MOLTO-IT

A **M**ulti-**O**bjective **L**ow-**T**hrust **O**ptimizer for **I**nterplanetary **T**rajectories

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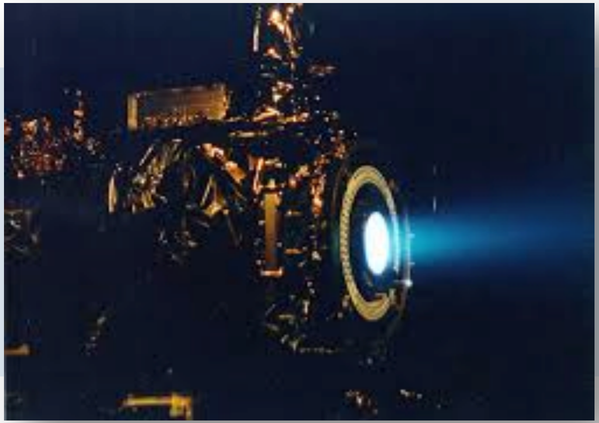

INTRODUCTION

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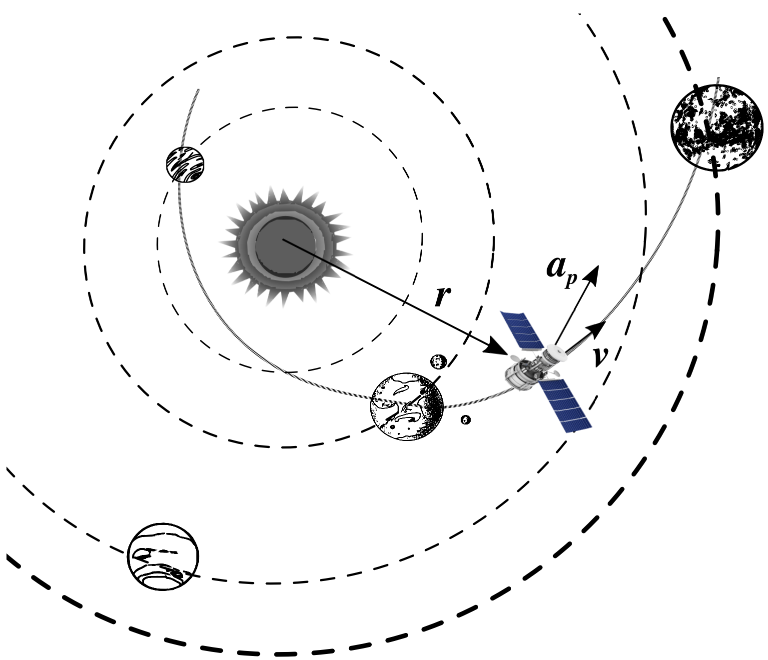
The goal is to design a low-thrust trajectory for a spacecraft to travel from the departure planet to the target planet with minimum cost



The spacecraft may have:

- Multiple-gravity assists
- Multiple revolutions

Solution comprises:

- Launch dates
- Flight times
- Propellant consumption
- Number and sequence of flybys
- Thrust steering law
- On/off switching times

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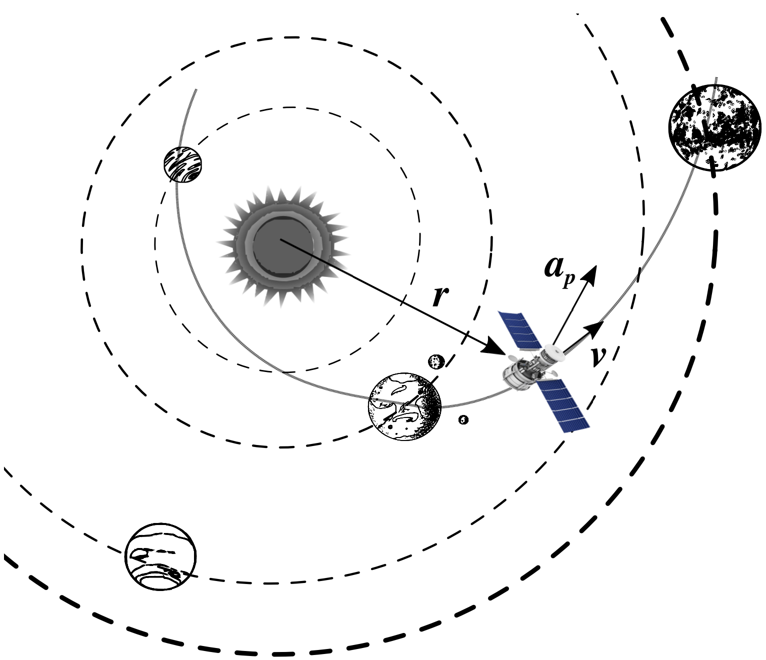
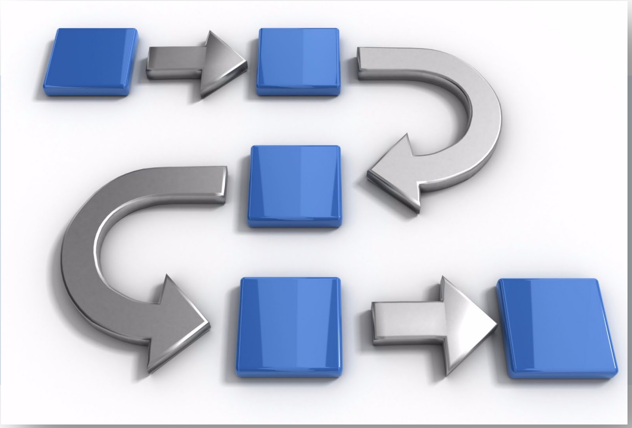


Tool Requirements:

- Automatic selection of the flybys
- Multi-objective search
- Reduced computational times
- Use of realistic models
- Inclusion of operational constraints
- Flexibility

The problem is challenging:

- Combinatorial complexity
- Real and Integers design variables
- Nonlinear dynamics



MOLTO-IT: AN OVERVIEW

User-Defined parameters

Description	Variable
Departure Body	b_o
Arrival Body	b_f
Mission type	Flyby/Rendezvous
Launch Window	$[t_{0,min}, t_{0,max}]$
Max/Min Flyby num.	$[n_{fb,max}, n_{fb,min}]$
Flyby bodies	$[b_1, \ldots, b_n]$
Max/Min Revolutions num.	$[n_{min}, n_{max}]$
Minimum Flyby radius	$r_{fb,min}$
Time of Flight	$[T_{i,min}, T_{i,max}]$
Max/Min Launch v_∞	$[v_{\infty 0,\min}, v_{\infty 0,\max}]$

MOLTO-IT

Muti-objective Low-Thrust Optimizer for Interplanetary Trajectories

MOLTO-IT STEP 1

Multi-objective Genetic Algorithm + Gradient-based solver

- Low-fidelity Model
- Unconstrained Thrust
- Free flyby number and sequence

INITIAL GUESS

MOLTO-IT STEP 2

Direct transcription + Gradient-based solver

- High-fidelity Mode
- Constrained Thrust
- Fixed flyby number and sequence

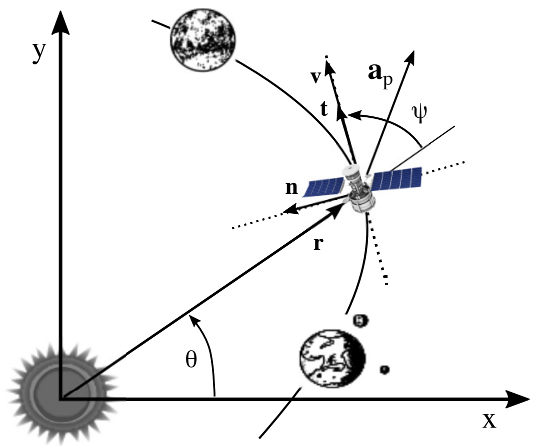
Outputs of Step 1:

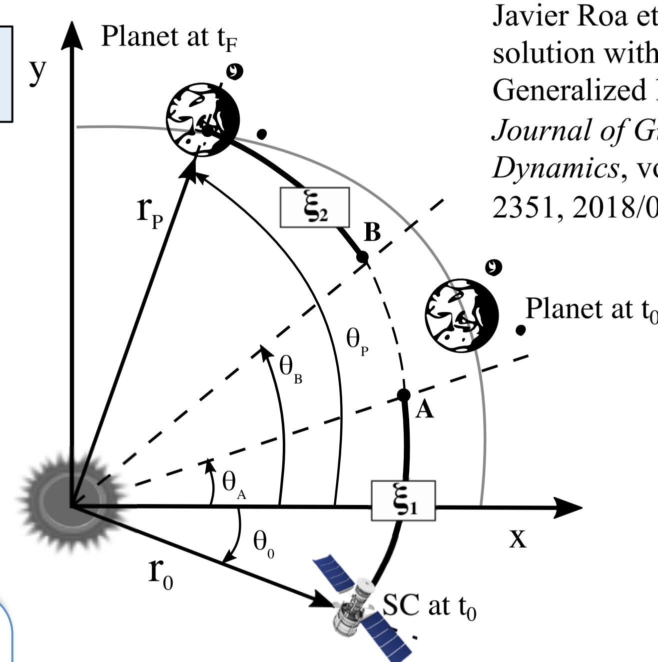
- Set of Pareto optimal solutions in one run
- Rapid trade-offs assessments for the preliminary design

Outputs of Step 2:

- Single optimized trajectory in one run
- High accuracy solutions for the detailed design

MOLTO-IT Step 1: Modeling





Javier Roa et al., "New analytic solution with continuous thrust: Generalized log- arithmic spirals," *Journal of Guidance, Control, and Dynamics*, vol. 39, no. 10, pp. 2336–2351, 2018/04/06 2016

Dynamics:

- Planar trajectories
- Constant orbital elements for ephemerides

Propulsion:

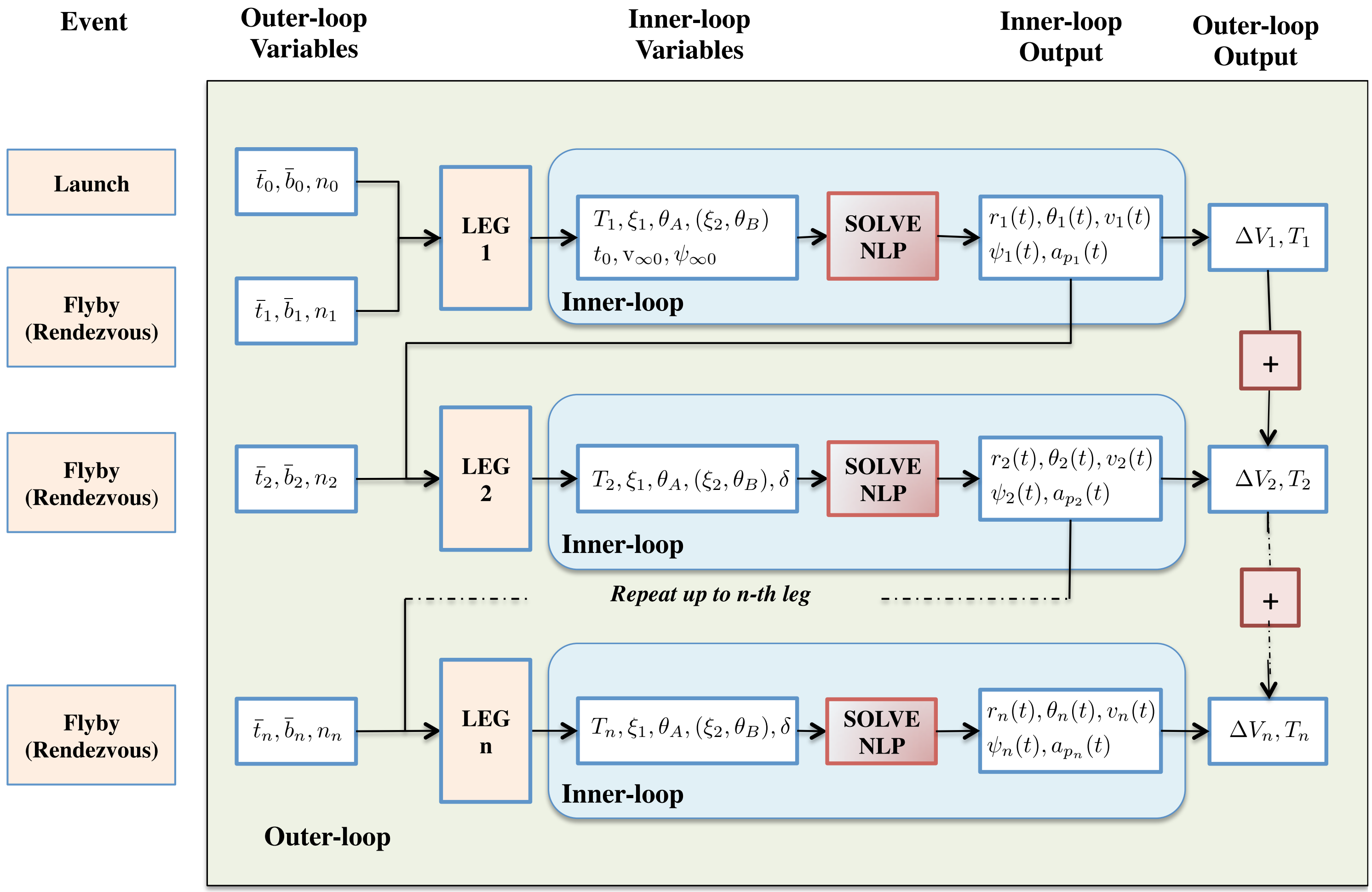
- Constant Specific Impulse
- Unconstrained thrust

$$\mathbf{a}_p = \frac{1}{r^2}(\xi \cos\psi\, \mathbf{t} + (1 - 2\xi)\sin\psi\, \mathbf{n})$$

$$r = f(r_0, v_0, \theta_0, \psi_0, t_0, \xi)$$

1 SPIRAL ARC	1 DoF
THRUST-COAS-THRUST	3 DoF

MOLTO-IT Step 1: Solution Approach



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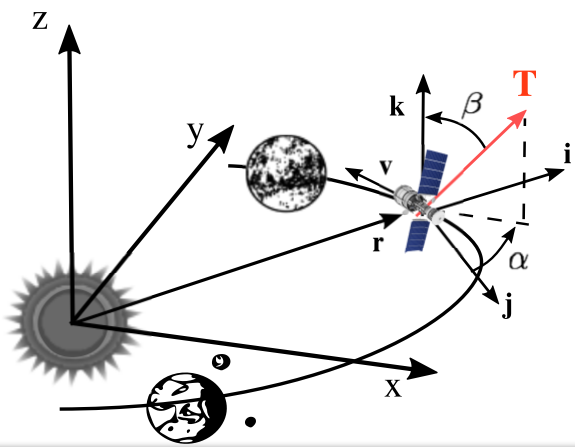
MOLTO-IT Step 2: Modeling



Dynamics:

- 3D + unconstrained control
- NIAF- SPICE toolkit ephemerides

Propulsion:

- Polynomial approximation for thrust, propellant rate and power

MOLTO-IT Step 2: Solution Approach

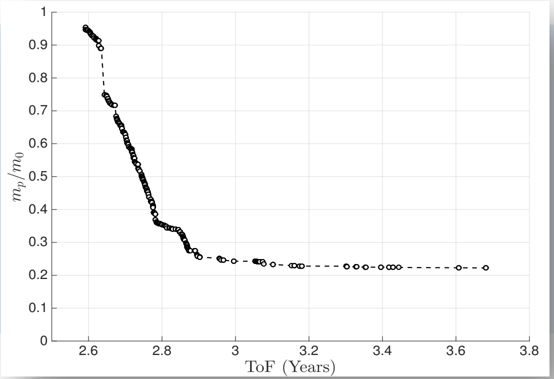
MULTI-PHASE CONTINUOUS OPTIMAL CONTROL PROBLEM

↓

DISCRETIZATION

↓

NONLINEAR PROGRAMMING PROBLEM



TEST CASES

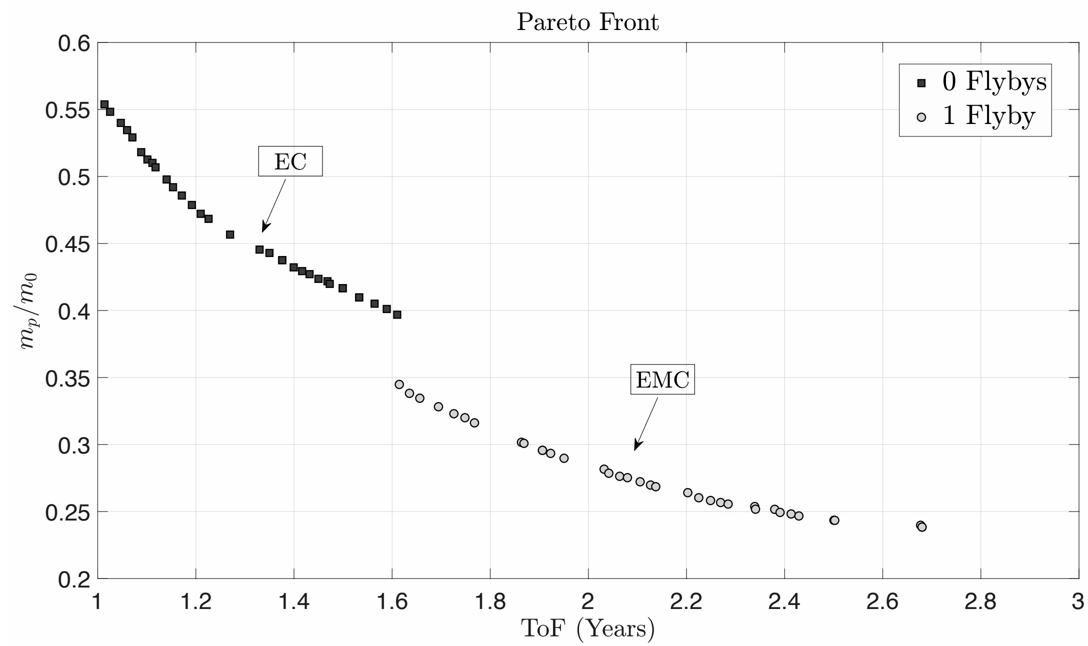
1. Introduction
2. MOLTO-IT: Overview
   - MOLTO-IT Step 1
   - MOLTO-IT Step 2
3. **Test Cases**
   - Earth to Ceres Rendezvous
   - Earth to Jupiter Flyby
   - Asteroid Mining Mission
4. Conclusions

EARTH TO CERES RENDEZVOUS

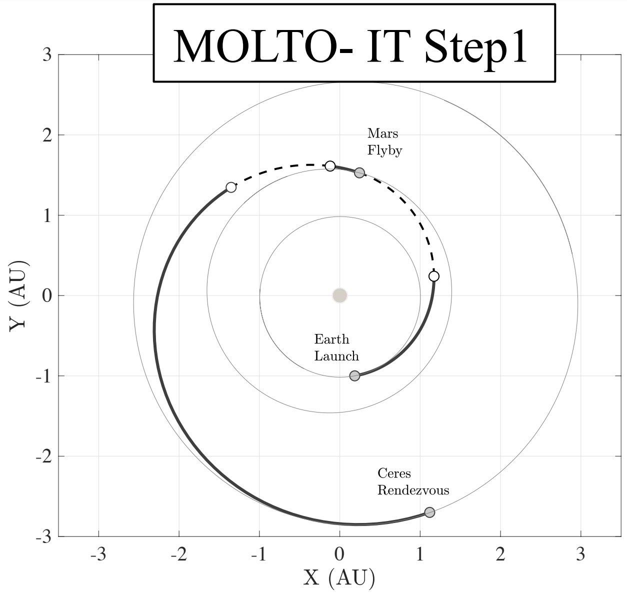
Population size	100
Generations	300
Mutation Fraction	0.3
Crossover Fraction	0.3

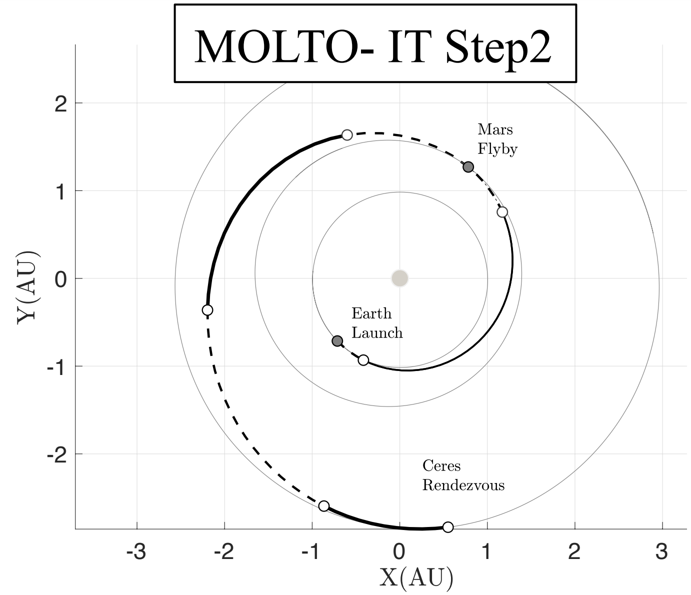
Variable	Lower Bound	Upper Bound
Launch Date	Jan 01, 2003	Dec 31, 2003
Launch v_∞ (km/s)	1.6	1.6
Flyby num.	0	1
Flyby Body	'Mars'	
h_{fb} (km)	200	10 000
Arrival v_∞ (km/s)	0	0
ToF (days)	200	500
m0 (kg)	568	
Engine	NSTAR	

"A. E. Petropoulos and J. M. Longuski, "Shape-based algorithm for automated design of low-thrust, gravity-assist trajectories," *Journal of Spacecraft and Rockets*, vol. 41, no. 5, pp. 787–796, 2004



Variable	Avg. CPU Time
Population	0.46 s
Generation	6.5 s
Total	5.4 min





		MOLTO-IT		Petropoulos and Longuski	
Parameter	Units	Step 1	Step 2	STOUR-LGTA	GALLOP
Launch Date	-	Jul 2, 2003	May 13, 2003	May 6, 2003	May 6, 2003
Launch v_∞	km/s	1.6	1.6	1.6	1.6
Mars Flyby Date	-	Feb 03, 2004	Dec 31, 2003	Feb 01, 2004	Feb 01, 2004
Mars Flyby v_∞	km/s	2.40	2.16	1.43	1.92
Mars B-Plane angle	deg	55.0	10.0	2.3	82.3
Mars Flyby Altitude	km	200	200	5432	200
Arrival Date	-	Mar 18, 2006	Jan 26, 2006	Jun 12, 2006	Feb 09, 2006
Arrival v_∞	km/s	0	0	0.237	0
Propellant mass fraction	-	0.224	0.229	0.256	0.233

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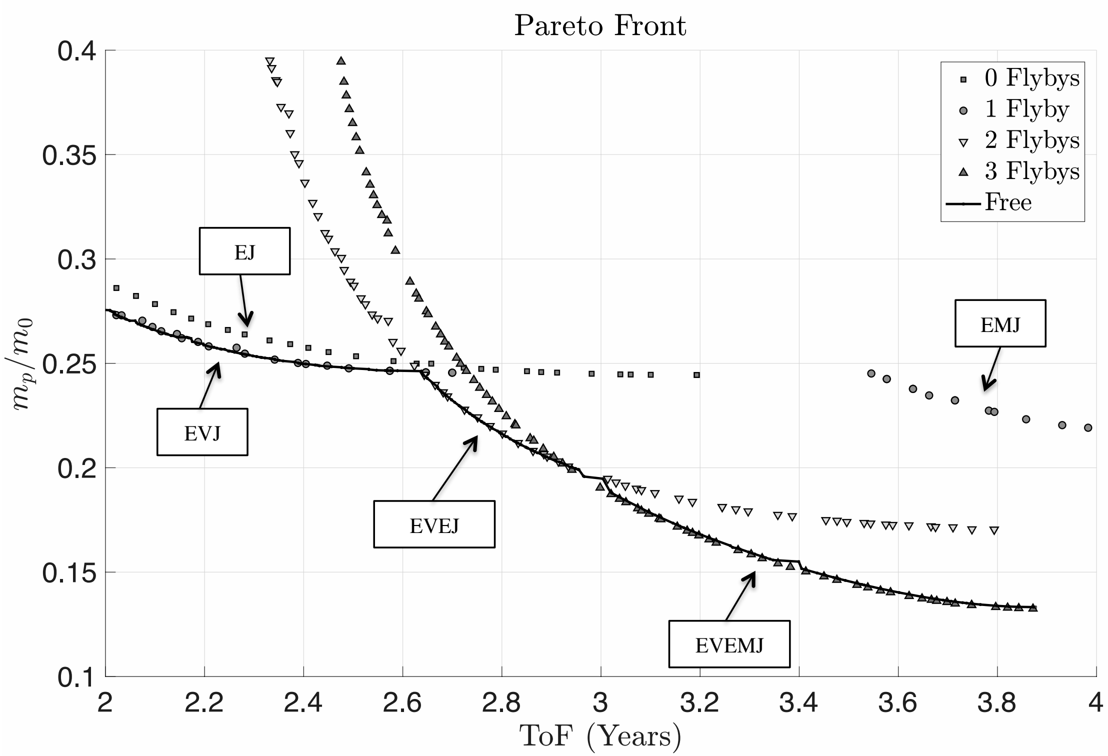
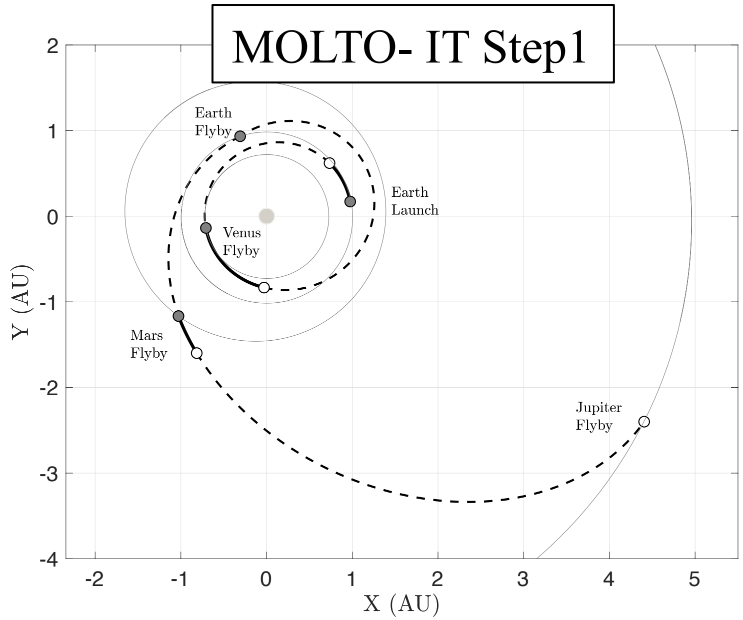
EARTH TO JUPITER FLYBY

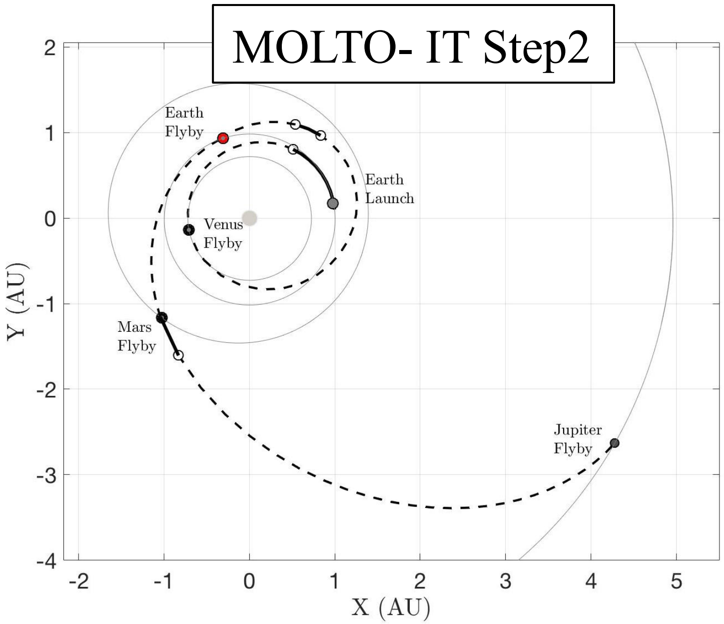
Population size	100
Generations	300
Mutation Fraction	0.3
Crossover Fraction	0.3

Variable	Lower Bound	Upper Bound
Launch Date	Jan 01, 2029	Dec 31, 2030
Launch v_∞ (km/s)	2	2
Flyby num.	0	3
Flyby Body	'Mars, Earth, Venus'	
h_{fb} (km)	200	10000
Arrival v_∞ (km/s)	-	-
ToF (days)	200	1500
m0 (kg)	360	
Engine	NSTAR	



Variable	Avg. CPU Time
Population	0.16 s
Generation	13 s
Total	11 min



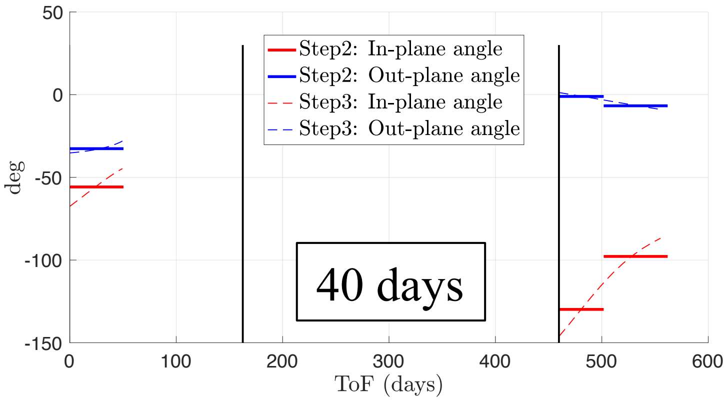


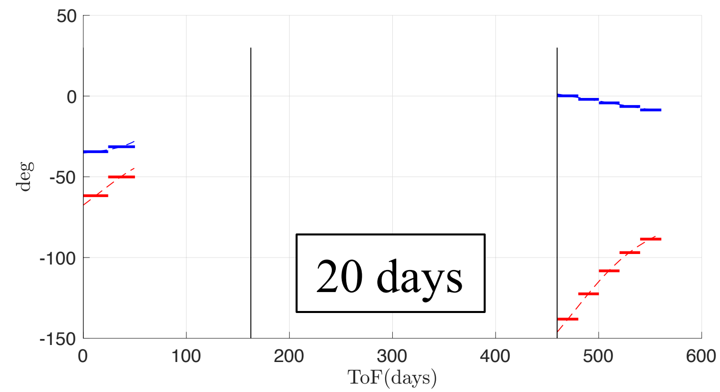
		MOLTO-IT		Petropoulos and Longuski	
Parameter	Units	Step 1	Step 2	STOUR-LGTA	GALLOP
Launch Date	-	Oct 1, 2029	Sept 28, 2029	Sept 3, 2029	Sept 3, 2029
Launch v_∞ (km/s)	km/s	2	2	2	2
Initial mass	kg	N/A	N/A	360	360
Venus Flyby Date	-	Feb 22, 2030	Mar 19, 2030	Feb 15, 2030	Feb 15, 2030
Earth Flyby Date	-	Jan 04, 2031	Jan 11, 2031	Jan 15, 2031	Dec 30, 2030
Mars Flyby v_∞	km/s	15.21	15.43	13.70	11.26
Arrival Date	-	Aug 14, 2033	Aug 21, 2033	Jan 20, 2035	Jan 20, 2035
Arrival v_∞ (km/s)	km/s	5.65	5.62	5.85	6.25
Propellant mass fraction	-	0.132	0.088	0.294	0.256

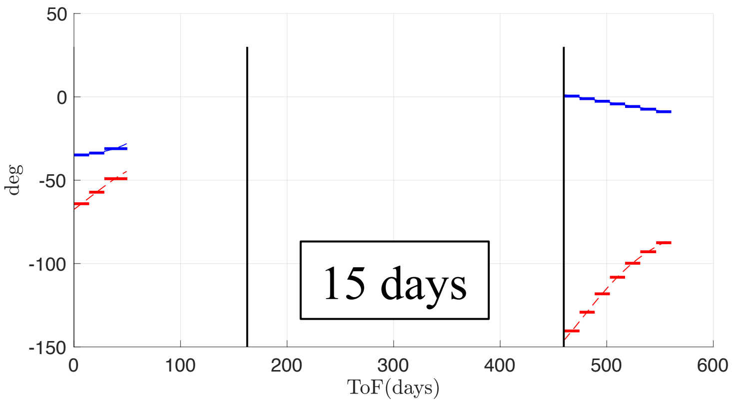
EARTH TO JUPITER FLYBY

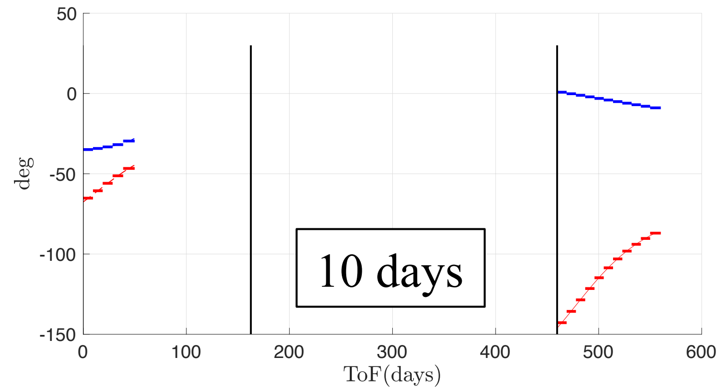
Fixed reorientation times constraint
E-V-E-J: ToF = 2.9 years, mp = 44 kg

Case	Propellant mass fraction (%)
Free	0.1220
10 days	0.1220
15 days	0.1223
20 days	0.1224
40 days	0.1236









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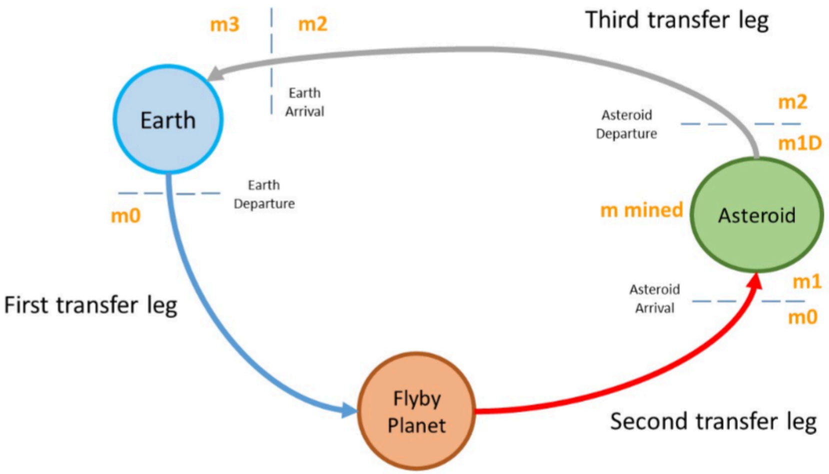
ASTEROID MINING TO RYUGU

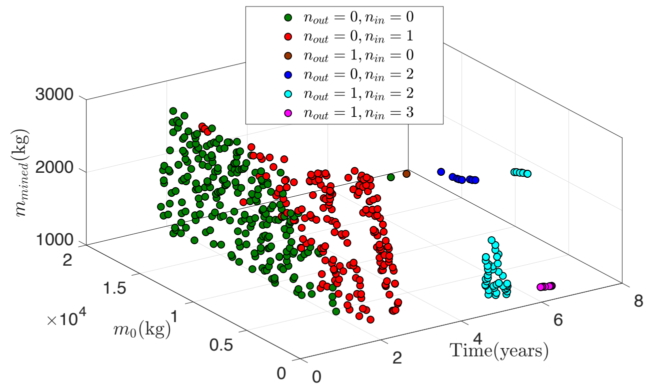
Variable	Lower Bound	Upper Bound
Launch Date	Jan 01, 2019	Dec 31, 2029
Launch v_∞ (km/s)	2	2
ToF (days)	300	1470
revolution	0	4
Mines mass (kg)	810	2600
Max. m0 (kg)	20 000	
On-surface time (days)	90	730
Engine	NEXT-C	

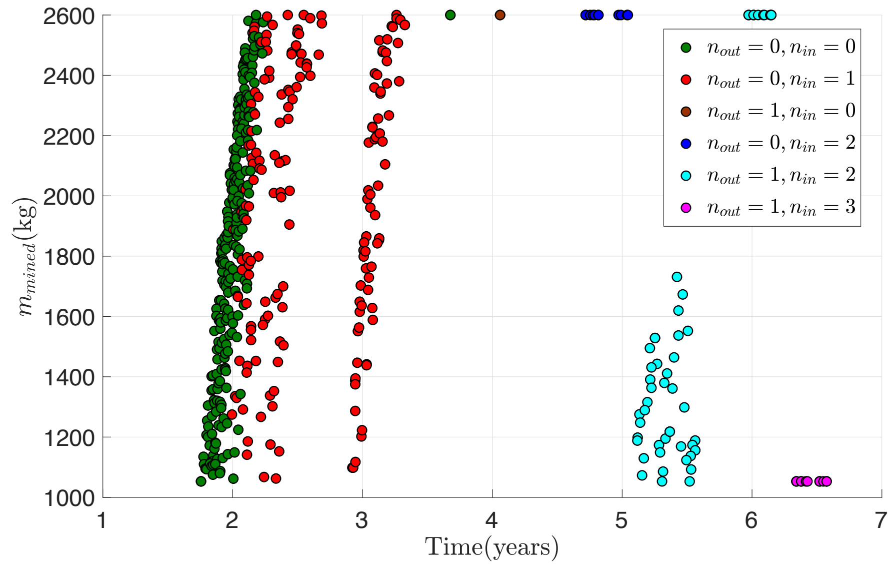


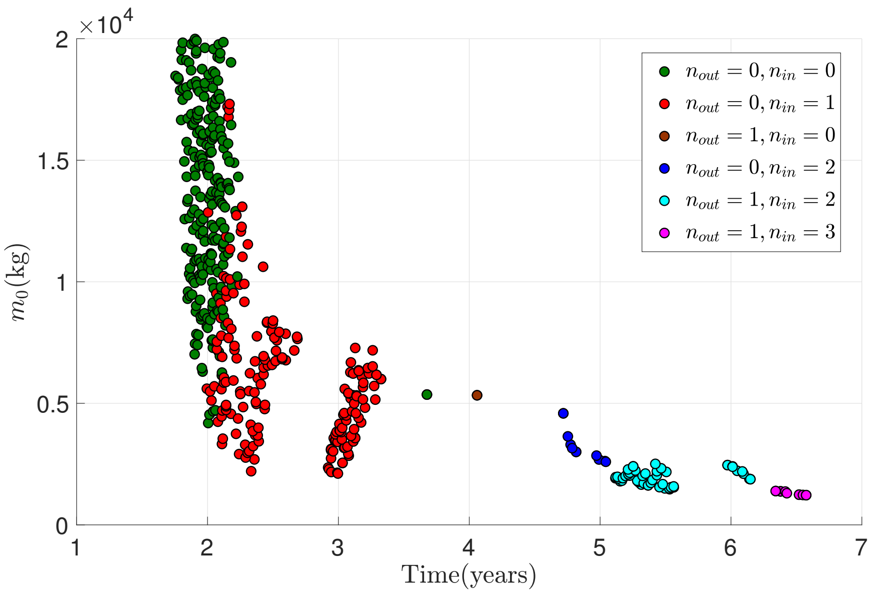
Population size	100
Generations	300
Mutation Fraction	0.3
Crossover Fraction	0.3

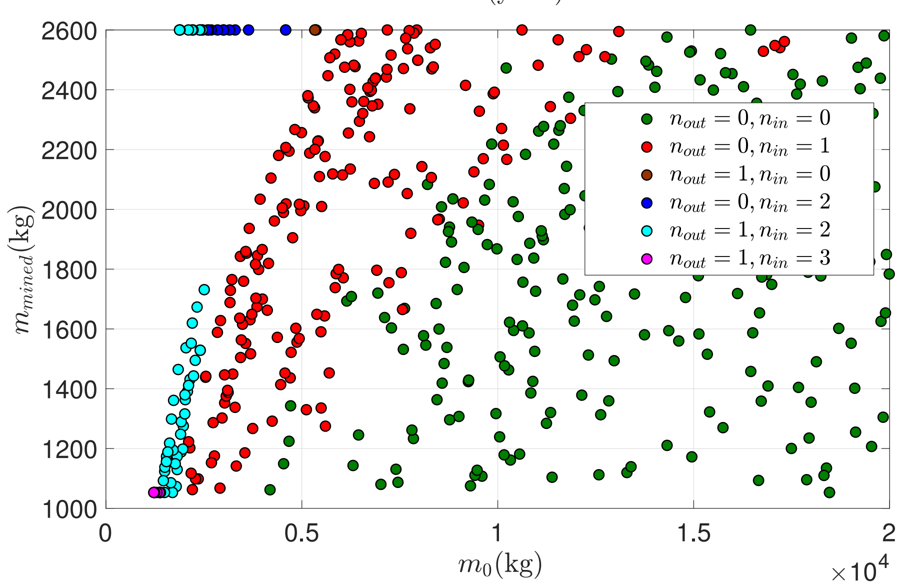
Variable	Avg. CPU Time
Population	0.011s
Generation	3.37s
Total	11.13 min

ASTEROID MINING TO RYUGU



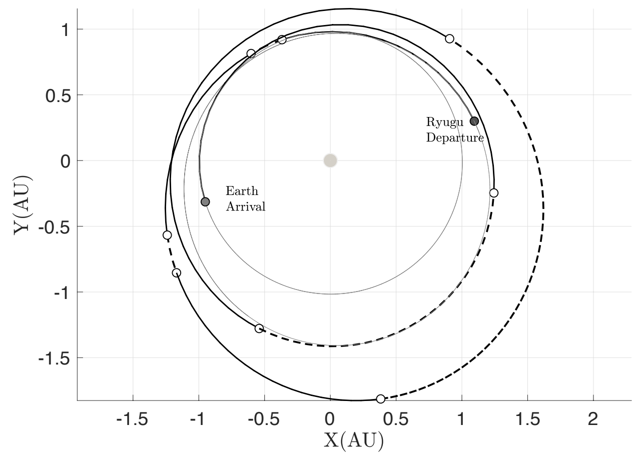




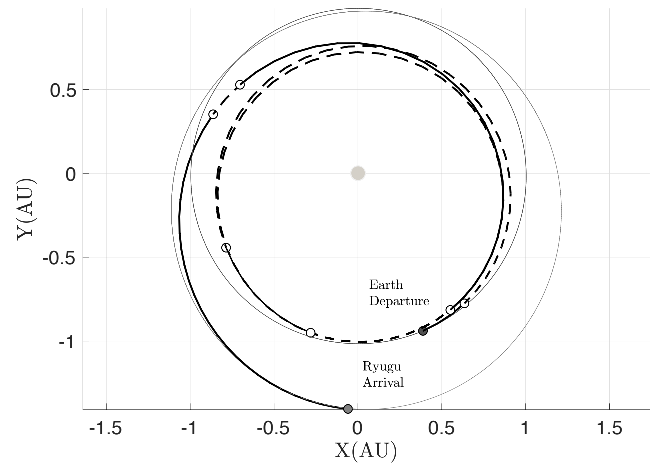


ASTEROID MINING TO RYUGU

OUTBOUND



INBOUND



		OUTBOUND FLIGHT		INBOUND FLIGHT	
Parameter	Units	Step 1	Step 2	Step 1	Step 2
Launch Date	-	Jul 15, 2025	Jul 15, 2025	Jul 28, 2028	Jul 28, 2028
Launch v_∞ (km/s)	km/s	2	2	0.1	0
Initial mass	kg	1222	1222	1416	1854
Revolutions	-	1	2	3	3
Arrival Date	-	Dec 30, 2027	Feb 01, 2028	Feb 09, 2032	Apr 08, 2032
Propellant mass fraction	km/s	0.5041	0.1454	0.3757	0.2011

CONCLUSIONS

- The suitability of **MOLTO-IT Step 1** for providing quick preliminary trade-offs assessments has been evaluated

- The suitability of **MOLTO-IT Step 2** for providing accurate solutions for the detailed designed has been evaluated.

- **MOLTO-IT Step 1** has been proven to be a good initial guess for **MOLTO-IT Step 2.**

- A minimum time reorientation constraint has been succesfully tested.

- The tool automatively determines the flyby sequence in terms of a multi-objective function.

- Include the target body as a optimization variable
- Derivation of a criteria to assess the feasability of the soltutions from **MOLTO-IT Step 1** for a certain engine.
- Application to more complex scenarios: mission to comets, multi-rendezvous…
- Include Launcher performances
- Development of a user-friendly interface

Thank you for your attention.

Questions?