Algorithms in the sky: How to design an optimal airspace?

Valentin Polishchuk
Linkoping University

Agenda:
- How air traffic is different from other “traffic”
- Volume, complexity, uncertainty
- Solution approaches: be flexible, think 4D
Industry infrastructure

- Airports
  - Runways
  - Terminals
  - Ground transport interface
  - Servicing
- **Air traffic management (ATM)**
  - Communications
  - Navigation
  - Surveillance
  - Control
- Weather
  - Observation
  - Forecasting
  - Dissemination
- Skilled personnel
- Cost recovery mechanism
Industry infrastructure

- Airports
- Runways
- Terminals
- Ground transport interface
- Servicing

- Air traffic management (ATM)
  - Communications
  - Navigation
  - Surveillance
  - Control

- Weather
  - Observation
  - Forecasting
  - Dissemination

- Skilled personnel
- Cost recovery mechanism

- Airports built
- Connections decided and priced
- Tickets bought
Air traffic management (ATM)

• Given
  – (A,B) pairs
• Find
  – Paths for aircraft
• Subject to
  – safety
  – punctuality
• Minimize cost
  – fuel consumption
  – environmental impact (emission, noise)

Q: What's so hard about it?
A: Volume
US
• 60000 flights/day
• 14000 ATCs (18 ATCCs)
• 250 Airports

Europe
• 30000 flights/day
• 20000 ATCs (80 ATCCs)
• 500 Airports
Long-term view and forecast

ESRA08 - Grand Total

IFR Movements (000s)

Actual
ScA
ScC
ScC'
ScD

vLTF13 solid line
vLTF13_unc dashed line

©EUROCONTROL 2013 www.eurocontrol.int/STATFOR
Figure 8 Growth from 2005 to 2020 now forecast at 30% vs 2005 forecast of 73%
The more the merrier

**Graph Description:**
- **Y-axis:** IFR Flights Per Year in EUROCONTROL Statistical Reference Area (Million)
- **X-axis:** Years (1970 to 2030)
- **Lines:**
  - Actual
  - Scenario A
  - Scenario B
  - Scenario C
  - Scenario D

**Scenario Descriptions:**
- **Actual:**
  - Strong globalised economies;
  - Environmental issues mitigated;
  - Strong bizjet growth
- **Scenario A:**
  - Business as usual
- **Scenario B:**
  - Strong economies;
  - Environmental and other regulation;
  - Fuel costs rise
- **Scenario C:**
  - Tension between regions;
  - Weak economies;
  - Steep rise in fuel costs

**Source:**
EUROCONTROL 2004 long-term forecasts

[http://www.eurocontrol.int/statfor/gallery/content/public/forecasts/forecast_leaflet.pdf](http://www.eurocontrol.int/statfor/gallery/content/public/forecasts/forecast_leaflet.pdf)
Challenges

• Volume
Related

- Cars, trains
- Military
- Ships routing
- Data transfer

High volume…
Packets collision and loss
Separation standards

Separation loss

CD&R
Protected airspace zone (PAZ)
Protection Volume

Example of ACAS Protection Volume between 5000 and 10000 feet

http://www.skybrary.aero/index.php/Airborne_Collision_Avoidance_System_(ACAS)
Challenges

• Volume
• Safety

Separation assurance
Cars on roads:
High volume, separation requirement
Jets in the sky: Highly supervised

Code courtesy T. Myers
Workload: System constraint

Conflict Resolution workload

Coordination workload
Challenges

- Volume
- Safety
- Complexity

RVSM (2000 feet → 1000 feet):
http://www.youtube.com/watch?v=i58OteU3gZ4
http://www.youtube.com/watch?v=wlOQIUBsxRY
Airspace Sectorization Problem
Motivation

• The existing sectors boundaries
  – determined by historical effects
  – have evolved over time
  – not the result of analysis of route structures and demand profiles
• Hence the sectors are not WL balanced

• Also of the 15,000 Air Traffic Controllers, 7,000 are retiring in next few years

• Novel Partitioning : Non-static (Steiner) points
Objectives

• Design and implement efficient algorithms to compute optimal (or nearly-optimal) airspace configurations
• Devise novel methods that may assist in maximizing safe utilization of airspace
• Explore future concepts of operations

“Provide flexibility where possible and structure where necessary.”

Parimal Kopardekar (NASA Ames)
Design for Control

• Determine a mapping of controllers (or oversight processes) to flights.

• Approaches:
  – Partition airspace into sectors, other structural elements
  – Partition aircraft (e.g., into “gaggles”)
  – (Possible) future: ATC/flight
    • full en-route portion
Designing Configuration Playbooks

• **Goal:** Identify good configurations corresponding to mined historical data scenarios

• **Rationale:** Certain traffic patterns may tend to repeat over different time intervals, in response to certain events (e.g., weather impact)

• **What time intervals?**  **What events?**

• Clustering, mining trajectory data
Clustering Trajectories: Discovering Dominant Flows

[A Weighted-Graph Approach for Dynamic Airspace Configuration 2007]

[Algorithmic Traffic Abstraction and its Application to NextGen Generic Airspace 2010]
Airspace Sectorisation using Constraint-Based Local Search 2013
State of the art
EU:
- 36 ANSPs
- 9 FABs
EU: establishing FABs is more of political decision than RnD Q

DK-SE FAB assessment @ Entry Point North air traffic services Academy, Sturup

Conclusions

• Not much benefits (no harm either 😊)
• DK-SE: good cooperation before FAB
• Improvements visible where things are bad?
  – “Bring competence to the European level” lol

PBN Implementation Handbook: This kind of implementation envisages various lower limits and is already in use in areas such as Denmark, Sweden, Portugal, Ireland i.e. European periphery and lower density.
Resectorization

- US: Dynamic Airspace Configuration (DAC)
- EU: dynamic Demand & Capacity Balancing (dDCB)  
  [http://www.youtube.com/watch?v=RH6ZXdKsQbM](http://www.youtube.com/watch?v=RH6ZXdKsQbM)
An example of "cracking" style Gerrymandering: where the urban (and mostly liberal) concentration of Columbus, Ohio is split into thirds and then each segment outweighted by attachment to largely conservative suburbs.

A gerrymandered Congressional District, the 11th CD of CA (now occupied by Democrat Jerry McNerney), drawn to favor Republican Richard Pombo. While the Danville area is a traditional Republican stronghold, Morgan Hill is not, and that largely Democratic district was added to obtain the proper population numbers for the 11th after Livermore was assigned to the 10th at the behest of the incumbent Democrat (Ellen Tauscher), since it contains the Lawrence Livermore National Laboratory (located near the "580" shield) and she sits in the House Energy Committee. The 10th CD is immediately north of the 11th in Contra Costa and Solano Counties. See the California 11th congressional district election, 2006 for an unexpected result that overcame this gerrymander.
Challenges

• Volume
• Safety
• Complexity
• Uncertainty

Modeling: Experts interaction

- Separation assurance
- Human-in-the-loop
- Contingency plans
1. RISK OF OPERATIONS WITHOUT TRANSPONDER OR WITH A DYSFUNCTIONAL ONE
Operations without transponder or with a dysfunctional one constitute a single threat with a potential of “passing” through all the existing safety barriers up to “see and avoid”.

2. LANDING WITHOUT CLEARANCE
For various reasons, aircraft sometimes land without ATC clearance resulting in Runway Incursions that are often only resolved by ‘providence’.

3. DETECTION OF OCCUPIED RUNWAY
Some Runway Incursion incidents could have been prevented if controllers had had better means to detect that the runway was occupied at the time of issuing clearance to the next aircraft to use the runway.

4. “BLIND SPOT” – INEFFECTIVE CONFLICT DETECTION WITH THE CLOSEST AIRCRAFT
Loss of separation “Blind Spot” events are typically characterised by the controller not detecting a conflict with the closest aircraft. They usually occur after a descent clearance and in the context of a rapidly developing situation – often when the conflicting aircraft are 1000ft and 15 nm apart.

5. CONFLICT DETECTION WITH ADJACENT SECTORS
Losses of Separation in the En-Route environment sometimes involve “inadequate coordination” of clearance with an adjacent sector. These typically involve either an early (premature) transfer of control to or from the neighbouring sector.
Boundary crossing: Communication between ATCs
Boundary crossing: Communication between ATCs
Conforming flow

But wait a minute…
Q: What is rigid: routes or sectors?
A: None!

Feedback loop: Iterative adjustment of routes to sectors and sectors to routes
Flexible Use of Airspace (FUA): conditional routes, temporary areas,… 

**ATM systems**

- Airspace management
  - design skyways
- ATFCM
  - flight plans - available capacity
- ATC
  - lead through

**Non-rigid sectors**

**dDCB, DAC**

**Non-rigid network**

**FF, FRA, Direct routes**

**FUA: ATFCM**

**Flow Management**

**Are we ready, algorithmically?**
Research so far:

State-of-the-art techniques for 2 separate problems
Problem 1. Sectorization

- Flener and Pearson ’13, Automatic Airspace Sectorisation: A Survey
- Yousefi and Donohue ’04, Temporal and spatial distribution of airspace complexity for air traffic controller workload-based sectorization
- ...

[Map of the United States with sectorized regions]
Problem 1 (cont.):

- Geometric Algorithms for Optimal Airspace Design and Air Traffic Controller Workload Balancing [ALENEX, ACM Journal on Experimental Algorithmics’09]
- Flow conforming operational airspace sector design [ATIO’10]
- Balanced Partitioning of Polygonal Domains [PhD thesis’13]
- …
Problem 2. Traffic flow planning
Problem 2 (cont.). Theory

Paths and flows in polygonal domains:

MaxFlow/MinCut [Mitchell, SoCG’89]

Flow decomposition [Mitchell, P, SoCG’07]

Menger’s Thm, Disjoint paths [Arkin, Mitchell, P, SoCG’08]

MinCost (monotone) flow [Eriksson-Bique, P, Sysikaski, SoCG’14]

Kth shortest path [Eriksson-Bique, Hershberger, P, Speckmann, Suri, Talvitie, Verbeek, Yıldız, SoDA’15]
The Grand Challenge

Simultaneous optimization

Sectors

+ 

Traffic flows

Solve both Problems 1 and 2
Guinea pig: Terminal airspace

Arrival/departure trees

Sectors
State of the art: Modeling

Why one airspace configuration is better than another?

Objective criteria (even subjective hard to express)
THE PROBLEM

“Aircraft arrivals get delayed by unscheduled airspace closure.”
• Optimal DESign of Terminal Airspace

• Linköping University + LFV (Luftfartsverket) + reference group

• Funding for 2015--2018
  – Swedish Gov. Agency for Innovation Systems
Optimal design of terminal airspace

Scandinavian-based case study focuses on vicinity of airports where the most congestion happens, capacity has its bottleneck and delays occur.

Projected growth of air traffic industry is a sign of healthy economic and technological development, as well as an unprecedented challenge to mankind. Since a great deal of air traffic congestion happens during the initial and final phases of flights, super-dense operations (SDD) in terminal areas are a recurring topic in air traffic research. Case in point: Three out of four presentations in the Capacity and Airspace Design session at 2015 SESAR (Single European Sky ATM Research) Innovation Days (the main vehicle through which SESAR disseminates the results of its long-term and innovative research program and which has become a landmark event in the European research calendar) were about terminal maneuvering areas (TMAs).

By Valentin Polishchuk
PhD position

• Linköping University
• 2016--2019
• Skills: Optimization, data handling
  – Air traffic expertise: in-house

• Practice-oriented
  – Theory @ nights & weekends