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

Nima Barraci and Uwe Klingauf
Technische Universität Darmstadt
Institute of Flight Systems and Automatic Control
Darmstadt, Germany 64287
Email: {barraci,klingauf}@fsr.tu-darmstadt.de

***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 $15°$. If a manoeuvre causes a bank angle of more than $30°$ 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].

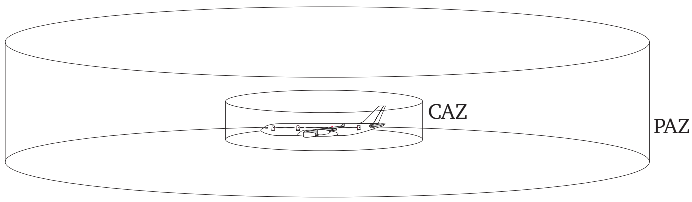

Figure 1. Zones around aircraft after [1]

C. Parameters to be compared

As described above, the bank angle ϕ and the maximum bank angle ϕ_{max} are of interest in order to conclude the type of manoeuvre. Furthermore, the minimum distance d_{min} during the Conflict Resolution as well as the distance at which the CR module initiated a resolution manoeuvre $d_{CR,start}$ 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 $RTO(\text{tcp}_n)$. 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 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 $\vec{F}_{res}$ acting on ownship is defined as

$$\vec{F}_{res} = g_i \cdot \sum_{i=0}^{n} \vec{F}_i + g_{WPT} \cdot \vec{F}_{WPT},$$

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

$$\begin{aligned} \vec{F}_i &= V \cdot (\cos(\psi_r), \sin(\psi_r), 0)^T \text{ with} \\ V &= \begin{cases} 0 & , p_i \notin Z \\ 1 - (d_{h,c}/d_{h,min}) & , \text{else} \end{cases} \\ \psi_r &= \phi_i - \psi_o. \end{aligned}$$

ψ_o and ϕ_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 $Z_z \subset \mathcal{Z}$ 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

$$\begin{aligned} Z_c = &\{(x, y, z) | |z_o - z| \leq d_v \\ &\wedge (x - x_o)^2 + (y - y_o)^2 \leq d_h\}. \end{aligned} \tag{1}$$

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

$$\begin{aligned} Z_{ce} = &Z_c \cup \\ &\{(x, y, z) | (x - x_o) \geq 0 \wedge |y - y_o| \leq d_{lat} \\ &\wedge (x - x_o) \geq \sqrt{\left(1 - \frac{(y - y_o)^2}{d_{lat}^2}\right) \cdot d_{lon}^2}\}. \end{aligned} \tag{2}$$

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

$$d'_{lon} = \max(d_{lon}, \vec{v}_{o,gs} \cdot t). \tag{3}$$

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 ϕ. 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 $(\text{tcp}_{o,n}, \text{tcp}_{o,m})$,
- all intruder trajectory segments $(\text{tcp}_{i,k}, \text{tcp}_{i,j})$ which (partially) overlap regarding the time with ownships trajectory segment $(\text{tcp}_{o,n}, \text{tcp}_{o,m})$ and
- the applicable separation minima.

The Force Field CR is implemented as a fast time simulation with $RTO(\text{tcp}_{o,n})$ being the start time. All intruders with $RTO(\text{tcp}_{i,k}) < RTO(\text{tcp}_{o,n})$ are moved before starting the simulation to $RTO(\text{tcp}_{o,n})$. 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

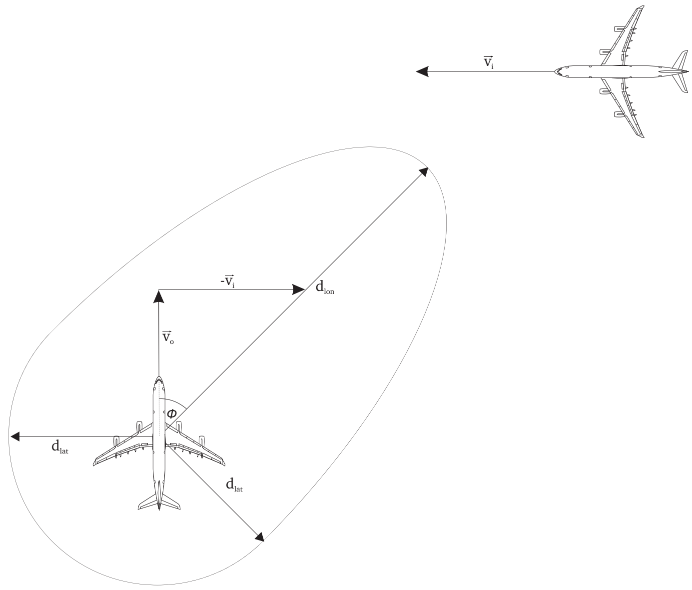

Figure 2. Depiction of relative speed dependant PAZ

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 (λ , ϕ , 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 ownship updates its 4D Trajectory.

B. Control Variables

The library which encapsulates the aircraft model *inter alia* allows commanding

- a heading ψ,
- 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 (ownship 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 ownships 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 ownship acr$_o$ and intruder acr$_i$ are flying on parallel tracks towards each other. Table I and II summarize the ownship and intruder flight plans. All waypoints in both flight plans are fly-over waypoints.

Waypoint	λ [deg]	ϕ [deg]	altitude [m]	RTO [hh:mi:ss]
WPT$_{o,1}$	50.0	8.0	5000	14:23:00
WPT$_{o,2}$	51.0	7.0	5000	16:24:00
WPT$_{o,3}$	53.0	2.0	5000	18:20:00

Table I
Ownship Flightplan - Scenario One

Waypoint	λ [deg]	ϕ [deg]	altitude [m]	RTO [hh:mi:ss]
WPT$_{i,1}$	51.01	7.0	5000	14:23:00
WPT$_{i,2}$	50.01	8.0	5000	18:20:00

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 $614.70m$.

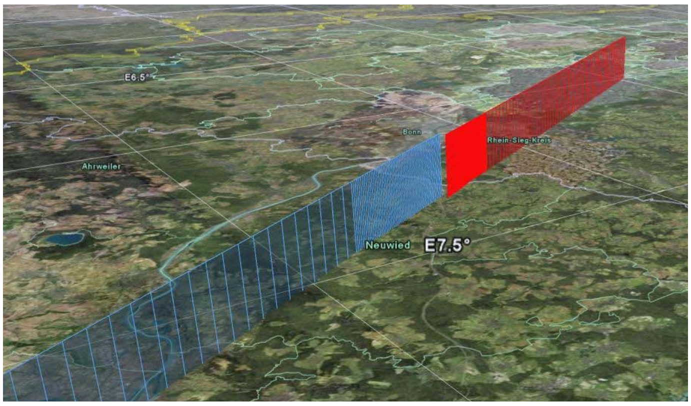

Figure 3. Scenario One – Aircraft Trajectories until CPA (Google Earth)

2) Crossing tracks: In the second scenario both aircraft are flying on crossing tracks. The distance d_{CPA} at CPA is $259.02m$. 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 acr$_o$ coming from the lower left and acr$_i$ from the upper left corner.

Waypoint	λ [deg]	ϕ [deg]	altitude [m]	RTO [hh:mi:ss]
WPT$_{o,1}$	50.0	8.0	5000	12:00:00
WPT$_{o,2}$	52.0	8.0	5000	12:28:00
WPT$_{o,3}$	53.0	8.0	5000	12:56:00

Table III
OWNSHIP FLIGHTPLAN - SCENARIO TWO

Waypoint	λ [deg]	ϕ [deg]	altitude [m]	RTO [hh:mi:ss]
WPT$_{i,1}$	51.0	7.0	5000	12:00:00
WPT$_{i,2}$	51.0	9.0	5000	12:28:00

Table IV
INTRUDER FLIGHTPLAN - SCENARIO TWO

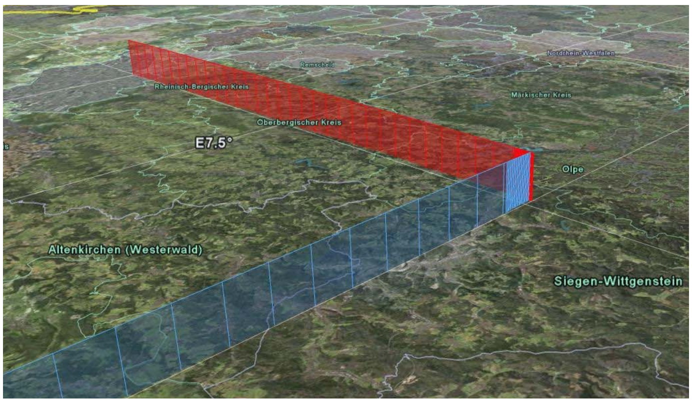

Figure 4. Scenario Two – Aircraft Trajectories until CPA (Google Earth)

D. Results

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

PAZ	Scenario One		Scenario Two	
	$d_{CPA}[m]$	$d_{CR,start}[m]$	$d_{CPA}[m]$	$d_{CR,start}$ [m]
Circle	842.2	4963.66	1509.2	4959.57
Elliptic	3267.7	19703.50	2184.9	8200.76
Speed	4459.8	132513.00	2245.3	8818.25
rel. Speed	4904.3	132513.00	4854.0	95573.40

Table V
DISTANCE AT CPA AND AT START OF CR

PAZ	$\phi_{max}[deg]$	
	Scenario One	Scenario Two
Circle	26.9486	32.9869
Elliptic	29.9872	23.9878
Speed	19.3274	20.9949
rel. Speed	18.0	30.0123

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. Similarily, Figure 6 shows the Conflict Resolution causing the smallest bank angle in scenario two which is the speed dependant PAZ (ownship coming from the lower left corner).

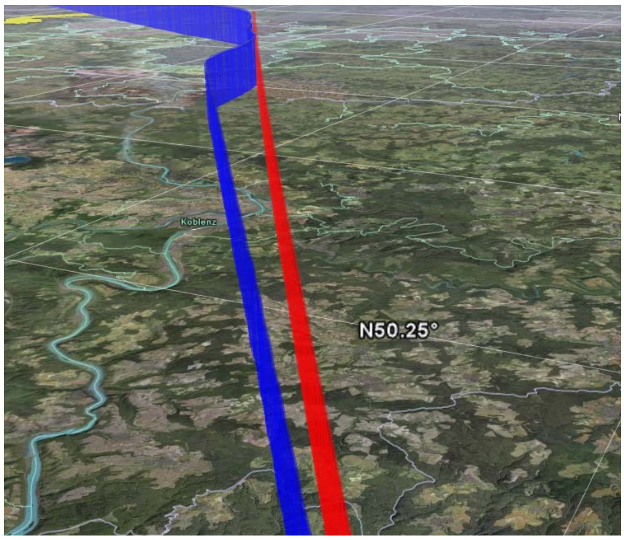

Figure 5. Scenario One – Relative Speed Zone Resolution

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.

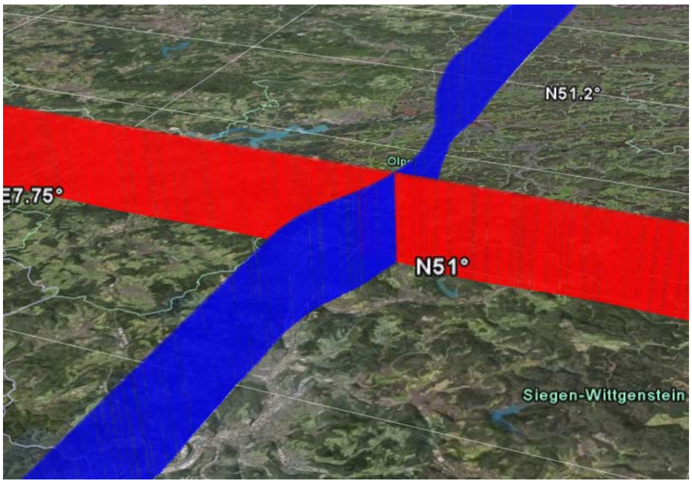

Figure 6. Scenario Two – Speed Zone Resolution

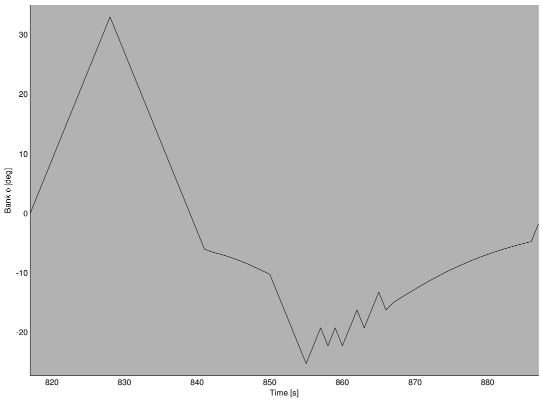

Figure 7. Scenario Two – Circle PAZ Bank Angle

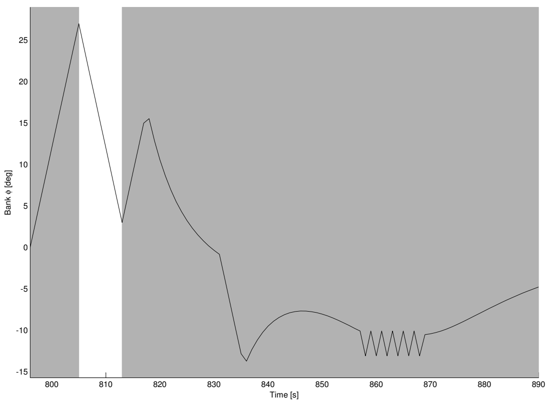

Figure 8. Scenario Two – Elliptic PAZ Bank Angle

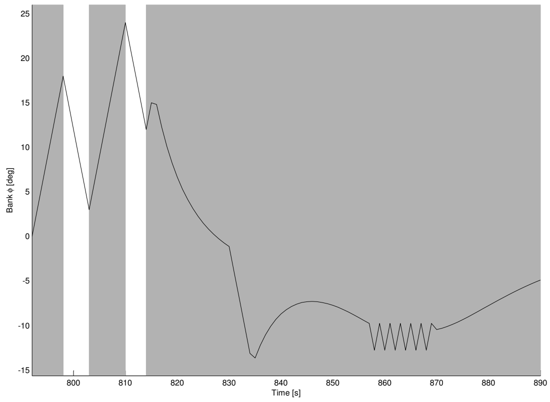

Figure 9. Scenario Two – Speed PAZ Bank Angle

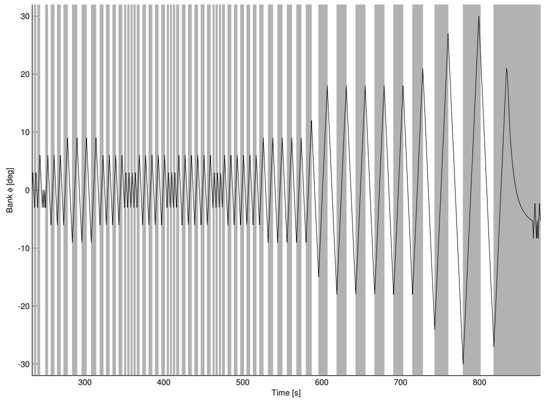

Figure 10. Scenario Two – Relative Speed PAZ Bank Angle

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

[1] *Application of Airborne Conflict Management: Detection, Prevention & Resolution*. Tech. rep. RTCA/DO-263. RTCA - Special Committee 186, 2000.

[2] Nima Barraci et al. *DI-125 Information Fusion & HMI Specification*. Internal Deliverable. Produced under the EC contract prop. AIP4-CT-2005-516167. 2006.

[3] *Concept of Operations for the Next Generation Air Transportation System*. 125th ed. Next Generation Air Transportation System - Joint Planning and Development Office, 2007.

[4] Vu N. Duong and Karim Zeghal. "Conflict Resolution Advisory for Autonomous Airborne Separation in Low-Density Airspace". In: *Proceedings of the 36th Conference on Decision & Control*. 1997.

[5] *Global Air Traffic Management Operational Concept*. Doc 9854 - AN/458. International Civil Aviation Organization, 2005.

[6] North Atlantic Systems Planning Group. *NORTH ATLANTIC MNPS AIRSPACE OPERATIONS MANUAL*. ICAO European and North Atlantic Office, 2005.

[7] Jacob Marten Hoekstra. "Designing for Safety: the Free Flight Air Traffic Management Concept". PhD thesis. Technische Universiteit Delft, 2001.

[8] Peter J. Howells. *Aircraft Trajectory - Prediction and Control in the Air Transport Flight Management Computer Systems*. Tech. rep. Volume 1. NATO Advisory Group for Aerospace Research & Development AGARD AG-301, 1990.

[9] Wallace E. Kelly III. "Deconfliction of Multiple, Autonomous Vehicles". In: *Unmanned Systems 2000*. 2000.

[10] *Introduction to TCAS II - Version 7*. Tech. rep. U.S. Department of Transportation, Federal Aviation Administration, November 2000.

[11] Kuchar and Yang. *Survey of Coflict Detection and Resolution Modelling Methods*. Tech. rep. Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, 1997.

[12] *Manual On Required Navigation Performance (RNP)*. International Civil Aviation Organization. 1999.

[13] *Minimum Aviation System Performance Standards For Automatic Dependant Surveillance Broadcast (ADS-B)*. Tech. rep. RTCA/DO-242A. RTCA - Special Committee 186, 2002.

[14] Volker Roth. "Entwicklung einer ereignisgesteuerten Verkehrssimulation als Teil einer Validierungsplattform für Air Traffic Management Konzepte". Diplomarbeit. Technische Universität Darmstadt, Institut für Flugsysteme und Regelungstechnik, 2007.

[15] *SESAR Concept of Operations - WP 2.2.2/D3*. DLT-0612-222-01-00. SESAR Consortium, 2007.

[16] Harro von Viebahn. "Konzeption und Untersuchung eines bordautonomen Systems zur Vermeidung von Kollisionen im Luftverkehr". Dissertation. Technische Universität Darmstadt, 1997.

[17] Karim Zeghal. "A review of different approaches based on force fields for airborne conflict resolution". In: *AIAA Guidance, Navigation and Control Conference, Boston*. 1998.

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