National Aeronautics and Space Administration

Multi-objective Hybrid Optimal Control for Interplanetary Mission Planning

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code 595

NAVIGATION & MISSION DESIGN BRANCH

NASA GSFC

Introduction to the Low-Thrust Interplanetary Mission Design Problem

- 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

Traditional Methods of Low-Thrust, Multi-Flyby Trajectory Design

- Several methods of picking the destination and flyby sequence:
  - Grid search over all possible choices of destinations, flyby sequence, launch date, 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)

Automated Mission Design via Hybrid Optimal Control

- 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)

Multi-Objective Hybrid Optimal Control

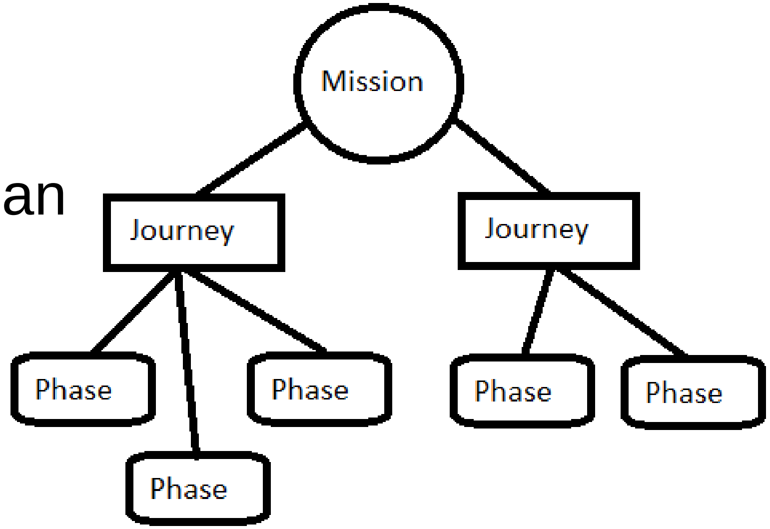
- The customer (scientist or project manager) most often does not want just one point solution to the mission design problem
- Instead, an exploration of a multi-objective trade space is required
- For a typical main-belt asteroid mission the customer might wish to see the trade-space of:
  - Launch date vs
  - Flight time vs
  - Deliverable mass
  - While varying the destination asteroid, planetary flybys, launch year, etc.
- To address this question we use a multi-objective discrete outer-loop which defines many single objective real-valued inner-loop problems

Outer-Loop Transcription and Optimization

- 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

Anatomy of a Mission

- Break mission into a set of “journeys,” each of which in turn is broken into “phases”
- The endpoints of a journey are chosen in the problem assumptions
- The endpoints of a phase (i.e. a flyby target) may be chosen by the user or an Outer-Loop solver



Outer-Loop Transcription: An Example

Launch Year

Code	Year
0	2020
1	2021
2	2022
3	2023
4	2024
6	2025
7	2026
8	2027
9	2028
10	2029

Flight Time Upper Bound

Code	# Years
0	5
1	6
2	7
3	8
4	9
5	10
7	11
8	12

First Asteroid

Code	Body
0	Ceres
1	Pallas
2	Juno
3	Vesta
4	Astraea
5	Hebe
6	Iris
7	Flora
…	(475 choices)

Second Asteroid

Code	Body
0	Ceres
1	Pallas
2	Juno
3	Vesta
4	Astraea
5	Hebe
6	Iris
7	Flora
…	(475 choices)

First Journey First Flyby

Code	Body
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

First Journey Second Flyby

Code	Body
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

Second Journey Flyby

Code	Body
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

Sample Mission

	Flight Time Upper Bound	Asteroid 1	Potential Planetary Flyby 1	Asteroid 2	Potential Planetary Flyby 2
Code	4	0	1	1	1
Translation	8 y	Ceres	Mars	Pallas	none

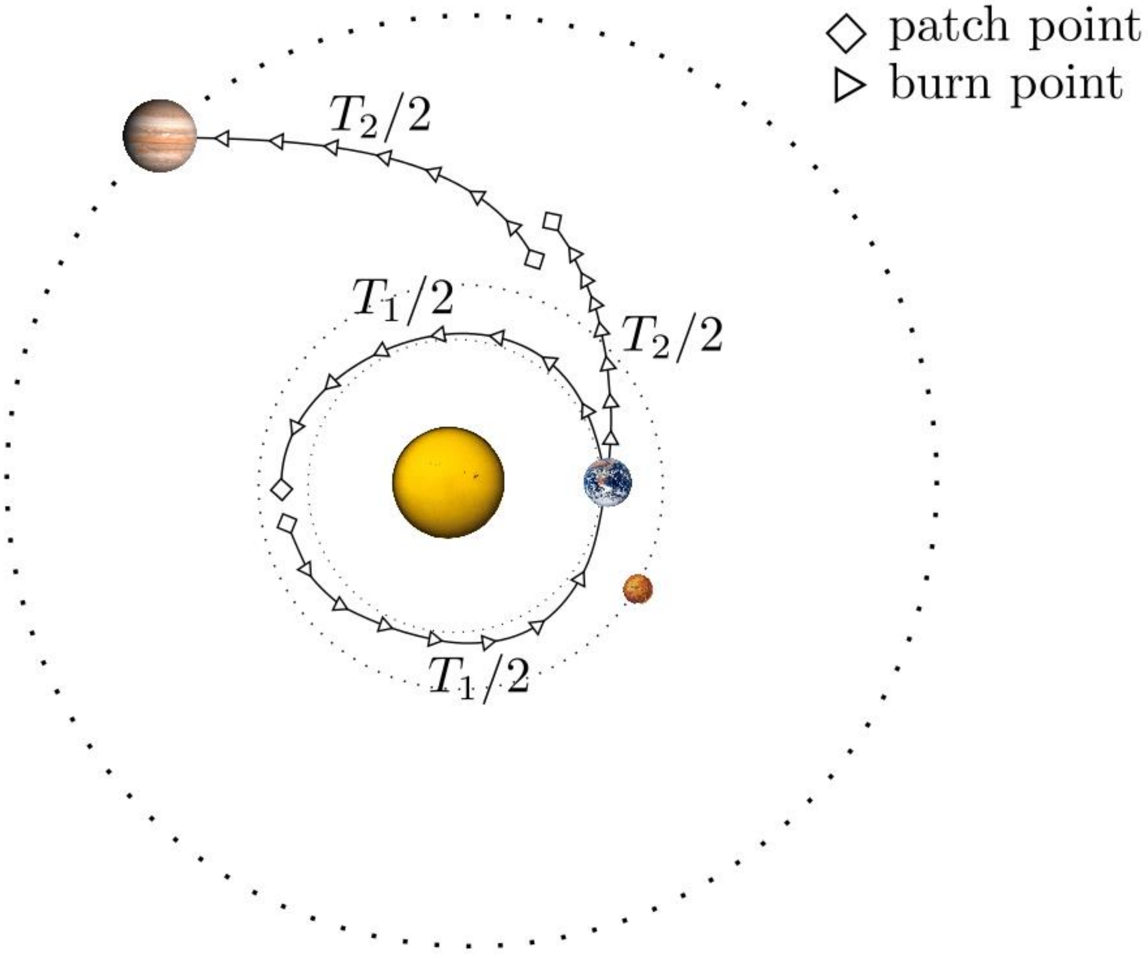
Multi-Objective Optimization via NSGA-II

- The outer-loop optimization problem is solved using a discrete multi-objective solver, in this case Non-Dominated Sorting Genetic Algorithm II (NSGA-II)
- NSGA-II finds the non-dominated front, surface, or hyper-surface between any number of objectives chosen by the user

Inner-Loop Modeling and Optimization

- The inner-loop solves a real-valued trajectory optimization problem which is defined by each candidate solution to the outer-loop problem
- The inner-loop must function autonomously because the problems are generated in real time and there is no opportunity for human intervention
- The outer-loop is only as good as the solutions to the inner-loop problem, so the inner-loop must be robust
- A given run of the outer-loop may require hundreds or even thousands of runs of the inner-loop, so the inner-loop must be fast
- If the individual inner-loop runs are independent then many of them can be run in parallel

Multiple Gravity Assist with Low-Thrust (MGALT) via the Sims-Flanagan Transcription



Power, Propulsion, and Ephemeris Modeling

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

$$m_{delivered} = (1 - \sigma_{LV})\left(a_{LV}C_3^5 + b_{LV}C_3^4 + c_{LV}C_3^3 + d_{LV}C_3^2 + e_{LV}C3 + f_{LV}\right)$$

where σ_{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 τ is the solar array degradation constant

- Ephemeris data for solar system bodies is provided via the SPICE toolkit

Inner-Loop Solver: Nonlinear Programming (NLP)

Minimize $f(\boldsymbol{x})$

Subject to:

$$\boldsymbol{x}_{lb} \leq \boldsymbol{x} \leq \boldsymbol{x}_{ub}$$

$$\boldsymbol{c}(\boldsymbol{x}) \leq \boldsymbol{0}$$

$$\boldsymbol{A}\boldsymbol{x} \leq \boldsymbol{0}$$

where:

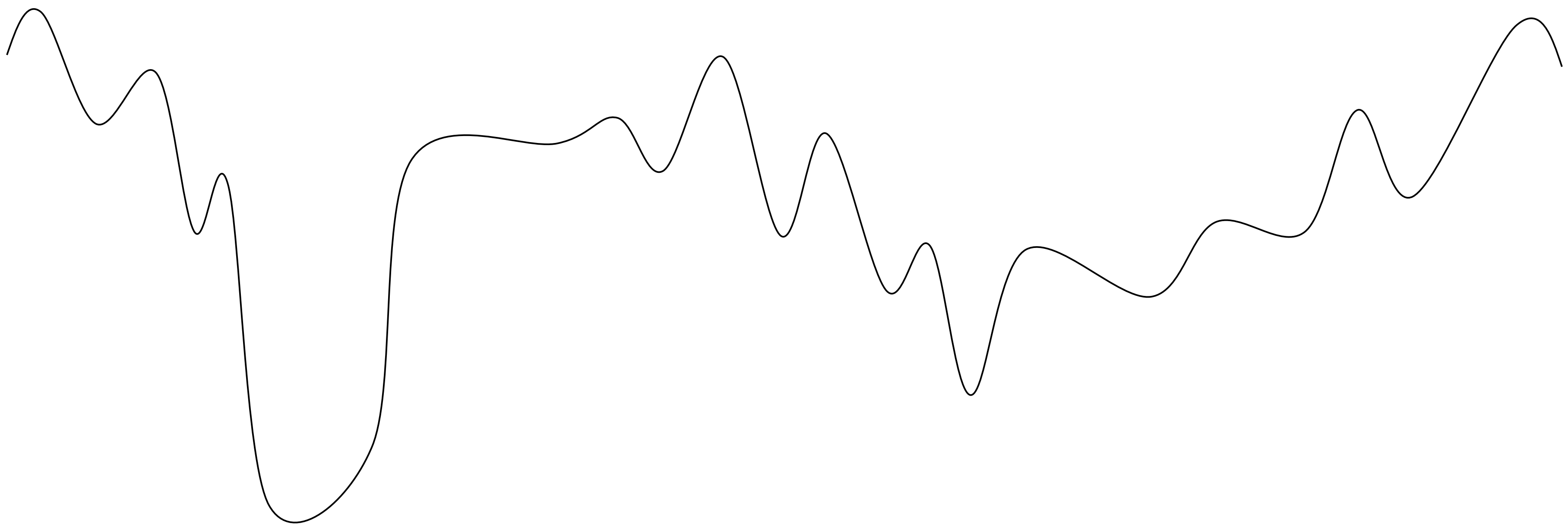
$\boldsymbol{x}_{lb}$, $\boldsymbol{x}_{ub}$ are lower and upper bounds on the decision variables

$\boldsymbol{c}(\boldsymbol{x})$ is a vector of nonlinear constraints

$\boldsymbol{A}\boldsymbol{x}$ is a vector of linear constraints

- There are several third party solvers that do this (SNOPT, IPOPT, fmincon, vf13AD)
- But all of these methods require an initial guess…

Inner-Loop Solver: Monotonic Basin Hopping (MBH)



Leary, 2000
Vasile, Minisci, and Locatelli, 2009
Yam, di Lorenzo, and Izzo, 2011
Englander (dissertation), 2013
Casioli *et al.*, 2013
Englander and Englander, 2014

Improved from standard MBH by:

1. "Feasible point finder" aggregate penalty method
2. Non-uniform (Pareto) perturbation step
3. "Time-hop" operator (Casioli *et al.*)

Example: Main-Belt Two Asteroid Tour

Mission Objective	Visit two main-belt asteroids with diameter greater than 50 km (475 bodies meet this filter)
Launch Vehicle	Atlas V 401
Power System	
Array power at 1 AU	15 kW
Cell performance model	$1/r^2$
Spacecraft bus power	800 W
Power margin	15%
Propulsion System	
Thruster	NEXT (throttle table 11, high-Isp mode)
Number of thrusters	1
Duty cycle	90%
Propellant tank	unconstrained
Mission Sequence	up to two planetary flybys are permitted before the first asteroid and up to one between the first and second asteroids
Inner-Loop Objective Function	Maximize delivered mass to second asteroid
Outer-Loop Objective Functions	Delivered mass to second asteroid Launch year Flight time

Main-Belt Two Asteroid Tour: Outer-Loop Menu

Launch Year	
Code	**Year**
0	2020
1	2021
2	2022
3	2023
4	2024
6	2025
7	2026
8	2027
9	2028
10	2029

Flight Time Upper Bound	
Code	**# Years**
0	5
1	6
2	7
3	8
4	9
5	10
7	11
8	12

First Asteroid	
Code	**Body**
0	Ceres
1	Pallas
2	Juno
3	Vesta
4	Astraea
5	Hebe
6	Iris
7	Flora
…	(475 choices)

Second Asteroid	
Code	**Body**
0	Ceres
1	Pallas
2	Juno
3	Vesta
4	Astraea
5	Hebe
6	Iris
7	Flora
…	(475 choices)

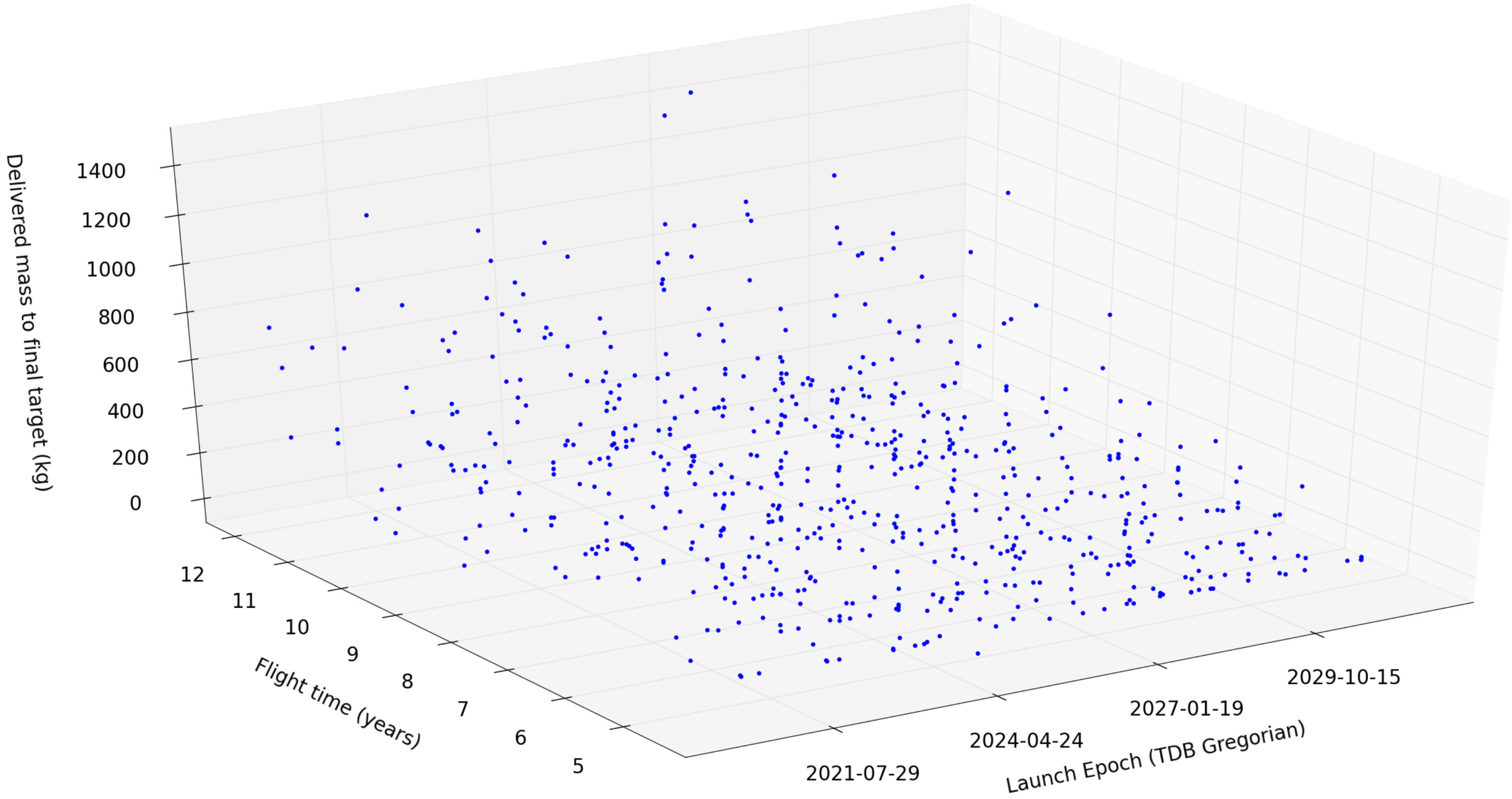
First Journey First Flyby	
Code	**Body**
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

First Journey Second Flyby	
Code	**Body**
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

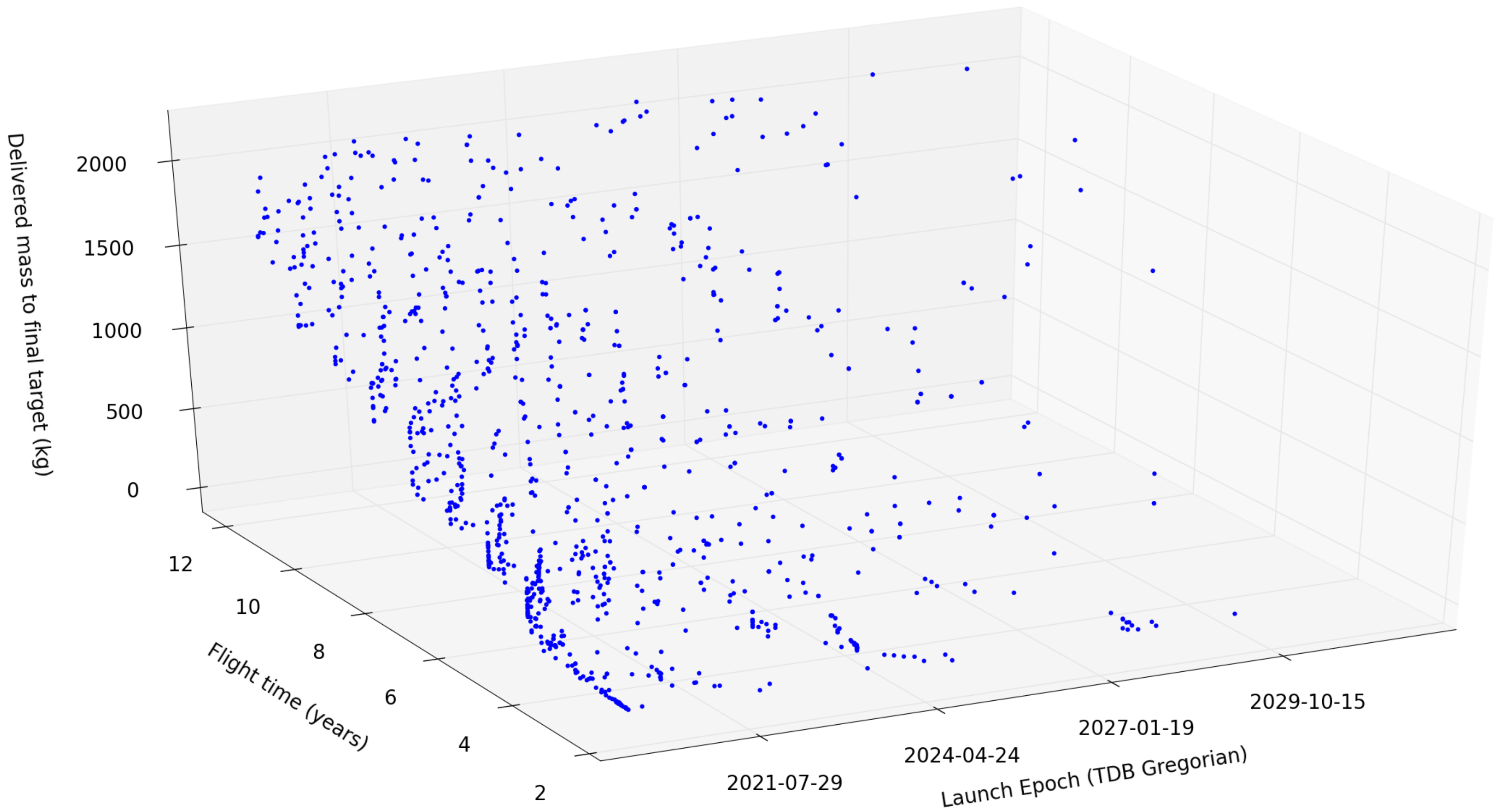
Second Journey Flyby	
Code	**Body**
0	Earth
1	Mars
2	Jupiter
3	No flyby
4	No flyby
5	No flyby

1.16×10^9 possible combinations, 4.82×10^9 with duplicates

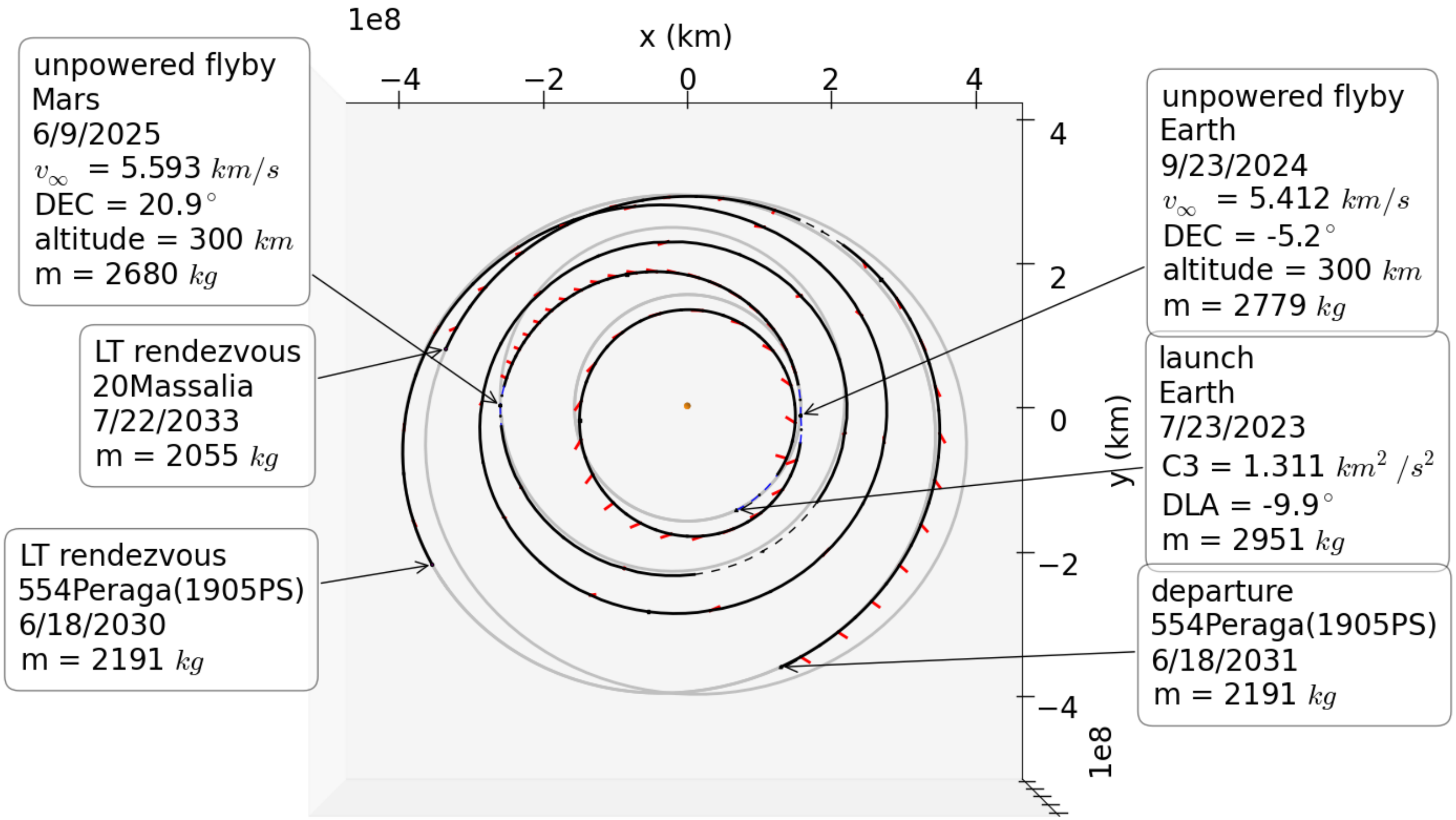
Main-Belt Two Asteroid Tour: First Generation Trade Space



Main-Belt Two Asteroid Tour: Final Generation Trade Space



Main-Belt Two Asteroid Tour: Example Trajectory



A 10-year mission launching in 2023 delivers 2055 kg to Peraga and Massalia

Conclusions

- The low-thrust interplanetary mission design problem may be posed as a multi-objective hybrid optimal control 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 trade space in an efficient, automated manner
- The algorithm described here has revolutionized the low-thrust interplanetary mission design process at NASA Goddard Space Flight Center
  - We can now study multiple mission design cases simultaneously, limited only by available computing power
  - Mission design engineers can now spend more time with the customer and with spacecraft hardware engineers so that we can fully understand the scientific and engineering context of our work
  - Good mission ideas are much less likely to be rejected due to lack of time to work on mission design, and bad ideas are much more likely to be rejected before they consume too many resources

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Thank You

EMTG is available open-source at

https://sourceforge.net/projects/emtg/