Airspace Encounter Models for Conventional and Unconventional Aircraft

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Future Needs for Collision Avoidance

Collision avoidance systems have an important role in the future of aviation

- Integration of unmanned aircraft into the airspace will require sense and avoid capability with proven target level of safety

- Next generation of air traffic control concepts will require enhancement of existing collision avoidance system onboard manned aircraft (TCAS)

Before deployment of new systems, rigorous safety analysis is required

- Determine required surveillance performance
- Evaluation of performance on different categories of aircraft
- Assessment of interoperability with existing systems
Problem Statement and Requirements

What are the encounter geometries that a collision avoidance system needs to resolve in the airspace?

• Statistically-representative of actual encounters
  – Approx. 1 minute window near point of closest approach
  – Provide realistic mix of encounter geometries and situations

• Physically-realistic dynamics
  – Aircraft equations of motion
  – Three-dimensional, able to handle multiple maneuvers / accelerations
  – Derived from operational data

• Cooperative and non-cooperative intruder characteristics
  – Cooperative situations may include ATC intervention
  – Wide range of possible aircraft performance characteristics

• Support fast-time simulation
Safety Assessment Simulation Framework

-**Raw radar data** → Tracking and fusion
- Feature extraction → Aircraft flight profiles and dynamics
- Collision avoidance system models (sensors, algorithms) → Encounter models
- Fast-time simulation → Relative risk analysis
- Density models → Encounter rate estimation
- Sensor environment model → Density processing
- Track database

**Collisions per encounter** → **Collisions per flight-hour**

**Encounter rate estimation**
- **Encounters per flight-hour**
- **Density models**
- **Collision avoidance system models (sensors, algorithms)**
- **Feature extraction**
- **Tracking and fusion**
- **Raw radar data**

**Density processing**

**Sensor environment model**

**Track database**

**Cooperative:** Observed encounters per flight-hour
- Proportional to traffic density and airspeeds

**Non-coop:**
Encounter Model Development History

**Increasing fidelity and data requirements**

- **1980**: MITRE (US) - Vertical-motion encounters only, 12 radar sites, 1,683 encounters
- **1985**: ICAO (U.S. & Europe) - 3D, single acceleration periods, 6 radar sites, 2,387 encounters
- **1990**: Eurocontrol (Europe) - 3D, multiple acceleration periods
- **1995**: Lincoln Laboratory (US) - 134 radar sites, 427,367 encounters
- **2000**: TCAS Mandate (US)
- **2005**: TCAS Mandate (Worldwide)

**MIT Lincoln Laboratory**
Encounter Model Categories

<table>
<thead>
<tr>
<th>Aircraft of interest</th>
<th>Discrete code</th>
<th>1200/VFR</th>
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Conventional: General Aviation typical of 1200-code aircraft
Unconventional: balloons, gliders, ultralights,…

Appropriate Model

- **Correlated (cooperative)**
  - Prior U.S. model needed to be updated, captures RVSM
  - Assumes ATC involvement

- **Uncorrelated 1200-code (non-cooperative surrogate)**
  - First model to capture encounters between VFR aircraft
  - Assumes no ATC involvement

- **Uncorrelated (unconventional aircraft)**
  - Models vehicles unlikely to carry transponders
  - Assumes no ATC involvement
Data Sources

Models based on continuous, real-time radar data from Air Force 84th Radar Evaluation Squadron (RADES)

- Includes raw and unprocessed data for both cooperative and non-cooperative aircraft
- 134 ASR and ARSR sensors used in model
- Total airspace coverage results in traffic density characterization

Difficult to create an encounter model using primary only tracks
- Unconventional models created using pilot-uploaded GNSS data
Encounter Model Taxonomy

Unconventional model composed of 9 individual models

- Need to simulate against each type to determine specific system deficiencies
Airspace Encounter Models

Model Development Overview

Radar tracker

Radar tracker

Radar tracker

Airspace Statistics

Fusion tracker

Encounter Database

Feature Extraction

i.e.,
Class D airspace
1200 ft AGL
3 deg/s turn
1500 ft/min climb
80 kt airspeed
0 kt/s acceleration

VFR Track Database

Feature Extraction

Uncorrelated Model

Models encounters between two aircraft
~800,000 encounters; 16 variables

Correlated Model

Models nominal
VFR flight
~100,000 VFR flight hours
6 variables

GPS tracker

GPS Post-Processing

Feature Extraction

Unconventional Model

Models unconventional aircraft—e.g., paragliders, balloons, skydivers
~100,000 flight hours
5 variables

134 radar sites
~10 GB per day

~100,000 VFR flight hours
6 variables

134 radar sites
~10 GB per day
Model Development Process

1. **Observed Track Database**
   - Outlier removal
   - Track smoothing
   - Interpolation

2. **Synthetic Track Database**
   - Track Generation

3. **Feature Extraction**
   - Feature Smoothing
   - Quantization

4. **Table Construction**
   - $P(\text{turn rate at } t+1 | \text{turn rate at } t, \text{altitude})$

5. **Sampling**
Encounter Construction

Uncorrelated Encounters

Uncorrelated Model

Randomly initialize AC2 trajectory on surface of the encounter cylinder centered on AC1

AC1 Trajectory

AC2 Trajectory

Correlated Encounters

Correlated Model

Configure trajectories so that the sampled horizontal miss distance, vertical miss distance, relative heading, and relative bearing are accomplished at time of closest approach

AC1 Trajectory

AC2 Trajectory
Model Validation

- Unmodeled features of randomly-generated encounters compared to observed
  - Altitude crossing and slow closure encounter rates

- Compared uncorrelated model characteristics against true primary-only tracks
  - Model characteristics similar to a large class of non-cooperative tracks
  - Other non-cooperative aircraft tracks captured by unconventional model

- Examined seasonal and regional variations
  - Densities very sensitive
  - Trajectory characteristics not sensitive
• Model description reports
• Data tables
• Software to generate trajectories
• Traffic density database

Current users
- JHU/APL
- MITRE/CAASD
- MTSI
- Northrop Grumman Corp.
- USAF Simulation and Analysis Facility (SIMAF)
TCAS Safety Analysis
- Re-analyzed the performance of TCAS II versions 7.0 and 7.1
- Used to determine relative benefits of logic and surveillance modifications

Unmanned Collision Avoidance Systems
- Examined the use of TCAS on Global Hawk UAS, focusing on sensitivity to latency
- Models used to analyze candidate systems for Global Hawk and Predator B UAS
- Demonstrated electro-optical field of view and range trade-off study

*Risk Ratio = P(Near Mid-Air Collision with System)/P(Near Mid-Air Collision without System)
Future Development and Applications

- Multi-threat encounter model
  - Encounters between more than two aircraft occur more often than anticipated

- Update encounter models and density database to reflect future changes in the airspace

- Exploit models within future collision avoidance architecture, involving probabilistic intruder trajectory propagation

![Notional Threat Logic](image_url)

Airspace Encounter Models - 15
Summary

• Developed a new statistical approach to encounter modeling, optimally leveraging recorded data
  – Models validated using several quantitative and qualitative techniques

• Created first encounter models that capture non-cooperative aircraft, including conventional and unconventional aircraft
  – Models and software to generate samples are publicly available

• Models are being used by several organizations for manned and unmanned collision avoidance system development and analysis