A Distributed Framework for Traffic Flow Management in the Presence of Unmanned Aircraft

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Background: Congestion leads to delays

Congestion is caused by capacity-demand imbalances
  • Periods of reduced capacity (e.g., bad weather)
  • Periods of high demand and volume

Delays have significant economic impact
  • Domestic flight delays in US estimated to cost $41B/year\(^1\)
  • Enroute ATFM delays + route extensions in Europe estimated to cost €3.7B/year\(^2\)

Air Traffic Flow Management (ATFM)
  • Process that strategically allocates airspace and airport resources in order to mitigate impact of delays

\(^1\) Joint Econ. Committee, US Senate, 2008
\(^2\) EUROCONTROL Perf. Rev. Comm., 2008
Evolving demand

Increased commercial air carrier operations, unmanned aircraft, and on-demand mobility services
Motivation: Need for ATFM transformation

Air Traffic Flow Management must transform to meet challenges posed by evolving demand

- **Autonomy**: Each aircraft (operator) should be able to determine its own trajectory based on internal costs/tradeoffs
- **Safety through constraint satisfaction**: Trajectories should satisfy dynamic capacity constraints, geofences, etc.
- **Efficiency**: Maximize utilization of congested resources
- **Scalability**: Manage significantly larger numbers of aircraft, as well as more dynamic/unpredictable demand
- **Robustness**: Handle reasonable levels of inaccurate/obsolete information
- **Equity and incentives**: Fair allocation of resources among competing aircraft operators
Capacity constraints cause large delays
Flight connectivity poses a challenge

Only 6% of aircraft in the US fly just one flight per day\textsuperscript{[3]}

- Results in delay propagation
- Rolling horizon optimization is suboptimal

\textsuperscript{[3]} Bureau of Transportation Statistics, 2016
\textsuperscript{[4]} EUROCONTROL CODA, 2016
Airport and airspace capacities

Airport arrival/departure rate tradeoffs (capacity envelopes)
  • Depend on visibility, wind, etc.

Airspace is divided into sectors subject to max occupancy limits
  • Depend on geometry, traffic patterns, workload, weather, etc.

Trajectory-Based Operations (TBO)

Use of a 4D trajectory (set of points in space-time) in order to describe the most likely path of an aircraft[7]

Trajectory then used to coordinate decisions between different facilities, agents, and time-scales

• Used to ensure tactical safety (deconfliction of trajectories)
• A trajectory implicitly requires the allocation of resources
  • Can be used to plan and coordinate resource allocations
  • TBO can be leveraged for enhancing ATFM, and for integrating heterogeneous types of demand (manned and unmanned) in the resource allocation process

Air Traffic Flow Management problem

Given set of flights with assigned aircraft and capacity profiles, identify a trajectory for each aircraft to maximize system-wide benefit, and satisfy operational constraints

• Constraints:
  • Airport/airspace sector capacity limits including geofences
  • Flight connectivity and turn-around times
  • Maximum/minimum transit times and speeds

• Control actions:
  • Ground/airborne delays
  • Rerouting
  • Cancellations

## Prior research on ATFM

| Reference                  | Control                                           | Scale                                                                 | Horizon/discretization | Run times |
|----------------------------|---------------------------------------------------|                                                                      |                        |           |
| Maugis (1995)              | Ground holds; cancellations                       | 4,743 flights; 1,153 sector-saturated time periods (no airport capacity limits) | 1 day/ 5 min          | 2+ hr     |
| BERTSIMAS & STOCK-PATTERSON (1998) | Ground/air holds                              | 1,002 flights; 18 airports; 305 sectors                          | 8 hr/ 5 min          | 8+ hr     |
| BERTSIMAS & STOCK-PATTERSON (2000) | Ground/air holds; limited rerouting              | 71 flights; 4 airports; 42 sectors                              | 8 hr/ 5 min          | 4 min     |
| BERTSIMAS ET AL. (2011)    | Ground/air holds; rerouting network               | 6,745 flights; 30 airports; 145 sectors                           | 8 hr/ 15 min         | 10 min    |
| WEI ET AL. (2013)          | Aggregate model; air holds                        | 3,419 flights; 284 sectors                                      | 2 hr/ 1 min          | 21 min    |
| BALKRISHNAN & CHANDRAN (2014) | Ground/air holds; unrestricted rerouting network; cancellations | 17,500 flights; 370 airports; 375 sectors                         | 24 hr/ 5 min         | 5 min     |
Trajectory definition

Sequence of node-time combinations representing flight path of an aircraft (time is discretized into 1-min intervals)
maximize total benefit of selected trajectories

s.t. Select only one trajectory for each aircraft

Sector capacity constraints

Airport capacity envelope constraints

Binary variable indicating selected trajectory
Solution process

Very large-scale Integer Program

LP relaxation (Restricted Master Problem) solved using column generation

- Sub-problems solved independently for each aircraft (“tail”)
- Formulated as longest-path problem on a DAG
- Solved using dynamic programming
- Enables parallel implementation

Effective heuristic to obtain bounds and assess optimality gap

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Schematic of solution process

Flight schedules; initial flight plans; capacity forecasts; operational constraints

Start

Check feasibility \rightarrow Generate prices

Prices \lambda_{s,t} \mu_{n,t,j}

Yes \rightarrow New trajectories?

Sub-problem 1 \rightarrow x_1, \rho_1

Sub-problem 2 \rightarrow x_2, \rho_2

Sub-problem \(L\) \rightarrow \ldots \rightarrow x_L, \rho_L

Trajectories + Valuations

Distributed nodes

Select optimal trajectories \rightarrow End

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Distributed Resilient Framework for TBO (DRIFT)
Computational experiments: Projected demand (2030)

Manned air traffic demand from FAA’s SWAC simulation[8]

- ~40,000 flights within the US; ~25,000 unique airframes
- Assumes two types of constraints
  - 955 sectors, with same capacities as today
  - Airport capacity envelopes (2030 improvements)

Realistic UAS dataset[9]

- ~35,000 flights + varying missions (typically smaller airports)
  - Communications, fish spotting, cargo, etc.
  - Altitudes: 100-60,000 ft
- No alternative routing for unmanned aircraft
- Incorporate geofencing where needed

~50 combinations of costs, schedules and capacities

[9] Wieland et al., 2013
ATFM in 2030

- Optimize ~77K flights (≤ 0.1% of optimal) in under 4 min
- 1-minute trajectory fidelity, 5-minute constraint fidelity
- “Rolling horizon” mode: ~6-8 hr with ~25K flights: < 1 min
## Comparison to prior work

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<td>76,900 flights; 2,400 airports (+4,000 UAS ones); 955 sectors</td>
<td>24 hr/1 min</td>
<td>4 min (Linux X-Large machine w/ 40 cores on AWS)</td>
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Geofencing

Certain classes of aircraft may be restricted from entering some portion of airspace at some time\(^{[10]}\)

- Implemented via the pricing signals

\(^{[10]}\) D’Souza et al., 2016
Summary

Distributed framework for large-scale ATFM

- Addresses challenges posed by UAS (autonomous trajectory generation, geo-fencing, dynamic/unscheduled demand)
- Scalable
  - ~77K aircraft over 24-hr/1-min trajectory discretization in < 4 min (≤ 0.1% of optimal)
  - ~77K aircraft over 24-hr/1-min trajectory discretization in < 7 min (≤ 0.01% of optimal)
  - Rolling horizon implementation with 8-hr planning window (2-hr overlap and freeze window) in < 1 min
- Accommodates concepts such as Best-Equipped, Best-Served\(^\text{[11]}\)
- Can be extended to stochastic ATFM (with scenario trees)\(^\text{[12]}\)
- Investigating mechanisms for ensuring equity

Accessible via API

- Contact [hamsa@resilientops.com](mailto:hamsa@resilientops.com) if interested

\(^{[11]}\) Churchill et al., 2011
\(^{[12]}\) Balakrishnan & Chandran, 2014