Safety Analysis Methodology for UAV Collision Avoidance Systems

James K. Kuchar

6th USA / Europe Seminar on Air Traffic Management Research and Development

27-30 June 2005

This work is sponsored by the Air Force under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the U.S. Government.
Federal Aviation Regulation
14 CFR Part 91.113 b

Vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft

See-and-Avoid Requirement to Operate Within Civil Airspace

Global Hawk Certificate of Waiver or Authorization

IFR flight plan plus:
- Primary radar, or
- Visual observation (air or ground), or
- Forward and side looking cameras, or
- Electronic detection equipment
On-Board UAV Collision Avoidance Systems

- See-and-avoid systems (visual, IR, laser, radar)
  - Potential to satisfy see-and-avoid requirement and enable file-and-fly access
  - Under development (limited flight demonstrations)

- Traffic Alert and Collision Avoidance System (TCAS)
  - Existing, well-understood, certified (for manned aircraft)
  - Not a complete solution
    - Detects only cooperative / transponder aircraft
UAV Collision Avoidance System Concerns

• Lack of on-board pilot to monitor and respond
  – Remote pilot response to resolution advisories
    Communication and control latencies can induce collisions
  – Autonomous response to resolution advisories
    Reliability requirements, ability to detect failure and intervene
  – Use of traffic display
    Cannot aid visual acquisition; not intended to support maneuvering

• UAV performance characteristics
  – Different types of encounters with air traffic (low airspeed, high vertical rate)
  – Maneuvering limits may constrain response

• Interoperability: ATC, TCAS, see-and-avoid on other aircraft
Global Hawk TCAS Safety Study

• Objectives
  – Build agreement between FAA, ICAO, and USAF on certification process
  – Design and implement safety analysis infrastructure
  – Perform safety analysis of TCAS on Global Hawk, reach certification decision
  – Test-case to trailblaze certification process for future see-and-avoid systems

• Coordination
  – US Department of Defense (Air Force, Navy)
  – FAA (Certification, Flight Standards, Air Traffic)
  – Industry (Northrop Grumman, Honeywell, MITRE/CAASD, Access 5)
  – RTCA SC-147 (TCAS), RTCA SC-203 (UAVs)
  – ICAO Surveillance and Conflict Resolution Systems Panel (SCRSP)
Safety Study Composition

• Collision avoidance performance is sensitive to situation, pilot/vehicle response
  – Flight tests / demonstrations are useful for extracting system characteristics and limited validation, but cannot explore all situations

• Core: fast-time simulation over broad range of conditions
  – Simulate millions of representative traffic encounters
  – Compile statistics: safety with TCAS relative to safety without TCAS
  – Couple with failure mode analysis and variations in pilot/vehicle response

• Suitability
  – Process based on accepted methods that have evolved over years of TCAS development in US and Europe
  – General agreement that process is appropriate for TCAS, UAVs, and see-and-avoid systems (included in ICAO ACAS Manual)
Safety Assessment Elements

Traffic Encounter Model → Simulation → Performance Metrics

- P(NMAC) and Risk ratio
- P(NMAC with TCAS)
- P(NMAC without TCAS)

Near Mid-Air Collision (NMAC) < 500 ft horizontal and < 100 ft vertical separation
Encounter Model Development

Large set of operationally-realistic close encounters (characteristics and likelihoods)

Example: Eurocontrol TCAS Study (2001)

- Radar Data
  - 5 Secondary Surveillance Radars in Europe
  - 5,585 hours of data (692,243 flight-hours)

- Encounter Filter
  - 1,243 close encounters

- Observed Parameter Distribution (e.g., miss distance)
- Random samples

- Database

- Random samples

- Vertical miss distance
- Horizontal miss distance
- Approach angle
- Lateral maneuver / bank angle
- Longitudinal acceleration
- Vertical maneuver / load factor
- Initial position and velocity
Encounter Model Status

• Several encounter models are available from prior TCAS studies
  – ICAO standard model (1990s US + European data); European model (2001)
  – Currently implemented in Lincoln Lab simulation framework

• New models are needed
  – Existing models do not capture UAV flight profiles
  – Traffic data outdated (old fleet mix), limited coverage (e.g., Europe only)

• Near-term efforts
  – Currently adapting existing models for Global Hawk flight profile
  – New US encounter model
Simulation Components

Manned Aircraft

- Visual acquisition
- TCAS
- Pilot response model
- Aircraft dynamic model

UAV

- TCAS
- See-and-avoid system
- Comm
- Pilot response model
- Comm
- UAV dynamic model

- = areas of planned growth
Example Encounter Scenario: Late Descent by Aircraft 2

Closest Point of Approach

Aircraft 1
Aircraft 2

Altitude (ft)

Time (s)
Example Encounter Scenario with TCAS

Standard pilot response model
5 second delay for both aircraft

Miss distance: 725 ft

Aircraft 1

Aircraft 2

Altitude (ft)

Time (s)

3000 3200 3400 3600 3800 4000 4200 4400 4600 4800 5000

0 10 20 30 40 50

Increase Descent

Descend

Do Not Climb

Clear of Conflict

Increase Climb

Climb

Increase Climb
Example Encounter Scenario with TCAS and Increased Delay for Aircraft 1

Aircraft 1: 10 second delay
Aircraft 2: 5 second delay

Situation 10 seconds before Closest Point of Approach
Example Encounter Scenario with TCAS and Increased Delay for Aircraft 1

Aircraft 1: 10 second delay
Aircraft 2: 5 second delay

Miss distance: 60 ft
• Logic Risk Ratio for TCAS equipage = 9%
  – Of which 3.7% is due to induced risk
  – Ideal conditions (no failures, pilots respond correctly)
  – Also compute logic risk ratios for other cases

\[ P(\text{NMAC}) = p \approx 2.7 \times 10^{-3} \]
System Risk Ratio: Fault Tree Analysis

Includes consideration of
System failures
Mixed intruder equipage
Variable pilot response
ATC intervention

Eurocontrol study:
System Risk Ratio ~ 27%

Fragment from
Eurocontrol ACASA TCAS fault tree (2000)
Summary

• UAV Collision Avoidance Systems are under development to improve safety and meet see-and-avoid requirement
  – Complex dynamic problem
  – Safety concerns must be resolved with high level of confidence

• Safety analysis method has been defined and implemented
  – Certification requires broad statistical simulation and analysis
  – Accepted through close interaction with FAA and ICAO

• Initial analysis: TCAS on Global Hawk
  – Provide data to support certification decision-making
  – Extension to see-and-avoid systems also underway