Parallel High-fidelity Trajectory Optimization

with Application to CubeSat Deployment in an Earth-moon Halo Orbit

Hongru Chen
Mickaël Gastineau, Daniel Hestroffer, Vishnu Viswanathan

Observatoire de Paris - IMCCE
Background (1)

Earth CubeSats
- no much orbit maneuver

Interplanetary CubeSats
- Orbit change and deployment
- Limited space for propulsion

Interplanetary Spacecraft
- Orbit change
- Loose margin for propulsion

Propellant budget critical to interplanetary CubeSats
Background (2)

- Electric propulsion systems
  - Pro: high Isp $\rightarrow$ high $\Delta v$ budget, promising for CubeSats
  - Con: low thrust

- Gravity of celestial bodies influence trajectories
  - Positive or negative influence depending on the Julian Date

Low-thrust trajectories should be validated in the full-ephemeris model
High-fidelity Trajectory Optimization

- Propagation considers:
  - Continuous thrust, mass loss
    \[ \dot{v} = -I_{sp} g \cdot \frac{1}{m} \dot{m} \quad F_T = I_{sp} g \dot{m} \]
  - Ephemeris and gravity
    - of Sun, Earth, moon, Mars, Jupiter, etc
    - Julian date matters
  - Solar radiation pressure
  - Higher-order gravitational terms (not yet included)

- Minimize propellant cost \( \Delta m \)
Parallel multiple shooting

Pros:
- Less sensitive to initial guess → robust
- Uncoupled segments → trajectory states and derivatives computed separately
- Compatible with parallel computing
Optimization tool

- **Optimization**
  - Direct optimization
  - SNOPT – sparse nonlinear optimizer

- **Parallel propagation**
  - Matlab Parfor
  - Propagate both orbit states and \( 1^{\text{st}} \)-order partial derivatives
    - Objective and constraint derivatives (\( \frac{\partial x_{k+1}}{\partial x_k}, \frac{\partial m}{\partial F_k} \)) facilitates optimization

- **Ephemeris software**
  - **CALCEPH** (Observatoire de Paris - IMCCE)
    - Works in parallel environment compared to SPICE (JPL)
    - C, Fortran 77/2003, Matlab/Octave, Python
      (https://www.imcce.fr/recherche/equipes/asd/calceph/)

---

Optimize: \( x_k, F_{T,k} \) (\( k=1,\ldots, N \))

Minimize: \( \Delta m \)

Constraints:
- \( x_0, x_f = \) desired halo orbit states
  (fixed z at x-z plane crossing) at \( t_0 \) and \( t_f \)
- \( x_k^- = x_k^+ \)
- \( \|F_T\| < F_{\text{max}} \)
Applications to interplanetary CubeSat trajectories

➢ **BIRDY-3 CubeSat (left)**
  ➢ To perform radio science around a small body

➢ **Deployed CubeSat positioning constellation in an Earth-moon halo orbit (right)**
  ➢ To support positioning of assets on the far-side of the moon

Preliminary BIRDY-3 mission concept (Quinsac et. al, 2017)
Applications to interplanetary CubeSat trajectories

➢ BIRDY-3 CubeSat (left)
  ➢ To perform radio science around a small body

➢ Deployed CubeSat positioning constellation in an Earth-moon halo orbit (right)
  ➢ To support positioning of assets on the far-side of the moon

Preliminary BIRDY-3 mission concept (Quinsac et al, 2017)
## CubeSat specifications

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Components</th>
<th>Mass, g</th>
</tr>
</thead>
</table>
| Structure  | 1 3-6U frame  
             2 deployable panels | 1100 |
| Power      | Solar arrays (max. 33W)  
             1 battery (72Whr) | 1200 |
| ADCS       | 4 reaction wheels  
             1 star tracker  
             1 MEMS IMU  
             5 sun sensors | 750 |
| Communication | 4 UHF antennas  
             4 X-band antennas  
             1 radio transponder | 700 |
| C&DH       | OBC | 200 |
| Other      | 1 crystal oscillator | 220 |
| Total      | | 4200 |

Note: w/o propulsion system
Deployment trajectories

- Need to evenly distribute 4 CubeSats along a halo orbit.
- Deployment trajectories first designed in the circular-restricted 3-body problem (CR3BP) using 2 impulsive $\Delta v$.

<table>
<thead>
<tr>
<th>CubeSat</th>
<th>$\Delta v$, m/s</th>
<th>time, day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sat-1</td>
<td>55</td>
<td>34</td>
</tr>
<tr>
<td>Sat-2</td>
<td>99</td>
<td>60</td>
</tr>
<tr>
<td>Sat-3</td>
<td>101</td>
<td>48</td>
</tr>
<tr>
<td>Sat-4</td>
<td>42</td>
<td>56</td>
</tr>
</tbody>
</table>

H. Chen, J. Ma “Phasing Trajectories to Deploy a Constellation in a Halo Orbit”, Journal of Guidance, Control, and Dynamics, 10 (40), pp. 2662-2667, 2017
Optimize in the CR3BP

Optimize continuous-thrust trajectories with varied thrust acceleration ($a_{\text{thr}}$)

No solution if $a_{\text{thr}} < 7.4 \times 10^{-5}$ m/s$^2$

(For $M_{\text{sat}} = 5.3$ kg, $F_{\text{min}} = 0.4$ mN)

$\Delta v$ vs $a_{\text{thr}}$
### Propulsion system options

<table>
<thead>
<tr>
<th>Model</th>
<th>Type</th>
<th>Power, W</th>
<th>Dry mass, kg</th>
<th>Size, U</th>
<th>Standard prop., kg</th>
<th>Thrust, mN</th>
<th>Isp, s</th>
<th>Δv budget, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerojet MPS-120</td>
<td>Chemical</td>
<td>10</td>
<td>1.06</td>
<td>1</td>
<td>0.38</td>
<td>250</td>
<td>206</td>
<td>142.5</td>
</tr>
<tr>
<td>VACCO Hybrid AND</td>
<td>Chemical</td>
<td>14</td>
<td>1.01</td>
<td>1</td>
<td>0.53</td>
<td>100</td>
<td>200</td>
<td>192.2</td>
</tr>
<tr>
<td>JPL MarCO</td>
<td>Cold-gas</td>
<td>10</td>
<td>1.56</td>
<td>2</td>
<td>1.93</td>
<td>50</td>
<td>40</td>
<td>106.5</td>
</tr>
<tr>
<td>Busek BET-1mN</td>
<td>Electrospray</td>
<td>15</td>
<td>1.07</td>
<td>1</td>
<td>0.08</td>
<td>0.7</td>
<td>800</td>
<td>119.6</td>
</tr>
</tbody>
</table>
Optimize in the full-ephemeris model starting on different Julian dates

CubeSat mass w/o ppl: 4.2 kg
Busek BET-1mN

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>0.7 mN</td>
</tr>
<tr>
<td>Dry mass</td>
<td>1.07 kg</td>
</tr>
<tr>
<td>Propellant mass</td>
<td>0.08 kg</td>
</tr>
<tr>
<td>Isp</td>
<td>800 s</td>
</tr>
</tbody>
</table>

Remarks:
- Feasibility varies greatly → analysis in simplified model not sufficient!
- $\Delta v$ saving up to 25.5 m/s if mission start date favorable. Not applicable for 2nd payloads 😞
- Chemical and cold-gas systems more suitable in this case needing for quick maneuverability.
Trajectory example

Optimal Low-thrust (0.7mN) trajectory in the full-ephemeris model compared to baseline trajectory in CR3BP
Summary

➢ A parallel high-fidelity trajectory optimization tool being developed

➢ For design and analysis of interplanetary CubeSat trajectories with propulsion system specifications.

➢ Parallel optimization algorithm implemented in the parallel computing environment

➢ Propagate trajectory state and 1st-order derivatives for optimization

➢ For low thrust, trajectory feasibility and Δv greatly depend on the mission date

➢ Low-thrust trajectories should be confirmed in the full-ephemeris model
Thank you!

Hongru Chen
hongru.chen@obspm.fr
hongru.chen@hotmail.com
Backup slides - CubeSat design

3U

6U