AUTOMATED SENSITIVITY ANALYSIS OF INTERPLANETARY TRAJECTORIES

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JUNE 8TH, 2017

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AGENDA

- Motivation
- Methodology
- Global Optimization
- Case Study 1
- Case Study 2
- Summary
MOTIVATION

- First task for mission designer is typically to create a nominal/baseline trajectory.
- Second task is often to perform sensitivity analysis. The objective is to quantify the effects of changes to:
  - Operational constraints
  - Sub-system requirements
  - Off-nominal spacecraft performance
- Mission design is human-labor intensive and therefore expensive.
- Computation time is not and is therefore cheap.
- **Goals:**
  - Transfer as much work-load as possible to computers (automation!)
  - Quantify entire design space
  - Find better mission design solutions than possible otherwise.
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METHODOLOGY

EMTG = Evolutionary Mission Trajectory Generator
SNOPT = Stanford Numerical OPTimizer
PEATSA = Python EMTG Automated Trade Study Application
METHODOLOGY

1. Parse PEATSA options
2. Create EMTG cases
3. Run EMTG cases
4. Parse EMTG results
5. Has the case met stopping criteria?
   - Yes: This case is done!
   - No: Find an improved initial guess from the results
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GLOBAL OPTIMIZATION

- If trajectory solver has no global optimization capability (local only), then re-seeding with improved initial guesses is crucial
- If trajectory solver DOES have global optimization capability, improved re-seeding is still helpful
- EMTG uses monotonic basin-hopping for global optimization
  - This process is stochastic.
  - No deterministic way to know if a global optimum has been reached — trendlines can help
  - No deterministic way to determine necessary run-time — frequent iterations can eliminated wasted run-time after optimal solution has been found
  - Currently, EMTG hoppers are serial only — re-seeding effectively creates parallel hoppers
- Global optimality also includes modify options that can’t be modified in a fixed local optimization
  - Between iterations, PEATSA can modify these fixed parameters
    - Flyby sequence
    - Target small-body
GLOBAL OPTIMIZATION

Parse PEATSA options

Create EMTG cases

Run EMTG cases

Parse EMTG results

Has the case met stopping criteria?

Yes

No

This case is done!

Find an improved initial guess from the results

Randomly modify trajectory parameters (i.e. gravity assist sequence)
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CASE STUDY 1 – URANUS MISSION LAUNCH WINDOW

- Goal: Uranus moon tour
- Assume that designer has zero knowledge of useful flyby sequence
- Launch sometime in late 2024 or early 2025
- Required 8 minutes of human labor for setup, and 12 wall clock-hours of computation time on a 64 core server

<table>
<thead>
<tr>
<th>Mission Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion model</td>
<td>impulsive</td>
</tr>
<tr>
<td>Maximum flight time</td>
<td>12 years</td>
</tr>
<tr>
<td>Maximum numbers of DSMs</td>
<td>1 per flyby</td>
</tr>
<tr>
<td>Launch Vehicle</td>
<td>Atlas V 551</td>
</tr>
<tr>
<td>Spacecraft Isp</td>
<td>220 seconds</td>
</tr>
<tr>
<td>Intercept velocity</td>
<td>&lt; 7 km/s</td>
</tr>
<tr>
<td>EMTG objective</td>
<td>maximum mass</td>
</tr>
<tr>
<td>EMTG run-time per iteration</td>
<td>60 seconds</td>
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</table>

<table>
<thead>
<tr>
<th>PEATSA Options</th>
<th>Values</th>
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<tbody>
<tr>
<td>run_type</td>
<td>launch window</td>
</tr>
<tr>
<td>sorting_criteria</td>
<td>launch date</td>
</tr>
<tr>
<td>comparison_criteria</td>
<td>maximum final mass</td>
</tr>
<tr>
<td>wait_for_guess</td>
<td>yes</td>
</tr>
<tr>
<td>modify_flybys</td>
<td>yes</td>
</tr>
<tr>
<td>maximum_flybys</td>
<td>5</td>
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<tr>
<td>flyby_bodies</td>
<td>Venus, Earth, Mars, Jupiter, Saturn</td>
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<tr>
<td>options_to_vary</td>
<td>launch date</td>
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<tr>
<td>option_ranges</td>
<td>July 2024 through June 2025</td>
</tr>
</tbody>
</table>
CASE STUDY 1 – URANUS MISSION

- Iteration 0
CASE STUDY 1 – URANUS MISSION
CASE STUDY 1 – URANUS MISSION

- Iteration 2

- Iteration 10

Arrival Mass, kg

Date of Launch

07/13/24 08/18/24 09/23/24 10/29/24 12/04/24 01/09/25 02/14/25 03/22/25 04/27/25

1 Venus Flyby, 1 Earth Flyby

1 Earth Flyby

1 Venus Flyby, 1 Earth Flyby family

1 Earth Flyby family
CASE STUDY 1 – URANUS MISSION

- Iteration 80
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- Goal: quantify design space for return of a sample from asteroid 1949TG Daphne (ecc > .2, inclination > 10 deg)
- Launch sometime in late 2024 or early 2025
- Required 12 minutes of human labor for setup and 32 wall clock-minutes of computation time on a 64 core server

<table>
<thead>
<tr>
<th>Mission Parameters</th>
<th>polynomial thrust, mass flow rate vs. power available</th>
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</thead>
<tbody>
<tr>
<td>Propulsion system</td>
<td>2 NEXT engines(^7)</td>
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<tr>
<td>Maximum flight time</td>
<td>10 years</td>
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<tr>
<td>Earth return velocity</td>
<td>&lt; 10 km/s</td>
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<tr>
<td>Duty cycle</td>
<td>90%</td>
</tr>
<tr>
<td>Propellant margin</td>
<td>10%</td>
</tr>
<tr>
<td>Power margin</td>
<td>15%</td>
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<tr>
<td>Bus power</td>
<td>1 kW</td>
</tr>
<tr>
<td>Stay time</td>
<td>&gt; 500 days</td>
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<tr>
<td>EMTG run-time per iteration</td>
<td>20 seconds</td>
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<td>Low-thrust transcription</td>
<td>Finite Burn(^8)</td>
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</table>

**PEATSA Options**

<table>
<thead>
<tr>
<th>run_type</th>
<th>trade study</th>
</tr>
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<tbody>
<tr>
<td>comparison_criteria</td>
<td>maximum final mass</td>
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<tr>
<td>wait_for_guess</td>
<td>yes</td>
</tr>
<tr>
<td>flyby_bodies</td>
<td>none</td>
</tr>
<tr>
<td>options_to_vary</td>
<td>launch vehicle; solar array size; electric propellant load</td>
</tr>
<tr>
<td>option_ranges</td>
<td>Atlas V - 401 (0), 411 (1), 421 (2), 431 (3), 541 (9) or 551(10); 20 to 40 kW; 900 to 1500 kg</td>
</tr>
<tr>
<td>trade_study_type</td>
<td>vary each option separately</td>
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</tbody>
</table>
Electric Propellant Tank Sizing

Final Mass, kg vs. Electric Propellant Constraint, kg
CASE STUDY 1 – URANUS MISSION

- Launch vehicle selection
  - 1 = Atlas V 401
  - 2 = Atlas V 411
  - 3 = Atlas V 421
  - 4 = Atlas V 431
  - 9 = Atlas V 541
  - 10 = Atlas V 551
CASE STUDY 1 – URANUS MISSION

- Solar Array Sizing
MISSED-THRUST

![Graph showing fault length sustainable, days against fault date.](image-url)
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Sensitivity analysis is no longer a task that requires significant hands-on time for mission designer

PEATSA allows simplified viewing of trade study effects, missed maneuver planning, etc.

Overall computation time decreases greatly, because individual runtime decreases

PEATSA increases global optimization capability