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:

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

Controller: [proportional-derivative (PD)]

\[
\begin{bmatrix}
\ddot{p}_e \\
\ddot{p}_n \\
\phi_d \\
\theta_d \\
M_\phi \\
M_\theta
\end{bmatrix} =
\begin{bmatrix}
k_p (p_{e,d} - p_e) + k_d (\dot{p}_{e,d} - \dot{p}_e) \\
k_p (p_{n,d} - p_n) + k_d (\dot{p}_{n,d} - \dot{p}_n) \\
m \begin{bmatrix}
- \sin \psi & - \cos \psi \\
\cos \psi & - \sin \psi
\end{bmatrix}^{-1} \begin{bmatrix}
\ddot{p}_e \\
\ddot{p}_n
\end{bmatrix} \\
\frac{m}{F_z} \begin{bmatrix}
- \sin \psi & - \cos \psi \\
\cos \psi & - \sin \psi
\end{bmatrix} \begin{bmatrix}
\phi_d \\
\theta_d
\end{bmatrix} \\
\begin{bmatrix}
k_{p,\phi} (\phi_d - \phi) + k_{d,\phi} (\dot{\phi}_d - \dot{\phi}) \\
k_{p,\theta} (\theta_d - \theta) + k_{d,\theta} (\dot{\theta}_d - \dot{\theta})
\end{bmatrix} l
\]

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

When wind gets strong, deviation increases.

\[ V_g = 5 \text{ m/s} \]

\[ K_p \text{ and } K_d \text{ fixed} \]

\[ \text{Wind varied} \]
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:
  \[ E = \frac{100 z_c S_x}{x \sqrt{n}} \]
- Monte Carlo is widely used in finance and engineering
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Scenario

- Six quadrotors with $V_g = 5 \text{ m/s}$
- 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</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>0.01</td>
<td>0.08</td>
</tr>
</tbody>
</table>

\[ E = \frac{100 z_c S_x}{\bar{x} \sqrt{n}} \]
## 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>Error(%)</td>
<td>mean</td>
</tr>
<tr>
<td>3 1</td>
<td>Right turn</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3 1</td>
<td>Left turn</td>
<td>0.847</td>
<td>0.36</td>
<td>3.46</td>
</tr>
<tr>
<td>3 1</td>
<td>Hover</td>
<td>0.04</td>
<td>0.20</td>
<td>38.9</td>
</tr>
</tbody>
</table>
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)