1. INTRODUCTION: NEED FOR A 4D MICRO-MODEL ATM VIEW

“A lack of a proper coordination among the main air traffic management (ATM) actors through their different decision making processes limits the actual system capacity and leads to an inefficient and congested air transport system.”

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1. Introduction: need for a micro-model 4D view of the ATM
2. Test-bed Platform for ATM Studies (TPAS)
3. Micro-scale data framework to store and manage ATM state-space information
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5. How to use TPAS (APIs and functionalities)
6. Practical example: temporal looseness for ground delays
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ATM CAPACITY AND MAIN ATM ACTORS

ATM capacity = “amount of aircraft that can be managed safely by Air Traffic Management system in a period of time”

Actors:

- **Demand**: Airspace Users (AUs), e.g., airlines
- **Supply**: Air Traffic Control (ATC) centers and Airport Operators (AOs)
- **Network Manager** (in Europe, EUROCONTROL, in charge of ATFCM to ensure Demand and Capacity Balancing)
CURRENT ATM OPERATIONS
Assume NO conflicts

ATFCM VIEW OF THE ATM
Assumed maximum sector pre-declared capacity: 5/5

ATC VIEW OF THE ATM
Sector capacities satisfied

ATFCM does not see what is happening at micro-scale/trajectory level

PREDICTION:
SIMULATION TIME 1

Assumed maximum sector pre-declared capacity: 5/5

ATFCM does not see what is happening at micro-scale/trajectory level

PREDICTION:
SIMULATION TIME 2

ATC VIEW OF THE ATM
Sector capacities satisfied

Conflict predicted
Regulation Applied (delay)
ATC intervention required

ATFCM VIEW OF THE ATM
Conflict predicted
Regulation required
ATC intervention required

Sector capacities satisfied

A network micro-scale view is required to identify the Emergent Dynamics of local decisions and to coordinate the main ATM actors.

SESAR ATM MODEL

New Concept of Operations (SESAR programme):
- Trajectory-based operations (4D Trajectory)
- Collaborative planning (sharing of information and decisions)
- Good trade-off between efficiency and capacity
- Reduction of the Emergent Dynamics problem
- Dynamic airspace (flexible route structures and sectors)
- New and innovated technologies (automation, precision, reliability, efficiency...)

4D contract: AU assume the compromise of flying the trajectory planned for the full flight with enough precision in the 4 dimensions (3D + time), and the ATM services agree to facilitate.
**DESIRABLE ATM MODEL:**
**TBO (SESAR, NEXTGEN...)**

- A microscopic 4D trajectory model of the traffic flows
- Automated and coordinated stakeholders’ DSTs to ensure a more precise and stable traffic synchronization along the network
- Allow the participation of the Airspace Users through arbitrated negotiation processes during the entire network planning process
- A common overall sight of the ATM current and predicted states
- The anticipation of the potential emergent dynamics at the network due to local decisions shared among all the ATM stakeholders DSTs

**TBO-BASED ATM MODEL**
**(SESAR, NEXTGEN...)**

- Focus on synchronized 4D trajectories (arbitrated by Network Manager)

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**2. TEST-BED FOR ATM STUDIES (TPAS)**

**EXAMPLE: STREAM WP-E**

Strategic de-confliction of 4000 trajectories over Europe in 2 hour look-ahead

Processing about 20 million of waypoints (including what-if trajectories)

Computational time to find a solution < 60 sec. (with a regular computer)
3. SPATIAL DATA STRUCTURE (SDS)

A micro-scale data framework to support the representation of the air traffic demand on the different airspace sectors at aircraft trajectory (microscopic) level. “ATM 4D snapshot”

### SDS

![SDS Image]

- Safety envelope in a given instant
- Turbulence generated in a given instant

### SPATIAL DATA STRUCTURES

- Spatial Data Structure (SDS) is a database that represents a spatial region (e.g., an air sector) by using individual memory positions to represent each of the discrete (3D) coordinates of the sector.
- Spatial data: spatial information (e.g., discrete trajectory representation) and non-spatial information (e.g., Flight Number id).
- Such memory positions are sorted in a way that, given a certain coordinate, the information stored inside the SDS is easily recoverable applying linear mathematical formulae:

\[
SDS(x, y, z) = x \times Y \times Z + i
\]

### Physical concept of a SDS

<table>
<thead>
<tr>
<th>Y</th>
<th>Z</th>
<th>i</th>
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<tbody>
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### Logical concept of a SDS

<table>
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<tr>
<th>Y</th>
<th>Z</th>
<th>i</th>
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Other non-spatial state-space info can be added.

Similar (but different) types of data structures:

- **Occupancy grids**: specialized usage of SDSs used in robotics to build in real-time maps (for navigation purposes).
- **Hash tables**: to store keys/pointers—and only keys/pointers—to the data values of interest (not necessarily related with any kind of spatial data).
- **Look-up tables**: to store pre-calculated values for a given function in order to avoid online—time consuming—calculations.

### ANY DECISION MUST PRESERVE SAFETY

<table>
<thead>
<tr>
<th>Safety</th>
<th>Avoid accidents &amp; incidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be sustainable</td>
<td>Environment impact</td>
</tr>
<tr>
<td>Capacity</td>
<td>Allocate demand</td>
</tr>
<tr>
<td>Cost efficiency</td>
<td>Minimum cost</td>
</tr>
</tbody>
</table>

ATM services: facilitate orderly and safe air transportation systems.
Two methods of Confliction Detection based on SDS:

1. Build and store the safety envelope (4D tube)
2. Store the point-mass position and pairwise comparisons (only between two cells)

Conflicts are detected at the moment of storing the position by comparing distances at each time-step.

Each trajectory processed is stored and compared with trajectories using same spatial resources.

Time-windows comparison is only performed here. No comparison is needed!!!
Constant bin size
- Optimal size: 10NM (≈20Km)

Bin-size variable with latitude
- 0.2º in latitude = 12NM
- 0.5º in longitude ≈ 30NM in Equator
- 26NM in lat 30º
- 10NM in lat 70º

Optimal size: 10NM (≈20Km)

Planar SDS
- Geodesic SDS
- Current physical concept of the SDS
- Current physical concept of the TSDS

SDS FOR CONFLICT DETECTION (PERFORMANCE)

TSDS allows storing current and future states
- Time discretization: 1 sec.
- For 2-hour prediction look-ahead: 7200 SDSs

Ideal for real-time Strategic De-confliction

TPAS FUNCTIONALITIES

BASIC FUNCTIONS OF THE INFORMATION MANAGER:
- Management of aircraft/flight information
- Management of original trajectories/flight plans
- Management of what-if trajectories
- Generate trajectories from the routes/flight plans
- Add ATM information to the SDS (e.g. 4D trajectories)
- Delete ATM information from the SDS (e.g. 4D trajectories)
- Extract ATM State Space information from SDS (e.g. conflicts, temporal looseness, complexity map...)
- Management and classification of ATM State Space information (e.g. temporal sorting of conflicts, computation of basic metrics...)
- Coordination of modules functionalities
TPAS FUNCTIONALITIES

Basic functions to manage:
- Coordinates (geodesic and UTM)
  - Also includes: Computation of 2D/3D distances between 2 coordinates (great circle or loxodromic)
  - Conversion from Geodesic to UTM and vice versa
- Routes
- Trajectories
- Flights
  - Also includes: Parameterization of FAA models
- Spatial Data Structures
- Input-Output operations
  - Including: G.Earth, FACET, GNUPlot, AIDL, cvs, txt, among others

Advanced functions (modules):
- Conflict Detection (time-based or spatial-based)
- Conflict Resolution (with Geometric Optimization Approach)
- Clusterizer (return sets of trajectories in conflict)
- Interaction Causal Solver (CR considering domino effects)
- Temporal looseness calculation (No-go zones and First Range Looseness)
- Ground Delays
- Statistics, metrics and tools for ATM uncertainty

CONFLICT RESOLUTION

2 problems: Conflict avoidance and recovery

CONFLICT RESOLUTION

EXEMPLE: 2 trajectories in conflict and 4 possible solutions

DOMINO EFFECTS

Domino Effects may appear during conflict resolution in the presence of multiple trajectories (surrounding traffic)

The State-Space stored SDS can be used to explore Domino Effects
**TPAS FUNCTIONALITIES**

- Reduce the solution space combinatorial exploration

**INTERACTION CAUSAL SOLVER**

- Causal model with a discrete event approach
- Reduces the search to the Pareto Frontier of the feasible solutions

**FLIGHT PLANS**

(ORIGINAL TRAJECTORIES)

**CONFLICT DETECTION (CD)**

**RESOLUTION TRAJECTORY GENERATOR (RTG)**

**STATE SPACE GENERATION**

**INTERACTION CAUSAL SOLVER (ICS)**

Alternate trajectories are sorted by preferences of the Airspace Users

Ideal solution: \([1, 2, 3, 4, 5, \ldots, N-1, N]\)

Non feasible solution:

New Pareto-efficient solution:

Ideal solution: \([1, 2, 3, 4, 5, \ldots, N-1, N]\)

Non feasible solution:

New Pareto-efficient solution:

Ideal solution: \([1, 2, 3, 4, 5, \ldots, N-1, N]\)

Non feasible solution:

New Pareto-efficient solution:
**STRATEGIC DE-CONFLICTION**

Layers of safety in ATM (separation of flights):
- **Operational**: avoid imminent crashes (e.g., TCAS)
- **Tactical**: medium term planning of the traffic within a sector (i.e., ATC separation tasks 20-30 min. in advance)

- **Strategic De-confliction**: planning actions taken from several hours in advance up to few minutes before to the execution phase, in order to anticipate the separation of flights even before they takeoff, and also while they are airborne, but always with enough anticipation to allow a Collaborative Flight Planning subject to the applicable safety standards

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**SIMULATIONS WITH FACET TOOL**

4010 direct route trajectories over European ATM
311 conflicts
286 resolution maneuvers

Results of WP-E STREAM
Yellow zones indicate potential conflicts if the temporal dimension changes.

Delay applied to flight A.

Departure times of B and D remain constant.

Early departure applied to flight A.

Departure times of B and D remain constant.

TPAS FUNCTIONALITIES

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\[ A - \{D_{\text{early}}, D_{\text{late}}\} = [-3, +5] \]

\( \lambda \) = First Range Looseness (FRL)
HOW TO USE TPAS?

- Obtain TPAS: email to sergio.ruiz@uab.es
- Installation
  1. Static method requires .dll, .lib and .h files
  - Add .lib to "additional dependencies" of the linker
  - Add the .h to your code
  - Call the .dll from your code
  2. Dynamic method: Only .dll file
  - Use the method loadLibrary()
  - Call the functions as given in the APIs documentation

The static method is easier in C++ and the dynamic is easier in Java and C#.
6. HANDS-ON EXAMPLE

7. HANDS-ON EXAMPLE

Current scenario data:
Flight 1: (61, 2)
Flight 2: (3, 2)
Flight 3: (7, 2)
Flight 4: (9, 2)

Change entry time of flight 1

Current scenario data:
Flight 1: (61, 2)
Flight 2: (3, 2)
Flight 3: (7, 2)
Flight 4: (9, 2)

8. OTHER ATM STUDIES AND FUTURE DEVELOPMENTS

INTEGRATION WITH SWIM

AIRPORT INTEGRATION (NOP+AOP)

FATIN
(System presented in the Eurocontrol's challenge of SWIM Master Class 2013)

STRATEGIES FOR ATM UNCERTAINTY
Traffic Robustness Analysis and Assessment of Uncertainty Impact

<table>
<thead>
<tr>
<th>Normal</th>
<th>WPE1</th>
<th>WPE2</th>
<th>ETI1</th>
<th>ETI2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2NM (EI)</td>
<td>299</td>
<td>304</td>
<td>276</td>
<td>294</td>
</tr>
<tr>
<td>2NM (CC)</td>
<td>239</td>
<td>234</td>
<td>211</td>
<td>239</td>
</tr>
<tr>
<td>7NM (EI)</td>
<td>237</td>
<td>242</td>
<td>228</td>
<td>237</td>
</tr>
<tr>
<td>7NM (CC)</td>
<td>430</td>
<td>426</td>
<td>415</td>
<td>426</td>
</tr>
</tbody>
</table>

- A strategic buffer of 10NM/12NM could absorb big part of the WPE and ETD uncertainties, thus providing a more robust network.
- Trade-off: More stable/robust network (predictability) vs. additional CR amendments required (efficiency) and less space available due to the extra buffers (capacity).

9. Future Work

Network Disruptions

- If few hours before (e.g. 60') flight execution severe weather is predicted, the optimal 4D trajectory is updated.

Since \( p<0.5 \) a new trajectory can be computed considering new waypoint in the halfway.

Severe weather is definitely not going to happen (\( p=0 \)).
Weather predictions are updated and RBT is modified in consequence.

Severe weather is definitely going to happen (\( p=1 \)).
Weather predictions are updated and RBT is modified in consequence.

New Uncertainty Models

ATM planning should consider at \( t_0 \) (and before) the probability of both probable trajectories diverging at \( 90^\circ-30^\circ \).

Note: weather predictions and SBT/RBT updates will be continuous and not in 30' steps.
PUBLICATIONS

ATM UNCERTAINTY
Uncertainty grows with time → It seriously affects Strategic De-confliction
- Navigational imprecision and tracking errors
  - E.g., relatively little trajectory deviations
  - Typical lateral buffer: 1NM
- Individual-level perturbations
  - E.g., delays, deviations…
  - “The one that deviates the one that pays”
- Network-level perturbations
  - E.g., convective weather, sudden loss of airport/sector capacity…
  - Full re-panning: need for real-time Strategic De-confliction

NEW UNCERTAINTY MODELS
Risk-of-deviation
- PLANNED
- EXECUTION

FEEDBACK AND QUESTIONS ARE WELCOME
Thanks for your attention
Email: Sergio.ruiz@uab.es
Now the route is sub-optimal but it is more robust and will reduce the workload of tactical controllers.