Low C-SWaP Detect and Avoid: Defining Well Clear

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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

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

- Well Clear is a separation standard required for UAS to satisfy 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 and avoid collisions
  - 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)
Classes of UAS
Example Attributes Relevant to DAA and Well Clear

**Large UAS**
- Example: Reaper
- • Size: Business jet and up
- • Flight in all airspace
- • Integrate with all aircraft including TCAS equipped
- • DAA requirements developed through RTCA
- • Phase 1 DAA MOPS published – non-terminal ops in Class D/E/G – includes DAA radar
- • Phase 2 includes terminal

**Low Size Weight Power UAS**
- Example: TigerShark
- • Size: >55 lbs to several thousand pounds
- • Flight below 10,000 ft
- • Carry ADS-B but may not TCAS
- • DAA requirements developed through RTCA
- • Phase 2 MOPS includes Low C-SWAP UAS
- • Too small to carry Phase 1 DAA radar

**Small UAS**
- Example: Raven
- • Size: 55 lbs and below
- • Flight at very low altitude
  - Currently < 400 ft
- • Ops currently under Part 107
- • Regulations for expanded ops in development
  - FAA IPPs
- • DAA requirements developed through ASTM
  - In process

Focus of Talk
Previous Work

• In 2015, Sense and Avoid Science and Research Panel (SARP) developed a Well Clear Definition for large unmanned aircraft using distance and time, based on
  – Safety: Required Prob(NMAC) given a well clear violation < 5%, 2.2% achieved
  – Suitability*: Low rates of triggering a TCAS alert on the intruder aircraft
  – Intruder TCAS alerts were a major driver
  – RTCA SC-228 adopted definition within Phase 1 DAA MOPS (DO-365)
  – Led to DAA air-to-air radar requirements
  – Relaxing well clear definition and radar requirements may be possible when intruder is not equipped with TCAS

Phase 1 DAA well clear adopted by FAA

NMAC – Near mid-air collision (HMD ≤ 500 ft., VMD ≤ 100 ft.)
LoWC – Loss of Well Clear
HMD – Horizontal Miss Distance

* Various other suitability metrics were used as well
Objective: Define alternative DAA Well Clear (DWC) for UAS encountering aircraft without a transponder (noncooperative)

- Phase 1 DWC accounts for TCAS II alerts (Resolution Advisories)
  - Definition is very safe but maybe unnecessarily large for noncooperative aircraft, which do not have TCAS

- Low C-SWaP UAS are too small or budget-constrained to carry the large, high-power radar required by the Phase 1 MOPS

- A noncoop DWC may enable low C-SWaP UAS operations by reducing noncooperative surveillance requirements compared to RTCA SC-228 Phase 1

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

Focus of Talk
Outline

• Background

• Defining Well Clear Separation for Low C-SWaP UAS Encountering Noncooperative Traffic
  – Approach
  – Results

• Summary
DAA Well Clear Analysis

- **Objective:** identify and assess DAA Well Clear (DWC) candidates based on safety and operational suitability metrics
- **Approach:** Monte Carlo simulation* using one million realistic encounters to evaluate unmitigated (without DAA) and mitigated (with DAA) performance against noncooperative intruders

**Without DAA**
- Analysis does not include response to a Detect and Avoid system
- Evaluates baseline collision risk
- Narrows tradespace

**With DAA**
- Analysis includes DAA response using DAIDALUS algorithm
- Validates collision risk of DAA equipped aircraft

* Assumes perfect surveillance

Notional

DAIDALUS
(With modified parameters for each DWC)
Encounter Model
Low C-SWAP UAS vs Noncooperative Intruders

Encounter models generate random aircraft trajectories that are statistically representative of noncooperative trajectories observed from radar data.

- Results may not apply to higher speed UAS

VFR – Visual Flight Rules (non-TCAS equipped aircraft)
NAS – National Airspace

Synthetic Encounter Generation (Uncorrelated Encounter Model)

- NASA UAS Missions
- NAS Radar Data
- NASA UAS Track Database
- VFR Model
- MQ-19 Aerosonde

UAS Trajectory  Intruder Trajectory

Initialize aircraft geometry

Low C-SWaP UAS Encounter Characteristics

- Estimated PDF
- Altitudes (feet)
- Speeds (knots)
- Aerosonde
- Shadow

Frequency

Aerosonde  Shadow
Ownship  Type
Mitigated 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

*Additional metrics were computed but are not shown here

**Encounter Timeline:**
- Suggestive guidance to remain well clear
- Directive guidance to avoid collision

**Noncooperative Intruder**

\[\text{Well Clear volume}\]

\[\text{NMAC}\]

NMAC – Near mid-air collision (HMD ≤ 500 ft, VMD ≤ 100 ft)
LoWC – Loss of Well Clear
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Unmitigated Analysis: Trade Space Down Selection

- DWC Candidates chosen based on trade study [1] of potential DWC based on:
  - P - collision risk without DAA
  - MIR - maneuver initiation range

- Results
  - DWC1 achieves minimum MIR for 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%

<table>
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<tr>
<th></th>
<th>DWC1</th>
<th>DWC2</th>
<th>DWC3</th>
<th>DWC4</th>
<th>Phase 1</th>
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<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>
<td>450 ft</td>
<td>450 ft</td>
<td>450 ft</td>
<td>450 ft</td>
<td>450 ft</td>
</tr>
</tbody>
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HMD – Horizontal Miss Distance

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).

New DWC candidates support surveillance ranges down to 2 NM.

Note: Different y-axis scales
Summary

• Well Clear used in RTCA SC-228 Phase 1 is not well suited for encountering noncooperative aircraft
  – Overly conservative against aircraft not equipped with TCAS
  – Results in DAA radar requirements that cannot be met by Low C-SWaP UAS

• Objective was to examine if a smaller Well Clear would be suitable for DAA using low C-SWaP sensors

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

SC-228 selected 2200 ft horizontally, 450 ft vertically for UAS encountering noncooperative aircraft
Bibliography (images)

- MQ-9 Reaper by Lt. Col. Leslie Pratt, source image, public domain
- TigerShark by Ken Ulbirch, source image, NASA
- Raven by USGS, source image, public domain
Future Work

- Develop and validate sensor requirements based on the noncoop DWC
- Human factors evaluation of noncoop DWC
- Safety analyses in the presence of sensor noise
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 typically will not be able to carry the Phase 1 radar (> 50 lbs)
Alerting and Guidance Algorithm

- Detect and AvoID Alerting Logic for Unmanned Systems (DAIDALUS) as reference DAA algorithm

- Parameters for Corrective and Warning based on standard configuration for Phase 1
  - $t_{mod}^\ast$ and $h^\ast$ are not buffered
  - HMD$^\ast$ for alerting $\sim 1.519 \times$ HMD$^\ast$ for DWC
  - Time to the volume defined by HMD$^\ast$, $t_{mod}^\ast$, and $h^\ast$ for alerting
    - 30 seconds for Warning
    - 60 seconds for Corrective

- Guidance based on 7 deg/sec turn rate

- 4 second persistence and 2-of-4 (m of n) alerts
• Use SC-228 pilot model created by Lincoln Laboratory
  – Executed in deterministic mode
    • Always maneuvers horizontally in the direction of the minimum suggested maneuver; turns left if minimum suggestion is inconclusive
    • Follow guidance bands without buffer
  – Timing:
    • Decision updated according to alert state
    • Execution delay after decision: 3 sec

• Analyze horizontal maneuvers only
  – Low-SWAP turn rate: 7 deg/sec
    • Suitable for UAS speeds from 40 to 100 kts

<table>
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<tr>
<th>Alert Condition</th>
<th>Decision Update Period (s)</th>
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<tbody>
<tr>
<td>No Alert</td>
<td>24</td>
</tr>
<tr>
<td>Preventive Alert</td>
<td>15</td>
</tr>
<tr>
<td>Corrective Alert</td>
<td>9</td>
</tr>
<tr>
<td>Warning Alert</td>
<td>9</td>
</tr>
<tr>
<td>Regain DAA Well Clear Guidance</td>
<td>3</td>
</tr>
</tbody>
</table>
Safety Ratios

NMAC Risk Ratios

- Risk ratios are comparable among the DWC candidates
  - No statistically significant difference for risk ratios
- DWC1 and DWC2 have the lowest loss of well clear ratios

Risk ratios largely independent of DWC definition
• Time and range of alert are for any alert level
• Time of alert is the projected time to CPA when the alert occurs (to prevent DAA maneuvering from affecting the metric)
• Alerting time and range driven more by ModTau than HMD (DWC 1/2 difference)
• LoWCs have later alert times and ranges: indicates that LoWCs may be caused by late nominal (non-DAA) maneuvers