Low Thrust Trajectory Optimization for Autonomous Asteroid Rendezvous Missions

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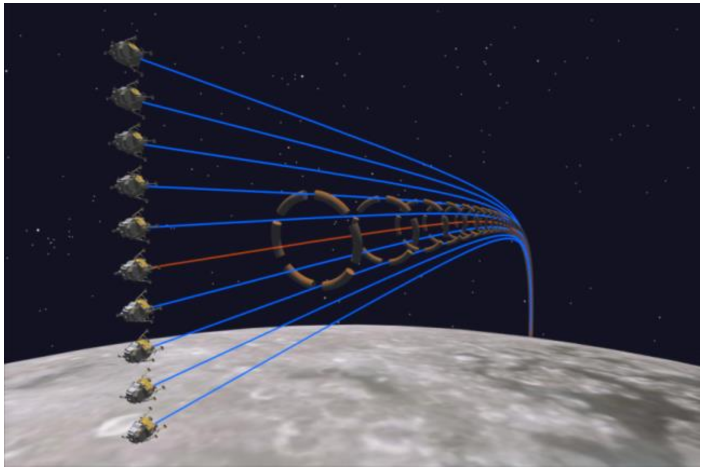
Challenges of Trajectory Optimization for Deep Space Missions

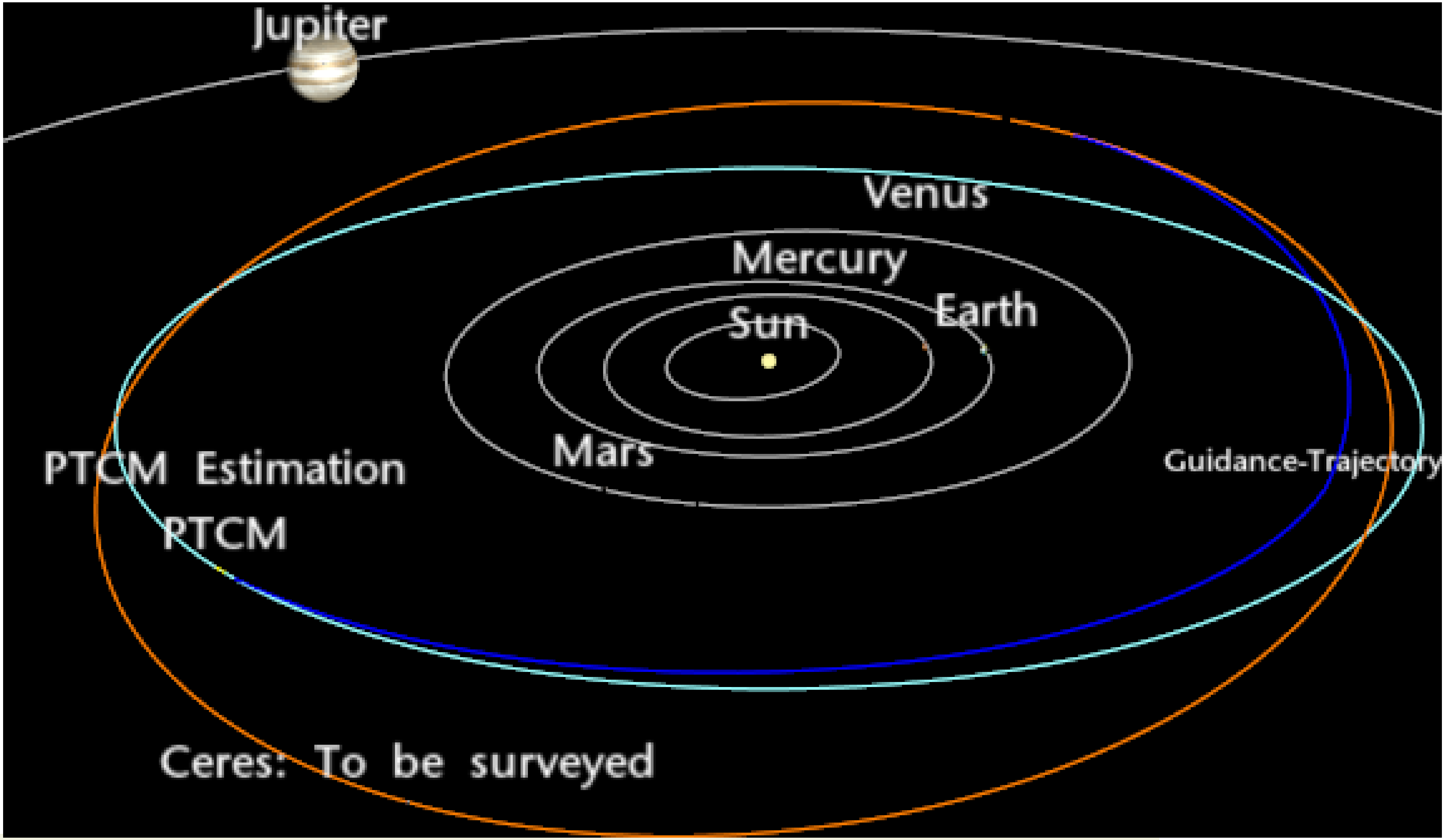
- Huge time scales
- Small control variables (low thrust)
- Scaling issues (e.g. Newton vs. AU)

➢ Highly precise and robust optimization method necessary



Outline

- Challenges of Trajectory Optimization for Deep Space Missions
- Mathematical Background
- Numerical Results
  - Electrically powered (continuous) propulsion system
  - Comparism to chemical (impulsive) thrusters
- Summary and Outlook


Jupiter
Venus
Mercury
Earth
Sun
Mars
PTCM Estimation
PTCM
Guidance-Trajectory
Ceres: To be surveyed

Optimal Control Problem (OCP)

How do thrust and attitude have to be **controlled** to get the **system fast** and with **low fuel** consumption from a **start** point to an **orbit** without **overloading**?

Optimal Control Problem (OCP)

$$\min_{u(t)} \quad \int_0^{t_f} g(x(t), u(t))dt$$

$$\begin{aligned} s.t. \quad \dot{x}(t) &= f(x(t), u(t)) \\ x(0) &= x_0 \\ \Psi(x(t_f)) &= 0 \\ C(x(t), u(t)) &\leq 0 \end{aligned}$$

Non-linear Optimization Problem (NLP)

- **OCP** → transcription techniques (direct approach) → **NLP**

$$\begin{aligned} \min_{z} \quad & F(z) \\ s.t. \quad & G_i(z) = 0,\ i = 1, \ldots, M_e \\ & G_i(z) \leq 0,\ i = M_e + 1, \ldots, M \end{aligned}$$

- Transcription: full discretization of states and controls

WORHP

- “We Optimize Really Huge Problems”
- Finite-dimensional non-linear optimization software
- Combining SQP and IP methods

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- Finite-dimensional non-linear optimization software
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- ➢ Efficient derivative approximation
- ➢ Considers sparsity of derivative matrices
- ➢ Especially efficient for solving high-dimensional problems like those resulting from discretization of OCPs

- Software library **TransWORHP** used for transcription

Problem Formulation

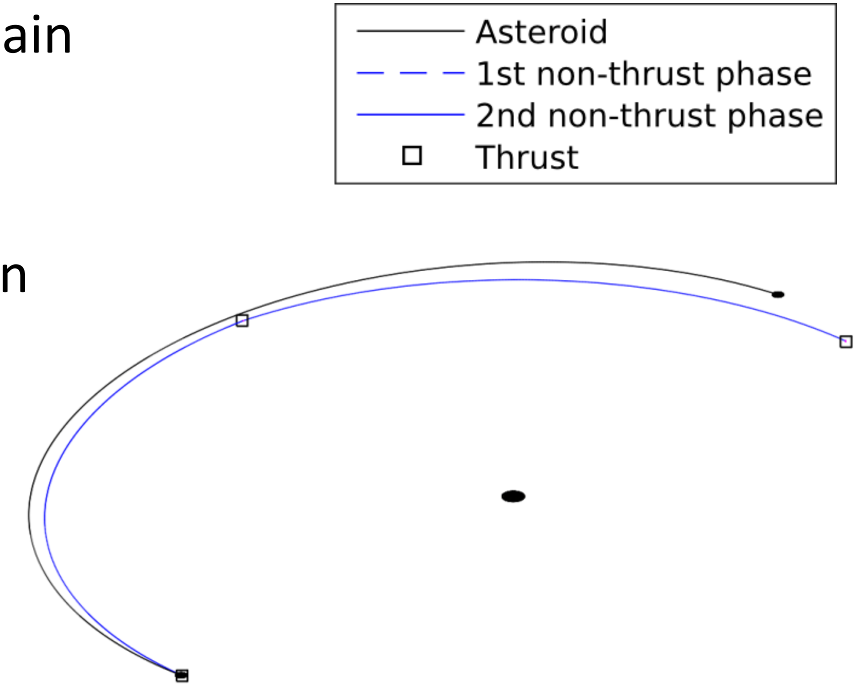
Dynamic system:

$$\dot{x} := \begin{pmatrix} \dot{p}_{sc} \\ \ddot{p}_{sc} \\ \dot{m}_{sc} \end{pmatrix} = \begin{pmatrix} \dot{p}_{sc} \\ \sum_{i \in I} \mu_i \cdot \frac{r_i}{\|r_i\|_2^3} + \frac{T}{m_{sc}} \\ -\frac{\|T\|}{g_0 Isp} \end{pmatrix}$$

p_{sc}	position vector of spacecraft
$\mu_i, i \in \{sun, mars, jupiter, saturn\}$	gravitational constant of celestial body
r_i	direction vector between spacecraft and body
T	thrust vector
m_{sc}	spacecraft ‘s recent mass

Impulsive Thrust Optimization

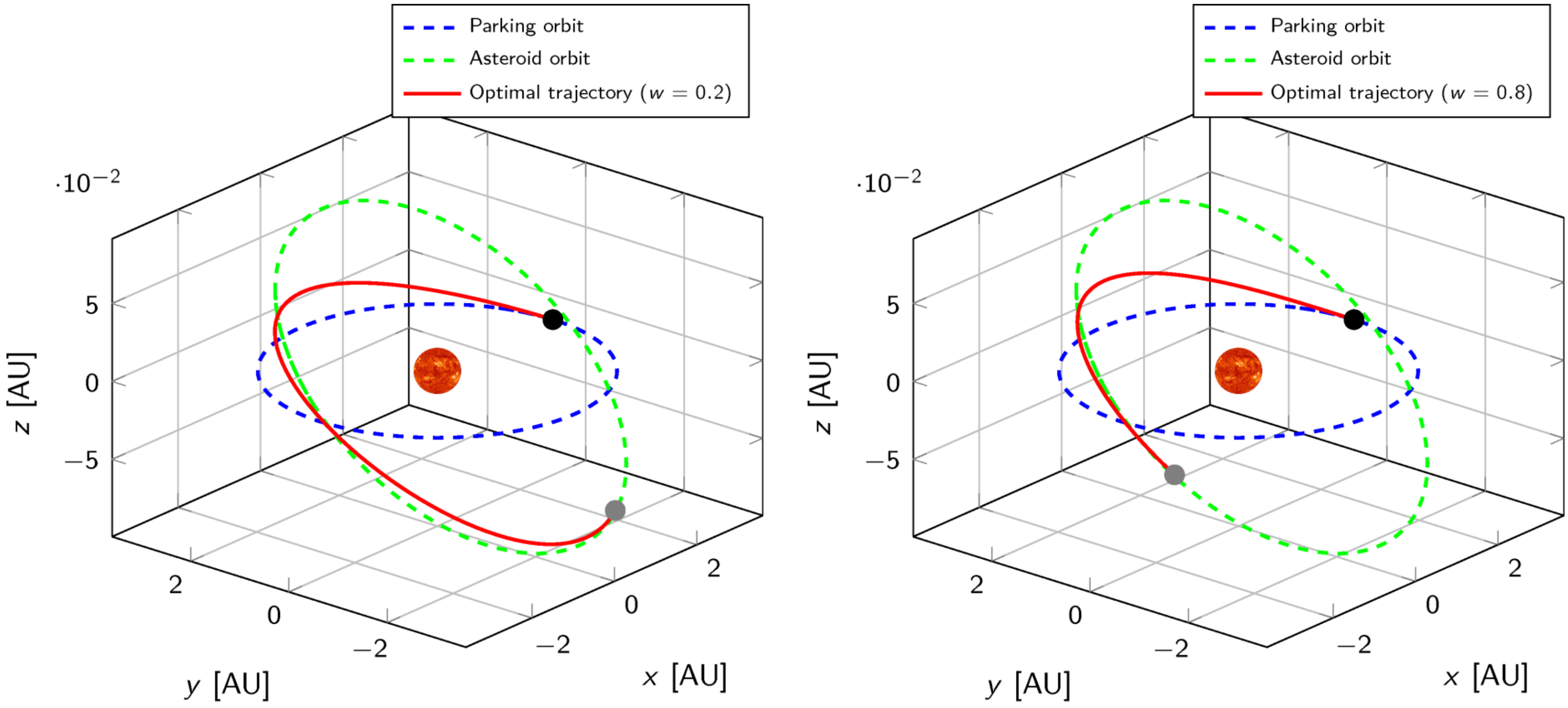
- Thrust: constant control over certain period of time
- Three thrust commands
- Two non-thrust phases in between
- Connecting conditions



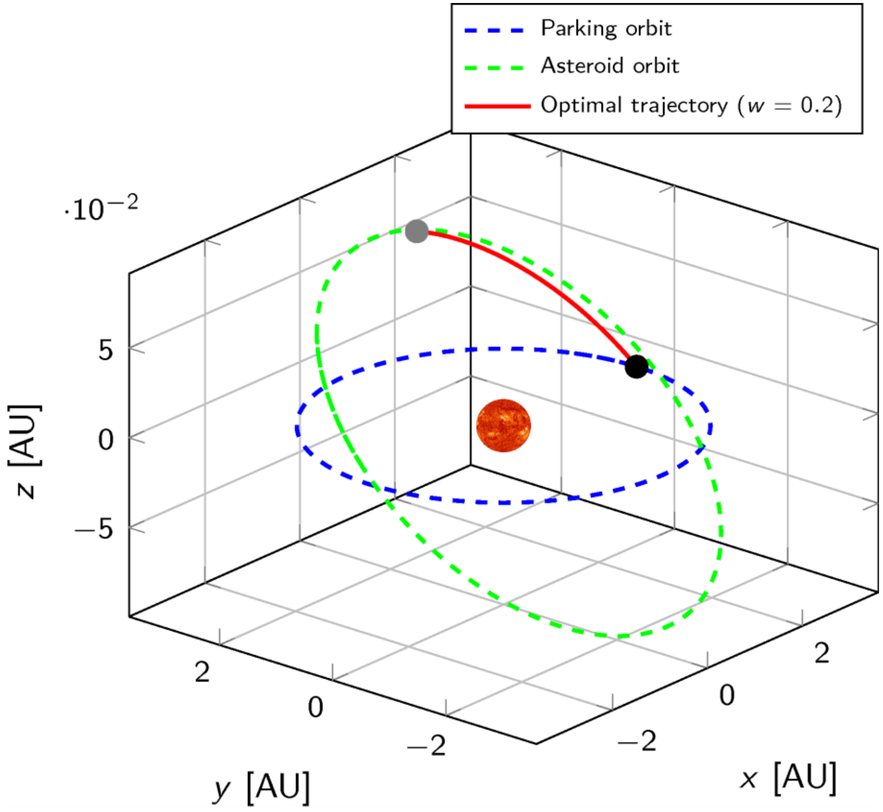
Objective Function

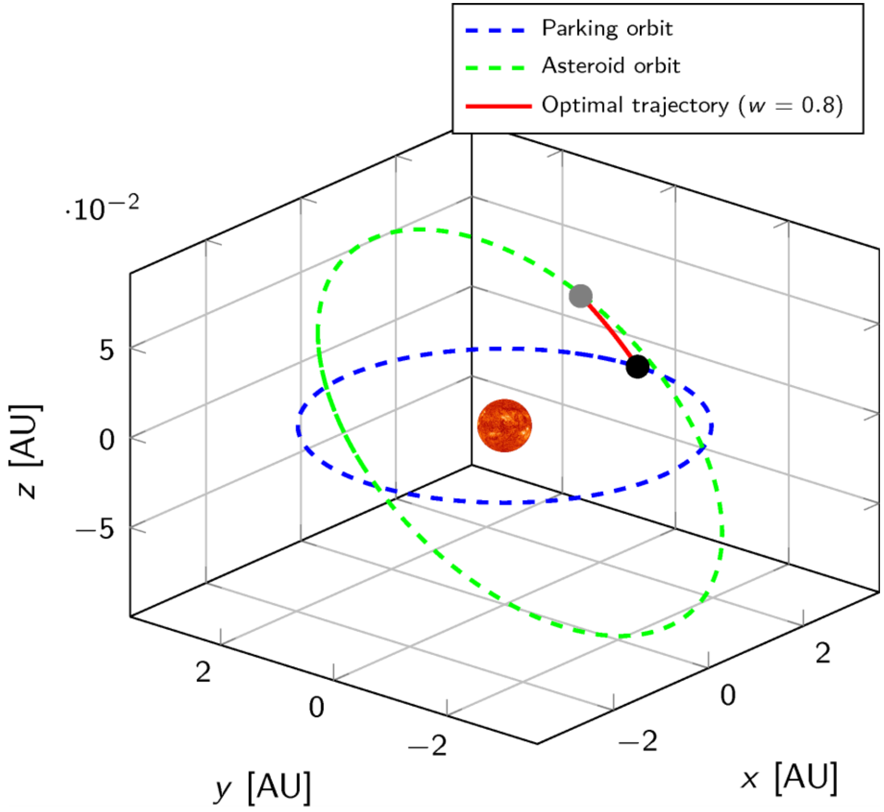
- Impulsive thrust: $F = t_f w - m_f (1-w), w \in [0,1]$
- Low thrust: $F = t_f w + x_{n,7} (1-w), w \in [0,1]$
- Optimization criterions for competitive mission objectives
  - Flight time
  - Energy consumption
- Spacecraft data
  - Impulsive: ISP 318 sec, max. thrust 440 N, min. thrust 340 N
  - Low thrust: ISP 4000 sec, max. thrust 0.154 N

Low Thrust

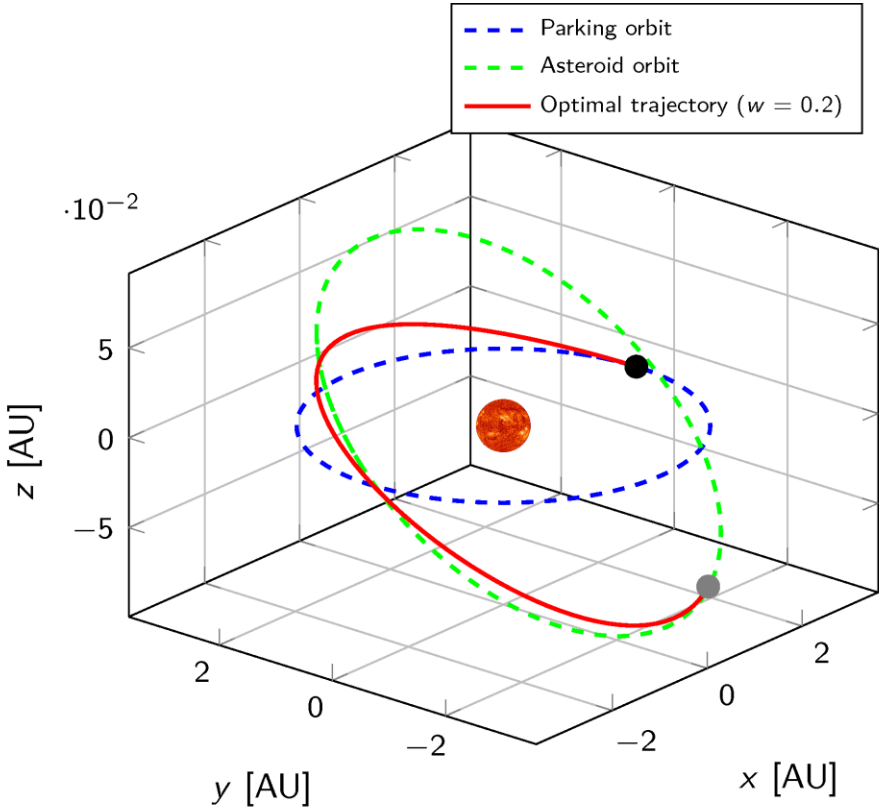

Parking orbit
Asteroid orbit
Optimal trajectory ($w = 0.2$)
$\cdot 10^{-2}$
5
0
−5
z [AU]
2
0
−2
y [AU]
2
0
−2
x [AU]
Parking orbit
Asteroid orbit
Optimal trajectory ($w = 0.8$)
$\cdot 10^{-2}$
5
0
−5
z [AU]
2
0
−2
y [AU]
2
0
−2
x [AU]

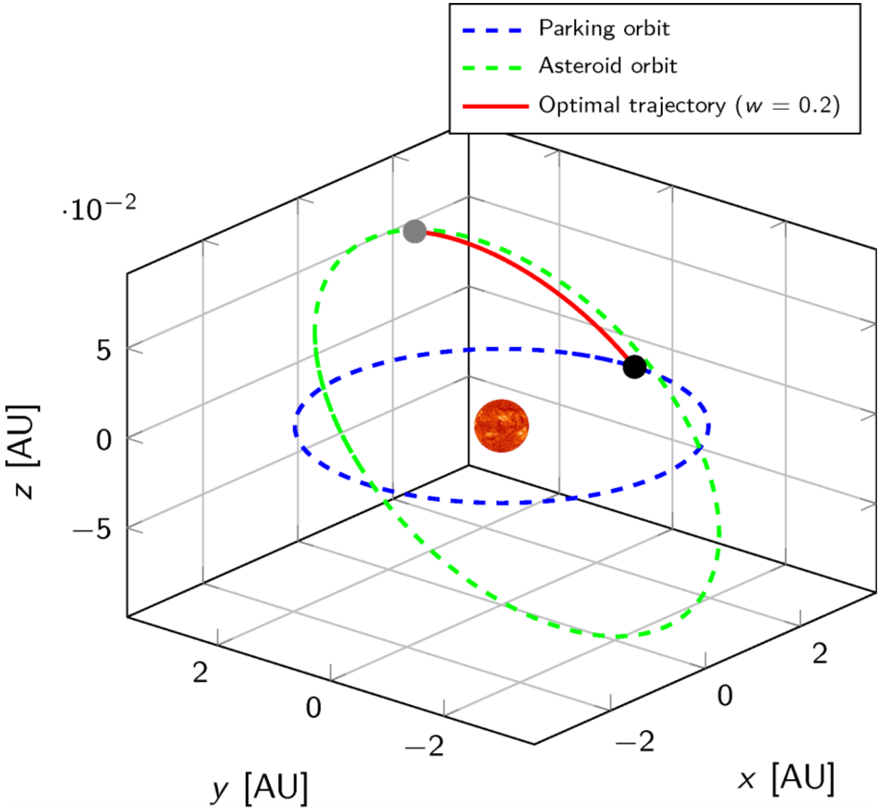
Impulsive Thrust





Low vs. Impulsive Thrust

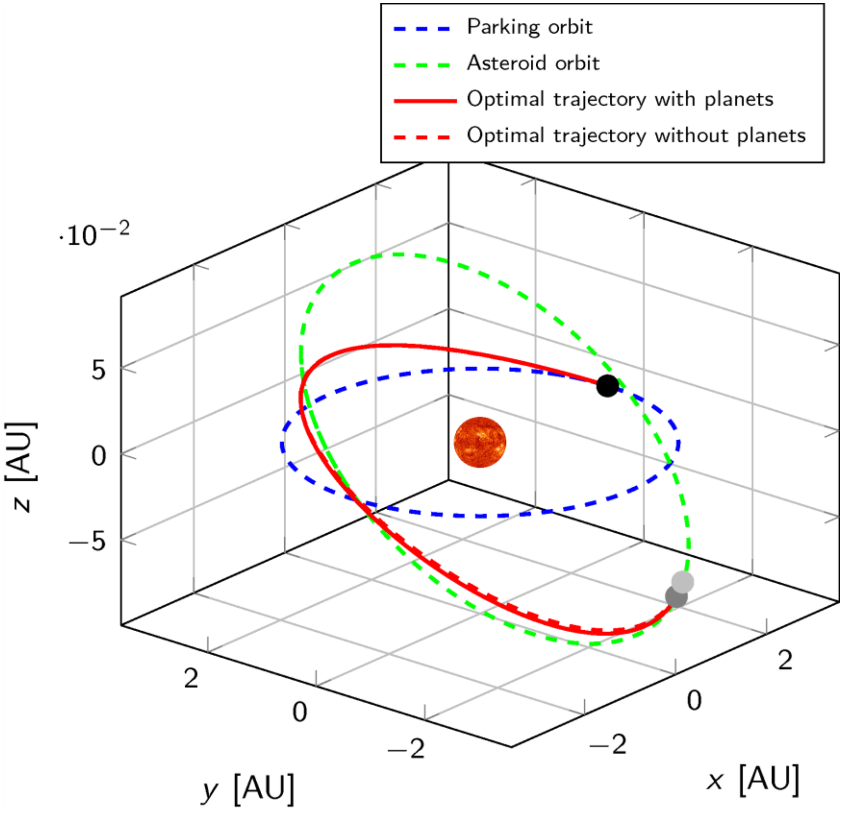


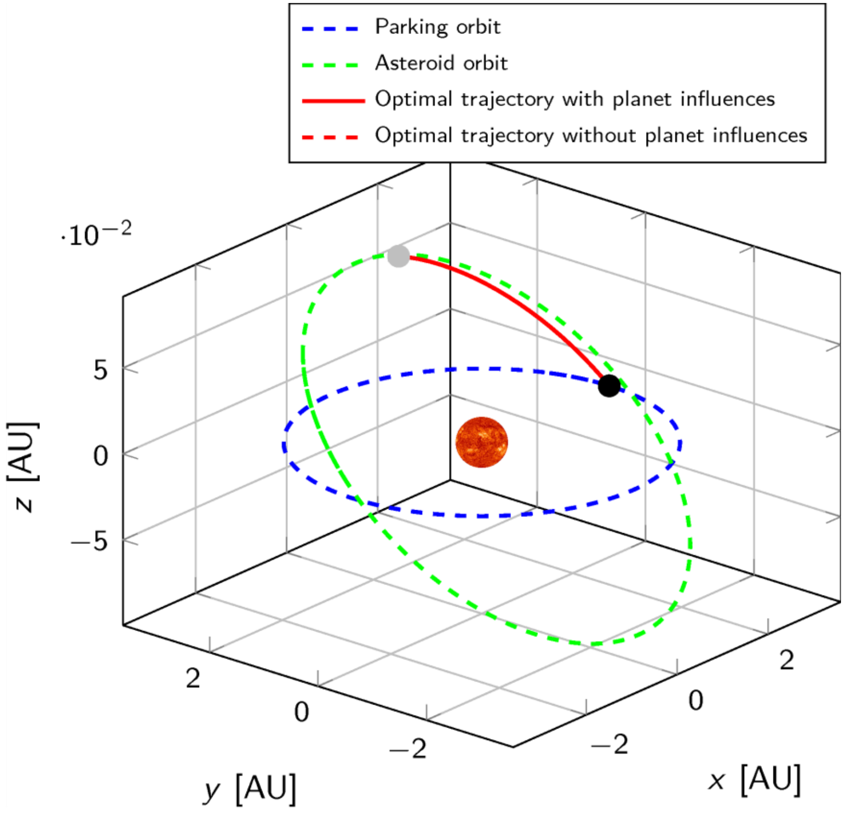


Low vs. Impulsive Thrust

Thurst	**low**		**impulsive**	
w	**0.2**	**0.8**	**0.2**	**0.8**
Time (d)	1289	840	308	*88*
Fuel (kg)	*149*	214	936	1431

Planets Influence





Planets Influence

Thurst	low		impulsive	
Planets	**w/**	**w/o**	**w/**	**w/o**
Time (d)	1289.23	1319.47	307.53	307.43
Fuel (kg)	148.66	147.38	935.88	936.63

Summary and Outlook

- Optimization provides very different trajectories dependent on thrust type and mission objective
- Foundation for autonomous decision making during deep space missions
- Applications like deep sea navigation or autonomous driving

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- ➢ Perturbance and parametric sensitivity analysis
- ➢ Real-time optimal control
- ➢ Multi-node techniques using high-order integration methods

Discussion

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