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

Min Xue and Joseph Rios

NASA Ames Research Center
Moffett Field, CA

AIAA Aviation Forum, 5-9 June 2017
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\[^{JGCD2016}\], Cook\[^{AIAA2016}\]

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

• Vehicle centric (single aircraft)
  • Reflection\[^{NASA-TP2006}\]
  • 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
• Summary
Small UAV Trajectory Model

Dynamics:

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

Controller: [proportional-derivative (PD)]

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

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

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

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

- $v_g = 5 \text{ m/s}$
- $K_p$&$K_d$ fixed
- Wind varied

When wind gets strong, deviation increases.
Impact of Desired Vehicle Ground Speed

Wind\( (w_n) = 5\text{m/s} \)
K\(_p\) & K\(_d\) fixed
V\(_g\) varied

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

![Graph showing the impact of desired vehicle ground speed on trajectory difference.](image)

- Desired trajectory
- \( v = 2 \text{ m/s} \)
- \( v = 5 \text{ m/s} \)
- \( v = 8 \text{ m/s} \)
- \( v = 10 \text{ m/s} \)
- \( v = 12 \text{ m/s} \)
Outline

• Overview of existing simulations
• Requirements of UTM simulations
  • Small UAV Trajectory model
  • Monte Carlo method
• Experiments using UTM simulations
• Summary
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: $O\left(\frac{1}{\sqrt{n}}\right)$
- Error percentage can be computed by:
  $$E = \frac{100z_cS_x}{\bar{x}\sqrt{n}}$$
- Monte Carlo is widely used in finance and engineering
Outline

• Overview of existing simulations
• Requirements of UTM simulations
• Experiments using UTM simulations
• Summary
Scenario

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

Ownership

Intruder

100 meters

20 meters

10 meters

30 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></td>
<td>mean</td>
<td>Std.</td>
<td>Error(%)</td>
</tr>
<tr>
<td>0</td>
<td>Right turn</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Right turn</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>Right turn</td>
<td>0.01</td>
<td>0.08</td>
<td>97.2</td>
</tr>
</tbody>
</table>

$$E = \frac{100z_c S_x}{\bar{x} \sqrt{n}}$$
### 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></td>
<td>mean</td>
<td>Std.</td>
<td>Error(%)</td>
</tr>
<tr>
<td>3</td>
<td>Right turn</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Left turn</td>
<td>0.847</td>
<td>0.36</td>
<td>3.46</td>
</tr>
<tr>
<td>3</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)