MIT Lincoln Laboratory Modeling & Simulation Activities for Air Traffic Management

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US-Europe Technical Interchange Meeting, 16-17 October 2019

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Outline

• Lincoln background & modeling/simulation overview

• Modeling & simulation deep dives
  – ATM recommender system
  – Trajectory Based Operations weather testbed
MIT Lincoln Laboratory
DoD Federally Funded Research and Development Center

Mission:
Technology in Support of National Security

Key Roles:
System architecture engineering
Long-term technology development
System prototyping and demonstration

Mission Areas:
- Air and Missile Defense
- Homeland Protection
- Air Traffic Control
- Communication Systems
- Advanced Technology
- Space Control
- ISR Systems and Technology
- Tactical Systems
- Cyber Security
- Engineering
Lincoln Development Model for ATC Technology Prototypes

- Understand stakeholder needs
- Identify problems & diagnose causes
- Apply capabilities to address
- Prototype solutions & tech transfer
**Historical Impacts of Lincoln ATC Prototypes**

<table>
<thead>
<tr>
<th>Year</th>
<th>System Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>Mode S beacon surveillance</td>
<td>• Unisys produced 135 for major US airports • Basis for TCAS and ADS-B 1090ES</td>
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<tr>
<td>1980</td>
<td>ASR-9 primary radar (WSP &amp; 9-PAC)</td>
<td>• Northrop Grumman produced 135 for major US airports</td>
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<td>1990</td>
<td>Corridor Integrated Weather System</td>
<td>• First operational SWIM Segment 1 capability</td>
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<td>2000</td>
<td>Route Availability Planning Tool</td>
<td>• Deployed to TFMS at Chicago, Philadelphia, Potomac, New York</td>
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<td>2010</td>
<td>Integrated Terminal Weather System</td>
<td>• Raytheon produced 45 systems covering 45 airports</td>
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<tr>
<td>2020</td>
<td>Traffic Alert and Collision Avoidance System</td>
<td>• Produced internationally • Mandated on over 20,000 aircraft</td>
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<tr>
<td>2020</td>
<td>Terminal Doppler Weather Radar</td>
<td>• Raytheon produced 45 for US airports at highest risk for wind shear hazard</td>
</tr>
<tr>
<td>2020</td>
<td>Runway Status Lights</td>
<td>• Saab Sensis deploying to 17 airports</td>
</tr>
</tbody>
</table>

**Timeline**

- **1970**: Mode S beacon surveillance
- **1980**: ASR-9 primary radar (WSP & 9-PAC)
- **1990**: Corridor Integrated Weather System
- **2000**: Route Availability Planning Tool
- **2010**: Integrated Terminal Weather System

**Technology:***
- **1970**: Mode S beacon surveillance
- **1980**: ASR-9 primary radar (WSP & 9-PAC)
- **1990**: Corridor Integrated Weather System
- **2000**: Route Availability Planning Tool
- **2010**: Integrated Terminal Weather System

**Manufacturers:**
- **Unisys**
- **Northrop Grumman**
- **Raytheon**
- **Saab Sensis**

**Applications:**
- **1970**: Mode S beacon surveillance (produced 135 for major US airports)
- **1980**: ASR-9 primary radar (produced 135 for major US airports)
- **1990**: Corridor Integrated Weather System (produced internationally)
- **2000**: Route Availability Planning Tool (produced on over 20,000 aircraft)
- **2010**: Integrated Terminal Weather System (produced 35 systems covering 45 airports)

**Deployment:**
- **1970**: Mode S beacon surveillance (produced 135 for major US airports)
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Lincoln ATC Simulation and Development Facilities

Live data streams and archives

- Air Traffic Surveillance Data
- Flight Plan Data
- Traffic Flow Management System (TFMS)
- Satellite & Lightning
- Weather Radars
- Surface Observations
- Numerical Models
- Lincoln Mode S Sensor (MODSEF)
- Flight Test Aircraft

Surveillance Laboratory

UAS Ground Control Station

Aircraft Performance & Virtual Cockpits

Lincoln Tower Simulator

AirTOp/Serious Gaming Simulation Engine

Aviation Environmental Tool Suite

Flight Management System & Avionics Lab

Weather Systems Integration Lab
• Web-based interactive scenario training & simulation capability
• Realistic data sources
  – CIWS-based weather & capacity algorithms
  – Airline flight schedules
• Models for several TMI decisions
• Operational metrics
  – FSM, AERO, Airline
• Configurable displays & metrics to respond to changing needs
• Authoring tools enable non-programmers to create scenarios

**NASPlay is an all-in-one Planning, Simulation, Playback, Training System**
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  – Trajectory Based Operations weather testbed
Background and Approach

• Collaborative Trajectory Options Program (CTOP) assigns delay and/or reroutes around one or more Flow Constrained Area-based airspace constraints in order to balance demand with available capacity.

• NASA’s Integrated Demand Management (IDM) program is exploring ways to use CTOP to precondition demand into time-based metering programs at airports in the Northeast United States.

• Estimates from strategic decision support systems (TFMS) may be inconsistent with delivery capability of tactical decision support systems (TBFM).

• Good estimates of airport/airspace capacity are needed to effectively control demand to the appropriate levels.

• Proposed Approach
  – Leverage reinforcement learning and integer programming to estimate airport and terminal airspace capacity.
  – Use fast-time simulation to evaluate performance of algorithms.
Simulation Details

**Inputs**
- CIWS/CoSPA Weather
- Flight Schedule
- Weather-Based Capacity Constraints
- Sector-Based Constraints
- Aircraft Separation Constraints
- Runway Separation Constraints

**NASPlay Simulation**

**Outputs**
- Ground Delay
- Airborne Delay
- Number of Arrivals
- Airborne Holding
- Diversions
- Cancellations
Simulation Details

NASPlay provides high fidelity simulation of national airspace but it is difficult to generate good solutions due to large search space.

Can we use optimization methods to expedite the process?

Inputs
- CIWS/CoSPA Weather
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Outputs:
1. Ground Delay
2. Airborne Delay
3. Number of Arrivals
4. Airborne Holding
5. Diversions
6. Cancellations
Case Study

- May 15, 2018: Airspace capacity in Northeast was compromised due to weather

- Case study: Estimate airport capacity at Newark Liberty International Airport (EWR) from 11:00am to 00:45am GMT

- NASPlay Baseline: no control strategy ("do nothing")
  - 388 aircraft landed in total (number of Arrivals = 34-40 per hour)
  - 161 aircraft accrued at least 15 minutes of holding before landing

- Goal: Find AFPs that achieve comparable throughput but reduce holding

AFP = Airspace Flow Program
Hourly rates need to be specified for each of three FCAs

Each solution has 30 dimensions: (3 FCAs) x (10 hr)

Optimization covers a 30-dimensional space
ε-Greedy Approach

If sampling entire space were tractable, we would simulate all possible points and find global optimum.

Sampling entire space is intractable due to:
- Size of search space
- Time required to run each simulation

Alternative is to search for optimum using combination of two strategies:

**Exploration**
Find new point by random sampling

**Exploitation**
Find new point by fitting model $f$ to current sample points and taking optimum

For iteration $i$, $P(\text{exploration}) = \frac{5}{4 + i}$

* Earlier iterations emphasize exploration
* Later iterations emphasize exploitation
Reinforcement Learning (RL) Details

• Run 5 iterations with random sampling to initialize RL algorithm
• Run subsequent iterations with RL-selected samples
  – RL algorithm selects exploration or exploitation
  – If exploitation is selected:
    • Surrogate model is generated using gradient tree boosting
    • Surrogate model predicts number of arrivals for 100,000 randomly sampled points
    • Choose sample point that maximizes predicted number of arrivals while limiting holding
• “Do Nothing” scenario resulted in 388 arrivals and 161 flights held for greater than 15 minutes

• We’d like to achieve a comparable throughput level with lower holding
• Typically, AFP programs identified through random sampling will reduce holding at the expense of the number of arrivals
Results

- Algorithm-based samples perform considerably better than random sampling
  - The $\varepsilon$-greedy algorithm outperforms other candidate approaches

AFP = Airspace Flow Program
IP = Integer Programming
IPRE = IP with Random Exploration
Reinforcement learning method demonstrates that effective balance of flight demand and airport capacity is achievable

- Optimal strategy results in 98% of the original throughput with 76% reduction in holding
- Airport can sustain 33-41 arrivals/hr even when compromised with significant convective weather
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Key Technical Challenges for the Future Air Traffic Control Environment

Trajectory Based Operations (TBO)
- Precise, multi-hour look-ahead trajectory predictions
- ATC automation systems to set appropriate time targets
- Aircraft automation systems to meet time targets

New Entrants
- Weather info tailored for emerging CONOPS for range of new entrants
- Decision support for safe, equitable airspace access across stakeholders

Data-Driven Decision-Making
- Algorithms to leverage rapidly expanding operational data sets
- Decision support tools to enhance collaborative decision-making between stakeholders

TBO is a critical enabler for enhanced efficiency, but requires foundational research and development to ensure operations will be robust and effective
Weather Impacts on TBO

TBFM = Time Based Flow Management
TSAS = Terminal Sequencing And Spacing

TBFM has no knowledge of convective weather along aircraft routes resulting in inaccurate schedule at the meter fix.

Actual trajectory deviates around convection.

Enroute ATC Automation

TSAS winds only updated every hour, possibly resulting in erroneous “bubble” locations presented to controllers, especially during compression.

Critical need to study integration of convective and compression effects into TBO.
Impacts on TBO

- TBO provides biggest benefits to the FAA during times of reduced capacity resources in the NAS

- Short term implementation of TBO (iTBO) relies on:
  - Spacing J-rings provided by TSAS in terminal airspace, and
  - Time-based metering using TBFM in enroute airspace

- TSAS’ J-rings provided to controllers for spacing are based on hourly forecasts

- TBFM’ schedule provided to controllers is calculated with winds updated every two hours

- TBFM trajectory modeler has no knowledge of convective WX (current or forecast) and metering is not used when convective WX exists

Critical need to study integration of convective and compression effects into TBO
Lincoln TBO/Weather Testbed Vision

• TBO testbed to enable flexible modeling and simulation to evaluate the impact of convective and compression effects
  – Incorporate key automation systems including Time-Based Flow Management (TBFM) and Terminal Sequencing and Spacing (TSAS)
  – Evaluate the use of advanced weather models (CWAM) into TBFM
  – Evaluate the use of aircraft-provided data into TBFM and TSAS:
    • Mode S EHS interrogation data (Mach, CAS, V/S, derived winds)
    • ADS-B Ver 3 future optional wind data

• Targeted studies to answer fundamental research questions on how key TBO systems perform during convective weather conditions:
  – Wind models accuracy impact on TBFM and TSAS performance to test aircraft-derived data into Time-Based Metering
  – Convective weather models impact on TBFM trajectory modeler performance
Vision of integrating FAA operational systems and advanced weather models in lab environment.
Exercise Testbed to Quantify TBFM/TSAS Compression Impact

**TBFM impact:**
1. Identify TBFM operational sites
2. Identify high compression day(s)
3. Identify current TBFM winds and aircraft-sensed winds from Mode S EHS data for the selected day(s)
4. Evaluate TBFM schedule accuracy with current and sensed winds

**TSAS impact:**
1. Identify TSAS operational sites
2. Identify high compression day(s)
3. Identify current TSAS winds and aircraft-sensed winds from Mode S EHS data for the selected day(s)
4. Evaluate TSAS speeds and slot markers with and without sensed winds

Criticality of wind sources into TBO systems will be assessed with these analyses

NASA has integrated CWAM with TBFM in a concept that requires Traffic Management Coordinators (TMCs) to review weather routes proposed by the system called DRAW.*

MIT LL will evaluate:

- Alternative algorithmic implementation(s) of CWAM weather polygons into TBFM Trajectory Synthesizer (TS)
- Stability of the resulting TBFM schedule of algorithmic CWAM integration approach(es)
- Perform benefits analysis of the integration

Feasibility of TBFM metering during convective weather will be evaluated with this analysis.

Isaacson, et al, Laboratory Evaluation of Dynamic Routing of Air Traffic in a En Route Arrival Metering Environment, AIAA Aviation, 2018
Summary

• Exploring the impacts of integrating different critical weather effects into TBO

• Wind data accuracy
  – The impact of different wind data sources on TBO operational systems needs to be evaluated to quantify the impact on the key time schedule information provided to the controller

• Convective weather data
  – Currently critical TBO systems have no information on convective weather cells affecting the accuracy of the trajectory prediction and therefore the usability of the systems

The MIT LL TBO weather testbed will support research on these fundamental TBO open questions
Disclaimer

This material is based upon work supported by the Federal Aviation Administration under Air Force Contract No. FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Federal Aviation Administration.

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