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VISUALIZATION OF MANEUVER CONSTRAINTS FOR AIRBORNE SELF-SEPARATION:
USE OF INTENT INFORMATION

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In the context of future airspace organization, an EID-inspired pilot support tool to support for airborne self-separation in cruise flight was developed and evaluated through pilot experiments. This paper describes follow-up research concerning the shift from the original no-intent design to a novel intent-based design. It analyses how the information exchange of the autopilot speed and heading settings, and the next trajectory change, can be introduced in the current design in the horizontal plane.

Introduction

In the context of future organization of airspace, e.g., Free Flight (RTCA, 1995) or Next-Generation Air Transportation System (Svenson, Barhydt and Landis, 2006) aircraft will fly more autonomously and would be allowed to fly a 4D trajectory of their choice while separating themselves from other traffic in certain parts of airspace. Under these conditions, pilots need support for airborne separation. Several support systems have already been investigated, e.g. Predictive Airborne Separation Assurance System (Hoekstra, 2001).

At Delft University of Technology an alternative interface, the eXtended Airborne Trajectory Planning system (X-ATP) was designed to support airborne self-separation embedded into tactical trajectory (re)planning support. The design is inspired by the Ecological Interface Design framework (Vicente, 1992). The upper levels of the Abstraction Hierarchy are given in Figure 1. The interface visualizes which maneuvers will prevent a loss of separation without causing new conflict situations (Van Dam, Mulder and van Paassen, 2007, Appleton, Mulder and van Paassen 2006, Van Dam, Abeloos, Mulder and van Paassen 2005, van Paassen, 2004). Details about the EID aspects can be found in the given references. A general overview of how the EID framework is applied to vehicle motion problems is presented in (Amelink, Borst, Van Dam, Mulder and van Paassen, 2007).

The resulting interface distinguishes itself from more traditional designs in two crucial ways. First, it shows maneuver constraints rather than an explicit conflict resolution. Hereby it preserves the 4D planning freedom and allows integration with other planning constraints. Second, the constraints are presented in an aircraft speed vector space. This presentation integrates velocity and heading constraints, enabling the pilots to efficiently resolve and prevent conflict situations in a coordinated fashion.

In X-ATP, only state information of the surrounding aircraft is retrieved through use of ADS-B technology. However, no intent information is exchanged amongst aircraft. At present, this assumption is limiting the potential of the interface. Two kinds of (intruder) intent information will be analyzed. The first broadcasts the autopilot settings (AP) of the aircraft state. The second broadcasts the next planned trajectory change of each aircraft. The impact of their use on the conflict representation and related maneuver strategy will be discussed, leading to a proposal for an intent-based X-ATP interface with an extended look-ahead horizon.

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Figure 1. Abstraction Hierarchy for Airborne Trajectory Planning

The No-intent Interface

The current version of the no-intent design is called the eXtended Airborne Trajectory Planning (X-ATP) (Van Dam et Al, 2007) and only works in the horizontal plane. The basic concept of ATP is to display which combinations of heading and speed will result in an intrusion into the Protected Zone (PZ) of an intruder aircraft and at what time such an intrusion would happen. The pilots should choose the speed-heading combination to stay free of conflicts. A conflict is defined as a predicted loss of separation within the next five minutes. Self-separation is achieved by resolving the conflict situation and preventing new conflicts to be triggered.
Conflict Representation

The calculations of (X)ATP are done primarily in the relative plane, Figure 2. By subtracting the speed vector of the intruder aircraft \(V_{\text{int}}\) from the own speed vector \(V_{\text{own}}\), the relative speed \(V_{\text{rel}}\) is calculated. If this vector lays within the “legs” of the Forbidden Beam Zone (FBZ) at some point in the future an intrusion will happen, unless action is taken that moves this vector outside the FBZ. Because it is not intuitively clear for pilots how to change the relative speed, the FBZ is translated by the speed vector of the intruder aircraft, thereby mapping it onto the absolute plane, Figure 3. The pilots can now see how to change the own speed vector, and aim to keep it out of the FBZ. The point where the two FBZ legs meet is called the “origin” of the FBZ. The location of the origin is determined by the intruder aircraft’s speed vector and therefore the intruder aircraft’s speed and heading are implicitly presented through the location of the FBZ origin, whereas a maneuver of the intruder can be interpreted from the translation of the origin.

In Figure 3, the options to change the own speed vector are further constrained. The speed of the own aircraft is limited by the constraints introduced by the flight envelope. These are shown as circular boundaries. The need to fly “towards” the destination of the aircraft excludes heading changes of more than 90° away from the heading towards the destination.

If the FBZ is clipped using these limits, the State Vector Envelope (SVE) is created.

At this point it is important to distinguish the FBZ from the SVE. The SVE is an “action state space” upon which domain constraints, such as separation, are mapped. Given the constraints, a desired state can be chosen and realized by manipulation of the own speed vector.

In practice such a manipulation is a heading and/or speed change, and will take time due to aircraft dynamics. During this time both aircraft move and the shape of the FBZ becomes wider as the aircraft get closer together. For heading maneuvers, this is accounted for. The FBZ legs are calculated using certain turn characteristics (Appleton et al., 2006).

In Figure 4 a progression of screenshots of the bottom part of the final XATP Navigation Display (ND) is given. In this image the intruder aircraft symbol is visible. The outer circle represents the PZ and therefore scales when the display is zoomed in or out. It is colored the same as the current situation (orange:red = less than 5:3 minutes to intrusion respectively). The inner icon indicates aircraft heading. Multiple conflicts result in multiple FBZ, mapped onto each other (Van Dam et al., 2007).

Figure 2: Calculating and Presentation of FBZ in relative plane

Figure 3. Mapping of the FBZ on the absolute plane, centering around the own speed vector, and adding the state limits to the FBZ, creates the State Vector Envelope

Figure 4. The progression of an XATP conflict (Appleton et al., 2006)
Maneuver strategy

In the example of the screenshot the conflict is resolved by the intruder. However, the chosen maneuver is a very inefficient way to resolve the conflict since both aircraft end up flying parallel to each other. As a result the intruder aircraft is not able to return to its original path. In order to resolve and prevent conflicts in an efficient way, a maneuver strategy can be specified regarding when pilots need to maneuver the speed vector out of the FBZ (Van Dam et Al, 2005):

- Minimize the state change (maneuver), i.e., “shortest-way-out”-principle
- Stay away from FBZ origin
- Preferably, do not trigger new conflicts by entering the FBZ generated by intruder aircraft

The “shortest-way-out”-principle also assures implicit coordination in one-to-one conflicts, given that single conflicts are always geometrically symmetrical. By staying away from the FBZ origin, the relative approach speed towards the intruder, $V_{rel}$, is kept away from zero, so that the conflict will totally disappear within a finite period of time and, hence, aircraft can return to their desired path.

Autopilot Speed and Heading Settings

The maneuver strategy, as used in the no-intent interface, does not allow to temporarily trigger a conflict situation in order to cross the FBZ. In the example in Figure 5, the other aircraft turns to the left to change its track. During this turn, a conflict is caused at point $a$ (entering the FBZ from one side), where as at point $b$ the conflict is resolved again (leaving the FBZ zone at the other side). If aircraft will pass each other soon, this behavior leads to very short-term conflict situations, and should be avoided. When both aircraft still have sufficient time available before passing each other, a “crossing”-maneuver does not jeopardize separation.

Note that when the XATP motion model uses the AP turn characteristics for prediction, the exact edges of the FBZ are shown. This means pilots are sure to enter and leave the FBZ without losing separation if, (1), the FBZ edge lies within the SVE envelope boundaries at the moment the crossing maneuver is initiated, and (2), the other aircraft does not make any counteractive “hostile” maneuver.

A crossing maneuver introduces ambiguity regarding the interpretation of intruder behavior. Until the own aircraft leaves the FBZ again, the pilot of the other aircraft can not distinguish a crossing maneuver from a hostile maneuver, i.e., entering the FBZ but not leaving it. In order to prevent ambiguity, the pilot of the other aircraft has to be aware of the nature of the maneuver: crossing (go in and out FBZ) or hostile (stay inside FBZ). A straightforward way to implement this into the current design would be to include the autopilot (AP) speed and heading settings within ADS-B message. A maneuvering aircraft broadcasts the autopilot settings for groundspeed and track, and hence other aircraft receive the “final state” of the aircraft’s maneuver, allowing them to distinguish a crossing maneuver from a hostile maneuver. The pilot can perceive this final state by drawing gray FBZ-border lines according to this state.

Figure 6 gives a new example of a conflict situation where the final state of the intruder vector $V_{int}(1)$ is used to present the gray FBZ-border lines. This example leads to more general motivations to use AP information in the SVE. First, with the no-intent design, the perception of intruder maneuvers is done by interpreting the translation of the FBZ. For this the pilot needs to devote considerable attention to the display, so that the (slow) change on the other
aircraft’s heading and/or speed can be detected. This difficulty was acknowledged by pilot feedback in two pilot experiments (Van Dam et Al, 2005, Appleton et Al, 2006). With the AP information on the SVE, the pilot should now be able to perceive the direction of the movement in one glance. Second, the intruder’s final state is presented, so pilots know where the translation is going to stop. Hence, it is clear where the FBZ will exactly be positioned after the maneuver. As a consequence, pilots can also more easily see how to coordinate with this maneuver.

In Figure 6 the intruder aircraft tries to resolve the conflict with the own aircraft by moving the speed vector from $V_{int}(0)$ to $V_{int}(1)$, hence, making a turn to the right and decreasing speed. The gray lines indicate the position of the FBZ when the intruder maneuver will be finished. With this notion, the ownship pilot can start a cooperative resolution maneuver increasing speed and turn left, i.e., going in the opposite direction of the FBZ translation.

Summarizing, the AP settings are used to present pilots the future FBZ. It is expected that pilots can more easily perceive the ongoing maneuver intent of other aircraft, which then facilitates the execution of coordinated maneuvers. Moreover, the maneuver strategy can be adapted. Temporarily triggering could be allowed. When the one aircraft temporarily triggers a conflict in order to trespass the FBZ, the other aircraft can now identify this type of maneuver, and hence, differentiate it from a hostile maneuver, and even coordinate with the maneuver.

Next Planned Trajectory Change

The second type of intent information would be to use of the next planned trajectory change. Using this information, the motion prediction of the surrounding traffic remains accurate after the trajectory change, hence, the predictions can be used over a larger look-ahead time. The SVE representation is expected to become applicable in the tactical (up to 15-20 minutes) rather than short-term time domain (5-6 minutes).

SVE representation

Similar as for an ongoing intruder maneuver (AP settings), the planned trajectory change will translate the FBZ. The problem differs from the former one because the maneuver is not ongoing but will happen in the near future. Two different types of resolution maneuvers from the ownship can be identified. The pilot can maneuver in such a way that the intruder aircraft is passed either before or after this intruder aircraft changes trajectory.

In Figure 7, a conflict situation is given where the intruder aircraft makes a trajectory change at given time $t_{wpt}$. “CPA” indicates the Closest Point of Approach, thus the point were both aircraft pass each other. The CPA on the figure represents the CPA for the current direction of $V_{rel}$. If the vector magnitude of $V_{rel}$ would be decreased to the point it touches the red dotted circle, the own aircraft would reach the CPA exactly at $t_{wpt}$, the instance that the intruder aircraft makes the trajectory change maneuver. In fact, all points on the circle represent relative speed vectors $V_{rel}$ that result in a time to CPA, $t_{CPA}$, equal to $t_{wpt}$. The geometrical relations that result in this circle are given in Figure 8. Several CPA points (CPA, CPA’, CPA’’) with their respective $V_{rel}$ (red arrows; a, a’, a’’') are given.
Since the current $V_{rel}$ in Figure 7 is outside the circle, the own aircraft will pass the intruder aircraft it before the intruder maneuvers. Any speed-heading state outside of the circle will make both aircraft pass each other before the trajectory change is made, and hence, the part of the FBZ that lies outside the circle can be directly used on SVE as shown on Figure 7.

What if the the ownship makes a maneuver that causes the relative speed to go inside the red circle? In that case the trajectory change needs to be accounted for. In order to come up with a FBZ that holds for the conflict geometry of the new situation, a ghost image of the intruder aircraft is created. The ghost position as drawn in Figure 9 is calculated by taking the position of the trajectory change at $t_{wppt}$ and calculate the position back to where it would be at $t_0$ using $V_{int}(1)$. This position is used to calculate a new FBZ, with its respective CPA points and “break”-circle. In this case, the part of the FBZ inside the circle needs to be used as they represent ownship maneuvers that reach the CPA point after the intruder trajectory change maneuver. If both SVE representations, Figure 7 and 9 are merged into one SVE, the final SVE can be drawn, Figure 10.

Summarizing, the next planned trajectory change can be integrated in the FBZ representation by using two FBZ’s in the SVE representation. One presents the speed-heading maneuver constraints with respect to maneuvers that solve the conflict before the intruder makes a planned trajectory change. The other represents the maneuver constraints with respect to maneuvers that resolve the conflict after the trajectory change is made. It is expected to increase the look-ahead time in which the display can be properly used, making it a more adequate support for tactical trajectory (re)planning on-board.

Concluding remarks

Based on the use of information on the intent of the intruder aircraft, two extensions to an existing no-intent display for airborne self-separation were discussed.

The ecological character of the SVE representation remains in the proposed intent-XATP. The resulting representation encourages skill-based behavior, move out or stay out FBZ (self-separation), while high-level behavior is possible due to the one-to-one mapping of domain constraints related to several functions and their relations in the work domain. To name a few: self-separation, path deviation, slot realization, and aircraft motion. The strength of the representation lies in the coupling between the state of controlled pilot-aircraft system variables, i.e. aircraft maneuvers, and the goal-directed constraints. The intent-based representation seems to even succeed in revealing the intruder behavior and strategies onto the existing action space. This is not achieved by mapping additional constraints on the SVE, but by adapting the current constraint visualization for separation.

More research needs to be done on design alternatives for presenting intent information. The inclusion of the next planned trajectory change for the own aircraft still needs to be addressed. The
current designs will be implemented, and evaluated through pilot experiments in order to prove its proper functioning and pilot acceptance.

References


