Automated Methods to Maintain Aircraft Separation

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November 14, 2011
The Air-Transportation System
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Talk Outline

• A large optimization problem
• Decomposing the problem
• Areas of research
• Separation assurance
• Strategic resolution
• Robust separation automation
Benefits of Efficient Operations

- People and property arrives as quickly as possible
- Reduced environmental impact (fuel burn and noise)
- In 2007 delays cost over $32 billion (UC Berkeley)
Challenges

• Airport growth is constrained and expensive
• Humans must be able to maintain safety
• Weather and other uncertainties
Large Optimization Problem

• Constraints:
  – Cannot occupy the same space
  – Performance limits
  – Restricted airspace

• Controls:
  – Departure times
  – Routes
  – Speeds
Decomposing the Problem

• Different regions have different constraints and functions

• Different accuracies are important at different time scales
  – To deal with arrival constraints hours away, aircraft can be dealt with in the aggregate
  – An impending aircraft collision must be dealt with very precisely
Regions of Control
Optimization Time Scales

Course
- Traffic Flow Management
- Weather Rerouting
- Arrival Scheduling
- Separation Management

Required Accuracy

Precise
Airport Research

• Issues:
  – Departure scheduling for taxi and takeoff
  – Efficient use of parallel runways

• Methods:
  – Efficient scheduling algorithms
  – Procedures for low visibility
Around the Airport (TRACON)
TRACON Research

• Issues:
  – Main task is delivering aircraft to airport runways as closely as allowed
  – Continuous descents
  – Maintaining separation

• Methods:
  – Efficient scheduling algorithms
  – Design of human computer interfaces
  – Trajectory prediction
Enroute Operations
Impact of Convective Weather on New York Area Arrivals

Created Using
Future ATM Concepts Evaluation Tool (FACET)

Created for Aviation Systems Division (AF) NASA Ames Research Center
System-Wide Research

• Issues:
  – Maintain airport and airspace constraints
  – Efficient departure scheduling
  – Flow around weather
  – Airspace design

• Methods:
  – Linear programming
  – Vornoi diagrams
  – Data mining
Regions of Control
Optimization Time Scales

- Traffic Flow Management
- Weather Rerouting
- Arrival Scheduling
- Separation Management
Maintaining Aircraft Separation
Maintaining Aircraft Separation

Strategic Separation Assurance (20 minutes to 2 minutes before LOS)

Tactical Separation Assurance (2 minutes to LOS)

Collision Avoidance (1 minute to Collision)
Maintaining Aircraft Separation

- **Strategic Separation Assurance** (20 minutes to 2 minutes before LOS)
- **Tactical Separation Assurance** (2 minutes to LOS)
- **Collision Avoidance** (1 minute to Collision)
Part Two

- Enroute
- Separation Assurance
- Strategic
Separation Assurance

- Aircraft must remain 5 mi and 1000 ft from one another
- Currently performed by Air-Traffic Controllers (minimal tools)
Automated Separation Assurance

• Want the system to be safe
• Want to impact the system as little as possible (efficiency)
• Want to provide resolutions to aircraft which are understandable to pilots
• Needs to be robust to uncertainty
Identifying Issues

Need to identify if two aircraft will be within 5 mi and 1000 ft in the future
Predicting Aircraft Trajectories

- Create models of aircraft performance using physics
- Models can be either kinematic or kinetic

\[ V_a \] - Airspeed
\[ \gamma_a \] - Flight Path Angle
\[ \psi \] - Heading
\[ p \] - Roll Rate
Example Kinetic Model

\[ \dot{V}_a = \frac{T - D}{m} - g \sin(\gamma_a) \]
\[ \dot{p} = L_p p + \tau \]
\[ p = \dot{\phi} \]

\[ \dot{\gamma}_a = \frac{L \cos(\varphi) - mg \cos(\gamma_a)}{mV_a} \]
\[ \dot{\psi} = \frac{g \tan(\varphi)}{V_a} \]

- \( T \) - Thrust
- \( D \) - Drag
- \( L \) - Lift
- \( \tau \) - Roll Force
Aircraft Controller

- Inner loop control for aircraft stability and desired attitude
- Outer loop guidance for aircraft lateral navigation between waypoints
Predicted Trajectories

Numerical integration provides discrete predictions of future locations
Geometric Conflict Detection
Geometric Conflict Detection

- Check vertical and horizontal distance
- There are temporal and spatial buffers to deal with uncertainty
Geometric Conflict Detection

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- There are temporal and spatial buffers to deal with uncertainty
Geometric Conflict Detection

- Check vertical and horizontal distance
- There are temporal and spatial buffers to deal with uncertainty
A loss of separation has been predicted
Generate a maneuver and predicted how the aircraft will fly it
This maneuver is predicted to not solve the problem
The problem is predicted to be resolved by this maneuver
Maneuver Types

• Maneuvers can be difficult to communicate
• Want to use common current maneuvers
• Have three types of maneuvers:
  – Altitude maneuvers
  – Horizontal maneuvers
  – Speed maneuvers
Altitude Maneuvers
Horizontal Maneuvers
Speed

![Speed Diagram]

- A1
- A2
- Mach
- Time

Diagram showing the relationship between Mach and time for A1 and A2.
Resolution Search

Conflict Parameters

- Direct-To
- Altitude
- Analytical Turn
- Route Offset
- Path-Stretch
- Speed
Resolution Search

Possible Attempts

2  Direct-To

~16  Altitude

6  Analytical Turn

4  Route Offset

~80  Path-Stretch

~20  Speed

~128 Options
Resolution Search

Possible Attempts  Possible Successful

2  Direct-To  2

~16  Altitude  4

6  Analytical Turn  1

4  Route Offset  2

~80  Path-Stretch  4

~20  Speed  2

~128 Options  15 Possible

Conflict Parameters
Resolution Iterations

Conflict Parameters

Possible Attempts | Possible Successful
--- | ---
2 | Direct-To | 2
~16 | Altitude | 4
6 | Analytical Turn | 1
4 | Route Offset | 2
~80 | Path-Stretch | 4
~20 | Speed | 2

~128 Options | 15 Possible

Least-time solution is preferred choice
Results with No Uncertainty

Resolved 100% of conflicts

Average Delay per Resolution (seconds)

Traffic Density Relative to Current Day

Non-Arrival  Arrival

Resolved 100% of conflicts
Uncertainty in Simulations

Any trajectory prediction will have some error
Major Sources of Uncertainty

- Wind error
- Aircraft weight error
- Pilot intent error
- Communication delay
- Control system modeling
Adding Uncertainty in Simulation

Create an exact copy at the same time to have a truth trajectory
Resulting Prediction Errors

Altitude Error
Resulting Prediction Errors

Altitude Error

Cross-Track Error
Resulting Prediction Errors

Altitude Error

Cross-Track Error

Along-Track Error
Resulting Prediction Errors

Altitude Error

Cross-Track Error

Along-Track Error

Top-of-Descent Error
Missed and False Alerts
Missed and False Alerts

Missed Alert

False Alert
Missed Alerts with Errors

Missed Alerts (%)

- Wind
- Cruise Speed
- Weight
- TOD
- Descent Speed

10 Minutes to Loss
Missed Alerts

- Maximum Error: 10 Minutes to Loss
- 5 Minutes to Loss

Missed Alerts (%)

- Wind
- Cruise Speed
- Weight
- TOD
- Descent Speed

10 Minutes to Loss
5 Minutes to Loss
Prediction Errors
Prediction Errors

Increasing prediction horizon

Along Track Error

Along Track Error Histogram at 24 Minutes
Prediction Errors

Increasing prediction horizon

Along Track Error

Along Track Error Histogram at 24 Minutes

TOD Time Error
Prediction Errors

- Along Track Error
- Along Track Error Histogram at 24 Minutes
- TOD Time Error
- Climb Altitude Error

Increasing prediction horizon
Probabilistic Conflict Detection

• Use knowledge of prediction errors to improve conflict detection performance
• Remove arbitrary buffers and time thresholds

![Diagram showing probabilistic conflict detection with a probability distribution curve leading to the probability of conflict.]
Factors in Position Uncertainty

- Prediction time extent
- Currently changing state
- Distance from next state change
- Distance from top of descent
- Aircraft type

![Diagram of probabilistic conflict detection]

Probabilistic Conflict Detection → Probability of Conflict
• A Loss of severity 0.2 will occur.
• At 8 minutes to go, there is a 30% probability of loss
Probability of Conflict

Probability versus Time to Loss (Showing Severity)

No Uncertainty

Conflict Probability

Severity

Time to Loss
Trade-off with False Alerts

- Easy to have zero missed alerts if almost everything is declared a conflict
- This leads to a high number of false alerts
Large Error Comparison

[Graph showing the relationship between False Alerts and Missed Alerts. The point labeled "Current Geometric Method" is plotted.]
Large Error Comparison

Increase in Missed Alerts (%)

Increase in False Alerts (%)

Current Geometric Method

Probabilistic Method
Small Error Comparison

Increase in Missed Alerts (%)

Increase in False Alerts (%)

Current Geometric Method

Probabilistic Method
Improving Resolution Robustness

Conflict Parameters → Different resolution possibilities → Least-Time

Preferred Resolution
Improving Resolution Robustness

Use probability of conflict reoccurring for resolution choice
Automated Separation Assurance

• Have shown that automation works well under perfect conditions
• Currently being adapted as a tool for controllers
• Have made progress in improving the robustness to errors
A Large Optimization Problem

Efficient Modernized Transportation

Robust Strategic Enroute Separation Assurance

Individual Research Topics

Dependencies

Research Areas

Dependencies

Efficient Modernized Transportation
Questions

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