Automated Conflict Resolution for Air Traffic Management Using Cooperative Multi-agent Negotiation

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Introduction - Goals & Approach

• Implement an automated, cooperative, multi-agent conflict detection and resolution system.

• Demonstrate viability of multi-agent solutions for air traffic domain problems.
Many automated conflict resolution systems have been proposed, but none use multi-agent cooperation and negotiation. Benefits:

- Take into account aircraft preferences via cost functions.
- Can obtain more efficient results than non-cooperative methods.
Background - Agents

• Agents are self interested software programs.
• Receive input data from environment
• Process data to make control decisions.
Background - Agents

• Multi-agent systems used to model environments with many independent actors.
• Very natural for the national airspace system.
• Treat each aircraft as an agent with goals, and allow those agents to negotiate resolutions when those goals conflict.
• Monotonic Concession Protocol.
Background - The MCP

The Monotonic Concession Protocol

- Simple protocol designed for multi-agent negotiation.
- Captures spirit of incremental concessions.
- Can resolve resource conflicts or to redistribute tasks.
Background - The MCP

- Agents begin with a set of possible ‘deals’.
- Agents use cost functions to express preferences for certain deals.
- Repeated proposals and concessions until agents agree on one deal to be implemented.
In order to apply the MCP to CD&R we require:

- Cost functions for flight plans.
- Conflict, or fall back, deal. Conflict deal required to define ’utility’ and to provide a safe fall back.
- Negotiation set of possible solutions.
Cooperative CD&R process consists of several major steps:

- Conflict Detection
- Negotiation Set Generation
- Negotiation
- Resolution
A simple conflict detection and prediction process was implemented for this system.

- Nominal state propagation.
- Conflict defined by an overlap of two protected zones.
- First and last conflict times stored for later use.
The MCP requires a conflict deal to function correctly

- Used to calculate utility values
  \[ Utility(A) = Cost(Conflict) - Cost(A) \]

- Serves as a fall back if negotiation fails

The air traffic domain lacks a natural conflict deal, so we must create one.
There are several possible ways to acquire a usable conflict deal

- Request deconfliction procedure from ATC.
- Pilots manually confer to determine fall back procedure.
- Worst case analysis.

We use worst case analysis.
CD&R System - Negotiation Set

- The MCP also requires a set of deals over which negotiation will take place.
- Must be generated by the agents prior to the negotiation process.
- Set of six prescribed course deviations.
CD&R System - Negotiation Set

Six prescribed deviations fall into three pairs

- Turn left/turn right.
- Increase/decrease altitude.
- Increase/decrease speed.
CD&R System - Negotiation Set

Left/right alternate generation (top view):

Original Course

--- Alternate Trajectories

Left Alternate Trajectory

3 Nautical Mile Deviation

Right Alternate Trajectory

Last Point of Conflict

First Point of Conflict
Climb/descend alternate generation (side view):


CD&R System - Utility Functions

- Required to express agent preferences.
- Can be as simple as flight time or distance.
- Other terms: fuel efficiency, pilot workload, size of course deviation.
Example:

\[
\text{Cost} = dD + a\Delta A + h\Delta H
\]

- \(D\) = nautical miles traveled in flight plan.
- \(\Delta A\) = total altitude changes.
- \(\Delta H\) = total heading changes.
- \(d, a, h\) = coefficients for preference weighting.
Once the negotiation set has been finalized the actual negotiation process can occur.

- Agents execute MCP to select a deal from negotiation set.
- Pair of trajectories with largest product of utilities for each agent is selected.
Once a pair of alternate trajectories has been selected, it is presented to the pilot for approval and execution.

In a real air traffic situation the pilot may then be required to obtain final approval from ATC.

In our simulations, pilot and agent are the same entity, so the new plan is simply implemented as soon as it is selected.
Evaluation - Test Process

- Random generation of scenarios involving two aircraft with impending conflicts.
- Two separate test cases using different combinations of cost functions. 100 random trials conducted for each case.
Evaluation - Scenario Generation

Randomly selected headings and velocities

Point of intended conflict

Random time to conflict used to generate start positions
Evaluation - Test Criteria

Testing both safety and efficiency of the system.

- Safety: did a conflict occur during the course of a test run?
- Efficiency: is the resulting pair of flight plans of lower cost than the fall back worst case deal?
**Evaluation - Results, Test 1**

Cost function:

\[ \text{Cost}_{Both} = D \]

<table>
<thead>
<tr>
<th></th>
<th>Conflict Cost (Avg)</th>
<th>Negotiated Cost (Avg)</th>
<th>Percent Improvement</th>
<th>Std Dev</th>
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<td>160.04</td>
<td>144.65</td>
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100 trials.
Cost functions:

\[ \text{Cost}_{A1} = D \]
\[ \text{Cost}_{A2} = D + \Delta A + \Delta H \]

<table>
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<tr>
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<td>218.01</td>
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100 trials.
Evaluation - Overall Results

- 100% conflict avoidance in our test scenarios.
- Agents were able to select routes that fit their needs.
- In some cases, with strong preferences a large improvement was realized.
Conclusions

We have demonstrated:

- Multi-agent negotiation can resolve air traffic conflicts
- The system gives aircraft the ability to express preferences for certain flight plans and that those preferences are reflected in the resulting solutions.
Future Work

- More sophisticated trajectory generation
- Multiple conflicts
- Communications load analysis