Sense and Avoid for Unmanned Aircraft Systems: Integrity and Continuity

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Scope of Research

- New methods to quantify safety of sense and avoid (SAA) sensors for Unmanned Aircraft Systems (UAS) by evaluating integrity and continuity risks
  - Sensing to alert is addressed, avoidance maneuvering is not

- Methods to establish:
  - Integrity risk of not detecting imminent loss of self-separation
  - Probability of false alert, the continuity risk

- Results can be used to set sensor requirements
Overview

- Background
- Methodology
- 3D Sensitivity Analysis
The Need for Sense and Avoid

- FAA Modernization and Reform Act of 2012
  - Congressional mandate for broader UAS access into NAS
  - For safety, a UAS requires "sense and avoid" (SAA) capability
    - Analogous to "see and avoid" responsibility for manned aircraft

- Pilot must see and avoid non-cooperative intruders
  - Cooperative aircraft employ a transponder or ADS-B

- UAS will require a SAA system to sense intruder aircraft
  - Non-cooperative intruders will need to be sensed
  - Potential sensors include electro-optical, infrared or radar

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Self Separation and Collision Avoidance (CA)

- Self-separate to remain "well clear"
  - "Well clear" subjectively referenced in regulations\(^2\)
  - RTCA SC-228 defined a well clear threshold\(^3\)
    - Time to horizontal closest point of approach (CPA), \(\tau\), of 35 sec
    - Horizontal and vertical miss distances (MD) of 4000 ft and 450 ft\(^4\)

- CA maneuver to avoid a near mid-air collision (NMAC)

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\(^4\) RTCA SC-228, Draft *Detect and Avoid (DAA) Minimum Operational Performance Standards (MOPS)*, Sep 2015
Problem Statement and Response

- **Quantify SAA safety given sensor uncertainty**
  - Sensors can be noisy

- **In response, this research:**
  - Defines UAS SAA integrity risk and continuity risk methods
    - Ensures a predetermined level of safety
  - Maps and bounds sensor requirement trade space
    - Using single intruder, constant velocity model
    - Maintaining desired integrity and continuity
Integrity Risk and Continuity Risk

- **Integrity risk**: Probability of Hazardously Misleading Information (HMI) without providing a timely warning
  - SAA system senses no hazard when hazard is present

- **Continuity risk**: Probability of false alert (FA) where an alert is issued when no hazard is present
  - SAA system senses hazard when none present
  - FA's can lead UAS to maneuver unexpectedly
    - Potential increased workloads for ATC and intruder pilots
    - Induced hazards with different intruders

- **SAA integrity and continuity depend on sensor errors**
  - Certification can use both to allocate sensor requirements
Methodology and the Measurement Model

- **Methodology**
  - Define measurement model and trajectory states
  - Account for sensor error uncertainty
  - Define hazard states
    - Time to closest point of approach (CPA), tau
    - Horizontal CPA
    - Vertical distances at WCT circle entry and exit
  - Define integrity and continuity requirements
  - Set limits on hazard threshold buffers to meet integrity/continuity
  - Determine if sensors meet requirements or explore trade space

- **Measurement model**
  - Can be used for any sensor or any set of sensors
  - Trajectory states are intruder relative position and velocity
  - Determine trajectory state estimate error covariance
**Hazard States**

- Well Clear is lost when $5 \left( \tau_{\text{mod}} \leq \tau_{\text{SS}} \right) \cap \left( r_{\text{CPA}} \leq r_{\text{MD}} \right) \cap \left( z \leq \pm z_{\text{MD}} \right)$

- Four **hazard states** are derived from trajectory states
  - $\tau$, time to horizontal CPA: $\tau_{\text{mod}} = D_{\text{mod}}^{2} \left( \ddot{x} - \ddot{y} \right)^{2} \frac{x x + y y}{x x + y y} \quad \tau_{\text{true}} = \frac{-(x \ddot{x} + y \ddot{y})}{x x + y y}$
  - $r_{\text{CPA}}$, horizontal CPA distance: $r_{\text{CPA}} = \sqrt{(x + \tau_{\text{true}} \dot{x})^2 + (y + \tau_{\text{true}} \dot{y})^2}$
  - $z_+$ and $z_-$, vertical distances at 2D WCT circle entry and exit
    - Given $r_{\text{CPA}} \leq r_{\text{MD}}$: $z_{\pm} = z + \dot{z} \tau_{\pm} \quad r_{\text{MD}} = \sqrt{(x + \tau_{\pm} \dot{x})^2 + (y + \tau_{\pm} \dot{y})^2}$

- **Hazard estimate errors based on trajectory estimate errors**
  - Hazard state estimates $\hat{\tau}, \hat{r}_{\text{CPA}}, \hat{z}_+, \text{and } \hat{z}_-$ are correlated

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5. RTCA SC-228, Draft DAA MOPS, Sep 2015
Tau-only Integrity Risk

- **HMI**: a hazard exists, but that hazard is not sensed

- **Adjusted threshold for integrity**
  - At $\tau = \tau_{SS}$, probability of HMI is an unacceptable 50%
  - Adjust threshold by adding $k_{\tau} \sigma_{\tau}$ to $\tau_{SS}$
  - $Q(x)$ is the tail probability of the normal distribution

\[ P_{HMI} = P(\hat{\tau} > \tau_{SS} + k_{\tau} \sigma_{\tau} | \tau \leq \tau_{SS}) \quad (1) \]

- $P_{HMI}$ needs to be less than a given integrity requirement, $I_{\tau}$
  - To account for this, $k_{\tau} = Q^{-1}(I_{\tau})$
Integrity Risk for all Hazard States

- Horizontal and vertical thresholds are adjusted for integrity
  - $k_r \sigma_r$ is added to horizontal miss distance (MD) threshold, $r_{MD}$
  - $k_+ \sigma_+$ and $k_- \sigma_-$ are added to vertical MD threshold, $z_{MD}$

- HMI: a hazard exists, but that hazard is not sensed
  - $P_{\text{HMI}} = P[\text{Sense No Hazard} | \text{Hazard Exists}]$
Integrity Risk for all Hazard States

- $\hat{\tau}, \hat{r}_{CPA}, \hat{z}_+, \text{ and } \hat{z}_-$ are correlated
  - $P_{HMI}$ is computationally expensive quadruple integral
  - Analytic upper bounds are more appropriate for aviation

- **HMI must be less than the integrity requirement, $P_{HMI} \leq I_{SS}$**
  - HMI overbounded by Q-functions that are bounded by $I_{SS}$

![Diagram showing the risk for all hazard states with key variables and bounds]
Tau-only Continuity Risk

- False Alert (FA): no hazard exists, but a hazard is sensed

\[ P_{FA} = P(\hat{\tau} \leq \tau_{SS} + k_\tau \sigma_\tau | \tau > \tau_{SS}) \]  (2)

- \( P_{FA} \) needs to be less than a given continuity requirement
  - To account for this we select \( \ell_\tau = -\Phi^{-1}(C_\tau), \Phi(x) = 1 - Q(x) \)
  - When \( \tau_{SS} < \tau < (\tau_{SS} + k_\tau \sigma_\tau + \ell_\tau \sigma_\tau) \), FA rate is worse than \( C_\tau \)
Continuity Risk for All Hazard States

- Continuity buffers added to horizontal and vertical thresholds

- FA: a hazard is sensed, but no hazard exists
  - \( P_{FA} = P(\text{Sense Hazard}|\text{No Hazard Exists}) \)
Continuity Risk for All Hazard States

- Bound ensuring $P_{FA}$ is less than required continuity, $C_{SS}$
Operational Limits

- We inflate WCT to meet integrity/continuity requirements

- We want small \((k + \ell)\sigma\) to minimize impact on airspace
  - We choose an \(\epsilon\) as an operational limit on \((k + \ell)\sigma\)
  - Hazard state estimate standard deviations decrease with time

- \(\tau\) operational limits are \(\tilde{\sigma}_\tau \triangleq \frac{\epsilon\tau_{SS}}{k_\tau + \ell_\tau}\) and \(\tilde{\tau} \triangleq (1 + \epsilon)\tau_{SS}\)
  - Establishes top-level sensor requirements

- A good sensor will reduce each \(\sigma\) below \(\tilde{\sigma}\) prior to \(\tilde{\tau}\)
Applying Self-Separation Tests

- Similar curves and limits for $r$, $z_+$ and $z_-$
- For continuity, self-separation testing must be minimized
- Once all hazard $\sigma$'s are below their $\tilde{\sigma}$'s, one test is required
3D Example: Nominal Parameters

- Start with nominal spherical sensor
  - Radar: 5 Hz, $\sigma_\dot{\rho} = 0.5 \text{ ft}/\text{s}$, $\sigma_\rho = 5 \text{ feet}$\(^6\), 8 NM range\(^7\)
  - EO: $\sigma_\theta = 0.05^\circ$, $\sigma_\phi = 0.05^\circ$\(^8\)

- Use RTCA SC-228 Well Clear Threshold
  - $\tau_{SS} = 35 \text{ sec}$, $r_{MD} = 4000 \text{ feet}$, $\epsilon_{\tau} = \epsilon_r = 10\%$
  - $z_{MD} = 450 \text{ feet}$, $\epsilon_z = 56\%$, $z_{MD}(1 + \epsilon_z) = 700 \text{ feet}$

- $I_{SS} = 10^{-6}$ and $C_{SS} = 10^{-3}$
  - Set $k_{\tau} = k_r = k_+ = k_- = 4.98$ and $\ell_{\tau} = \ell_r = \ell_+ = \ell_- = 3.4$

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\(^6\)Chen, R. H., et al., *Multi-Sensor Data Integration for Autonomous Sense and Avoid*, AIAA Infotech@Aerospace, St Louis, MO, Mar 2011

\(^7\)Edwards, M., *A Safety Driven Approach to the Development of an Airborne Sense and Avoid System*, AIAA Infotech@Aerospace, Garden Grove, CA, Jun 2012

\(^8\)Chen, R. H., et al., *Multi-Sensor Data Integration for Autonomous Sense and Avoid*, AIAA Infotech@Aerospace, St Louis, MO, Mar 2011
3D Example: Trajectories

- Seven constant-velocity 3D intruder trajectories
  - Four head-on trajectories
    - Three descending: top-back, bottom-front, collision course
    - Level top
  - Three tangent trajectories
    - Level top, descend top, descend bottom
  - 370 knots closure, 5000 fpm for non-cooperative intruders

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9 RTCA SC-228, Draft DAA MOPS, Sep 2015
3D Example: Nominal Case

- All trajectories meet $\sigma_\tau$ and $\sigma_r$ requirements

![Nominal $\sigma_\tau$ vs $\tau$](chart1)

![Nominal $\sigma_r$ vs $\tau$](chart2)
3D Example: Nominal Case

- Trajectories do not meet $\sigma_+$ and $\sigma_-$ requirements

- Tangent trajectories are furthest from meeting requirements
  - Climb/descent rates largest impact: $z_{\pm} = z + \dot{z} \tau_{\pm}$

Nominal $\sigma_+$ vs $\tau$

Nominal $\sigma_-$ vs $\tau$
3D Example: Adjustment

- $\sigma_\theta$ improved slightly to $0.02^\circ$
- All trajectories now meet requirements
- Other options: range, sample rate, $k$'s, $\ell$'s, $\epsilon$'s
3D Example: Conclusions from Analysis

- Applied a method to determine sensor trade space
- Carried out a sensitivity analysis of sensor elements
  - Tangent trajectories most restrictive
  - Improving $\sigma_\theta$ had the most impact
Conclusions and Future Work

- **Developed SAA safety evaluation methods**
  - Advanced method quantifying UAS SAA integrity and continuity risk
    - Ensures a predetermined level of safety
  - Mapped and bounded sensor requirement trade space in 3D
    - Quantified performance with single intruder, constant velocity model

- **Future research**
  - Multiple intruder problem
  - Accounting for uncertainty of aircraft dynamics
  - Fault detection
  - Testing on hardware
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