An Air Traffic Control Model Based Local Optimization over the Airways Network

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Analysis of Aircraft Radar Tracks

- Data about flight plans (before ATC) and radar updated tracks (after ATC) in Europe (DDR data.)
- Time resolution $\sim 2$ min: conflicts cannot be spotted!
- Sectors structure.
- Safety Dataset: data about Short-Term Conflict Alerts (STCAs) [1]

Navigation Point Networks

Planned  Follows the airways structure.
Real    Topological changes due to ATC.
Navigation Point Networks

Degree

- Creation of longer links, the traffic over the network becomes more homogeneous
Delays

\[ \delta t_{tot} = \delta t_{dep} + \delta t_{enr} \]

- Delays of aircraft crossing the Italian Airspace in June 2011.
Delays: Correlations

\begin{center}
\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{fig1.png}
\caption{\(R^2 = 0.96\)}
\end{figure}
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\begin{center}
\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{fig2.png}
\caption{\(R^2 = 0.32\)}
\end{figure}
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\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{fig3.png}
\caption{\(R^2 = 0.05\)}
\end{figure}
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Dynamical Metrics and STCAs

- Short-Term Conflict Alert (STCA) $\rightarrow n_{STCA}$ & $P_n(STCA)$
- Dynamical Metrics [2]:
  - Horizontal Movements ($Frac$, $Fork$ ...)
  - Vertical Movements ($Alt$)
  - Generated Delays ($Positive$ $Delays$ and $Negative$ $Delays$)

- Vertical Deviations used in critical and highly trafficked nodes.
- Horizontal Deviations used in non-critical and low-trafficked nodes.
Air Traffic Model: Conflict Detection

a) $m_n \alpha t_m t_n$

B) $\xi_n t_m \beta n$

c) $m_n \alpha t_m t_n$

d) $t_m \alpha t_n n$
Air Traffic Model: Conflict Resolution

IN

OUT

Vectoring
Model Validation

- Simulation of full day schedules in a chosen airspace (Estonian, Greek and Italian)
- Data inferred management protocol:
  - Vertical Deviations allowed
  - IN-OUT protocol
  - Direct Assignment
  - Sectors Capacity Constraints
- External disturbances: penalty delay generating areas
Coarse Grained Validation

- Measure of Network Metrics Variations on the Airways Network due to ATC
- Degree $k$ of a node: the number of other nodes that are linked to the considered one.
- Strength $s$ of a node: the sum of the weights of all the links connected to the considered node (Traffic Load)
- Betweenness Centrality $b$ of a node: this metric measures the “importance” of a node in the network.
Microscopic Validation

- Measure single trajectory variations from flight plans to real trajectories.
- $\delta l$: variation in length.
- $\delta n$: variation in the number of crossed navigation points.
- $\delta t_{enr}$: en-route delay.
Validation: Trajectories Statistics

\[ P(\delta_l) \] vs \( \delta_l \) (NM)

\[ P(\delta_n) \] vs \( \delta_n \) (NM)

\[ P(\delta_{tenr}) \] vs \( \delta_{tenr} \) (min.)

\( \delta_{tenr} \) (no ext. dist.)

\( \delta_{tenr} \) (with ext. dist.)
High-Traffic Simulations

- Simplified conflict resolution protocols: IN-OUT, OUT-IN, Vectoring-OUT, IN-OUT (Vertical Deviations).
- Realistic protocol used in validation.
- Random schedule of $N$ aircraft departing in a time frame of 2 h
- Simulation is over when every aircraft arrives at destination.
The model is suited to test new trajectory planning and airspace structures.

Built a new solution for the planned trajectories and use the model to compare them with the current ones.

Local Optimization (ATC) $\rightarrow$ Global Optimization
Extremal Optimization Algorithm

- Based on the Self-Organized Criticality Phenomenon (SOC): optimization via avalanche dynamics.
- \( C(\gamma) = \sum_i \gamma_i \).
- \( x_i = \{ (n_{\text{start}}, t_{\text{start}}), (n_1, t_1), \ldots, (n_{\text{stop}}, t_{\text{stop}}) \} \)
- \( \gamma_i = I(x_i) + \frac{\epsilon}{2} \sum_{j=1,j\neq i}^N m(x_i, x_j) \) (Fitness of the \( i^{th} \) trajectory)
- Parameter \( \epsilon \) allows to modulate between straight and conflict-free flight plans.
- Sectors Capacity constraints are enforced.
Suboptimal Flight Plans

![Graph](image)

- **a)**
  - Graph showing the function $\langle l(x_i) \rangle$ against $\varepsilon$
  - The function initially increases slowly and then sharply increases near $\varepsilon = 2$

- **b)**
  - Graph showing the number of conflicts $\eta_{conflicts}$ against $\varepsilon$
  - The number of conflicts decreases as $\varepsilon$ increases
Suboptimal Flight Plans

a) Current

b) Sub-Optimal
Efficiency Against Perturbations

- External disturbances have not been included in the optimization process
- How these solutions behave under their influence?
- What are the differences with respect to the current situation?
- Departure Delays: from a uniform distribution in \([-\tau, \tau]\)
- External disturbances: penalty delay generating areas
Efficiency Against Perturbations

- Every aircraft flies according to a flight plan obtained with the EO algorithm for various values of $\epsilon$.
- The structure of the sectors is unvaried with respect to the current situation. After every redirection an aircraft is sent directly to its destination following a straight line.
- Directs in order to speed up the traffic are not considered.
- Controllers solve conflicts using the IN-OUT protocol.
- Capacity constraints are enforced.
- Efficiency: Number of Action Performed by the ATCs
Depature Delays

# of actions

En-Route Delay
Perturbed Areas

# of actions

En-Route Delay
Conclusions

- Developed a model of ATC using historical data
- The action of the ATC is modeled as a local optimization over the network of the Airways.
- Used the Extremal Optimization Algorithm to build sub-optimal flight plans.
- Their efficiency have been compared to the current flight plans.