AUTOMATED SENSITIVITY ANALYSIS OF INTERPLANETARY TRAJECTORIES

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AGENDA

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

Parse PEATSA options

Create EMTG cases

Run EMTG cases

Parse EMTG results

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: This case is done!
- No: Find an improved initial guess from the results

No

Randomly modify trajectory parameters (i.e. gravity assist sequence)
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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>impulsive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion model</td>
<td></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>
</tr>
<tr>
<td>PEATSA Options</td>
<td></td>
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<tr>
<td>run_type</td>
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<tr>
<td>sorting_criteria</td>
<td>launch window</td>
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<tr>
<td>comparison_criteria</td>
<td>launch date</td>
</tr>
<tr>
<td>wait_for_guess</td>
<td>maximum final mass</td>
</tr>
<tr>
<td>modify_flybys</td>
<td>yes</td>
</tr>
<tr>
<td>maximum_flybys</td>
<td>yes</td>
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<tr>
<td>flyby_bodies</td>
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<tr>
<td>options_to_vary</td>
<td>Venus, Earth, Mars, Jupiter, Saturn</td>
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<tr>
<td>option_ranges</td>
<td>launch date</td>
</tr>
<tr>
<td></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
CASE STUDY 1 – URANUS MISSION

Iteration 80

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 06/02/25 07/08/25
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  - Case Study 2
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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>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion model</td>
<td>2 NEXT engines</td>
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<tr>
<td>Propulsion system</td>
<td>10 years</td>
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<tr>
<td>Maximum flight time</td>
<td>&lt; 10 km/s</td>
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<tr>
<td>Earth return velocity</td>
<td>90%</td>
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<tr>
<td>Duty cycle</td>
<td>10%</td>
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<tr>
<td>Propellant margin</td>
<td>15%</td>
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<tr>
<td>Power margin</td>
<td>1 kW</td>
</tr>
<tr>
<td>Bus power</td>
<td>&gt; 500 days</td>
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<tr>
<td>Stay time</td>
<td>20 seconds</td>
</tr>
<tr>
<td>EMTG run-time per iteration</td>
<td>Finite Burn</td>
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<td>Low-thrust transcription</td>
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<tr>
<td>PEATSA Options</td>
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<td>run_type</td>
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<td>comparison_criteria</td>
<td>maximum final mass</td>
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<tr>
<td>wait_for_guess</td>
<td>yes</td>
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<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>
</tr>
</tbody>
</table>
Electric Propellant Tank Sizing
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
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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.