Determining the Value of Information for Minimizing Controller Taskload
A Graph Based Approach

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Major Research Question

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Major Research Question

How does the design, capabilities, and underlying policy of an advisory conflict-detection and resolution system affect the conflict-resolution taskload?

Definition: Conflict-resolution taskload is the number of resolution actions required to separate aircraft.
Major Research Question

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Three Fundamental Questions:
**Major Research Question**

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What is the value of information towards reducing conflict-resolution taskload?
How often should trajectory and conflict information be updated?
How does the quality of information affect controller taskload?
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Three Fundamental Questions:
The three questions directly relate to the design and capabilities of CDR systems
Major Research Questions

These fundamental questions will be addressed by modeling the conflict-detection and resolution process through a graph-based framework.
Background
Researchers and air navigation service providers hypothesize that semi/full-automation will reduce or transform the workload of controllers.

*Workload*: “the amount of effort, both physical and psychological, expended in response to system demands (task load) and also in accordance with the operators internal standard of performance.”

...and support the necessary increase in airspace capacity.

*Capacity*: Nominally, the maximum number of aircraft allowed in an airspace at any instance of time.
**Why Introduce Automation into ATC?**

Potential and actual conflicts require significant effort from controllers.

- Detect, monitor, and assess potential conflicts
- Generate resolutions to maintain separation
- Communicate resolution commands to pilots
- Monitor implementation
Automation in Conflict Resolution

Ideally automation

- Aids/replaces controllers in generating resolutions and reduces mental workload.
- Ensures safety at high traffic volumes.
- Provides optimal solutions to improve service and throughput.
Automated Conflict Resolution

There still remain challenges:

- Difficulty in guaranteeing safe and feasible solutions.
- Slow uptake of advanced avionics to fully support automated tactical control.
Conjecture: Before the transition to a completely automated system, there will be an imperative for systems to aid air traffic controllers without replacing them.
The research presented here focuses on the technical design and implementation of advisory decision-support tools for simultaneous conflict-detection and resolution.
Human-In-The-Loop Control

Assertion: The design of advisory conflict-detection and resolution tools requires a fundamentally different approach when compared to automated system.

- Acknowledge the role of the controller
- Accommodate their abilities (dynamics)

Besides allocation of function, many human-factors concerns are not addressed in the design of CDR tools; they’re an after-thought.

Excellent Exception: ERASMUS project, which introduces concept of ‘subliminal control’.
(Requires advanced avionic systems)
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Motivation:
Why should we care about the design of advisory CDR systems?
Example Study on Human-In-The-Loop Control


- Air traffic controllers (students & retired).
- Simulate traffic from 1X to 3X traffic levels.
- Advisory conflict-detection and resolution tool.
- Automated data communication systems
- Trajectory based operations.
- Surveyed controllers on workload.
Thoughts on The Example Study

- The advisory conflict-resolution tool was initially conceived as a part of a completely autonomous tool (Advanced Airspace Concepts - Erzberger).
  - Rule-based – fixed search procedure.
  - Pair-wise sequential solver.
  - No guarantee of finding feasible solutions.
- Not all conflicts were identified and resolved by the CDR tools.
Example Study on Human-In-The-Loop Control

Interesting/expected results:

- Advisory CDR tools reduced controller workload.
- Controllers adjusted work practice.
- Identified key complexity variables:
  - Resolution mode (advisory vs. trial planning)
  - Number of impending conflicts **
  - Number of aircraft
  - Separation criticality index
  - Degrees of freedom index for aircraft in conflict.

**To be discussed later.
Interesting/expected results:
“At the 3X level controllers and students accepted almost all advisories (∼ 98%) due to time pressure.”
Thoughts on the Example Study

- Time-pressures appear to have ‘removed the controller from the loop.’
- Potential negating the purpose of human-in-the-loop control by limiting the greatest asset of the human controllers: Safety fall-back.
- Effectively, system resorts to automated/supervisory control

“There is a long history of cases in which operators are reportedly unaware of automation failures and do not detect critical system state changes when acting as monitors of automated systems.” [Endsley, 1996]
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Research Goal: Enable the design of advisory conflict-detection and resolution tools consistent with human dynamics, particularly, tools that reducing the number of resolution commands required to resolve conflicts (in order to reduce time-pressures), by making the best use of information.

Pairwise sequential solvers will always be sub-optimal in this regard.
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A Graph Based Approach to Conflict-Detection and Resolution

- *Provides* theoretical performance bounds on controller conflict-resolution taskload based on abstractions of system capabilities and implementation architectures.
- *Methodology*: Describe and model traffic and conflict resolution process utilizing graphs.
Problem Modeling:
Graph-based conflict-detection and resolution
**Graph Representation of Traffic Conflicts**

**Air Traffic**
- Consider a set of \( N \) aircraft (3D space, need not be planar)
- Aircraft have the potential to be in multiple conflicts.

**Graph:** \( G = (V, E) \)
- Aircraft represented by nodes
- Conflicts represented by edges

Conflict resolution process results in removing edges.
Conflict-free airspace \( \iff \) Completely disconnected graph.
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Conflict-free airspace $\iff$ Completely disconnected graph.
1. Initialize with set of aircraft
2. Over the next time-step
   - Aircraft/exit enter the airspace.
   - New potential conflicts are detected.
3. Potential conflicts occurring within $\delta t$ are resolved.
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Corresponds to a Receding-Horizon Control Framework

- Every $\delta t$: information updated, resolution problem solved.
- Potential conflicts identified upto $H$ minutes in advance.
- Resolution commands are conflict-free for $H$ minutes.

Assumes symmetric capabilities: If conflicts can be detected $H$ minutes in advance, then resolution tools can find trajectories conflict-free for $H$ minutes.
Implementation of CDR Tools

Implies the creation of dynamic graphs \((\mathcal{G}(k) = (\mathcal{V}(k), \mathcal{E}(k)))\) that are operated on by the conflict-detection and resolution process.
Receding horizon framework is suboptimal compared to complete knowledge (local optimization without complete information of future aircraft).
What defines a potential conflict?

Standard value indicating action by controller: 5NM

![Diagram showing flight levels and NM distances with color-coded zones for action thresholds.]

However, due to uncertainties in wind, performance, and radar, controllers tend to take a more conservatively safe approach.

Action by controller occurs even when $D_{sep} > 5NM$.
**What defines a potential conflict?**

Standard value indicating action by controller: 5NM

![Graph showing flight paths and distance](image)

CDR tools must be design to behave in the same manner. (Conflict-detection sub-systems provide information to the conflict-resolution tool)
What defines a potential conflict?

Standard value indicating action by controller: 5NM

Potential conflicts are identified by the parameter $D_{sep}$. 
**Conflict-Resolution Policies**

Consider two different policies:

- **Minimum Conflict-Resolution Taskload (MCRT)**
  Least number of required aircraft movements

- **First-Come First-Serve (FCFS)**
  Simple priority ordering
**Minimum Conflict-Resolution Taskload Policy**

*Question:* What is the minimum number of aircraft movements to resolve all potential conflicts?

*Methodology:* Problem is equivalent to the Minimum Vertex problem.

Minimum Vertex Problem: What is the minimum number of nodes to remove such that graph is completely disconnected.

Removal of nodes is equivalent to resolution commands.
Minimum Conflict-Resolution Taskload Policy

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FIRST-COME FIRST-SERVE POLICY

Aircraft that entered the airspace first have priority when deciding who to issue resolution commands to.
**Graph-based Modeling**

Graph based modeling does not provide information about the type of resolution issued.

Represents an approximate lower bound (tighter approximation for TBO)
Abstraction of CDR Tools

Parameters

- Update Rate: $\delta t$
- Look-ahead time: $H$
- Separation Quality: $D_{sep}$
- Policy: FCFS or MCRT
Abstraction of CDR Tools

Parameterization related to the three fundamental questions:

- What is the value of information towards reducing conflict-resolution taskload? $H$
- How often should trajectory and conflict information be updated? $\delta t$
- How does the quality of information affect controller taskload? $D_{sep}$
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Simulation Modeling
Simulation Procedure

- Generate 50 days of flight-plans (1X-3X Intensity)
  Increasing intensity decreases length of day
  (e.g. 3X → 8hr day)
- Apply graph-based CDR tool according to parameters
  - Look-ahead: \( H \)
  - Update Rate: \( \delta t \)
  - Quality: \( D_{sep} \)
  - Policy
- Analyze conflict-resolution taskload
Using 28 days of PDARS data for Minneapolis Center, the simulation model attempts to approximate the conflict-event process within a sector for traffic above FL200.
Basic Sector Analysis

Number of uncontrolled conflicts = \( \text{card}(E) \)

\[ (D_{sep} = 5\text{NM}) \]

Rate of uncontrolled conflicts increases during peak hours
Basic Sector Analysis

Number of uncontrolled conflicts = \( \text{card}(E) \)
\[
(D_{sep} = 5\text{NM})
\]

Total number of uncontrolled conflicts increases exponentially with traffic intensity
(Similar to previous research using FACET)
**Basic Sector Analysis**

Number of aircraft in each conflict-cluster  
(Same definition used by Granger and Durand)

Supports the need for conflict-resolution algorithms to expend beyond sequential pair-wise formulations.
Simulation Analysis
ZMP42
As $H \to \infty$, system approaches complete information.
(ensures conflict-free resolutions)
**Analysis: MCRT** \( (D_{sep} = 8\text{NM}) \)

As \( H \to \infty \), system approaches complete information. (ensures conflict-free resolutions)
Analysis: MCRT ($D_{sep} = 8\text{NM}$)
As $\left(H, \delta t\right) \to 0$, system behavior is reactionary.
More significant conflict-resolution taskload reduction occurs at higher intensity levels - (esp. during peak traffic hours)
Analysis: Quality vs. Look-ahead (MCRT)
**Analysis: Quality vs. Look-ahead (MCRT)**

For most cases, improving quality of information ($D_{sep}$) provides greater benefit for reducing conflict-resolution taskload.
Analysis: Quality vs. Look-ahead (MCRT)

Linear improvement due to quality:
Distribution of uncontrolled minimum miss-distances approximately linearly distributed.
Conclusion and Future Work
Conclusion

Review:

- Proposed graph-based model to describe the conflict-detection and resolution process
- Parameterized CDR systems ($H$, $\delta t$, $D_{sep}$, policy)
- Related the design and capabilities of CDR tools the quantity, quality, and update rate of information.
Conclusion

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Results:

- Provided adequate quality and quantity, the update rate is not as critical to reducing conflict-resolution taskload.
- The underlying policy dictating the CR process becomes increasingly important as traffic levels increase.
- The largest gains in reducing conflict-resolution taskload will come from improving the quality of information.
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Future Research

Remove assumption of symmetric capabilities of CDR systems
Introduce independent look-ahead times: $H_D$ and $H_R$.

Classification of a potential conflict is time-dependent: $D_{sep}(t)$
When $t \sim 0$, $D_{sep}(t) \sim 5\text{NM}$, else, $D_{sep}(t)$ grows with $t$.

Consider more complex priority policies.
How resolution commands can be spaced in time to maintain steady conflict-resolution taskloads, while considering other tasks (e.g. acknowledgements/hand-offs).

Unregulated Dynamics

Resolution Command

Take into account co-operative conflict-resolution.
Future Research

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Regulated Dynamics

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Sponsors

NASA
FAA
Air Force
Questions?