Constraint-Based Techniques for Managing Movement in Crowded Airspaces

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Outline of Talk

- Management of Crowded Airspaces
- Dynamic Airspace Deconfliction Project
  - Building Conflict-Free Movement Schedules
  - Integrating with distributed, real-time airspace deconfliction processes
- Future directions
Airspace Deconfliction: Civilian Aviation

- Increasing volume of aircraft and congestion around airports
- Complexity of determining corridors and sequencing for takeoff, landing and holding

Illustration by Peter Arkle for the New York Times - 26 August 2007
Airspace Deconfliction: Military Aviation

- Concurrent missions
- Localized and heavily populated environment
- Dynamically generated mission routes
- Increasingly autonomous aircraft
- Pop-up threats, friendly forces
- Strict partitioning of airspace is inefficient
Emerging Concepts: Dynamic Airspace Configuration

- Automated separation assurance (via ground-based or distributed airborne systems)
- User-preferred trajectories
- Dynamic traffic management (adaptive speed control, route modification)
- Adaptable airspace to meet user demand, react to changing weather, maintain safety, etc.
- “DAC allocates airspace as a resource to meet user demand …”

Dynamic Airspace Deconfliction

Joint Boeing–CMU research collaboration

Goal: Technology components to support planning and execution of conflict-free air operations

Technical Approach:

- Leverage previous work in constraint-based scheduling and task allocation
- Investigate and incorporate techniques for representing and reasoning about spatial constraints
- Couple mechanisms for centralized global mission planning with real-time distributed deconfliction processes
Starting Point: Dynamic Task Allocation and Scheduling

Core Technology: Incremental, Constraint-based Search

Applications:

- **AMC Allocator** - day-to-day mgnt. of airlift & tanker missions

- **ACS (Air Campaign Scheduler)** - streaming ATO generation

- **DARPA Coordinators** - distributed management of high-quality joint plans
Constraint-Based Search Models

Components:
- Commitment Strategies/Heuristics
- Active Data Base (Current Solution)
- Constraint Propagation
- Conflict Handling

Properties:
- Modeling Generality/Expressiveness
- Incrementality
- Compositional
Building Conflict-Free Movement Schedules

Approach:

- View space as a *capacitated* resource and treat airspace deconfliction as an extended resource allocation problem.
- Exploit *Octree* representation of air space volumes over time.
- Generalize the notion of contention-based search heuristics:
  - Construct and use a profile of spatial contention to make vehicle-routing and sequencing decisions.
The Octree

- Hierarchical, three-dimensional data structure (an extension of the 2D **quadtree**)
- Recursively subdivides a spatial volume into smaller subvolumes (called **octants**)
- Localizes common objects indexed by [x,y,z] coordinates
The Linear Octree

- Represents the octree as a balanced binary tree
- Locational codes computed from the \([x,y,z]\) coordinates of each octant’s origin serve as keys in the binary tree
- The result is a leaner and more efficient data structure
Storage and Manipulation of Vehicle Routes

- Allocating vehicle routes to octants (a route is a sequence of 4D vectors)
- Determining conflicts using spherical MAZes (Maneuver Avoidance Zones) and the Closest Point of Approach
Allocating Vehicle Routes to Octants

- Vectors are apportioned across all intersecting octants
- A conflict is signaled by the spatial and temporal overlap of two or more vector segments within an octant
Octant Subdivision in Response to a Conflict

Conflicted octant:

Intersecting vectors: v1 & v2 at •

Subdivided octants:
- 1 conflicted
- 4 unconflicted
- 3 empty

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Determining Conflicts

- A conflict between two vehicles is centered around the time of its closest point of approach (CPA)
- The duration of a conflict is measured from the beginning to the end of the spatial overlap
Searching for Conflicts Among Neighboring Octants

- Neighboring octants must be searched for conflicting vectors whenever a vector is too close to an octant boundary.
Generating Conflict-Free Schedules

• **Approach:**
  - start with a base scheduling algorithm for computing a resource-feasible schedule for a set of itineraries
  - incorporate a route-planning component
  - extend algorithm to allocate space in the octree

• **Two phase schedule generation procedure:**
  - **priming** phase – build a resource-feasible schedule that ignores spatial capacity constraints
  - **scheduling** phase – use spatial contention profile to build extended solution that enforces spatial constraints
Air Vehicle Mission Routes

Note: vertical and horizontal axes are on different scales
Phase One: Priming the Octree

- The octree is populated by scheduling all expected missions
- Airspace is allocated without consideration of spatial constraints
- Red octants indicate resulting areas of contention
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Phase Two: Deconfliction Scheduling

- The primed octree is used to guide the construction of a conflict-free schedule
- Traffic is directed to uncongested areas
- Routes are modified as necessary to avoid conflicts with other vehicles
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Evaluation: The Problem Set

- 20 data sets
  - 50 to 1000 randomly generated targets (in increments of 50)
  - Two 700-miles-square target areas
  - 10 identically equipped bases
Evaluation: Two Deconfliction Strategies

- **Baseline Approach**
  - No primed octree *(myopic)*: if a conflict is detected, an attempt is made – based on the current partial state – to deconflict through route modification

- **Profile-based Approach**
  - Create and utilize the primed octree to guide route modification in response to conflicts
Evaluation: Results

Additional overhead for building the spatial contention profile is compensated for by an improvement in overall scheduling performance for sufficiently sized runs.
Multi-Level Airspace Deconfliction Framework

Airspace Sensitive, Multi-Mission Scheduling
- Mission trajectories, timings
- Potential conflicts

Predictive Guidance (Potential Conflicts)

Myopic Avoidance Actions

Downstream Impact

Distributed Real-time Airspace Deconfliction
- Turn left, slow down

Conflicted Airspace:
- Option 1
- Option 2
- Pop-up Directed Energy Weapon

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Integrating with Real-Time Deconfliction Processes

- Use globally computed information to drive local deconfliction processes
  - Routes (i.e., sequences of waypoints)
  - Potential Conflicts (time and location)
  - Airspace Volume (given a 3D/4D region, where is the traffic?)
  - Airspace Corridor (are there sequences of under-populated 3D regions over time?)

An example query: given a route, determine its traversed octants and all conflicting vectors (in green)
Operating Concept

- Distributed airborne processes assume responsibility for local deconfliction at execution time
- Global guidance is computed to provide an appropriate envelope of operations
- When any local route change is made, a query is made to the global scheduler to determine downstream impact and re-compute guidance
Computing Potential Conflicts

- **Neighborhood size** – the number of aircraft allowed to simultaneously violate separation constraints within an octant before a conflict is signaled.

- **Encounter region** – the sum of the separation constraint and the distance a vehicle is allowed to deviate from its path to avoid a conflict.

- **Encounter list** – for a given neighborhood size > 1, the set of other air vehicles falling within the encounter region of a given aircraft’s itinerary. This list constitutes the set of potential conflicts.
Encounter Lists

neighborhood size = 3 (or larger)

encounter-list(1) = {}
encounter-list(2) = {}

encounter-list(1) = [3]
encounter-list(2) = [1]
encounter-list(3) = [1]

encounter-list(1) = [3]
encounter-list(2) = [4]
encounter-list(3) = [1, 4]
encounter-list(4) = [2, 3]
Status

- Initial, distributed deconfliction process operational (running in simulation)
  - Formulated as a distributed constraint satisfaction problem
  - Protocol for conflict resolution via cooperative partial centralization
  - Encounter lists determine who to interact with
- XML API in place for requesting and communicating global guidance
Future Directions

- Expansion of the spatial constraint model
- Consideration of more real-world constraints (e.g., maneuverability, fuel)
- Strategic analysis of conflict trajectories
- More sophisticated search and optimization procedures
Reference