Managing Separation of Unmanned Aerial Vehicles Using High-Integrity GNSS Navigation

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Outline

• Unmanned Aerial Vehicle (UAV) Networks
  – Applications
  – Ground-driven architecture
  – Local-Area Differential GNSS (DGNSS) Navigation

• Concept of Operations

• Risk Model for Safe Separation

• Error Model for Safe Separation

• Future Work: KAIST flight testing
UAV Applications (1): Scientific Observations, Photography

Ice Monitoring in Arctic

Source: A. Armstrong, NOAA

Volcanic Ash Monitoring

Source: (concept) G. Gao,
(picture) H. Thorburn, Wikimedia
Commons, 2010
UAV Applications (2): Reconnaissance, Surveillance

White Sands
Missile Range, NM

Boeing/Paine
Field, WA

Source: USGS/Wikimedia Commons

Source: Google Maps

90 km

4.3 km

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UAV Applications (3): Reconnaissance, Surveillance

Inwood and nearby (gated) subdivisions, San Antonio, TX

Source: Google Maps
Concerns over Threat to Privacy

Source: TIME Magazine (cover), 11 February 2013.
Constraints of Commercial UAV Network Environment

• **Service must be cost-effective**

• UAV design and flight operations dominate achievable performance
  
  – Low-power/weight/cost receiver chipsets
  
  – Airborne dynamics are larger than for manned aircraft.
  
  – Flying (relatively) close to ground objects → significant airborne multipath from ground reflections

• **Two-way datalink required for guidance**
  
  – Monitoring separation is a key responsibility of the ground controller
Local-Area UAV Network Concept

Manned aircraft

Upper buffer ($b_{\text{high}}$)

UAVs on station

Deployment pathway ($b_{\text{out}}$)

Return pathway ($b_{\text{in}}$)

Max. Alt. ($D_{\text{high}}$)

Pathway sep’tn. ($b_{\text{sep}}$)

Lower buffer ($b_{\text{low}}$)

Ground obstructions

Min. Alt. ($D_{\text{low}}$)

GNSS Ctrl

Data

UAV base

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Simplification of GBAS for UAV Networks


Ground Facility

Aircraft

Ground-to-air datalink

Add air-to-ground datalink

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Separation for UAV Networks using GNSS
Safe Separation: Definitions of Terms

• “In-network” UAVs: UAVs in the same network
  – Share the same source of guidance
  – Share the same LADGNSS differential corrections

• “Out-of-network UAVs”: all other UAVs
  – May share use of GNSS, but do not share guidance or differential corrections
  – Fly in the same general airspace allocated to UAVs

• “Manned aircraft”: aircraft with human occupants
  – Assumed to fly in their own airspace (separate from UAVs)

• “Ground obstructions”: the ground and any people, buildings, etc. attached to the ground
Components of Separation Budget

“In-network” UAV

UAV Navigation Error ($U_{nav}$)

UAV Path-Following Error ($U_{path}$)

UAV Guidance Error ($U_{guidance}$)

Target Guidance Error ($T_{guidance}$)

Target Path-Following Error ($T_{path}$)

Target Navigation Error ($T_{nav}$)

Altitude Limit or Other Vehicle (“Target”)

Min. Sep. $(b_x)$
Risk Model for Total Separation
(example numbers for suburban applications)

\[
\Pr(\text{HH} \mid \text{SV}) = \Pr(\text{HH} \mid \text{CO}) \times \Pr(\text{CO} \mid \text{SV})
\]

\(harm\) to humans \(\Rightarrow\) separation violation \(\Rightarrow\) collision

<table>
<thead>
<tr>
<th>Scenario</th>
<th>(\Pr(\text{CO} \mid \text{SV})) (mean)</th>
<th>(\Pr(\text{HH} \mid \text{CO})) (mean)</th>
<th>(\Pr(\text{HH} \mid \text{SV})) (mean)</th>
<th>(\Pr(\text{HH} \mid \text{SV})) (worst case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-network UAV</td>
<td>(10^{-4})</td>
<td>(10^{-5})</td>
<td>(10^{-9})</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>Out-of-network UAV</td>
<td>(10^{-5})</td>
<td>(10^{-4})</td>
<td>(10^{-9})</td>
<td>(10^{-4})</td>
</tr>
<tr>
<td>Upper limit (manned a/c)</td>
<td>(10^{-7})</td>
<td>(10^{-2})</td>
<td>(10^{-9})</td>
<td>(10^{-2})</td>
</tr>
<tr>
<td>Lower limit (ground)</td>
<td>(10^{-4})</td>
<td>(10^{-3})</td>
<td>(10^{-7})</td>
<td>(10^{-3})</td>
</tr>
</tbody>
</table>
Required Prob. of Separation Violation

Solve for $Pr(SV)$ to meet total safety requirement:

$$Pr(HH \mid SV) \times Pr(SV) \leq 10^{-9}$$

Target level of safety

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$Pr(SV)$ (mean)</th>
<th>$Pr(SV)$ (worst case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-network UAV</td>
<td>1.0</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Out-of-network UAV</td>
<td>1.0</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Upper limit (manned a/c)</td>
<td>1.0</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Lower limit (ground)</td>
<td>0.01</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>
### Preliminary Error Budget
(3-D separation between in-network UAVs)

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Bounding Sigma (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>User navigation</td>
<td>0.2</td>
</tr>
<tr>
<td>User path-following</td>
<td>0.6</td>
</tr>
<tr>
<td>User guidance</td>
<td>0.3</td>
</tr>
<tr>
<td>Target navigation</td>
<td>0.2</td>
</tr>
<tr>
<td>Target path-following</td>
<td>0.6</td>
</tr>
<tr>
<td>Target guidance</td>
<td>0.3</td>
</tr>
<tr>
<td>RSS</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Very highly correlated*

*highly correlated*
## Preliminary Error Budget (vertical separation from manned aircraft)

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Bounding Sigma (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>User navigation</td>
<td>1.5</td>
</tr>
<tr>
<td>User path-following</td>
<td>2.0</td>
</tr>
<tr>
<td>User guidance</td>
<td>1.0</td>
</tr>
<tr>
<td>Target navigation</td>
<td>3.0</td>
</tr>
<tr>
<td>Target path-following</td>
<td>4.0</td>
</tr>
<tr>
<td>Target guidance</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>RSS</strong></td>
<td><strong>5.7</strong></td>
</tr>
</tbody>
</table>

*potentially correlated, but assumed independent*
Out of Network UAVs: “Sense and Avoid”

• Safe separation from out-of-network UAVs requires some form of “sense and avoid” technology.

• **Most practical solution:** requirement for UAVs to broadcast position information at regular intervals
  
  – “ADS-B-OUT” for UAVs, but with much simpler, miniaturized components.
  
  – Report aircraft type, position, velocity, and source of navigation (e.g., a variation of GNSS)
  
  – “ADS-B-IN” function may be delegated to ground controller for short-range systems

• Guidance adaptation to out-of-network UAVs, particularly “non-friendly” ones, is a major challenge.
Future Work: KAIST Experiments

• Test elements of UAV network architecture with flying airborne vehicles.

• Utilize “IMT” GBAS prototype developed by Prof. Jiyun Lee at KAIST (Daejeon, Korea) along with existing commercial DGPS system.

• Key test objectives:
  – Examine receiver performance of existing UAVs in different environments (using static “pseudo-user” as control).
  – Evaluate correlated errors of UAVs close to each other.
  – Map resulting UAV error models to separation standards proposed here.
GBAS IMT Reference Receivers at KAIST

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- IMT Antennas/Receivers (2013)
- Pseudo-User Antenna/Receiver
- IMT Antennas/Receivers (now)
Vicinity of KAIST GBAS
Summary

• A concept for autonomous UAV networks supported by local-area DGNSS has been proposed.
  – Medium-range photography / data-collection
  – Short-to-medium reconnaissance / surveillance

• A model for separation standards between networked UAVs and obstacles/other aircraft (including other aircraft) has been developed.
  – Based on risk and consequences of potential UAV collisions

• Flight tests to come using KAIST GBAS prototype.
  – Identify UAV navigation and flight technical errors under various conditions.
Summary

- A concept for autonomous UAV networks supported by local-area DGNSS has been proposed.
  - Medium-range photography / data-collection
  - Medium-to-short range reconnaissance / surveillance

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• Thank you for your attention。
  ご清聴、ありがとうございました。

• Questions are welcome!
  ご遠慮なく、英語でも日本語でも質問してください。
GBAS Architecture Overview
(supports CAT I Precision Approach)

airport boundary
(encloses GBAS Ground Facility)

Corrected carrier-smoothed-code processing
– VPL, LPL calculations

LGF Ref/Mon Receivers and Processing

VHF Data Broadcast

GPS Antennas

VHF Antennas

GPS, L1 only

Cat I

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