Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities

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Seventh Framework Programme
Research Project in Collaboration With:

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National Aerospace Laboratory (NLR)
Ecole Nationale de l’Aviation Civile (ENAC)
Deutsches Zentrum für Luft- und Raumfahrt (DLR)
Outline

1. Introduction

2. Metropolis Setting for 2050 and Beyond

3. Design of Airspace Concepts

4. Simulation Development and Experiment Design

5. Results

6. Conclusions
1. Introduction
Unmanned Aerial Vehicles (UAVs)
A Multitude of Possibilities

Remote Sensing

Internet Broadcasting

Package Delivery

Search and Rescue

Peace Keeping / Military

And many more...
Personal Aerial Vehicles (PAVs)
Solution to Traffic Congestion Problems?

ConvairCar Model 118 (1947)
Terrafugia Transition (2009)
Moller M400 (2003)
PAL-V One (2012)
AeroMobil 3.0 (2014)
Airspace Access
Current Status

• At present, most countries limit the use of PAVs and UAVs in civilian airspace*

• FAA guidelines for UAVs < 25 kg#: 
  • Altitude < 500 ft  
  • Visibility > 5 km  
  • LOS and daylight operations only  
  • No flights over populated areas

• Globally, NAS integration efforts gaining pace, but lags behind vehicle hardware development*

  ➔ For safe operations in urban environments, an airspace design that can effectively separate and organize large numbers of aircraft is required

*[G.Warwick 2013]  #[FAA 2015]
Airspace Design
Previous Research – Free Flight

- Free Flight studies have shown that **capacity can be increased** with **airborne separation assurance** and **reducing structural constraints**#

- Free Flight
  - Increases robustness by distributing conflict resolution tasks#
  - Increases flight efficiency with direct routing&
  - Reduces conflict rate/probability*

# [J.Hoekstra et al 2002]
& [V.Clari et al 2000]
* [M.Jardin 2005]
Airspace Design

Previous Research – Trajectory Based Operations

- Pre-planned conflict free routes are used**

- Safe separation relies on aircraft meeting arrival time constraints at waypoints along the route

- Uncertainties of aircraft positions can be reduced, allowing for closer packing of aircraft, increasing structure and capacity over current operations

* [T.Pervot et al 2003]
# [J.W.Andrews 2006]
Airspace Design
Phase Transition

Introduction - Setting for 2050 - Airspace Concepts - Simulation Development - Results - Conclusions
1. How should traffic be structured to handle high density PAV/UAV traffic over urban areas?

2. Does more or less structuring lead to higher capacities for demand levels greater than what is observed for commercial air transport today?
   a. Is there a density transition point beyond which further increases in capacity require a switch from one approach to another?
Metropolis Project
Capacity Along the Dimension of Structure

four Airspace Concepts of Increasing Structure

Introduction - Setting for 2050 - Airspace Concepts - Simulation Development – Results - Conclusions
2.

Metropolis Setting for 2050 and Beyond
**Assumption 1**
Continued Population Growth Leads to Mega Cities

- Metropolis scenarios use population size as a starting point to estimate traffic volumes
- Population growth of the Paris metropolitan area used as a baseline:

\[
y = 60.317x - 109.461.805 \\
R^2 = 1
\]

2050: 14 million*

*[INSEE 2013]*
**Assumption 1**
Continued Population Growth Leads to Mega Cities

- **Four scenarios** defined to evaluate concepts for multiple traffic demand levels
- Traffic demand then follows from population size and per capita demand
Assumption 2
PAVs Have Become Widely Available

- Current per capita vehicle ownership: **0.257***
- Assumed PAV market penetration: **16.7 %**
Assumption 2
PAVs Have Become Widely Available

- Expect both conventional and VTOL PAVs
  - Horizontal velocity needs to be maintained during flight
  - Small runway needed for take-off and landing
  - Adds additional constraint for airspace design

- Raised platforms above streets to be used as ‘PAV-ports’
  - Most PAVs under development are road-able designs
  - Best option for space restricted areas
  - Large number needed for ‘door to door’ operations
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Assumption 3
UAVs Will Be Used For Cargo Delivery

- UAV package demand:
  - 13.4 packages ordered online*
  - 48% are express deliveries*
  - 86% of orders are suitable for UAV delivery#

- 5.5 packages per capita, per annum

- Only local deliveries within a short distance

* [R. Ducret et al., 2013]
# [Tam, 2013]
Assumption 4
PAVs and UAVs Will Fly Over Buildings

- **Commercial traffic is separate**: Lower airspace region selected for urban air traffic (1100-6500ft)

- Due to **safety and privacy concerns**, it is unlikely that PAVs and UAVs will fly in between buildings

- PAVs and UAVs are separated due to significant performance and operational differences
3.

Design of Airspace Concepts
Concept 1: Full Mix

- ‘Completely’ **unstructured** design

- **Focus on efficiency:**
  - Direct horizontal route
  - Optimum altitude and speed

- Decentralized traffic separation using the Modified Voltage Potential (MVP) CD&R algorithm#
  - Nominal, state-based conflict detection
  - Combined heading, altitude and speed resolutions
  - Cooperative resolutions
  - No priority

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# [J. Hoekstra et al 2002]

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Introduction - Setting for 2050 - **Airspace Concepts** - Simulation Development – Results - Conclusions
Concept 2: Layers

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<th>Layer Heading Range</th>
<th>Height (ft)</th>
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<tr>
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<td>45°</td>
<td>1950</td>
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<tr>
<td>0°</td>
<td>1650</td>
</tr>
</tbody>
</table>

Layer Heading Range: 45°
Layer Height: 300 ft

- Airspace segmented into vertically stacked bands
  - Each ‘Layer’ limits horizontal travel within an allowed heading range: **hemispheric rule**

- **Improves safety** by decreasing conflict probability for cruising aircraft at same layer

- **Reduces efficiency** as altitude is determined by direction to destination

- MVP for decentralized traffic separation
  - No altitude resolutions for cruising aircraft
  - Priority for cruising aircraft
Concept 3: Zones

- Segments traffic based on similarity of travel direction in the **horizontal plane**
  - Takes **city layout** into account

- Two Zone Types:
  - **Circular zones** are similar to ‘ring roads’
  - **Radial zones** facilitate travel towards and away from city center

- **Altitude is selected flexibly** based on distance to destination

- MVP used for separation and merging traffic between circular and radial zones
  - No heading resolutions allowed
Concept 4: Tubes

- Tubes provide a **fixed route structure in four dimensions**
- Tube Topology
  - Bidirectional and fits only 1 aircraft
  - **Tubes never intersect** in the horizontal plane (except at the nodes)
  - Decreases in granularity with altitude
- Uses **time based separation**
  - Speed prescribed per Tube layer
  - Only one aircraft can ‘occupy’ a node within a given time interval
  - Take-off delay applied if conflict route not found
Concept Comparison
Capacity Along the Dimension of Structure

Four Airspace Concepts of Increasing Structure

- **Full Mix**
  - 4 Degrees of Freedom
  - X Position
  - Y Position
  - Altitude
  - Speed

- **Layers**
  - 3 Degrees of Freedom
  - X Position
  - Y Position
  - Speed

- **Zones**
  - 2 Degrees of Freedom
  - Altitude
  - Speed

- **Tubes**
  - 0 Degrees of Freedom

Capacity?
4.

Simulation Development and Experiment Design
Simulation Platform
Traffic Manager (TMX)

• Medium fidelity desktop simulation application developed by the NLR

• Features:
  • Simultaneous simulation of up to 10,000 aircraft
  • Multiple CD&R algorithms
  • Point mass aircraft models with BADA 3 performance limits
  • 4D FMS guidance and much more

• PAV/UAV dynamics simulated by modifying parameters to performance specifications available for vehicles under development
Design of Metropolis City

City Map

- Outer ring
- Inner ring
- City Center
- Experiment area
- Background area

Dimensions:
- 80 km
- 29 km
- 50 km
- 24 km
- 8 km
Design of Metropolis City

City Map

- Outer ring
- Inner ring
- City Center

Radial Basis Function

Distance From Focus Point [m]

Office Ratio [\( r \)]

Residential areas
Commercial areas

Introduction - Setting for 2050 - Airspace Concepts - Simulation Development - Results - Conclusions
Design of Metropolis City Infrastructure

Infrastructure

Introduction - Setting for 2050 - Airspace Concepts - Simulation Development - Results - Conclusions

Design of Metropolis City Infrastructure

PAV RWY

Phantom RWY

Rogue RWY

Dist Center

Demand Loc

UAV Distribution Centers

PAV-Ports

Demand Loc

Dist Center

UAV Distribution Centers

PAV RWY

Phantom RWY

Rogue RWY
Traffic Scenarios

Traffic Volume

- Instantaneous PAV traffic volume was computed by setting the average trip time to 15 minutes
- UAV package demand was determined based on the population density of the 2 considered distribution centers
Traffic Scenarios

Traffic Pattern

- Road traffic patterns
  - **Morning**: converging to city center
  - **Evening**: diverging from city center
  - **Midday**: mixed

- Scenarios created using an origin-destination algorithm
Traffic Scenarios

Scenario Files

Common scenario files created for fair comparison of four concepts
Concept Implementation

Introduction - Setting for 2050 - Airspace Concepts - Simulation Development - Results - Conclusions
Simulation of ‘Real-World’ Phenomena

Two Types of Uncertainties

- **Wind**
  - Uniform time invariant vector field
  - Random speed and direction
  - Difference predicted and true wind
  - Wind deliberately omitted from TMX trajectory planning functions to study how safety is affected

- **Rogue Aircraft**
  - Fly haphazardly irrespective of airspace concept
  - Very large protected zone
  - Introduced randomly in the simulation
  - Other aircraft expected to avoid rogue aircraft
Simulation Simplifications

• UAVs always use Full Mix concept
  • UAVs do not avoid other UAVs as this would be the same for PAV concepts
  • UAVs will have an impact on PAV trajectories near the PAV-UAV airspace boundary
  • Safety metrics measured for UAV-PAV interactions

• Landing not simulated
  • Aircraft deleted when within 2NM of destination runway
  • Time interval between successive landings logged to study influence of structure on approach sequencing

Introduction - Setting for 2050 - Airspace Concepts - Simulation Development - Results - Conclusions
Investigation of the relationship between **airspace structure** and capacity

- **Independent variables:**
  - **4 Concepts:** Full Mix, Layers, Zones and Tubes
  - **4 Densities:** Low, Medium, High and Ultra

- **Repetitions:**
  - 3 Traffic Patterns: Morning, Lunch and Evening
  - 2 Repetitions
  - 2 Conflict Resolution (CR) switches: CR On and CR Off

- A total of $4 \times 4 \times 3 \times 2 \times 2 = 192$ Runs
Experiment 2
Non-nominal Experiment

Comparison of the relative **robustness** of the four airspace concepts to non-nominal situations

- Independent variables:
  - **4 Concepts**: Full Mix, Layers, Zones and Tubes
  - **2 Scenarios**: Four and Eight Rogue Aircraft

- Repetitions:
  - 3 Traffic Patterns: Converging, Diverging and Mixed
  - 2 Repetitions
  - 2 Conflict Resolution (CR) switches: CR On and CR Off

- A total of $4 \times 2 \times 3 \times 2 \times 2 = 96$ Runs

- Non-nominal experiment used the ‘Low’ traffic density
5.

Results
Tubes concept used take-off delay resulting in fewer flights.

Tubes concept has higher density due longer flights.
Traffic Volume
Total Throughput vs. Density

- Tubes concept used take-off delay resulting in **fewer flights**
- Tubes concept has higher density due **longer flights**
Efficiency
Route Efficiency vs. Work Done

- Route Efficiency: horizontal trajectory only
  - Higher is better

- Work Done: horizontal and vertical trajectory
  - Lower is better
Efficiency

Route Efficiency vs. Work Done

- Full Mix has the highest efficiency
- Tubes has the lowest efficiency due to significantly longer flights
Efficiency
Route Efficiency vs. Work Done

- Full Mix has the highest efficiency
- Tubes has the lowest efficiency due to significantly longer flights
Efficiency

Arrival Sequencing

- Tubes concept has the highest intervals due to pre-departure delay

- Average interval high enough for all concepts to absorb high arrival rates using quasi-decentralized approaches such as the point-merge system
Safety

Intrusion Definition

Intrusions occur when the minimum separation requirements are violated
Safety

PAV-PAV Intrusion Number

- More structured concepts have more intrusions
Safety

PAV-PAV Intrusion Number

- More structured concepts have more intrusions
- Layers concept has the lowest number of intrusions
Safety

Intrusion Severity

\[
\text{Intrusion Severity} = \max_{t_0-t_f} \left[ \min\left(\hat I_h(t), \hat I_v(t)\right) \right]
\]
Safety

PAV-PAV Intrusion Severity

- Intrusion severity is not related to traffic density
- Tubes has the highest number and severity of intrusions
Safety

UAV-PAV Intrusion Number and Severity

- Tubes has the lowest number of PAV-UAV intrusions
  - Tube topology designed to take into account locations UAV distribution centers
Abnormal events affect the Tubes concept the most

- Rogue aircraft not taken into account during trajectory planning
Conclusions
Metropolis Project
Capacity Along the Dimension of Structure

Four Airspace Concepts of Increasing Structure

Layers shows the best balance between safety and efficiency metrics
Conclusions

- Some structure can be beneficial in terms of traffic separation, but too much structure only reduces performance
  - Some structure makes it easier for distributed CD&R algorithms to solve conflicts
  - No reversal found for the densities simulated

- Prediction uncertainties make it difficult to pre-plan conflict routes prior to take-off
  - More airspace has to be used to provide separation
  - Significantly reduces airspace capacity

Some structure, combined with decentralized airborne separation, shows the best overall safety and efficiency
Layers: The Way of The Future?

Strict structuring not necessary to align velocity vectors and reduce relative velocity between neighboring aircraft.
Thank You For Your Attention!