SmallSat Formation Flying

JHU Small Missions Workshop

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Personal Introduction

What do I know?

• Mission Design and GNC Engineer at APL since 2014
  - Aerospace Engineer at Emergent 2012-2014
  - Graduate student at GWU from 2006-2012
  - Intern at APL from 2008-2011
  - Intern at Orbital Sciences from 2006-2007

• Formation Flying experience:
  - DARPA F6 project to disaggregate a traditional spacecraft into multiple small satellites
    ▪ Developed FSW for relative navigation (GPS+ranging) and guidance and control
  - CAT mission is currently in LEO with two 3U cubesats flying together via differential drag steering (no propulsion)
  - ADD mission to fly multiple ~24U smallsats in formation at distances of 1-75km in LEO
  - Various research projects, studies and proposals
Formation Flying
And Other Variants

• Constellations:
  - Independently controlled vehicles; typically spaced far apart
    ▪ GPS, OneWeb, etc.

• **Formation Flying**:
  - Jointly controlled vehicles flying in close proximity (typically between 1 and 100 km)
  - Typically identical or similarly sized vehicles
  - Typically cooperative formation control

• ProxOps
  - Vehicles flying in very close proximity (<1 km)
  - Often non-cooperative

• Rendezvous
  - Physically docking of vehicles
  - Common with ISS and servicing concepts
Formation Flying
Dynamics of Relative Motion

- Linearized dynamics of relative motion assuming two-body and close proximity
  \[
  \begin{bmatrix}
  \ddot{x} \\
  \ddot{y} \\
  \ddot{z}
  \end{bmatrix} = \begin{bmatrix}
  2\gamma + \dot{\theta}^2 & \dot{\theta} & 0 \\
  -\dot{\theta} & -\gamma + \dot{\theta}^2 & 0 \\
  0 & 0 & -\gamma
  \end{bmatrix}
  \begin{bmatrix}
  x \\
  y \\
  z
  \end{bmatrix} + 2
  \begin{bmatrix}
  0 & \dot{\theta} & 0 \\
  \dot{\theta} & 0 & 0 \\
  0 & 0 & 0
  \end{bmatrix}
  \begin{bmatrix}
  \dot{x} \\
  \dot{y} \\
  \dot{z}
  \end{bmatrix} + \begin{bmatrix}
  f_x \\
  f_y \\
  f_z
  \end{bmatrix}
  \]

- Assuming circular orbits, equations reduce to Clohessy-Wiltshire-Hill:
  \[
  \begin{align*}
  \dot{x} &= 3n^2 x + 2n\dot{y} \\
  \dot{y} &= -2n\dot{x} \\
  \dot{z} &= -n^2 z
  \end{align*}
  \]

- Provides simple equations of motion and closed-form solution for quick analyses and coarse guidance
Formation Flying
Disturbances and Uncertainty

- Dominant env’t disturbances include differential drag (in-track drift) and oblate earth (periodic & secular drift)
- Formation flying performance is also significantly impacted by uncertainty in the system model and estimation performance

<table>
<thead>
<tr>
<th></th>
<th>Position (1σ)</th>
<th>Velocity (1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Nav</td>
<td>10 m</td>
<td>10 cm/s</td>
</tr>
<tr>
<td>CDGPS</td>
<td>1 m</td>
<td>1 cm/s</td>
</tr>
<tr>
<td>DDGPS</td>
<td>1 cm</td>
<td>1 mm/s</td>
</tr>
<tr>
<td>In-Situ</td>
<td>&lt; 1 cm</td>
<td>?</td>
</tr>
</tbody>
</table>
Formation Flying
Mission Planning and Optimization

- Formation planning can be optimized using a centralized architecture, distributed architecture or some hybrid of both
- Encompasses both dynamical optimization, mission constraints and resource management

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Global Guidance</th>
<th>Local Guidance</th>
<th>SOF</th>
<th>Range Violations</th>
<th>Data Exchange</th>
<th>Pros</th>
<th>Cons</th>
<th>Impacted Subsys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centralized Optimization</td>
<td>Optimized by Chief</td>
<td>Optimized for global constraints</td>
<td>Incorporated into local optimizations and Pc monitoring</td>
<td>Invalidate maneuvers Reweight constraints Emergency targeting</td>
<td>Rel states Sys states Mnrs  Opt states</td>
<td>Realtime SOF directly incorporated</td>
<td>Sensitive to Chief faults Scales poorly Large &amp; frequent crosslinks</td>
<td>Crosslinks Flight PC</td>
</tr>
<tr>
<td>Distributed Optimization</td>
<td>Optimized across constellation</td>
<td>Optimized along with global objectives</td>
<td>Incorporated into the ongoing optimizations</td>
<td>Invalidate maneuvers Reweight constraints</td>
<td>Rel states Sys states Mnrs  Opt states</td>
<td>Realtime SOF directly incorporated</td>
<td>Process OH Frequent crosslinks Mission spec.</td>
<td>Crosslinks Flight PC</td>
</tr>
<tr>
<td>Hierarchical Optimization</td>
<td>Optimized by sub-chiefs</td>
<td>Optimized along with sub-cluster global objs</td>
<td>Incorporated into the ongoing optimizations</td>
<td>Invalidate maneuvers Reweight constraints</td>
<td>Rel states Sys states Mnrs  Opt states</td>
<td>Realtime SOF directly incorporated Neighbors only</td>
<td>Sensitive to sub-chief faults Frequent crosslinks More complex</td>
<td>Crosslinks Flight PC</td>
</tr>
<tr>
<td>Ground Optimization</td>
<td>Optimized by Ground</td>
<td>Optimized for global constraints</td>
<td>Incorporated into local optimizations and Pc monitoring</td>
<td>Invalidate maneuvers Emergency targeting</td>
<td>Rel states Sys states Mnrs</td>
<td>Less OH No Chief Flexible</td>
<td>Non realtime SOF violations more disruptive</td>
<td>Ground</td>
</tr>
<tr>
<td>Cluster Flight</td>
<td>None</td>
<td>Optimized local objectives</td>
<td>Pc monitoring</td>
<td>Invalidate maneuvers Emergency targeting</td>
<td>Rel states Sys states Mnrs</td>
<td>Less OH Mostly local</td>
<td>Non realtime No global optimization SOF violation disruptive</td>
<td>Ground</td>
</tr>
<tr>
<td>No FF</td>
<td>None</td>
<td>Optimized local objectives</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Simplest Most heritage</td>
<td>Non realtime No SOF</td>
<td>Ground</td>
</tr>
</tbody>
</table>

Global objectives = relative geometry constraints, range constraints
Local objectives = track target, minimize fuel use
Formation Flying
Safety of Flight Considerations

- Given the covariance of two vehicles, one can compute the Probability of Collision
  \[ p = \int \int \int \left( \frac{\exp(-r^T P_{rr}^{-1} r/2)}{\sqrt{(2\pi)^3 |P_{rr}|}} \right) dV \]

- There are also analytical simplifications for onboard computation
- Can be incorporated as part of the mission planning process (SOF constraints) and/or monitored in flight based on latest Nav estimates.
- SOF violation response requires careful design
  - Precanned maneuvers, autonomous maneuvering, abort all maneuvers
CubeSats
Capabilities are Improving at a Rapid Pace

- Many organizations are developing their own small satellite technologies ranging from:
  - Components
    - Sensors: Star Trackers, Sun/Earth Sensors, Gyros, Accelerometers, Magnetometers
    - Actuators: Reaction Wheels, Torque Rods, Thrusters
    - Power: Batteries, Solar Panels
    - Electronics: Processors, Flash
  - Subsystems
    - ADCS
    - Propulsion
  - Vehicles
    - Bus
- Biggest challenges include
  - Size, Weight and Power (SWaP)
  - Availability
  - Radiation hardness
  - Integration
CubeSats + Formation Flying
Challenges and Considerations

- Formation Flying requires many complex subsystems
  - Integrating into a small form factor is a challenge

Guidance and Control
  - Attitude Control
  - Maneuver Execution
  - Safety of Flight

Propulsion
  - Fuel Tank
  - Thrusters
  - Valves

Navigation
  - GPS Tracking
  - Relative Navigation

Power
  - Batteries
  - Solar Panels
  - Load Management

Flight Software
  - GNC Wrapper
  - Fault Management
  - Hardware Interfaces

Comms
  - Ground Link
  - Cross Link

Ground
  - Operation Planning
  - Formation Planning
  - Resource Management
Scientific Applications
That I’m Aware Of

• Atmospheric, Radiation and Magnetic Environment measurements
• Simultaneous Imaging/Sensing
• Space Situational Awareness (SSA)
• Sparse Apertures
• Reconfigurable Telescopes
• Comms Network
• Gravimetry
• Disaggregation of Resources
• Technology Demonstrations
Final Thoughts

• Formation Flying is a compelling area of study
  - Some success stories to date include
    ▪ TanDEM-X (DLR, Stanford)
    ▪ CanX-4&5 (UTIAS/SFL)
    ▪ ANGELS (AFRL)
    ▪ Lots of ProxOps demos (ISS, etc.)

• CubeSats are evolving at a rapid pace, but are still very limited in capability

• Any proposal to fly a FF mission using CubeSats face daunting challenges
  - Relative Navigation
  - Communications constraints
  - Limited fuel capacity
  - Orbit selection, environment and radiation effects

• Risks should be traded against mission objectives and evaluated early and often
  - Government and industry is subject to stricter risk requirements than academia
  - COTS vendors usually overpromise their capabilities and performance