Establishing a Risk-Based Separation Standard for Unmanned Aircraft Self Separation

Roland E. Weibel, Matthew W.M. Edwards, and Caroline S. Fernandes
MIT Lincoln laboratory
Surveillance Systems Group

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UAS Airspace Access Requirement: Sense & Avoid Capability

- **U.S. Federal Aviation Regulation (FAR) General Flight Rules**
  
  FAR 91.111: ...not operate so close to another aircraft as to create a collision hazard
  FAR 91.113: Vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft”
  “[In certain situations] pilots shall alter course to pass well clear of other air traffic”

- **Unmanned Aircraft Systems (UAS) inherently lack an onboard pilot to see & avoid other aircraft**
  - Technology performs “sense & avoid” as a means of compliance with “see and avoid” general flight rules
  - Requirements for sense & avoid performance currently under development

- **Sense & avoid systems must meet demanding safety performance requirements in performing separation functions**
  - Risk targets expected to be on the order of $10^{-7}$, $10^{-9}$ collisions/hr
  - Methods to evaluate safety performance to the required fidelity require analytical performance objectives
Sense and Avoid Elements

System Elements

- COTS ground based 3D radar, FAA
- Airborne sensor development
- Data fusion and Tracking
- Threat detection and Maneuver
- Sensors
- Algorithms

Sense and Avoid System

Decision Support Aids

Fault Tree & Event Trees to Assess Risk

- Loss of separation (Encounter)
- Miss
- Miss
- Miss
- Midair Collision
- Well Clear Violation
- ATC saves
- Manned See & Avoid saves
- Self Separation saves Collision Avoidance saves
- ATC fails
- See & Avoid fails
- SS fails
- CA fails

Standards

- Modeling & Simulation
- Airspace Characterization
- Safety Case
- Open Architectures
- Testbeds

MIT Lincoln Laboratory Support Activities
Sense and Avoid Concepts

Ground-Based

- Rapid deployment enabled by leveraging existing ground-based surveillance and tools
- The same surveillance and support hardware supports a diverse range of platforms
- Operational volume limited by surveillance coverage

Airborne

- Unconstrained operations enabled by surveillance volume fixed to platform
- Longer timelines associated with developing and certifying airborne components
- Smaller platforms may not have the size, weight, or power to support airborne hardware

Path forward: GBSAA ➔ ABSAA ➔ Hybrid
Well Clear as a Separation Standard

- General flight rule requirements dictate that aircraft must remain “well clear”
  - US FAR Part 91
  - ICAO Rules of the Air

- Two generally accepted sense & avoid functions
  - Self separation: performance of maneuvers to remain well clear
  - Collision avoidance: aggressive maneuvers to avoid collision

- Well clear is a standard for performing the self separation function
  - Performance measure for visual separation from other traffic
  - Not previously quantified due to lack of sensor distance measures
  - Consistent with ICAO definition of separation minima*: 
    “The minimum displacements between an aircraft and a hazard which maintain the risk of collision at an acceptable level of safety”

• **Objective for UAS:** separation standard would provide a measurable threshold for UAS sense & avoid safety
  – Sets a clear measure for failure of a function, and supports:
    - design of self separation algorithms/ decision support
    - fast time safety simulation
  – Scalable for future airspace changes beyond UAS

• **Approach:** separation standard modeling of risk
  – Assess separation standard relationship to risk of near midair collision (NMAC)
  – Utilize encounter models to determine relationship of relative state and risk over large number of representative encounters

• **Other aspects are also important, but not considered here**
  – E.g.: wake vortex, collision avoidance system alerts, etc.

**Analytical Definition of Well Clear**

Derived Using Separation Standard Methodology

- Aircraft 1
- Aircraft 2
- Relative State between Aircraft 1-2
- Future trajectories
- Collision Risk
- Acceptable Risk
- Well clear
- Relative State
Conditional Probability of Near Midair Collision

$P(\text{NMAC}|\text{state})$

- 2 trajectories pass through the state shown
- 1 trajectory results in an NMAC
- Therefore 1/2 of trajectories through state counted as an NMAC, and 1/2 not counted
- $P(\text{NMAC}|\text{state}) = 0.5$

Notional example:

- 2 trajectories pass through the state shown
- 1 trajectory results in an NMAC
- Therefore 1/2 of trajectories through state counted as an NMAC, and 1/2 not counted
- $P(\text{NMAC}|\text{state}) = 0.5$

Note: Modeling performed in 3 dimensions
Encounter Model Used and Associated Assumptions

• Uncorrelated encounter model: probabilistic model of aircraft dynamics based on surveillance data
  – Highest fidelity encounter model to date of the NAS
  – Based on approximately one year of data from 134 radars from the US Air Force 84th Radar Evaluation Squadron (RADES)
  – Validated framework for TCAS safety studies
  – Allows for large-scale Monte Carlo simulations
  – Derived from 1200-code (VFR) aircraft

• Assumptions from Models
  – Aircraft randomly blunder into each other
  – Modeling does not include visual acquisition and avoidance maneuvers of either aircraft
  – Modeled P(NMAC) values will be higher than expected
Results

- Risk contours of $P(NMAC \mid \text{state})$
  - Distance as state measure: horizontal & vertical views
  - Time to CPA ($\tau$) as state measure: risk curve, mean values

- TCAS resolution advisories
  - Likelihood of TCAS RA: horizontal & vertical views

- Risk contours indicate potential well clear boundary definitions
  - If intruder aircraft crosses boundary, it is no longer well clear

- TCAS alert contours indicate potential interoperability concerns
Horizontal Position Contours

Assumptions
• 3D simulation
• 10 million encounter pairs
• MIT LL uncorrelated encounter model
• No avoidance mitigations
• NMAC = 500 ft radius x 200 ft cylinder
Vertical Position Contours

Assumptions
- 3D simulation
- 10 million encounters
- MIT LL uncorrelated encounter model
- No avoidance actions taken
- NMAC = 500 ft radius x 200 ft cylinder
Time to CPA

**Assumptions**
- 3D simulation
- 10 million encounters
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**Notes**
- Tau shown in seconds
- TCAS sensitivity level varies
- TCAS Version 7.1
Mean Unmodified Tau Values: Horizontal

Assumptions
• 3D simulation
• 10 million encounters
• MIT LL uncorrelated encounter model
• No avoidance actions taken
• NMAC = 500 ft radius x 200 ft cylinder

Notes
• Includes both corrective and preventative RAs
• TCAS sensitivity level varies
• TCAS Version 7.1
Probability of RA in Effect: Horizontal

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- 3D simulation
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Probability of RA In Effect: Vertical

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- 3D simulation
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Conclusions

• Analysis of well clear as a separation standard is a viable approach to deriving an analytical definition
  – Builds on ICAO 9689 airspace planning guidance
  – Initial results are promising and straightforward

• A preliminary definition based on a 5% P(NMAC | state) would be:
  – Horizontal: Ellipse 8000 ft ahead, 5,000 ft behind, 3,000 ft laterally
  – Vertical: +/- 300 ft in altitude

• Continued development of an analytical standard for UAS SAA compliance with well clear is ongoing
Questions

Caroline Fernandes
Associate Technical Staff
Surveillance Systems
Email: caroline.sieger@ll.mit.edu
Phone: (781) 981-8161

Matt Edwards
Associate Technical Staff
Surveillance Systems
Email: matthew.edwards@ll.mit.edu
Phone: (781) 981-4709

Roland Weibel
Technical Staff
Surveillance Systems
Email: roland.weibel@ll.mit.edu
Phone: (781) 981-6913