A New Framework for Solving En-Route Conflicts

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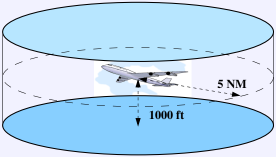
The conflict resolution problem

Make sure than any 2 aircraft do not get closer to each other than a given *separation norm* (usually 5NM horizontally).



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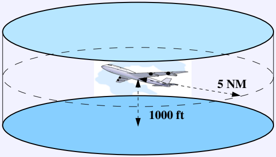

- Widely studied in the last two decades
- Relies on a realistic trajectory prediction (handling of uncertainties)
- Model is (too) often closely linked to the resolution method

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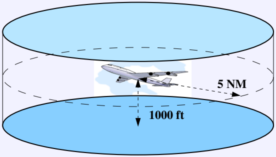

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We propose...

- A new framework that separates the model from the resolution
- A public benchmark
- Two approaches to the problem resolution

Contents

Trajectories

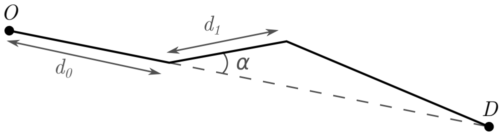
Trajectories are...

- defined in the horizontal plane
- sampled into time steps of duration τ
- from origin O to destination D

O and D can be any 2 successive waypoints in the aircraft route.

In the proposed benchmark, $\tau = 3\,\mathrm{s}$ in order to be able to catch even the shortest conflicts (two facing aircraft at maximal speed)

Maneuver model



- n_0 possible values for d_0
- n_1 possible values for d_1
- n_α possible values for α

Possible maneuvers per aircraft:

$$n_{\mathsf{man}} = n_0 \times n_1 \times (n_\alpha - 1) + 1$$

Handling Uncertainties

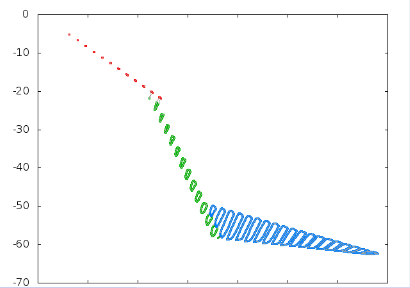
Uncertainties on maneuvers and speed

- Maneuver starts at $d_o \pm \varepsilon_0$
- Maneuver distance is $d_1 \pm \varepsilon_1$
- Maneuver angle is $\alpha \pm \varepsilon_\alpha$
- Speed is $s \pm \varepsilon_s$

Trajectory hull model

At each time step τ, aircraft position is a modelled as a convex hull containing all possible positions

- Red: aircraft did not turn yet
- Green: aircraft is being maneuvered
- Blue: aircraft is heading towards destination again



Model

Decision variables

$$M = \{m_i,\ i \in [1, n]\}$$

$\forall i,\ m_i \in [1, n_{\mathsf{man}}] \quad \longrightarrow \quad$ size of the search space: n_{man}^n

Optimization

- Cost of a single maneuver:

$$\mathsf{cost}_{\mathsf{man}}(m_i) = \begin{cases} 0 & \text{if } \alpha = 0 \\ (n_0 - k_0)^2 + k_1^2 + k_\alpha^2 & \text{otherwise} \end{cases}$$

  where m_i is the maneuver described by the tuple $\langle k_0, k_1, k_\alpha \rangle$

- Total cost:

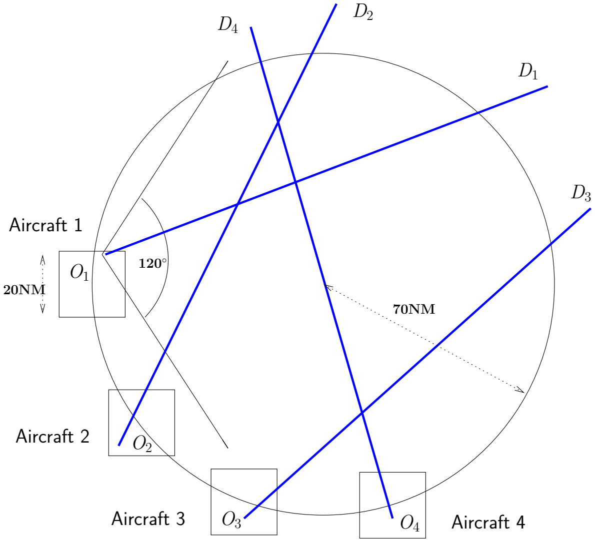
$$\mathsf{cost} = \sum_{i=1}^{n} \mathsf{cost}_{\mathsf{man}}(m_i)$$

Versatility

This model can be easily modified and refined with:

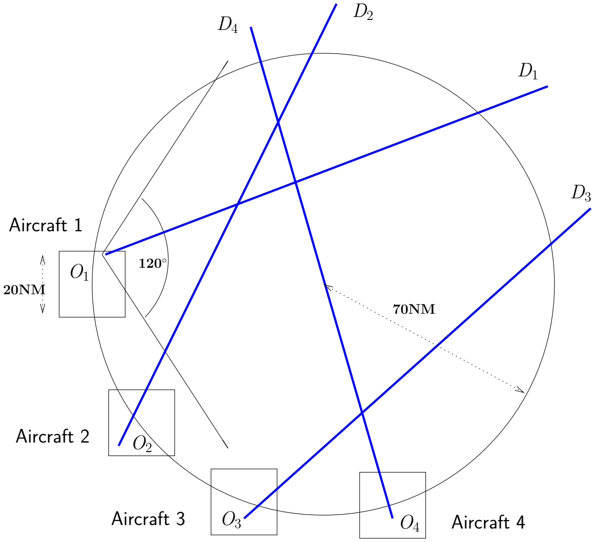
- other trajectory prediction methods
- other modelings for uncertainties
- different kinds of maneuvers
- other cost functions (fuel consumption, CO_2 emission, delay...)

Scenarios



D_4
D_2
D_1
D_3
Aircraft 1
O_1
120°
20NM
70NM
Aircraft 2
O_2
Aircraft 3
O_3
O_4
Aircraft 4

Scenarios



Scenario parameters:

- n
- n_{man}
- $\varepsilon = \langle \varepsilon_0, \varepsilon_1, \varepsilon_\alpha, \varepsilon_s \rangle$

Conflict Detection

Conflict between trajectories t_i and t_j

for all time steps τ **do**
  if dist(`convex_hull`(m_i, τ), `convex_hull`(m_j, τ)) < 5NM **then**
    return true
  end if
end for
return false

Given n aircraft, a 4D matrix C is built:

$\forall i, j \in [1, n],\ i < j$
$\forall m_i, m_j \in [1, n_{\text{man}}]$ where m_i, m_j are maneuvers of aircraft i and j respectively

$$C_{i,j,m_i,m_j} = \begin{cases} \text{true} & \text{if there is a conflict between those trajectories} \\ \text{false} & \text{otherwise} \end{cases}$$

Benchmark

For a given set of parameters, matrix C forms the benchmark for the corresponding instance.

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Instance files and current results available at:
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Currently available instances:

- $n \in \{5, 10, 15, 20\}$
- $n_{\text{man}} = 151$
- $\varepsilon \in \{\varepsilon_{\text{low}}, \varepsilon_{\text{mid}}, \varepsilon_{\text{high}}\}$

$$\begin{aligned}\varepsilon_{\text{low}} &: \varepsilon_0 = 1\text{NM}, \varepsilon_1 = 1\text{NM}, \varepsilon_\alpha = 1^\circ, \varepsilon_s = 1\%\\ \varepsilon_{\text{mid}} &: \varepsilon_0 = 2\text{NM}, \varepsilon_1 = 2\text{NM}, \varepsilon_\alpha = 2^\circ, \varepsilon_s = 2\%\\ \varepsilon_{\text{high}} &: \varepsilon_0 = 3\text{NM}, \varepsilon_1 = 3\text{NM}, \varepsilon_\alpha = 3^\circ, \varepsilon_s = 3\%\end{aligned}$$

More to come...

Contents

Evolutionary Algorithm

Inspired by natural evolution: manipulation of a population of candidate solutions with selection, crossover and mutation operators

Fitness function

$$F = \begin{cases} \dfrac{1}{2 + \displaystyle\sum_{i<j} C_{i,j,m_i,m_j}} & \text{if } \exists (i,j),\ i<j,\ C_{i,j,m_i,m_j} \neq 0 \\ \dfrac{1}{2} + \dfrac{1}{1 + \text{cost}} & \text{if } \forall (i,j),\ i<j,\ C_{i,j,m_i,m_j} = 0 \end{cases}$$

- Using a *sharing* process to avoid premature convergence towards local optima
- Taking advantage of *partial separability* of the cost function to build adapted crossover and mutation operators

Constraint Programming

CSP Model

- Variables: $M = \{m_i,\ i \in [1, n]\}$
- Domains: $\forall i,\ m_i \in [1, n_{\mathsf{man}}]$
- Constraints: $\forall (i, j),\ c_{i,j} = \{(k, l) \mid C_{i,j,k,l} = 1\}$

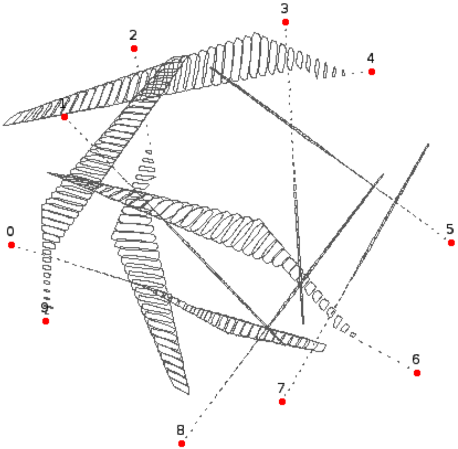
We note $|c_{i,j}|$ the cardinality of the constraint $c_{i,j}$

Solution search and Optimization

- *Branch and Bound*
- *Weighted degree* adaptative heuristic

Optimality proof obtained for most instances

A solution to a 10-aircraft conflict



Cost of solutions

Average on 10 instances with the same parameters.

	n							
	5		10		15		20	
	CP	EA	CP	EA	CP	EA	CP	EA
ε_{low}	5.3		29.8		86.3	86.8	185.8	176.9
ε_{med}	4.2		46.6		104.0	104.0	267.6	282.8
$\varepsilon_{\text{high}}$	5.1		45.7		170.4	156.3	299.0	305.0

- Each maneuver has a cost in the interval $[0, 50]$
- CP and EA equivalently efficient

Cost of solutions

The cost is closely related to the number of forbidden maneuver pairs.
We define the *intrinsic difficulty* of an instance by:

$$\rho = \sum_{i<j} |c_{ij}|$$

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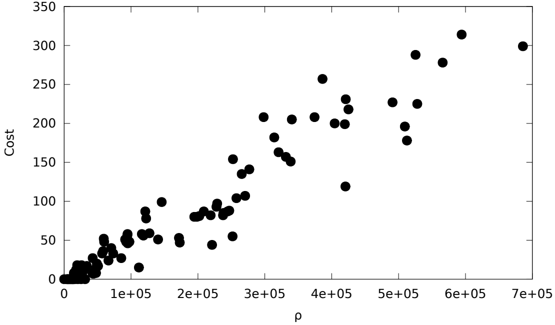

Computing times for finding best solution

All runs were limited to 5 minutes.
Average on 10 instances with the same parameters.

	n							
	5		10		15		20	
	CP	EA	CP	EA	CP	EA	CP	EA
ε_{low}	0.00	0.02	0.22	0.97	24.08	2.01	75.14	95.98
ε_{med}	0.00	0.02	0.27	1.44	45.17	32.60	79.61	184.61
$\varepsilon_{\text{high}}$	0.00	0.02	1.04	0.37	48.59	93.19	58.44	274.16

- Unfeasible instances are proved inconsistent (CP only) within 1 second
  $\Rightarrow$ possibility to generate a new instance with more maneuvers allowed
- A first solution is found within seconds for almost all instances

Conclusions

- A new framework for conflict resolution
- Separation of the model from its resolution
- Many configuration opportunities
- Benchmark available at: http://clusters.recherche.enac.fr
- Two possible approaches for the resolution: Constraint Programming and Evolutionary Algorithm
- Optimality proof obtained for most instances with CP

Further Work

- Vertical maneuvers
- Scenarios issued from real data (simulated flight plans)
- Embedded resolution (i.e. integration into fast-time simulator)
- Tabu Search algorithm, hybridization