which reduces the number of actions which must be taken by the pilot.

6.4.3 Improving feedback

Ballas (1991) describes the development of an MMI for tactical aircraft operations and points out that *'semantic distance is reduced if the interface presents the information in a form identical to how the pilot is thinking about it. Because the domain is fundamentally spatial and includes objects of tactical importance, a graphical representation with icons symbolic of the tactical objects should minimize semantic distance'*. Shneiderman (1982) coined the term *direct manipulation* to describe user interfaces exhibiting the following characteristics:

- Continuous representation of the objects of interest.
- Physical actions or labeled button presses instead of complex syntax and command names.
- Rapid incremental reversible operations whose impacts on the object of interest are immediately visible.

MMI's providing direct manipulation have the potential to improve the interaction between the pilot and the guidance and navigation system. Hutchins et al. (1986) indicate this advantage of direct manipulation as follows: *'The promise of direct manipulation is that instead of an abstract computational medium, all the "programming" is done graphically, in a form that matches the way one thinks about the problem'*. Pawlowski and Mitchell (1991) present a number of MMI design guidelines regarding direct manipulation interfaces for supervisory control.

For the task of generating a new forcing function by selecting and setting the parameters describing it, feedback can be improved by directly visualizing the forcing function as a command path while the parameters describing it are being set. The forcing function can be visualized on the primary flight display and on the navigation display. The command path makes the abstract visible by presenting the predicted results of a certain selection of separate goals in an integrated fashion. As a result of this instantaneous feedback, the interactivity increases. Color coding can be used to indicate conditions which require a change in thrust to maintain the desired airspeed.

6.4.4 Application

The concept for short term guidance towards another forcing function is based on a selection of the future position by indicating the direction towards a reference. By indicating the desired intercept location, the pilot commands the FMS to generate a forcing function from the current position in the desired direction towards the reference. The visualization of this forcing function is referred to as an *intercept tunnel*. Fig. 6.23 presents an example of an intercept tunnel towards an ILS approach path, Fig. 6.24 presents an exocentric view of the same situation, and Fig. 6.25 explains the additional elements used in Figs. 6.23 and 6.24.

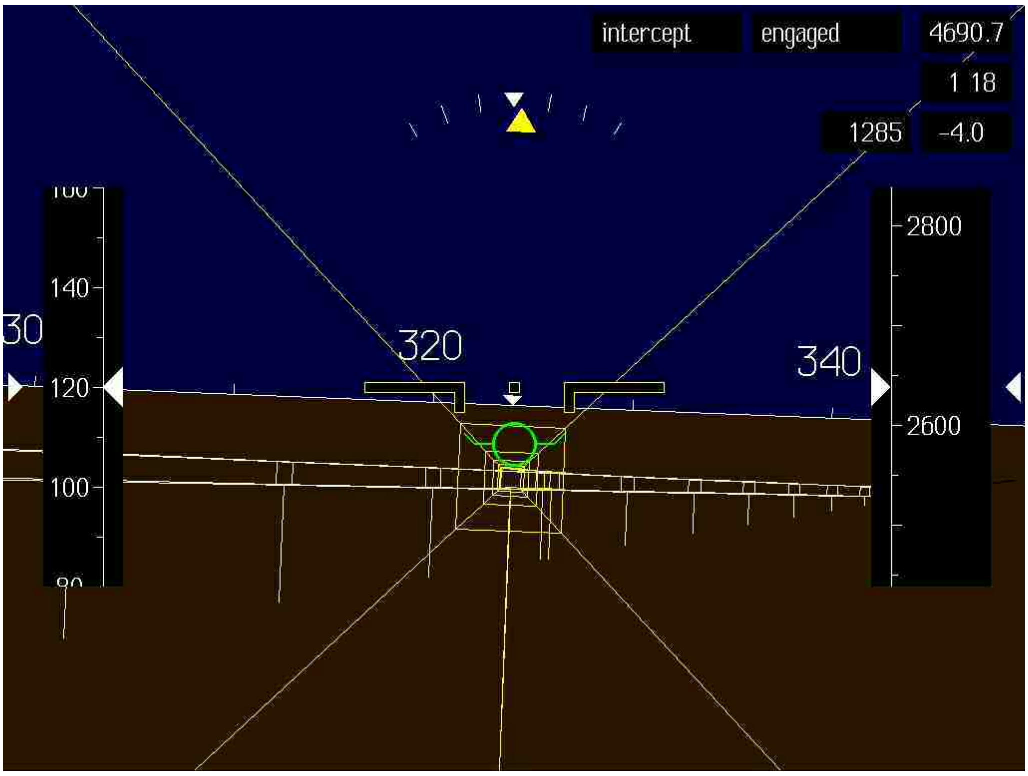


Fig. 6.23. *Intercept tunnel towards the approach path. The symbology is explained in Fig. 6.25.*

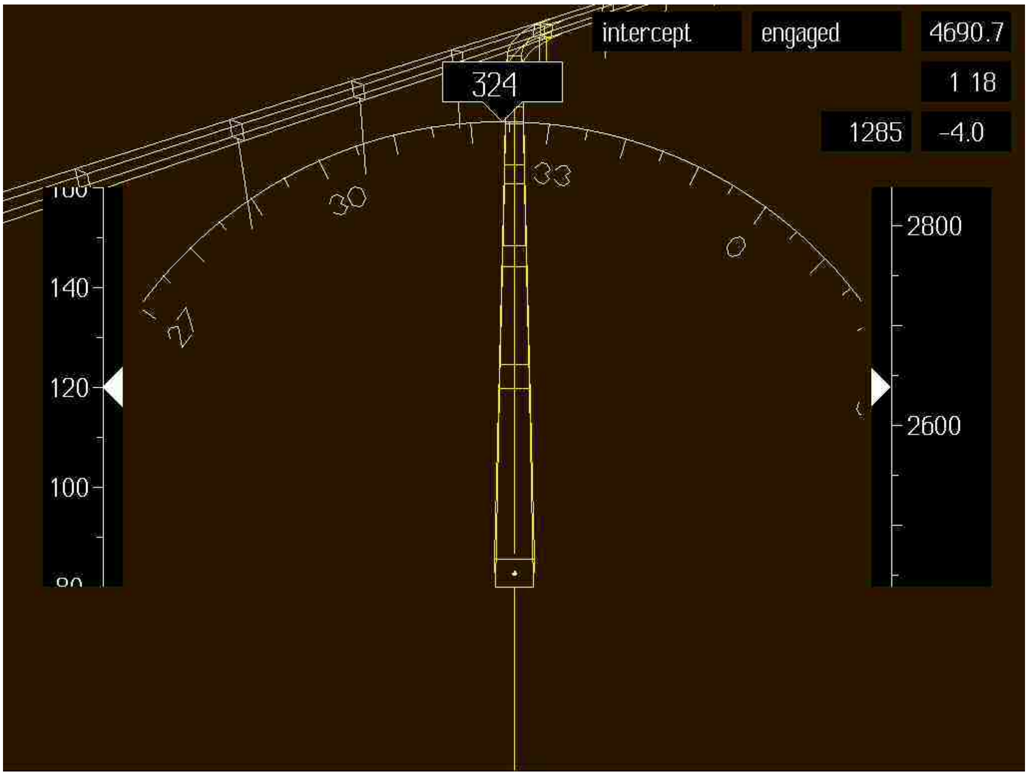


Fig. 6.24. *Exocentric view of the intercept tunnel presented in Fig. 6.23.*

6.5 Other applications

6.5.1 Taxi guidance

Besides presenting navigation information to fly from origin to destination, the concept of spatially integrated trajectory preview has merit for presenting the pilot with the data which is required to reach the desired gate after the aircraft has successfully completed its landing. Especially under bad visibility conditions, the lack of adequate information needed to navigate to the desired gate poses a serious bottleneck to airport capacity. Concepts are being investigated in which the pilot is presented with data from millimeter-wave sensors to allow him to navigate towards the desired gate. An example of a taxi guidance system investigated by Rockwell-Collins (1995) presents MMW radar data in a C-scope[8] format. To compensate for the limited spatial resolution of the sensor data, such a format can be enhanced by the presentation of computer generated guidance data in a dimensionally compatible way. The raw data presented by the MMW sensors provides the information which is needed to detect obstacles, whereas the computer generated imagery provides the data needed for guidance. The required information can be divided into a part which is needed to allow the pilot to guide the aircraft along the desired taxiways, and the more global picture which allows him to establish were he is. Due to the much lower velocity of the aircraft on the ground, the magnitude of the dynamic cues is smaller. Additional augmentation by means of a fixed-distance ground track predictor can provide the information about the result of control actions even when the aircraft is not moving. An additional exocentric view can depict the position of the aircraft relative to the complete airport. To obtain a conformal picture, the height of the viewpoint must be equal to the height of the MMW sensors.

6.6 Implementation

6.6.1 Introduction

The implementation requires hardware and software. The software needed to implement the specified MMI can be divided into two parts. One part processes the inputs to the software and uses a set of predefined rules to determine which elements of the MMI must be visualized and how. It generates an abstract representation. Fig. 1.2 presented an overview of the systems involved in the presentation of navigation data. Fig. 5.1 illustrated which elements of the representation and transform rules must be specified. To allow for an investigation into the different possibilities, an implementation must provide the possibility to select between different rules. When using Fig. 5.1 as a reference, Fig. 6.26 presents an overview of the functionality which has been implemented to satisfy this requirement.

[8] A C-scope format displays azimuth angle in the horizontal axis and elevation angle in the vertical axis, resulting in a perspective image that is conformal with normal human vision.

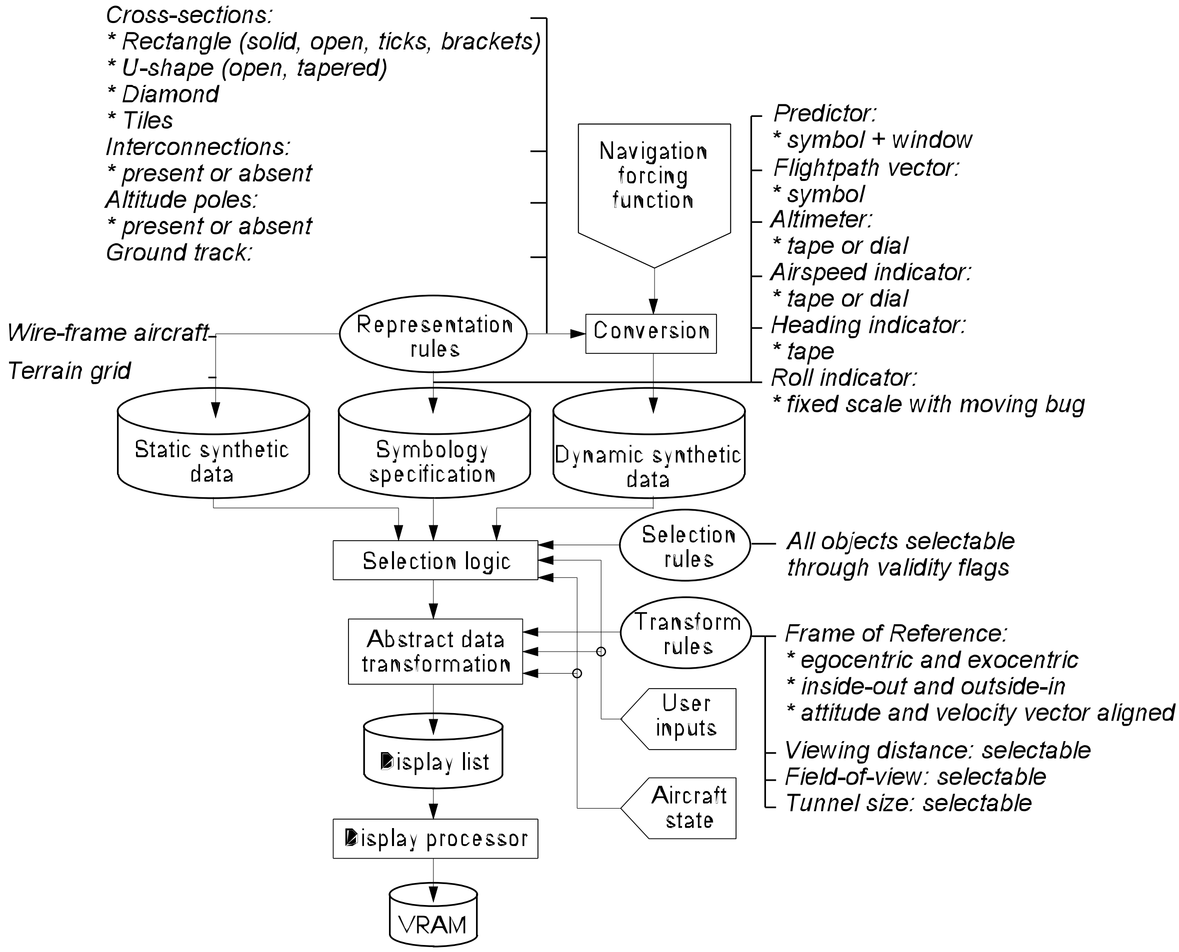


Fig. 6.26. *Overview of the functionality which has been implemented. The user has the possibility to select between different types of representation and transform rules, which allows him to evaluate different design options.*

The first part of the software comprises the implementation of the following three modules:

1. The *conversion* function which translates the navigation forcing function into dynamic synthetic data according to the *representation rules*.

2. The *selection logic* which uses *selection rules*, *user inputs* and *aircraft state* information to select the data which must be visualized.

3. The *abstract data transformation*, which translates, rotates and scales the data based on *transform rules*, *user inputs* and *aircraft state information*.

The second part, represented by the block *display processor*, translates this abstract representation specified in the *display list* into a collection of pixels which together form an image. These two processes are inherently sequential.

6.6.2 Performance requirements

The basic requirement was that the implementation should provide a smoothly animated presentation of the desired display format with acceptable latency. A software development environment should support the rapid implementation of display formats from a specification. In Sect. 3.6.1 it was discussed that when the data update-rate of the display exceeds approximately 10 Hz, the successive snapshot images of the situation yield a sensation of continuous motion. In Sect. 5.11.3, display latency was discussed in the context of inner-loop stability. It was indicated that research results demonstrated that pilots can certainly cope with display latencies up to 300 ms, but that this influences the perceived handling qualities. Display latency is the sum of all system latencies involved between the measurement or simulation of the variable to be presented and the actual presentation. The contribution of the graphics system which translates input variables into a picture is inversely proportional to the update-rate. In case a pipelined architecture is used, latency is proportional to the number of stages in the pipeline divided by the update-rate.

To satisfy basic perceptual requirements, an update-rate of 10 Hz was specified as the absolute minimum. This might yield an undesirable large latency for certain control tasks. However, 10 Hz is the minimum requirement for the anticipated maximum in format complexity. Less complex formats should allow a higher update-rate and thus yield a lower latency. It was anticipated that based on the type of control task for which the display was going to be used, trade-offs could be made to achieve the desired latency.

To be able to present all required data, the display itself must be at least as large as current state-of-the-art EFIS displays, preferably even a bit larger. This, in turn, poses requirements on the resolution of the picture the graphics system is able to generate and the display device can visualize. In 1990, typical EFIS displays had a visible display area of 6.5x6.5", and larger versions of 8x8" were announced. The hybrid raster-stroke techniques used with conventional EFIS displays allow the update-rate of the elements to be varied on an element by element basis, providing some opportunity to optimize overall performance. The huge cost associated with hybrid raster-stroke systems necessitated the use of a raster-only graphics system. The absence of stroke-writing techniques increases the requirements on resolution. Typical graphics systems provided a discrete number of resolutions. It was found that 640x480 pixels would be an acceptable minimum requirement.

6.6.3 Hardware

Research oriented systems are often characterized by highly interactive hardware and software. In the design of such systems it is of crucial importance to integrate software requirements with hardware design synthesis. Due to the rapid increases in performance of computer hardware this is not easy. Plant (1993) refers to the effect of the rapidity of technology changes in the area of information technology as the 'ΔT *effect*'. He states that *'unless management and developers control their software processes through an understanding of the impact that hardware, software, practical and theoretical developments have upon it, these technology changes may have a serious and detrimental effect upon the developers software creation process'*. In recent years, the IBM PC architecture has been flooding into embedded system applications. The main reason is the enormous reduction in cost which can be achieved by using commercial off-the-shelf technology. This development has been recognized by the military avionics industry. Their commercial technology insertion concept (CTI) embraces the use of commercial standards such as laptop PC card-based computers, software translators and real-time operating systems, asynchronous transfer mode networks, and wireless technologies for producing low-cost digital avionics systems (Schiavone, 1996). In the context of the Delft program for hybridized instrumentation and navigation systems, it was decided in 1990 to pursue the development of display systems for simulator and in-flight application based on commercial off-the-shelf technology. App. B briefly discusses software and hardware. A more elaborate discussion can be found in Theunissen (1991, 1993a, 1994b, 1994c).

6.7 Summary

In the previous chapter, guidelines for the specification of format and functionality were developed. This chapter discussed the specification and implementation of a perspective flightpath display based on these guidelines. As indicated in Ch. 1, an initial specification lacks the detail required for a specific implementation. Therefore, an implementation has been generated which provides the possibility to change both the representation and the transform rules. In this way, the various options for the representation can be used to obtain feedback from domain experts and end-users, allowing the level of detail to be increased. Furthermore, some potential improvements for the generation of forcing functions have been proposed, and it was indicated that the perspective presentation of trajectory constraints might be useful for taxi guidance applications.

By performing pilot-in-the-loop studies in which the design parameters are varied, hypothesis about the influence of the design parameters on task performance can be tested. The next chapter will discuss the evaluations in more detail.

7 EVALUATION

7.1 Introduction

In the previous chapter the specification and implementation of a perspective flightpath display have been discussed, and it was indicated that feedback from end-users is required to increase the level of detail. The implementation which was generated allowed the representation rules, transform rules and symbology to be selected from a predefined set. For the representation rules the set included combinations of cross sections, interconnections, altitude poles and a ground track. The additional symbology comprised a flightpath vector and a flightpath predictor. Predefined transform rules comprised different combinations of translations and rotations of the viewpoint to allow the following frames of reference: Egocentric inside-out attitude aligned, egocentric inside-out velocity vector aligned, egocentric outside-in, and exocentric outside-in. Furthermore, the transform rules allow the magnification of the horizontal and vertical tunnel dimensions providing the possibility to change the splay gain.

The evaluation of various representation rules and the inside-out/outside-in transform rules will be discussed in Sect. 7.2. An evaluation of pilot tracking performance and control activity as a function of splay gain, both in the absence and presence of predictive information are discussed in Sect. 7.3. Sect. 7.4 discusses an experiment which was performed to gain more insight into error-neglecting control, and Sect. 7.5 presents the results of a study which investigated the effects of a velocity vector aligned frame of reference. Together, the evaluations provided enough data to specify and implement a version for in-flight testing. This will be discussed in Sect. 7.6.

7.2 Representational aspects

In the previous chapter the general specification of a 4-D navigation display format has been discussed. To gain some practical experience with the concept, a very basic perspective flightpath display format was implemented in a flight-simulator located at the Faculty of Aerospace Engineering of Delft University of Technology. This is a moving base simulator with three degrees

Neither a position predictor nor a flight path vector was presented. Tunnel size was increased and decreased by a factor of two, and the representation was modified by varying the presence of one or more of the following elements: Ground track, altitude poles, interconnections between the frames, and upper line of the cross sections. In some conditions, turbulence was added.

The basic condition was presented both in an inside-out (Fig. 7.2) and an outside-in (Fig. 7.3) frame of reference.

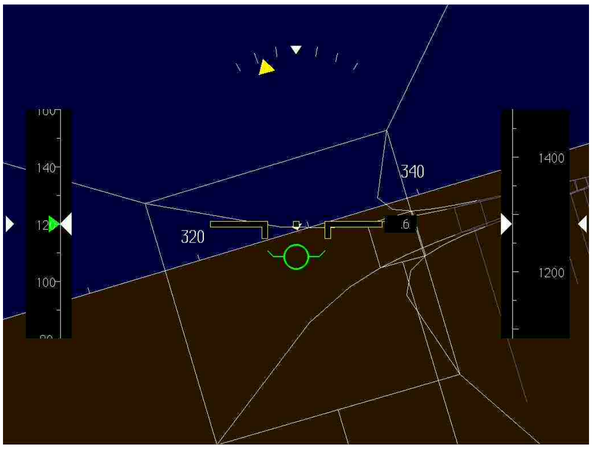


Fig. 7.2. *Inside-out frame of reference. In this frame of reference the aircraft symbol is fixed and the horizon rotates and translates the same way as the horizon the pilot perceives when looking through the windshield.*

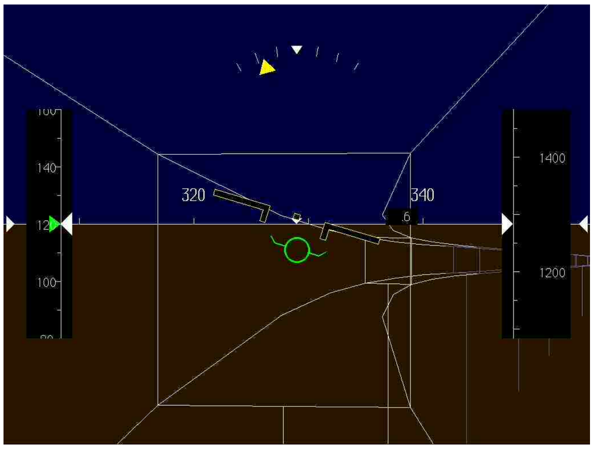


Fig. 7.3. *Outside-in frame of reference. In this frame of reference the horizon is fixed and the aircraft symbol moves the same way as the real aircraft when seen from a position behind it.*

Although pilot comments varied, most agreed that the ground track did not really present any useful cues and probably only caused clutter. The same comment was initially made with respect to the altitude poles, but during further evaluations pilots commented that the altitude poles were quite useful for accurately aligning the aircraft with the runway on final. Apparently the cues resulting from the line-up of the altitude-poles were more useful for this task than the distortion of symmetry. Most pilots disliked presentations in which the interconnection were removed, or at least preferred the ones in which the interconnection were present. The opinion about the upper line of the intersections varied. Some pilots preferred the channel representations while others deemed the tunnel to be better. A potential drawback of the channel representation is that pilots only regard the bottom of the tunnel as a hard limit and fly more towards the top, thus creating a bias. Although this would go against the tendency to maintain a symmetrical condition, such behavior has been observed and may be explained by a tendency to err on the safe side of caution. With respect to the tunnel size, pilots commented that the basic tunnel (45 m) was flyable although requiring much attention, the smaller tunnel (22.5 m) was really hard to fly, whereas the larger one (90 m) allowed very relaxed control. Combined with the fact that about equal ratio performance improvements were found when varying tunnel size, this indicated that the range over which the tunnel size was varied was within the range in which the functional variable behaves linear (Owen, 1990b). Pilots also commented that they had the illusion of an increase in velocity with the smaller tunnels. Since the spacing between the reference frame was kept constant, this indicates that pilots were sensitive to global optical flow induced velocity cues.

With respect to the frame of reference, most pilots commented that they preferred the inside-out frame of reference, which is understandable since this is the way attitude information is presented on current attitude indicators. Although pilots could fly the approach with the outside-in frame of reference while remaining inside the tunnel, one particular event demonstrated a significant drawback of the outside-in alignment.

With the outside-in frame of reference, several pilots reached very high angles of attack before they responded by pitching the nose down. This never occurred with the inside-out alignment.

When flying the outside-in version, an increase in pitch is conveyed through the movement of the aircraft symbol towards the top of the screen (Fig. 7.4). In contrast, with a inside-out alignment, an increase in pitch yields a downward translation of the display (Fig. 7.5), providing a dominant cue. A potential solution to this problem is to use the hybrid alignment employed in Russian attitude indicators, which has been discussed in Sect. 5.3.2.

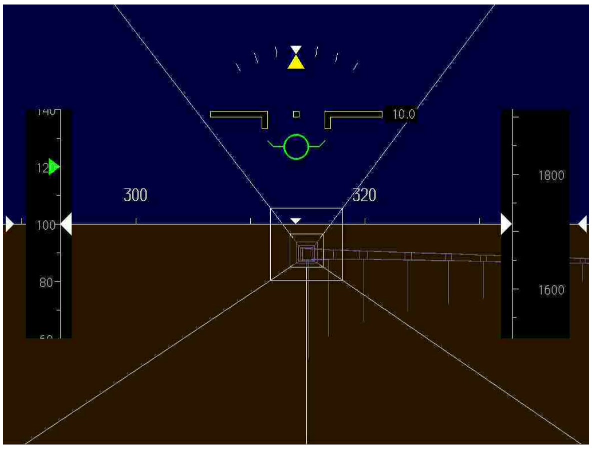


Fig. 7.4. *Effect of 10 degrees pitch with an outside-in frame of reference. In this frame of reference, the dominant cue resulting from horizon motion is lacking, and the displacement of the aircraft symbol indicates the pitch angle.*

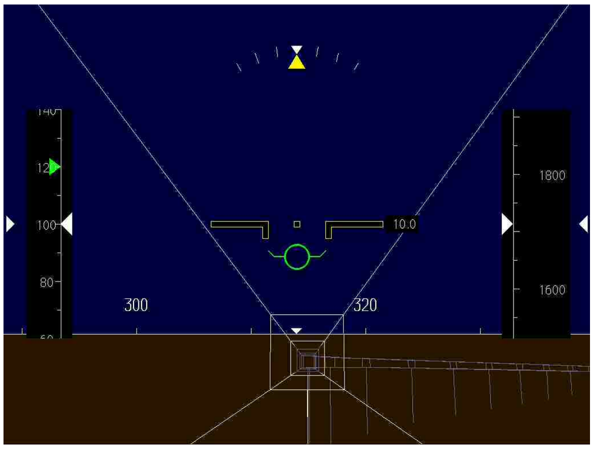


Fig. 7.5. *Effect of 10 degrees pitch with an inside-out frame of reference. In this frame of reference, the pitch angle is coupled to the vertical translation of the displayed scene which is much more compelling as the motion of the single aircraft symbol in the previous figure.*

Although the addition of turbulence required more attention from the pilot to stabilize angular motion, the need for an additional pitch tape was only expressed by a few. With a conventional attitude indicator, the scaling of the pitch tape allows the pilot to estimate pitch angle and use the translation of the pitch tape to stabilize the angular motion. Several options to integrate a pitch tape in the presentation were tried, but the resulting interference with the perspective flightpath caused this approach to be abandoned. Some pilots commented that although the cues conveyed through the vertical translation of the horizon allowed them to stabilize pitch, they would like information about the actual pitch angle. Therefore, an indicator presenting the actual pitch angle alphanumerically was integrated. It must be stressed here that this indicator is by no means meant to be used to stabilize angular motion, but to convey the required information to the pilot in case he needs accurate information about pitch angle.

Some pilots commented that the high intensity of the tunnel at a far distance from the viewpoint was distracting. The cause of this problem was discussed in Sect. 5.8 and was later solved by reducing the intensity of the tunnel beyond a certain viewing distance.

After the pilot study, three simulator studies have been performed. To avoid confusion, it is stated in advance that the goal of these experiments was neither to uncover some laws of behavior of people when presented with spatially integrated data, a subject which clearly belongs to the field of experimental psychology, nor to identify a pilot model for a control task based on spatially integrated data. The goal was to validate assumptions and gain more insight into specific design aspects in order to increase the level of detail of the design guidelines without sacrificing generalizability.

A major factor determining the generelizability of quantitative data resulting from experiments are the dynamics of the system to be controlled. One potential approach is to make drastic simplifications and select basic functions such as an integrator and a double integrator. The results from such experiments can be used to construct a data base which can be applied to the design of a perspective display for a specific application. The generation of such an experimental data base which can be used in the design of perspective flightpath is a typical goal of engineering psychology. Since such a database does not yet exist, however, it is uncertain how much effort is needed to translate the data to the application of a specific aircraft. It can be expected that the major influence of the aircraft dynamics is on the range of possible values for the tunnel size and the necessity to include augmented symbology. It was decided to select a particular aircraft model and perform the experiments in a flight simulator rather than using a part-task setup with drastically simplified dynamics. It could be argued that such an approach restricts the usefulness of the results to the specific one-time application determined by the experimental conditions. However, through sound selection of specific task-related experimental variables based on a theoretical framework, the qualitative data gained can provide insights which transcend the specific conditions of the experiment and the quantitative data can be used to aid in the design of the MMI for the specific aircraft. In comparison to a part-task setup with simplified system dynamics, the full flight simulator approach provides the possibility to perform the experiments in a situation which closely resembles the real application environment.

The first experiment addressed the influence of position error gain which was discussed in Secs 3.5 and 5.6 and position prediction, which was discussed in Sect. 5.10.3. The second one investigated the cues used for error neglecting control, which was discussed in Secs 4.3 and 4.4. In Secs 3.5, 3.6 and 5.3, the differences between an attitude and velocity vector aligned frame of reference have been discussed. The third experiment served to gain more insight in the differences by obtaining feedback from pilots.

7.3 Error gain and position prediction

Several studies have been conducted in which the effects of variations in one of the design parameters were investigated. In Sect. 3.5 it was hypothesized that splay-rate is the functional variable for position control, and that in the middle range of sensitivity, an equal-ratio improvement in splay rate gain produces an equal-interval improvement in performance. With a perspective flightpath display, splay rate gain is inversely proportional to tunnel size. Wilckens (1973) investigated the effect of different tunnel sizes on tracking performance and control activity for straight-in approaches. He reports that performance and control activity increased with decreasing tunnel size. Grunwald et al. (1980) investigated the potential benefits of predictive symbology in a perspective flightpath display for curved helicopter approaches, and demonstrated that adding a position predictor increases tracking performance and reduces control activity. In a later study, Grunwald (1984) compared pilot performance and control activity when flying curved approaches for tunnel sizes of 300 ft and 450 ft in the presence of a position predictor. Similar to Wilckens, the results illustrate an increase in tracking performance and control activity with decreasing tunnel size. Since the tunnel sizes were only varied in the presence of a position predictor, potential interactions between tunnel size and predictive symbology could not be determined. Furthermore, performance and control activity results are summed for the complete trajectory, and no differentiation was made between straight and curved segments. To investigate the combined effects of tunnel size and prediction on both straight and curved segments, two experiments have been conducted.

7.3.1 Experiments

Experimental design. A two factor repeated measures within subject design (Norusis, 1988) was used. The first factor is *tunnel size* which has three levels (22.5, 45, and 90 m width and height). The second factor is *prediction* which can be either absent (flightpath vector configuration) or present (predictor configuration). Each condition was repeated five times. Since the data from the experiment indicated a linear trend between increases in position error gain and tracking performance, a second one in which the tunnel size was varied between 4.5 m and 9 m was conducted. These sizes may seem small, but as indicated in Sect. 5.6.1, the dimensions of the tunnel are not necessarily constrained to physically relevant values. The goal of the second experiment was to gain more insight into tracking performance and control behavior when presented with very high position error gains. Tables 7.1 and 7.2 present an overview of the different conditions used in the first and second experiment, respectively.

Table 7.1. *Overview of the conditions used in Experiment I.*

Condition	Predictor	Tunnel size [m]
F22.5	N	22.5
F45	N	45.0
F90	N	90.0
P22.5	Y	22.5
P45	Y	45.0
P90	Y	90.0

Table 7.2. *Overview of the conditions used in Experiment II.*

Condition	Predictor	Tunnel size [m]
F4.5	N	4.5
F9	N	9.0
P4.5	Y	4.5
P9	Y	9.0

Hardware. The experiment was conducted in the moving-base flight-simulator of the Faculty of Aerospace Engineering at the Delft University of Technology. The aircraft model which was used was that of a Cessna Citation 500. In the initial conditions, the gear was down and flaps were set at 20 degrees.

Subjects. Five subjects (three licensed pilots and two student pilots) participated in the first experiment. Table 7.3 provides an overview of the total number of flying hours of each subject, and whether the subject was male or female.

Table 7.3. *Overview of the subjects.*

Subject	Flying hours	Male/Female
1	5300	M
2	320	M
3	100	M
4	student pilot	M
5	student pilot	F

The experience of Subject 1 included Boeing 737 and Boeing 767. Subject 2 had experience on a twin engine business jet. The experience of Subjects 3,4, and 5 was limited to single engine airplanes. All subjects had prior experience with the perspective flightpath display, although the amount varied quite a lot between the subjects. Subject 3 often participated in trial sessions with the perspective flightpath display. The difference in age between the oldest and the youngest subjects was approximately 20 years.

Task. As discussed in Sect. 4.4, pilot performance and control strategies are influenced by a number of self chosen thresholds for variables such as cross track error and track angle error. It is assumed that when subjects are motivated to minimize these thresholds, similar control strategies may result. Thus, to maximize the possibility that subjects applied the same control strategy, and to prevent them from applying some kind of an error-neglecting control strategy, subjects were instructed and motivated to fly the approach as accurate as possible. They started their flight at an altitude of 1200 ft about 4 miles away from the runway threshold. Fig. 7.6 presents a plan view of the trajectory.

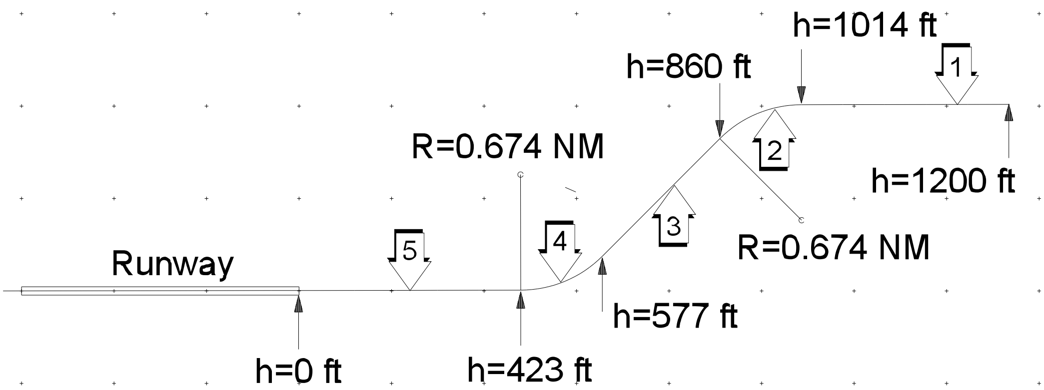


Fig. 7.6. *Plan view of the trajectory used in the experiment.*

At the time the experiment was performed, the flight simulator software did not yet provide the possibility to select between different approach paths during an experiment. Therefore, only a single trajectory was used. As correctly indicated by Grunwald (1996a), the familiarization with a particular trajectory increases pilot skill and as a result performance. However, this is not likely to influence performance between conditions.

Subjects were instructed to maintain an airspeed of 120 knots. This reference airspeed was indicated by a green bug on the speed-tape. At the beginning of each flight, the aircraft was in the landing configuration, and no aircraft configuration changes had to be made by the subject. Subjects controlled aileron and elevator deflections by means of a central control column. Fig. 7.7 presents the display format for the flightpath vector (FPV) configuration and Fig. 7.8 for the predictor (FPP) configuration.

Measure	Unit	Meaning
σ_{roll1}	deg	Mean of the roll angle on straight segments
σ_{roll2}	deg	Mean of the roll angle on curved segments

Schedule. Before the experiment started, subjects were briefed on the display and the approach. The total briefing lasted for approximately an hour. Following the briefing, the first training session commenced. This was either the FPV or the FPP configuration. After the training sessions, a 15 minute break was given. For the data sessions, each pilot had to fly a total of 30 approaches. These approaches were divided over 4 sessions. Pilots were given the opportunity to indicate when they thought there performance was affected due to some distraction. In this case, the particular condition was repeated. Depending on whether pilots wanted to repeat a particular approach, between 8 and 10 flights were performed in a single session. Each flight lasted approximately 3 minutes. The first flight in each session served as a test flight and this data was not used in the analyses. In the morning, pilot typically performed the first training session and one data session. In the afternoon the other training session and three data sessions were performed. Table 7.5 presents an overview of the schedule which was used.

Table 7.5. *Overview of the schedule used in the experiment.*

Activity	Time
Briefing	09:00 - 10:00
Training session	10:00 - 10:45
Break	10:45 - 11:00
First data session	11:00 - 11:45
Lunch	
Second data session	13:30 - 14:00
Break	14:00 - 14:15
Training session	14:15 - 14:45
Break	14:45 - 15:00
Third data session	15:00 - 15:45
Break	15:45 - 16:00
Fourth data session	16:00 - 16:45
Debriefing	16:45 - 17:00

Training. Training was performed with a tunnel size of 45 m width and height. Both the flightpath vector and the flightpath predictor configuration were presented. δ_{XTE} and δ_{VTE} were used as a measure of performance. When performance reached a sufficient level, the training flights ended. If subjects indicated that they thought they could still improve their performance, more training flights were issued. To be able to compensate for possible transfer effects between the FPV and the FPP configuration, the order in which the configurations were presented was balanced between subjects. Figs 7.9 to 7.16 present the performance during the training per subject and per condition.

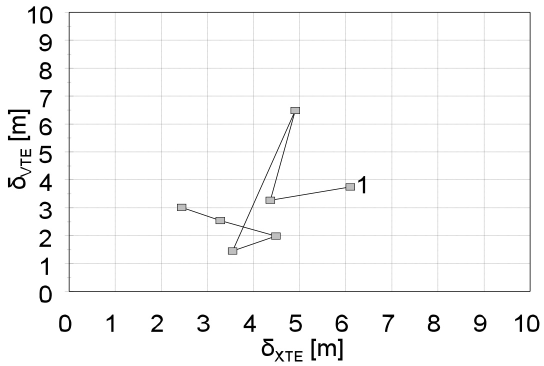


Fig. 7.9. *Performance of Subject 1 during training in FPV configuration.*

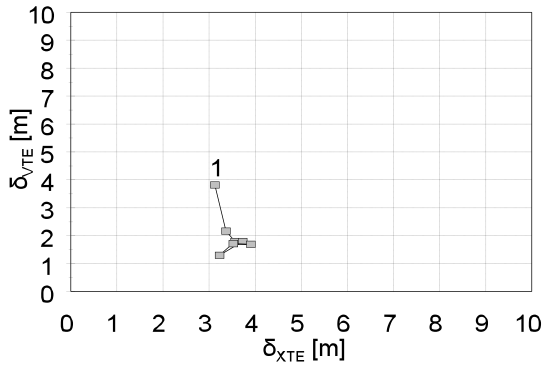


Fig. 7.10. *Performance of Subject 1 during training in FPP configuration.*

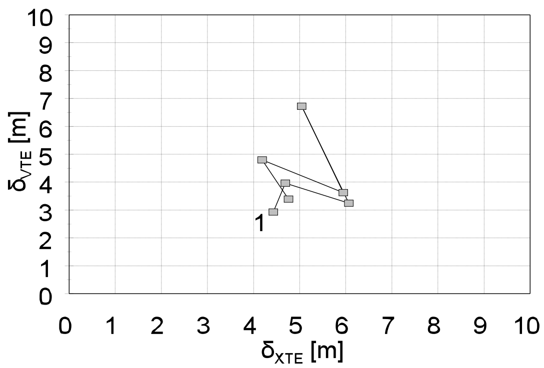


Fig. 7.11. *Performance of Subject 2 during training in FPV configuration.*

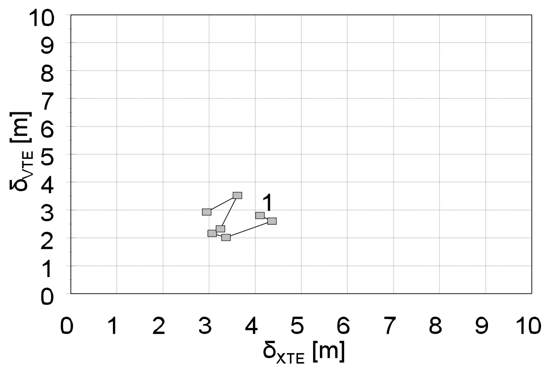


Fig. 7.12. *Performance of Subject 2 during training in FPP configuration.*

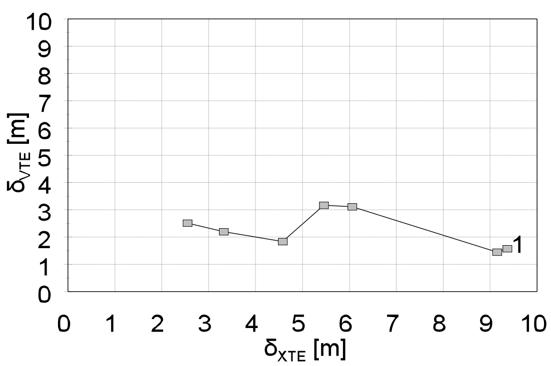


Fig. 7.13. *Performance of Subject 3 during training in FPV configuration.*

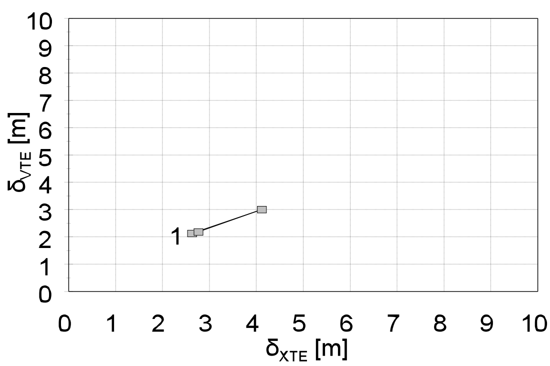


Fig. 7.14. *Performance of Subject 3 during training in FPP configuration.*

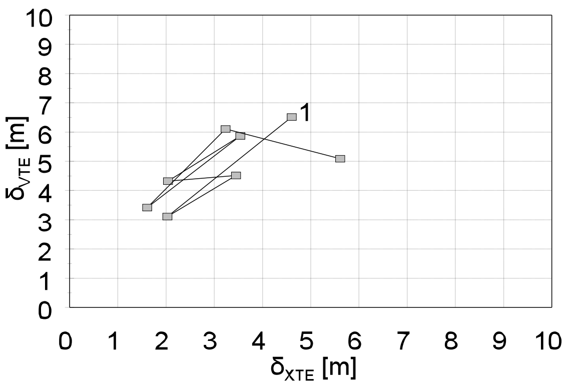


Fig. 7.15. *Performance of Subject 4 during training in FPV configuration.*

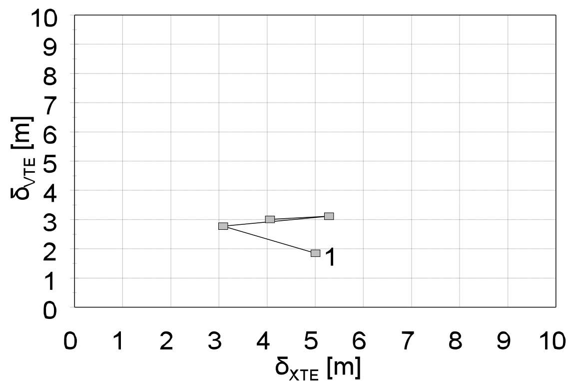


Fig. 7.16. *Performance of Subject 4 during training in FPP configuration.*

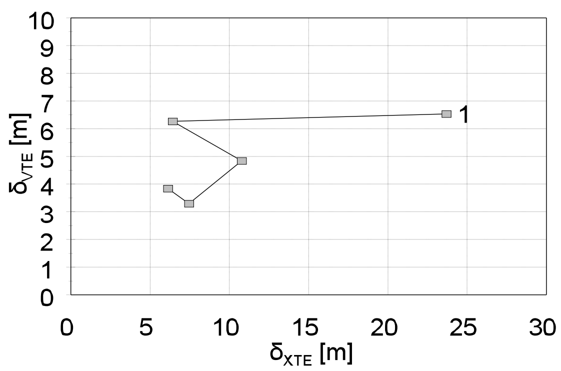


Fig. 7.17. *Performance of Subject 5 during training in FPV configuration.*

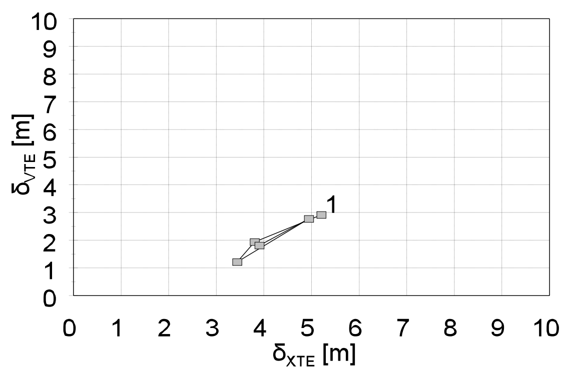


Fig. 7.18. *Performance of Subject 5 during training in FPP configuration.*

The training sessions showed that both experienced pilots and student pilots could rapidly achieve a high level of tracking performance. Subjects 1,2, and 4 already achieved a high tracking performance during their first training flight. Subjects 3 and 5 needed two training flights to improve their tracking performance to a level similar to that of the other subjects.

7.3.2 Data analysis and results

During the experiment, aircraft state and pilot inputs were recorded at a rate of 14 Hz (Appendix B). From this data, distributions of position and orientation errors were calculated. For Subject 3, the data for one run contained an error and could not be used in the analysis, resulting in a total of 24 sets of data per condition instead of 25. Since it was a within subject repeated measures design, this was not considered to affect the outcome of the analysis. A first analysis of the data was performed by calculating the means and standard deviations of δ_{XTE} and δ_{VTE} for the F45 and P45 condition for each pilot separately. The means provide an indication of the average performance per subject, and the resulting standard deviations give an indication of the variation in performance within a subject. Figs. 7.19 to 7.22 give an overview of the lateral and vertical tracking performance of the subjects for both conditions. These figures show that the variation of performance within the subjects is rather small. The variation of performance between subjects is somewhat larger.

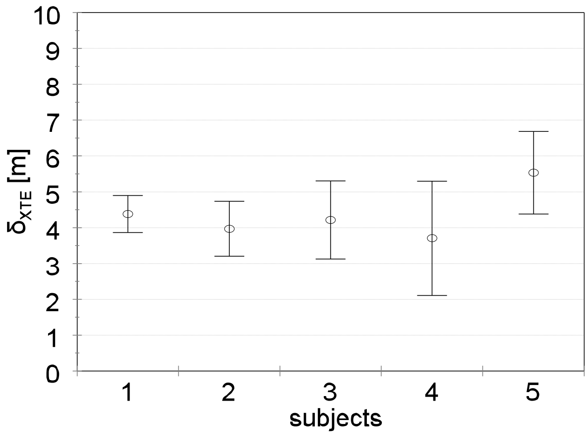


Fig. 7.19. *δ_{XTE} per subject in F45 condition.*

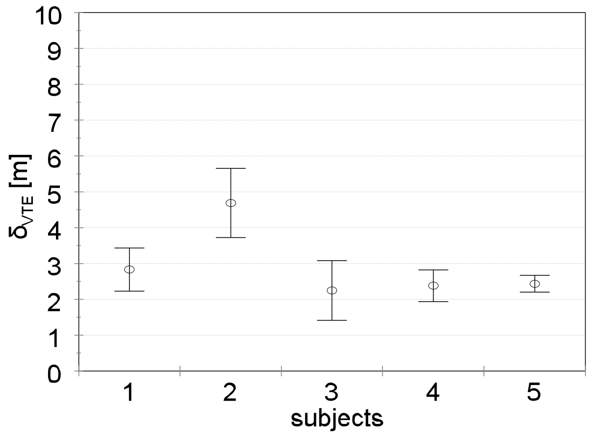


Fig. 7.20. *δ_{VTE} per subject in F45 condition.*

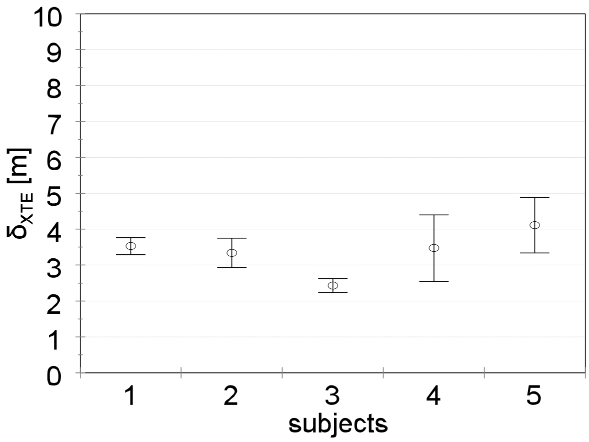


Fig. 7.21. *δ_{XTE} per subject in P45 condition.*

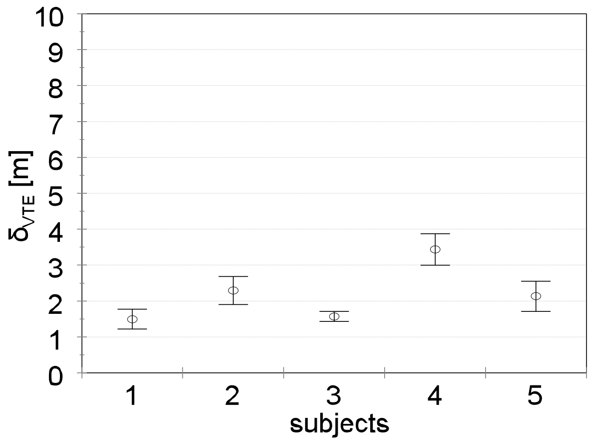


Fig. 7.22. *δ_{VTE} per subject in P45 condition.*

For a detailed analysis, the resulting data were divided into categories for the straight Segments 1 and 5, and the curved Segments 2 and 4 (Fig. 7.6). For each condition this yielded a total of 48 data sets for the straight segments and 48 data sets for the curved segments. For each segment, the means and standard deviations of the distributions of the performance measures listed in Table 7.4 were computed. Furthermore, the standard deviations of the average roll angle were computed for each segment. Figs 7.23 to 7.34 present results from the first experiment. The six different conditions are indicated on the horizontal axis. The first letter is either an 'F' indicating a flightpath vector condition, or a 'P' indicating a flightpath predictor condition. The numbers after this letter indicate the size of the tunnel in meters. To analyze the transitions from straight to curved sections, time histories of the bank angle were used. Fig. 7.35 presents five time histories of a subject in the FPV configuration, and Fig. 7.36 five time histories for the FPP configuration.

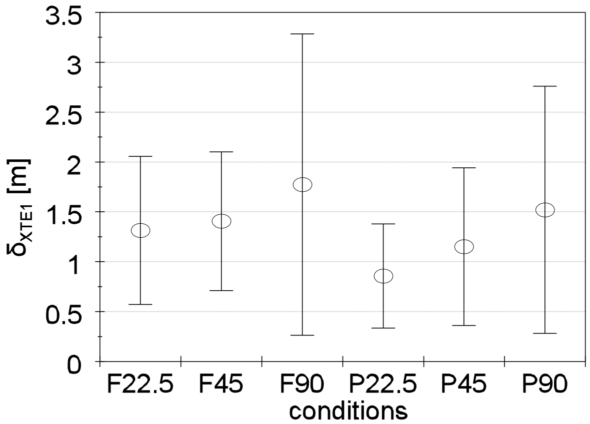


Fig. 7.23. *Lateral tracking performance on straight segments.*

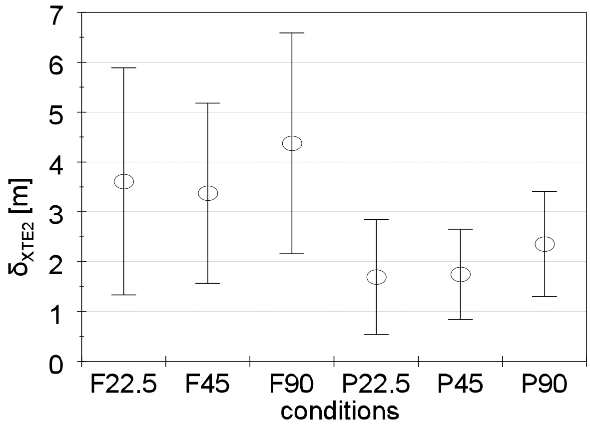


Fig. 7.24. *Lateral tracking performance on curved segments.*

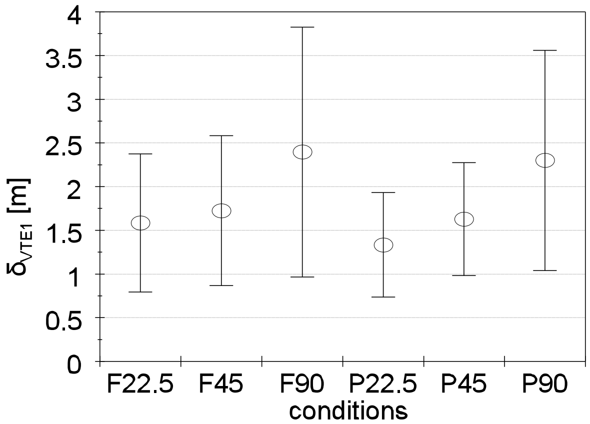


Fig. 7.25. *Vertical tracking performance on straight segments.*

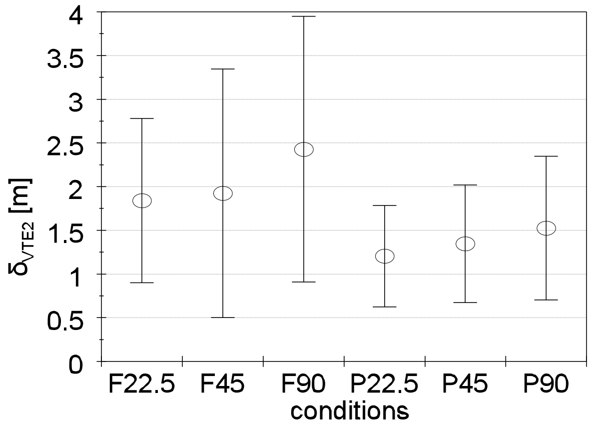


Fig. 7.26. *Vertical tracking performance on curved segments.*

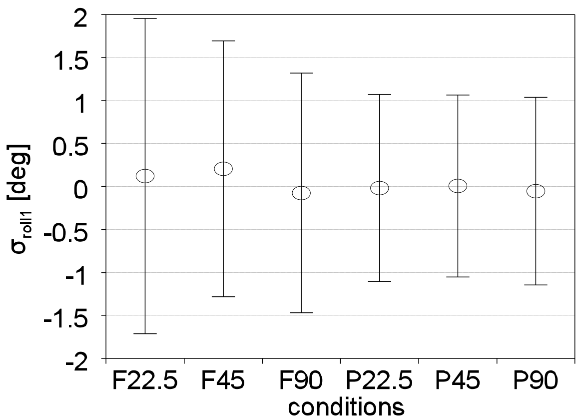


Fig. 7.27. *Roll angle distribution on straight segments.*

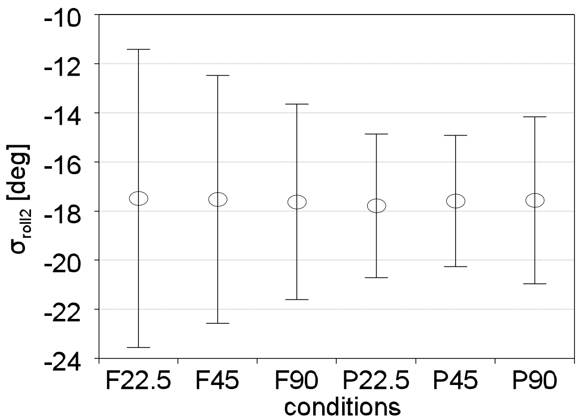


Fig. 7.28. *Roll angle distribution on curved segments.*

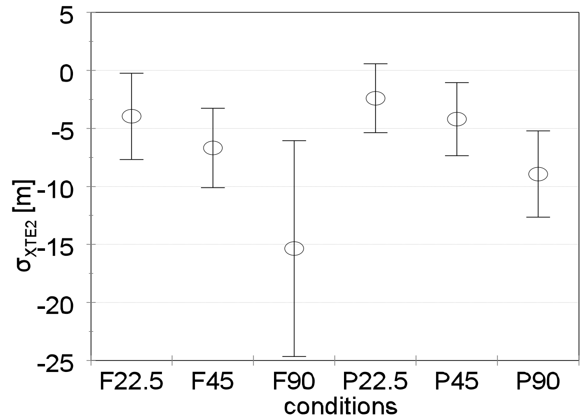


Fig. 7.29. *Average cross-track error on curved segments.*

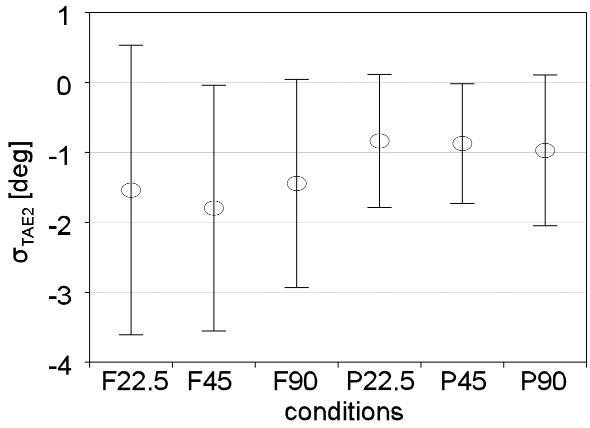


Fig. 7.30. *Average track angle error on curved segments.*

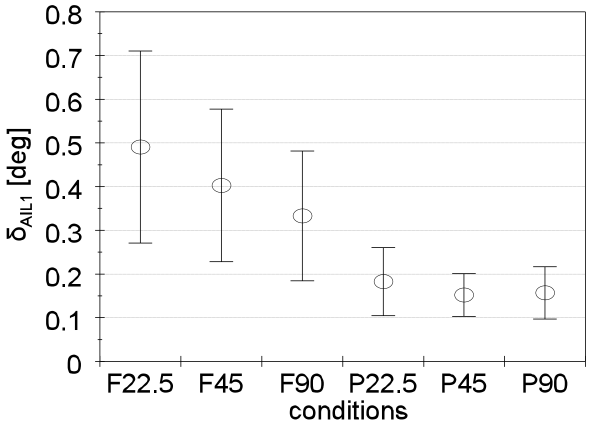


Fig. 7.31. *Aileron control activity on straight segments.*

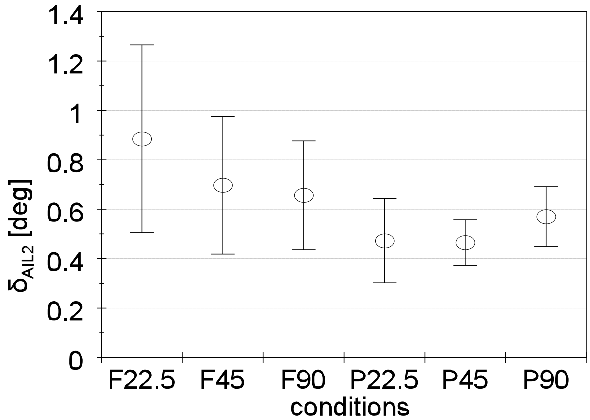


Fig. 7.32. *Aileron control activity on curved segments .*

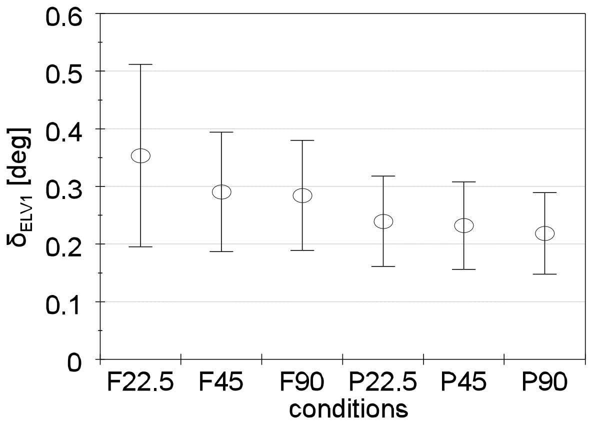


Fig. 7.33. *Elevator control activity on straight segments.*

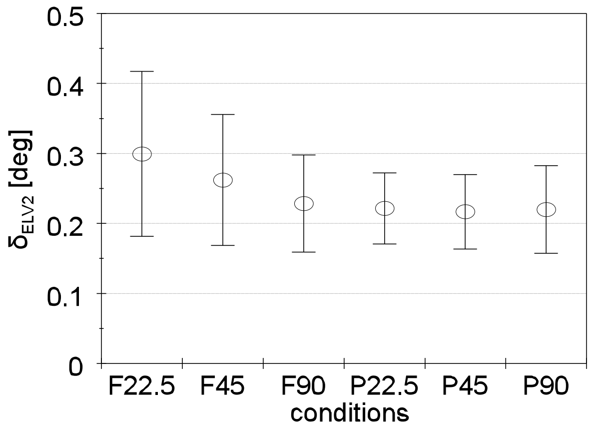


Fig. 7.34. *Elevator control activity on curved segments.*

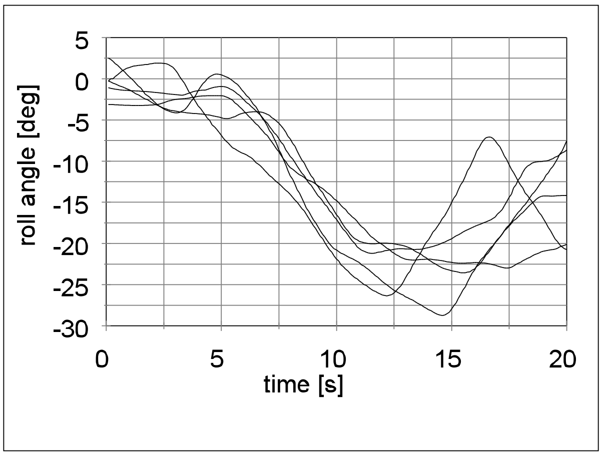


Fig. 7.35. *Time histories of roll angle in the absence of a position predictor.*

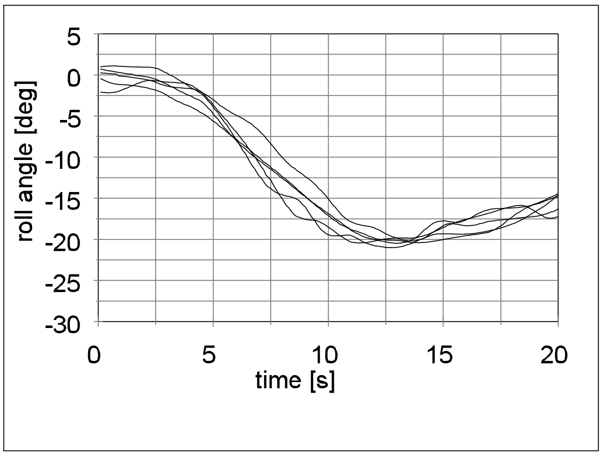


Fig. 7.36. *Time histories of roll angle in the presence of a position predictor.*

To check for statistically significant differences between conditions, a repeated measures analysis of variance was performed. Table 7.6 presents an overview of the results from the statistical analyses.

Table 7.6. *Summary of the results from the two factor repeated measures analysis of variance for the performance measures listed in Table 7.4 and the data from Experiment 1. Both the effects of tunnel size and prediction were tested, and it was tested whether there was an interaction between the two factors. Findings which are significant at* $\alpha=0.05$ *are accentuated.*

Measure	tunnel size (dF=2,94)	prediction (dF=1,47)	interaction (dF=2,94)
δ_{XTE1}	F=8.84, p<0.0005	F=9.46, p=0.003	F=0.43, p=0.649
δ_{VTE1}	F=20.7, p<0.0005	F=2.5, p=0.120	F=0.29, p=0.748
δ_{AIL1}	F=23.23, p<0.0005	F=153.73, p<0.0005	F=11.98, p<0.0005
δ_{ELV1}	F=10.28, p<0.0005	F=79.33, p<0.0005	F=5.1, p=0.008
σ_{XTE2}	F=116.70, p<0.0005	F=33.78, p<0.0005	F=9.82, p<0.0005
δ_{XTE2}	F=6.06, p=0.003	F=86.57, p<0.0005	F=0.32, p=0.726
δ_{VTE2}	F=6.37, p=0.003	F=23.89, p<0.0005	F=0.72, p=0.488
δ_{AIL2}	F=5.31, p=0.007	F=67.37, p<0.0005	F=14.71, p<0.0005
δ_{ELV2}	F=5.78, p=0.004	F=25.04, p<0.0005	F=7.38, p=0.001

Straight segments. Fig. 7.23 shows the distribution of δ_{XTE1} for the different tunnel sizes, Fig. 7.25 the distribution of δ_{VTE1}, and Fig. 7.27 the distribution of the roll angle. Figs 7.31 and 7.33 show the distribution of δ_{AIL1} and δ_{ELV1}, respectively.

As can be seen from Table 7.6, there is both an effect of size and prediction on δ_{XTE1}. No interaction was found between the two factors. With respect to δ_{VTE1}, there is a significant effect of size but there is no significant effect of prediction. As with δ_{XTE1}, no interaction is found between tunnel size and prediction.

When looking at the aileron deflections, there is both an effect of size and prediction. Furthermore, an interaction is found between the two factors. Fig. 7.31 shows that in the presence of a position predictor, control activity is hardly influenced by the tunnel size. Further analysis shows in the predictor configuration there is an effect of tunnel size which is caused by the smallest tunnel, but no significant effect is found between tunnel sizes of 45 m and 90 m.

Finally, when looking at the distribution of the elevator deflections, a significant effect for both size and prediction is found. Here too, an interaction between the tunnel size and prediction is found. When looking at Fig. 7.33, it appears that the effect of tunnel size may be caused by the condition FPV 22.5. Further analysis of the data reveals that in the predictor configuration no significant effect of tunnel size exists and that in the absence of a position predictor there is no significant difference between tunnel sizes of 45 m and 90 m. This confirms that the effect of tunnel size is solely caused by the FPV 22.5 condition.

Curved segments. Fig. 7.29 shows the distribution of σ_{XTE2} for the different tunnel sizes, and Fig. 7.30 the distribution of the average TAE. As can be seen from these figures, a bias exists. Fig. 7.24 shows the distribution δ_{XTE2}, Fig. 7.26 the distribution of δ_{VTE2}, and Fig. 7.28 the distribution of the roll angle. Figs 7.32 and 7.34 show the distribution of δ_{AIL2} and δ_{ELV2}, respectively. A repeated measures analysis of variance shows that there is both a significant effect of size and prediction on σ_{XTE2}. Furthermore, no interaction between tunnel size and prediction is found. An analysis of the standard deviation of the δ_{XTE2} reveals a significant effect for size and a significant effect of prediction. Here too, no interaction between the factors is found. With respect to δ_{VTE2}, there is a significant effect of size and a significant effect for prediction. As with δ_{XTE2}, no interaction between the factors is found.

When looking at the aileron deflections (Fig. 7.32), there is both an effect of size and prediction. Similar to the straight segments, an interaction is found between the two factors. Further analysis shows that in the presence of a position predictor there still is a significant effect of tunnel size, but that no significant difference for aileron control activity exists between tunnel sizes of 22.5 m and 45 m. For a tunnel size of 90 m aileron control activity seems to increase again.

Finally, when looking at the distribution of the elevator deflections (Fig. 7.34), a significant effect for prediction and a significant effect for size is found. Here too, an interaction between tunnel size and prediction is found. It seems that in the predictor configuration elevator control activity is hardly influenced by tunnel size. Further analysis confirms that there is no significant effect of tunnel size in the predictor condition.

7.3.3 Discussion

Straight segments. When flying the tunnel display without predictor, feedback on position error and error rate is obtained only by the dynamic presentation of the tunnel. The error gain and resolution increase with decreasing tunnel size. Similar to the results reported by Wilckens (1973), in the absence of a position predictor, lateral tracking performance and aileron control activity reduce with a decrease in error gain. The analysis of the data shows an interaction between tunnel size and prediction for aileron control activity. In contrast to the results reported by Grunwald (1984), control activity hardly changes among the various tunnel sizes in the presence of a position predictor (Fig. 7.31). This leads to the hypothesis that with the current display, pilots dominantly use the information presented by the predictor, and not the raw information presented by the tunnel. When flying the flightpath predictor configuration, the error gain presented by the predictor symbol is independent of the tunnel size. Since a smaller tunnel size yields a smaller reference window for the predictor symbol, the error resolution increases, allowing pilots to fly more accurately because it is easier to determine the center of the prediction window. This is confirmed by the results. The magnitude of the roll angle cues are not affected by tunnel size or position prediction. When looking at the distribution of the roll angle, it can be seen that in the absence of a position predictor the standard deviation increases with decreasing tunnel size, whereas in the presence of a position predictor it remains almost constant. Thus, a position predictor yields a more stable flight. The vertical tracking task is easier than the lateral tracking task since the vertical dynamics of the aircraft are of a lower order. The results illustrate that vertical tracking performance is only influenced by error gain, but not by position prediction. Elevator control activity, however, is both influenced by error gain and position prediction. As with aileron control activity, an interaction was found between tunnel size and position prediction. When looking at the elevator control activity (Fig. 7.33), a pattern similar to that for aileron control activity can be observed, and further analyses showed that in the presence of a predictor no significant effect of tunnel size exists. Therefore, it is hypothesized that here too the predictor suppresses the effects of tunnel size on elevator control activity. Summarizing, the results indicate that for the vertical tracking task the cues presented by the tunnel allow the pilot to achieve equal performance as with a position predictor, at the expense of an increase in elevator control activity.

Curved segments. In a curved segment the difficulty of the lateral control task increases. Furthermore, track angle error cannot be perceived directly and to maintain the cross track error within certain limits both cross track error its rate must be used. In contrast to the track angle error gain, the gain of cross track error rate is inversely proportional to tunnel size. In the presence of a position predictor, pilots can use the deviation of predictor symbol and do not have to determine cross track error rate. This change in control task is reflected by increased lateral tracking performance (Fig. 7.24) and reduced aileron control activity (Fig. 7.32). When comparing lateral tracking performance between straight (Fig. 7.23) and curved (Fig. 7.24) segments, the decrease in performance in curves is apparent. For the FPV conditions, this can be attributed to the lack of track angle error cues and the increased difficulty of the control task. In the FPP conditions, the predictor should be able to compensate for the lack of track angle error cues, and therefore it is assumed that the difference in tracking performance is mainly caused by the increased difficulty of the tracking task. When looking at the distribution of the roll angle (Fig. 7.28), a pattern which is similar to the one for straight segments (Fig. 7.27) is observed. Here too, in the presence of a position predictor, the standard deviation of the roll angle seems hardly affected by changes in tunnel size. The bias found in the σ_{XTE2} (Fig. 7.29) is in the direction of the inner side of the curve, so pilots are cutting the curve. Fig. 7.30 shows the distribution of the track angle error, which reveals a dependence on prediction, but not on size. Apparently, the cross track error cues in the curve cause a constant track angle error. In the absence of position and orientation errors, the outside wall of the tunnel intersects the viewing volume at a shorter viewing distance than the inner wall of the curved section. A possible explanation for the bias toward the inner side of the curve is that pilots interpret the resulting cues as a cross track error toward the outer wall, and therefore fly more towards the inner side. When the pilot would solely rely on the position predictor, and the predictor is accurate (does not have a bias itself), the offset should disappear in the predictor condition. As can be seen from the latter three symbols in Fig. 7.29 however, the bias toward the inner side of the curve is reduced but still present. In contrast to the straight segment, vertical tracking performance is not only influenced by error gain, but also by the position predictor. It is hypothesized that this is partly caused by the coupling of lateral and vertical controls due to the bank angle of approximately 18 degrees, and partly by the increased difficulty of the lateral tracking task. Just as with the straight segment, both for aileron and elevator control activity an interaction was found between tunnel size and position prediction. When comparing the distributions of aileron and elevator control activity for the different conditions in the straight segments (Figs 7.31 and 7.33, respectively) with the curved segments (Figs 7.32 and 7.34), a similar pattern is observed. Further statistical analyses revealed that in the presence of a predictor the effect of tunnel size is only caused by the 90 m condition, whereas for elevator control activity no effect of tunnel size is found. This leads to the conclusion that both on straight and curved segments the presence of a position prediction reduces the effects of tunnel size on pilot control activity.

Transitions. In the absence of a position predictor, the information required for determining the timing and magnitude of the required anticipatory control action must be extracted from the perspective flightpath. A correctly tuned position predictor might aid the pilot with this task. Fig. 7.35 presents five time histories of the bank angle during a transition from a straight to a curved segment in the flightpath vector configuration, and Fig. 7.36 presents five time histories for the predictor configuration. Both figures present the result for one subject, and one tunnel size. Fig. 7.35 clearly shows a larger variation in bank angle, indicating a less accurate timing and magnitude of the required anticipatory control action. This increases the required closed loop control actions to compensate for the resulting errors. Time histories have been plotted for all subjects and show that the performance in the absence of a predictor is more variable. Thus, when transitioning between straight and curved segments, a correctly tuned flightpath predictor enables the pilot to better determine the timing and magnitude of the required anticipatory control action. This reduces the gain required for the closed-loop portion, yielding less oscillations.

7.3.4 Results from Experiment II

The results presented in Figs 7.23 to 7.26 indeed suggest that an equal-ratio improvement in splay rate gain produces an equal-interval improvement in performance. To determine whether tracking performance would still improve with an increase in splay-rate gain, and to investigate the influence of a predictor in this situation, an additional number of flights were performed with an increased splay rate gain. All other conditions remained the same. Limitations in the available time allowed for only two of these five subjects (1 and 4) to participate in the second experiment. On the one hand, one might argue that this does not produce any generalizable results. On the other hand, the variability in performance between subjects in the first experiment was rather small, and therefore it could be expected that at least an indication of the effects of these higher error gains could be obtained. Tunnel sizes of 9 and of 4.5 m were used. Figs 7.37 to 7.44 show the results. To check for statistically significant effects of tunnel size and prediction an analysis of variance (ANOVA) was performed. The results are listed in Table 7.7.

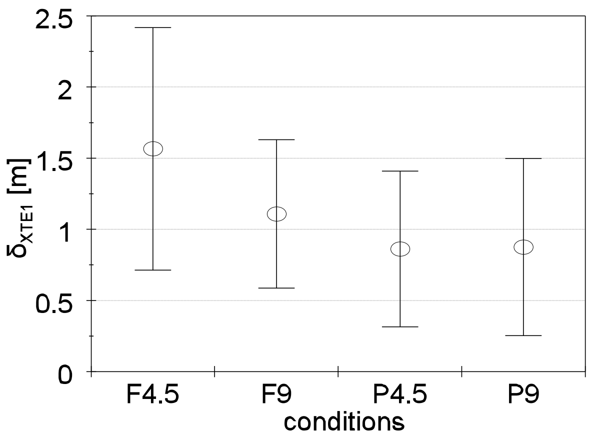


Fig. 7.37. *Lateral tracking performance.*

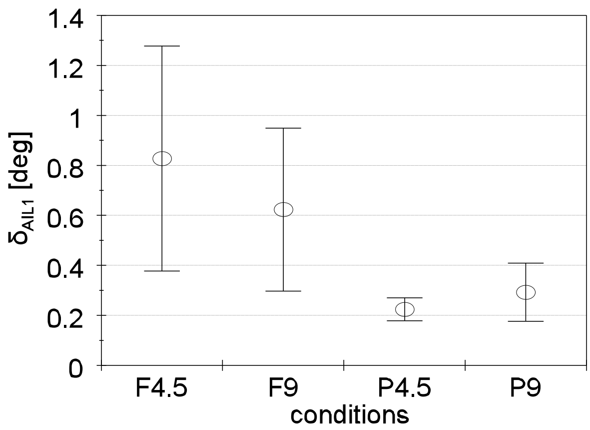


Fig. 7.38. *Aileron control activity.*

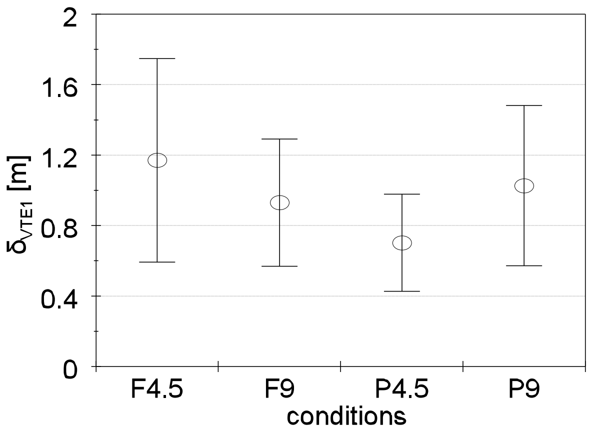


Fig. 7.39. *Vertical tracking performance.*

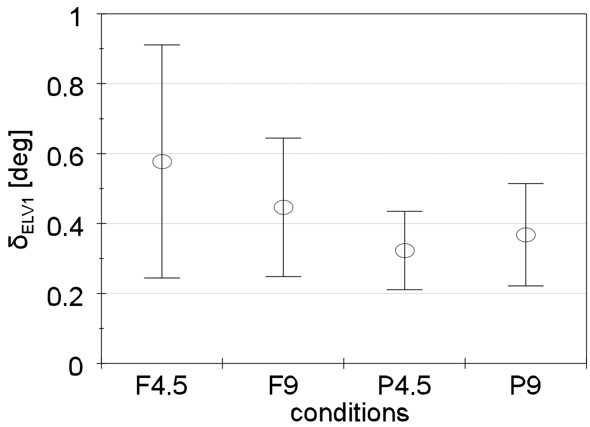


Fig. 7.40. *Elevator control activity.*

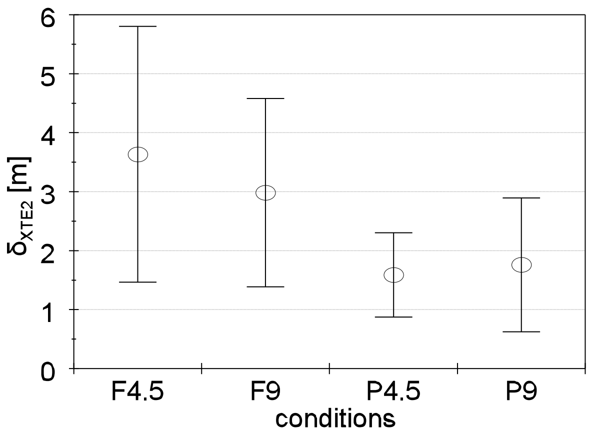


Fig. 7.41. *Lateral tracking performance in curves.*

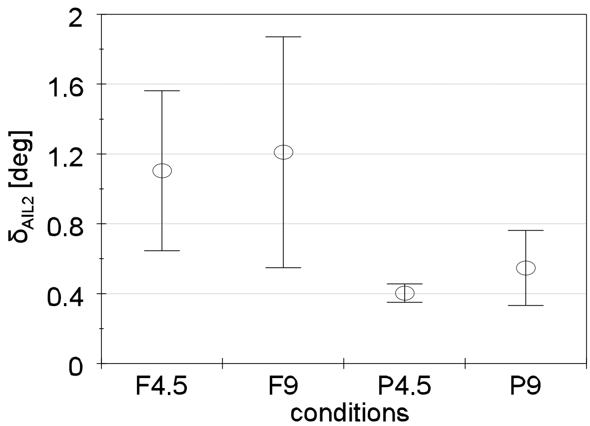


Fig. 7.42. *Aileron control activity in curves.*

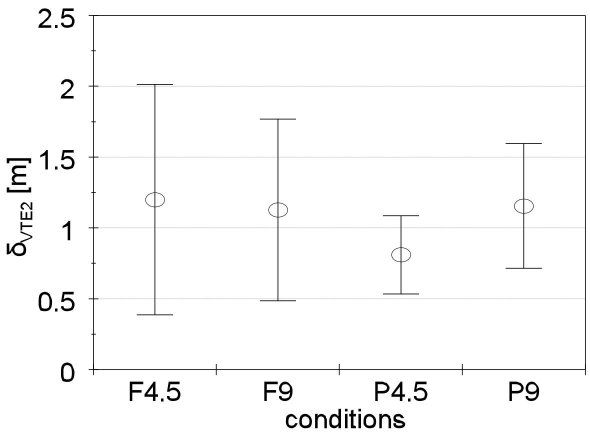


Fig. 7.43. *Vertical tracking performance in curves.*

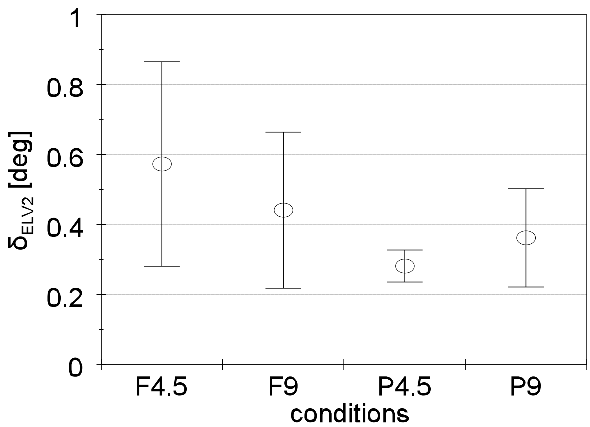


Fig. 7.44. *Elevator control activity in curves.*

Table 7.7. *Summary of the results from the two factor repeated measures analysis of variance for the performance measures listed in Table 7.4 and the data from Experiment II. Both the effects of tunnel size and prediction were tested, and it was tested whether there was an interaction between the two factors. Results which were significant at* α*=0.05 are accentuated.*

Measure	tunnel size (dF=1,19)	prediction (dF=1,19)	interaction (dF=1,19)
δ_{XTE1}	F=3.00, p=0.100	F=8.82, p=0.008	F=3.29, p=0.086
δ_{VTE1}	F=0.23, p=0.634	F=4.45, p=0.048	F=11.05, p=0.004
δ_{AIL1}	F=2.61, p=0.122	F=39.53, p<0.0005	F=10.18, p=0.005
δ_{ELV1}	F=1.36, p=0.257	F=16.43, p=0.001	F=6.39, p=0.021
δ_{XTE2}	F=0.38, p=0.547	F=32.24, p<0.0005	F=1.53, p=0.232
δ_{VTE2}	F=1.41, p=0.249	F=1.55, p=0.228	F=3.56, p=0.74
δ_{AIL2}	F=2.43, p=0.135	F=55.89, p<0.0005	F=0.08, p=0.782
δ_{ELV2}	F=0.91, p=0.353	F=17.16, p=0.001	F=12.15, p=0.002

7.3.5 Discussion

Although the Figs 7.37, 7.39, 7.41 and 7.43 all show a trend that both lateral and vertical tracking performance decrease with decreasing tunnel size, thus indicating a reversal as compared to the previously observed relation, this trend did not reach significance. Still, the results show that with these small tunnel sizes, the splay-rate gains are no longer in the region in which an equal ratio improvement in splay-rate gain yields an equal interval improvement in performance. Compared to the results presented in Table 7.6, the main difference is that no significant effect of tunnel size is found. Similar to the result in Table 7.6, the addition of a position predictor yielded a significant increase in lateral and vertical tracking performance on straight segments and a significant increase in lateral tracking performance in curved sections. When looking at Fig. 7.39 presenting vertical tracking performance on straight segments, there is a trend that in the absence of a predictor performance decreases with an increase in splay-rate gain whereas in the presence of a position predictor performance increases. This causes the interaction found for vertical tracking performance on straight segments. In spite of the fact that only two subjects were used in a repeated measures design, the results clearly confirm what was to be expected when further reducing tunnel size.

7.3.6 Summary and conclusions

The averages of δ_{XTE}, δ_{VTE}, δ_{AIL}, and δ_{ELV} for tunnel sizes from 4.5 to 90 m are presented in Figs 7.45 to 7.48, respectively. Each figure shows the results for straight and curved segments, both in the absence and the presence of a predictor. Similar to the results reported by Wilckens (1973) and Grunwald (1984), lateral control activity and lateral performance increase with decreasing tunnel size, both for straight and for curved segments.

The variation in the size of the tunnel shows the effect on tracking performance which is to be expected when changing the gain of the functional variable for position control.

On straight segments, the addition of a position predictor did not lead to an improvement in vertical tracking performance for the tunnel sizes investigated in the first part of the experiment. However, it improved vertical tracking performance in curved segments.

The results of the study show no interaction between error gain and position prediction for lateral or vertical tracking performance in the area of linear behavior. For aileron and elevator control an interaction between error gain and position prediction was found. In contrast to the results reported by Grunwald (1984), in the presence of a position predictor, control activity hardly increased with an increase in error gain. It is concluded that both on straight and curved segments the presence of a position prediction reduces the effects of tunnel size on control activity.

With a position predictor, splay rate is no longer the functional variable for position control.

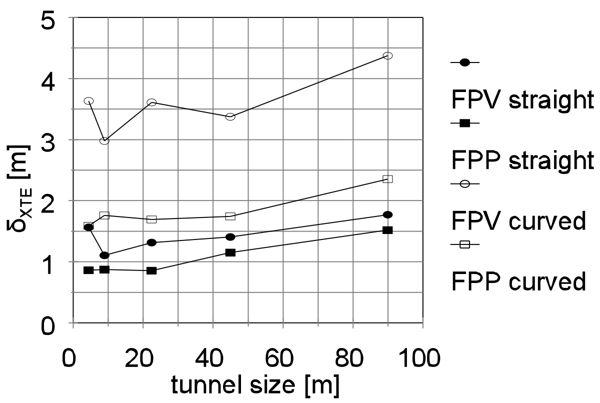


Fig. 7.45. *Overview of average lateral tracking performance for the different conditions tested.*

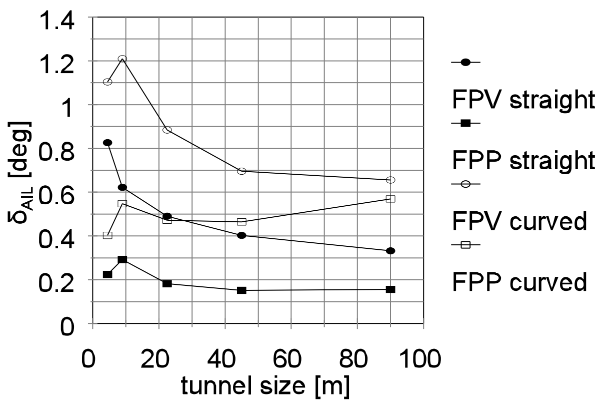


Fig. 7.46. *Overview of average aileron control activity for the different conditions tested.*

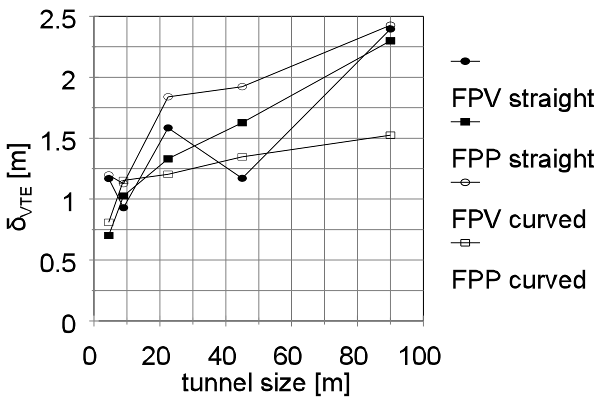


Fig. 7.47. *Overview of average vertical tracking performance for the different conditions tested.*

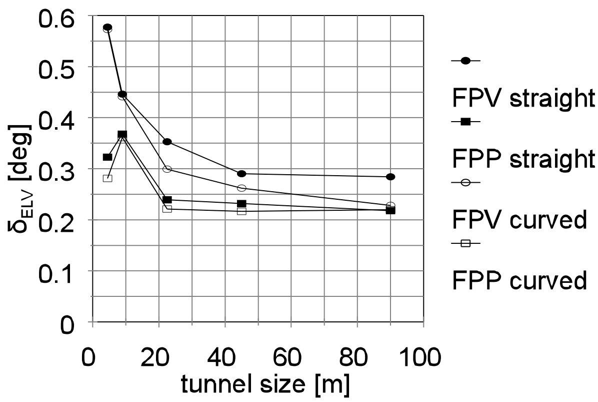


Fig. 7.48. *Overview of average elevator control activity for the different configurations tested.*

With respect to the use of information it is hypothesized that in the presence of an adequate prediction of the future position and attitude, the pilot focuses on the error presented by the predictor for the control task, and as a result control behavior will be dominated by closed-loop pursuit control. One might argue that this again reduces the pilot to a servo-mechanism whose task it is to keep the predictor centered. However, in contrast to the flight director, the predictor presents physically interpretable information which in combination with the trajectory preview provides the pilot with the freedom to decide how much attention is required to satisfy the guidance requirements and does not enforce a continuous compensatory control strategy. As pointed out by Grunwald (1996b), *'in contrast to the compulsory information provided by flight directors, however, the information provided to the pilot by the predictor is optional. This, for example, allows the pilot to leave the predictor for several seconds to scan other parts of the display to return to it later'*. The perspective presentation of the flightpath provides the information which allows the pilot to anticipate changes in the trajectory. When transitioning between straight and curved segments, a flightpath predictor enables the pilot to better determine the timing and magnitude of the required anticipatory control action. As a result, performance without the predictor is more variable.

Integration of a position predictor allows the pilot to increase the accuracy of the anticipatory control actions, both in timing and magnitude.

7.4 Error-neglecting control

As indicated in Sect. 3.5, one of the fundamental differences between a flight director command display and a perspective flightpath display is the nature of the visual cues for the control task. Haskell and Wickens (1993) indicated that task strategy depends on the type of displays used for the task. The combination of trajectory preview and information about the future position constraints allows the pilot to apply different control strategies. It is hypothesized that the answer to the question of how the pilot uses the preview presented by the tunnel depends on the task he is confronted with. When he is told to fly as accurate as possible, he will use the information with the highest error gain he can process to perform his task. The experiment discussed in Sect. 7.3 showed that in case of an additional predictor, the pilot will mainly concentrate on the information presented by this indicator. In Ch. 4 it was discussed that when the pilot's task is to keep the error below the thresholds indicated by the walls of the tunnel, he can apply a much wider variety of control strategies. An important aspect which characterizes the boundary control task is the fact that the pilot has the possibility to willingly ignore position and orientation errors. This type of control behavior is referred to as error-neglecting control. Thus, in contrast to the flight director task where the pilot functions as an error correcting mechanism, the preview on future position constraints allows the pilot to select a task and situation dependent control strategy. It is expected that when the task of the pilot changes from flying as accurate as possible to that of remaining within the boundaries represented by the walls of the tunnel, he will willingly ignore certain position and orientation errors.

As a result of this change in task strategy, his control behavior will change. This raises the question what cues the pilot uses to determine when to switch from error-neglecting to error-correcting control. If the decision to intervene would be based on separate thresholds for position and orientation errors, the pilot would not be utilizing information about the future position of the aircraft relative to the constraints.

It is expected that as a result of the multitude of visual cues conveying position and orientation information relative to the spatial constraints, the perceptual response of the operator is based on a combination of the available cues and not on a single position or orientation error which exceeds a certain threshold.

A better understanding of the control strategy requires more insight into the specific combinations of cues which causes the pilot to intervene. In Sect. 4.4 it was indicated that the moment an error-corrective control action is initiated might be related to the time-to-wall crossing (TWC). In Sect. 3.6.4 it was indicated that pilots might be able to make a better than first-order estimate of the TWC. To verify whether the moment the pilot initiates an error-corrective control actions is related to a prediction of the TWC, and, if so, whether the TWC can be approximated with a first or second-order model, an experiment has been performed.

7.4.1 Experiment

Experimental design. A repeated measures design was used, in which the task was performed 30 times.

Hardware. The experiment was conducted in the 3 degrees-of-freedom (DOF) moving-base flight-simulator of the Faculty of Aerospace Engineering at the Delft University of Technology. As in the previous experiment, the aircraft model was that of a Cessna Citation 500. In the initial conditions, the gear was down and flaps were set at 10 degrees. In contrast to the previous experiment, a side-stick was used to control elevator and aileron deflections.

Subjects. Five subjects, all professional airline pilots and all male, were instructed to fly an approach to landing. The difference in age between the youngest and the oldest subject was approximately 20 years. Table 7.8 gives an overview of the piloting experience of the subjects. None of the subjects had prior experience with the perspective flightpath display.

Table 7.8. *Piloting experience of the subjects.*

Subject	Flying hours
1	9000
2	250
3	1200
4	2500
5	3200

Task. The subjects were instructed to fly a curved approach to landing. As indicated previously, the preview on future position constraints allows the pilot to select a task and situation dependent control strategy. In an experiment, this makes it very difficult to investigate the relation between aspects of a certain control strategy as a function of visual cues. In the experiment discussed in Sect. 7.3, limits in tracking performance were investigated, and therefore pilots were motivated to maximize performance. In the current experiment, pilots have to be motivated to abandon continuous compensatory control and apply a dominantly error-neglecting control strategy. Although this is certainly not representative for the actual control strategy, it is believed that in this way it is easier to isolate the specific cues which allow an error-neglecting control strategy to be applied.

To prevent the subjects from applying a dominantly closed-loop compensatory control strategy, they were informed that the goal was not to fly as accurate as possible, but to remain inside the tunnel using a minimal amount of control actions. Subjects were explicitly instructed to intervene only at the moment when they thought the aircraft would otherwise leave the tunnel. To prevent them from executing extremely aggressive maneuvers, they were told that the resulting maneuvers should not be so aggressive that they would be perceived as uncomfortable. No direct constraint in terms of maximum roll angle or roll rate was given, leaving the qualification of uncomfortable to the pilots.

To reduce the cues which might stimulate the pilot to apply compensatory control, the experiment was performed in the absence of turbulence, and a relatively low error gain was used by presenting tunnels with a width of 135 meters.

To prevent the pilots from becoming accustomed to a particular approach, six different approaches were presented in a random order during the familiarization-, training-, and data flights. Each approach started at 2000 ft with a straight segment. This segment was followed by a curved segment which required a total change in heading of either +45 or -45 degrees. Table 7.9 presents an overview of the parameters describing the six approach trajectories.

Table 7.9. *Description of approach trajectories.*

Trajectory	Initial heading [deg]	Radius of curve [m]
1	45	1008
2	45	1370
3	45	2081
4	-45	1008
5	-45	1370
6	-45	2081

The radii of the curves in the different approach trajectories were 2081 m, 1370 m, and 1008 m. With an approach speed of 125 kts, this required pilots to bank approximately 10, 15, and 20 degrees, respectively.

Measures. With error-neglecting control, variables indicating the deviation from the forcing function cannot be used to compare performance since the deviation is not important as long as it remains within the constraints. Variables indicating the deviation from the constraints at the moment an error correcting control action is initiated can provide more insight into the visual cues the pilot uses to determine the moment to initiate an error-correcting control action. The measures which were used were cross track error, track angle error, and a first and second-order model of the time-to-wall crossing at the moment the pilot initiated an error-corrective control action. Table 7.10 presents an overview of these measures.

Table 7.10. *Overview of the measures used in the experiment.*

Measure	Unit	Meaning
XTE_C	m	Cross track error at the moment an error-corrective control action is initiated
TAE_C	deg	Track angle error at the moment an error-corrective control action is initiated
TWC_{C1}	s	First-order prediction of the time-to-wall crossing at the moment an error-corrective control action is initiated
TWC_{C2}	s	Second-order prediction of the time-to-wall crossing at the moment an error-corrective control action is initiated

Schedule. Subjects were given an instruction about the goal of the experiment, the Tunnel-in-the-Sky display format, and the control strategy they should apply. After this instruction, the subjects could acquaint themselves with the simulator and the display in a number of familiarization flights. The average instruction time including these flights was approximately one hour. After these flights, the training flights for the error-neglecting control strategy commenced.

The data flights were distributed over 5 sessions. In each session, the pilot flew the six different approaches in random order. Each approach lasted approximately 3 minutes, and after each approach approximately 3 minutes were needed to go to the next approach condition. After each session, which lasted approximately 35 minutes, a 15 minute break was given. Table 7.11 presents an overview of the schedule which was used.

Table 7.11. *Overview of the schedule used in the experiment.*

Activity	Duration (minutes)
Briefing	40
Familiarization flights	20
Training flights	100
Break	30
5 data sessions + breaks	250
Debriefing	15

Training. After a session of ten approaches, the number of control actions for each flight were used to determine how well the subject was able to apply an error-neglecting control strategy. These results were also presented to the subject to show him his progress. Although no direct criteria with respect to the aggressiveness of the maneuvers was given, all subjects indicated that they had soon learned which magnitude of the control actions still yielded a comfortable maneuver. At the end of the training, all subjects could apply a dominantly error-neglecting control strategy.

7.4.2 Data analysis

During the experiment, data was recorded at a sample rate of 11 Hz (Appendix B). For the analysis of the data, the error correcting control actions had to be separated from the control actions which always follow a corrective maneuver. Furthermore, the moment of initiation of the error-correcting control actions had to be determined. Detection of control actions was performed with the aid of an algorithm which uses aileron deflections as a function of along track distance as input and outputs the along track distances at which an aileron deflection is detected. To identify the error-correcting control actions, the resulting data is analyzed through visual inspection (Van Dorp, 1995). After the error neglecting control actions had been identified, the consistency between the direction of the control actions and the prediction of the tunnel intersection based on the first and second-order model of the TWC variable (left or right) was analyzed. When the model predicts an intersection of the left tunnel wall, and the pilot initiates an error corrective action to the left, the outcome of the model is regarded as inconsistent with pilot control behavior. The first-order model predicted such inconsistent actions in 5 out of a total of 91 analyzed situations, whereas the second-order model always predicted consistent actions. Therefore, only the TWC of the second-order model is used in the rest of the analyses (TWC_{C2}). From the resulting data, probability density functions of XTE_C, TAE_C, and TWC_{C2} were computed.

Whereas the total distribution of cross track error and track angle error are likely to approximate a normal population, a subset based on samples taken at the moment an error-correcting control action is initiated might not satisfy the criterium of normality. If this proves to be the case, the method of analysis of variance can not be applied to check for statistically significant differences and a non-parametric test is needed. A statistical analysis (non-parametric Kolmogorov-Smirnov), showed that indeed none of the distributions were from a normal population (van Dorp, 1995). Furthermore, no statistically significant differences were found between the distributions of control actions related to preventing crossing the right or left tunnel walls, allowing both distributions to be combined.

7.4.3 Results and discussion

Because the analyses showed that none of the variables were from a normally divided population, Fig 7.49 shows box plots of the distributions of TAE_C, XTE_C, and TWC_{C2} rather than plot of the means and standard deviations.

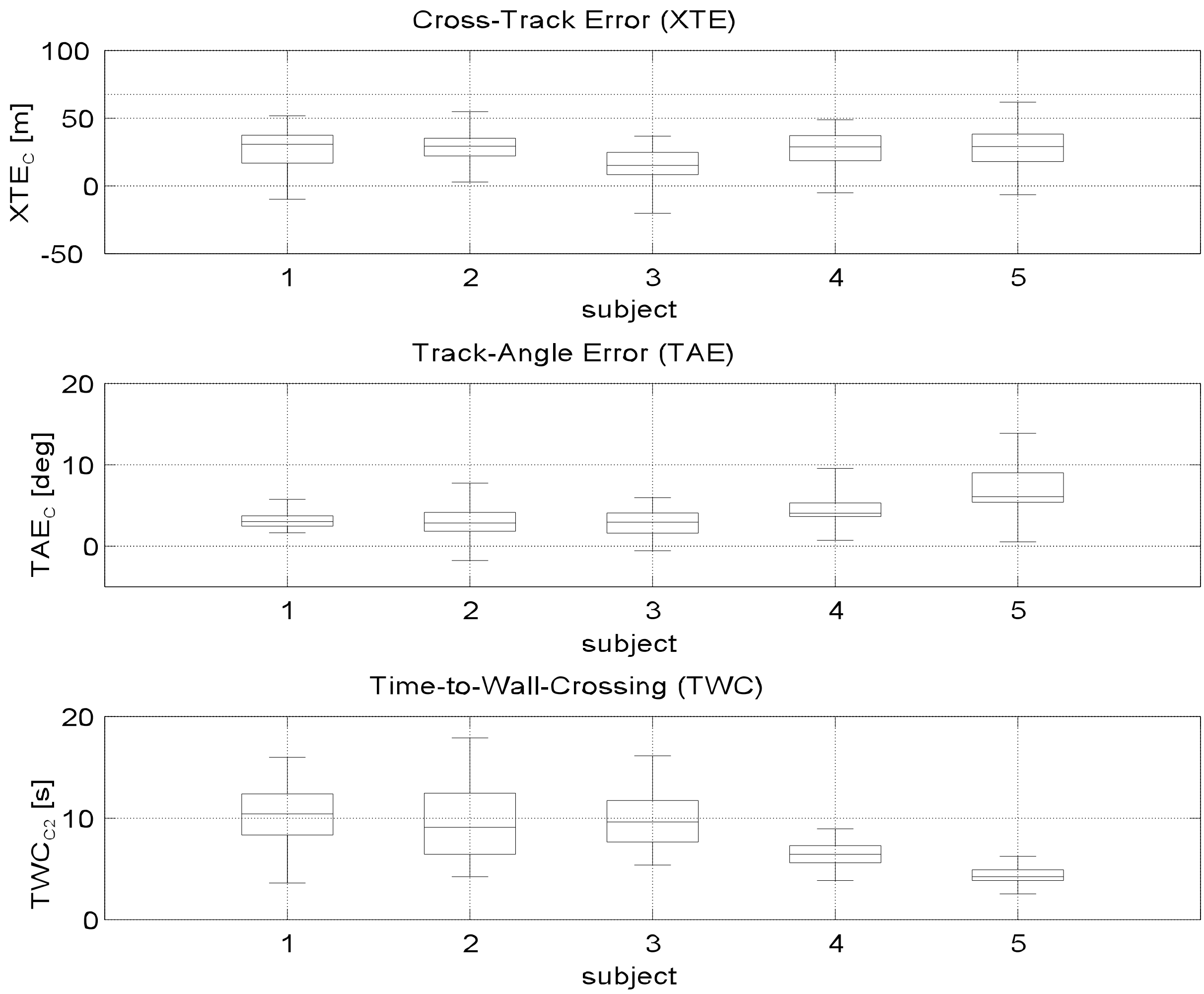


Fig. 7.49. *Box plots of cross-track error, track angle error and time-to-wall crossing.*

As can be seen from Fig. 7.49, the error-corrective control actions are initiated for a wide range of values of both XTE_C and TAE_C. Furthermore, the box plots of the TWC_{C2} show that the temporal spacing varies between pilots. The amount of temporal spacing is believed to be determined by a self-chosen safety margin which, in turn, is largely determined by the familiarity the pilot has with the airplane and its handling qualities.

Figs 7.50 and 7.51 present the estimated probability density function of the XTE_C and TAE_C variables, respectively. These figures indicate that there exists a large variation between the magnitudes of these variables and the number of initiated control actions. Furthermore, since no minimum threshold can be established in the distributions, it can be concluded that neither the cross track error nor the track angle error is solely responsible for switching from error-neglecting to error-correcting control. Fig. 7.52 presents the estimated probability density function of the TWC_{C2} based on a second-order model.

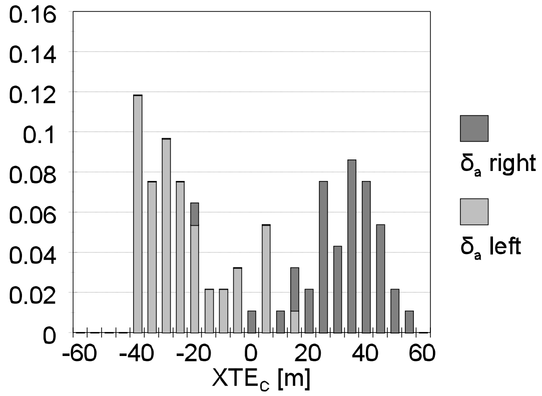


Fig. 7.50. *Estimate of the probability density of XTE_C, the cross-track error at the moment the pilot performs an error-correcting control action.*

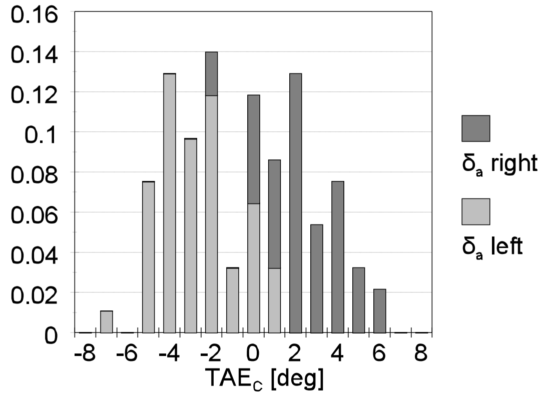


Fig. 7.51. *Estimate of the probability density of TAE_C, the track angle error at the moment the pilot performs an error-correcting control action.*

When examining the probability density function of the TWC_{C2} (Fig. 7.52), it can be seen that no control actions were made for TWC_{C2} values smaller than approximately 4 to 5 seconds. This strengthens the hypothesis that pilots maintain a certain temporal spacing from the boundaries represented by the tunnel walls, which they directly perceive from the display.

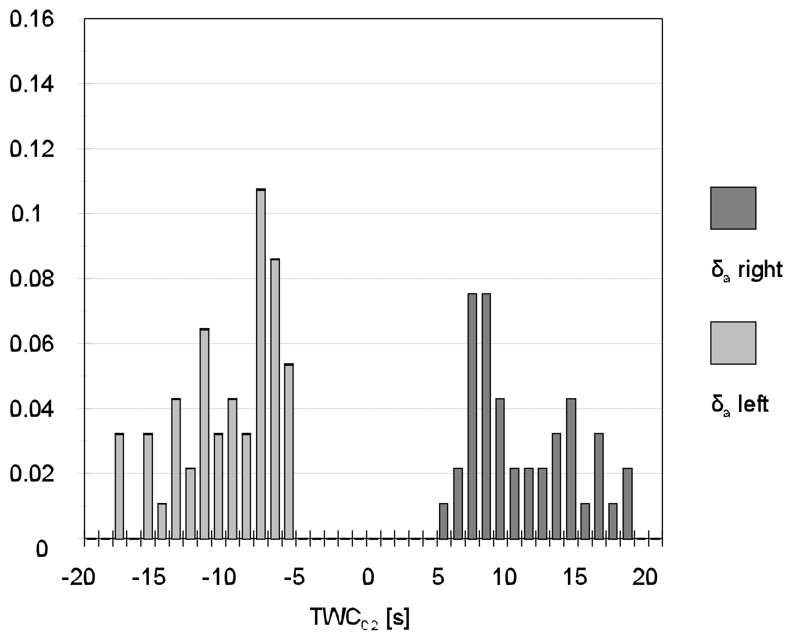


Fig. 7.52. *Estimate of the probability density function of TWC_{C2}, the 2nd order prediction of the time-to-wall crossing at the moment the pilot performs an error-corrective control action.*

To get an impression of the tracking performance which is achieved when using a dominantly error-neglecting control strategy, the standard deviation of the cross track error (δ_{XTE}) is calculated for each trajectory. The results have been averaged per pilot. Fig. 7.53 presents the average δ_{XTE} for the five subjects in the current experiment.

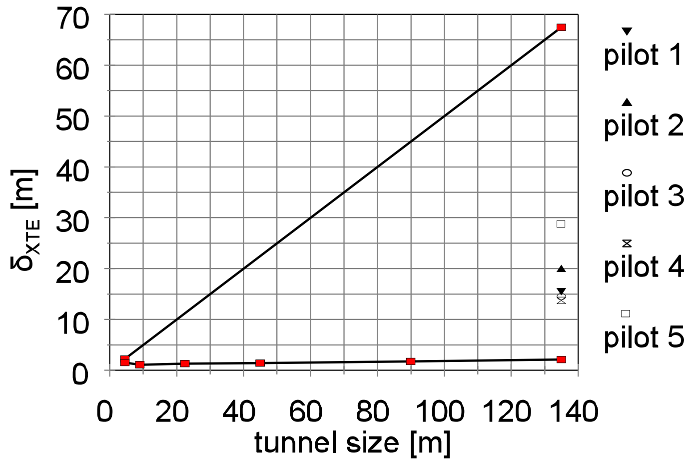


Fig. 7.53. *Lateral tracking performance of the five subjects during error-neglecting control relative to performance with continuous compensatory control. The lower line is based on the results from the experiment discussed in Sect. 7.3 and gives an indication of the maximum lateral tracking performance which can be achieved when applying a continuous compensatory control strategy. The upper line indicates the value of* δ_{XTE} *which would be obtained when flying exactly at the tunnel wall, thus representing the largest allowable value.*

The lower line in Fig. 7.53 is based on the results from the previous experiment in which pilots were instructed to minimize their position error and therefore provides an indication of the maximum performance which can be achieved. The upper line shows the theoretical value of the maximum δ_{XTE} in case pilots would fly just inside the tunnel. This figure shows that pilots were clearly not minimizing their position error.

7.4.4 Conclusions and recommendations

The study showed that neither in the distribution of the cross track error nor in the distribution of the track angle error, a lower limit could be identified below which pilots did not intervene.

As a result of the multitude of visual cues conveying position and orientation information relative to the constraints, the perceptual response is not based on a single position or orientation error exceeding a certain threshold, but on a combination of these cues.

The type of display determines the control strategies the pilot can apply. When a task calls for a continuous minimization of position errors, regardless of the required effort, a continuous closed-loop control strategy is likely to produce the most optimal results. Aircraft navigation requires the position errors to be maintained within predefined constraints.

Using instruments which force the pilot to continuously minimize position errors will unnecessarily increase task demanding load. Instruments which allow the pilot to apply an error-neglecting control strategy provide the pilot with the opportunity to make a trade-off between workload and performance.

Error neglecting control requires the pilot to make a prediction about the future position of the aircraft relative to the constraints. The efficiency of the control strategy depends on the accuracy of the prediction. For prediction time spans in the order of seconds, an aircraft trajectory can be predicted rather accurately with a second-order model. This study illustrates that with an egocentric perspective flightpath display, pilots perform better than a first-order predictor.

The spatially integrated presentation of guidance data allows pilots to extract information which allows them to make better than first-order estimates of the time when the aircraft would cross a tunnel wall, enabling them to apply an efficient error-neglecting control strategy.
Since pilots do not have to mentally integrate the values of position and angular errors and error rates and verify whether the outcome exceeds a certain threshold, which would be required for error-neglecting control with non-integrated displays, a perspective flightpath display reduces the task demanding load required for error neglecting control.

As indicated in Sect. 4.1, when comparing different display concepts it is necessary to go beyond performance measures such as distribution of position errors and control activity. Whereas the distribution of errors is very useful for comparing display concepts in terms of performance, the amount of attention needed to maintain performance within the predefined constraints is of interest with respect to potential trade-offs between performance and workload. Additional measures are needed to compare different display concepts in terms of the attention needed to satisfy task requirements. For boundary control tasks, an unnecessarily large safety margin towards the constraints is likely to indicate that the pilot either does not have sufficient information about his performance relative to the constraints, or does not apply an error-neglecting control strategy. In both cases, he spends more attention to control than is required by the task. For display evaluation, pilots can be instructed to apply an error-neglecting control strategy. To be able to compare different display concepts for this task, variables indicating the deviation from the constraints are needed. Since several studies indicate that, when presenting subjects with an error-neglecting control task, they tend to maintain a certain temporal distance towards the constraints, the second-order model of the TWC can be used as a measure which indicates how well a guidance display provides cues for error-neglecting control.

When comparing different display concepts for the guidance task, an analysis of the TWC variable provides more insight into the pilot's ability to utilize information about constraints.

7.5 Attitude and velocity vector aligned frames of reference

For the maneuvering task with the attitude aligned format, the pilot has to extract information about a flightpath angle change from the relative motion between the horizon and the FPV symbol (Fig. 7.54), whereas in the velocity vector aligned format the required data is directly conveyed through the vertical motion of the display (Fig. 7.55).

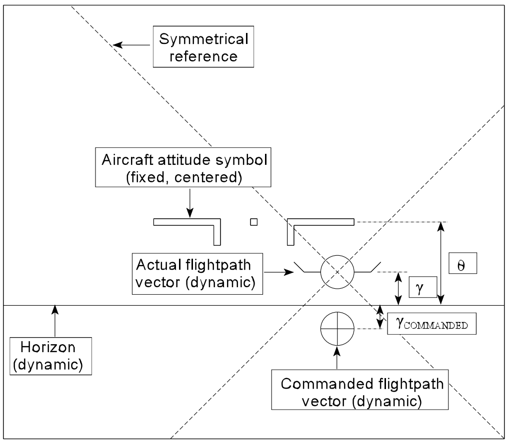


Fig. 7.54. *Attitude aligned frame of reference.*

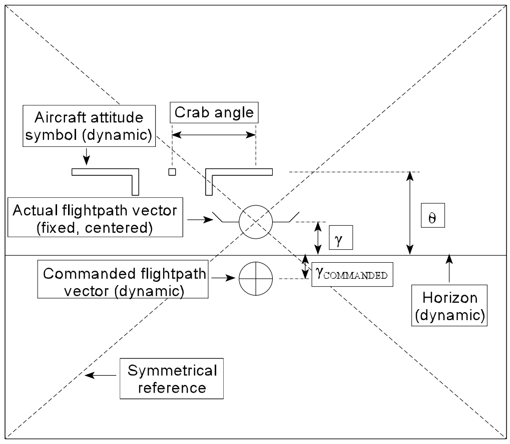


Fig. 7.55. *Velocity vector aligned frame of reference.*

In the attitude aligned condition the horizontal reference position of the tunnel is proportional to the difference between track and heading. In the velocity vector aligned format, the reference condition is always the center of the display. It is hypothesized that the absence of a symmetrical reference condition in the center of the screen increases the difficulty of the maneuvering task. Furthermore, dominant cues conveying information which is not directly needed for the task at hand might interfere. With respect to the effects of the frame of reference on display dynamics, it is hypothesized that when flying through the tunnel, the vertical motion of the display provides the pilot with a very convincing cue suggesting a directional change. With an attitude aligned presentation this is misleading information which may interfere with directional control. As discussed in Sect. 5.3.3, a velocity vector aligned perspective flightpath display is considered a more task oriented display. From a control theoretical point of view, it is quite clear that the stabilization task is better served by an attitude-aligned frame of reference. Since it is expected that future fly-by-wire aircraft provide full inner-loop stability augmentation, the fact that a velocity vector aligned display does not provide the required damping data through dominant visual cues becomes less of a problem. This raises the question whether with a perspective flightpath display the maneuvering task is indeed better served by a velocity vector aligned frame of reference. Another question, which emerged from the discussion in Sect. 5.11, is the influence of outer-loop data latency on perception and control. As indicated in Sect. 5.11, experimental evidence suggests that pilots are perceptually unaware of data latencies which already influence control behavior. Furthermore, the findings of Filarsky and Hoover (1983) suggest that the threshold for detecting latencies might be higher for integrated presentations. To obtain some feedback from pilots and gain more insight into the differences between attitude aligned and velocity vector aligned presentation of flightpath information for the maneuvering task, and test whether pilots would notice a significant latency in the position data, an experiment has been conducted.

7.5.1 Experiment

Experimental design. A two factor repeated measures within subject design was used. The factors are alignment, which is either attitude (A) or velocity vector (V), and a one second latency in the position data which can be either absent or present. In both alignment conditions, the same data needed to perform the maneuvering task was presented. The only difference was an offset as a result of the difference between track and heading, and different dynamic behavior with respect to the fixed screen.

Hardware. The experiment was conducted in the 3 degrees-of-freedom (DOF) moving-base flight-simulator at the Faculty of Aerospace Engineering of Delft University of Technology. As in the two previous experiments, the aircraft model was that of a Cessna Citation 500. In the initial conditions, the gear was down and flaps were set at 10 degrees. A side-stick was used to control elevator and aileron deflections. The simulator software did not provide an augmented flight control system needed to completely remove the pilot from the stabilization loop. To make sure that the pilots could focus on maneuvering the aircraft along the trajectory and did not have to spend a lot of effort on the stabilization task, the experiment was conducted with a well trimmed aircraft in the absence of turbulence. Since no flight control system to implement a control loop as represented in Fig. 5.11 was available, the option to display the commanded flightpath angle (γ_C) was omitted.

Subjects. Four professional airline pilots, all male, participated in the experiment. The difference in age between the oldest and the youngest subject was less than 10 years. Table 7.12 presents an overview of the piloting experience of the subjects. None of the subjects had any prior experience with perspective flightpath displays.

Table 7.12. *Piloting experience of the subjects.*

Subject	Flying hours
1	1850
2	1400
3	2700
4	2200

Task. A general problem when comparing different configurations with a perspective flightpath display is that the nature of control task (boundary control instead of error-zeroing) allows a wider variety of control strategies to be applied as compared to a more elementary display such as the flight director. As a result, the pilot has more possibilities to select a certain trade-off between control activity and performance. The fact that both control activity and performance may change between conditions makes a comparison quite difficult. One option to deal with this is to create conditions in which performance has to be maximized, forcing the pilots to employ a continuous compensatory control strategy and requiring them to minimize their thresholds for position and orientation errors. The alternative is to allow pilots to select the same control strategy for both conditions, and use their opinion and the computed control activities between the conditions as a criterium. The first approach is useful for situations in which the emphasis lies on determining performance limits. In reality, pilots do not continuously have to minimize their position error but must meet a certain performance criterium. The second approach requires the pilot to select approximately equal thresholds for position and orientation errors between the two conditions, but does not force them to minimize these thresholds. The previous two experiments focused on limiting cases, i.e. maximizing performance and maximizing the error-neglecting control time span. This was necessitated by the desire to evaluate the relation between the magnitude of certain cues and task performance. In this case, the opinion of the pilot is needed, and therefore the pilot is not instructed to apply a particular control strategy, only to remain within the constraints. This is considered more representative of the general situation and therefore this approach was selected.

To prevent them from becoming accustomed to a particular approach, six different approaches were presented in a random order. These approaches were the same ones as used in the previous experiment, and a description can be found in Sect. 7.4.1. To be able to compensate for possible learning effects, the order in which the conditions were presented was balanced between subjects. Subjects started each flight at an altitude of 1200 ft approximately 4 miles away from the runway threshold and were required to maintain an airspeed of 120 knots. This reference airspeed was indicated by a green bug on the speed-tape. At the beginning of each flight, the aircraft was in the landing configuration, and no aircraft configuration changes had to be made by the subject. A wind of 20 knots perpendicular to the runway was present in all conditions. As a result, only the velocity vector aligned presentation provided the pilot with a symmetrical reference condition in the center of the screen. With the attitude aligned version, the required crab angle of approximately 9 degrees on final approach yielded a translation of the flightpath approximately 17% of the display size. Since the crab-angle only yields a horizontal translation of the visual scene, the nominal splay angles were hardly affected. With the aircraft model which was simulated, the differences in lateral display dynamics were small. In contrast, the differences in vertical display dynamics were significant.

Measures. Tracking performance and control activity served as objective measures to compare between the conditions whereas pilot opinion on the ease of the control task served as a subjective measure. The standard deviations of the lateral and vertical position errors were used as performance measures. The standard deviation of the elevator and aileron deflections were used as measures for control activity. Table 7.13 gives an overview of the measures.

Table 7.13. *Overview of the measures which will be used in the statistical analysis of the data.*

Measure	Unit	Meaning
δ_{XTE}	m	Standard deviation of the cross track error
δ_{VTE}	m	Standard deviation of the vertical track error
δ_{AIL}	deg	Standard deviation of the aileron deflections
δ_{ELV}	deg	Standard deviation of the elevator deflections

Based on the results reported by Steinmetz (1986) it was anticipated that the resulting differences in performance might be quite small and that pilot opinion would provide the best indication.

Schedule. Before the experiment started, subjects were briefed on the display and the approach. The fact that in two approaches a latency in the position data was present was not mentioned on purpose. Pilots were informed that the goal was to keep the aircraft inside the tunnel and that they were not required to fly exactly in the center of the tunnel. After the briefing, the training sessions started. On the first day of the experiment, a break of 30 minutes was issued after the first training session. Subjects, however, commented that the control task was so easy that they did not experience any fatigue and just as well would like to continue. Furthermore, since the training data showed that subjects which were trained in the attitude aligned configuration also performed well in the velocity vector aligned configuration, the rest of the training and data sessions were combined. The total duration of the experiment was about half a day. Since the flight simulator was only available for two days, this limited the number of subjects to four. Table 7.14 presents an overview of the schedule which was used.

Table 7.14. *Overview of the schedule used for the experiment.*

Activity	Duration (minutes)
Briefing	60
Training configuration 1	30
Break	30
Data session	20
Break	20
Training configuration 2 and data session	40

Training. The performance which can be achieved is determined by the complexity of the control task, the resolution of the presented data and the amount of effort which can be invested. In this experiment, the resolution of the data and the complexity of the control task are the same between the conditions. As a result of the different dynamics and reference condition, the effort for extracting and using the required information might differ.

For Subject 1 and 4, training started in the velocity vector aligned configuration. For the other two subjects, training started in the attitude aligned configuration. Figs. 7.56 to 7.63 show the performance during the training flights for the curved segment and the final straight segment per subject.

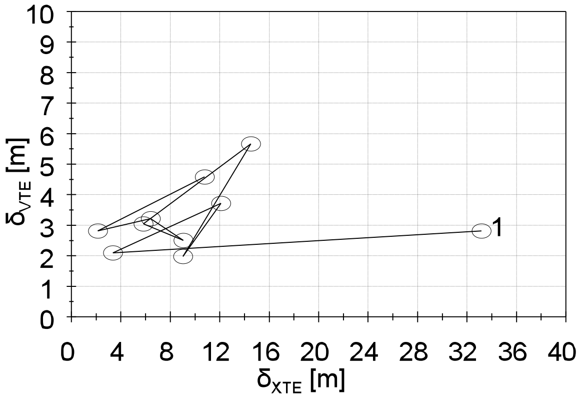


Fig. 7.56. *Performance per flight of Subject 1 in the curved segment.*

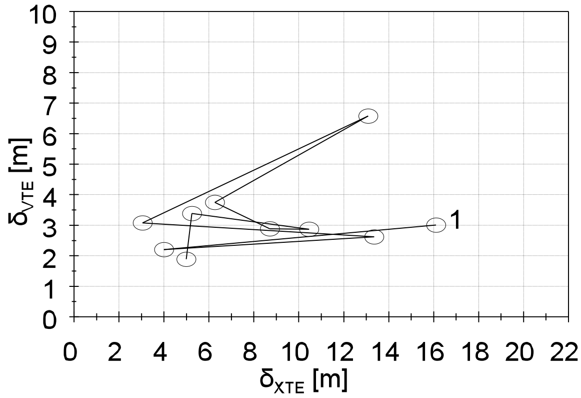


Fig. 7.57. *Performance per flight of Subject 1 on the final segment.*

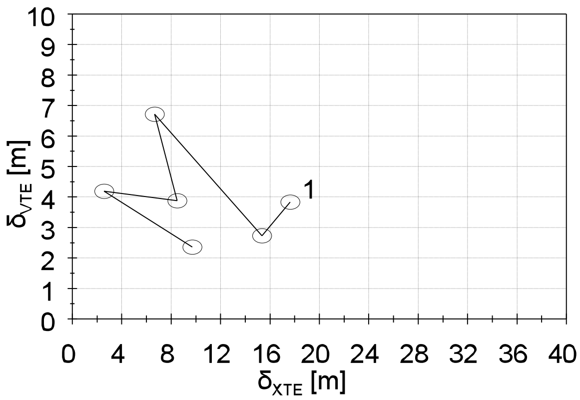


Fig. 7.58. *Performance per flight of Subject 2 in the curved segment.*

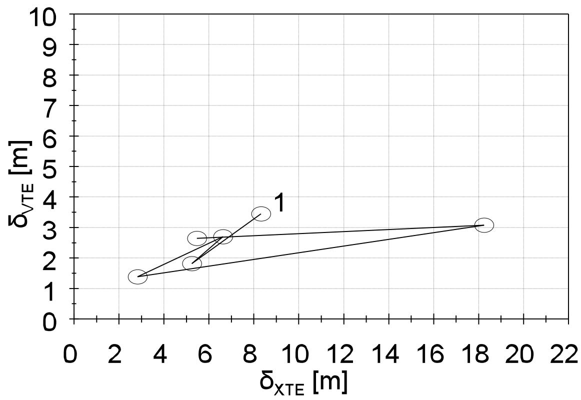


Fig. 7.59. *Performance per flight of Subject 2 on the final segment.*

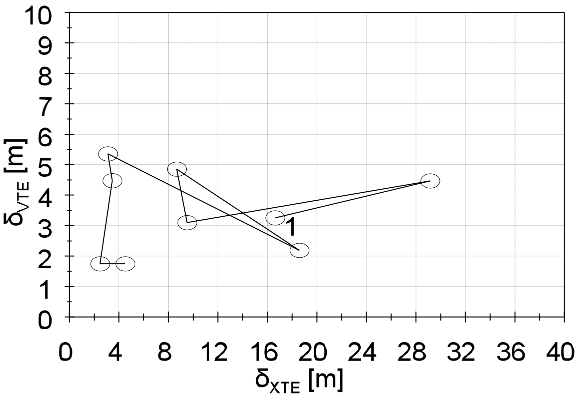


Fig. 7.60. *Performance per flight of Subject 3 in the curved segment.*

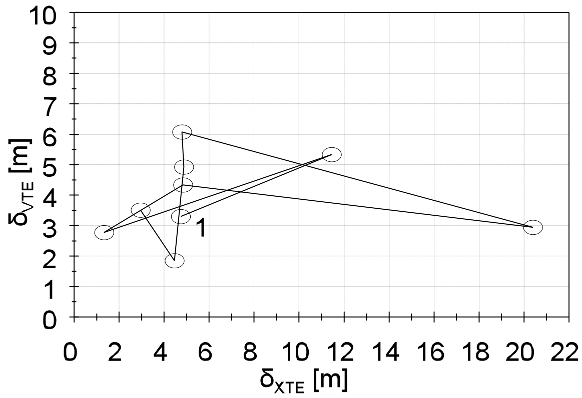


Fig. 7.61. *Performance per flight of Subject 3 on the final segment.*

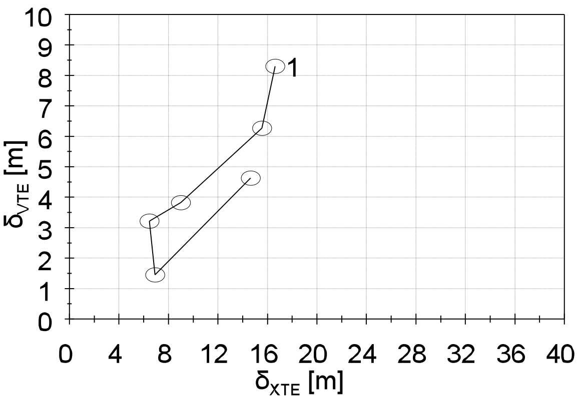


Fig. 7.62. *Performance per flight of Subject 4 in the curved segment.*

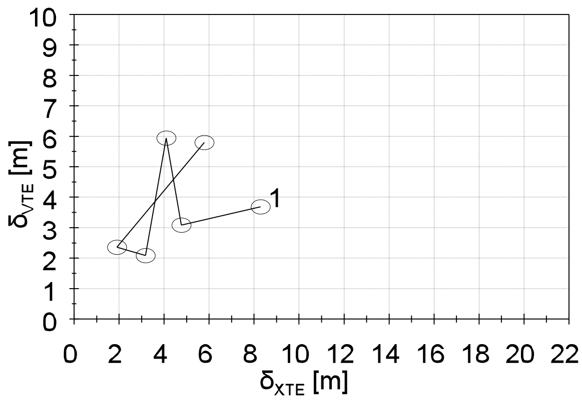


Fig. 7.63. *Performance per flight of Subject 4 on the final segment.*

As can be seen from Figs. 7.56 to 7.61, Subjects 1 to 3 started with quite a large value of δ_{XTE}, but were able to improve their tracking performance in a few sessions. Subject 4 already achieved quite a low value of δ_{XTE} on the first flight. Pilots commented that the display was easy to understand and easy to use. This agrees with the rapid improvement in performance shown in the previous figures.

7.5.2 Data analyses and results

During the experiment, aircraft state and pilot inputs were recorded at a rate of 14 Hz (Appendix B). From this data, position and orientation errors were calculated. The resulting data were divided into a category for the initial straight segments, a category for the curved segment, and a category for the final segment. Since anticipation cues are not considered when using splay angle and display translations, transitions between straight and curved segments were not analyzed. Since each of the four pilots flew five approaches in both conditions (attitude aligned and velocity vector aligned), twenty measures of δ_{XTE}, δ_{VTE}, δ_{AIL}, and δ_{ELV} were available for each of the three segments. Figs 7.64 to 7.67 show the average and standard deviation of these measures. The condition is indicated by a letter (A for attitude aligned, V for velocity vector aligned), and the segment by a number (1=initial, 2=curve, 3=final). To check for statistically significant differences between conditions per segment, a repeated measures analysis of variance was performed. Table 7.15 presents the results of the statistical analyses. Tests which reached a significance of α=0.05 are accentuated.

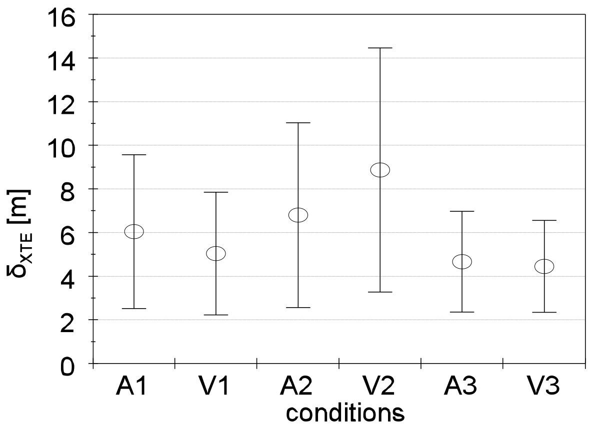


Fig. 7.64. *Lateral tracking performance for the attitude aligned condition (A) and the velocity vector aligned (V) condition for all three segments.*

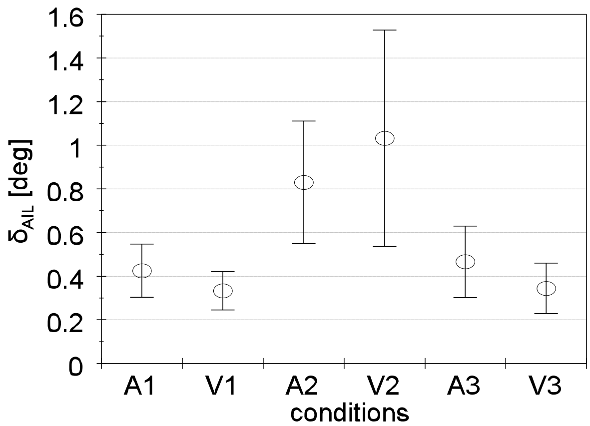


Fig. 7.65. *Aileron control activity for the attitude aligned condition (A) and the velocity vector aligned condition (V) for all three segments..*

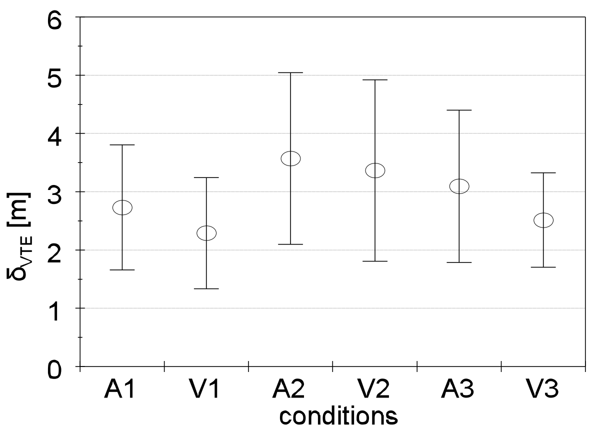


Fig. 7.66. *Vertical tracking performance for the attitude aligned condition (A) and the velocity vector aligned condition (V) for all three segments.*

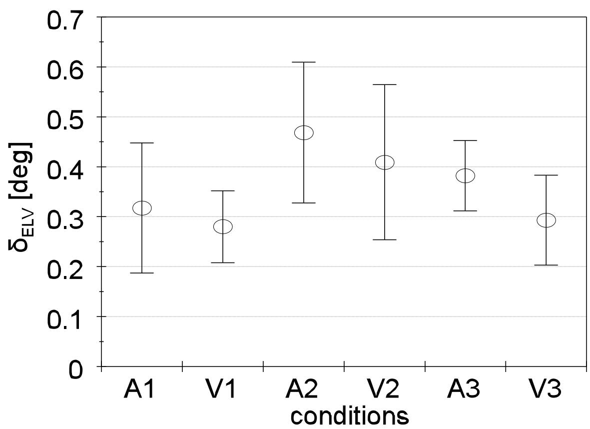


Fig. 7.67. *Elevator control activity for the attitude aligned condition (A) and the velocity vector aligned condition (V) for all three segments.*

Table 7.15. *Results from repeated measures ANOVA on attitude vs. velocity vector aligned for the measures listed in Table 7.13. The analysis was performed for the initial segment, the curved segment, and the final segment. As can be seen from this table, for the final segment, there is a significant difference in both aileron and elevator control activity. The only other significant difference is aileron control activity on the initial segment.*

Parameter	Initial (dF=1,19)	Curve (dF=1,19)	Final (dF=1,19)
δXTE	F=2.15, p=0.159	F=1.92, p=0.182	F=0.16, p=0.691
δVTE	F=3.32, p=0.084	F=0.23, p=0.636	F=2.74, p=0.114
δAIL	F=5.59, p=0.029	F=3.02, p=0.099	F=11.29, p=0.003
δELV	F=2.47, p=0.133	F=1.54, p=0.230	F=15.13, p=0.001

After the experiment, each subject was asked about his preference. Similar to the results reported by Steinmetz (1986), subjects unanimously preferred the velocity vector aligned frame of reference. Pilots commented that it was easier to fly and described the difference between the attitude and velocity vector aligned format as follows: *'With the attitude aligned format it feels like I am continuously chasing the tunnel, whereas with the velocity vector aligned display I'm flying through it'*. Pilots also mentioned that in the velocity vector aligned presentation they did not need the aircraft symbol. Pilots were also asked whether they noticed any particular differences. Two pilots commented that they thought the aircraft dynamics had changed slightly, but none of them noticed any conflicting visual cues. Furthermore, pilots commented that it was hard to anticipate the required bank angle needed to fly the curved segment.

7.5.3 Discussion of the results

The fact that in the velocity vector aligned presentation pilots commented that they did not need the aircraft attitude symbol in combination with the small number of control inputs made by the pilots, confirms that the effort required for stabilizing the aircraft was minimal and they could focus on the maneuvering task. The lag of the flightpath angle (γ) did not cause any problems for the maneuvering task, which is in contrast to the results reported by Lambregts et al. (1979). This is probably caused by the difference in control task and the visual feedback. In the experiments of Lambregts et al. (1979), subjects were required to track a reference γ signal. In the current experiment, γ_{ref} changed only once, at the beginning of the three degree glidepath. Rather than tracking a changing γ_{ref}, pilots were to maintain their position error below the threshold indicated by the tunnel walls, allowing them to apply a lower gain which reduces the effects of the response lag.

Since pilots were instructed to remain inside the tunnel, but not to fly as accurate as possible, they were free in determining the initiation of control actions and their performance criterium. The performance data in Fig 7.64 and 7.66 shows, that both with the attitude aligned and the velocity vector aligned format the pilots were able to stay well inside the tunnel. This indicates that in spite of the differences caused by the frame of reference, both displays provide the cues to achieve the desired performance. The statistical analysis did not reveal a significant difference in performance between the two conditions. This strengthens the assumption that pilots were able to use approximately equal thresholds for position and orientation errors in the two conditions. As a result, pilot opinion and control activity are considered good indicators of the influence of alignment on task difficulty.

With the attitude-aligned format, the cues for directional and position control are influenced by aircraft attitude. With respect to aileron control activity, a significant reduction is found for the velocity vector aligned format on both straight segments. Since the lateral display dynamics for both conditions were almost the same, it is assumed that the increase in control activity is caused by the fact that the pilot has to infer the required information from the relative motion between two display elements.

For elevator control activity, a significant reduction is found on the final straight segment. The reduction in control activity suggests that with the velocity vector aligned format it is easier to perform the maneuvering task. This agrees with the opinion of the subjects. The higher control activity in the attitude aligned configuration and the fact that the difference in reference position is very small, suggest that with the attitude-aligned format the dominant pitch cue increased elevator control activity unnecessarily.

In curves there is no symmetrical reference condition for lateral control. As a result no direct cues for directional control are available. Pilots have to infer their orientation error from position error-rate which is best conveyed by the changes in splay angle of the tunnel lines intersecting the screen boundaries. The dynamics of these cues are not influenced by the frame of reference, which agrees with the fact that no significant difference in aileron control activity is found between the two conditions. Kahneman (1981) proposed that all attributes of a single object are processed in parallel. Given the fact that the tunnel is holistically perceived and the splay angles are affected both by horizontal and vertical position errors, it is hypothesized that pilots also use the splay-rate cue for vertical control. This agrees with the fact that for the curved segments no significant difference in elevator control activity is found.

In Sect. 5.11.5, it was indicated that a position data latency might cause a perceived change in handling qualities due to the delayed temporal range cues. It was also indicated that when the mismatch between the actual pattern and the expected pattern exceeds a certain threshold, a perceptual conflict will occur. The comments made by the subjects suggest that they were perceptually unaware of the position data latency. Their remarks about the perceived change in handling qualities agree with what was expected.

The remarks that subjects had difficulty anticipating the required bank angle in the curved segment agree with the discussion in Sect. 3.5.5. Such remarks were not made by the subjects participating in the experiment discussed in Sect. 7.2. However, in that experiment only a single approach trajectory was used, and therefore the subjects knew how much bank angle was required. This allowed them to apply a more accurate open-loop control action for the initiation of the curve and results in less overshoot, yielding a better tracking performance. This fact has also been pointed out by Grunwald (1996a).

7.5.4 Conclusions

Subjects perceived the use of a velocity vector aligned display as a reduction in task difficulty. In spite of the small number of subjects, the unanimous agreement about the superiority of the velocity vector aligned frame of reference for the maneuvering task provides confidence that the concept has potential.

> For flight control systems which do not require the pilot to perform the stabilization task, a velocity vector aligned display is likely to result in a reduction of task demanding load.

Of course, it is important to realize that this research only investigated the influence on the maneuvering task, and other factors (e.g. training) must also be taken into account when selecting the frame of reference. Results from the training sessions and comments made by the subjects showed that they had no difficulty in adapting between the two different alignments.

> It is very likely that only very little training time is needed to transition between an attitude and a velocity vector aligned format.

Unlike some virtual reality systems in which cue consistency requirements determine the frame of reference, a task oriented approach may have advantages for certain applications. For a perspective flightpath display this implies that although the display itself is fixed relative to the aircraft, this should not be the only motivation to select the frame of reference.

7.6 In-flight testing

7.6.1 Introduction

In the context of the research into the multimode integrated approach system (MIAS) which is performed at the Faculty of Electrical Engineering of Delft University of Technology (Breeuwer et al., 1993; Breeuwer et al., 1995), flight trials were planned to demonstrate the feasibility of uplinking differential GPS corrections through the MLS auxiliary data words. It was clear that these flight trials provided an excellent opportunity to demonstrate the feasibility of the DELPHINS Tunnel-in-the-Sky concept in a real aircraft.

7.6.2 Experiment

Hardware. The experiment was conducted with a Cessna Citation II aircraft.

Display format and functionality. The display format used was the basic tunnel display with tape indicators for altitude and airspeed (Fig. 7.1). An egocentric inside-out attitude aligned frame of reference was used. The width and the height of the tunnel were set at 45 m. Functionality of the software included the possibility to generate a flightpath in the direction of the current pitch and heading, and to generate intercept tunnels (Sect. 6.4.4). A small database contained the coordinates of the runway in Aberdeen, and two straight-in ILS approach paths. The laboratory aircraft was not equipped with an inertial reference system (IRS), and as a result no information to directly drive an earth-referenced velocity vector was available.

Subjects. Since this was a flight test to demonstrate the feasibility of the system, only a single pilot participated. The pilot had approximately 5600 logged flying hours, and due to his participation in the experiment described in Sect. 7.3 and the participation in various demonstrations in the flight simulator, possessed considerable experience in flying the Tunnel-in-the-Sky display.

Task. The task was to safely fly the aircraft and stay inside the tunnel during a number of test cases.

7.6.3 Results and discussion

To allow for a final complete test of the system, the display was initially installed in the passenger cabin. The first test took place on December 19, 1994. During take-off a minor problem in the communication with the MIAS system was detected which was caused by a specification error. This problem was easily solved, and about 5 minutes after take-off the system worked properly and was subsequently installed in the cockpit.

After this, the display was installed in the cockpit. The pilot in the right seat performed the tests, and the pilot in the left set acted as safety pilot. Initial tests were performed on the flight to

Aberdeen. During these tests, no differential GPS corrections were available, and as a result of the selective availability the navigation system error exhibited a low frequency oscillation. For these tests, trajectories were generated during the flight. These trajectories consisted of straight tunnel segments with a width and height of 45 m in the direction of the aircraft's heading and started at the actual location of the aircraft. As a result, in the presence of crosswind the pilot had to change his track each time a new tunnel was generated. The fact that the pilot had to change his track to remain inside the tunnel caused him to initially cross the tunnel wall shortly after entering the tunnel. However, the pilot soon was able to intercept the tunnel and fly at the crab angle which was required to remain inside the tunnel. Since there was no direct indication of the inertial direction of flight, the pilot had to rely on the cross track error and cross track error rate cues for lateral control. Combined with the high position error gain this required quite an aggressive control strategy and caused some oscillations in the lateral position. Fig. 7.68 shows the cockpit with the perspective flightpath display during a test in a straight tunnel segment.

In the neighborhood of the airport of Aberdeen the MLS dataword channel could be received and the MIAS system transmitted the differential GPS corrections to the aircraft by using the auxiliary datawords of the MLS system. On December 20, several approaches to an altitude of 200 ft were flown with the display. The pilot commented that it was difficult to stay inside the tunnel size when a crosswind was present. This was expected, as no direct indication of the inertial velocity was available. Furthermore, the pilot commented on the need for a pitch tape. Clearly, the effort required to stabilize the inner-loop was more than was expected from simulator trials. In Sect. 5.10.1 two potential solutions to this problem, the integration of additional symbology and the color coding of the horizon, have been proposed.

7.6.4 Conclusion

The success of the in-flight demonstration showed that with currently available of-the-shelf components, a low-cost perspective flightpath display can be implemented. It is important to realize that the display system hardware for this project was developed because existing display systems for aircraft were too expensive and did not offer rapid prototyping capabilities. From an architectural point of view, the system which was developed closely resembles those of today's electronic flight displays. For a production version, most of the development cost will be caused by concept certification and software development. Thus, although initial development cost will be high, from a hardware point of view, a production version does not have to be more expensive than today's primary flight displays. With respect to the presentation, the tests indicated that additional cues may be required to increase the resolution of the pitch angle information.

Fig. 7.68. *In-flight test of the perspective flightpath display on December 19, 1994. The pilot has to remain inside the tunnel. The presentation of the flightpath has been accentuated.*

7.7 Summary and future tests

Fig. 1.2 provided an overview of the systems involved in the presentation of navigation data. For an implementation, the representation rules and the transform rules must be specified. In Ch. 5 guidelines for the specification were developed, and in Ch. 6 an initial specification and implementation were discussed. As indicated in Sect. 1.6 and illustrated in Fig. 1.3, increasing the level of detail of the design guidelines is an iterative process requiring pilot-in-the-loop evaluations. In this chapter, a number evaluations have been presented which served to increase the level of detail of the design guidelines. The guidelines have been used to specify format and functionality for in-flight testing. Data from the simulator experiments and pilot comments showed that the display is easy to learn and easy to use. The in-flight demonstration showed that no fundamental technical limitations exist which prevent the application of a perspective flightpath display for aircraft navigation and guidance.

To gain experience with the additional functionality described in Sect. 6.4, an initial interaction concept was developed in 1994 and the functionality was implemented for use during the in-flight proof-of-concept demonstration in Aberdeen. During 1995, the concept was extended to be used in a future ATC scenario, allowing uplinks and visualization of proposed trajectories. Laboratory demonstrations of the concept to pilots were subsequently given, and an in-flight concept demonstration of this method is scheduled in the last quarter of 1996 in cooperation with the Avionics Engineering Center (AEC) of Ohio University in Athens. Fig. 7.69 shows the installation of the display system in the cockpit of the DC-3 laboratory aircraft of the AEC.

Fig. 7.69. *Display system installed in the DC-3 laboratory aircraft of the Avionics Engineering Center of Ohio University in Athens.*

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The research described in thesis focused on the development of an integrated design approach for an MMI based on the presentation of spatially integrated data. In Sect. 1.7 it was stated that the goal of this thesis is to identify, structure and place into context the technical, control-theoretical, perceptual, and cognitive aspects involved in the design process of an MMI for 4-D navigation based on the presentation of spatially integrated data. The research described in this thesis has resulted in the following conclusions:

- To exploit the simplification mechanism of the human perceptual system which is developed through years of repeated confrontation with the rules of perspective scenes and therefore allows rapid interpretation of otherwise complex visual scenes, the required flightpath must be presented as it would be seen when it was actually painted in the sky (Sect. 2.7.2).
- The presence of preview on the future trajectory and its constraints provide the pilot with the opportunity to anticipate changes in requirements, and thus allows him to stay ahead of the situation (Sect. 3.3).
- An essential difference between a flight director and a perspective flightpath display is that a perspective presentation of the flightpath allows the extraction of position and orientation errors, which is impossible from a flight director display (Sect. 3.4).
- In an attitude aligned frame of reference, the cues resulting from a single snapshot of the situation provide not enough information to zero the orientation errors. Additional information, contained in the dynamic cues resulting from the presentation of successive images, is needed to extract the direction of travel from the center of optic outflow (Sect. 3.5.3).
- For control, the basic requirement is that the pilot is able to extract splay angle, splay rate, and amount of translation of the tunnel from the presentation (Sect. 3.5.4).

- Since the velocity cues resulting from the dynamic presentation of the flightpath cannot be considered reliable indicators for either absolute or relative velocity and are inertially referenced, additional data about the velocity relative to the airmass must be presented, for example by means of a separate airspeed indicator (Sect. 3.6.3).
- The presence of a range of error gains allows the operator to select his own weighting function, and choose to neglect errors and error rates within certain constraints (Sect. 4.6).
- The freedom in timing to switch between the different strategies allows the pilot to better distribute his resources (Sect. 4.6).
- When using an egocentric display for the guidance task, a satisfactory level of global and navigational awareness calls for the use of an additional, exocentric view of the situation (Sect. 5.3.1).
- Since the size of the tunnel is the parameter with which the gain of the functional variable for position control is determined, the selection of the dimensions of the tunnel should be based on requirements with respect to the maximum allowable flight technical error (Sect. 5.6.1).
- Since at present no validated pilot models for use with a perspective flightpath display are available, the relation between splay gain and tracking performance must be obtained through pilot-in-the-loop experiments (Sect. 5.6.1).
- The representation of the flightpath should be designed so, that it is perceived as an object, not as a collection of elements (Sect. 5.5.4).
- To exploit symmetry as an emergent feature, the representation should be symmetrical about the horizontal and vertical axis (Sect. 5.5.4).
- To provide cues for resolving ambiguity and allowing the perception of temporal range information, cross section frames should be included. Since the magnitude of the cues reduces with increasing distance from the viewpoint, cross section frames are no longer needed beyond a certain viewing distance (Sect. 5.5.4).
- To exploit the capability of humans to accurately judge horizontalness and verticalness, the cross section should contain horizontal and vertical elements (Sect. 5.5.4).
- To allow the direct perception of perspective splay angle, interconnections between the cross sections should be used (Sect. 5.5.4).
- To provide cues which allow the temporary use of an error gain which is independent of tunnel size, the cross sections should contain an indication of their center (Sect. 5.5.4).
- To increase velocity cuing, these interconnections can consist of line segments which must be equally spaced in 3-D to yield correct edge rate and flow rate cues (Sect. 5.5.4).

- When using spatially integrated data presentation, one should distinguish between the need for veridical perception of the spatial layout and the goal of reducing the required effort for integration and interpretation of the displayed data. The latter requirement is much easier to satisfy than the former one and allows much more trade-offs to be made (Sect. 5.4.3).
- The level of detail of the representation of objects should be high enough to allow spontaneous recognition. The representation should be consistent between different displays, and allow the manipulation of certain attributes to attract the pilot's attention (Sect. 5.9).
- For the specification of the display size, the angular compression should be used as a criterium. The maximum allowable angular compression follows from stability and guidance requirements, which dictate thresholds with respect to the minimum perceivable display motion. When the physical limitations in display size dictate an angular compression which exceeds the maximum allowable angular compression, presentation of predictive data can be used to compensate for the reduction in stability (Sect. 5.7).
- The question whether a perspective flightpath display can be presented on a HUD should be changed into the question *whether*, and if so, *how much* the design constraints imposed by the display medium influence the possibility of a display format to satisfy the task requirements which governed its design (Sect. 5.12).
- When using a perspective flightpath display in combination with a flight control system which allows the pilot to directly control flightpath angle rate, the presentation of the commanded flightpath angle might be required (Sect. 5.10.6).
- As a result of the enormous freedom in the design, a comparison between a certain flight director and a certain perspective flightpath display in terms of tracking performance can not produce any generalizable results (Sect. 5.13).
- The variation in the size of the tunnel shows the effect on tracking performance which is to be expected when changing the gain of the functional variable for position control (Sect. 7.3.6).
- With a position predictor, splay rate is no longer the functional variable for position control (Sect. 7.3.6).
- Integration of a position predictor allows the pilot to increase the accuracy of the anticipatory control actions, both in timing and magnitude (Sect. 7.3.6).
- As a result of the multitude of visual cues conveying position and orientation information relative to the constraints, the perceptual response is not based on a single position or orientation error exceeding a certain threshold, but on a combination of these cues (Sect. 7.4.4).
- Using instruments which force the pilot to continuously minimize position errors will unnecessarily increase task demanding load. Instruments which allow the pilot to apply an error-

neglecting control strategy provide the pilot with the opportunity to make a trade-off between workload and performance (Sect. 7.4.4).

- The spatially integrated presentation of guidance data allows pilots to extract information which allows them to make better than first-order estimates of the time when the aircraft would cross a tunnel wall, enabling them to apply an efficient error-neglecting control strategy (Sect. 7.4.4).
- Since pilots do not have to mentally integrate the values of position and angular errors and error rates and verify whether the outcome exceeds a certain threshold, which would be required for error-neglecting control with non-integrated displays, a perspective flightpath display reduces the task demanding load required for error neglecting control (Sect. 7.4.4).
- When comparing different display concepts for the guidance task, an analysis of the time-to-wall crossing variable provides more insight into the pilot’s ability to utilize information about constraints (Sect. 7.4.4).
- For flight control systems which do not require the pilot to perform the stabilization task, a velocity vector aligned display is likely to result in a reduction of task demanding load (Sect. 7.5.4).
- It is very likely that only very little training time is needed to transition between an attitude and a velocity vector aligned format (Sect. 7.5.4).
- No fundamental technical limitations exist which prevent the application of a perspective flightpath display for aircraft navigation and guidance (Sect. 7.7).

8.2 Recommendations

- The investigation into the extraction of temporal range information towards constraints such as the tunnel walls, showed that it is very likely that pilots are able to make better than first-order estimates of the time-to-wall crossing. The mechanism behind this estimation process should be addressed in more detail.
- The in-flight experiment indicated a need for an increase in the resolution of pitch angle cues. Two potential solution, the integration of additional symbology and the color coding of the horizon in different levels of initensity, were proposed in Sect. 5.10.1, and both should be evaluated.
- Existing designs have been compared in terms of design parameters, and it is not always obvious why a certain design performs better than another. This makes it difficult to justify design decisions and analyze trade-offs without extensive pilot-in-the-loop experiments. To get a better insight in the differences between designs, they should be compared in terms of the presence and magnitude of task related visual cues.

As indicated in the introduction, the reason why better displays are needed is to increase safety in order to allow an increase in airspace capacity. To achieve this goal, this thesis focused on an integration of knowledge from different disciplines in order to structure the design process of displays which present spatially integrated data about the desired trajectory. This allows the efficient development of technically feasible solutions which exploit specific capabilities of the human operator to minimize the effort which is required for perception, interpretation and evaluation of the presented data. However, this is only a first step. The following recommendations aim at improving the possibility that perspective flightpath displays will be introduced in the near future:

- To reduce the number of pilot-in-the-loop studies which are needed to determine the values of tunnel width and tunnel height in order to meet the performance requirements, models describing pilot control behavior when using a perspective flightpath display for the tracking of curved and straight segments must be developed.
- For the integration of this concept in an aircraft, the data which is required to drive the display must be available from the onboard sensors. In Sect. 5.11 it was indicated that this data must meet control theoretical and perceptual requirements, and that since margins exist, trade-offs are possible. It was also indicated that at present no criteria exist which specify how these trade-offs should be made. To determine minimum system requirements, this topic must be addressed in more detail.
- The next step is the detailed design of a display format and the selection of the design parameters for a specific airplane. To prevent a wide variety in display formats, standards for the symbology should be proposed and agreed on by the pilots, the avionics manufacturers and the certification authorities.
- Before any new display concept for aircraft guidance can be introduced, certification is required. An important aspect is to demonstrate that the concept meets the performance requirements. This comprises pilot-in-the-loop demonstrations in real flight and in a flight simulator. Numerical fast-time simulation could also aid in the certification process. Therefore, here too, validated models for describing pilot control behavior with a perspective flightpath display are needed.

To address these challenges in an efficient way, a close cooperation is needed between the institutes performing research into perspective flightpath displays, the avionics manufacturers, and the certification authorities. To continue the research into perspective flightpath displays and start to solve many of the remaining problems, the department of Telecommunications and Traffic Control Systems (TVS) of the Faculty of Electrical Engineering initiated phase II of the Delft program for hybridized instrumentation and navigation systems (DELPHINS II), which runs from 1996 to 2000. This research is mainly supported by the Dutch Science Foundation (STW).

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LIST OF SYMBOLS

α	angle of attack
γ	flightpath angle
γ_C	commanded flightpath angle
ΔS	change in splay angle
ΔS_{VTE}	change in splay angle caused by a vertical track error
ΔS_{XTE}	change in splay angle caused by a cross track error
ΔTAE	change in track angle error
δ_a	aileron deflection
δ_e	elevator deflection
δ_{AIL}	standard deviation of the aileron deflections
δ_{ELV}	standard deviation of the elevator deflections
δ_{VTE}	standard deviation of the vertical track error
δ_{XTE}	standard deviation of the cross track error
η	current cross track error
θ	pitch angle
θ_{nom}	nominal pitch angle
ξ	spatial angle to define location of point on viewplane in terms of azimuth and elevation
$d\xi /dt$	rate of change of spatial angle ξ
σ_{roll}	average roll angle
σ_{TAE}	average track angle error
σ_{XTE}	average cross track error
φ	roll angle
φ_{nom}	nominal roll angle
ψ	the location of the point in the curved segment specified by the relative change in track
ε	error to be zeroed
d	looking distance, the distance from the viewpoint to the point in the 3-D world
d_c	distance remaining to the curvature
d_{min}	distance between viewpoint and cross section frame which is just inside the field of view
d_v	distance between the eye reference point and the display

d_w	distance towards the tunnel wall
f	frame number
h	tunnel height
l	frame spacing
n	dimensionless ratio of frame-spacing and tunnel size
r	yaw rate
w	tunnel width
x	distance between the central display axis and a reference point
x_{err1}	horizontal deviation on the viewplane from the reference position due to a position error
x_{err2}	horizontal deviation on the viewplane from the reference position due to an orientation error
x_n	distance between location of the projection of P_n on the viewplane and the central display axis

D_{persp}	perspective distortion
FOV	geometric field of view
FPAE	flightpath angle error
G_s	sensitivity of the curvature cues, indicating the ratio of the relative change in display location and the relative change in curvature for a reference point in a curve
G_v	velocity gain
G_{yaw}	yaw gain
H_{AFCS}	representation of flight control system dynamics
H_c	representation of aircraft dynamics
H_{disp}	representation of display dynamics
H_p	representation of pilot dynamics
K_n	weighing factor applied to cues n
K_{wh}	constant to relate changes in horizontal splay angle to cross track error
K_{hw}	constant to relate changes in vertical splay angle to vertical track error
K_{TAE}	gain of the track angle error
K_{VTE}	gain of the vertical track error
K_{XTE}	gain of the cross track error
P_n	reference point n
R_c	ratio of geometric field of view and observer field of view
R_f	frame spacing ratio

R_n	radius of curve n
R_{wh}	ratio of tunnel width and height
S	splay angle
S_0	splay angle in the absence of position errors
S_{XTE}	splay angle resulting from a cross track error
S_{VTE}	splay angle resulting from a vertical track error
SC	screen size
T_x	horizontal image translation
T_y	vertical image translation
TAE	track angle error
TAE_C	track angle error at the moment an error-corrective control action is initiated
TAE_X	track angle error at the moment the aircraft crosses the tunnel wall
TTP	time before an element passes the plane in which the viewpoint lies
TTP_{min}	TTP at the moment the particular element which conveys the TTP information leaves the viewing volume
TWC_{C1}	first-order estimate of the time-to-wall crossing
TWC_{C2}	second-order estimate of the time-to-wall crossing
V	velocity
V_{AC}	velocity relative to the air mass
V_G	velocity relative to the ground
V_W	velocity of the air mass
VTE	vertical track error
XTE	cross track error
XTE_C	cross track error at the moment an error-corrective control action is initiated

ACRONYMS AND ABBREVIATIONS

1-D	One Dimensional
2-D	Two dimensional
2DE	2-D 3-D effect
3-D	Three Dimensional
4-D	Four Dimensional
A/C	AirCraft
ADI	Attitude Director Indicator
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance-Broadcast
AEC	Avionics Engineering Center
AFCS	Automatic Flight Control System
AFD	Adaptive Flight Display
AI	Artificial Intelligence
AIMS	Airplane Information Management System
AMLCD	Active-Matrix Liquid Crystal Display
ANIP	Army Navy Instrumentation Program
ANOVA	ANalysis Of VAriance
AP	AutoPilot
ATA	Air Transport Association
ATC	Air Traffic Control
ATM	Air Traffic Management
CALAHF	Computer Aided Low-Altitude Helicopter Flight
CDTI	Cockpit Display of Traffic Information
CDU	Control Display Unit
CFIT	Controlled Flight Into Terrain
CFPD	Command FlightPath Display
CGI	Computer Generated Imagery
CIG	Computer Image Generator
CNS	Communication, Navigation, and Surveillance
COM	Cross-Over Model
CRT	Cathode Ray Tube

CTI	Commercial Technology Insertion
CWIN	Cockpit Weather INformation
D^3S	DELPHINS Display Design System
DARPA	Defense Advanced Research Projects Agency
DDM	Difference in Depth of Modulation
Dec	DECEMBER
DEU	Display Electronics Unit
deg	DEGrees
DELPHINS	Delft Program for Hybridized Instrumentation and Navigation Systems
DGPS	Differential Global Positioning System
DIS	Distributed Interactive Simulation
DME	Distance Measuring Equipment
DOF	Degrees Of Freedom
EADI	Electronic Attitude Director Indicator
EFIS	Electronic Flight Instrument System
EHSD	Electronic Horizontal Situation Display
EHSI	Electronic Horizontal Situation Indicator
EOD	End Of Descent
ERF	Ego-centered Reference Frame
ESAS	Enhanced Situation Awareness System
EVS	Enhanced Vision System
FAA	Federal Aviation Authorities
FAF	Final Approach Fix
FANS	Future Air Navigation System
FBW	Fly-By-Wire
FCC	Flight Control Computer
FCS	Flight Control System
FL	Flight Level
FMS	Flight Management System
FOV	Field of view
FPA	FlightPath Angle
FPAE	FlightPath Angle Error
FPV	FlightPath Vector

ft	FeeT
FTE	Flight Technical Error
GFOV	Geometric Field Of View
GLS	Global positioning system Landing System
GPIP	Glide Path Intercept Point
GPS	Global Positioning System
h	Hours
HDD	Head-Down Display
HDG	HeaDinG
HFOV	Horizontal Field Of View
HMD	Helmet Mounted Display
HSI	Horizontal Situation Indicator
HUD	Head-Up Display
Hz	HertZ
IATA	International Air Transport Association
IBM	International Business Machines
ICAO	International Civil Aviation Organization
IFPC	Integrated Flightpath and Propulsion Control
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
IR	InfraRed
IR&D	Independent Research and Development
IRS	Inertial Reference System
JANAIR	Joint Army-Navy Aircraft Instrumentation Research
kts	KnoTS
LCD	Liquid Crystal Display
LLL	Low Light-Level
m	Meters
MB	MegaBytes
MCAIR	MCdonnell AIRcraft corporation
MCP	Mode Control Panel
MFPD	Maneuvering FlightPath Display

MIAS	Multimode Integrated Approach System
min	Minutes
MIPS	Million Instructions Per Second
MLS	Microwave Landing System
MMI	Man Machine Interface
MMW	Millimeter Wave
ms	MilliSeconds
NASA	National Aeronautics and Space Administration
NAV	NAVigation
NBAA	National Business Aircraft Association
ND	Navigation Display
NLR	National Aerospace Laboratory
NSE	Navigation System Error
NTSB	National Transportation Safety Board
OCM	Optimal Control Model
OFOV	Observer Field Of View
PA	Pilot's Associate
PC	Personal Computer
PCP	Proximity Compatibility Principle
PFD	Primary Flight Display
PHARE	Program for Harmonized Air traffic Research in Eurocontrol
PITS	Pathway-In-The-Sky
rad	RADians
RNG	RaNGe
RNP	Required Navigation Performance
RPV	Remotely Piloted Vehicle
RTCA	Radio Technical Committee for Aeronautics
s	Seconds
SAE	Society of Automotive Engineers
SBC	Single Board Computer
SVS	Synthetic Vision System
TAE	Track Angle Error
TCAS	Traffic Collision Avoidance System

TIFS	Total In-Flight Simulator
TIP	Turn Initiation Point
TECS	Total Energy Control System
TLC	Time-to-Line Crossing
TMS	Texas instruments Microprocessor System
TOD	Top Of Descent
TRK	TRacK
TSE	Total System Error
TSRV	Transport Systems Research Vehicle
TTC	Time-To-Contact
TTP	Time-To-Passage
TVS	Telecommunication and Traffic Control Systems
TWC	Time-to-Wall Crossing
UAV	Unmanned Aerial Vehicle
U.S.	United States
VE	Vertical Error
VFOV	Vertical Field Of View
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VPD	Vertical Profile Display
VRAM	Video Random Access Memory
VSD	Vertical Situation Display
VTE	Vertical Track Error
VWP	Virtual Way-Point
WRF	World Reference Frame
XTE	Cross Track Error

APPENDIX A: SPLAY ANGLE AND SPLAY RATE GAIN

Eq. (3.5) expressed the splay angle S_0 in the absence of position errors as:

$$S_0 = \arctan(\frac{w}{h}). \quad \textbf{(A.1)}$$

A position error *XTE* causes a change in splay angle by an amount ΔS_{XTE} to a value of S_{XTE}. Eq. (A.2) presents the relation between S_{XTE} and *XTE*.

$$S_{XTE} = \arctan(\frac{w/2 - XTE}{h/2}). \quad \textbf{(A.2)}$$

When introducing R_{wh} as the ratio between tunnel width *w* and tunnel height *h*, for a cross-track error XTE, the relation can be written as:

$$S_{XTE} = \arctan(R_{wh} \cdot (1 - \frac{2 \cdot XTE}{w})). \quad \textbf{(A.3)}$$

To express the change in splay angle (ΔS_{XTE}) as a function of the cross track error, Eq. (A.3) must be differentiated. This yields Eq. (A.4).

$$\dot{S}_{XTE} = 2 \cdot R_{wh} \cdot \cos^2(S) \cdot \frac{\dot{XTE}}{w}. \quad \textbf{(A.4)}$$

Thus, the splay rate gain is equal to:

$$G_{\dot{S}} = 2 \cdot R_{wh} \cdot \cos^2(S) \cdot \frac{1}{w}. \quad \textbf{(A.5)}$$

Thus, the gain is determined by the ratio of the tunnel width and height, the current splay angle, and the tunnel width. R_{wh} and w follow from the design parameters. Splay rate gain is inversely proportional to tunnel width, and can therefore be controlled through selection of the tunnel width w. However, as a result of the $cos^2(S)$ term, splay rate gain depends on the actual splay angle and will increase with an increase in the ratio of the actual cross track error and the tunnel width.

Fig. A.1 shows how the correction factor $2\ R_{wh}\ cos^2(S)$ varies as a function of the ratio of cross track error and tunnel width (*XTE/w*) for values of R_{wh} between 1 and 4.

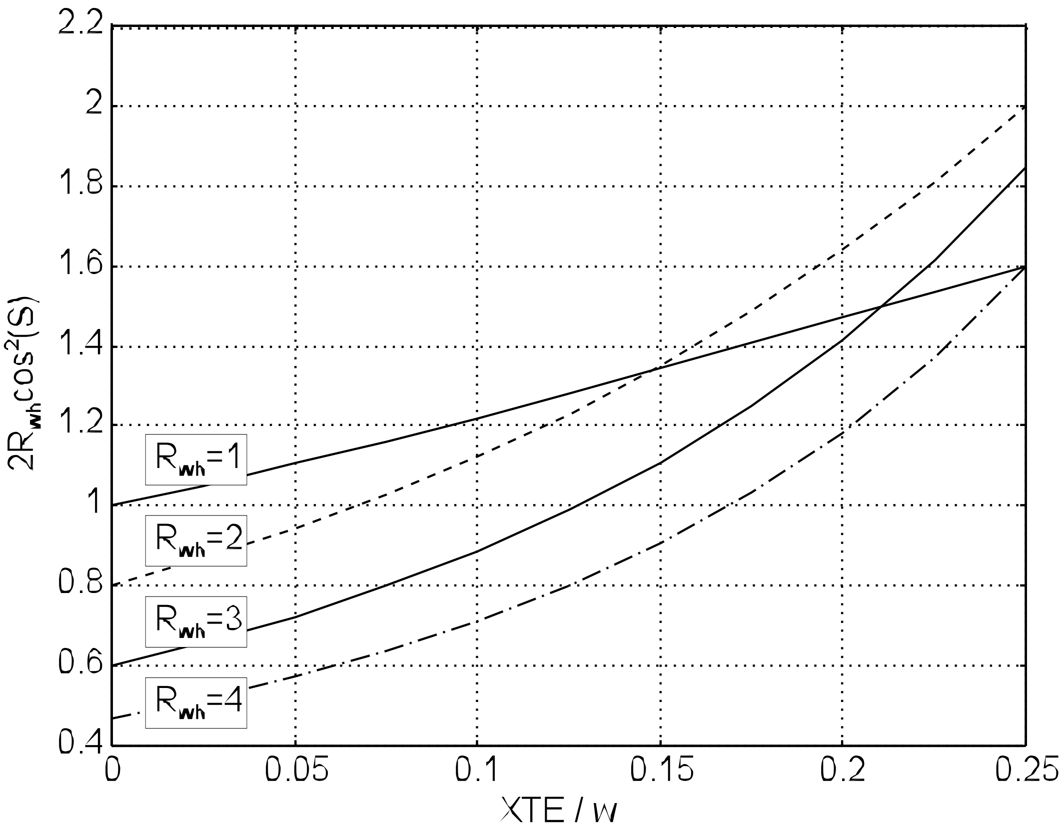

Fig. A.1. *Magnitude of the correction factor $2R_{wh}\cos^2(S)$ as a function of relative position error XTE/w for different width to height ratios R_{wh}.*

As can be seen from this figure, splay rate gain increases with an increasing ratio of cross track error over tunnel width.

For small changes in position error, S can be substituted by S_0, yielding Eq. (A.6)

$$\dot{S}_{XTE} = 2 \cdot R_{wh} \cdot \cos^2(\arctan(R_{wh})) \cdot \frac{\dot{XTE}}{w} \tag{A.6}$$

When replacing the term $2R_{wh}\cos^2(\arctan(R_{wh}))$ with K_{wh}, and integrating Eq. (A.6) over a time ΔT, this yields the following expression for a change ΔS_{XTE} in splay angle:

$$\Delta S_{XTE} = \frac{K_{wh}}{w} \cdot XTE \tag{A.7}$$

Table A.1 lists the values of K_{wh} for a ratio R_{wh} of 1,2,3, and 4.

Table A.1. *Constant K_{wh} for a ratio of tunnel width and height between 1 and 4.*

R_{wh}	K_{wh}
1	1.0
2	0.80
3	0.60
4	0.47

Fig. A.2 shows the true values of ΔS_{XTE} as a function of the ratio of cross track error and tunnel size.

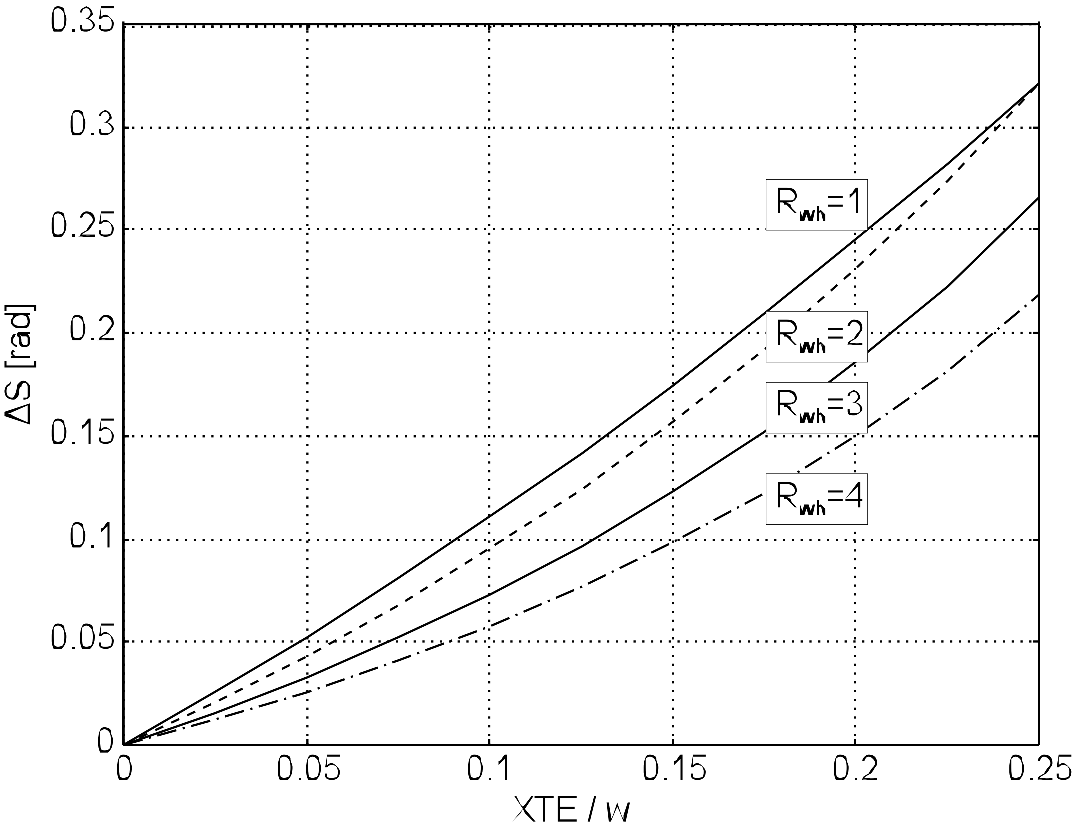

Fig. A.2. *This figure shows the actual change in splay angle as a function of the ratio of cross track error and tunnel width. From this figure it can be seen that when the cross track error is small compared to the tunnel width, the approximation is quite good.*

Fig. A.3 shows the error which is made with the approximation.

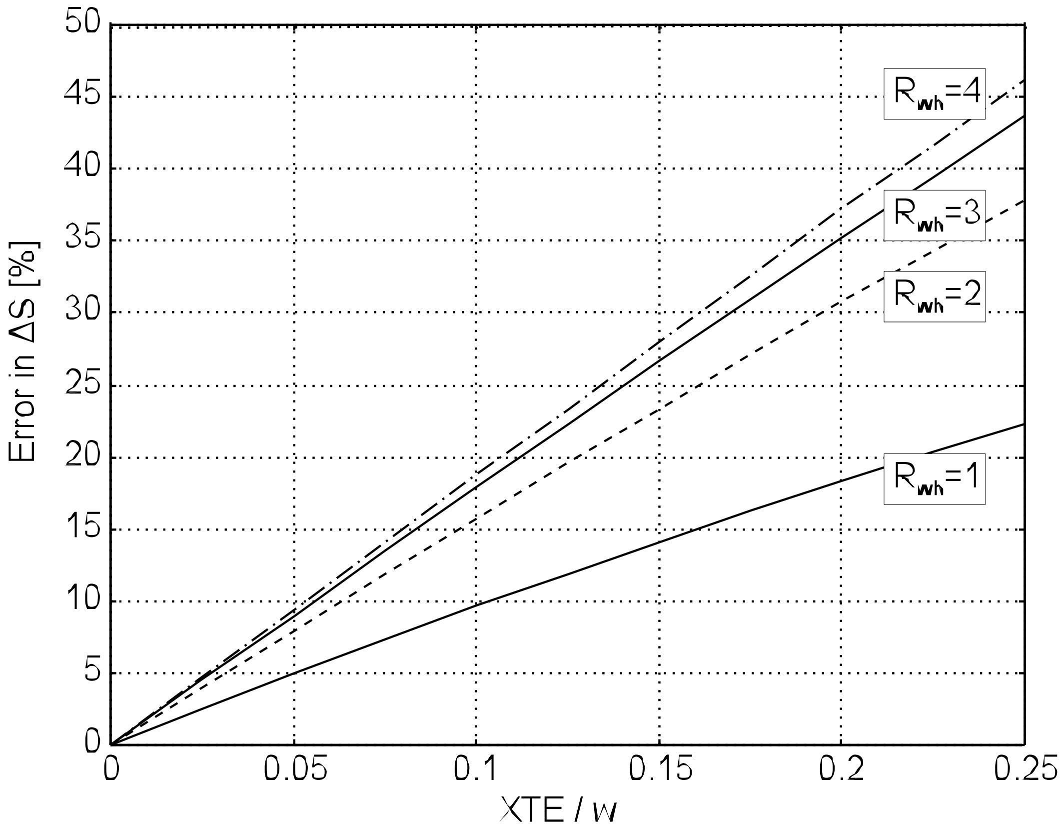

Fig. A.3. *Error in the estimate of ΔS_{XTE}.*

For vertical track errors, the splay angle S_{VTE} can be written as:

$$S_{VTE} = \arctan\left(\frac{w/2}{h/2 - VTE}\right). \tag{A.8}$$

Taking the derivative yields:

$$\dot{S}_{VTE} = \frac{2}{R_{wh}} \cdot \sin^2(S) \cdot \frac{\dot{VTE}}{h}. \tag{A.9}$$

For small changes in position error, S can be substituted by S_0, yielding Eq. (A.10)

$$\dot{S}_{VTE} = \frac{2}{R_{wh}} \cdot \sin^2(\arctan(R_{wh})) \cdot \frac{\dot{VTE}}{h}. \tag{A.10}$$

When replacing the term $2/R_{wh} \cdot \sin^2(\arctan(R_{wh}))$ with K_{hw}, and integrating Eq. (A.10) over a time ΔT, this yields the following expression for a change ΔS_{VTE} in splay angle:

$$\Delta S_{VTE} = \frac{K_{hw}}{h} \cdot VTE. \tag{A.11}$$

Table A.2 lists the values of K_{hw} for a ratio R_{wh} of 1,2,3, and 4.

Table A.2. *Constant K_{hw} for a ratio of tunnel width and height between 1 and 4.*

R_{wh}	K_{hw}
1	1.0
2	0.80
3	0.60
4	0.47

APPENDIX B: HARDWARE AND SOFTWARE

Hardware. In 1990, the graphics adapters used in personal computers (PC's) did not meet the performance requirements, but several types of graphics workstations did. Furthermore, several types of rapid-prototyping systems for two-dimensional display formats were commercially available for graphics workstations, but none to support the development of 3-D display formats. Developments in the area of special purpose graphics engines promised an opportunity to achieve adequate performance while using PC hardware. Based on the available graphics processors in 1990, it was concluded that it was possible to develop and build a PC-based display system utilizing a dedicated graphics processor to achieve the desired performance. The graphics hardware which was selected supported resolutions between 640x480 and 1024x768 pixels. This hardware was installed in the flight simulator in 1991. Fig. B.1 shows the interior of the flight simulator with the display installed in the right side of the instrument panel.

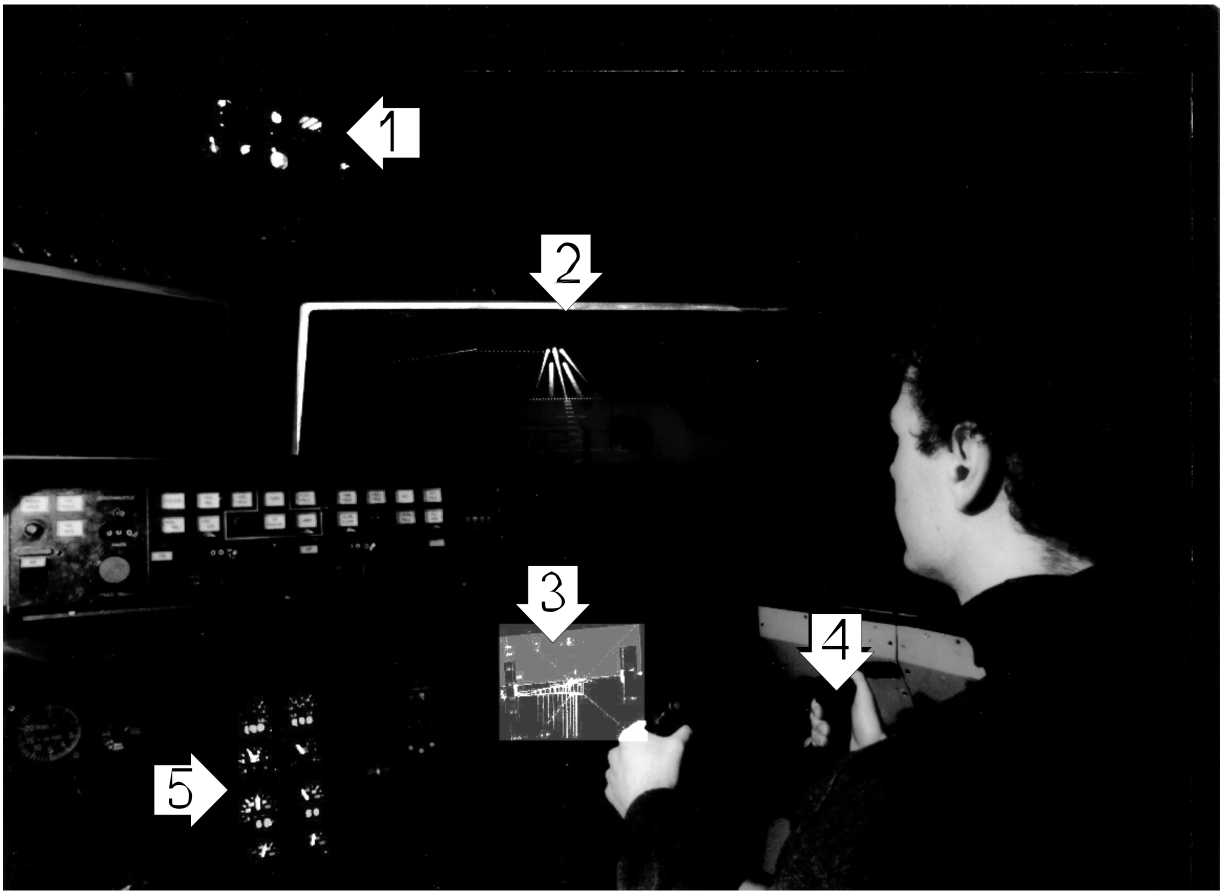

Fig. B.1. *Interior of the flight simulator. Arrow 1 shows the overhead panel, arrow 2 the scene generated by the visual system, arrow 3 points at the display device which is used to present the tunnel-in-the-sky, arrow 4 points at the control column, and arrow 5 indicates the engine instruments.*

Because the laboratory aircraft was not equipped with a programmable EFIS for research applications, it was decided to build a compact display electronics unit (DEU) and modify a commercial off-the-shelf flat panel display for use as a display device. Similar to the system used in the flight simulator, The DEU consisted of a 486 single board computer and a TMS 34020 graphics engine. Communication with the MIAS PC providing the data necessary to drive the displays was performed through a real-time Ethernet based network developed by Lamerigts (Theunissen and Lamerigts, 1994). An active matrix LCD (AMLCD) was used as a display device. Connecting the LCD screen to the TMS 34020 graphics engine required an additional converter. Fig. B.2 shows the display installed in the cockpit of the laboratory aircraft.

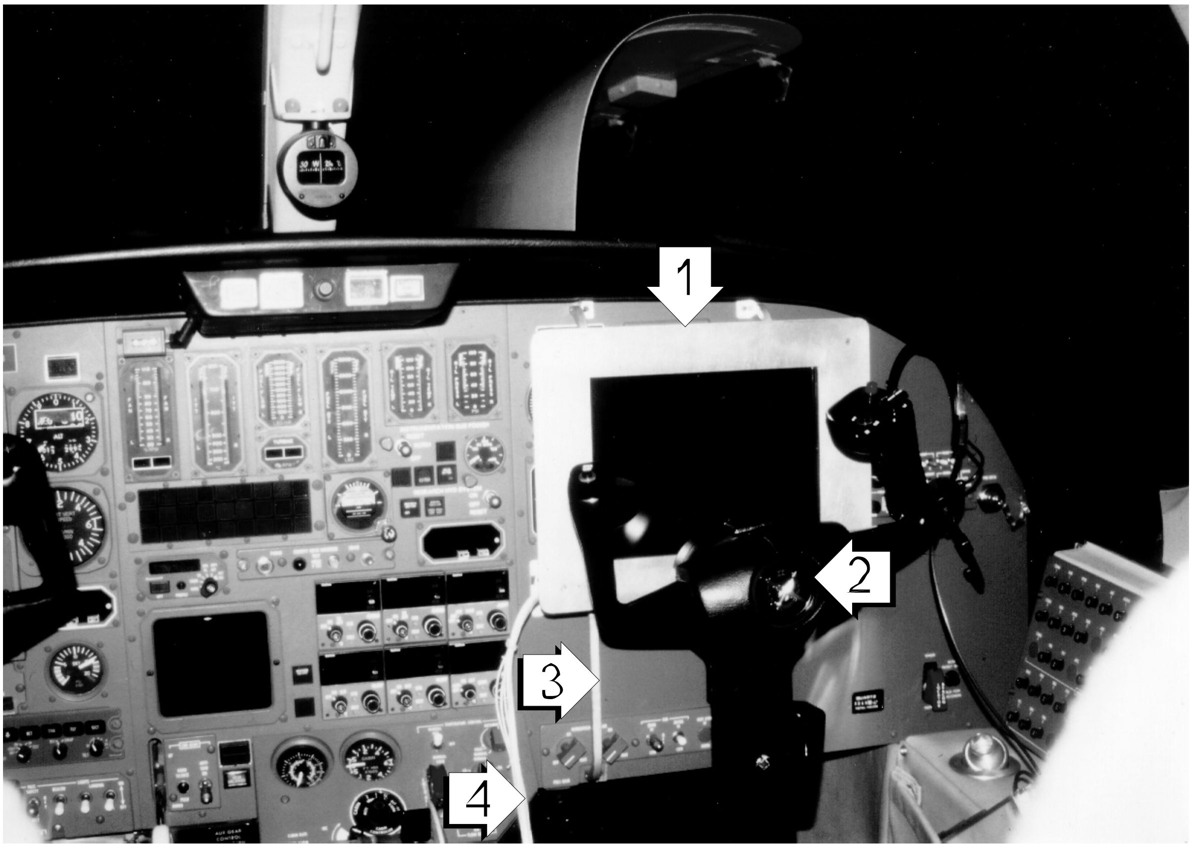

Fig. B.2. *Installation of the display device in the cockpit of the laboratory aircraft. The display (1) is installed between the instrument panel and the right control column (2). The display is mounted on rails (3) and can be removed by lifting it. The cable (4) supplies power and the video signal from the display electronics unit.*

Software. A software development system, allowing the user to specify the desired format and functionality and translate this specification into an implementation, was developed (Theunissen, 1991). Besides an implementation of the functionality for data presentation, functionality for the generation of a forcing function had to be implemented, which was written by hand.

Performance and trade-offs. To increase performance, dedicated hardware can be used to implement the functionality needed to translate the abstract representation into a collection of pixels. This hardware must be utilized by dividing the software into a process which transforms the input signals into the abstract presentation and a process which performs the graphics operations. Since the two processes run separately, the update-rate is determined by the slowest of the two. The factor influencing the update-rate of the process which generates an abstract representation is determined by the complexity of the desired functionality and the amount of 3-D data which must be transformed. The update-rate of the process which translates the abstract representation into a collection of pixels is determined by the amount of elements to be displayed, and the desired resolution. Furthermore, due to synchronization requirements, the graphics processor does not allow a smooth degradation in performance. The minimum time is always an integer multiple of the inverse of the vertical refresh rate (56 Hz), resulting in segments of 18 ms. Performance evaluations showed that the graphics processor is typically the performance bottleneck. When running in the highest resolution, only very basic formats such as a wire-frame tunnel without full color artificial horizon can be updated at 56 Hz. At a resolution of 640x480 pixels, an update-rate of 28 Hz can be achieved for the basic format. At a resolution of 1024x768 pixels, the maximum update-rate for the basic format is approximately 18 Hz (3 frame times). More complex versions require 4 or 5 frame times, yielding update-rates of respectively 14 and 11 Hz.

Data processing and latency of the in-flight hardware. In Sect. 5.11 the requirements on the position and orientation data were discussed. The orientation data was continuously available from an analog attitude determination system. The position data was available at 1 Hz, and an extrapolation algorithm using a Kalman predictor was implemented to increase the position update-rate (Breeuwer et al., 1993; Breeuwer et al., 1995). The interrupt clock of the MIAS PC, which runs at an update-rate of 18 Hz, was used to synchronize the sampling of the orientation data, the Kalman predictor, and data transport to the display electronics unit. This yielded a worst case data latency of 55 ms and a data update-rate of 18 Hz which was deemed sufficient to provide a smoothly animated presentation.

Due to time limitations, the software in the display electronics unit was not modified to be driven by an external clock, but synchronized with the clock determining the vertical refresh rate of the display. As a result it ran asynchronously to the computations performed by the MIAS PC. With the graphics hardware, the vertical refresh was fixed at 56 Hz, yielding cycles of 18 ms. The implementation needed approximately 30 ms to generate a new image, thus requiring 2 cycles and yielding a display update-rate of 28 Hz. Total worst case latency was estimated at 55+36=91 ms, and therefore, it was expected that adequate inner-loop stability could be achieved. Due to the differences between data update-rate and display update-rate, an aliasing effect might be expected at approximately 10 Hz.

SAMENVATTING

Door het toenemende aantal luchtreizigers en ten gevolge hiervan het groter aantal benodigde vliegtuigen, beginnen er knelpunten te ontstaan in de capaciteit van het beschikbare luchtruim. Hierdoor wordt een limiet bereikt waarna een verdere toename van het aantal vliegtuigen tot onacceptabele vertragingen zal leiden. De capaciteitsproblemen zullen zich voornamelijk in de omgeving van luchthavens gaan afspelen, zodat ook daar naar een oplossing moet worden gezocht. De basisgedachte is om af te stappen van de huidige naderingsprocedures, waarbij vliegtuigen worden gedwongen om al ver voor de baan een rechte weg te volgen. Met de huidige stand van de techniek is het mogelijk om vliegtuigen op van te voren bepaalde lokaties op deze rechte weg te laten invoegen via een gekromde nadering. Hierdoor krijgt de luchtverkeersleiding meer opties om het luchtverkeer te begeleiden, waardoor de mogelijkheid ontstaat om de beschikbare capaciteit te vergroten. Bijkomend voordeel is dat het mogelijk wordt delen van de weg die over woongebieden gaan te ontzien, waardoor de geluidshinder wordt beperkt.

Dit concept gaat echter gepaard met een grotere mentale belasting voor de vlieger. In tegenstelling tot het huidige rechte naderingstraject, zal hij in de toekomst gekromde naderingen moeten vliegen. Doordat het vliegtuig tijdens dit deel van de vlucht relatief vaak van richting zal veranderen, is het moeilijker om het juiste oriëntatiegevoel te behouden. Dit vereist meer inspanning, omdat de vlieger het navigatiedisplay vaker moet raadplegen. Gezien de reeds hoge werkbelasting van de vlieger tijdens de nadering, zal de introductie van complexere naderingsroutes de veiligheid verlagen. Door de vlieger van informatie te voorzien die hem in staat stelt de vliegtaak even eenvoudig als, of zelfs eenvoudiger dan voorheen uit te kunnen voeren, terwijl tegelijkertijd zijn oriëntatiegevoel op pijl blijft zonder het raadplegen van extra displays, is het mogelijk dergelijke complexe naderingen uit te voeren, zonder dat de veiligheid afneemt.

Het doel van het onderzoek was het verbeteren van de veiligheid door meer gebruik te maken van de flexibiliteit in datapresentatie die programmeerbare displaysystemen bieden. Hiertoe is een analyse verricht naar mogelijkheden om de mentale belasting van de vlieger tijdens de navigatie taak te verlagen door de datapresentatie te verbeteren. Uit deze analyse en resultaten van eerder onderzoek blijkt dat displays die een ruimtelijke voorstelling van het te volgen traject presenteren - zogenaamde *perspective flightpath displays*-, voordelen hebben ten opzichte van de huidige displays. Hierdoor kan de complexiteit van de te vliegen routes worden verhoogd zonder dat aan veiligheid wordt ingeboet. Deze voordelen ontstaan doordat de vlieger zelf minder informatie hoeft te integreren en de natuurlijke presentatie de interpretatie en evaluatie vereenvoudigt. Tevens bleek, dat gedetailleerde richtlijnen voor het ontwerpen van dit soort displays, waarbij rekening wordt gehouden met de specifieke eigenschappen van de mens met betrekking tot het waarnemingsproces (perceptie), het interpretatie- en evaluatieproces (cognitie), en het genereren van stuuracties (regeltheorie), schaars zijn. Dit resulteert voor de ontwerper in talloze *hoe* en *waarom* vragen betreffende de specificatie van een display voor de navigatie en besturing van een vliegtuig. Het maakt het totale proces onoverzichtelijk, en kan leiden tot het over het hoofd zien van belangrijke aspecten.

Om hierin verandering te brengen, is onderzocht hoe bij het beantwoorden van ontwerpvragen gebruik kan worden gemaakt van bestaande kennis op het gebied van perceptie, cognitie, en systeemtheorie. Er is gekozen om de specifieke ontwerpvragen om te zetten in vragen, die vanuit de voorgaande domeinen kunnen worden beantwoord. Hiertoe is de informatie-inhoud van de presentatie beschreven door een relatie af te leiden tussen positie- en oriëntatiefouten van het vliegtuig en de resulterende veranderingen in de positie en oriëntatie van het perspectivisch gepresenteerde traject. Vervolgens is onderzocht hoe de verschillende ontwerpaspecten deze relatie beïnvloeden, wat de gevolgen zijn voor de verwerking van de data tot zinvolle informatie en hoe bruikbaar de informatie is voor het toepassen van een bepaalde stuurstrategie. Op basis van deze analyse zijn richtlijnen voor het specificeren van een perspective flightpath display afgeleid. Om bepaalde ontwerpvragen in meer detail te kunnen onderzoeken, is het concept geïmplementeerd met de mogelijkheid om de verschillende ontwerpaspecten te kunnen variëren. Deze implementatie is gebruikt voor het verkrijgen van feedback van beroepsvliegers, het uitvoeren van pilot-in-the-loop studies in een vluchtsimulator, en het testen van het concept in de werkelijke vlucht.

CURRICULUM VITAE

Eric Theunissen was born on October 28th 1967 in Kerkrade. From 1979 to 1985 he attended the Rombouts College in Brunssum. In 1985 he became a student at the Faculty of Aerospace Engineering, and as a result of his fascination for avionics, in 1988 he also became a student at the Faculty of Electrical Engineering. In the same year, he founded Informatie Systemen Delft, a small company which developed and sold dedicated data terminals. In June 1991 he obtained his M.Sc. degree (ir.) in Electrical Engineering, and in August 1991 his M.Sc. degree (ir.) in Aerospace Engineering, both cum laude. In November 1991, he received the award for the best thesis work in Electrical Engineering from the University Fund of the Delft University of Technology. Between October 1991 and March 1996, he conducted research at the department of Telecommunications and Traffic Control Systems (TVS) of the faculty of Electrical Engineering, and its results are the subject of this thesis. Currently, Eric works as a researcher at the Faculty of Electrical Engineering on a four year project for the Dutch Science Foundation (STW). It's goal: The integration of perspective flightpath displays in the flightdeck.

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