

Conflict Resolution with Time Constraints in Trajectory-Based Arrival Management

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Outline

- 1 Introduction
- 2 Trajectory Patterns
- 3 Trajectory Prediction
- 4 Conflict Detection
- 5 Conflict Resolution
- 6 Results
- 7 Summary and Future Work

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Introduction

- **Arrival management** involves two high-level functions at the strategic level:
 - traffic management: performs runway assignment, sequencing and scheduling.
 - **separation management**: synthesizes intents that meet the traffic management **schedule** and ensures that the arrival plan is **conflict free**.
It relies on the combination of TP, CD, and CR functions.
- **Objective of this work**: development of a CR algorithm to generate efficient, conflict-free trajectories that meet the scheduled times of arrival, using parametric optimization theory.
 - **Hard constraint**: to maintain safe separation.
 - **Primary objective**: to meet the schedule (or at least to be as close as possible).
 - **Secondary objective**: to minimize the deviation from the intended trajectories.

Resolution algorithm

- **Centralized** and **strategic**.
- Based on the **parameterization of the flight intents (predefined trajectory patterns)**. Advantages:
 - **simplicity**: intents described in terms of a small number of parameters.
 - **flyability**: standard airline procedures and ATC regulations are considered.
- The CR problem is formulated as a **multivariable optimization problem subject to constraints**. It is solved in **three steps**:
 - 1 **avoidance**,
 - 2 **recovery**, and
 - 3 **optimization**.
- Trajectory modeling: **dynamic**, nonlinear point-mass model with variable mass.

Outline

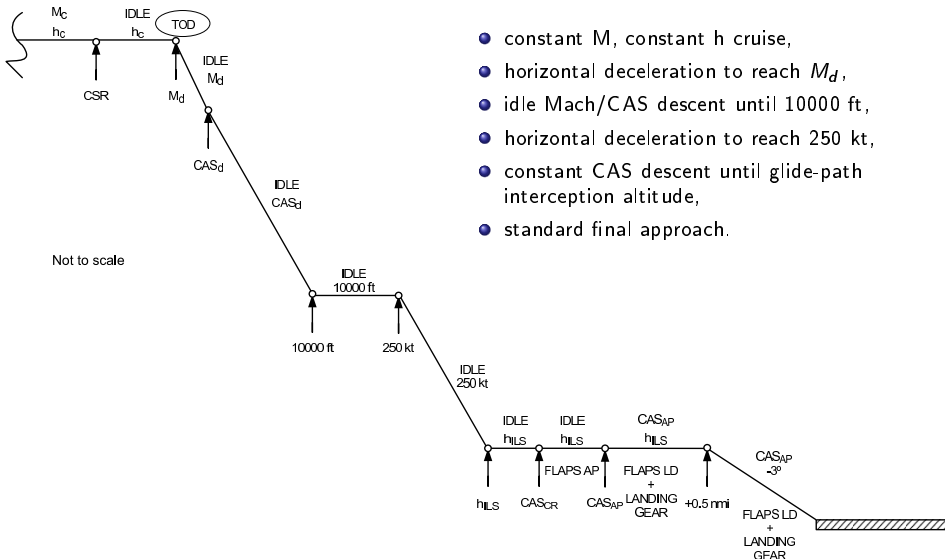
- 1 Introduction
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Trajectory Patterns

- They are **flight intents** that can be described in terms of a **small number of parameters**. Some parameters are **fixed**, whereas others are **free**.
The **optimization** is performed on the set of free parameters.
- They model both the **vertical profile** and the **lateral profile**.
- Two types of trajectory patterns are considered:
 - **Nominal trajectory patterns**: which model the aircraft intended (preferred) trajectories.
 - **Resolution trajectory patterns**: which model the aircraft resolution trajectories. They are modifications of the nominal trajectory patterns.
Each aircraft can have a different resolution trajectory pattern assigned.
- **Simplifications**: instantaneous heading, path-angle and thrust changes.

Nominal Trajectory Pattern (Vertical Profile)

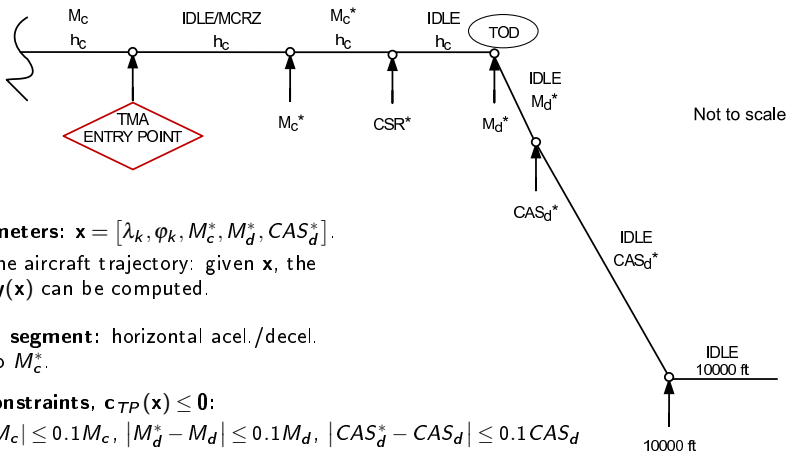
- constant M , constant h cruise,
- horizontal deceleration to reach M_d ,
- idle Mach/CAS descent until 10000 ft,
- horizontal deceleration to reach 250 kt,
- constant CAS descent until glide-path interception altitude,
- standard final approach.



Resolution Trajectory Patterns

- **Lateral profile:** waypoint changes (vectoring) between the TMA entry point and the IAF, keeping fixed the total number of waypoints.
- **Vertical profile:** speed changes above 10000 ft: cruise Mach (M_c), descent Mach (M_d) and descent CAS (CAS_d).
- **Different patterns** are considered depending on the flight phase the aircraft is flying when it enters the TMA:
 - **Pattern A:** the aircraft enters TMA while cruising.
 - **Pattern B:** the aircraft enters TMA while cruising, between CSR and TOD points.
 - **Pattern C:** the aircraft enters TMA while descending, flying the constant-Mach descent segment.
 - **Pattern D:** the aircraft enters TMA while descending, flying the constant-CAS descent segment.

Resolution Trajectory Pattern A (Vertical Profile)



- **Free parameters:** $\mathbf{x} = [\lambda_k, \varphi_k, M_c^*, M_d^*, CAS_d^*]$.

$\mathbf{x}$ defines the aircraft trajectory: given $\mathbf{x}$, the trajectory $\mathbf{y}(\mathbf{x})$ can be computed.

- **New flight segment:** horizontal accel./decel. from M_c to M_c^* .

- **Pattern constraints, $c_{TP}(\mathbf{x}) \leq 0$:**

- $|M_c^* - M_c| \leq 0.1 M_c$, $|M_d^* - M_d| \leq 0.1 M_d$, $|CAS_d^* - CAS_d| \leq 0.1 CAS_d$
- $M_d^* \leq M_c^*$
- $CAS_d^* \geq 250$ kt
- $10000 \text{ ft} \leq h_{TR}(M_d^*, CAS_d^*) \leq h_{CR}$

Transition altitude between 10000 ft and the cruise altitude

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Trajectory Prediction

- Scalar equations considered for flight in a vertical plane (heading angle χ_A):

$$m \frac{dV}{dt} = T - D(V, h, L) - mg \sin \gamma$$

$$mV \frac{d\gamma}{dt} = L - mg \cos \gamma$$

$$\frac{dm}{dt} = -c(V, h) T$$

$$(R_E + h) \frac{d\varphi}{dt} = V \cos \gamma \cos \chi_A$$

$$(R_E + h) \cos \varphi \frac{d\lambda}{dt} = V \cos \gamma \sin \chi_A$$

$$\frac{dh}{dt} = V \sin \gamma$$

$$G_1(V, \gamma, m, \varphi, \lambda, h, T, L, t) = 0$$

$$G_2(V, \gamma, m, \varphi, \lambda, h, T, L, t) = 0$$

DAE system reduced to ODE system through the explicit utilization of the flight constraints.

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Conflict Detection

- **Horizontal distance** is measured (along a great circle):

$$d_{ij} = R_E \cos^{-1} [\sin \varphi_i \sin \varphi_j + \cos \varphi_i \cos \varphi_j \cos(\lambda_j - \lambda_i)]$$

- The **separation minimum** considered, d_s , depends on the wake turbulence separation minima:

		Preceding aircraft		
		Heavy	Medium	Light
Succeeding aircraft	Heavy	4	3	3
	Medium	5	3	3
	Light	6	5	3

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- d_{ij} is measured at **discrete times**:

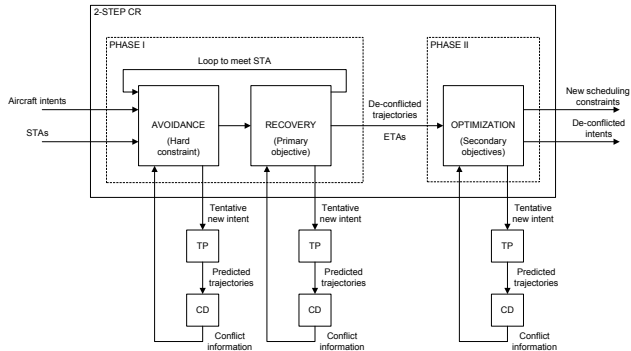
$$t_k = t_0 + k\Delta t$$

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Conflict Resolution: 2-step Algorithm

- 2-step Algorithm

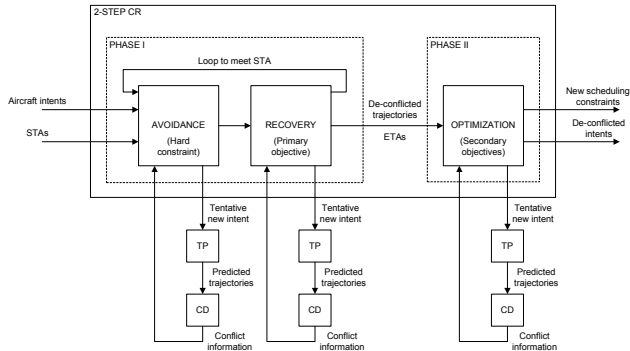


Conflict Resolution: 2-step Algorithm

2-step Algorithm

Phase 1: sequential, aircraft are processed according to the landing sequence.

While aircraft i is processed, the only conflicts considered are those with the $i - 1$ previous aircraft.



Conflict Resolution: 2-step Algorithm

2-step Algorithm

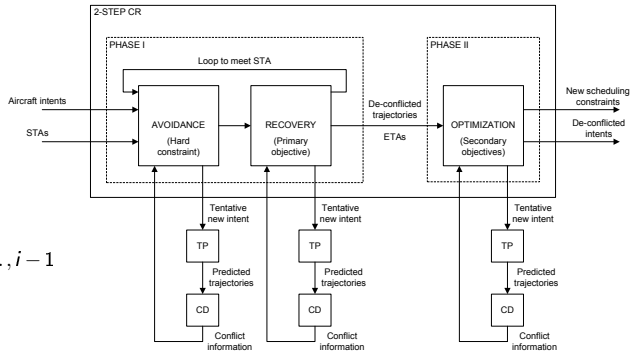
Phase 1: sequential, aircraft are processed according to the landing sequence.

- Avoidance:** a conflict-free trajectory is randomly obtained. It satisfies

$$\begin{aligned} c_{TPi}(\mathbf{x}_i) &\leq 0 \\ (d_{ij})_{min} &\geq d_{s,ij}, \quad \forall j = 1, \dots, i-1 \\ t_{ETA,i} &> t_{STA,i-1} \end{aligned}$$

where

$$\begin{aligned} (d_{ij})_{min} &= d_{min}(\mathbf{y}_i(\mathbf{x}_i), \mathbf{y}_j(\mathbf{x}_j)) \\ t_{ETA,i} &= t_{ETA}(\mathbf{y}_i(\mathbf{x}_i)) \end{aligned}$$



Conflict Resolution: 2-step Algorithm

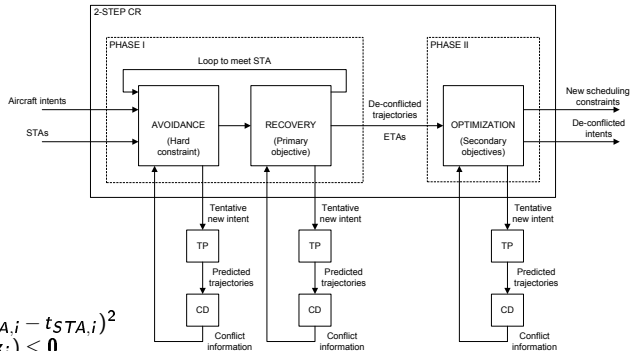
2-step Algorithm

Phase 1: sequential, aircraft are processed according to the landing sequence.

- **Avoidance:** a conflict-free trajectory is randomly obtained.
- **Recovery:** minimizes the deviation with $t_{STA,i}$.

$$\begin{aligned}
 &\text{minimize} && f(\mathbf{x}_i) = (t_{ETA,i} - t_{STA,i})^2 \\
 &\text{subject to} && c_{TPi}(\mathbf{x}_i) \leq 0 \\
 & && (d_{ij})_{min} \geq d_{s,ij}, \\
 & && t_{ETA,i} > t_{STA,i-1}
 \end{aligned}$$

$\forall j = 1, \dots, i-1$



Conflict Resolution: 2-step Algorithm

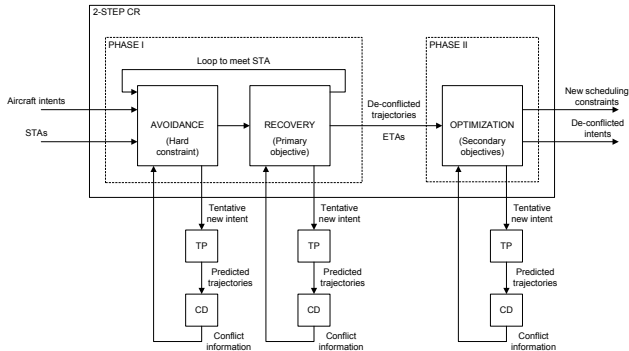
2-step Algorithm

Phase 1: sequential, aircraft are processed according to the landing sequence.

- **Avoidance:** a conflict-free trajectory is randomly obtained.
- **Recovery:** minimizes the deviation with $t_{STA,i}$.

Phase 2: global.

- **Optimization:** minimizes the lateral deviation.



$$\text{minimize} \quad f(\mathbf{x}_1, \dots, \mathbf{x}_n) = \frac{1}{n} \sqrt{\sum_{k=1}^q [(\lambda_k - \lambda_k^0)^2 + (\varphi_k - \varphi_k^0)^2]}$$

subject to

$$\begin{aligned} c_{TP,i}(\mathbf{x}_i) &\leq 0 \\ (d_{ij})_{\min} &\geq d_{s,ij} \\ t_{ETA,i} - t_{ETA,i}^1 &= 0 \end{aligned}$$

$$\begin{aligned} \forall i &= 1, \dots, n \\ \forall i, j &= 1, \dots, n, j \neq i \\ \forall i &= 1, \dots, n \end{aligned}$$

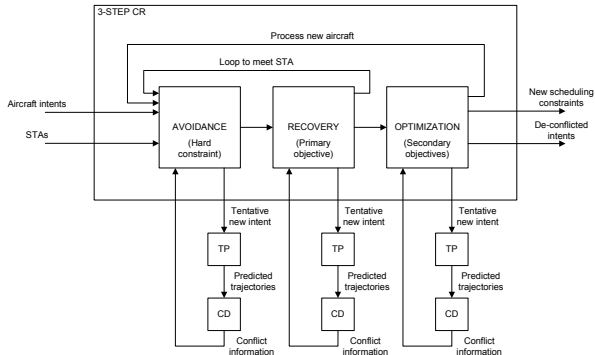
Conflict Resolution: 3-step Algorithm

3-step Algorithm

● **Avoidance:** no change.

● **Recovery:** no change.

● **Optimization:** sequential, minimizes the lateral deviation.



$$\begin{aligned}
 &\text{minimize} && f(\mathbf{x}_i) = \sqrt{\sum_{k=1}^{q_i} \left[(\lambda_k - \lambda_k^0)^2 + (\varphi_k - \varphi_k^0)^2 \right]} \\
 &\text{subject to} && \mathbf{c}_{TPi}(\mathbf{x}_i) \leq 0 \\
 & && (d_{ij})_{\min} \geq d_{s,ij} \\
 & && t_{ETA,i} - t_{ETA,i}^1 = 0
 \end{aligned}
 \quad \forall j = 1, \dots, i-1$$

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Results

- **Matlab environment:**

- *randn* (normally distributed pseudorandom numbers),
- *fmincon* (sequential quadratic programming, *SQP*).

- Aircraft models based on **BADA 3.6**.

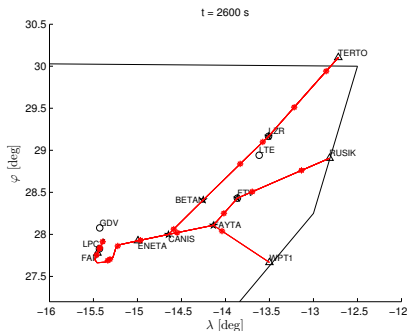
- Conflict detection **time step** $\Delta t = 0.1$ s.

- **Two** different **scenarios**.

Scenario 1 (I)

• Nominal Trajectories

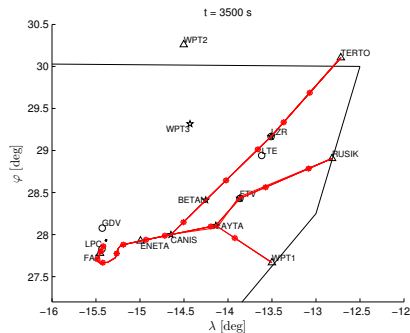
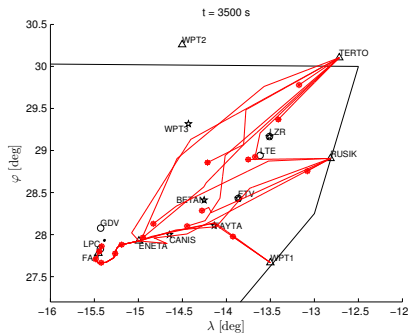
- TMA of Canarias with 3 entry points.
- 30 medium aircraft arriving in 1 hour, ahead of schedule, and landing every 2 minutes.



Max deviation time: 148.0 s.
Mean deviation time: 61.3 s.
No. of conflicts: 12.

Scenario 1 (II)

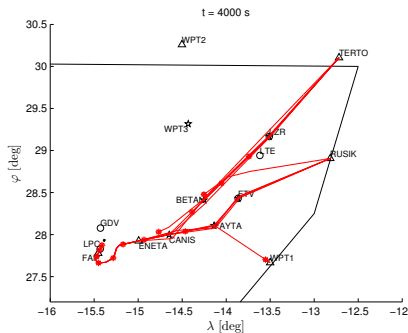
- Resolution trajectories:** with 2-step algorithm.



Indicator	Value
Objective function value after phase 1, f_1 [deg]	0.1324
Objective function value after phase 2, f_2 [deg]	0.0048
Maximum deviation time, [s]	0.10

Scenario 1 (III)

- Resolution trajectories: with 3-step algorithm.



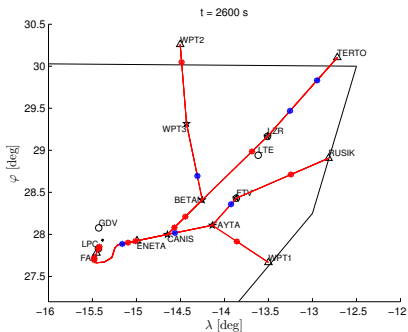
Phase 1

Indicator	Value
Objective function value, f [deg]	0.0488
Maximum deviation time, [s]	0.28

Scenario 2 (I)

• Nominal trajectories

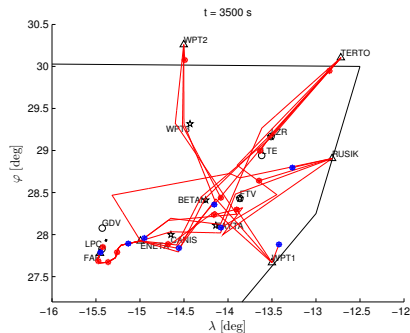
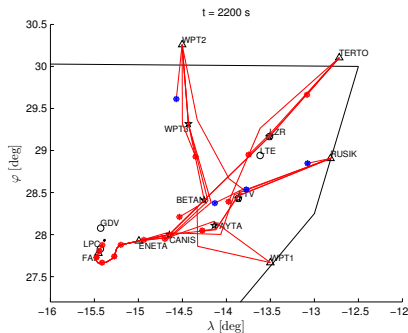
- TMA of Canarias with 4 entry points.
- 35 medium (red) and heavy (blue) aircraft arriving in 60 minutes, ahead of schedule, and landing every 2 minutes.



Max deviation time: 630.8 s.
Mean deviation time: 274.2 s.
No. of conflicts: 30.

Scenario 2 (II)

- Resolution Trajectories:** with 3-step algorithm.



Indicator

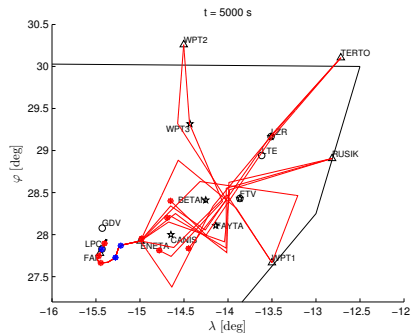
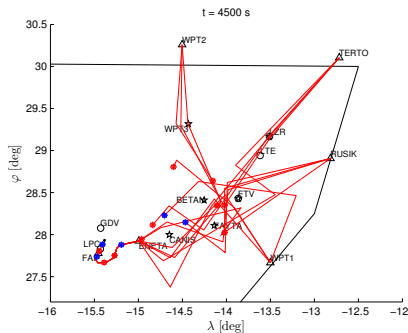
Value

Objective function value, f [deg]

0.0873

Maximum deviation time, [s]

38.47



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Summary

- A method to generate efficient, conflict-free trajectories that meet (when possible) the **scheduled times of arrival** have been presented.
- It is based on the parameterization of the aircraft intents (**predefined trajectory patterns**), and on the use of **parametric optimization** theory.
- The resolution method is formed by 3 steps: **avoidance**, **recovery**, and **optimization**.
- **Two algorithms** have been presented:
 - **2-step algorithm**: in which the optimization step is applied globally. Adequate for scenarios which are not very demanding.
 - **3-step algorithm**: in which the optimization step is applied locally. Adequate for very demanding scenarios.

Future Work

- **Departing aircraft** and **locked aircraft** (whose trajectories cannot be modified).
- **Altitude changes** in the resolution patterns.
- Different **route** structures.
- Other **traffic** conditions:
 - mixture of early and late aircraft,
 - schedules with more incoming aircraft.
- **Uncertain traffic**: analysis of delay propagation.

Acknowledgements

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