Towards Integrating Traffic and Terrain Constraints into a Vertical Situation Display

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Future airspace operations will allow flight crews to plan and fly their own preferred route and time of arrival without much intervention from air traffic control. Thereby, pilots will become more responsible for planning their own route while maintaining safe separations from traffic and/or terrain. This demands for strategic and tactical planning tools that supports pilots in these tasks. The work in this paper focuses on supporting the airborne separation assurance task in the vertical plane by means of portray traffic and terrain conflict zones onto an enhanced Vertical Situation Display. In a simulator evaluation the experimental display was compared to a baseline display that only showed a terrain profile and intruder aircraft location relative to ownship. The experiment results revealed that although the overlays decreased pilot workload, and resulted in slightly less traffic conflicts, decision-making and conflict awareness did not significantly improve.

To meet the future demand of air transport, in terms of flight safety and its environmental impact, airspace operations are changing. New concepts for Air Traffic Management, such as NextGen and SESAR, permit a more flexible use of airspace (SESAR Consortium, 2007). That is, air traffic operations will be based on trajectory optimization instead of procedural control and each aircraft operating within this new environment will be responsible to adhere to its planned trajectory while maintaining safe separations from traffic, terrain, and adverse weather cells. In other words, more and more Air Traffic Control (ATC) tasks will shift towards the flight deck. To prevent an increase in pilot workload and undesirable side effects, new tools on the flight deck are required to support pilots in these tasks.

One approach may be to delegate airborne separation assurance tasks to the automation. This may be a valid choice, because the employment of automation in aircraft has shown to significantly increase flight technical performance, decrease workload, and increase flight safety over the last three decades. An example of a successful piece of automation is the aircraft’s flight management system, that is able to optimize the flight and minimize the fuel use much better than any human could ever perform by means of consulting aircraft operating manuals.

Despite numerous other benefits, automation has also led to a host of human performance problems, including “out-of-the-loop” situation awareness and vigilance problems, transient workload peaks, skill degradation, difficulties in reassuming manual control, and decreased job satisfaction. Billings extensively discussed the pitfalls of current aviation automation and advocated a more human-centered approach to flight deck design since the flight crew still has the final authority and responsibility to ensure safety (Billings, 1997). A human-centered approach starts with the recognition that humans, unlike (current) technology, can adapt their behavior under new circumstances. When human operators are well-informed, this variance in behavior can provide a positive outcome from unexpected events where automation would have dramatically failed. Supporting such adaptive behavior requires a paradigm shift in flight deck design.

A requirement for promoting effective cooperation between humans and automation is that the automation is transparent enough to allow for observing its performance and for comprehending its functionalities well enough. In this paper we explore a constraint-based approach to interface design to accomplish a synarchy between humans and automation. This approach is inspired by the Ecological Interface Design (EID) framework that recognizes the tight inter-connection between humans and technology (Flach, Vicente, Tanabe, Monta, & Rasmussen, 1998). Previous studies in the horizontal plane showed that such a constraint-based approach can be successful (Van Dam, Mulder, & Van Paassen, 2008). The focus of this paper is on the operational context of airborne self-separation tasks in the vertical plane. Therefore, a Vertical Situation Display (VSD) will be used and enhanced to support such tasks.

Towards a Tactical Planning Tool

A VSD is standard in most modern civil aircraft such as the B737-800, the A380, and the B787. A common layout of a VSD, shown in Figure 1, portrays the aircraft’s vertical flight status by using the along-track distance on
Figure 1: A typical VSD layout showing: 1) altitude, 2) along-track distance, 3) planned trajectory, 4) terrain profile, and 5) position and flight direction of another aircraft.

the horizontal axis and the altitude on the vertical axis. This status picture allows pilots to monitor the flown trajectory, observe traffic, and preview the terrain profile along the planned trajectory.

In a nominal situation, such a status view allows pilots to monitor the aircraft’s path following performance relative to the aircraft’s intentions. However, in case another aircraft is going to cross the intended flight path, tactical deconfliction may be required to ensure safe separations. It may be clear from Figure 1 that such a status view does not indicate potential conflicts, safe fields of travel, and hint what can be done to circumvent a potential conflict. For example, a deviation from the planned trajectory to mitigate a conflict could very well result in another conflict with other traffic and/or terrain. Of course on the short-term, a Traffic Collision Avoidance System (TCAS) or Terrain Awareness Warning System (TAWS) may issue an alert and command a resolution advisory to prevent a direct collision with another aircraft or terrain, respectively. However, these last-resort warning systems are not well integrated, are known to issue false alarms, and they do not allow pilots to anticipate on and evaluate conflicts and their resolutions (Billings, 1997).

To allow for tactical deconfliction (in the vertical plane) from traffic as well as terrain on a medium-term time scale (such as 5 minutes prior to impact), an extension to the VSD would be necessary. Instead of designing a new type of command display and associated automated algorithms, the automation can supply the visualizations that pilots can use to make their own decisions. Previous studies in the horizontal plane showed that meaningful mappings of the work domain constraints can be visualized in such a way that they allow pilots to directly perceive the nature of the conflict and the actions that can be undertaken to ensure safe separations (Van Dam et al., 2008). Inspired by that study, it is hypothesized that similar visual mappings can be useful for the vertical flight situation as well.

**Extended Vertical Situation Display**

A constraint-based approach to interface design starts with a work domain analysis to identify the constraints governing the work domain. Once a representation of the work domain has been composed, EID continues by finding a visualization for the constraints thus discovered. The goal of EID is to transform a cognitive task into a perceptual task by providing meaningful information about the work domain that humans can directly perceive and act on accordingly. Previous studies in the application of EID in aviation demonstrated that making the internal (e.g., aircraft maneuvering performance) and external constraints to flight (e.g., terrain and traffic) – and their relationships – perceptually evident on the interface can promote sound decision-making (Van Dam et al., 2008; Borst, Mulder, & Paassen, 2010).

**Internal Constraints**

The internal constraints are formed by the limitations of the aircraft itself. The internal constraints are divided into maneuvering constraints and energy constraints. The aircraft’s vertical maneuver space is defined by its minimum speed, its maximum speed and its climbing capabilities. The minimum speed is defined by the stall characteristics, the maximum speed by the structural limitations, and the climbing capabilities by the maximum thrust of the engines.
Also the gliding capabilities without thrust may be of interest, for example, when an engine failure has occurred. Altogether these constraints form a boundary for stationary flight conditions, called the performance envelope, see Figure 2. To accomplish a stationary (climbing or descending) flight, it is important that pilots use the throttle and elevator to control the energy state of the aircraft in such a way that the kinetic energy (speed) does not increase or decrease during the climb/descent. Failing to perform a proper energy management strategy can result in stall or overspeed conditions. The aircraft’s instantaneous flight path vector and total energy state can also be mapped in the performance envelope (Figure 2).

External Constraints

In this paper, only traffic and terrain are considered as external constraints to flight. Regarding traffic, minimum safe separation with respect to other aircraft can be defined using a virtual coin-shaped area around each aircraft, known as the Protected Zone (PZ). The dimensions of this area are the current separation minima: a height of 1,000 ft above and below the aircraft and a radius of 5 NM, see Figure 3. When an aircraft enters the PZ of another aircraft, the separation criteria are violated. The external terrain constraints are formed by the shape of the terrain and (man-made) obstacles. In order to have a safe obstacle clearance a Minimum Safe Altitude (MSA) of 1,000 ft is generally adopted.

Interface Mappings

Enabling pilots to evaluate potential conflicts and the opportunities for resolutions, the external constraints to flight should be made observable relative to the internal constraints. Regarding traffic constraints, basic vector calculus can be applied to construct a conflict geometry that indicates whether or not two or more aircraft are on a collision course. Figure 4 indicates how this is done: from the ownship position two lines are drawn to the left and right most points of the intruder aircraft’s PZ. This triangular shape is called the Conflict Zone (CZ). As long as the relative flight path vector stays outside of the CZ, there will be no loss of separation. However, steering the relative flight path vector is a rather difficult and not intuitive task. By applying basic vector geometry the CZ can be translated to the absolute plane such that pilots only have to steer their own flight path vector out of the CZ. The CZ can be directly mapped within the performance envelope: the CZ then marks the area within the performance envelope where the tip of the flight path vector may not be located. Regarding terrain constraints, the highest peak along the route demands the aircraft’s minimum climb rate (or potential energy rate) to safely clear the peak. Extending a line from the mountain peak towards the ownship altitude, and within the maneuvering envelope, then defines the safe field of travel (Figure 5). To ensure the opportunity to clear the peak, the terrain peak line should be below the upper boundary of the envelope.

Working with the Cues

Figure 6 shows a screen capture of the extended VSD (EVSD) with an identical situation as displayed in Figure 1. Contrary to Figure 1, it is now clear that there is a traffic conflict and the pilot can resolve the conflict by reducing the airspeed while continuing on the planned trajectory. Thus the status view of object positions has now been extended to a status view of conflicts as well as the opportunities for resolution. The constraint overlays are
continuously presented, even when there is no immediate threat to safety. As such, pilots can early detect possible threats to safety and avoid them by choosing an efficient and ‘economic’ maneuver.

Mapping all constraints into one display was challenging as they apply to different domains: traffic and internal maneuvering constraints are primarily defined in the speed and altitude domain, whereas terrain constraints are defined in the distance domain. Combining these two domains into a single display was done by adding a horizontal speed and vertical speed tape along the axes of the EVSD, whereby the speed and altitude domains and linked by a look-ahead time. Therefore, the flight path vector not only indicates the airspeed (length) and flight path angle (direction), but also the horizontal distance and altitude that can be reached within the look-ahead time.

To evaluate the severity (or proximity) of a traffic conflict, pilots can observe the geometry of the CZ. That is, the angle between the legs of the CZ gives pilots an idea of the distance of the intruder aircraft. A large angle between the legs indicates that a conflict is close, whereas a small angle indicates that the intruder aircraft is far away. To resolve a conflict, pilots should simply aim flight path vector outside the CZ by adjusting speed and/or flight direction. The means to aim the flight path vector outside CZ are the throttle (to manipulate the vector’s length) and/or the elevator (to manipulate the vector’s direction).

For terrain conflicts, the steepness of the terrain peak line indicates the severity or proximity of the conflict. That is, a steep peak line consuming a large portion of the maneuvering envelope indicates a high mountain peak far ahead, or a relatively small peak very nearby. Which one of the two possibilities applies can easily be detected from the shown terrain profile in the distance domain. To avoid a terrain conflict, while performing a steady symmetric climb, the flight path vector and the energy line should be aligned and aimed above the terrain peak line.
Experimental Evaluation

To evaluate the EVSD as a tactical planning and decision-support tool, a pilot-in-the-loop evaluation (in a fixed-base flight simulator) was done using 12 professional glass-cockpit airline pilots in a mixed within- and between-subjects setup. The pilots were instructed to follow a reference trajectory with associated speed commands and avoid any traffic and terrain conflict by solely adjusting either their airspeed or altitude, or both. They were not given specific strategies to solve the conflicts, because the display was meant to support decision-making, rather than command it. Therefore, they were told to solve conflicts in a safe way, with minimum deviations from the intended flight path and airspeed. The trade-off between safety and flight path efficiency was to be made by the pilots themselves.

The independent variables of the experiment were the conflict scenario (SCENE, a within-subjects variable) and the display configuration (DISP, a between-subjects variable). SCENE had 12 levels: 4 traffic conflicts, 3 terrain conflicts, 4 mixed conflicts, and one conflict-free scenario. DISP had two levels: a baseline VSD (as shown in Figure 1) and the EVSD. The pilots were divided into two groups. Six pilots only operated with the EVSD while the remaining six operated with the baseline VSD.

The dependent measures in the experiment were: 1) the performance, evaluated in terms of target speed deviations, flight-path deviations, and instantaneous load factor, 2) the pilot conflict awareness, subjectively measured by means of a verbal questionnaire during the runs, 3) the pilot workload by means of a NASA TLX rating scale, and 4) the safety in terms of crashes, PZ incursions, and MSA incursions.

Results

Analysis of the performance measure showed that only SCENE had a significant effect on the performance \( (F(11,110) = 4.036, p < 0.01) \). The results, grouped per conflict type, can be seen in Figure 7. Post-hoc analysis (SNK, \( \alpha = 0.05 \)) did not reveal significant differences between these groups. From the figure it can be seen that in the traffic conflict scenarios the average performance scores were higher for the EVSD, meaning that pilots adopted a more efficient strategy to resolve a traffic conflict. When using the VSD, pilots opted for a safe solution by executing the steepest possible climb more frequently. Although safe, these maneuvers were less efficient in most cases. Terrain conflicts, however, were less efficiently resolved by the pilots when using the EVSD. When avoiding traffic, pilots sometimes flew too close to the terrain, causing an MSA incursion and performance penalty.

Regarding conflict awareness, no significant effects were found for neither DISP nor SCENE. Although pilots were inclined to be more ‘conflict aware’ and confident about their answers when operating with the EVSD, no hard conclusions can be drawn.

![Figure 7: Average performance scores per conflict type.](image)

![Figure 8: Boxplot of the inflight traffic awareness answers with the percentages of correct and certain answers.](image)
Since workload was only measured at the end of each run and not for each individual scenario, a separate ANOVA (only for DISP) was done. This result was significant \(F(1, 47) = 11.542, p < 0.01\). Figure 9 shows a boxplot of the measurements that indicate a higher workload for VSD compared to the EVSD. Investigation of the TLX subscales revealed that the factors ‘mental demand’ and ‘temporal demand’ were much higher for the VSD pilots.

Regarding safety, the number of PZ intrusions, MSA incursions and crashes are shown in Figure 10. For EVSD all traffic incursions occurred in one and the same scenario, where the pilots initially solved the conflict by decreasing speed, but they did not anticipate on a later climb, where they needed an additional speed decrease. The MSA incursions for EVSD pilots was because pilots tried to fly as close as possible to the terrain to stay as close as possible to the intended flight path. Additionally, presenting constraint information also invites pilots to fly close the limits of safe system performance (Borst et al., 2010). Despite these results, no crashes have been recorded.

Conclusions and Recommendations

The extended Vertical Situation Display (EVSD), designed using a constraint-based approach to interface design, should allow pilots to diagnose traffic and terrain conflicts in the vertical plane and perceive the opportunities for resolution. An experimental evaluation showed, however, that the EVSD did not prove to be a significant improvement over a baseline VSD in terms of conflict awareness, resolution efficiency, and safety.

For further development of the EVSD, it is recommended to explore scenarios with multiple intruders, changing aircraft configurations (flaps, speedbrakes, gear), and malfunctions. Also, intent information should be included in the conflict zone visualizations to allow for a strategic planning tool. Finally, the effect of wind conditions on the performance envelope and solution space should be investigated since the EVSD relates the aircraft performance envelope, defined in the velocity domain, to distances relative to the ground.

References


