MIT Lincoln Laboratory Support to Unmanned Aircraft Systems Integration into the US National Airspace

MIT Industrial Liaison Program Research and Development Conference

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• Background
• Sense and Avoid overview
• Sense and avoid development
• Summary
Growing Demand for UAS Operations in the National Airspace

- Crew Training
- CONUS Basing for International Missions
- Oceanic and Littoral Surveillance
- Coastal Surveillance
- Border Surveillance
- Environmental Monitoring (Law Enforcement, Disaster Relief)

Diverse operational requirements for UAS in the national airspace
Growth in UAS Operations

“2009 is the first year the AF will train more ground-based UAV operators than ‘fighter jockeys’ and bomber pilots.”
- Gen. Stephen Lorenz, head of Air Education and Training Command

Steady increase in operations will outgrow DoD airspace
UAS Airspace Operations

Today

• Lengthy COA process
  – Mean time to complete 150 days
  – Requires advanced ATC coordination planning prior to operations

• See and Avoid surrogate outside Class A and restricted airspace
  – Chase aircraft or ground observers

• Conduct operations above 18,000 ft if no chase aircraft

• Visual flight conditions

Desired Future

File and Fly

• Same process as manned aircraft
  – No advanced coordination required

• Seamlessly integrate with traffic in all airspace classes
  – See and Avoid performed by UAS

• Conduct operations at any altitude

• No constraints on visual conditions

Need incremental progress toward open access to the national airspace
### Barriers to UAS Airspace Integration*

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Time</th>
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<tr>
<td></td>
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<tr>
<td>Pilot Qualifications</td>
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<td>Airworthiness</td>
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<td>Ops Stds &amp; Procedures</td>
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<td>Equipage</td>
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<tr>
<td>Sense-and-Avoid (SAA)</td>
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Lincoln focus

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**Sense and avoid is the principal technical hurdle to airspace integration**

* JUAS COE “Airspace Integration Capabilities Based Assessment”, 2009.
Outline

• Background

• Sense and Avoid overview

• Sense and avoid development

• Summary
“SAA is the capability of an unmanned aircraft to remain well clear from and avoid collisions with other airborne traffic”*

- **Self-separation** – strategic maneuvering to maintain “Well Clear”
- **Collision avoidance** – tactical, last-minute maneuver to avoid a collision

- **Principal sub-functions are:**
  - Airspace surveillance
  - Threat detection
  - Threat avoidance maneuver

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*SAA is the capability of an unmanned aircraft to remain well clear from and avoid collisions with other airborne traffic*

*FAA Sponsored “Sense and Avoid” Workshop Final Report, 2009.*
Sense and Avoid Concepts

- 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

Path forward: GBSAA ➔ ABSAA ➔ Hybrid
Sense and Avoid Elements

System Elements

- COTS ground based 3D radar, FAA
- Airborne sensor development
- Sensors

Data fusion and Tracking

- Threat detection and Maneuver
- Algorithms

Decision Support Aids

Sense and Avoid System

Enabling Activities

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

• Background
• Sense and Avoid overview

• Sense and avoid development
  – Standards
  – Threat detection and maneuver guidance
  – Modeling and simulation
  – Testbeds to demonstrate capabilities

• Summary
Sense and Avoid Standards Development

- FAA-sponsored Sense & Avoid Workshops
  - Defined “sense and avoid”
  - Defined key essential elements of any SAA system

- OSD Target Level of Safety (TLS) Workshop
  - Define DoD’s understanding of target level of safety

- RTCA Special Committee 203
  - Industry, FAA, and DoD committee to define minimum SAA standards

MIT/LL is Strongly Engaged in UAS Community and Regulatory Standards Development
Standards Development: Well Clear

**Well Clear Definition**

- FAA-sponsored workshop requirement for SAA system to perform self separation
  - Ability to stay “well clear” of air traffic
  - Well clear concept from regulatory language, but is not defined

- MIT LL is establishing a risk-based separation standard based on our safety assessment framework
  - Provides quantitative, analytical definition as the basis for system evaluation
  - Definition based on risk of collision after crossing the separation boundary

**Analytical Well Clear Boundary**

- Well clear threshold
  - Derived based on unmitigated probability of NMAC from random encounters

Laboratory is playing key role in developing and defining standards to support UAS airspace integration.
Standards Development: Target Level of Safety

Required target level(s) of safety is currently being determined by the FAA/DoD/NATO

* Aircraft not under ATC control
## Lincoln ACAS-X based Logic Development Efforts

**FAA**
- Airborne Collision Avoidance System (ACAS X)
- 4 year FAA effort to replace TCAS
- Designed to be highly adaptable to changes in sensors, airspace and aircraft performance
- FAA prototype effort flight test in FY13
  - Existing TCAS surveillance, new threat logic developed by MIT LL

**Army/Air Force GBSAA**
- Maneuver algorithm adapted from FAA ACASA-X development
  - Self separation
  - Collision avoidance
- Conflict avoidance algorithms being evaluated in CASSATT
- Integration in Army testbed at Dugway Proving Grounds

**DHS ABSAA**
- Prototype low cost, size, weight and power SAA sensor
  - Electronically scanned phased array
  - Applicable to Pred-B, Fire Scout, and other mid-sized UAS
- Flight tests of sensor in FY12 on surrogate manned aircraft
- Conflict avoidance studied off-line
First Use of Lincoln Maneuver Algorithm Approach
Airborne Collision Avoidance for Unmanned Aircraft

• Internally funded in FY08

• Initial application was to unmanned aircraft (in collaboration with MIT CSAIL)
  – Vertical collision avoidance
  – Autonomous (no pilot delay)
  – Different sensor systems, dynamics, and performance constraints
  – Consistent approach applied (build model, choose cost metric)

• Led to the FAA funded effort to build next generation collision avoidance algorithms

<table>
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<tr>
<th>Modality</th>
<th>Measurement Accuracy</th>
<th>Coverage</th>
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<td>TCAS</td>
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<td>Radar</td>
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<td>EO/IR</td>
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<td>ADS-B</td>
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ACAS X Problem Statement

NextGen procedures and surveillance necessitate changes to TCAS

• TCAS logic is heuristic and difficult to revise
• Challenges to collision avoidance logic development
  – Uncertainties due to sensor noise and aircraft behavior
  – Aircraft performance and operational constraints
  – Need to maximize safety while minimizing unnecessary alerts
• Solution is a decision-theoretic approach to collision avoidance logic development
  – Uses explicit models of sensor and dynamic uncertainty
  – Optimizes logic according to objective performance measure
  – Leverages advances in computation and algorithms
Logic Development Comparison

Legacy TCAS Development Cycle

- Human effort focused on pseudocode
- Time-consuming process
- Many parameters require tuning
- Unlikely to be optimal

Model-Based Optimization Approach

- Human effort focuses on models
- Computers generate lookup table
- Optimal logic
  - Low false-alert rate
  - High degree of system safety

Model-based approach is much more easily adapted to NextGen needs
ACAS Logic Accounts For Uncertainty

• Previous methods use extrapolation of intruder path
  – Leads to single point of closest approach
  – Depending on situation uncertainty in point of closest approach can be high
  – May lead to induced encounters if probabilities of other intruder maneuvers are not accounted for

• Solution is to determine actions taking into account uncertainties in intruder path

• Other probabilistic aspects of collision avoidance:
  – UAS pilot response
  – Aircraft performance
  – State uncertainty (measurement error)
Dynamic Programming Logic Development and Implementation Overview

Offline Logic Optimization
Performed on high-performance computers

- Pilot, Intruder, Aircraft Dynamics Models
- Performance Metric
  Model Discretization
- Dynamic Programming
  Expected Cost Table

Real-time Logic Usage
Executed onboard aircraft (once per second)

- Expected Cost Table
- Sensor Measurements
  Tracker
  State, inc Uncertainty
- Action Selection
  Action (no alert, climb, descend)

Model-based, accounts for uncertainties
Adapting ACAS-X Algorithm for UA SAA

Key Differences with ACAS

- Different track error characteristics
- UA have different performance limits than manned aircraft
- UA sense and avoid must perform self-separation and collision avoidance
- Two different levels of alert urgency

Adaptation Steps

- Adapt aircraft dynamic model to UA
- Change action space from vertical maneuvers to horizontal for self-separation
- Same action space for collision avoidance

Next Steps

- Performance modeling
- Develop coordination with manned collision avoidance (with NIEC)

ACAS-X model-based algorithm modified to support UA SAA
Safety Modeling and Simulation Framework

Realistic Fast-Time Simulation: millions of encounters

Raw radar data → Tracking and fusion → Feature extraction → Encounter models

Surveillance model → Aircraft flight profiles and dynamics → Collision avoidance system models (algorithms) → Fast-time simulation

Collisions per encounter → Relative risk analysis

Collisions per flight-hour

Track database → Density processing → Density models → Encounter rate estimation

Encounters per flight-hour

Target Level of Safety risk analysis

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

Density models

Encounter Rate Model

MS-57023B
M&S Applied to Notional GBSAA

Simulation of close encounters

Track Intruder
Self Separation
Collision Avoidance

Three radar system
Horizontal
Vertical

10 million encounters
10 million outcomes

Couple simulation results with airspace density

Estimated unmitigated collision rates

Unmitigated collision rate (per flight hr) | With mitigation collision rate (per flight hr)
---|---
25%-tile: $5 \times 10^{-8}$ | $1 \times 10^{-9}$
50%-tile: $3 \times 10^{-7}$ | $7 \times 10^{-9}$
75%-tile: $2 \times 10^{-6}$ | $5 \times 10^{-8}$

CASSATT framework is being used to refine and analyze threat detection and maneuver logic
### Testbed Efforts

<table>
<thead>
<tr>
<th>Army (GBSAA)</th>
<th>Air Force (GBSAA)</th>
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<tbody>
<tr>
<td>• Elimination of ground observers</td>
<td>• Focus on consolidating ground observer task</td>
</tr>
<tr>
<td>• Reference architecture to support RFP</td>
<td>• Cannon and Grey Butte</td>
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<tr>
<td>• First deployment to Dugway Proving Grounds</td>
<td>Lincoln roles:</td>
</tr>
<tr>
<td>summer 2011</td>
<td>• Airspace characterization</td>
</tr>
<tr>
<td>- Restricted airspace allows for unfettered testing</td>
<td>• Algorithm development</td>
</tr>
<tr>
<td>• Open architecture</td>
<td>• Modeling and simulation to support safety case</td>
</tr>
<tr>
<td>• Effort includes data fusion/tracking and Airman</td>
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<tr>
<td>maneuver algorithm development</td>
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<thead>
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<th>DHS (ABSAA)</th>
<th>FAA</th>
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<tr>
<td>• Demonstrate flexible, scalable airborne radar</td>
<td>• Army testbed efforts briefed to FAA Research and Technology Development (RTD)</td>
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<tr>
<td>system customizable to a broad set of UAS</td>
<td>office</td>
</tr>
<tr>
<td>• Prototype a flexible low SWAP phased array radar</td>
<td>• FAA RTD has expressed interest in the concept and potential application to</td>
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<tr>
<td>for SAA surveillance</td>
<td>support UAS research initiatives and NexGen technology implementation activities</td>
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<tr>
<td>• Flight tests on surrogate manned aircraft</td>
<td>• MIT and FAA RTD office to hold further discussions</td>
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<tr>
<td>• Test with both JOCA and MITCAS maneuver logic</td>
<td>• Discussions underway with TCAS program office to explore unmanned – manned</td>
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<td>aircraft collision avoidance coordination</td>
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- **MIT LL Lightweight Notch Array**

- **Sentinel or ASR-11**

- **STARS Lite**
Army
Ground-Based Sense and Avoid Program

Lincoln Roles

- Define Open Reference Architecture for sense and avoid
- Self separation and collision avoidance requirements and algorithms
- Sensor fusion and tracking requirements and algorithms
- Assessments of system components: sensors, avoidance logic, display concepts

Deployed to Dugway Proving Grounds summer 2011
Customs and Border Protection
Southern Border Patrol Operations

- Requires Certificate of Authorization
- Advanced coordination with ATC
- Observers/chase aircraft < 18K ft
- Generally daylight, visual conditions
- Mission ops at 19,000 ft only

- Desire ability to drop to 5,000 ft AGL for close-up observations
- Requires airborne sense and avoid

Under ATC Control

• Requires Certificate of Authorization
• Advanced coordination with ATC
• Observers/chase aircraft < 18K ft
• Generally daylight, visual conditions
• Mission ops at 19,000 ft only

• Desire ability to drop to 5,000 ft AGL for close-up observations
• Requires airborne sense and avoid
Surveillance System

- Key challenge is low cost, low power, lightweight, low profile active electronically scanned arrays (AESAs) (20kg, 200 W, $200K)
- MIT to build and demonstrate late FY12

Alerting Systems

AFRL Automatic Jointly Optimal Collision Avoidance

- Modified by NG/Bihrlle for Predator-B

MIT LL ACAS-X based logic*

- Current results for collision avoidance only

* Adapted from ACAS-X
Outline

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Summary

- Substantial progress in enabling UAS airspace integration is being made

- Laboratory roles:
  - Developing standards for UAS integration
  - Modeling and simulation to demonstrate safety
  - Sensor and algorithm development
  - Real-time architectures
  - Engaged with multiple stakeholders: DoD, DHS, FAA
  - Programs spanning airborne and ground-based sense & avoid
    - FAA engagement through the UAS Program Office and TCAS Program Office