Causal Decision Support Tools for Strategic Trajectory De-confliction to Enable Seamless Aircraft Conflict Management (STREAM)

Clustering and Interaction Causal Solver Models

Speakers:
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Jenaro Nosedal (UAB)
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3: Problem description  
4: Causal analysis and models  
5: Simulation  
6: To conclude
1: Introduction to STREAM

- Project Consortium & Networks
- Project contents
- STREAM in 2012
Introduction to STREAM

Project Consortium & Networks

Advanced Logistics Group (ALG)

Boeing Research & Technology Europe (BR&TE)

Universitat Autònoma de Barcelona (UAB)

A project under

SESAR WPE

HALAB! RESEARCH NETWORK

- Small project launched on 16th March 2011
Project Contents: Objectives

High level objective

• To perform **conflict detection at pre-departure phase**, thus allowing the integration of appropriate conflict resolution manoeuvres at a strategic level

Derived intermediate objectives

1. **To develop time-efficient algorithms** for the strategic detection and resolution of traffic conflicts:
   - capable of adopting a combination of **different resolution strategies**;
   - that are computational efficient with respect to the number of trajectories considered;
   - and manage a **high quantity of information describing 4D trajectories** and to ensure that resolutions maintain traffic complexity under control — at local(ACC), regional (FAB) and even global (ECAC) levels

2. **To explore the requirements on the reliability and robustness of traffic predictions** in order to allow the new strategic trajectory de-confliction algorithm that would efficiently modify SBTs

3. **To define metrics for assessing** the proposed algorithms performance towards an increased automation of the ATM system

4. **To perform simulations in a common environment** in order to assess the proposed algorithms and metrics
Introduction to STREAM

STREAM in 2012

- STREAM is in its final phase: only 4 months to the end of the project
- An Advanced Solution for algorithms and metrics has been delivered (Phase 2)
- Phase 2 CD&R algorithms developments are in a mature status, integration and calibration of modules is performed
- From the lessons learnt in Phase 1, a new set of metrics has been defined for the execution of the Final Solution Simulations and Performance Assessment
- A direct routing scenario has been defined and tests are currently being undertaken
Introduction to STREAM

STREAM in 2012

Deliverable D4.1 – Preliminary Performance Assessment (2012)

• Performance Evaluation of the initial CD&R Algorithms proposed by STREAM during 2011 (D2.1)
• Development of a Simulation Framework fed by the methodology and metrics proposed in 2011 (D3.1)
• Validation of the framework and performance evaluation leading to valuable inputs for the Algorithms development in Phase 2
• Use of a synthetic complex traffic scenario over Gran Canaria to test the CD&R capabilities and obtain meaningful results through the computed metrics
• Use of a pan-European scenario to stress the algorithms and explore further requirements for the Advanced Solution (new resolution strategies, geodesic projections, etc.)
Introduction to STREAM
STREAM in 2012


- The limitations of the initial solution (presented in 2011) for tackling European scale scenarios are addressed in this Final Solution.
- Scalability redesign of the SDS considering the curvature of the Earth and need to migrate to a 64-bit platform
- New sub-module to obtain multiple resolution efficient trajectories for each conflict through geometrical closed-form analytical formulae
- Another sub-module based on CPN models to analyse the network effects of those resolutions with a global optimization scope
- New models to tackle the uncertainty and hints about how these models could be implemented are shown
- A proof-of-concept application connecting STREAM algorithms with SWIM communication platform is also presented
Introduction to STREAM
STREAM in 2012

Deliverable D3.2 – Final Metrics and Methodology (2012)

• Description of the framework proposed for the final evaluation of the CD&R algorithms to be presented in D4.2.

• In the definition of final set of metrics for the performance assessment, a new concept for the capacity metric is introduced: “Impact on capacity”. This metric does not quantify the capacity improvements related to specific controller workload, but it identifies positive/negative impacts in capacity for the airspace divided in arbitrary defined sectors.

• The Fairness and equity metrics are alternatively defined to be aggregated in an Airspace User basis instead of a flight basis in order to better monitor and assess the performance of CD&R algorithms affecting all stakeholders.

• The methodology proposed for a fast-time air traffic simulation platform includes the generation of scenarios, generation of a baseline for comparison and computation of metrics for assessment; and it is adapted to encompass the “offline” study of the impact of Trajectory Prediction uncertainties.
2: Introduction to the paper

- Paper Outline
- Solution Framework
Introduction to the paper

Paper Outline

- STREAM
  - Technological framework

- Problem description
  - NP hard

- Causal analysis
  - Reduce combinatorial
  - Optimal searching

- Conclusions and Next steps

- Clustering model

- ICS model

- Simulation results
Introduction to the paper

STREAM
Solution framework
STREAM
Solution process

FLIGHT PLANS
(ORIGINAL TRAJECTORIES)

CONFLICT DETECTION
(CD)

CONFLICTS

TRAJECTORIES GENERATION
(TG)

ALTERNATIVE TRAJECTORIES

STATE SPACE GENERATION

SDS

CONFLICTS

INTERACTION

CAUSAL SOLVER
(ICS)

GEOMETRIC
OPTIMIZATION
APPROACH

AIRCRAFT | TRIALS TRAJECTORY
---|---
1 | 769, 520, 231, 452, 904, 392, 175, 712, 872
2 | 784, 207, 146
3 | 2045
4 | 562, 543, 876, 436, 644
5 | 324, 166
6 | 688, 588, 108, 649, 455, 876, 855, 244, 333
7 | 765, 257, 848, 418
8 | 536
9 | 651, 342
10 | 606, 780, 454, 852, 923
11 | 246
12 | 538, 099, 654
13 | 976, 576, 374, 436, 984, 194
14 | 123, 830, 012, 681, 354, 951, 787
N-1 | 786, 511
N | 856, 555, 786, 487, 001
3: Problem description
Problem description

A1

C1 (Tr1,Tr2)

A2

A4

C2 (Tr4,Tr3)

A3
Problem description

A1

Tr21

A2

Tr11

A4

Tr41

Tr31

A3
Problem description

A1

A2

Tr11

A3

A4

Tr3

C3 (Tr11, Tr3)

Tr2

Tr41
Problem description
Problem description

A1

Tr21

A2

Tr1

A3

Tr3

A4

Tr41
Problem description

A1

A2

C1 (Tr1, Tr2)

C2 (Tr1, Tr3)

A3
Problem description
Problem description

Inputs --> Outputs

![Diagram of aircraft trajectories and interactions]

### Elements

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>R0</th>
<th>R1</th>
<th>R2</th>
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### Interactions

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</table>

### Solution requirements:

1. One trajectory per aircraft
2. Conflict free (compatible trajectories)
Problem description

Total possible combinations considering an equal amount of alternative trajectories per aircraft.

$K^N = (K_{A1})(K_{A2})(K_{A3})(K_{A4})...(K_{AN})$ possible combinations
4: Causal analysis and models

- Causal analysis
- Clustering Model
- ICS Model
Causal analysis

The search and construction of solutions is computed using three discrete events:

1. Trajectories selection.
2. Conflicts between trajectories.
3. Trajectories combination.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Solution space exploration</th>
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<tr>
<td>Pure combinatorial</td>
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<tr>
<td>Causal</td>
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<tr>
<td>Causal with Constraints propagation</td>
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### Causal analysis

#### Aircraft

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#### Conflicts

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\[
K^N = (K_{A1})(K_{A2})(K_{A3})(K_{A4})...(K_{An}) \text{ possible combinations}
\]
## Causal analysis

### Aircraft

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### Conflicts

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### Causal analysis

#### Aircraft vs. Conflicts

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</table>

#### Example

- **A1** conflicts with **C1** (Tr1, Tr2)
- **A2** conflicts with **C2** (Tr2, Tr4)
- **A3** conflicts with **C3** (Tr31, Tr1)
- **A4** conflicts with **C4** (Tr11, Tr32)
- **An** conflicts with **Cm** (Trx, Try)
Causal analysis and models

Causal analysis

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>R0</th>
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(1) \((K_{A2} - KC_{Tr})(K_{A3} - KC_{Tr})(K_{A4} - KC_{Tr})... (K_{An} - KC_{Tr})\) compatible combinations < \(K^N\)
## Causal analysis

<table>
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Combination of conflict free trajectories (construction of solutions)
Causal analysis and models

Causal analysis

The combinatorial increases considerably with the amount of aircrafts and trajectories.

Partition in groups of aircrafts which do not share any conflict.

Feasible solution combinations

Feasible solution combinations
  For cluster A

Feasible solution combinations
  For cluster B

Avoiding unnecessary combinatorial.
Feasible solution space (FS)

Local optimization of resolution trajectories → Reduce the search of global solutions to the Pareto frontier.

F(x1)

FS

F(x2)

Pareto solution frontier
Clustering model

Clustering model specified with Colored Petri Nets (CPN) formalism.

Interactions: Events for cluster construction.
Interaction Causal Solver model specified with Colored Petri Nets (CPN) formalism.

1. Trajectories selection.
2. Conflicts between trajectories.
3. Trajectories combination.
5: Simulation Results

- STREAM solution performance
STREAM solution performance

The complete technological framework described before, including the clustering and interaction causal solver models, has been implemented in C++.

Test:

An European ATM Scenario of 3600 real trajectories of 1 hour average-length (from TMA to TMA).

The hardware used in the simulations was a medium-range computer (10,000 MIPS) with 64GB RAM (around 40GB were used during the simulation).
STREAM solution performance

Results for the test scenario.

Simulation results

402 conflicts

97% \leq 6 A/C

reduced combinatorial size

97%
6: To conclude

- Conclusions
- Next steps
Conclusions

Air Traffic Networks are dynamic and adaptive systems, the causal analysis approach of interactions provides intelligence to explore their evolution.

Based on causal constraint propagation search, clustering and Pareto frontier exploration it is possible to downsize the combinatorial expansion problem, thus improving the computational performance and resolution capacity of the tool.

The technological framework developed under STREAM project is currently capable to efficiently find conflict free solutions for 97% of conflicts in a realistic scenario composed by 3600 trajectories over Europe.
To conclude

Next Steps

Development and implementation of metrics for selection of optimal solutions at network level.

Development performance analyses with more complex and denser scenarios.

Improve the nominal model with the introduction of uncertainties.
Danke Schön!

Questions or comments?

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jenaro.nosedal@e-campus.uab.cat
Extra material
Causal analysis and models

Causal analysis

Colored Petri Net formalism for modeling and simulation with discrete events.

CPN model makes it possible to determine:

All the system states that can be reached starting from a certain set of initial system operating conditions.

The transition sequence to drive the system from an specific initial state to a desired end state.

Complex systems are represented by:

Places

Transitions

Arc expressions

Colors

State vectors

![Diagram of a Colored Petri Net (CPN) model]
### Description.

<table>
<thead>
<tr>
<th>Colors</th>
<th>Description</th>
<th>Definition</th>
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<tr>
<th>Places</th>
<th>Colors</th>
<th>Description</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>conflict</td>
<td>nc, ax, ay, c</td>
<td>The tokens placed here correspond to all the conflicts (interactions between pairs of aircraft) of the global scenario or system.</td>
<td></td>
</tr>
<tr>
<td>ac</td>
<td>ax, mx, ay, my</td>
<td>The tokens placed here correspond to all the aircraft in the global scenario or system.</td>
<td></td>
</tr>
<tr>
<td>s</td>
<td>s</td>
<td>This token is the sequence number for processing the conflicts.</td>
<td></td>
</tr>
<tr>
<td>cont</td>
<td>n</td>
<td>This token is the sequence number to assign conflicts.</td>
<td></td>
</tr>
<tr>
<td>clusters</td>
<td>nc, ax, ay, c</td>
<td>In this place, the tokens are removed from the set of conflicts once a cluster has been assigned.</td>
<td></td>
</tr>
</tbody>
</table>

#### Transitions

<table>
<thead>
<tr>
<th>Transitions</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>clustering</td>
<td>Picking of conflicts and aircraft to assign the corresponding cluster number based on the preprocessed conflicts.</td>
</tr>
</tbody>
</table>
Causal analysis and models

ICS model

Description.

<table>
<thead>
<tr>
<th>Colors</th>
<th>Definition</th>
<th>Description</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>r</td>
<td>Int 1…N</td>
<td>Sequence number</td>
<td></td>
</tr>
<tr>
<td>id</td>
<td>Int 1…N</td>
<td>Aircraft id</td>
<td></td>
</tr>
<tr>
<td>tr</td>
<td>Int 1…N</td>
<td>Trajectory id</td>
<td></td>
</tr>
<tr>
<td>k</td>
<td>Int 1…N</td>
<td>Total interactions for a trajectory</td>
<td></td>
</tr>
<tr>
<td>tx, ty</td>
<td>Int 1…N</td>
<td>Trajectory id</td>
<td></td>
</tr>
<tr>
<td>ac</td>
<td>Int 1…N</td>
<td>Aircraft id</td>
<td></td>
</tr>
<tr>
<td>n</td>
<td>Int 1…N</td>
<td>Total interactions for a trajectory</td>
<td></td>
</tr>
<tr>
<td>tc</td>
<td>Int 1…N</td>
<td>Trajectory id</td>
<td></td>
</tr>
</tbody>
</table>

Places

<table>
<thead>
<tr>
<th>Colors</th>
<th>Description</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>p1</td>
<td>r, id</td>
<td>Tokens stored here represent the aircraft involved in the scenario for which a path should be assigned and in this case are processed according to the value of r from lowest to highest.</td>
</tr>
<tr>
<td>p2</td>
<td>tr, id, k</td>
<td>The tokens stored here correspond to the feasible paths, defined for each plane and which have the number of interactions.</td>
</tr>
<tr>
<td>p3</td>
<td>r</td>
<td>This token is a sequence number</td>
</tr>
<tr>
<td>p4</td>
<td>tr, id, k</td>
<td>When depositing a token in this place it is because you chose a path for an aircraft, for further analysis of the trajectory’s compatibility with the rest of the aircraft.</td>
</tr>
<tr>
<td>p5</td>
<td>r</td>
<td>This place is assigned the following sequence and functions as a switch.</td>
</tr>
<tr>
<td>p6</td>
<td>r, tx, ty</td>
<td>In this place you have stored conflicts which identify interactions between pairs of trajectories.</td>
</tr>
<tr>
<td>p7</td>
<td>tr, id, ty</td>
<td>Here the trajectories analyzed and processed (feasible scenarios and unconflicted) are stored.</td>
</tr>
<tr>
<td>p8</td>
<td>tr, id, k</td>
<td>In this place, the trajectories discarded based on interactions with the selected paths are stored.</td>
</tr>
</tbody>
</table>

Transitions

<table>
<thead>
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<th>Explanation</th>
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</thead>
<tbody>
<tr>
<td>T1</td>
</tr>
<tr>
<td>T2</td>
</tr>
<tr>
<td>T3</td>
</tr>
<tr>
<td>T4</td>
</tr>
<tr>
<td>T5</td>
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</tbody>
</table>
### Cluster 3

#### Space State construction

<table>
<thead>
<tr>
<th>Cluster 3</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
</tr>
</thead>
<tbody>
<tr>
<td>M0</td>
<td>1'(1,16), 1'(2,17), 1'(3,18), 1'(4,19)</td>
<td>Tr’s</td>
<td>1'(1)</td>
<td></td>
<td></td>
<td>Conflict’s</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>Tr’s</td>
<td>1'(5)</td>
<td>Conflict’s</td>
<td></td>
<td></td>
<td>Sol n</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn+1</td>
<td>Tr’s</td>
<td>1'(5)</td>
<td>Conflict’s</td>
<td></td>
<td></td>
<td>Sol n+1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Reachability tree**
Problem description

In some cases intended to solve a conflict can generate other conflicts that previously did not exist.

These network effects depend on space-time interactions within the element of the system.
Problem description

Combinations of incompatible trajectories conduced by conflicts

\[ C_1 (\text{Tr}_{x_1}, \text{Tr}_{y_1}) \]
\[ C_2 (\text{Tr}_{x_2}, \text{Tr}_{y_2}) \]
\[ C_3 (\text{Tr}_{x_3}, \text{Tr}_{y_3}) \]
\[ \vdots \]
\[ C_M (\text{Tr}_{x_M}, \text{Tr}_{y_M}) \]

2^M

\[ M = \text{number of conflicts } (\text{from } 1 \text{ to } N) \]
Simulation results

Flow chart process

Complete scenario Aircraft & Trajectories & Conflicts

Clusterig

N clusters
ac/tr/nc
1 = ?/?/?
2 = ?/?/?
... 
N = ?/?/?

ICS

Several conflict free combinations

Demo synthetic scenario:
25 aircraft
17 aircraft with 12 primary conflicts, and 91 secondary and tertiary conflicts.
Simulation results

Clustering example

Complete scenario
Aircraft & Trajectories & Conflicts

Clusterig

5 clusters
ac/tr/nc
1 = 3/13/10
2 = 5/19/25
3 = 4/30/52
4 = 3/15/15
5 = 2/4/1

ICS

Several conflict free combinations

Set of conflicts for Cluster 3
Ac: 16,17,18 y 19.
TP uncertainty
Nominal trajectories are not really in conflict, but the risk of collision in case of deviation is too high (i.e. tactical ATC will consider it as a conflict).

Consider a risk-of-deviation model.
TP uncertainty

Now the route is sub-optimal but it is more robust and will reduce the workload of tactical controllers.