A Display for Managing the Vertical Flight Path - an Appropriate Task with Inappropriate Feedback -

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ABSTRACT
This paper focuses on feedback for managing the vertical flight path in automated glass cockpits. Current aircraft displays provide feedback for lateral path management and vertical path control. When pilots use a higher level of automation for navigating in the vertical domain, automation surprises may result in serious incidents or accidents. The paper presents a Vertical Situation Display (VSD) that is being developed and evaluated at NASA Ames Research Center. The VSD shall provide valuable feedback for glass-cockpit pilots managing automated vertical navigation devices. Capacity and economic constraints may require aircraft to use high levels of automation to follow predetermined 3D/4D flight paths precisely from takeoff to touchdown in the near future.

Keywords
Automation, Flight Management, Display, Task Analysis, Feedback, Man Machine Interaction, Vertical Navigation, Situation Awareness

INTRODUCTION
Navigating modern aircraft in the vertical domain is usually full of automation surprises and altitude busts occur frequently. CFIT accidents due to a loss of vertical situation awareness are the most serious consequences of unsuccessful vertical flight path management. Research by Wiener [26], Sarter and Woods [19][28], Palmer et al. [14], Funk et al. [9], Degani [3], Feary et al. [7] and others demonstrate that automation surprises are common events in all automated aircraft types. Furthermore they are mostly evident in the vertical domain [1][22]. This problem is so serious that certain air carriers have disabled the possibility to engage the 'vertical navigation' function of their flight management system or do not train their flight crews on using it [11].

In the long term, such drastic means may result in less cost-effective flights and incompatibilities with future air traffic requirements. Programs aimed at increasing airspace capacity are focused on using ground-based and airborne automation. Tools like the NASA/FAA Center TRACON Automation System [5] are most effective, if the aircraft flight paths are highly predictable from take off to touchdown. A contributing factor to increase flight path accuracy and efficiency is the usage of FMS departure, arrival and approach routes. Such routes allow aircraft to fly at the highest level of automation close to the ground, while having to meet a set of charted constraints concerning particular altitudes and speeds at several waypoints along the route.

Clearly vertical navigation is shifting towards strategic vertical flight path management. Nevertheless, there will always be situations, when pilots have to revert from highly automated to less automated or manual modes. In order to cope with these requirements, current and future cockpit systems should be carefully reviewed with regard to providing the necessary feedback for the different tasks. In the course of this paper a Vertical Situation Display (VSD) will be proposed, well aware of the fact that this is an old idea and that other VSDs exist in operation (Gulfstream) and research [6][11][22][23]. Nevertheless, such a display is increasingly important to cope with current and future air traffic requirements. In the first part of the paper it is explained, for which kinds of tasks feedback should be provided and where the feedback is already there and more appropriately situated on other displays. In the second part a VSD designed to this task specification is introduced.

TASK DECOMPOSITION AND ALLOCATION
For the subsequent discussion the relevant elements of the overall task to perform a commercial air transport mission are decomposed into the tasks management, navigation, flight planning, guidance and control. More comprehensive but slightly different descriptions of the task decomposition can be found by others [2] [21].

The (flight) management task entails programming and/or selecting those aircraft systems that are appropriate in a given situation to comply with all given constraints necessary to complete the mission. Parts of the management task can currently be carried out by the flight management system, others like flight planning remain with the flight crew. It includes navigation, flight planning, guidance and control (and more).

The navigation task consists of deriving the current aircraft state in terms of position, velocities and accelerations from a number of redundant information sources. This task is generally considered to be completely performed by automated systems. However, it should be noted that the absolute position information derived from these functions is only valuable for cockpit crews, if it is referenced to known meaningful locations, like airports, waypoints, elevations or meaningful flight plan values. Thus, the automated navigation task is most useful to the pilot if he or she can derive the relative position information necessary to perform or understand the flight planning and the guidance tasks.

The goal of the flight planning task is to determine the four-dimensional path to be flown by the aircraft, typically referred to as the flight plan. This task can be performed by the cockpit crew or ground based semi-automatic systems used by the air carrier or air traffic control and communicated into the aircraft. In experimental cockpit systems like the Cockpit Assistant System (CASSY), the flight planning task has also been automated and flight tested with promising results [16][17]. The European Advanced Flight Management (AFMS) System utilizes some of these functions and is currently in experimental use as part of European air traffic management projects[27].

While full operational use of airborne flight planning functions is still a few years ahead, the guidance task can already be delegated to the flight management system, if a flight plan has been stored and activated. The guidance task compares the actual position of the aircraft with the flight plan and issues respective commands to the control task. Based on this the control task generates the commands that manipulate the aircraft's control surfaces and thrust to achieve these targets. The control task is usually performed by the automation in modern aircraft except for the flight portions on or close to the ground.

The following section reviews how feedback is provided in most of the current glass cockpit aircraft concerning these tasks.

FEEDBACK IN CURRENT AIRCRAFT COCKPITS

Current aircraft displays provide feedback for lateral path management and vertical flight path control. Lateral flight path management has been enabled through the integration of an electronic map display into modern glass-cockpits. With few exceptions (like some Gulfstream aircraft) there is nothing equivalent for the vertical domain [1].

One of the most important accomplishments of the map display in glass-cockpits is to enable flight crews to assess their lateral position as determined by the navigation task. This enables flight crews to derive the relative position information necessary to perform and understand lateral flight planning and guidance tasks. This information, depicted on the map display with its MAP mode for local areas and its PLAN mode for extended areas, allows pilots to program flight plans into the flight management system and graphically evaluate the resulting lateral flight path. When the lateral guidance of the aircraft is delegated to the FMS, flight crews can monitor the state of the aircraft relative to the lateral flight path and anticipate the future behavior as far out as the display range they have selected. The control task can be monitored using the Flight Mode Annunciation (FMA), the heading indicator and the Attitude Direction Indicator (ADI), where the bank angle represents the direct feedback of the roll steering commands the control function generates. Thus, all management tasks Ðnavigation, flight planning, guidance and controlÐ regarding the horizontal domain can be monitored by the cockpit crew. This kind of appropriate feedback has resulted in very good performance in terms of lateral flight path management in modern glass-cockpit aircraft.

In the vertical domain the displays only depict information supporting the control task [12][21]. The FMA annunciates the speed and pitch control modes. The altitude, vertical speeds and pitch can be derived from the ADI. Feary et al. [7] developed a guidance FMA, that annunciates the operational procedures used to develop the guidance behavior of the MD 11 aircraft. This FMA was evaluated during training sessions in order to determine, whether it helps pilots understanding of the vertical navigation of the aircraft. Although it revealed positive results, the guidance FMA does not completely resolve the problem.

It helps pilots within the limitations of current cockpits with the guidance task, but does not provide additional feedback for the navigation (and flight planning) task. The relative position of the aircraft in the vertical domain still has to be inferred from a variety of sources. The absolute position is given at the altitude tape while the reference positions of the flight path are depicted in an alphanumeric format on the CDU LEGS page or on the map display attached to the flight plan waypoints, when selected by the pilot. Since easing position assessment for flight crews was one of the main accomplishments in the lateral domain, this can also be the key for appropriate feedback for vertical flight path management. This holds true also for other outcomes of the navigation task, like the airspeed and the vertical speed.

One reason for the feedback discrepancy between lateral and vertical flight path management is that the displays have not kept up with FMS evolution. Older and less sophisticated flight management systems provide only automation for lateral path management and require that the pilots perform most of the tasks in the vertical domain in less automated modes. Additionally, vertical flight path management is only important in climb and descend phases of flight (and the transitions between different flight phases). In today's ATC systems, these phases are mainly subject to tactical flight level changes instructed by air traffic controllers. There are several developments that will require increasing use of vertical flight path (including speed) management in the near future. Some of them are briefly covered in the next section.

THE NEED FOR VERTICAL FLIGHT PATH MANAGEMENT

Many of the aircraft incidents reported to the Aviation Safety Reporting System can be attributed to problems in the vertical domain [22]. This section is focused the discussion on one major safety concern –Controlled Flight Into Terrain (CFIT)– and two upcoming economic and capacity issues –FMS routes in terminal areas and new air traffic control tools– All three underline the increasing importance of vertical flight path management in the current and future air traffic environment.

CFIT

CFIT (Controlled Flight Into Terrain) is one of the main categories of aircraft accidents. Clearly flight crews controlling their aircraft into terrain have not been able to manage their vertical flight path appropriately. Although they may have been aware of their absolute altitude, the relative altitude to the ground elevation has not been inferred correctly and early enough to initiate corrective actions. Enhanced Ground Proximity Warning Systems (EGPWS) shall use a terrain data base to predict possible ground impacts and warn pilots early enough to avoid this kind of accident. Although this will certainly prevent several CFIT accidents, ultimately the feedback problem in the vertical domain is not resolved. If the aircraft state information was presented appropriately in relation to the terrain elevation, flight crews would have a better opportunity to assess the situation themselves and make reasonable adjustments without having to rely on yet another automated warning system in the cockpit. EGPWS should be the last guard not the first.

FMS routes in terminal areas

The Federal Aviation Administration (FAA), several Civil Aviation Authorities (CAAs) and air carriers are currently advocating the establishment of FMS routes in terminal areas. The goal is to be able to use the aircraft flight management system for vertical and lateral path management during almost all phases of flight. This requires that continuous flight paths be defined and depicted on arrival and transition charts. These routes including altitude and speed constraints can be loaded into the FMS. Without having the necessary feedback, pilots will have to trust their flight management automation to meet all given constraints. Additionally, if pilots have to cancel this highest level of automation because of traffic or other constraints, they have to have the complete situation awareness in order to switch to a lower level of automation.

New air traffic control tools

The constraints imposed on the aircraft by FMS routes are generally static once the route has been identified. If a flight management system cannot comply with these constraints flight crews have to select a lower level of automation. New decision support tools for air traffic controllers add a dynamic dimension to the constraints for generating vertical flight paths. In Frankfurt (am Main) the COMPAS system aids air traffic controllers in sequencing and assigning runways [24]. FMS routes are put into place that allow for adjustments of the final approach length in the flight plan [20]. In the United States the NASA/FAA Center TRACON Automation System (CTAS) provides decision support tools for center and TRACON controllers in order to increase the capacity of major US airports. Arriving aircraft will be able to communicate their preferred routing to certain CTAS tools. CTAS then computes constraints on the flight path that may be necessary to avoid conflicts and to manage the traffic arriving at certain metering fixes or runways [9][18]. Understanding and compliance with these dynamically generated constraints is a major flight management task in the cockpit and crucial for beneficial air traffic management.

DISPLAY DESIGN

The previous discussion leads to the conclusion that there is a strong need to provide feedback for the vertical flight management tasks of navigation, flight planning and guidance for certain flight phases. Regarding the fact that flight path management is at least a three dimensional task the question of the display dimensionally has to be raised. A variety of research has addressed this. One common result is that the appropriate format is task dependent.

Display dimensionally

It was decided to use a co-planar view consisting of MAP display and VSD based on the following thoughts:

- First, feedback for the flight path management task shall provide global situation awareness, while aircraft control feedback (e.g. pitch and thrust modes) shall still be provided through the information on the ADI and the FMA. Information for global situation awareness is better represented in a co-planar view, control feedback in a perspective view.
- Secondly, one of the main goals of the VSD is to display the vertical position information unambiguously (navigation task). 3D scenes are always ambiguous as to the true position of any point in space.
- Thirdly, the flight management system manages the lateral and the vertical flight path mainly independently. A co-planar view provides the same kind of feedback.
- Finally, as noted earlier vertical flight path management is only important in certain phases of flight. During other long portions (like the cruise flight) the profile view may not be necessary and can be turned off. The available region for the map display can increase, without changing the main internal display geometry. Thus, the pilot does not have to accommodate a new display in his representation.

By choosing the co-planar view one should be aware of the mental geometry necessary for pilots to integrate the information on the VSD and the ND. But as neither map display nor VSD are intended to provide the essential feedback for the control task, this shortcoming is considered less problematic but can be addressed during the evaluation.

Color-coding

The color-coding used for the VSD shall reflect the color-schemes used in the particular aircraft. Therefore, for an operational implementation the color schemes have to be adapted to be as analogous as possible to the MAP display. The currently implemented prototype uses the following underlying scheme:

magenta: active targets (active FMS flight plan, active waypoint, commanded speed, commanded MCP altitude, if the vertical flight path is not managed by the FMS)

white: preselected values (modified FMS flightplan, altitude and speed constraints, if the FMS is managing the vertical flight path)

white (on gray background): aircraft state information for current altitude and speed, green: extrapolation of the current flight path (projection of the green arc on the Map display)

amber: altitude and speed constraints, if the vertical flight path is not managed by the FMS in order to draw the pilot's attention to upcoming constraints.

INTEGRATING THE VSD WITH THE MAP DISPLAY

Before describing the particular feedback elements in relation to the identified tasks, the VSD integration with the MAP display is addressed subsequently. Since the VSD may not be needed during all phases of flight, it should be selectable. It could be argued whether an automatic selection or a pilot selection is preferable. However to avoid a complicated logic and be consistent with the current display selection philosophy it was integrated to be brought up upon pilot request. The VSD can be selected at the navigation display control panel in addition to the MAP display in two co-planar combinations. The display has been implemented in the part-task and the full mission version of NASA Ames Advanced Concepts Flight Simulator. Figures 1 and 2 represent two possible pilot selections:

The waypoint and wind information in the upper left and right corners of the display remain unchanged. The range of the VSD is slaved to the range of the map display and similar color conventions are used.

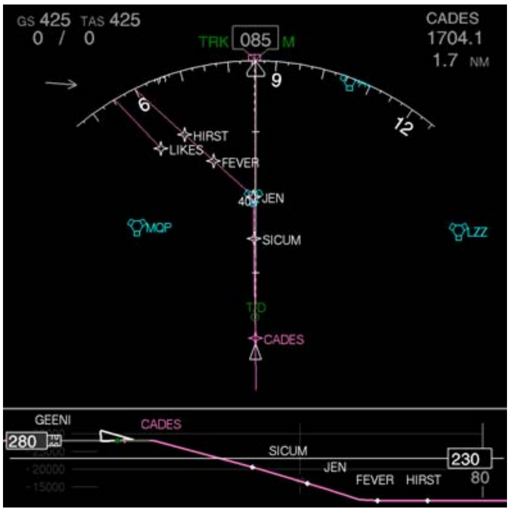

Figure 1: 80% MAP / 20% VSD

In cases, where pilots want to focus only on the lateral domain, the VSD can be turned off and the graphical map display remains unchanged. In figure 1 the map display has been rescaled to 80% of its original size and translated above the VSD. Pilots may select this view if they consider the lateral domain more important than the vertical domain, but want to maintain vertical situation awareness.

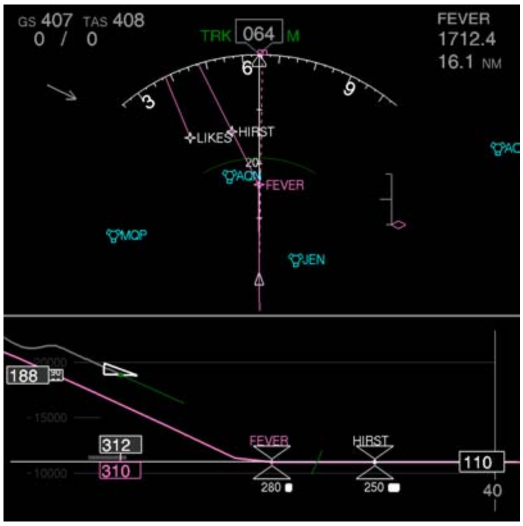

Figure 2: 60% Map/ 40% VSD

Figure two represents a view, where the MAP uses 60 % and the VSD utilizes 40% of the display space. The map display has been rescaled and translated accordingly. In this case, the VSD provides a more comprehensive view of the future flight situation. Additionally a speed indicator (current vs. commanded) is depicted, which is now possible because of the increased display space. This more detailed view could be useful in situations, where vertical path management is more important and complicated. Feedback for the lateral domain is always given.

CHARACTERISTICS OF THE VSD

The particular VSD characteristics will be described using the flight situations depicted in figure 2 and figure 3. In this example the display is scaled to a range of 40 nautical miles. The altitude range is scaled such that most of the future flight path is visible. Up to a selected display range of 80 NM the range/altitude ratio remains constant to allow pilots to create a mental picture of a steep vs. a shallow path. The altitude range in feet is determined as the selected display range (NM) times 500. (E.g. a selected display range of 40 NM leads to an altitude range of 20.000 feet). The aircraft symbol (white triangle) is at a constant position at the lower half during climb and at the upper half during descent, like in this case. When the aircraft approaches the ground (or the cruise altitude), the aircraft symbol moves down (or up) and the altitude scale remains constant. Thus, the closure to the ground (cruise altitude) becomes visible.

The display supports vertical navigation, flight planning and guidance tasks as follows:

Navigation

To support the flight crews understanding of the navigation task, the display indicates the aircraft position and velocity in the vertical domain in relation to meaningful and important objects. The aircraft symbol is indicated as a triangle, rotating according to the current pitch angle around the reference point depicted as a green dot. The green line starting from this dot represents the current flight path angle. The aircraft altitude is displayed on the left side. The example above shows that the aircraft (white triangle) is high on the descent path in 18890 feet. The current altitude target is 11000 feet,

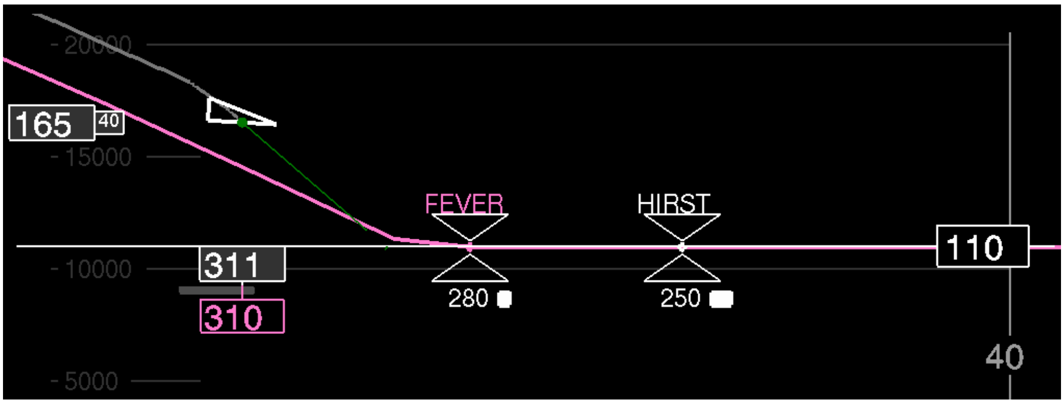

Figure 3: VSD in 40 % view: In figure 2 the aircraft was depicted high on the path, because of flying direct to the waypoint FEVER and levelling off for a while. The green flight path prediction indicated that the aircraft, would continue flying parallel and high on the path, if no corrective action was be taken. After adding drag (extending speed brakes) figure 3 shows that the aircraft will return to the computed flight path before the deceleration segment inserted by the FMS to reduce the airspeed from 310 knots in the descent to 280 knots necessary to meet the constraint. The current excessive airspeed is indicated as a box on the right side of the speed constraints.

which is indicated by the number (110) in the box on the right side and a line across the display. The line is solid, if the MCP altitude constraints the descent and dashed, if not. The airspeed is indicated in relation to the commanded (magenta) or preselected (white) speed underneath the aircraft symbol. When both differ significantly the gap between current and target speed becomes visible. The shaded area between them indicates the current speed envelope limitations

Flight planning

The display supports vertical flight planning tasks by depicting the current state of the active flight plan and any modification to it as it will be used for managing the aircraft in an along track picture. Therefore, all points along the flight plan, at which new commands will be issued to the guidance system are displayed. Furthermore, it indicates constraints along the flight path and enables flight crews to determine, whether the generated flight plan will meet the constraints. Altitude constraints are indicated as triangles, speed constraints in alphanumeric format below. A modified flight plan is indicated as a white line overlaying the magenta line of the active flight plan

Guidance

The display shows the current target values for altitude and speed and clearly indicates, whether the FMS manages the vertical flight path or the flight crew must guide the aircraft along the path. This is achieved by using a solid flight path line if the FMS manages the vertical flight path, and a dashed flight path line, if not. The green line extrapolates the aircraft velocity vector for one minute. The relation of the green predictor line to the magenta flight path allows pilots to assess, whether the aircraft is trying to get back to the path. The relation of the current airspeed to the commanded airspeed indicates, whether the speed is held. This combination shall allow flight crews to anticipate the future behavior of the aircraft as far out as necessary to issue commands to the control task that will lead to compliance with constraints in the vertical domain.

RELATION TO OTHER VSD DESIGNS

Unlike other co-planar displays [11][13][22] this VSD is not intended to provide direct control mode information. Hutchins' Integrated Mode Management Interface (IMMI) [11] combines a lateral and a vertical mode manager (including a VSD) as an integrated interface to the autoflight control system for FMS equipped aircraft and represents a new approach to mode management. The VSD proposed in this paper is less comprehensive and radical. It complements current aircraft displays rather than replacing them.

The main characteristics of this display are similar to the display elements and geometry described in [6] although less alphanumeric information is presented to keep the VSD as simple and uncluttered as possible and to integrate it with the MAP display instead of replacing it. Other vertical situation displays that appear similar to the one introduced in this paper also include and focus on control mode information in their design.

The MIT developed Electronic VSD [22] includes alphanumeric control mode information for current and future states. The vertical situation display used for the Georgia Tech developed VNAV tutor [13] is aimed at training pilots and also depicts the current control mode in an alphanumeric format. However, as discussed above the tasks that are mainly lacking feedback in the operational use are navigation, flight planning and guidance. In terms of mode management, specific emphasis is put only into visualizing otherwise salient but critical transitions from an FMS-managed mode to a pilot-managed mode through color changes and broken vs. solid lines.

A SOURCE OF AUTOMATION PROBLEMS?

Since the benefits of almost all additional automation in the cockpit so far have been accompanied by new kinds of problems with the automation it is a valid and important issue to raise with regard to the VSD. In the author's opinion the automation (VNAV) is already there and causing the problem, because the appropriate feedback (the VSD) is missing. However, the introduction of the VSD may cause pilots to lose even more basic piloting skills and manual control may be less possible than ever. This is traded off against a better understanding of how the automation is working and improved capabilities for managing the aircraft. However the main effects of new kinds of automation unfortunately become apparent and observable only after the automation is being used in day to day operation for a significant amount of time. A thorough context-bound evaluation can only contribute in avoiding a disastrous misconception, but can hardly detect and resolve the long-term effects.

PLANNED EVALUATION

The VSD is currently implemented in a mid-fidelity part task simulator at NASA Ames. Comments on the VSD of pilots using this simulator were extremely positive.

The VSD is being evaluated using a variety of methods. The first two evaluations use low cost methods to detect flaws and problems in early design stages. One evaluation uses a set of meaningful MAP/VSD snapshots and a questionnaire to each snapshot. The goal is to identify, whether pilots can gain an understanding of the flight situation by looking at the map/VSD combination, and where problematic areas in the display design are. Additionally, Polson et al. at the University of Colorado use a modeling approach to investigate whether the display provides the necessary information to support the task. A comparison to other displays for the vertical domain will also be made.

The current part task implementation provides additional input for another refinement step in preparation of a simulator based evaluation. The display will be one variable in a full mission experiment focusing on CTAS/FMS integration in NASA Ames Advanced Cockpit Flight Simulator.

CONCLUDING REMARKS

Vertical flight path management is currently one of the most problematic areas in glass cockpit aircraft. The need for this kind of strategic flight management will increase in the near future. Additional feedback is required to enable pilots carry out the navigation, flight planning and guidance task in the vertical domain. A vertical situation display addressing these tasks has been introduced and is being evaluated at several fidelity levels.

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