The use of intent information in an airborne self-separation assistance display design

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In the context of future airspace organization, an ecological pilot support tool for state-based airborne self-separation in cruise flight in the horizontal plane was developed and evaluated. The design visualizes tactical maneuvering constraints in a speed-heading vector ‘action space’, imposed by the need to separate from other traffic. This paper describes how Target State (TS) and Trajectory Change Point (TCP) intent information of the own aircraft and the surrounding traffic reshapes the typical conflict geometry used to present tactical maneuver constraints of the own aircraft. The ‘break-circle’ technique is used to determine whether own aircraft maneuvers will make both aircraft pass each other ‘before’ or ‘after’ the TS or TCP maneuver occurs. The ‘ghost image’ technique is used to correctly visualize the conflict geometry for the situation after the TS or TCP maneuver. Furthermore, it is also discussed how these maneuver constraints should be mapped on the Navigation Display so that pilots can be aware of the effect of aircraft mode control changes on the constraints. This results in an intent display concept that helps pilots to effectively deal with both state-based and intent-based ‘FMS-enabled’ conflict situations across different aircraft control modes.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tr>
<td>ASAS</td>
<td>Airborne Separation Assurance System</td>
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<tr>
<td>ATP</td>
<td>(eXtended) Airborne Trajectory Planning</td>
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<tr>
<td>CPA</td>
<td>Closest Point of Approach</td>
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<td>EID</td>
<td>Ecological Interface Design</td>
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<tr>
<td>FBZ</td>
<td>Forbidden Beam Zone</td>
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<tr>
<td>FCU</td>
<td>Flight Control Unit</td>
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<td>FMS</td>
<td>Flight Management System</td>
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<td>MCP</td>
<td>Mode Control Panel</td>
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<td>ND</td>
<td>Navigation Display</td>
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<tr>
<td>PZ</td>
<td>Protected Zone</td>
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<tr>
<td>POST</td>
<td>trajectory after TCP</td>
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<td>PRE</td>
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<tr>
<td>TCP</td>
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<td>TCR</td>
<td>Trajectory Change Report</td>
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<tr>
<td>TSR</td>
<td>Trajectory State Report</td>
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<tr>
<td>SVE</td>
<td>State Vector Envelope</td>
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Subscripts

<table>
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<tr>
<th>Subscript</th>
<th>Meaning</th>
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<tr>
<td>int</td>
<td>intruder aircraft</td>
</tr>
<tr>
<td>own</td>
<td>own aircraft</td>
</tr>
<tr>
<td>rel</td>
<td>relative</td>
</tr>
<tr>
<td>on</td>
<td>FMS on, MCP-FCU mode</td>
</tr>
<tr>
<td>off</td>
<td>FMS off, FMS-RNAV mode</td>
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I. Introduction

In future airspace environments,¹,² aircraft will fly more autonomously and would be allowed to fly a 4D trajectory of their choice. In certain parts of the airspace unmanaged by Air Traffic Controllers, pilots will be responsible for separating their own aircraft from others. Under these conditions, pilots need

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support for airborne separation. At Delft University of Technology an alternative interface, the eXtended
Airborne Trajectory Planning system (XATP) was designed to support airborne self-separation embedded
into tactical trajectory (re)planning support. The design is inspired by the Ecological Interface Design
framework. The interface visualizes which maneuvers will prevent a loss of separation without causing new
conflict situations. The design assumes general definitions for conflicts and airborne self-separation
including a 5NM horizontal separation and a 5 minute look-ahead horizon for conflict detection.

The resulting interface distinguishes itself from more traditional designs, such as P-ASAS, 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,
allowing the pilots to efficiently resolve and prevent conflict situations in a coordinated fashion. Details
about the EID aspects and pilot experiments can be found in previous publications. A display design for
the vertical design and a general overview of how the EID framework is applied to vehicle motion problems
is presented in the following publications.

In the XATP system, only state information of the surrounding aircraft is retrieved through use of ADS-B
technology. However, ADS-B technology can also be used to exchange intent information with nearby traffic.
In this design study, the ADS-B Target State (TS) and Trajectory Change (TC) reports will be used to
enhance the state-based XATP display with intent information from the intruder. This information will be
used together with the own state and own FMS information to enhance the already existing presentation of
tactical maneuver constraints, imposed by the need to separate from the intruder and presented in the own
aircraft’s speed vector maneuver space. To do so, the vector ‘break circle’ and ‘ghost image’ techniques are
used in order to calculate the effect of including intruder TS (TS_{intr}) and Trajectory Change Point (TCP)
(TCP_{intr}), and the own aircraft’s TCP (TCP_{own}, on the geometry of the maneuver constraints .

In the lines of the ecological approach and Gibson’s direct perception-action coupling, the main purpose
of enhancing the maneuver constraints is to present them in such a way that pilots can, one, directly perceive
whether the trajectories of the own aircraft and the surrounding traffic will cause a conflict, and if so, two,
perceive which pilot maneuver actions can be done to resolve the situation effectively. Introducing FMS
enabled flight in the tactical navigation work domain introduces a new dimension to the pilots action space
in the sense that the pilot makes aircraft control mode changes, e.g., going from trajectory control to target
state control, Figure 1. When the FMS of any aircraft is disconnected, this ‘mode change’ action discretely
and instantly changes the predictions on aircraft motion. Special attention will be given to make pilots aware
of the effect of FMS mode changes on the conflict situation ‘before’ the control action is done, i.e., before the
FMS is (de)activated. Given the tactical, and therefore time-critical nature of the navigation support tool,
the manipulation of the flight plan Trajectory Change Points (TCP) points using the Control Display Unit
is not considered in this work. For the same reason and also to avoid too much complexity at this stage of
research, only the first TCP of each FMS path is considered.

In the next section the basic no-intent design is discussed. Then the ADS-B Trajectory Change (TC)
and Trajectory State (TS) reports are detailed and some related intent terminology is given. In the work
domain analysis, details are given on the work domain boundaries, the conflict resolution task, the effect
of TS and TCP information and aircraft control mode changes on the maneuver constraint geometry, the
Forbidden Beam Zone (FBZ). The findings of the analysis are used to come up with an enhanced mapping
symbology of the FBZ maneuver constraints on the XATP-intent interface design. An adapted pilot action
strategy allows pilots to effectively work with the display in both Trajectory control mode, FMS_{on}, and TS
control mode, FMS_{off}.

II. The state-based XATP system

The current version of the no-intent design is called the eXtended Airborne Trajectory Planning (XATP) and
only works in the horizontal plane. A complementary design has been made for the vertical plane in
order to integrate both. The basic concept of ATP is to display which combinations of heading and speed
will result in an intrusion into the intruder’s Protected Zone (PZ) 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.
A. Conflict representation

The calculations of (X)ATP are done primarily in the relative plane, Figure 2(a). By subtracting the speed vector of the intruder aircraft $\vec{v}_{\text{intr}}$ from the own speed vector $\vec{v}_{\text{own}}$ the relative speed $\vec{v}_{\text{rel}}$ 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 2(b). 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(a), 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 degrees 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’ or maneuver space upon which work 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 $\vec{v}_{\text{own}}$.

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 approach each other. For turn maneuvers, this is accounted for with the FBZ legs are calculated using autopilot turn characteristics.

B. Interface mapping

In Figure 4 the state-based XATP system is shown. The SVE is mapped onto the ND at the own aircraft’s position, presenting a speed vector overlay on the ND plan view position space. 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 according the predicted time to loss of separation for the current speed $\vec{v}_{\text{own}}$ (orange;red =
(a) Calculating FBZ in relative plane. \( \vec{v}_{\text{rel}} \) lies inside the FBZ and therefore the aircraft will move inside the intruder’s Protected Zone (PZ).

(b) Translation of the FBZ to the absolute plane, centering around the own speed vector \( \vec{v}_{\text{own}} \).

Figure 2. Calculation of the Forbidden Beam Zone (FBZ)

(a) State Limits

(b) State Vector Envelope

Figure 3. Adding performance boundaries to the state vector space (a) creates the State Vector Envelope (SVE) (b)

less than 5.3 minutes to intrusion respectively). If no conflict exists, i.e., \( \vec{v}_{\text{own}} \) is located outside the FBZ, the FBZ area is filled in gray and the intruder PZ is outlined in gray too. The inner icon indicates aircraft heading, and points in the direction where one can find the origin of the related FBZ on the SVE. Multiple conflicts result in multiple FBZ’S, mapped onto each other allowing the pilot to resolve all conflicts with one maneuver (moving out of FBZ’s), and prevent the creation of new conflicts.

C. Maneuver strategy

In order to resolve and prevent conflicts in a safe and efficient way, i.e., to minimize total path deviation from the original trajectory while safely resolving the conflict, a maneuver strategy can be specified. When a conflict is detected, pilots move the speed vector \( \vec{v}_{\text{own}} \) out of the FBZ. The following maneuver strategy rules apply:

- Minimize the state change (maneuver), i.e., ”shortest-way-out”-principle
- Stay away from FBZ origins
- Avoid entering other FBZ’s (do not trigger new conflicts)

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, \( \vec{v}_{\text{rel}} \), is kept away from zero. This strategy rule encourages the selection of a fast ‘crossing’ maneuver over a slow ‘parallel’ maneuver, hereby promoting a low time to Closest Point of Approach (CPA), a fast return to the desired path.

Note that because the XATP motion model uses the AP turn characteristics for motion prediction, the exact edges of the FBZ are shown. This means pilots are sure to enter and leave the FBZ without
loosing separation if, (1), the FBZ edge lies within the SVE envelope boundaries at the moment the crossing maneuver is initiated, and (2), the intruder aircraft does not make any counteractive "hostile" maneuver. However, 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, since a state-based system can not inform the maneuver intent to other aircraft in the surrounding, i.e., pilots are unable to identify safe maneuvers that temporarily trigger a conflict from dangerous or hostile maneuvers that trigger real conflict situation.

### D. Lack of intent information

A similar pilot reaction can be expected in the traffic situation sketched in Figure 5. According the FMS planned trajectory, the intruder will make a Fly-By turn at the TCP waypoint. Moreover, the intruder aircraft reaches it’s TCP point before both aircraft pass by each other, i.e., before the Closest Point of Approach (CPA) is reached. Looking at the FBZ constraint before, during and after the TCP turn. There is no conflict situation before or after the turn maneuver of the intruder, Figures 5(a) and 5(c). During the turn maneuver however, the speed vector enters the FBZ, Figure 5(b). When this happens, the pilot of
the own aircraft could consider this intruder action as hostile, and could counter-act by steering the speed vector away from the FBZ, i.e., initiate a turn to the left. This would cause the SVE to remain similar to Figure 5(b) as long as the intruder is turning. If the pilot would be aware of the intent of the intruder turn maneuver, he or she would not react.

It is clear that the present state-based system should be enhanced with information that enable pilots to deal properly with initiated or ongoing maneuvers as well as with future trajectory changes of both the own aircraft and the surrounding traffic. This calls for the inclusion of TC and TS report information into the representation of maneuver constraints used in the XATP system. The following section describes the available ADS-B technology and explains some intent terminology used throughout the paper.

III. ADS-B and Intent Terminology

ADS-B transponders are used to enable airborne data communication between aircraft in each other’s vicinity. In addition to current state information the messages can also contain intent information. The transmitting aircraft must support ‘FCU-MCP’ TS mode to acquire TS commands and ‘FMS-RNAV’ trajectory control mode to get the flight plan information. The requirements regarding the message contents are laid down in a RTCA report and is used as a general guideline. Based on the technical specifications, it is assumed plausible that the capacity and update rates of the system are sufficient to properly support an intent-based separation assistance tool. There are multiple types of data messages that are sent through ADS-B. Aircraft state reports include actual position and speed information that is used by the state-based XATP system. For intent messages, two message types exist. First, the Trajectory Change (TC) report gives information on the aircraft’s FMS flight plan. The Target State (TS) report provides information about the aircraft’s target state commands, e.g., target heading entered by the pilot in order to make an autopilot controlled turn. Figure 1 presents an overview of aircraft control states.

A. Trajectory Change (TC) and Target State (TS) reports

The FMS system is a navigation aid database that contains intent information in the form of waypoints. The information of a waypoint is detailed in a so-called ‘Trajectory Change Point’ (TCP). Up to four TCP’s are defined in one ‘TC report’. TC report cycle numbers make it possible to distinguish between TCP’s and they define the sequence order of the waypoints for reconstructing the flight trajectory. Table 1 lists the elements provided in a TC report. Included are waypoint elements such as Time-To-Go, position, turn radius, track to TCP, track from TCP, and the command/planned flag for different TC types, e.g. a Fly-By turn or a Direct-to-Fix transition. TC reports can only be sent when the FMS is enabled and the aircraft is flying in accordance with the flight path depicted by the FMS. In case the pilot uses the the FCU-MCP to command an autopilot maneuver, the FMS is disabled. From then on all TC reports are still sent out but have the flag type set on ‘Planned’ instead of the ‘Command’ indicating that the FMS has been disengaged and the listed TCP points are not ‘active’ anymore. With the FMS disabled, additional TS reports are sent out, containing the MCP target heading. When the pilot updates and activates the FMS again, the TS reports are suspended. The elements of a TS Report are also given in Table 1. This table is adapted from the RTCA report.

B. Intent terminology

Throughout the paper the trajectory parts of the own and intruder aircraft will be labeled as shown in Figure 6. Aircraft control modes are described as follows: $FMS_{\text{int(on)}}$ refers to the intruder aircraft flying FMS enabled, also referred to as FMS-RNAV mode or trajectory control mode. $FMS_{\text{own( off)}}$ refers to the own aircraft flying FMS disabled, also referred to as MCP-FCU mode or TS control mode.

The acronym PRE refers to the trajectory part before the TCP is reached. $PRE_{\text{int}}$ refers to the intruder trajectory before the TCP point according the FMS plan, $FMS_{\text{int(on)}}$. $POST_{\text{own( off)}}$ refers to the own trajectory after the TCP that would be flown if the own FMS would be disabled, $FMS_{\text{own( off)}}$. $POST_{\text{int(on)}}$ refers to the own trajectory after the TCP that would be flown if the own FMS would be disabled, $FMS_{\text{int(on)}}$. 

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Table 1. Selection of Trajectory Change (TC) and Trajectory State (TS) Report elements.\textsuperscript{15}

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<th>Element</th>
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<th>TS Content</th>
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<td>version</td>
<td>TCR cycle number</td>
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<tr>
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<td>Time To Go</td>
<td>idem</td>
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<td>Horizontal</td>
<td>Horizontal data available and TC Type</td>
<td>Target Source Indicator</td>
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<td></td>
<td>Vertical Command/Planned Flag</td>
<td>Vertical Mode Indicator</td>
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</table>

Figure 6. Conflict situation with intent for both aircraft. Geometry and definition of trajectory. \textit{PRE} refers to the trajectory before the TCP is reached. \textit{POST(on)} refers to the trajectory after the TCP point according the FMS plan, \textit{FMS(on)}. \textit{POST(off)} refers to the trajectory after the TCP that would be flown if the FMS would be disabled, \textit{FMS(off)}.
IV. Work Domain Analysis (WDA)

For the state-based XATP design a work domain analysis has been made. The Abstraction Hierarchy (AH) was used as a tool to identify and relate functions and constraints of the work domain that shape the behavior of the worker. The reader is for now referred to previous publications to look up the AH in detail. In this paper the domain analysis will only focus specifically on the effect of including intent information on the visualization of the FBZ maneuver constraints and the effect of using aircraft control mode changes.

Before the domain analysis is detailed, however, the pilot work and the work domain boundaries have to be specified. The work being analyzed in this paper is tactical navigation in the horizontal plane during cruise flight with initially all aircraft flying FMS enabled. As stated in the introduction because of the tactical time horizon and also to limit the complexity of the design challenge, only one future TCP waypoint for each aircraft will be taken into account in the analysis. It is assumed that pilots fly FMS(on) mode while they are confronted with a conflict situation. At all times all aircraft are allowed to disengage the FMS and can enter TS commands on the MCP.

The pilot task consists of the on-board path (re-)planning of speed and turn maneuvers, with the main goal of separating themselves from other traffic in the vicinity. After analysis of the situation, the pilot has three options to deal with the situation:

- the pilot does not act and continues flying FMS-enabled;
- the pilot disengages the FMS, but does not give any TS Commands on the MCP; and
- the pilot gives State Commands on the MCP and hereby the FMS is automatically disengaged.

When the conflict is resolved and both aircraft have passed each other, the pilot will initiate the path recovery maneuver by flying a Direct-to to the closest TCP waypoint on the FMS flight path. Updating and activating the FMS again are left outside the scope of this paper, but could be included in future research.

The interface should regardless the active control mode always show ‘separation’ in direct relation with the pilot action space. The FBZ constraint areas should therefore show the separation problem, or conflict, in such a way that:

- In both FMS modes, the pilot are aware of the conflict status (perception);
- In both FMS modes, the pilots should be aware which actions can effectively solve the conflict situation without triggering a new one (action).

In the context of pilot action capabilities, the main difference with the state-based work domain is that pilot control actions are not limited to aircraft maneuvers (velocity vector state changes on the SVE), but also the aircraft control mode changes. These discrete actions, change the motion path calculations for the aircraft, and can instantly cause state ‘jumps’ for the variables that govern the FBZ constraints, e.g. the deactivation of the intruder’s FMS can instantly trigger or resolve conflicts, move and (un)hide FBZ areas on the SVE. Direct perception-action coupling of separation is realized by showing how disengaging the FMS affect the appearance of the FBZ maneuver constraint areas. The effect of the control change should be perceivable before the actual mode change is made.

In the following sections, first the pilot navigation work dealing with conflict situations will be briefly described together with the work domain boundaries that apply to this analysis. Then, it is analyzed how a TCP int affects the calculation of FBZ maneuver constraints. In continuation, the effect of introducing TCP own is investigated. Using TCP int or TCP own trajectory information in the calculation of FBZ areas, it will become apparent that different types of FBZ constraint areas exist. The characteristic of the FBZ area depends on the trajectory part it refers to and the aircraft control mode that is currently active. The last section of the work domain analysis will therefore set up a typification of FBZ areas, which can be used as a basis for a new mapping symbology for the FBZ constraints on the interface.

A. The effect of intruder Trajectory Change Points (TCP) on the FBZ constraints

The traffic situation as sketched in Figure ?? is used to explain the problem of FBZ constraint calculation when intent information is used. It shows how the intruder turn maneuver depicted, will translate the FBZ with respect to the current situation. Calculating the constraint area for the actual situation using the
calculations and visualization of the state-based XATP system would normally result in the SVE given in Figure 5(a). However, within the SVE state space there might be vector states of $V_{\text{own}}$ that will result in a situation where the intruder reaches the TCP before both aircraft pass each other, i.e., $t_{TCP} < t_{CPA}$. In that case the FBZ will translate during the turn maneuver, Figure 5(b), and after the turn will it look like Figure 5(c). If on the contrary, a state vector $V_{\text{own}}$ is chosen that results in a situation where both aircraft pass each other before the intruder moves, i.e., $t_{TCP} > t_{CPA}$, then the state-based constraint area can be used, Figure 5(a). From the above, it becomes apparent that the speed-heading SVE vector space in which the maneuver constraint area (FBZ) is drawn should be split up in two types of areas. One area represents the speed-heading states that will result in both aircraft passing each other before the intruder turns. In this area the original FBZ of Figure 5(a) will be drawn. The other area represents the speed-heading states that make both aircraft pass each other after the intruder turns, and would contain an FBZ similar to the one presented in Figure 5(c).

1. The break circle technique

In order to construct the boundary between both situations, the geometrical relationships of the conflict situation are analyzed in order to find a useful description for the boundary where $t_{CPA}$ equals $t_{TCP}$.

A large circle in Figure 7 is constructed from all relative speed possibilities, i.e., all directions of $v_{rel}$ that go towards the intruder position. The collection of all CPA points form a circle containing both the position of the intruder and the own aircraft, i.e., the diameter of the circles equals the distance between both aircraft. Each CPA point of the circle will contain exactly one $V_{rel}$ for that direction that holds the condition that $t_{CPA}$ equals $t_{TCP}$. If for all possible directions, the related $V_{rel}$ is drawn again a circle appears connecting the vector endpoints, see the smaller circle in Figure 7. The situation is described in the relative plane, i.e., it expresses the relative motion of the own aircraft with respect to the intruder. Note that the FBZ as shown in Figure 2(a) is also calculated in the same relative plane, and thus this small circle can be used in the same way to break up the SVE in two zones. The small circle is defined as the ‘break circle’ throughout this paper.

![Figure 7. Calculation of the break-circle that represents $t_{CPA}$ equals $t_{TCP}$ in the relative plane](image)

Equation 1 expresses the geometrical relation between $V_{rel}$ and the location of the TCA:

$$\frac{V_{int}}{d_{int}} = \frac{V_{rel,i}}{d_i} \text{ with } i = 1, 2, 3$$  \hspace{1cm} (1)
$V_{int}$ is the intruder velocity, $d_{int}$ is the distance from the intruder to the TCP along the flight-path, $V_{rel,i}$ is the relative velocity for $t_{TCP} = t_{CPA}$, and $d_i$ is the distance to the CPA point. The vector $V_{rel,i}$ in Figure 7 is the vector that defines the break-circle. $V_{rel,i}$ has a CPA point $CPA_1$ that lies exactly on the position of the intruder aircraft and both aircraft will collide fully into each other. If $V_{rel,i}$ is taken, this collision will occur exactly on the TCP. $V_{rel,i}$ can easily be obtained from equation 2. From the geometrical relations in Equation 3-1 it follows that:

$$\frac{V_{int}}{d_{int}} = t_{TCP} = t_{CPA} = \frac{V_{rel,i}}{d_i}$$  

(2)

The intruder time to TCP is known from the TC reports (TCR). Since the distance between both aircraft is the sum of $d_1$ and $V_{rel,i}$, the only unknown in the equation is $V_{rel,i}$. $V_{rel,i}$ defines the diameter of the break-circle and therefore the boundary geometry by means of the break circle is known.

2. Pre-TCP calculation using the ‘break circle’

The break-circle can now be translated to the absolute plane to fit in the SVE. The intersection with the original FBZ indicates which part of the FBZ applies to the current situation. When the tip of the own speed vector is inside the circle, the own aircraft will reach the CPA after the intruder has made the turn at $TCP_{int}$. The area outside the circle represents all possible velocity vector solutions where CPA is reached before the intruder reaches $TCP_{int}$. Figure 8(a) shows how the constraint area is presented in the SVE.

![Figure 8](image)

Figure 8. $TCP_{int}$: Calculation of FBZ areas for (a) PRE$_{int}$ and (b) POST$_{int(on)}$ trajectory parts using break-circle and ghost image technique.

3. Post-TCP calculation using the ‘break circle’ and the ‘ghost image’ technique

To come up with the FBZ constraint shape related to the situation after the intruder turned, a ghost image position needs to be calculated, Figure 8(b). The break-circle can now be calculated by using the ghost position instead of the current position of the intruder.

In the example situation the own speed vector is inside the circle. In this case the TCP will be reached before the CPA and the velocity state of the intruder at the end of the transition must be taken into account to be able to predict, calculate and visualize the constraint area with that velocity state. To calculate the constraint area in the SVE that belongs to this velocity state in current time, calculate the position back in time using the velocity state at the transition end-point. In other words, create an image at present time as if the intruder would have always flown on the flight-path it will fly after the transition end-point. Figure 9 shows the geometry and the resulting constraint areas in the SVE. The SVE shows that neither before
nor after the intruders TCP turn there will be a conflict. Figure 5(b) shows that the system without intent information reports a conflict during the turn maneuver.

![Diagram showing TCP int: Both FBZ constraint areas are mapped on the SVE. FBZ area types (1), (4) are shown, area type (7) remains invisible in the state-based XATP interface mapping, see Table 2 for area type definitions. (1) refers to the intruder trajectory before turn, PRE int, (4) refers to the intruder trajectory after the turn when following the FMS trajectory, POST int(on)](image)

Figure 9. TCP int: Both FBZ constraint areas are mapped on the SVE. FBZ area types (1), (4) are shown, area type (7) remains invisible in the state-based XATP interface mapping, see Table 2 for area type definitions. (1) refers to the intruder trajectory before turn, PRE int, (4) refers to the intruder trajectory after the turn when following the FMS trajectory, POST int(on)

### B. The effect of intruder Target State (TS) information

The ghost image technique can be equally used during ongoing intruder turn maneuvers. Using the target state heading value the related turn can be calculated. From the turn end point a ghost image can be made. The FBZ of the ghost image can be used to show the own pilot how the maneuver constraints are affected by the TS maneuver of the intruder aircraft. Figure 10 shows a sketch of the SVE during a turn maneuver. The blue FBZ represents the FBZ of the ghost image where as the red FBZ is layered below it to show the location of the original state-based FBZ.

### C. The effect of the own TCP-point

In the same way as in the above sections, calculations for the break-circle and FBZ-areas can be made to visualize the effect of on intent information. Figure 11 shows screenshots of a traffic situation where the own aircraft will turn to the left. In Figure 11(a) information and drawings were added to show how the ‘ghost image’ of ‘own’ aircraft is constructed in the same way as it was showcased for the ‘intruder’ aircraft in Section 3. A ghost-SVE is shown located at the hypothetical position of the own aircraft at current time, ‘if it would already fly according the ‘post-TCP’ trajectory. In an early design version of the intent display, both SVE’s were mapped on the actual aircraft position, i.e., the ghost-SVE was translated to the actual position and rotated so that the ghost state vector was exactly on the actual state vector \( V_{\text{own}} \). Note that for the plotting of the FBZ areas the state-based XATP symbology is used.

Two important issues came to surface when testing this display in a simulation environment. First, it became apparent that, when using own intent, FBZ area (4) related to the intent part of the trajectory, \( \text{POST}_{\text{own}}(\text{on}) \), can only be used to detect a conflict situation but this area, i.e., pilots would know a conflict would continue or be triggered when the state vector \( V_{\text{own}} \) is inside this area, but entering a TS command that would put the state vector out of this area would not assure the conflict is resolved, i.e., it can not
Figure 10. Calculation of ghost image of intruder TS state image. The FBZ based on the ghost technique.

Figure 11. Intent-based XATP display for the example conflict situation with own intent.
be used as an instant maneuver constraint area. When considering TS maneuver options only resolve the conflict, only areas (1) and (7) are direct maneuver constraint to be considered, Figure 11. Note that since there is no conflict flying FMS enabled the pilot would not maneuver unless other events would call for such an action.

Supposing the pilot needs to maneuver for an additional reason, a second issue comes to surface. Once the pilot gives a State Command on the MCP, the FMS deactivates and the SVE would switch from the early intent design screenshot in Figure 11(b) to the no-intent state-based display screenshot, Figure 4. Post hoc, the pilot realizes that FMS deactivation triggers a conflict, i.e., $V_{own}$ is located inside FBZ area (7), Moreover, area (2) has disappeared. Note that for this traffic situation, areas (1) and (7) together result in the original state-based FBZ geometry, Figure 4.

D. Categorization of FBZ constraint areas

Given the different nature of the FBZ constraint areas a categorization is set up. FBZ types can be related to the part of the trajectory they apply, both for the own aircraft and the intruder aircraft. As defined in Figure 6, each aircraft has three trajectory paths. This means that theoretically 9 combinations exist where loss of separation is possible. The FBZ constraint types are labeled according these combinations, resulting in 9 types labeled (1) to (9), Table 2. Throughout this paper FBZ areas have been and will be labeled according this table.

| Table 2. FBZ Constraint types for trajectory part combinations where they apply to | Table 3. Quadrant of possible FMS mode combinations for a single conflict |
|---|---|---|
| OWN | POST(on) | POST(off) |
| PRE | 1 | 4 | 7 |
| INT | 2 | 5 | 8 |
| POST(on) | 3 | 6 | 9 |

According the work domain boundaries specified earlier, it is assumed that pilots would start out with a situation where both aircraft are flying FMS enabled, ‘ON-ON’. During the resolution of the conflict however, three more FMS mode combinations are possible in a single conflict: ‘OFF-ON’, the own FMS is switched off while the intruder FMS is still active, ‘ON-OFF’, the intruder’s FMS is switched off while the own FMS is still active, ‘ON-ON’, both aircraft have their FMS switch off the FMS. Table 3 shows the labeling used for these combinations. The nine types of FBZ areas never apply at the same time but depend on the currently active FMS combination and the specific geometry of both FMS trajectories, i.e., where both trajectories are close enough to each other to lose separation. Table 4 specifies for each FMS mode combination which FBZ types apply.

Using these table one can clearly see how certain FBZ areas appear or disappear when the intruder or own aircraft disengages the FMS. Disengaging the own FMS while $FMS_{int}(on)$ means going from the ON-ON table to the OFF-ON table. One can see that types (4), (5) would disappear and types (7), (8) appear.

Figure 12 presents the SVE maneuver space for the four FMS mode combinations as it would look like in the state-based XATP design for the traffic situation as described in Figure 6 when both fly FMS engaged. Note that both aircraft have their own TCP point much more closer than the other one’s TCP point. This implies that within the maneuver capabilities of the own aircraft it is not possible to lose separation in the pre-TCP trajectory path of the other aircraft, and therefore no break-circles exist within the SVE boundaries. In total four constraint types exist for this example: (5), (6), (8), and (9). In Figure 12, the constraint types appear and disappear due to mode control changes according Table 4. Areas (8) and (9) are instant maneuver constraints whereas (5) and (6) are not because they are based on the $POST_{own}(on)$ trajectory part.

E. Discussion on the WDA analysis

In the line of the ecological approach, the research challenge is to present separation affordances in a visual format so that pilots can directly perceive a conflict situation, and how to deal with it safe and effectively. From the WDA analysis, it is clear that it is possible to account for the effects of intruder and own intent
Table 4. Active FBZ constraint types for the four FMS mode combinations. Disengaging the own FMS, $FMS_{own(on)}$ to $FMS_{own(off)}$, results in areas (4) and (5/6) to be replaced by areas (7) and (8/9) respectively. Disengaging the intruder’s FMS, $FMS_{int(on)}$ to $FMS_{int(off)}$, results in areas (2) and (5/8) to be replaced by areas (3) and (6/9) respectively. Areas (1), (3), (7) and (9) together define the FBZ as calculated in the state-based display, Figure 2. Section

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Figure 12. Presentation of the same conflict situation for the four possible FMS-mode combinations as they would appear using the state-based XATP symbology.
information in the geometry of the FBZ. However, a few complexities are introduced by the use of own intent information and FMS mode changes.

The own intent TCP divides the own trajectory in three parts \( PRE_{own} \), \( POST_{own}(on) \), and \( POST_{own}(off) \). The conflict situation used in Section C, Figure 11, showed that the FBZ-area related to the \( POST_{own}(on) \) trajectory part can inform if there is a conflict or not on that trajectory part in the current FMS-engaged mode, it can not be used as an instant maneuver constraint. After the categorization of FBZ constraints we can generalize this by stating that FBZ area types (4), (5) and (6) are no instant maneuver constraints and should be given a different symbology then the other constraint types.

Figure 12 clearly shows that FMS mode changes displace the FBZ, and can trigger or resolve conflict situations. Since pilots should be able to be aware of the impact of their own FMS mode change, this should be made visual on the interface. From Table 4 one can see that switching from ‘ON-ON’ to ‘OFF-ON’ mode, type (4) will switch to (7), and (5) to (8). While switching from ‘ON-OFF’ to ‘OFF-OFF’ mode, type (4) will switch to (7) again, and (6) will switch to (9). The important thing to realize is that the couples, i.e. (4)-(7), (5)-(8), (6)-(9), should be both visible in both FMS modes, \( FMS_{own}(on) \) and \( FMS_{own}(off) \), moreover within-couple there should be a symbolic difference between both elements, indicating which of both is ‘active’ in the current mode.

V. Interface mapping

Figure 11(b) represents an earlier attempt to make a suitable intent display based on the knowledge of the FBZ break-circles. This design failed to meet the requirements to clearly show ‘instant’ maneuver areas and failed to show to present the active-inactive FBZ area ‘couples’ that allows to see the FMS mode change affordances. Therefore the old symbology is abandoned and a new one is created to explicitly distinct the different types of FBZ constraints. The following symbology rules are suggested for the new design:

1. ‘Instant’ maneuver constraints are presented in color, the others (4), (5) and (6) in gray.

2. ‘Active’ maneuver constraints are filled, ‘inactive’ areas are empty but outlined.

Applying these two symbology rules, Figure 13 shows how the SVE envelope is created. The total SVE is the result of mapping three overlays. Overlay 1 shows the FBZ areas (1), (2) and (3) related to the \( PRE_{own} \) trajectory. These FBZ areas in this layer are always colored and filled and are the top layer on the interface. Overlay 2 shows FBZ areas (7), (8) and (9) related to the \( POST_{own}(off) \) trajectory parts. These areas are always colored. Disengaging the own FMS will change them from empty to filled. Overlay 3 shows FBZ areas (4), (5) and (6) related to the \( POST_{own}(on) \) trajectory parts. These areas are always gray. Disengaging the own FMS they change from filled to empty.

Figure 14 shows the construction of SVE for the intent display for FMS enabled and disabled, respectively left and right. The situation is drawn for \( FMS_{int}(on) \). The SVE’s in Figures 14(e) and 14(f) can be compared with state-based XATP symbology, Figure 12(a) and 12(b). Equally, the SVE’s in Figures 15(a) and 15(b) can be compared with Figures 12(c) and 12(d) for the case that \( FMS_{int}(off) \). Figure 16(a) and 16(b) depict the new SVE design for the situation depicted in Figure 11.

A. Conflict resolution strategy

The conflict status can always be perceived by looking at all filled FBZ areas. If the vector lies inside any of the filled areas the aircraft is in conflict in the current aircraft control mode. The direct maneuver constraints are always visible as areas that are colored. Depending on the related time to loss of separation the zones can be colored differently, e.g. using orange and red as is done in the state-based XATP design.

The pilot flies FMS enabled unless the SVE speed vector lies inside a filled FBZ area. If, inside a filled FBZ area, the pilot remains in \( FMS_{own}(on) \) and analyze the SVE envelope and decides about the resolution action needed. The following rules will be applied in sequence to come up with the most effective action.

1. If the state vector lies outside all colored filled and empty areas, disengage the FMS without further maneuvering, otherwise follow step 2.

2. Disengage the FMS by choosing a target state that moves the vector out of the colored areas and use the state-based maneuver strategy as specified in Section C.
When the FMS is disengaged the empty colored areas will fill up, showing all instant maneuver constraints clearly filled. All gray areas representing the own intent are still outlined but empty. The motivation to still outline these lines is related to further research. Keeping these areas visible in $FMS_{own}(off)$ allows pilots to see if the own updated FMS trajectory would trigger a conflict when the pilot would choose to activate the FMS mode again.

B. Observing intruder behavior

Intruder TS commands are implicitly visible by replacing the $PRE_{int}$ and $POST_{int}(off)$ trajectory parts by the trajectory flown as a result of the TS input in the calculation of the FBZ constraint areas. In the TS example, The FBZ based on the TS ghost image will be shown, labeled ‘ts’, in stead of the state based FBZ, labeled ‘s’, Figure 10(b).

The effect of intruder mode change affordances are not visualized, i.e., the own pilot can not anticipate that FBZ area (5) would be replaced by (6), and (8) by (9), when the intruder disengages the FMS. When the intruder performs this action, the own pilot can of course observe the change. In Figures 14 and 15, the effect of disengaging the intruder FMS, $FMS_{int}(on)$ to $FMS_{int}(off)$, will discretely change the SVE from Figure 14(c) to the SVE in Figure 15(a) when $FMS_{own}(on)$. The SVE in Figure 14(f) will change in the one in Figure 15(b) when $FMS_{own}(off)$.

The main reason not to show the intruder mode change affordances on the own pilot’s SVE is to prevent information overload, or clutter on the SVE. The one scenario in which the own pilot would really benefit from knowing the intruder’s mode change action capabilities, would the situation in which the own pilot can see that the intruder could solve the conflict by simply disconnecting the FMS while for the own pilot the only possible way to resolve the situation would be a TS maneuver. This information would help the own pilot to do nothing, and wait for the intruder to disengage the FMS as this would be the most effective way to solve the conflict.
Figure 14. Construction of SVE for the intent display for FMS enabled and disabled, respectively. The situation is drawn for $FMS_{\text{on}}$. Compare with state-based XATP symbology, Figure 12(a) and 12(b).

Figure 15. SVE of the final intent display for, left side, $FMS_{\text{on}}$, and right side, $FMS_{\text{off}}$. The situation is drawn for $FMS_{\text{off}}$. Compare with state-based XATP symbology, Figure 12(c) and 12(d).
VI. Conclusions and Recommendations

The effect of own intent, \( TCP_{own} \), intruder intent, \( TCP_{int} \) and \( TS_{int} \) on the appearance of the FBZ maneuver constraints are calculated using the ‘break-circle and ‘ghost-image techniques.

**Ghost Image:** The ghost image technique is used to calculate the own FBZ maneuver constraints ‘at present’ of trajectory parts and states that are reached after completion of a TS (intruder only) or TCP maneuver (own or intruder aircraft). The ghost is created assuming the intruder would already be flying with the future state vector and aligned with the future trajectory part. The technique can be applied to intruder TS and intruder and own aircraft TCP maneuvers.

**Vector Break Circle:** For each TCP point affecting the maneuver constraints, a vector break circle is used to divide the speed-heading action space into two zones. In the case of an intruder TCP, a \( PRE_{TCP} \) zone, outside the circle, represents all the own aircraft maneuvers that will result in a motion path that passes by the intruder aircraft ‘before’ it makes the TCP maneuver. A \( POST_{TCP} \) zone, inside the circle, represents all the maneuvers that will result in a motion path where both aircraft will pass each other ‘after’ the intruder makes the TCP maneuver.

The effect of the break circle is only visible on the SVE if within the own maneuver space boundaries it is possible to perform a maneuver that would make both aircraft pass each other before the TCP point is reached. In many conflict situations this is no possible, and therefore the effect of the break circle on the FBZ constraint area is simply not visible because it is completely located outside of the SVE.

For calculation purposes, the ghost image and break circle techniques can be enhanced by dividing the maneuver trajectory path in several sequential sub paths and applying both techniques individually for each path. This would realize a smooth transition area connection the \( PRE_{TCP} \) and \( POST_{TCP}(on) \) maneuver area’s.

**FBZ types:** Assuming 1 TCP point for both intruder and own aircraft and assuming two aircraft control modes, \( FMS_{on} \) and \( FMS_{off} \), 9 trajectory part combinations can be identified where both aircraft could potentially lose separation. These are represented in 9 FBZ area’s, Figure 2

**Instant maneuver constraints:** Maneuver area’s (4), (5) and (6) are related to the own trajectory after the TCP turn when FMS enabled, \( POST_{own}(on) \). These constraints can be used for FMS-enabled conflict detection, but they can not be used as instant maneuver constraints used to find conflict-free speed-heading states to move own state vector \( \mathbf{V}_{own} \). In the interface mapping, instant maneuver constraints are colored whereas ‘\( POST_{own}(on) \)’ areas (4), (5) and (6) are in gray.

**Active maneuver constraints:** Aircraft control mode changes discretely change the appearance of FBZ areas on the SVE. Mode change pilot support is given by showing both the active FBZ, (filled), and the inactive (empty). This way the additional ‘action space’ variable ‘FMS mode change’ is mapped on the SVE, and is added to the speed-heading variables already visualized in the state-based design.
When considering to show the mode change effect of the intruder aircraft on the own maneuver constraints, this would mean 3 areas, 1 active and 2 inactive should be shown across the 3 possible Mode combination (e.g. ON-ON, ON-OFF, and OFF-ON), and also an additional symbology should be used. In this case a trade-off appears between pilot Situation Awareness and cognitive workload.

The final design visualizes conflict detection by means of filled areas (keep vector outside), conflict resolution/prevention by means of colored zones. The effect of own mode changes on both is also supported by always showing the FBZ constraints for both modes independent from the active mode.

More research should be done on defining what exactly is considered the most effective solution to a conflict problem, and how to cooperatively solve it, considering both the action space of the own pilot and intruder aircraft. If an FMS-based (ON-ON) conflict can be resolved by one aircraft only disengaging the FMS without further maneuvering, this solution seems more effective than the other aircraft disengaging AND having to maneuver. However, if this maneuver directs the aircraft towards its future TCP point, this solution might well be considered more effective, as it keeps the aircraft’s position close to the FMS-planned position. Especially in the case of multiple aircraft conflict situation, question should be raised if explicit automated decision support is needed to determine who exactly would need to act first. It remains of course the challenge of ecological designs to visualize the constraints that govern the actions made, even when the decision is automated.

References