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

Valentin Polishchuk
Linkoping University

Agenda:
• How air traffic is different from other “ Traffics”
• 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

- Air traffic management (ATM)
  - Communications
  - Navigation
  - Surveillance
  - Control
- Weather
  - Observation
  - Forecasting
  - Dissemination

Skilled personnel
Cost recovery

- 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

The more the merrier

**Graph Description**

- **Actual**: The actual number of IFR Flights per year in the EUROCONTROL Statistical Reference Area (in Million).
- **Scenario A**: Strong globalised economies; Environmental issues mitigated; Strong bizjet growth.
- **Scenario B**: Business as usual.
- **Scenario C**: Strong economies; Environmental and other regulation; Fuel costs rise.
- **Scenario D**: 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)
Figure 8: Growth from 2005 to 2020 now forecast at 30% vs 2005 forecast of 73%
Challenges

- Volume
Related

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

Internet

High volume…
Packets collision and loss
Separation standards
Protected airspace zone (PAZ)

PERSONAL SAFETY BUFFER

MINIMUM SEPARATION STANDARD

PROCEDURAL SAFETY BUFFER

SURVEILLANCE UNCERTAINTY

HAZARD ZONE

Protection Volume

Time criterion (300 kt closure rate)

Altitude criterion

Example of ACAS Protection Volume between 5000 and 10000 feet

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

• Volume
• Safety
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

Separation assurance
Human-in-the-loop
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]
Flow conforming operational airspace sector design 2010
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
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
TOP 5 ATM OPERATIONAL SAFETY PRIORITIES FOR 2013:

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” – INEFFICIENT 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 network

FF, FRA, Direct routes

Non-rigid sectors
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 showing sectors]
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]
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)
Optimizing airspace closure with respect to politicians' egos.
ODESTA Project

- Optimal DESign of Terminal Airspace

- Linköping University + LFV (Luftfartsverket) + reference group

- Funding for 2015--2018
  - Swedish Gov. Agency for Innovation Systems
PhD position

- Linköping University
- 2015--2018
- Skills: Optimization, data handling
  - Air traffic management expertise: in-house

- **Practice-oriented**
  - Theory @ nights & weekends