Effect of Protection Zone Geometry on Traffic Conflict Resolution based on Artificial Force Fields

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Abstract—Systems allowing on-board Conflict Detection & Resolution (CD&R) are a mandatory prerequisite for operation in Autonomous Operations Area (AOA) airspace [5]. Kuchar and Yang identified numerous approaches to Conflict Resolution (CR) [11]. One approach, originating in the field of robotics, is Conflict Resolution based on (Artificial) Force Fields [9, 17]. This paper surveys the effect of the aircraft’s Protected Airspace Zone (PAZ) geometry on lateral Conflict Resolution using an Artificial Force Field Approach.

I. INTRODUCTION

Two of the major research programmes addressing the rise in air traffic – the Single European Sky Air Traffic Management (ATM) Research (SESAR) and the Next Generation Air Transportation System (NextGen) programmes – introduce the concept of AOA airspace [3, 15]. While operating in AOA airspace, the responsibility for maintaining the applicable minimum separation is delegated from Air Traffic Control (ATC) to the flight deck crew [1]. This requires that aircraft flying through AOA airspace are equipped with means to allow them to identify and resolve conflicts autonomously [1, 5]. Unlike to short term CD&R systems like TCAS [10], the CD&R system required for AOA airspace should allow long term CD&R. In literature, the terms strategic or long term CD&R are used synonymously with Airborne Conflict Management (ACM).

For the scope of this paper the definitions from [2] for tactical (short term) and strategic (long term) manoeuvres will be used, knowing that those values only allow for a rough distinction. In the following a manoeuvre will be referred to as tactical if the bank angle exceeds $15^\circ$. If a manoeuvre causes a bank angle of more than $30^\circ$ it will be associated with a safety net function.

A. Rationale for strategic Conflict Detection & Resolution systems

Resolution manoeuvres for short term Conflict Detection & Resolution may result in higher G-Forces and higher bank angles than during undisturbed en-route flight [2]. Beside the reduced passenger comfort (possibly through an erratic manoeuvre), short term tactical manoeuvres may also lead to higher fuel consumption and cause more stress to the aircraft structure.

The necessity for strategic CD&R systems is enforced through the introduction of AOA airspace. In order to be able to operate within AOA airspace, aircraft are required to be equipped with the appropriate means to detect and resolve a traffic conflict within the strategic time-frame [5].

B. Zones around aircraft

It is common to define a Collision Avoidance Zone and a Protected Airspace Zone around ownship [1] as illustrated in Figure 1 in order to define which alerts a ACM system may trigger. The Collision Avoidance Zone (CAZ) ‘[...] is a safety zone based on aircraft size with appropriate buffers added to compensate for any necessary factors.’[1] while the PAZ ‘[...] is derived from normal legal separation requirements, subject to accepted tolerances.’[1].

![Figure 1. Zones around aircraft after [1]](image)

C. Parameters to be compared

As described above, the bank angle $\phi$ and the maximum bank angle $\phi_{\text{max}}$ are of interest in order to conclude the type of manoeuvre. Furthermore, the minimum distance $d_{\text{min}}$ during the Conflict Resolution as well as the distance at which the CR module initiated a resolution manoeuvre $d_{\text{CR,start}}$ are of interest. For the evaluations a Collision Avoidance Zone of 5000m around the aircraft has been chosen. Since only lateral CR manoeuvres are allowed, both aircraft fly on the same flight level and the CAZ and PAZ heights are not relevant.

D. Nomenclature

The CD&R system described in this paper operates on ownship’s and traffic’s Trajectory Change Points (TCPs) (denoted by tcp$_n$) [13]. Each TCP is attributed with a Required Time Over RTO(tcp$_n$). If necessary, elements belonging to either ownship (acr$_o$) or traffic (acr$_i$) are denoted by their respective indices. Aircraft positions are denoted by $p \in \{(x,y,z)\}$. Protected Airspace Zones are denoted by $\mathcal{Z}$. 

E. Conflict Resolution based on Artificial Force Fields

Upon detection of an infringement of ownships PAZ Conflict Resolution is initiated. The implementation of CR in this paper is based on Artificial Force Fields [4, 7, 9, 17].

The idea behind (Artificial) Force Field Conflict Resolution is to attribute all elements like the destination airport, the next waypoint and similar elements with a drawing force, and all hazardous elements like other traffic items with a repulsive force. This concept can be further evolved to also take other constraints such as time into account. For example, the drawing force of a waypoint can grow stronger depending on the difference between actual time and Required Time Over.

A similar approach as described in [4] has been taken for the implementation underlying the Conflict Resolution discussed in this paper. If ownships PAZ is infringed by another traffic item, the force \( \vec{F} \) acting on ownship is defined as

\[
\vec{F}_{res} = g_i \cdot \sum_{k=0}^{n} \vec{F}_i + g_{WPT} \cdot \vec{F}_{WPT},
\]

where \( n \) denotes the number of all traffic items, \( \vec{F}_i \) the force caused by the respective traffic item, \( \vec{F}_{WPT} \) the drawing force towards the next waypoint and \( g_i, g_{WPT} \) arbitrarily chosen gains.

The Force \( \vec{F}_i \) is defined as

\[
\vec{F}_i = -V \cdot (\cos(\psi_r), \sin(\psi_r), 0)^T \quad \text{with} \quad V = \begin{cases} 0 & \text{if } p_i \notin Z \\ 1 - (d_{h,c}/d_{h,min}) & \text{else} \end{cases} \]

where \( \psi_r \) and \( \phi_i \) denote ownship heading and ownship bearing to intruder, respectively. Here \( d_{h,c} \) denotes the current horizontal distance between ownship and intruder and \( d_{h,min} \) the minimum distance (which might depend on the relative location of the intruder depending on the PAZ).

II. ARTIFICIAL FORCE FIELD CONFLICT RESOLUTION WITH DIFFERENT PROTECTED AIRSPACE ZONES

Two static – one with a circular and one with an elliptic base – and two state dependant PAZ – one taking the current ownship speed and one taking the relative speed into account – will be presented in this section.

The zones \( Z_z \subset Z \) are defined as the set of all points \( p = (x, y, z) \) for which \( p \in Z_z \). The zones are defined around \( p_o \), which denotes the current position of ownship. For the sake of simplicity it is assumed that the geodetic and body-axis system correspond.

A. Static Protected Airspace Zone

1) Cylindric Zone with Circular Base: A cylindric zone \( Z_c \) around the current position \( p_o = (x_o, y_o, z_o) \) with the propagation \( d_{h} \) (minimum horizontal distance) and \( d_{v} \) (minimum vertical distance) is defined as

\[
Z_c = \{(x,y,z) | z_o - z | \leq d_v \land (x - x_o)^2 + (y - y_o)^2 \leq d_h^2 \} \quad \text{(1)}
\]

Since the CR implementation discussed in this paper only allows for lateral manoeuvres, the vertical component \( d_v, z \) can be disregarded.

2) Cylindric Zone with Elliptic Base: A cylindric zone \( Z_{ce} \) with an elliptic base around the current position \( p_o = (x_o, y_o, z_o) \) with the propagation \( d_{lat} \) (minimum lateral distance), \( d_{lon} \) (minimum longitudinal distance) and \( d_{v} \) (minimum vertical distance) is defined as

\[
Z_{ce} = Z_c \cup \{(x,y,z) | (x - x_o) \geq 0 \land |y - y_o| \leq d_{lat} \land (x - x_o)^2 + (y - y_o)^2 \leq d_{lon}^2 \} \quad \text{(2)}
\]

B. Aircraft state dependant Protected Airspace Zone

Available state information for state-dependant PAZ are
- ownship speed vector \( \vec{v}_{o,TAS} \) and
- intruder speed vector \( \vec{v}_{i,TAS} \).

1) Ownship speed dependant PAZ: The PAZ depending on ownship speed is similar to \( Z_{ce} \), only the minimum longitudinal distance \( d_{lon} \) in Equation 2 is replaced by

\[
d_{lon}'' = \max(d_{lon}, \vec{v}_{o,gs} \cdot t). \quad \text{(3)}
\]

In Equation 3, \( \vec{v}_{o,gs} \) denotes the ground speed component while \( t \) is the look-ahead time. For the scope of the evaluations in this paper \( t = 600s \) holds, which corresponds to the current longitudinal separation applied in North Atlantic (NAT) airspace [6].

2) Relative speed dependant PAZ: As illustrated in Figure 2, the relative speed dependant PAZ is a rotation of the ownship speed dependant PAZ by the bearing \( \phi \). While \( d_{lat} \) equals the minimum protection zone of 5000m, \( d_{lon} \) depends on the length of \( \vec{v}_{r,gs} = \vec{v}_{o,gs} - \vec{v}_{i,gs} \) and a time \( t \) (cf. Equation 3).

C. Conflict Resolution algorithm

The Conflict Detection (CD) system initialize CR with
- \( d_{CPA} \), \( t_{CPA} \) and Position of Closest Point of Approach (CPA),
- the ownship trajectory segment \( (tcp_{o,n}, tcp_{o,m}) \),
- all intruder trajectory segments \( (tcp_{i,k}, tcp_{i,j}) \) which (partially) overlap regarding the time with ownships trajectory segment \( (tcp_{o,n}, tcp_{o,m}) \) and
- the applicable separation minima.

The Force Field CR is implemented as a fast time simulation with \( RTO(tcp_{o,n}) \) being the start time. All intruders with \( RTO(tcp_{i,k}) < RTO(tcp_{o,n}) \) are moved before starting the simulation to \( RTO(tcp_{o,n}) \). As long as ownships PAZ is not infringed it follows its flight plan. As soon as an intruder violates ownships PAZ, the CR calculates a new heading in
order to resolve the conflict. Upon re-establishment of the safe separation CR is deactivated and the flight plan is being recaptured.

III. SIMULATION

For simulation and resolution of traffic conflicts the implementation of aircraft models based on the Base of Aircraft Data (BADA) devised by Roth [14] is used. This implementation is used at TUDs Institute of Flight Systems and Automatic Control as part of the research flight simulator [14], but also allows integration into other environments due to its modular structure.

A. Flight plan

The aircraft are initialized together with a flight plan, which inter alia specifies the
- Waypoint Position, target altitude \((\lambda, \phi, h)\) and Required Time Over (RTO),
- Waypoint Type (Fly-by or Fly-over) and
- the target speed \(V_{TAS}\).

The provision of a RTO is optional, but if given it overrides the target speed \(V_{TAS}\). The implementation of the aircraft model ensures that the aircraft is not operated outside its flight envelope [14]. Furthermore, in this implementation aircraft are required to bypass fly-over waypoints at a maximum distance of 185.2m, which corresponds to RNP class 0.1 [12]. Based on the flight plan the aircraft’s Flight Management System (FMS) may derive through fast time simulation [8] or by other means a set of TCPs.

A Conflict Detection module which is based on the Traffic Collision Avoidance System (TCAS) [10] algorithm as described in [16] calculates for each trajectory segment (connection between two consecutive TCPs) the time to the Closest Point of Approach \(t_{CPA}\) and the distance at the CPA \(d_{CPA}\).

If \(d_{CPA}\) is less than the minimum separation, the CD module generates a conflict and initiates the Conflict Resolution process. If no conflict exists, the aircraft follow their flight plans. The CD process is only restarted if either an updated set of TCP information is received or if ownership updates its 4D Trajectory.

B. Control Variables

The library which encapsulates the aircraft model inter alia allows commanding
- a heading \(\psi\),
- a target speed \(V_{TAS}\) and
- a target altitude \(h\).

For the scope of this paper and analysis the Force Field based Conflict Resolution only commands a new heading depending on the vicinity and the direction of the intruder aircraft.

C. Traffic Scenario

Two traffic scenarios each with two aircraft (ownership and one intruder) were set up. In both scenarios, the speeds were set automatically by the aircraft library according to the flight plan given times. The only information available to ownership CD&R system was a subset of the TCP information as defined for transmission via Automatic Dependant Surveillance - Broadcast (ADS-B) [13]. The information set includes
- the callsign,
- position of and altitude at waypoint and
- RTO at waypoint.

1) Same track: In the first scenario ownership \(acr_o\) and intruder \(acr_i\) are flying on parallel tracks towards each other. Table I and II summarize the ownership and intruder flight plans. All waypoints in both flight plans are fly-over waypoints.

<table>
<thead>
<tr>
<th>Waypoint</th>
<th>(\lambda) [deg]</th>
<th>(\phi) [deg]</th>
<th>altitude [m]</th>
<th>RTO [hh:mm:ss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPT_{o,1}</td>
<td>50.0</td>
<td>8.0</td>
<td>5000</td>
<td>14:23:00</td>
</tr>
<tr>
<td>WPT_{o,2}</td>
<td>51.0</td>
<td>7.0</td>
<td>5000</td>
<td>16:24:00</td>
</tr>
<tr>
<td>WPT_{o,3}</td>
<td>53.0</td>
<td>2.0</td>
<td>5000</td>
<td>18:20:00</td>
</tr>
</tbody>
</table>

Table I
OWNSHIP FLIGHTPLAN - SCENARIO ONE

<table>
<thead>
<tr>
<th>Waypoint</th>
<th>(\lambda) [deg]</th>
<th>(\phi) [deg]</th>
<th>altitude [m]</th>
<th>RTO [hh:mm:ss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WPT_{i,1}</td>
<td>51.01</td>
<td>7.0</td>
<td>5000</td>
<td>14:23:00</td>
</tr>
<tr>
<td>WPT_{i,2}</td>
<td>50.01</td>
<td>8.0</td>
<td>5000</td>
<td>18:20:00</td>
</tr>
</tbody>
</table>

Table II
INTRUDER FLIGHTPLAN - SCENARIO ONE

Figure 3 illustrate the flights of \(acr_o\) (coming from the lower left corner) and \(acr_i\) (coming from the upper right corner) until CPA. The distance at CPA \(d_{CPA}\) is 614.70m.
2) Crossing tracks: In the second scenario both aircraft are flying on crossing tracks. The distance $d_{CPA}$ at CPA is 259.02 m. Table III and IV summarize both flight plans. As in scenario one all waypoints are fly-over waypoints. Figure 4 illustrates the conflict situation with acro coming from the lower left and acr from the upper left corner.

![Figure 3](image3.png)

Figure 3. Scenario One – Aircraft Trajectories until CPA (Google Earth)

![Figure 4](image4.png)

Figure 4. Scenario Two – Aircraft Trajectories until CPA (Google Earth)

D. Results

In both scenarios all presented PAZ implementations failed to maintain at least the minimum distance of 5000 m (Table V). Furthermore, the maximum bank angle $\phi_{max}$ exceeded for all resolutions at least once 15° (Table VI).

![Table V](image5.png)

Table V
DISTANCE AT CPA AND AT START OF CR

![Table VI](image6.png)

Table VI
MAXIMUM BANK ANGLE DURING RESOLUTION

Figure 5 shows the Conflict Resolution using the relative speed zone PAZ. Ownship (left trajectory) returns to its original track right after it is clear of conflict. Similarly, Figure 6 shows the Conflict Resolution causing the smallest bank angle in scenario two which is the speed dependant PAZ (ownership coming from the lower left corner).

![Figure 5](image7.png)

Figure 5. Scenario One – Relative Speed Zone Resolution

Figures 7, 8, 9 and 10 illustrate the bank angle during the first initialization of a Conflict Resolution manoeuvre to the last in scenario two. The time spans where CR was active is highlighted through the grey shaded areas.
IV. CONCLUSION

In both scenarios, Conflict Resolution with a relative speed dependant Protected Airspace Zone has given, with respect to the distance at the Closest Point of Approach $d_{CPA}$, the best results. In its current implementation, the speed and relative speed dependant PAZs only affect the longitudinal propagation of the aircrafts PAZ $d_{lon}$ (i.e. the lateral propagation of the aircrafts PAZ is equal to the lateral propagation of its CAZ). Due to the nature of an CR implementation based on Artificial Force Field, the PAZ needs to be infringed before a force can act on the aircraft. Therefore it is expected that an extension of $d_{lat}$ in a similar fashion to the here proposed extension of $d_{lon}$ will enable a resolution which does not violate the minimum separation $d_{min}$.

Regarding the bank angles achieved during the simulation it becomes evident that the flight plan recapture function of the simulated aircraft and the CR function give opposed commands (Figures 9 and 10). In order to prevent this behaviour it should be considered to either keep Conflict Resolution active.
until the aircraft reaches its next planned Trajectory Change Point or to have the CR algorithm iterate multiple times over the resulting trajectory until an uninterrupted CR has been achieved.

Furthermore, it can be stated that especially the relative speed dependant PAZ implementation has produced promising results regarding the minimum distance. It is expected that the minimum distance and the maximum bank angle issues will both be addressed through the aforementioned adaptations.

Future work is directed towards a proper vertical definition for Protected Airspace Zones in order to enable vertical resolution manoeuvres. Further refinements to the CR algorithm as described above are also under development.

REFERENCES

ABBREVIATIONS
ACM
Airborne Conflict Management
ADS-B
Automatic Dependant Surveillance - Broadcast
AOA
Autonomous Operations Area
ATC
Air Traffic Control
ATM
Air Traffic Management
BADA
Base of Aircraft Data
CAZ
Collision Avoidance Zone
CD
Conflict Detection
CD&R
Conflict Detection & Resolution
CR
Conflict Resolution
CPA
Closest Point of Approach
FMS
Flight Management System
NAT
North Atlantic
NextGen
Next Generation Air Transportation System
PAZ
Protected Airspace Zone
RNP
Required Navigational Performance
RTO
Required Time Over
SESAR
Single European Sky ATM Research
TCAS
Traffic Collision Avoidance System
TCP
Trajectory Change Point