Rapid Preliminary Design of Interplanetary Trajectories Using the Evolutionary Mission Trajectory Generator

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The interplanetary design problem is composed of both discrete and real-valued decision parameters:
- Choice of destination(s), number of planetary flybys, identities of flyby planets
- Launch date, flight time(s), epochs of maneuvers, control history, flyby altitudes, etc.

For example, for a main-belt asteroid mission, the designer must choose:
- The optimal asteroid from a set of scientifically interesting bodies provided by the customer
- Whether or not to perform planetary flybys on the way to the main belt and, if so, at which planets
- Optimal trajectory from the Earth to the chosen asteroid by way of the chosen flyby planets
Brief History of Automated Interplanetary Trajectory Design

- Gage, Braun, and Kroo, 1994 – autonomous chemical design with variable mission sequence (no deep-space maneuvers)
- Vasile and de Pascale, 2005 – autonomous chemical design for fixed mission sequence
- Vinko and Izzo, 2008 – autonomous chemical design for fixed mission sequence
- Wall and Conway, 2009 – autonomous low-thrust design for fixed mission sequence (no planetary flybys)
- Chilan and Conway, 2009 – autonomous low-thrust and chemical design for fixed mission sequence (no planetary flybys)
- Yam, di Lorenzo, and Izzo, 2011 – autonomous low-thrust design for fixed mission sequence
- Englander, Conway, and Williams, 2012 – autonomous chemical design with variable mission sequence
- Englander (dissertation) 2013 – autonomous low-thrust design with variable mission sequence
Break the mission design problem into two stages, or “loops”

- “outer-loop” picks sets of destinations, planetary flybys, sizes the power system, can pick propulsion system – a discrete optimization problem
- “inner-loop” finds the optimal trajectory for a given candidate outer-loop solution – a real-valued optimization problem
- For the outer-loop to work, the inner-loop must function autonomously (i.e. no human interaction)
The customer (scientist or project manager) most often does not want just one point solution to the mission design problem.

Instead, an exploration of a multi-objective trade space is required.

For a typical main-belt asteroid mission the customer might wish to see the trade-space of:
- Launch date vs
- Flight time vs
- Deliverable mass
- While varying the destination asteroid, planetary flybys, solar array size, etc

To address this question we use a multi-objective discrete outer-loop which defines many single objective real-valued inner-loop problems.
The interplanetary mission design problem has two types of variables:

- **Discrete** variables encoding the mission sequence and choice of spacecraft systems (launch vehicle, power, propulsion)
- **Continuous** variables defining the trajectory

In *Hybrid Optimal Control*, the problem is divided into two nested loops.
- The *outer-loop* solves the discrete problem and identifies candidate missions.
- The continuous *inner-loop* then finds the optimal trajectory for each candidate mission.
- The outer-loop finds the non-dominated trade surface between any set of objective functions chosen by the user
- Non-dominated surface means “no point on the surface is superior to any other point on the surface in all of the objective functions”
- The outer-loop solver may choose from a menu of options for each decision variable
- The choices made by the outer-loop solver are used to define trajectory optimization problems to be solved by the inner-loop
Discrete Optimization of the Mission Sequence and Spacecraft Systems

- EMTG’s outer-loop finds the non-dominated set of missions, those which are not strictly better or worse than other missions in the set based on all of the analyst’s chosen objective functions.
- EMTG uses a version of the Non-Dominated Sorting Genetic Algorithm II (NSGAII) which can evolve to the final non-dominated trade front despite starting from complete randomness. No \textit{a priori} knowledge of the solution is required.
EMTG’s inner-loop finds the optimal trajectory using a stochastic global search method called Monotonic Basin Hopping (MBH) coupled with a gradient-based local search supplied by the third-party Sparse Nonlinear Optimizer (SNOPT).

EMTG does not require an initial guess and can find the global optimum autonomously.
Chemical Mission Modeling in EMTG

High-Thrust Example: Whack-a-Rock

- In the “Whack-a-Rock” problem we design a small bodies mission which delivers a high-speed impactor to a Near Earth Object (NEO) and then returns to rendezvous and perform detailed science some years later.
- All C-type NEOs with diameter of 500m or greater are admissible targets and are considered equally scientifically valuable.
- Planetary flybys can be added as appropriate.
- We want to know what the best C-type NEO is for this mission during the 2020s.
# Whack-a-Rock Problem Assumptions

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch year</td>
<td>outer-loop chooses in [2020, 2029]</td>
</tr>
<tr>
<td>Flight time</td>
<td>outer-loop chooses in [3, 12] years</td>
</tr>
<tr>
<td>Launch vehicle</td>
<td>outer-loop chooses Atlas V 401, 411, 421, 431, 541, or 551</td>
</tr>
<tr>
<td>Spacecraft Isp</td>
<td>320 s</td>
</tr>
<tr>
<td>Penetrator mass</td>
<td>20 kg</td>
</tr>
<tr>
<td>Arrival conditions</td>
<td>(first Journey) intercept with $v_\infty$ in [5.0, 10.0] km/s, $\theta_{illumination} \leq 70^\circ$</td>
</tr>
<tr>
<td></td>
<td>(second Journey) rendezvous</td>
</tr>
<tr>
<td>Number of flybys allowed</td>
<td>2 in each Journey</td>
</tr>
<tr>
<td>Flyby targets considered</td>
<td>Venus, Earth, Mars</td>
</tr>
<tr>
<td>Outer-loop objective functions</td>
<td>launch year</td>
</tr>
<tr>
<td></td>
<td>flight time</td>
</tr>
<tr>
<td></td>
<td>delivered mass</td>
</tr>
<tr>
<td></td>
<td>launch vehicle choice</td>
</tr>
<tr>
<td>Outer-loop population size</td>
<td>256</td>
</tr>
<tr>
<td>Outer-loop mutation rate</td>
<td>0.3</td>
</tr>
<tr>
<td>Inner-loop MBH run-time</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Inner-loop MBH Pareto $\alpha$</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Whack-a-Rock: First Generation Trade Space
Whack-a-Rock: Final Generation Trade Space
Whack-a-Rock: Example Trajectories

Atlas V 421, 11.25 year flight time

Atlas V 551, 2.45 year flight time
Low-thrust electric propulsion is characterized by high power requirements but also very high specific impulse ($I_{sp}$), leading to very good mass fractions.

Low-thrust trajectory design is a very different process from chemical trajectory design.
- Like chemical design, must find the optimal launch date, flight time, and dates of each flyby (if applicable).
- Unlike chemical design, must find a time-history of thrust control for the entire mission.

*Low-thrust electric propulsion mission design requires accurate modeling of propulsion and power systems. Every spacecraft design drives a unique trajectory design!*
Several methods of picking the destination and flyby sequence:
- Grid search over all possible choices of destinations, flyby sequence, propulsion system, power system, etc. (very expensive and often impractical)
- Intuition-guided manual design of the trajectory (even more expensive, can miss non-intuitive solutions)

Several methods of designing the trajectory:
- Local optimization from an initial guess provided by a chemical mission design (but sometimes the optimal chemical trajectory does not resemble the optimal low-thrust trajectory)
- Local optimization from an initial guess provided by a low-fidelity approximation to the low-thrust model, i.e. shaped-based methods (but sometimes the shape-based method cannot accurately approximate the true trajectory)
**Low-Thrust Modeling in EMTG Transcription**

- Break mission into phases. Each phase starts and ends at a body.

- Sims-Flanagan Transcription
  - Break phases into time steps
  - Insert a small impulse in the center of each time step, with bounded magnitude

- Optimizer Chooses:
  - Launch date
    - For each phase:
      - Initial velocity vector
      - Flight time
      - Thrust-impulse vector at each time step
      - Mass at the end of the phase
      - Terminal velocity vector

- Assume two-body force model; propagate by solving Kepler's problem

- Propagate forward and backward from phase endpoints to a “match point”

- Enforce nonlinear state continuity constraints at match point

- Enforce nonlinear velocity magnitude and altitude constraints at flyby

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**Global Trajectory Optimization Group**

NASA GSFC

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Low-Thrust Modeling in EMTG Spacecraft and Launch Vehicle Models

• Medium-fidelity mission design requires accurate hardware modeling
• Launch vehicles are modeled using a polynomial fit

\[ m_{\text{delivered}} = (1 - \sigma_{LV}) \left( a_{LV} C_3^5 + b_{LV} C_3^4 + c_{LV} C_3^3 + d_{LV} C_3^2 + e_{LV} C_3 + f_{LV} \right) \]

where \( \sigma_{LV} \) is launch vehicle margin and \( C_3 \) is hyperbolic excess velocity

• Thrusters are modeled using either a polynomial fit to published thrust and mass flow rate data

\[ \dot{m} = a_F P^4 + b_F P^3 + c_F P^2 + d_F P + e_F \]
\[ T = a_T P^4 + b_T P^3 + c_T P^2 + d_T P + e_T \]

or, when detailed performance data is unavailable

\[ T = \frac{2 \eta P}{I_{sp} g_0} \]

• Power is modeled by a standard polynomial model

\[ \frac{P_0}{r^2} \left( \frac{\gamma_0 + \frac{\gamma_1}{r} + \frac{\gamma_2}{r^2}}{1 + \gamma_3 r + \gamma_4 r^2} \right) (1 - \tau)^t \]

where \( P_0 \) is the power at beginning of life at 1 AU and \( \tau \) is the solar array degradation constant
Asteroid Redirect Robotic Mission: return asteroid boulder or entire asteroid
- Extensibility option is to return boulder from Deimos
- Want to understand how return mass & TOF are affected by array size, # of thrusters

→ 4 optimization objectives: max. return mass, min. TOF, min. EOL power, min. # of thrusters (all coupled)

### System Design Variables

<table>
<thead>
<tr>
<th>Design Variable</th>
<th>Integer</th>
<th>Value</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch option</td>
<td>[0, 1]</td>
<td>{Delta IV-H from LV curve, Delta IV-H with LGA}</td>
<td>-</td>
</tr>
<tr>
<td>Solar array size</td>
<td>[0, 15]</td>
<td>[25, 95] kW</td>
<td>5 kW</td>
</tr>
<tr>
<td>Launch window open epoch</td>
<td>[0, 9]</td>
<td>{8/1/2020, …, 8/1/2030}</td>
<td>1 year</td>
</tr>
<tr>
<td>Flight time</td>
<td>[0, 26]</td>
<td>[700, 3300] days</td>
<td>100 days</td>
</tr>
<tr>
<td>Engine mode</td>
<td>[0, 2]</td>
<td>{high-Isp, medium-thrust, high-thrust}</td>
<td>-</td>
</tr>
<tr>
<td>Number of engines</td>
<td>[0, 7]</td>
<td>[2, 9]</td>
<td>1</td>
</tr>
</tbody>
</table>

207360 possible combinations

### Notional Mission Parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch window</td>
<td>1 year</td>
</tr>
<tr>
<td>Wait time at Deimos</td>
<td>[150, 600] days</td>
</tr>
<tr>
<td>Min. spacecraft mass with 2 thrusters &amp; 25 kW array</td>
<td>5703.5 kg</td>
</tr>
<tr>
<td>Additional dry mass per extra thruster</td>
<td>75 kg</td>
</tr>
<tr>
<td>Additional dry mass per kW of array power above 25 kW</td>
<td>12.5 kg</td>
</tr>
<tr>
<td>Max. depart. mass if lunar gravity assist (C_3 \leq 2.0 \text{ km}^2/\text{s}^2)</td>
<td>11191 kg</td>
</tr>
<tr>
<td>Max. departure mass if direct launch (C_3 = 0.0 \text{ km}^2/\text{s}^2)</td>
<td>10796 kg</td>
</tr>
<tr>
<td>Maximum (C_3) if direct launch</td>
<td>6 km^2/s^2</td>
</tr>
<tr>
<td>Lunar DRO insertion (\Delta V)</td>
<td>75 m/s</td>
</tr>
<tr>
<td>Thruster duty cycle</td>
<td>90%</td>
</tr>
<tr>
<td>Solar array modeling</td>
<td>1/r^2</td>
</tr>
<tr>
<td>Spacecraft bus power</td>
<td>2 kW</td>
</tr>
<tr>
<td>Propellant margin</td>
<td>6%</td>
</tr>
</tbody>
</table>
Best Non-Dominated Front

All non-dominated solutions after 56 generations form representation of Pareto front

4th objective dimension not shown here (minimize # of thrusters)
Optimal Trade Space

All non-dominated solutions after 56 generations projected in 2D objective space

- Sharp increase in return mass up to 6 yr TOF
- 2 yr TOF gap along max. return mass
- Higher power enables short TOF solutions

High-Isp Engine

High-Thrust Engine

Medium-Thrust Engine

• High-Isp mode optimal for highest return mass cases
• High-thrust mode optimal for Short TOF, low-power cases
All non-dominated solutions after 56 generations projected in 2D objective space

- Increase in array dry mass decreases available propellant
- Shorter TOFs benefit from higher power
- Most solutions only require 2 or 3 thrusters
- Short-TOF enabled by 4 or 5 thrusters
- Some 6-9 thruster cases hidden in plot
Trajectory Examples

**Highest Return Mass Trajectory**
- 9.6 t boulder return
- 8.3 year TOF
- 50 kW EOL solar array
- High-Isp mode thruster
- 2 thruster strings
- LGA on Earth departure

**Shortest TOF Trajectory**
- 0.6 t boulder return
- 3.3 year TOF
- 95 kW EOL solar array
- Med.-thrust mode thruster
- 5 thruster strings
- LGA on Earth departure
EMTG Design Capabilities

- **Propulsion Types**
  - High-thrust chemical
  - Low-thrust electric

- **Mission Components**
  - Deep-space maneuvers
  - Gravity Assists
  - Asteroid Rendezvous/Flyby
  - Sample Return/Planetary Landing
  - Launch Vehicle selection

- **Spacecraft Systems**
  - Power system sizing
  - Propulsion system sizing

- **Mission Objectives**
  - Maximize science payload
  - Minimize flight time
  - Visit as many diverse bodies as possible
  - Maximize encounter energy (for planetary defense)

- **Operational and Science Constraints**
  - Atmospheric entry
  - Solar distance
  - Any other constraints on final orbit
Conclusion

- Interplanetary mission design problems, whether using high-thrust chemical or low-thrust electric propulsion, may be posed as multi-objective hybrid optimal control problems (HOCP).
- The HOCP may be augmented to include spacecraft hardware parameters such that the trajectory design problem becomes a coupled mission and systems design problem.
- The combination of a multi-objective discrete NSGA-II outer-loop with a MBH+NLP inner-loop is a very powerful way to explore a mission and systems trade space in an efficient, automated manner.
- Mission design mathematics may easily be automated. Communication and understanding cannot be. The method presented here allows analysts to focus their attention on understanding the needs of their customers (scientists) and the capabilities of the spacecraft while leaving the repetitive work to the computer.
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- Various customers at Goddard
EMTG is available open-source at
https://sourceforge.net/projects/emtg/