Initial Study of An Effective Fast-time Simulation Platform for Unmanned Aircraft System Traffic Management

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Objective: Initial study and justification of developing an effective fast-time simulation platform
Outline

• Overview of existing simulations
• Requirements of UTM simulations
• Experiments using UTM simulations
• Summary
Simulation Categories

• Operations (multiple aircraft)
  • Manned aircraft: CTAS, FACET, ACES
  • Small UAV: Jenie\textsuperscript{[JGCD2016]}, Cook\textsuperscript{[AIAA2016]}

• Encounter (~two aircraft)
  • MIT Lincoln Lab
  • Mueller\textsuperscript{[MST2016]}

• Vehicle centric (single aircraft)
  • Reflection\textsuperscript{[NASA-TP2006]}
  • Others
### Comparison

<table>
<thead>
<tr>
<th>Simulation</th>
<th>UTM required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum number of vehicles per scenario</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Fidelity of vehicle models</td>
<td>&gt;medium</td>
</tr>
<tr>
<td>Vehicle’s controller modeled?</td>
<td>✓</td>
</tr>
<tr>
<td>Wind effect</td>
<td>Along-track + cross-track + vertical</td>
</tr>
<tr>
<td>Limited flight duration?</td>
<td>×</td>
</tr>
<tr>
<td>Capability of Monte Carlo simulations?</td>
<td>✓</td>
</tr>
<tr>
<td>Collision avoidance algorithm included?</td>
<td>✓</td>
</tr>
</tbody>
</table>
Outline

• Overview of existing simulations
• Requirements of UTM simulations
  • Small UAV Trajectory model
  • Monte Carlo method
• Experiments using UTM simulations
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Small UAV Trajectory Model

Dynamics:

\[
\begin{bmatrix}
\dot{p}_n \\
\dot{p}_n \\
\dot{p}_e \\
\dot{p}_e \\
\ddot{h} \\
\ddot{\phi} \\
\ddot{\theta} \\
\ddot{\psi}
\end{bmatrix}
= \begin{bmatrix}
\ddot{p}_n + (\omega_n) \\
-(\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi) F_z/m \\
\ddot{p}_e + (\omega_e) \\
(-\cos \phi \sin \theta \sin \psi + \sin \phi \cos \psi) F_z/m \\
g - \cos \phi \cos \theta F_z/m \\
M_\phi / J_x \\
M_\theta / J_y \\
M_\psi / J_z
\end{bmatrix}
\]

Controller: [proportional-derivative (PD)]

\[
\begin{bmatrix}
\ddot{p}_e \\
\ddot{p}_n
\end{bmatrix}
= \begin{bmatrix}
k_p (p_{e,d} - p_e) + k_d (\dot{p}_{e,d} - \dot{p}_e) \\
k_p (p_{n,d} - p_n) + k_d (\dot{p}_{n,d} - \dot{p}_n)
\end{bmatrix}
\]

\[
\begin{bmatrix}
\phi_{d} \\
\theta_{d}
\end{bmatrix}
= \frac{m}{F_z} \begin{bmatrix}
-\sin \psi & -\cos \psi \\
\cos \psi & -\sin \psi
\end{bmatrix}^{-1} \begin{bmatrix}
\ddot{p}_e \\
\ddot{p}_n
\end{bmatrix}
\]

\[
\begin{bmatrix}
M_\phi \\
M_\theta
\end{bmatrix}
= \begin{bmatrix}
k_{p,\phi} (\phi - \phi) + k_{d,\phi} (\dot{\phi} - \dot{\phi}) \\
k_{p,\theta} (\theta - \theta) + k_{d,\theta} (\dot{\theta} - \dot{\theta})
\end{bmatrix} l
\]

\[k_{p,\phi} = 4.5, k_{d,\phi} = 0.5, k_{p,\theta} = 4.5, k_{d,\theta} = 0.5, k_p = 7.5, k_d = 4.2\]
Impact of Wind Speed

When wind gets strong, deviation increases.

\( V_g = 5 \text{ m/s} \)

\( K_p & K_d \) fixed

Wind varied
Impact of Desired Vehicle Ground Speed

Wind($w_n$) = 5m/s
$K_p$&$K_d$ fixed
$V_g$ varied

When desired vehicle ground speed is set high, trajectory difference increases.
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Monte Carlo Method

• UTM requires parameter and uncertainty/error studies

• UTM uncertainties/errors are high-dimensional

• Monte Carlo method is independent of the problem dimension

• The rate of convergence of order is: \( O(1/\sqrt{n}) \)

• Error percentage can be computed by:

\[
E = \frac{100z_c S_x}{\bar{x} \sqrt{n}}
\]

• Monte Carlo is widely used in finance and engineering
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Scenario

- Six quadrotors with $V_g = 5$ m/s
- A rectangular north wind field with uncertainty
Setup

Ownership

Intruder

20 meters

10 meters

30 meters

100 meters
## Experiment #1: Impact of Wind

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Avoidance maneuver</th>
<th>Loss of separation (probability)</th>
<th>Extra flight distance (m)</th>
<th>Extra flight time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>Std.</td>
<td>mean</td>
<td>Std.</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>0.01</td>
<td>0.08</td>
</tr>
</tbody>
</table>

The equation for the error is:

\[ E = \frac{100z_c S_x}{\bar{x} \sqrt{n}} \]
## Experiment #2: Impact of Avoidance Maneuver

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Avoidance maneuver</th>
<th>Loss of separation (probability)</th>
<th>Extra flight distance (m)</th>
<th>Extra flight time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>Std.</td>
<td>mean</td>
<td>Std.</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td></td>
<td>0.847</td>
<td>0.36</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td></td>
<td>0.04</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### Notes:
- Avoidance Maneuvers: Right turn, Left turn, Hover
- Loss of separation probability refers to the probability of losing separation in the specified avoidance maneuver.
- Extra flight distance and time are measured in meters and seconds, respectively.
- Error (%) values indicate the variability of the measurements.
Summary

- Reviewed some existing simulations
- Identified UTM required attributes
- Conducted trajectory sensitivity analysis
- Conducted preliminary experiments using Monte Carlo
Future Work

- Implement the platform on the Cloud
- Incorporate and generalize more vehicle dynamic and control systems
- Implement and generalize more collision avoidance algorithms
- Implement onboard sensor and communication device models
- Environmental data (wind, temperature, etc.)
- Geographic Information System (GIS) data (terrain, population, etc)