Metaheuristic Approach to Probabilistic Aircraft Conflict Detection and Resolution Considering Ensemble Prediction Systems

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MOTIVATION AND OBJECTIVES

• The development of **automated decision support tools** is key in the future of **Air Traffic Management (ATM)** system. These tools must integrate and manage **uncertainty** present in the ATM.

• Sources of uncertainty:
  • Uncertainty in data and sensors.
  • Decisions taken by individuals.
  • **Weather uncertainty.**

• It is expected that by considering the weather prediction uncertainty, the **safety** and **efficiency** of the air traffic may be improved.

Objective:

• **Expand the time horizon** of CD tools currently in used in Europe (STCA, MTCD).

  **Strategic Conflict Detection and Resolution (CD&R)** methodology that considers **wind and temperature uncertainties** for hundreds of aircraft, and a **time horizon of 60 minutes**.
Introduction

APPROACH

Uncertainty source: wind and temperature

Ensemble Prediction Systems

COSMO-D2-EPS

Flight plans

Ensemble trajectory prediction

Time horizon: 60 min

N Aircraft

20 trajectory members

Probabilistic conflict detection (CD)

\( P_{\text{con}} \)

Grid-based conflict detection

Probabilistic conflict resolution (CR)

• Lower the prob. of conflict
• Vectoring
• Minimise deviation
• Simulated annealing
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ENSEMBLE PREDICTION SYSTEMS

• An ensemble weather forecast is a collection of members that constitute a representative simple of the potential states of the weather outcome.

• Using EPS for trajectory prediction:
  • Transformation approach.
  • Ensemble approach.
Ensemble Prediction Systems

COSMO 2D-EPS

- Developed and operated by the German Weather Service.
- 20 members.
- Horizontal resolution: 2.2km.
- Vertical resolution: 65 atmosphere levels.
- 27 hour forecast every 3 hours.
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ENSEMBLE TRAJECTORY PREDICTION: ASSUMPTIONS

- **N aircraft** flying in the same airspace and altitude.
- Multisegmented 2D trajectories defined by **waypoints**.
- **Initial positions are certain and known**.
- **Constant Mach** number, certain and known.
- The aircraft are affected by **horizontal uncertain winds** \((w_\lambda, w_\varphi)\), and **air temperature** \(\Theta\).
- Spherical, non-rotating Earth model.
- Aircraft motion: point mass with three degrees of freedom.
- Constant radius turns, with no turns at the origin and destination waypoints.
- Quasi-steady state, temporal derivatives of wind and temperature are negligible.
Problem formulation
ENSEMBLE TRAJECTORY PREDICTION: EQUATIONS OF MOTION

• Equations of motion of aircraft $i$:

\[
\begin{align*}
\frac{d\varphi_i}{dt} &= \frac{1}{R + h} V_{g,i} \cos \psi_i \\
\cos \varphi_i \frac{d\lambda_i}{dt} &= \frac{1}{R + h} V_{g,i} \sin \psi_i \\
\frac{dr_i}{dt} &= \frac{R}{R + h} V_{g,i} \\
\frac{d\psi_i}{dt} &= \frac{1}{R_i} \frac{dr_i}{dt}
\end{align*}
\]

\[
V_{g,i} = \sqrt{V_i^2 - w_{XT,i}^2} + w_{AT,i} \\
V_i = M_i \sqrt{\gamma g R \Theta}
\]
Problem formulation
ENSEMBLE TRAJECTORY PREDICTION: EQUATIONS OF MOTION

• Equations of motion of aircraft $i$:

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\frac{dr_i}{dt} &= \frac{R_E}{R_E + h} V_{g,i} \\
\frac{d\psi_i}{dt} &= \frac{1}{R_i} \frac{dr_i}{dt}
\end{align*}
\]
Problem formulation
CONFLICT DETECTION

• A conflict exists between two aircraft, \(i\) and \(j\), when their distance of closest approach, \(d_{ij}\), is predicted to be less than a given set of separation minima \((D = 5\text{NM})\).

• The probability of conflict between \(i\) and \(j\), \(P_{\text{con},ij}\), is computed as:

\[
P_{\text{con},ij} = \frac{1}{20} \sum_{m=1}^{20} c_{ij,m}, \quad c_{ij,m} = i, ji, \begin{cases} 1 & \text{if } d_{ij,m} \leq D \\ 0 & \text{if } d_{ij,m} > D \end{cases}
\]
Problem formulation
CONFLICT DETECTION

- **A grid-based approach** is used: the distance between aircraft is only computed if two aircraft are in the same or adjacent cells.
- **Reduce the computational cost** at the expense of additional required **computer memory**.
- **Hash table**: reduce memory requirement.
Problem formulation

CONFLICT RESOLUTION

• Resolution maneuver: vectoring.

• The CR is formulated as an optimization problem:
  • Lower the probabilities of the conflicts.
  • Minimise the deviation from the nominal paths.
  • Control variables: coordinates of the trajectory waypoints.

\[
\begin{align*}
\mathbf{u} &= \{u_1, u_2, ..., u_i, ..., u_N\} \\
\Phi &= \sum_{i=1}^{N} \Phi_i = \sum_{i=1}^{N} \left( \sum_{j=1, j \neq i}^{N} (C_{ij} - \delta_{ij}) + a \frac{A_i}{L_{0,i}} \right)
\end{align*}
\]

• Simulated Annealing.
**Problem formulation**

**CONFLICT RESOLUTION: OBJECTIVE FUNCTION AND CONSTRAINTS**

- **Objective function:**
  \[
  \Phi = \sum_{i=1}^{N} \Phi_i = \sum_{i=1}^{N} \left( \sum_{j=1, j \neq i}^{N} (C_{ij} + \delta_{ij}) + a \frac{A_i}{L_{0,i}} \right)
  \]

- **Conflict probability**
  \[
  C_{ij} = \begin{cases} 
  P_{\text{con},ij} & \text{if } P_{\text{con},ij} \geq P_\tau \\
  0 & \text{if } P_{\text{con},ij} < P_\tau 
  \end{cases}
  \]
  (high prob.)

- **Constraints:**
  - Minimum segment length.
  - Maximum waypoint lateral deviation.
  - Objective function:
    - Conflict probability
    - Loss of separation at the starting point → **tactically solved.**
    - Deviation from the nominal trajectories.
Problem formulation
CONFLICT RESOLUTION: SIMULATED ANNEALING

• **Neighbourhood function:** Starting from a current state $u_c$ and cost $\Phi_c$, it generates a neighbour state $u_n$ and cost $\Phi_n$.
  1. Randomly chose aircraft $i \in \{1, \ldots, N\}$.
  2. Randomly choose waypoint $k \in \{1, \ldots, K_i\}$.
  3. Coordinates of $u_{i,k}$ are randomly modified.

• **Acceptance function:** If the new cost is improved ($\Phi_n < \Phi_c$), the neighbor state is automatically accepted. Otherwise, it is accepted with a probability
  $$P_{\text{accept}} = e^{-(\Phi_n - \Phi_c)/T}$$
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Summary
• Traffic in Europe inside the COSMO-D2-EPS coverage area.
• 12:00 UTC, 14th of February 2019.
• Flight plans data from Eurocontrol’s Demand Data Repository.
• Aircraft Mach number and bank angle values from BADA 3.13.
• 2 scenarios:
  • Low-density scenario: N = 92 (FL380)
  • High-density scenario: N = 214 (artificially merging FL370-FL380-FL390)
Results

EFFECTS OF THE CONFLICT RESOLUTION METHODOLOGY

- Distance between two aircraft over time.
- 5NM: minimum separation requirement.
- Before CR: $P_{con} = 80\%$.
- After CR: $P_{con} = 0\%$. 
Results

LOW-DENSITY SCENARIO

- Number of low prob. conflicts: 2
- Number of high prob. conflicts: 11
- $\Phi = 9.9$

- Number of low prob. conflicts: 0
- Number of high prob. conflicts: 5
- $\Phi = 4.5 \cdot 10^{-4}$
Results

HIGH-DENSITY SCENARIO

- Number of low prob. conflicts: 12
- Number of high prob. conflicts: 88
- $\Phi = 146.5$

- Number of low prob. conflicts: 20
- Number of high prob. conflicts: 14
- $\Phi = 4.2$
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CONCLUSIONS

- A probabilistic CD&R methodology for en-route aircraft has been introduced:
  - 60 minutes time horizon.
  - Wind and temperature uncertainties, retrieved from EPS.
  - Probabilistic conflict detection:
    - Probability of conflict.
    - Ensemble trajectory prediction.
  - Probabilistic conflict resolution:
    - Lower the probabilities of conflict, while minimising deviation from nominal trajectories.
    - Tactical conflicts are omitted.
    - Resolution trajectories are generated using vectoring.

- The methodology has been successfully applied to two different en-route conflict scenarios. The number of high-probability conflicts was significantly reduced.
Summary
FUTURE WORK

2D CD&R

3D trajectories

Uncertainty sources
• Departure time
• Aircraft initial positions

EPS coverage
• Global EPS integration
• ECMFW

Control variables
• Aircraft airspeeds
• Flight level
• Departure time
THANKS FOR YOU ATTENTION