Unmanned Aircraft Collision Avoidance Technology Assessment & Evaluation Methods

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July 2007

7th ATM R&D Seminar
Barcelona, Spain

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“The development and use of unmanned aircraft systems is the next great step forward in the evolution of aviation”

— Nicholas A. Sabatini, Associate Administrator for Aviation Safety, July 13, 2006.
Key Operational and Technical Challenges

1. Cross-service C4ISR architecture and integration issues
2. Spectrum Management
3. UAS as threats and potential mitigations
4. Doctrine/Policies/Concepts of Operation
   - With wide-spread sharing of telemetry who maintains command authority over UAS?
   - Who has authority to fire weapons?
5. Airspace Integration
   - UAS and manned aircraft operating in the same airspace in theater
   - UAS Access to Civil Airspace
Civil Airspace Integration Issues
Balancing National Needs

National Security & Homeland Defense Needs
- Military Training & Readiness
  - Train like you fight
- Emergency Response
- Domestic-based Missions
- Border Patrol
- Law Enforcement …

Public Safety and Access to Airspace
- Mid-air Collision Risks
- Vehicle Reliability Posing Risks to Those on the Ground
- Airspace Deconfliction Reducing Airspace Access
  - TFRs not a scalable solution
- Air commerce and airspace efficiency
Some Civil Airspace Integration Issues

- Segregated airspace not a solution
  - Loss of access to airspace is a significant issue for stakeholders
- Target Level of Safety
  - Reliability issues – Safety of those on the ground
- **Collision avoidance: See and avoid → Sense and Avoid**
  - TCAS interoperability
- Air Traffic Control Interaction
  - Separation Standards
  - Communications Latency / Air-to-ground voice; Lost link
  - Flight Clearance vs. mission profile
  - Emergency procedures
  - Controller Workload → Potential Capacity implications
  - Air Traffic Flow Integration – Aircraft performance differences
- Operator/Pilot Qualifications
- Spectrum – Protected spectrum vs. military spectrum vs. unregulated spectrum
- Certification: Aircraft (especially autonomous software), Collision Avoidance, Pilots, GCS
Avoiding Collisions – Layered Approach

Instrument Flight Rules

Airspace Structure, Procedures

Strategic Separation Services – Conflict Probe

Radar Separation Services

Traffic Collision & Avoidance System (TCAS)/Cockpit Display of Traffic Information (CDTI)

See and Avoid

Risk of Collision Consistent with Target Level of Safety

Visual Flight Rules

Big Sky

Separation Assurance

Collision Avoidance

1

2

3

4

5
Challenges to UAS Collision Avoidance

Key Question: Can we introduce new traffic with mitigating collision avoidance that has Equivalent Level of Safety

- Target Level of Safety – Community accepted definition – Safe Case methods
  - Rate of collision vs. equivalence of a pilot
- Direct linkage to flight controls – Intensity of the degree of autonomy
  - Testing, Verifying, and certifying software-intensive autonomous flight critical systems
  - Non-deterministic inputs – Infinite number of system states.
- Limited Resources
  - Development of TCAS: $400M and 15 years\(^1\)
    - TCAS II RA Sense Reversal Logic – Small mod to existing TCAS resulting from Swiss collision – 5 years and $12.4 M\(^2\)
- Policy Issue: Single, government-provided solution vs. multiple solutions Acceptance of a definition of Equivalent Level of Safety

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1: Ann Drumm (MIT-Lincoln Lab), Lawrence J. Nivert FAA, Jerry L. Anderson (FAA)  
Use of TCAS/ACAS on Global Hawk – Presented to ICAO  
2: Steve George (FAA)
Challenges to UAS Collision Avoidance (concluded)

• Complex requirements:
  – IFR/VFR; Night/Day; Transponding and Non-transponding; with TCAS Aircraft; with ADS-B; minimal change to existing aircraft; Obstacles in the air and on the ground …
  – Backwards compatible with TCAS maneuvers
  – Range of aircraft
    • Size/weight/power Limitations
    • Flight Performance Differences
  – Integrated approach to collision avoidance
• Likely to depend upon State of the art for sensor technology
  – Suite of sensor modalities likely needed for range and bearing accuracy

UAS Collision Avoidance is significantly more complex than TCAS
Comprehensive Evaluation at Each Step

*System performance evaluated at the component level and end-to-end*

- Sensor measurements and target tracking
- Algorithms that determine threats and (optionally) provide resolution advice
- Communication link latency and accuracy, when a remote pilot is in the loop for collision avoidance
- Pilot latency and accuracy in avoiding the hazard, when in the loop
- Aircraft maneuverability (e.g., latency, acceleration, maximum bank or vertical speed)
## The Analytic Questions Leads to the Evaluation Method

### Analytic Questions

<table>
<thead>
<tr>
<th>Question</th>
<th>Evaluation Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>What does the sensor see? Range? Azimuth? Elevation? Speed?</td>
<td>✓</td>
</tr>
<tr>
<td>How large an object can it see? How far away?</td>
<td>✓</td>
</tr>
<tr>
<td>Are sensor specifications accurate?</td>
<td>✓</td>
</tr>
<tr>
<td>Does the system function together?</td>
<td>✓</td>
</tr>
<tr>
<td>Does collision avoidance capability provide safe separation from manned aircraft?</td>
<td>✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Do collision avoidance algorithms react in an acceptable way for other pilots?</td>
<td>✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>Does capability act in an acceptable way in the context of the operating environment (e.g., ATM)?</td>
<td>✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>What are the limits of the capability? Conditions? Size or number of targets?</td>
<td>✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>How does collision avoidance technology compare to “see and avoid”?</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
<tr>
<td>What is the overall system performance? i.e., resulting collision risk</td>
<td>✓ ✓ ✓ ✓ ✓ ✓</td>
</tr>
</tbody>
</table>
MITRE Sponsored Research
Sense and Avoid for Small Unmanned Aircraft
– PI Dave Maroney

- **Research Question**: Can small autonomous aircraft reliably detect conflict and avoid collision with objects (stationary and moving) in its path, that do not announce their position?
  - Combination of Sensors
  - Discover and refine the Sense and Avoid requirements by testing different combinations

- **Promising sensors**
  - Ultra wide-band ranging
  - Electro-optic/optical flow
  - Laser Range finder

**Findings – MITRE Research**
- Technology will not be ready in the near term
- Single sensor solution not likely
- Determining bounds on performance

- **VFR Airspace operation**, mixed with manned aircraft, without transponders
- Fixed and moving obstacles
- Reactive timeframe
- Add “ounces to pounds”
## Putting Bounds on Performance

<table>
<thead>
<tr>
<th></th>
<th>Active</th>
<th>Passive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Required</strong></td>
<td>More</td>
<td>Less</td>
</tr>
<tr>
<td><strong>Field of Regard of a single non-moving sensor</strong></td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td><strong>Sensor Resolution</strong></td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td><strong>Processing Requirement</strong></td>
<td>Less</td>
<td>Much More</td>
</tr>
<tr>
<td><strong>Targets</strong></td>
<td>Moving</td>
<td>Stationary</td>
</tr>
<tr>
<td><strong>Example Modes</strong></td>
<td>Laser Radar Acoustic</td>
<td>Electro-optic Thermal</td>
</tr>
</tbody>
</table>
# Qualitative Sensor Comparison

<table>
<thead>
<tr>
<th>Modality</th>
<th>Range</th>
<th>Bearing (Azimuth)</th>
<th>Bearing (Elevation)</th>
<th>Trajectory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode A/C Transponder</td>
<td>Cooperative</td>
<td>Accurate; 10s of miles</td>
<td>Calculated based on pressure altitude</td>
<td>Derived</td>
</tr>
<tr>
<td>ADS-B</td>
<td>Cooperative</td>
<td>Accurate; 10s of miles</td>
<td>Calculated based on GPS</td>
<td>Provided</td>
</tr>
<tr>
<td>Optical</td>
<td>Non-Cooperative, Passive</td>
<td>Not sensed</td>
<td>Accurate</td>
<td>Accurate</td>
</tr>
<tr>
<td>Thermal</td>
<td>Non-Cooperative, Passive</td>
<td>Not sensed</td>
<td>Accurate</td>
<td>Accurate</td>
</tr>
<tr>
<td>Laser/LIDAR</td>
<td>Non-Cooperative, Active</td>
<td>Accurate; 1000 ft</td>
<td>Narrow</td>
<td>Derived</td>
</tr>
<tr>
<td>Radar</td>
<td>Non-Cooperative, Active</td>
<td>Accurate; 1 mile</td>
<td>360 degrees (Depends upon antenna mounting)</td>
<td>Derived</td>
</tr>
<tr>
<td>Acoustic</td>
<td>Non-Cooperative, Active</td>
<td>Accurate; 100 ft</td>
<td>360 degrees</td>
<td>Derived</td>
</tr>
</tbody>
</table>
Conclusions

- Certifiable Sense and Avoidance capability is a key enabler but not a silver bullet
- Technology may also be applicable to manned aircraft
- Integrated collision avoidance system
  - Transponder-based CA (i.e., ACAS) must work in conjunction with Sense & Avoidance
  - Key research: Algorithms: Sensor Fusion – Position & Track, extensible to new sensors; Determine confidence level for maneuver; Determine appropriate maneuver
  - Leverage broad spectrum of available technologies in an integrated fashion including: TCAS/Mode S, ADS-B, RNP/RNAV containment zones
  - Collision avoidance standards must be considered in the context of operational concepts/procedures as well as other UAS-related standards especially communications
- Collision avoidance today relies upon human judgment
  - What will be the certification requirements for autonomous collision avoidance?
- A variety of evaluation methods are needed
  - Must consider total system when evaluating mechanisms to avoid UAS collisions – Not just the see and avoidance layer
- No single sensor will be sufficient to address all UAS collision avoidance requirements
  - Fused sensors → surveillance accuracy and system integrity
  - Algorithms for sensor fusion, collision detection, and maneuver determination

If we seamlessly operate unmanned & manned aircraft in the same airspace, we have transformed aviation.
Backups
Generic Process Model

Sense

Detect

Avoid

Surveillance

Identification of Risk

Determination of Appropriate Avoidance Maneuver

Maneuver

Return to Course

Outcome

Collision Avoided
(or Violation of Separation Averted)
Objectives

0 Demonstrate feasibility of lightweight, low-cost ADS-B radio for small UAS and GA aircraft to improve surveillance
0 Modular architecture to enable stand-alone unit or integration with other aircraft electronics

Activities

0 Develop portable, battery-operated transmitter with modular subsystems
0 Assess custom and commercial antennas for suitability
0 Flight test UAT Beacon radio to assess link performance and UAS integration
  ∙ Manned and Unmanned
Traffic-alert and Collision Avoidance System (TCAS)¹

• 1990 – FAA mandated installation on large passenger aircraft
  – Developed by MITRE and Lincoln Labs

• Surveillance – Mode C transponder
  – “Sees” about 40 miles

• Common avoidance algorithm provided by the FAA
  – TCAS I – Traffic Advisories (TA) only – ~40 seconds*
  – TCAS II – TAs and vertical Resolution Advisories (RA) – ~25 seconds*

• In 15 years, only two mid-air collision between two TCAS equipped aircraft
  – Germany July 2002 – One pilot ignored RA
    • Community revising algorithm
  – Brazil, Sept 2006 – B737 & Embraer Legacy
    • Cause still being investigated

• Key Safety Analysis Question: Does the reduction in collision risk due to TCAS warrant cost of deployment?
  – Risk ratio – Existing traffic mitigated risk of collision w/ new technology

  “ACAS should not be fitted to UAV at this stage”
  — ICAO Technical Committee

¹ ICAO uses the term Airborne Collision Avoidance System (ACAS)

* Depends upon altitude
Regulatory Requirements – “See and Avoid”

• CFR 14 Part 91 – General Operating and Flight Rules – Section 91.113: “When weather conditions permit, regardless of whether an operation is conducted under instrument flight rules or visual flight rules, vigilance shall be maintained by each person operating an aircraft so as to see and avoid other aircraft”
  – “may not pass over, under, or ahead of it unless well clear.”
  – Right-of-way rules defined

• Airman’s Information Manual - 5–5–8. See and Avoid
  – “Pilot. When meteorological conditions permit, regardless of type of flight plan or whether or not under control of a radar facility, the pilot is responsible to see and avoid other traffic, terrain, or obstacles.”

Sense and Avoid equivalent to See and Avoid not a silver bullet
Ensuring Aviation Safety

Federal Aviation Administration
- Establishes standards, regulations, polices, processes, and procedures
  - CFR 14
  - Advisory Circulars
  - Airworthiness Directives
  - FAA Orders
- Certifies aircraft, pilots, operations, airports, airlines, and operators
- Ensures safe and efficient air traffic flows
  - Air Traffic Management

Unmanned aviation changes everything

Acceptable Level of Safety
• Investigate sensing modalities
  - Range, FOV, Coverage, Size, Power,
• Appropriate sensor for appropriate region
• Applicability for air platforms
Exploring in Depth: SAA Testing

• Test Methodology (low hanging fruit from sensor investigation)
  – Lab
  – Ground
  – Air

• Airborne Testing
  – Architecture

• Test Fleet
  – Helos
  – Fixed wing

• Sample of Sensor testing
  – (air) Camera, LRF
  – (lab) Optic flow, acoustic, UWB
Testing Architecture

- **Gumstix Processor**
  - Sense Data Collect
  - Detect-Avoid Process
  - Steering Cues to auto

- **Computer**
  - "Data collect" SW
  - "Detect and avoid" SW provides steering cues to **human pilot**
  - Manual (uplink):
    - 4 channels for control surfaces
    - Automatic (uplink):
      - Program commands to fly waypoints
  - Downlink:
    - Craft status and GPS info
      - (loc, alt, spd, hdg)

- **Computer**
  - "Horizon" SW
  - 4 channels for control surfaces
  - 1 channel to switch PIC/CIC

- **DL**
  - CIC autopilot
  - PIC
  - Control surfaces

- **RF**
  - Radio control

- **sensor**
  - DL
  - Control surfaces
Fixed Wing Test Platforms

Senior Telemaster
- Power: Glowfuel 0.71 cu in
- Wingspan: 94 in
- Wing Area: 1,330 sq in
- Weight: 10.5 lb (no payload)
- Length: 64 in (1420 mm)
- Equipment: MicroPilot 2028g autopilot
  2.4GHz downlink to GCS

Nexstar
- Power: Electric
- Wingspan: 69 in
- Wing Area: 722 sq in
- Weight: 6.5 lb (no payload)
- Wing Loading: 21 oz/sq ft (no payload)
- Length: 56 in
- Equipment: Video Camera/2.4GHz downlink
  Eagle Tree data log (with GPS)

Ground Control Station
- MicroPilot Horizon on a Laptop
- Eagle Tree data logging
- 2.4GHz pt to pt modem at 19.2kbps
- 2.4GHz diversity video receiver
- Sony video camera
Rotary Wing Test Platforms

GasXcell
Power: Zenoah .231 cu in gas engine
Rotor span: 62 in
Weight: 15.1 lb (with payload)
Equipment: MicroPilot 2128g autopilot
Video Camera/2.4GHz downlink

Ground Control Station
MicroPilot Horizon on a Laptop
Oculus data visualization software
Point to point 19.2kbps modems
2.4GHz and 900MHz
2.4GHz diversity video receiver
Sony video camera

SpectraG
Power: Zenoah .260 cu in gas engine
Rotor span: 65 in
Weight: 19.0 lb (with payload)
Equipment: MicroPilot 2128g autopilot
Video Camera/2.4GHz downlink
4xGumstix network computers

Coming: Rotomotion
10lbs Payload Capacity
Ready-to-Fly Autonomous
802.11-based Telemetry System
Stable hover (Patent Pending)
25 Knots Top Speed