Design of Sensor Standards for RQ-7B Shadow under Loss-Link

Lack of See-and-Avoid Capability

Vulnerabilities of Command and Control Link

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Zach Moore
Sam Ogdoc
Jon Pearson

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Agenda

• Context Analysis
• Stakeholder Analysis
• Problem & Need Statement
• Scope Overview
• Design Alternatives
• Method of Analysis
• Results
• Conclusions and Recommendations
Unmanned Aircraft System

- A UAS is the unmanned aircraft and all of the associated support equipment, control station, data links, telemetry, communications and navigation equipment, etc., necessary to operate the unmanned aircraft.

<table>
<thead>
<tr>
<th>UAS Categories</th>
<th>Operational Altitude (ft)</th>
<th>Typical Payload</th>
<th>Airspeed (kts)</th>
<th>UAS Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>&gt; 40,000</td>
<td>RADAR</td>
<td>&gt; 250</td>
<td>Global Hawk</td>
</tr>
<tr>
<td>Group 2</td>
<td>≤ 40,000</td>
<td></td>
<td></td>
<td>Predator Reaper</td>
</tr>
<tr>
<td>Group 3</td>
<td>≤ 10,000</td>
<td>Moving Target Indicator (MTI)</td>
<td>≤ 250</td>
<td>Pioneer Dragonfly Eagle Eye</td>
</tr>
<tr>
<td>Group 4</td>
<td>≤ 5,000</td>
<td></td>
<td>≤ 100</td>
<td>Shadow Silver Fox ScanEagle</td>
</tr>
<tr>
<td>Group 5</td>
<td>≤ 1,000</td>
<td>E-O/IR</td>
<td>≤ 60</td>
<td>Hornet Raven MAV</td>
</tr>
</tbody>
</table>

[1]
Expanding Roles of UAS

- The Federal Aviation Administration (FAA) set a Target Level of Safety (TLS) of $10^{-7}$ (collisions per flight hour) in the System Safety Handbook (SSH).

[2],[3]
# Manned VS Unmanned

<table>
<thead>
<tr>
<th></th>
<th>Manned Aircraft</th>
<th>Unmanned Aircraft System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pilot Location</strong></td>
<td>Onboard</td>
<td>Ground Control Station</td>
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<tr>
<td><strong>Collision Avoidance</strong></td>
<td>See-and-Avoid</td>
<td>Sense-and-Avoid (SAA)</td>
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<tr>
<td></td>
<td>Visual Scanning</td>
<td>Sensors</td>
</tr>
<tr>
<td><strong>Avoidance Maneuver</strong></td>
<td>Direct Pilot Commands</td>
<td>Pre-Programmed Procedure</td>
</tr>
</tbody>
</table>

- See-and-Avoid
- Sense-and-Avoid (SAA)
- Visual Scanning
- Sensors
- Direct Pilot Commands
- Pre-Programmed Procedure
Sense-and-Avoid

• FAA (2009) – “Sense-and-Avoid (SAA) is the capability of a UAS to remain well clear and avoid collisions with other airborne traffic.”
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- Context Analysis
- **Stakeholder Analysis**
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## Stakeholder Analysis

<table>
<thead>
<tr>
<th>Primary Stakeholders</th>
<th>Objectives</th>
<th>Conflicts/Tensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAA</td>
<td>• Developing policy, guidance material, and Standards for the NAS</td>
<td>• No Standardization Requirements</td>
</tr>
<tr>
<td>DoD</td>
<td>• Military Operations</td>
<td></td>
</tr>
<tr>
<td>DHS</td>
<td>• Border Protection and maritime surveillance</td>
<td>• Put pressure on FAA to integrate UAS into the NAS to accomplish objectives</td>
</tr>
<tr>
<td>NASA</td>
<td>• Science and aeronautical research</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Objectives</th>
<th>Conflicts/Tensions</th>
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<tbody>
<tr>
<td>Air Traffic Controllers</td>
<td>• Secure and maintain the orderly flow of air traffic</td>
<td>• Increased Workload</td>
</tr>
<tr>
<td>Manned Aircraft Pilots</td>
<td>• Avoid collisions</td>
<td>• Sense-and-Avoid &lt;&lt; See-and-Avoid</td>
</tr>
<tr>
<td>UAS Manufacturers</td>
<td>• Manufacture UAS for operators</td>
<td>• Different procedures to perform SAA</td>
</tr>
</tbody>
</table>
Agenda

• Context Analysis
• Stakeholder Analysis
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**Problem / Need Statement**

- **Problem:** Currently, UAS sensors do not perform at the level necessary to ensure the TLS of $10^{-7}$ is met while operating under loss-link.

```
Level of Safety

<table>
<thead>
<tr>
<th>Sensor Capability</th>
<th>0</th>
<th>1</th>
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</table>
```

- **TLS**

- **Gap**

- **Need:** A safety analysis of sensor capabilities is needed to assure that sensors are capable of detecting the necessary amount of aircraft that allows the UAS to meet the TLS set forth by the FAA.
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Airspace Classifications

- **Airspace** – The space lying above the earth or a certain area above land or water; esp. the space lying above a nation and coming under its jurisdiction.
- In the United States, airspace jurisdiction is granted to the FAA by Title 49 of the United States Code.
RQ-7B Shadow

• Aircraft Armament Inc. (AAI)

• Mission: Provides near-real-time reconnaissance, surveillance, target acquisition, and enforce protection.

• Onboard sensors: Electro-optic/Infrared (E-O/IR)

• Currently equipped with POP300
  o Israel Aerospace Industries (IAI)

POP300 sensor
E-O/IR Sensors

• 2 sensors: Daylight CCD camera & Infrared Sensor
  o Daylight Visible CCD Camera – a visible light imaging ranged system which can only be used in the day time. Carries a high magnification and resolution.
  o Infrared sensor – infrared ranged light imaging system which senses and differentiates one object from another by their difference in temperature.

• E-O/IR Sensor Alternatives:

<table>
<thead>
<tr>
<th></th>
<th>Resolution (pix)</th>
<th>Azimuth (deg)</th>
<th>Elevation (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP300</td>
<td>640x480</td>
<td>±60 – 130</td>
<td>-60 – +15</td>
</tr>
<tr>
<td>POP300D</td>
<td>1280x1204</td>
<td>±180</td>
<td>-90 – +25</td>
</tr>
</tbody>
</table>
Scope Summary

• Class E Airspace at an altitude of 3000 ft. AGL
• Group 4 UAS: RQ-7B Shadow
• The UAS will be operating under loss link with no outside communication
• Operating in the X-Y plane
  o Only horizontal resolution considered
  o Elevation not a factor
• Only the RQ-7B Shadow and another aircraft will exist in the airspace at any given time
• No elevated terrain within the airspace
• No weather disturbances while under loss-link.
  o i.e. clouds, thunderstorms
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## Design Alternatives

<table>
<thead>
<tr>
<th>Sensor Model</th>
<th>Horizontal Resolution (pix)</th>
<th>Azimuth (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP300</td>
<td>640</td>
<td>+90°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±110°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±130°</td>
</tr>
<tr>
<td>POP300 x 2</td>
<td>1280</td>
<td>±130°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±150°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±170°</td>
</tr>
<tr>
<td>POP300D</td>
<td>1605</td>
<td>±180°</td>
</tr>
<tr>
<td>POP300D x 2</td>
<td>3210</td>
<td></td>
</tr>
</tbody>
</table>

- Small Azimuth = High Detection Range
- Large Azimuth = Low Detection Range
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Method of Analysis

Airspace Simulation

Sensor Performance Model

Gas Model of Aircraft Collisions

Generated Aircraft

SLS*: Simulated Level of Safety – No SAA
ELS*: Expected Level of Safety – Validation
ALS*: Actual Level of Safety – Design alternatives

A: Airspace Area
N: # Aircraft

E[Vr]: Expected Relative Velocity

SLS*: Simulated Level of Safety
ELS*: Expected Level of Safety
ALS*: Actual Level of Safety

Generated Aircraft

A: Airspace Area
N: # Aircraft

g: Aircraft Dimension
Airspace Simulation

- No SAA Performed
- Generated Aircraft Parameters
  - (X,Y) - random location on an edge of the airspace
  - P – Heading – random depending on initial location
  - V – Velocity ~ N(126.5,22.5) NM/hr
  - G – Dimension ~ N(29.86,3.58) ft.

- Outputs
  - $\beta$: projection of manned aircraft onto the UAS (degrees)
  - $E[Vr]$ - average of relative velocities for each aircraft with respect to the UAS
    \[ V_r = (v_i^2 + v_j^2 - 2v_i v_j \cos(\beta))^{1/2} \]
  - NMAC Data – X, Y, P, V, G, $\beta$, Vr – recorded whenever NMAC occurs
  - #NMACs & #Collisions
  - Simulated Level of Safety (SLS) - # Collisions / Flight Hours
Airspace Simulation Results

- 10,227,820 flight hours simulated
  - \( E[V_r] = 120.70 \text{ NM/hr} \)
  - \( S[V_r] = 7.67 \text{ NM/hr} \)
- Collisions = 3095
  - Collisions / Flight Hour (SLS) = \( 3.03 \times 10^{-4} \)
- Near Midair Collisions (NMAC) = 56,887
  - NMACs / Flight Hour = \( 5.65 \times 10^{-3} \)
Gas Model of Aircraft Collisions

- Derived from the Gas Model of Particle Collisions
- Validation for Airspace Simulation (SLS > ELS)
- Assumptions:
  - N aircraft operate in an airspace with area A
  - Each aircraft travels in a straight line with constant velocity
  - Aircraft headings ~ U(0°, 360°)
- Calculates rate of collisions per unit time, ELS:
  - \( ELS = (N - 1) \frac{2(g)(E[V_r])}{A} \)
  - \( ELS = (2 - 1) \frac{2(8.09 \times 10^{-5})(121.70)}{400} = 4.89 \times 10^{-5} \frac{\text{collisions}}{\text{flight hour}} \)
  - Recall: 3.03 \times 10^{-4}
Sensor Performance Model

- Minimum time to perform SAA
  - \( t_{total} = t_{detect} + t_{warn} + t_{turn} \)
    - \( t_{detect} + t_{warn} \approx 0 \text{s} \)
    - \( t_{turn} = 5.6 \times \sqrt{\frac{\pi}{2} - \phi} \text{ s} = 5.6 \times \sqrt{\frac{\pi}{2} - 30^\circ} = 5.73 \text{s} \)

- We assume the minimum detection threshold is 1 pixel

- Detection range, \( d \):
  - \( g \) – aircraft dimension
  - \( \theta = \frac{2 \times \text{Azimuth}}{\# \text{pixels}} \)
  - \( d = \frac{g}{\tan(\theta)} \)

- % NMACs detected
  - \( \frac{\# \text{NMACs detected}}{\text{Total \# NMACs}} \)

- Actual Level of Safety
  - \( ALS = (1 - \% \text{NMACs Det.}) \times P(C) \)
Sample Calculations

\( \theta = \frac{2 \times \text{Azimuth}}{\# \text{pix.}} = \frac{180^\circ}{640 \text{ pix.}} = 0.28^\circ \text{pix.} \)

\[ d = \frac{g}{\tan(\theta)} = \frac{0.005 \text{NM}}{\tan(0.28)} = 1.02 \text{NM} \]

\[ \% \text{NMACs Det.} = \frac{\# \text{NMACs Det.}}{\text{Total NMACs}} \]

\[ = \frac{10,259}{56,887} = 0.16 \]

\[ ALS = (1 - \% \text{NMACs Det.}) \times P(C) = (1 - 0.16) \times P(C) = 2.53 \times 10^{-4} \]

\[ \theta = \frac{2 \times \text{Azimuth}}{\# \text{pix.}} = \frac{260^\circ}{640 \text{ pix.}} = 0.41^\circ \text{pix.} \]

\[ d = \frac{g}{\tan(\theta)} = \frac{0.005 \text{NM}}{\tan(0.41)} = 0.70 \text{NM} \]

\[ \% \text{NMACs Det.} = \frac{\# \text{NMACs Det.}}{\text{Total NMACs}} \]

\[ = \frac{18,394}{56,887} = 0.32 \]

\[ ALS = (1 - \% \text{NMACs Det.}) \times P(C) = (1 - 0.32) \times P(C) = 2.05 \times 10^{-4} \]
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## Sensor Performance Results

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Azimuth (deg)</th>
<th>Avg. Detection Distance (NM)</th>
<th>Avg. TBN (s)</th>
<th>% NMACs Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP300</td>
<td>±90</td>
<td>1.10</td>
<td>8.88</td>
<td>16.53</td>
</tr>
<tr>
<td></td>
<td>±110</td>
<td>0.91</td>
<td>7.19</td>
<td>27.62</td>
</tr>
<tr>
<td></td>
<td>±130</td>
<td>0.82</td>
<td>5.90</td>
<td>32.33</td>
</tr>
<tr>
<td>2x POP300</td>
<td>±130</td>
<td>1.67</td>
<td>12.91</td>
<td>47.97</td>
</tr>
<tr>
<td></td>
<td>±150</td>
<td>1.41</td>
<td>11.09</td>
<td>69.16</td>
</tr>
<tr>
<td></td>
<td>±170</td>
<td>1.28</td>
<td>9.73</td>
<td>91.17</td>
</tr>
<tr>
<td>POP300D</td>
<td>±180</td>
<td>1.50</td>
<td>11.92</td>
<td>99.97</td>
</tr>
<tr>
<td>2x POP300D</td>
<td>±180</td>
<td>3.07</td>
<td>25.10</td>
<td>99.99</td>
</tr>
</tbody>
</table>
## ALS Results

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Azimuth (deg)</th>
<th>Actual Level of Safety</th>
<th>Utility</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP300</td>
<td>+90</td>
<td>2.53*10^{-4}</td>
<td>0.2899</td>
</tr>
<tr>
<td></td>
<td>+110</td>
<td>2.19*10^{-4}</td>
<td>0.3201</td>
</tr>
<tr>
<td></td>
<td>+130</td>
<td>2.05*10^{-4}</td>
<td>0.3349</td>
</tr>
<tr>
<td>2x POP300</td>
<td>+130</td>
<td>1.57*10^{-4}</td>
<td>0.3958</td>
</tr>
<tr>
<td></td>
<td>+150</td>
<td>9.33*10^{-5}</td>
<td>0.5250</td>
</tr>
<tr>
<td></td>
<td>+170</td>
<td>2.67*10^{-5}</td>
<td>0.7944</td>
</tr>
<tr>
<td>TLS Threshold 10^{-7}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POP300D</td>
<td>+180</td>
<td>8.51*10^{-8}</td>
<td>0.9995</td>
</tr>
<tr>
<td>2x POP300D</td>
<td>+180</td>
<td>3.72*10^{-8}</td>
<td>1.0000</td>
</tr>
</tbody>
</table>
Sensor Cost vs Utility

- Cost of 1 POP300: 260K
- Cost of 1 POP300D: 1.5*260K = 390K
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Conclusions and Recommendations

• In order for the RQ-7B Shadow to meet the TLS the sensors it is equipped with must have an azimuth range of ±180°, or be able to scan a 360° Field of View.

• The only sensor that performs at the level necessary to meet the TLS set forth by the FAA is this POP300D with an ELS of 8.51*10⁻⁸. If the RQ-7B Shadow is equipped with 2 POP300D sensors the ALS improves to 3.72*10⁻⁸.

• It is recommended that the RQ-7B Shadow’s onboard sensors be upgraded from the POP300 to the POP300D to assist the FAA in their goal of safely integrating UAS’s into the NAS.
Questions?
# Model Assumptions

<table>
<thead>
<tr>
<th>Aircraft</th>
<th># Produced</th>
<th>Cruise Speed</th>
<th>Cruise^2</th>
<th>Length</th>
<th>Wingspan</th>
<th>Area</th>
<th>Area^2</th>
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<tbody>
<tr>
<td>Cessna 172R</td>
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<td>14884</td>
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<td>Beechcraft Bonanza</td>
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<td>27.5</td>
<td>33.5</td>
<td>921.25</td>
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<table>
<thead>
<tr>
<th></th>
<th>E(x)</th>
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<th>SD</th>
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<td>810125.8990</td>
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References