Defining Well Clear Separation for Unmanned Aircraft Systems Operating with Noncooperative Aircraft

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ATOMS-15, UAS Traffic Management IV
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Detect and Avoid is the capability to remain well clear and avoid collisions

RTCA-228 Phase 1
Concept of DAA:

- Acquire Intruders
- Suggestive Guidance to Remain Well Clear
- Directive Guidance Issued to Avoid Collision
- Avoidance Maneuver
- Cooperative or Noncooperative Aircraft
- NMAC – Near Mid-Air Collision

*Notional Volumes
Does not indicate any temporal component that may exist

Cooperative – Transponder/ADS-B equipped
• DAA Well Clear is the UAS technical means of compliance for satisfying FAR 91.111 and 91.113

FAR 91.111: ...not operate so close to another aircraft as to create a collision hazard

FAR 91.113: Vigilance shall be maintained ... so as to see and avoid other aircraft ... pilots shall alter course to pass well clear of other air traffic

• Detect and Avoid (DAA) Systems provide surveillance, alerts, and guidance to Unmanned Aircraft Systems (UAS) to help them maintain well clear of other aircraft
  – Designed as an alternative means of compliance for see-and-avoid regulations
  – DAA systems are essential for safe integration of UAS into the National Airspace System (NAS)
Previous Work

• In 2015, Sense and Avoid Science and Research Panel (SARP) developed a Well Clear Definition for unmanned aircraft based on distance and time
  – RTCA SC-228 adopted definition within Phase 1 DAA MOPS (DO-365)
  – Phase 1 UAS is assumed to be equipped with ADS-B In, airborne active surveillance, and an air-to-air radar
  – Definition driven by TCAS II interoperability, but applied to all intruders regardless of equipage

Phase 1 DAA well clear adopted by FAA

\[ P(\text{NMAC}|\text{LoWC}) = 2.2\% \]

\[ h = +450 \text{ ft} \]

\[ HMD = 4000 \text{ ft} \]

\[ \tau_{mod}^* \text{ (estimated time to 4000 ft)} = 35 \text{ sec} \]

* Recommended \[ P(\text{NMAC}|\text{LoWC}) = 5\% \]
Phase 2 MOPS
DAA Well Clear Objective

Objective: Define alternative DAA Well Clear (DWC) for UAS encountering noncooperative aircraft (Noncoop DWC)

- Phase 1 DWC was designed to encompass TCAS II RA alerting thresholds
  - Resulting DWC is very safe but unnecessarily large for noncooperative aircraft, which do not have TCAS

- Noncoop DWC will enable low C-SWaP UAS operations by reducing noncooperative surveillance requirements compared to RTCA SC-228 Phase 1
  - Low C-SWaP UAS are too small or budget-constrained to carry the large, high-power radar required by the Phase 1 MOPS

- Noncoop DWC is anticipated to be applicable to both Phase 1 UAS and low C-SWaP UAS encountering noncooperative aircraft
Low C-SWaP UAS

• Typically operate at 500-10,000 ft MSL with speeds at or below 100 kts
• Extended operations in airspace classes D, E (non-terminal), or G (non-terminal) with transit operations in classes B and C
• Missions include air quality monitoring, aerial imaging and mapping, and law enforcement
• Can carry ADS-B and TCAS but may not be able to carry the Phase 1 radar (> 50 lbs)
Outline

• Background

• Defining Well Clear Separation for Unmanned Aircraft Systems Encountering Noncooperative Traffic
  – Approach
  – Low C-SWaP UAS Results
  – Phase 1 UAS Results

• Summary
DAA Well Clear Analysis for Noncooperative Intruders

- **Objective:** identify and assess DAA Well Clear (DWC) candidates based on safety and operational suitability metrics

- **Approach:** use realistic encounters* in fast-time simulation to evaluate unmitigated and mitigated performance against noncooperative intruders

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**Unmitigated**
- Unmitigated analysis does not include response to a Detect and Avoid system
- Evaluates inherent latent collision risk without mitigations
- Narrows tradespace

**Mitigated**
- Mitigated analysis includes DAA response using DAIDALUS algorithm
- Validates actual risk of each DWC

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Notional

- DAIDALUS (With modified parameters for each DWC)

* One million encounters

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Noncooperative DWC - 9
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DAA – Detect and Avoid
Encounter models generate random aircraft trajectories that are statistically representative of noncooperative trajectories observed from radar data.
Phase 1 UAS Encounter Model

Ownship speed is the main difference between the encounter sets
(Low C-SWaP: 40-100 kts, Phase 1: 40-250 kts)
Metrics*

• Safety metrics indicate whether desired separation is achieved
  - Risk ratio and loss of well clear ratios: \( \frac{P(\text{NMAC or LoWC}|\text{encounter, with mitigation})}{P(\text{NMAC or LoWC}|\text{encounter, without mitigation})} \)
  - Ratio less than 1 indicates that the mitigated system reduces the risk of NMAC or LoWC; e.g., risk ratio of 0.1 indicates 90% reduction in risk

• Operational suitability metrics indicate the appropriateness and severity of alerts required to remain well clear
  - Alert ratio: \( \frac{P(\text{Alert}|\text{encounter, with mitigation})}{P(\text{NMAC}|\text{encounter, without mitigation})} \)
  - Alert ratio measures the alert frequency relative to the nominal NMAC frequency; an alert ratio of 1 indicates the mitigated system only alerts when absolutely necessary
  - Severity: Counts of Caution and Warning alerts

*Additional metrics were computed but are not shown here
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Unmitigated Analysis: Trade Space Down Selection

- **DWC Candidates** chosen based on trade study [1] of potential DWC using unmitigated collision risk (P) and maneuver initiation range (MIR) as metrics:
  - DWC1 achieves smallest MIR of candidates with 5% unmitigated collision risk
  - DWC2 is simple because it does not have a time component
  - DWC3 was proposed for terminal area UAS operations
  - DWC4 achieves an unmitigated collision risk smaller than 5%

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<table>
<thead>
<tr>
<th></th>
<th>DWC1</th>
<th>DWC2</th>
<th>DWC3</th>
<th>DWC4</th>
<th>Phase 1</th>
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<tbody>
<tr>
<td>HMD*</td>
<td>2000 ft</td>
<td>2200 ft</td>
<td>1500 ft</td>
<td>2500 ft</td>
<td>4000 ft</td>
</tr>
<tr>
<td>$\tau_{mod}^*$</td>
<td>15 s</td>
<td>0 s</td>
<td>15 s</td>
<td>25 s</td>
<td>35 s</td>
</tr>
<tr>
<td>h*</td>
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HMD – Horizontal Miss Distance

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System Operating Characteristic for Low C-SWaP Encounters

- SOC allows simultaneous evaluation of safety and operational suitability.
- Risk and LoWC ratio are largely insensitive to DWC definition.
- HMD appears to have the largest effect on alert ratio.
  - DWC1 and DWC3 have the same $\tau_{mod}^*$, but DWC1 alerts more frequently.

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HMD – Horizontal Miss Distance
**Effect of Surveillance Range**

- **DWC 1, 2, 3** are largely insensitive to reduced surveillance ranges.
- **DWC 4 and Phase 1** experience large increases in risk ratio and loss of well clear ratio when surveillance range is reduced (see 2 NM blue bars).

**Note: Different y-axis scales**

- **New DWC candidates** support surveillance ranges down to 2 NM.
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• Summary
• Trends similar to results for low C-SWaP UAS
  – HMD appears to have the largest effect on alert ratio

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Risk or LoWC Ratio

Alert Ratio

Phase 1 NMAC Risk Ratios

- Induced
- Unresolved

0.10
0.02

Limited FOV
Full FOV

Risk Ratio
LoWC Ratio

DWC1
DWC2
DWC3
DWC4

Phase 1

System Operating Characteristic for Phase 1 UAS Encounters

HMD – Horizontal Miss Distance
FOV – Field of View

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Effect of Ownship Speed on Safety

- Sensitivity of DWC definition to ownship speed:
  - $HMD^*$ has the larger impact at low speeds
  - $\tau_{\text{mod}}^*$ has little effect on safety at low speeds
  - Smaller $\tau_{\text{mod}}^*$ reduces the safety ratios at high speeds

$\tau_{\text{mod}}$ may not be necessary in DAA Well Clear definition for noncooperative intruders
Conclusions

- Performed unmitigated and mitigated analysis of four candidate well clear definitions for low C-SWaP UAS against noncooperative intruders
  - NMAC and LoWC risk not sensitive to DWC parameters
  - Safety and operational suitability not dependent on $\tau_{mod}^*$
    - Indicates $\tau_{mod}^*$ may not be necessary

SC-228 selected DWC2 (2200 ft, 450 ft, 0 $\tau_{mod}^*$) for low C-SWaP UAS and Phase 1 UAS encountering noncooperative aircraft

- Future work:
  - Development and validation of sensor requirements based on the noncoop DWC
  - Additional human factors evaluation of noncoop DWC
  - Additional safety analyses in the presence of sensor noise
Bibliography (images)

- Aerosonde by Michael Paetzold, source image, Creative Commons Share-Alike License 3.0, text applied on bottom of image on slide 7