CAMDA: Capacity Assessment Method for Decentralized ATC

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Outline

Introduction

Airspace Stability & CAMDA Framework

Fast-Time Simulation Experiments

Results

Conclusions
1. Introduction
Centralized vs. Decentralized Airspace

Centralized ATC

Decentralized ATC

Separation

Routing

Decentralized ATC is expected to increase capacity
Previous Research

Airborne CD&I (ASAS)

Cockpit Displays

Flight Simulator Trials

Live Flight Trials (2005)
Open Problems

1. **Airspace Design/Structure**
   - How should traffic be organized in the context of decentralized separation?

2. **Safety Modeling**
   - How does the organization of traffic affect the number of conflicts in decentralized airspace?

3. **Capacity Modeling**
   - How does airborne CD&R affect the capacity of decentralized airspace?
Safety ≠ Capacity

Increasing separation between tracks improves airspace safety, but it can also decrease airspace capacity.
Capacity for Decentralized ATC

What **weighting** should be given to safety and efficiency?
Capacity for Decentralized ATC

- Safety
- Efficiency
- ?
- Capacity
Capacity for Decentralized ATC

Airspace stability considers the propagation of Conflict Chain Reactions
What is CAMDA?

- CAMDA uses the notion of airspace stability to measure the capacity of decentralized airspace concepts

- It can be applied to simulation data to determine capacity semi-empirically
  - Conflict chain reactions are unpredictable

- It uses measurable airspace properties as inputs

- It calculates the maximum theoretical capacity of an airspace as its main output
Research Goals

1. Develop the underlying models of the CAMDA framework

2. Demonstrate CAMDA for an unstructured direct-routing airspace concept that uses decentralized separation
2. Airspace Stability & CAMDA
Intrusions vs. Conflicts

Intrusion

\[ 2S_h \]

Conflict
Airspace Stability

<table>
<thead>
<tr>
<th>#</th>
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Airspace Stability

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</tr>
<tr>
<td>3</td>
<td>C-B</td>
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</table>

**Conflict Chain Reactions**

**Domino Effect Parameter**
Domino Effect Parameter (DEP)

\[ DEP = \frac{R3 - R1}{R1 + R2} = \frac{C_{total_{wr}}}{C_{total_{nr}}} - 1 \]

\[ C_{total_{nr}} = \text{Total conflicts no resolution} \]
\[ C_{total_{wr}} = \text{Total conflicts with resolution} \]

DEP is the number of secondary conflicts per primary conflict
DEP Example

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DEP Example

\[ \frac{C_{total_{nr}}}{C_{total_{wr}}} = 1 \]
\[ C_{total_{nr}} = 1 \]
\[ C_{total_{wr}} = 3 \]

\[ DEP = \frac{3}{1} - 1 = 2 \]

\[ \frac{C_{total_{nr}}}{C_{total_{wr}}} = 3 \]
\[ C_{total_{nr}} = 3 \]
\[ C_{total_{wr}} = 6 \]

\[ DEP = \frac{6}{3} - 1 = 1 \]

Higher DEP → Lower Stability
Capacity Measurement Using DEP

Conflict Chain Reactions:

- Reduce airspace **safety** by causing more conflicts
- Reduce airspace **efficiency** by increasing flight distances

Higher DEP → Lower Stability → Lower Capacity
CAMDA Capacity Definition
CAMDA Capacity Definition
CAMDA Capacity Definition

When $\rho \to \rho_{max}$, the resolution of any primary conflict causes an infinite number of secondary conflicts.

$$\lim_{\rho \to \rho_{max}} \frac{dDEP(\rho)}{d\rho} = \infty, \text{ where } \rho_{max} \equiv \text{capacity}$$

$$DEP(\rho) = \frac{C_{total wr}(\rho)}{C_{total nr}(\rho)} - 1$$
CAMDA Framework

Instantaneous Conflict Count Without CR

Total Conflict Count Without CR

Local Conflict Count Per Unit Distance Without CR

Assumption 1: Local Conflict Rate

Local Conflict Count Per Unit Distance Without CR

Assumption 2: Total A/C Count

Total Conflict Count With CR

DEP and Capacity

Without Conflict Resolution

With Conflict Resolution
CAMDA Framework

Instantaneous Conflict Count Without CR

- Total Conflict Count Without CR
- Local Conflict Count Per Unit Distance Without CR

Assumption 1: Local Conflict Rate

- Local Conflict Count Per Unit Distance Without CR

Assumption 2: Total A/C Count

- Total Conflict Count With CR

DEP and Capacity

Without Conflict Resolution

With Conflict Resolution
Instantaneous Conflict Count Without CR

Number of combinations of 2 aircraft

\[
\text{Inst. Conflict Count} = \frac{N(N-1)}{2} \times \text{Conflict probability between any 2 aircraft}
\]
Instantaneous Conflict Count Without CR

\[ C_{\text{inst},nr} = \frac{N_{\text{inst},nr} (N_{\text{inst},nr} - 1)}{2} \]
Instantaneous Conflict Count Without CR

\[ p = \frac{B_c}{B_{total}} \]
Instantaneous Conflict Count
Without CR

\[ p = \frac{B_{c,h} + B_{c,v}}{B_{total}} = \frac{4 S_h S_v \mathbf{E}(V_{r,h}) t_l + \pi S_h^2 \mathbf{E}(V_{r,v}) t_l}{B_{total}} \]

\[ \mathbf{E}(V_{r,h}) = \frac{4V}{\pi} \]

\[ \mathbf{E}(V_{r,v}) = V \sin(\gamma)(1 - \varepsilon^2) \]
CAMDA Framework

1. Assumption 1: Local Conflict Rate
2. Assumption 2: Total A/C Count

Without Conflict Resolution:
- Instantaneous Conflict Count Without CR
- Total Conflict Count Without CR
- Local Conflict Count Per Unit Distance Without CR

With Conflict Resolution:
- Local Conflict Count Per Unit Distance Without CR
- Total Conflict Count With CR
- DEP and Capacity
Conflict Resolutions Increase Flight Distances

\[ D_{wr} = D_{nr} + D_{cdr} C_{1,wr} \]
Extra Distance Searched and Flown Due to CD&R, $D_{cdr}$

- $D_{cdr}$ is influenced by conflict chain reactions

- Conflict chain reactions are unpredictable, and they are affected by:
  - Traffic Density
  - Interactions between the selected airspace design and CD&R algorithm

- The value of $D_{cdr}$ needs to be determined from simulation data for a particular airspace concept
  - CAMDA is semi-empirical
CAMDA Framework

Instantaneous Conflict Count Without CR

Total Conflict Count Without CR

Local Conflict Count Per Unit Distance Without CR

Assumption 1: Local Conflict Rate

Local Conflict Count Per Unit Distance Without CR

Assumption 2: Total A/C Count

Total Conflict Count With CR

DEP and Capacity

Without Conflict Resolution

With Conflict Resolution
DEP & Airspace Capacity

\[ DEP(\rho) = \frac{C_{total_{wr}}(\rho)}{C_{total_{nr}}(\rho)} - 1 \]

\[ DEP = \frac{2t_c (TV + D_{nr})}{2t_c (TV + D_{nr}) - \rho D_{cdr} TA} - 1 \]

\[ \lambda = \frac{2t_c (TV + D_{nr})}{1} \]

\[ \beta = \frac{1}{\rho D_{cdr} TA} \]

\[ DEP = \frac{\rho}{\lambda \beta - \rho} \]
DEP & Airspace Capacity

\[
\lim_{{\rho \to \rho_{\text{max}}}} \frac{d\text{DEP}(\rho)}{d\rho} = \infty, \text{ where } \rho_{\text{max}} = \text{capacity}
\]

\[
\frac{d\text{DEP}}{d\rho} \bigg|_{{\rho \to \rho_{\text{max}}}} = \frac{\lambda \beta}{(\lambda \beta - \rho_{\text{max}})^2} = \infty
\]

\[
\rho_{\text{max}} = \frac{2t_c (TV + D_{nr})}{pD_{cdr}TA}
\]

From Simulation Data
CAMDA Quick Start Guide

1. Perform two sets of simulations at multiple densities, $\rho$:
   a. Without conflict resolution to determine $C_{total_{nr}}$
   b. With conflict resolution to determine $C_{total_{wr}}$

2. Use simulation data to compute empirical Domino Effect Parameter for each density, $DEP(\rho)$:

   $$DEP(\rho)_{sim} = \frac{C_{total_{wr}}(\rho)}{C_{total_{nr}}(\rho)} - 1$$

3. Determine max theoretical capacity, $\rho_{max}$, using Least-Squares regression

   $$DEP(\rho)_{sim} = \frac{\rho}{\rho_{max} - \rho}$$
3. 

*Fast-Time Simulation Experiments*
BlueSky Open ATM Simulator

https://github.com/ProfHoekstra/bluesky
Conflict Detection: State Based
Conflict Resolution: MVP

Trajectory Recovery
• Horizontal: Direct to sector-exit waypoint
• Vertical: Return to pre-conflict FMS altitude
Three Experiments

1. Effect of Conflict Detection Parameters
   - Horizontal and vertical separation requirements
   - Look-ahead time

2. Effect of Conflict Resolution Dimension
   - Horizontal only (speed + heading)
   - Vertical only (vertical speed)

3. Effect of Ground Speed Distribution

More than 2 million flights simulated for all three experiments
4.

Results
## Conflict Detection Experiment

<table>
<thead>
<tr>
<th>Condition Name</th>
<th>Horizontal Separation [NM]</th>
<th>Vertical Separation [ft]</th>
<th>Look-Ahead Time [mins]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>2.5</td>
<td>500</td>
<td>5</td>
</tr>
<tr>
<td>Double Separation</td>
<td>5.0</td>
<td>1000</td>
<td>5</td>
</tr>
<tr>
<td>Double Separation + Half Look-Ahead</td>
<td>5.0</td>
<td>1000</td>
<td>2.5</td>
</tr>
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</table>
Conflict Detection Experiment

Separation requirements has a greater impact than look-ahead time on maximum airspace capacity.
Conflict Detection Experiment

\[ \rho_{\text{max}} = \frac{2t_c (TV + D_{nr})}{pD_{cdr} TA} \]

\[ p = \frac{4 S_h S_v \mathbb{E} (V_{r,h}) t_l + \pi S_h^2 \mathbb{E} (V_{r,v}) t_l}{B_{\text{total}}} \]

- A doubling of separation requirements leads to a quadrupling of conflict probability
- A doubling of look-ahead time leads to a doubling of conflict probability
- Therefore separation requirements have a greater effect on capacity than look-ahead time
Conflict Resolution Experiment

Horizontal (Speed + Heading)

Vertical (Vertical Speed)
Conflict Resolution Experiment

Vertical conflict resolution reduces capacity as traffic is more closely packed in the vertical direction in en-route airspace.

\[ \rho_{\text{max}} = 657.6 \]
\[ \rho_{\text{max}} = 219.8 \]
Speed Distribution Experiment

350kts  400kts  450kts

350kts  400kts  450kts
No substantial effect of speed distribution on the maximum capacity of unstructured direct-routing airspace
Conclusions
## CAMDA Pros and Cons

<table>
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<th>Cons</th>
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<tr>
<td>• Provides a physical definition of capacity in terms of conflict chain reactions</td>
<td>• Semi-empirical: Conflict chain reactions are difficult to predict analytically</td>
</tr>
<tr>
<td>• Can be used to understand the effect of airspace design parameters on capacity</td>
<td></td>
</tr>
<tr>
<td>• Reduce the number of simulations needed to evaluate an airspace design</td>
<td></td>
</tr>
<tr>
<td>• Unbiased and objective metric to compare different airspace designs and CD&amp;R algorithms</td>
<td>• No weighting/tuning required</td>
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Capacity of Unstructured Airspace

• Traffic separation requirements have a greater impact on capacity than look-ahead time
  – Separation requirements have a larger impact on conflict probability

• Restricting conflict resolutions to the vertical direction reduces airspace capacity
  – Aircraft are more closely packed in the vertical direction

• Ground speed distribution does not have a substantial effect on the capacity of unstructured direct-routing airspace
"Analyzing the Effect of Traffic Scenario Properties on Conflict Count Models"

Effect of Speed, Heading, Altitude and Spatial Distribution of Traffic on Safety

When: 11:40, Friday, Classroom C4-026V
Thank You For Your Attention!

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