Decentralized Path Planning For Air Traffic Management

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Outline

- **Background**
  - National Aviation System
  - Needs for Next Generation Air Traffic Management Systems
  - Air traffic control system from a control perspective

- **Hierarchical Decentralized Flight Planning**
  - Problem Formulation
  - Solution Procedure
  - Advantages Over the Current Planning Procedure
  - Simulation Results

- **Conclusions**
Motivations

National Aviation System is a large-scale Cyber-Physical System

14,500 traffic controllers, 4,500 safety inspectors, 5,800 technicians,
19,000 airports, 600 traffic control facilities, 50,000 flights each day

Physical components: large number of aircrafts, equipment and human agents

Cyber components: traffic & weather measurements, computation, prediction and communications.

Research Perspectives: FAA, traffic controllers, airline companies

My focus: System-level modeling and optimization methods for en-route traffic management and terminal area operations
The Needs for Next Generation ATM

Air traffic delays in 2007 has cost US economy $41 billion
- fuel: 740 million gallons, carbon dioxide: 7.1 million tons

Staffing Emergency in major ATC facilities across the nation

As of 2008:
- 11,077 certified controllers—lowest level in 15 years
- 10,000 are expected to retire before 2015
- Oakland Center: training ratio: 2-1 vs 12-1 in 2005
  operational error: 30 vs 14 in FY07
- planning to hire 12,000 before 2018

Jan, 2010
- Certified TRACONs controllers plummeted more than 25% in the last six years
- New York reaches post-1981 low

Situation gets much worse due to the expected two- to three-fold increase in air traffic

Need to modernize, (semi)-automate the ATC system NOW
Challenges

- Legacy systems
  - require continuous operations
- Critical Safety Standards
- Large number of competing users
- Human in the loop
  - fear of new working conditions
  - TRACON controllers are still using the same Radar system as they did in 1960s.

- Gradual change
- Respective the structure of the system
Background of ATM
Hierarchical Control Structure of ATM

FAA-ATM

Weather forecast

Flight tracks

AOC/Pilot clear hold plans FMS

Switching control

Spatially distributed local controllers
Towers, TRACONs, Centers, Sectors

Aircrafts
A major problem: lack of information exchange

- User does not know the traffic information
- only weather briefing is available before taking off
- FAA/ATM does not know users’ preferences

Consistent situation awareness is needed
With the traffic information

- User can find the best path (according to its specific preference) to avoid traffic according
- Decide whether to delay the flight or take the best available detour
Towards a New Flight Planning Framework

A framework with planning algorithm

- deal with large number of aircrafts in real time
- consider both weather and traffic restrictions, guaranteed safety with certain “optimality” for the nominal trajectories
- 4D trajectory (3D + time)
- practically feasible
Graph of Airways

- Spacial graph $G_s = (V_s, E_s)$
  - vertices (nodes): waypoints (Navigation aids, airports, “virtual” waypoint)
  - Edges: airways of jetways

Space-Time Graph $G = (V, E)$

$V = \{(x, t) : x \in V, t = 1, \ldots, N\}$

- Nodes are disconnected within the same layer
- Edges between layers determined by the dynamics of the aircraft
Planning Under Weather Uncertainty

Link weight ("length"):

\[ l(v_i, v_j) \]

- Fuel cost;
- Expected turbulence based on weather forecast;
- Infinite when crossing forbidden weather zone

Single aircraft path planning with weather data is a shortest path problem

Departure nodes:
\[ z_0 = \begin{bmatrix} x_0 \\ t_0 \end{bmatrix} \]

Destination:
\[ z_f = \begin{bmatrix} x_f \\ t_f \end{bmatrix} \]

Latest arrival time

\[ J(z_0, u; \lambda) = \phi(z_{t_f}) + \sum_{t}^{t_f-1} l(z_t, u_t) \]

Need to handle sector capacity constraints

\[ \sum_i 1_{s_j}(x^i_t) \leq \text{max sector counts} \quad \forall t, j \]
Planning with Traffic Restrictions

- Current way for Traffic control:
  - speed variation, ground delay program, holding pattern, vector for spacing, redirecting

- Traffic Regulation Function: \( \lambda(j,t) \)

\[
\lambda(j,t) = \begin{cases} 
0 & \text{sector } j \text{ open over } [t, t+1] \\
\infty & \text{otherwise}
\end{cases}
\]

- Each aircraft tries to minimize its own cost subject to the traffic rules specified by FAA

\[
J_i(z^i_0, u^i; \lambda) = \phi(z^i_{t_i}) + \sum_t [l(z^i_t, u^i_t) + \sum_j \lambda_{j,t} \cdot 1_{S_j}(z^i_t)]
\]

infinite link cost if crossing forbidden weather zone
infinite price if sector “sold out” over certain time period

Safety and satisfy all sector constraints
Decentralized Path Planning Algo

Planning /Rerouting Algorithm

1. Get weather data and traffic restrictions $\lambda$
2. Solve the shortest path problem
3. File the plan
   • ATM approve and update traffic rules $\lambda$

- $\lambda(j,t)$ is a tool for the ATM to regulate traffic
  - the above is First-Come-First-Serve rule
  - can achieve certain “fairness” by using the historical data
  - nominal plans are safe but capacity buffer is needed to cope with uncertainty
Distinctions and Advantages

• Traffic Flow Management
  • Bertsimas 98’, Waslander 08’

• Path Planning with Weather Uncertainty
  • Nilim (ACC03), Pannequin (GNC07), Kamgarpour (CDC10)
  • mostly centralized and only works for a small number of aircrafts
  • require same taking off time
  • does not consider traffic information

• Distinctions of our methods
  • decentralized
    • used for the entire NAS or different subregions of NAS
  • planning considering weather and traffic
  • 4D trajectory (3D + time)
  • guaranteed safety with certain “optimality”
  • respect current planning procedure, practically feasible in the near future
Simulation Results I

• 30 sectors, 2 deterministic weather zones, 12 airports, 100 flights
• randomly select departure and arrival airports, random departure time
• plans are made and filed in the order of departure time
Simulation Results II

Operational Evolution Plan (OEP) Airports
-- about 74% passengers and 69% operations

Flight schedules among OEP airports
-- Aug. 24, 2005

- We consider 34 OEP airports (except HNL)
- Consider flights depart between 7am EST and 5pm EST
- Proof of concept: the framework works for realistic traffic patterns and realistic number of flights
  - no weather data and no comparison with real flight tracts
  - assume all flights try to minimize travelling distance
  - uniform grids corresponding to roughly 3 minutes flight time
Unconstrained Flight Plans
Traffic Regulation Results

Without constraints,
• traffic concentrates on a few sectors
• the majority of the rest under-utilized
• 40 sectors have counts above 8 at some time

With traffic control
• meet capacity constraints at all time
• traffic in congested sectors diffused into neighbors
• increase 0.71% travel time
Result for Sector ZTL15

Satisfy capacity at all time
The new sector count does not always stay below the old one
Conclusion

- Proposed a Hierarchical Decentralized Flight Planning Framework
- Respect user’s preference and has potential to reduce delay and energy
- Future Work
  - Further validating the framework using realistic weather data
  - compare the fuel savings as compared with the real flight plans
Thank you very much!