Optimal control of trajectory of reusable launcher in OpenMDAO/dymos

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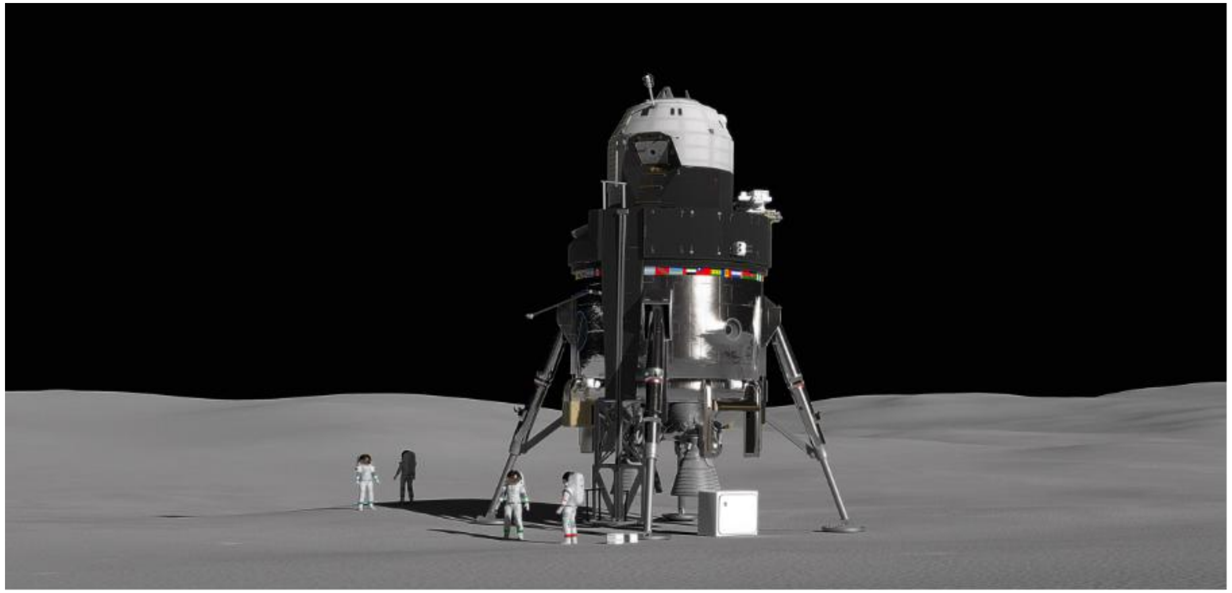
Outline

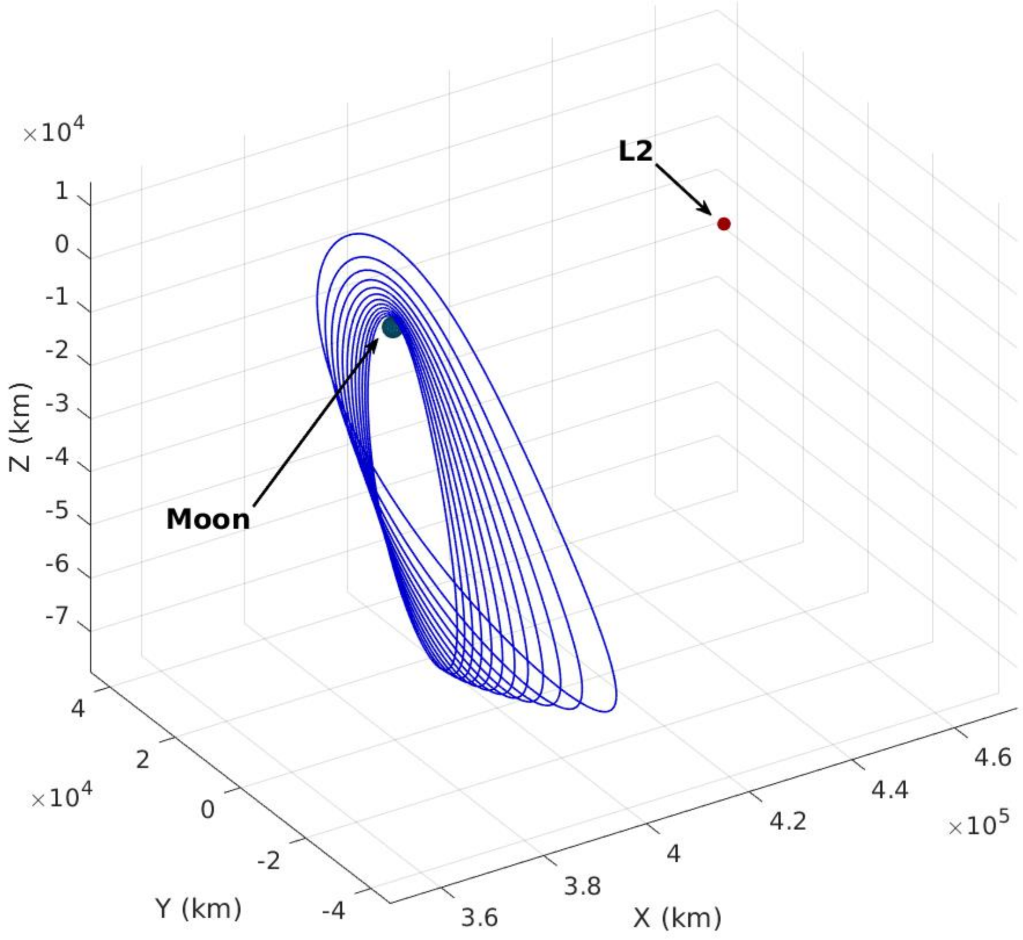
- *Context*
- *Optimal control problem*
- *Achievements of Semester 2*
- *2D Descent Trajectory*
- *2D Low Lunar Orbit to Highly Elliptical Orbit Transfer*
- *Surrogate Models*
- *LaTOM Software Package*
- *Conclusions & Future achievements*

Context

- Moon and Mars Exploration
- *In-situ* resources exploitation
- Lunar Orbital Platform Gateway
- L2 NRHO



Lunar Lander prototype. Credits: Lockheed Martin



L2 southern NRHO family

Optimal control problem: implementation

Formulation

- Optimal Control Theory
- EOMs
- Constraints

Transcription

- Gauss-Lobatto[1]
- Radau-Pseudospectral[2]
- OpenMDAO[3]
- dymos[4]

NLP Solution

- OpenMDAO[3]
- PyOptSparse[5]
- IPOPT[6,7]
- SNOPT[8]

[1]Herman et al. “Direct Optimization Using Collocation Based on High-Order Gauss-Lobatto Quadrature Rules.” Journal of Guidance, Control, and Dynamics (1996)
[2]Garg et al. “Direct Trajectory Optimization and Costate Estimation of General Optimal Control Problems Using a Radau Pseudospectral Method.” AIAA Guidance, Navigation, and Control Conference (2009)
[3]Gray et al. “OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization.” Structural and Multidisciplinary Optimization (2019)
[4]Hendricks et al. “Simultaneous Propulsion System and Trajectory Optimization.” 18th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference (2017)
[5]Perez et al. “PyOpt: A Python-Based Object-Oriented Framework for Nonlinear Constrained Optimization.” Structural and Multidisciplinary Optimization (2012)
[6]Wächter et al. “On the Implementation of an Interior-Point Filter Line-Search Algorithm for Large-Scale Nonlinear Programming.” Mathematical Programming (2006)
[7]HSL, A Collection of Fortran Codes for Large Scale Scientific Computation. http://www.hsl.rl.ac.uk/.
[8]Gill, P., et al. “SNOPT: An SQP Algorithm for Large-Scale Constrained Optimization.” SIAM Review (2005)

Optimal control problem: formulation

Mathematical formulation of a continuous-time optimal control problem

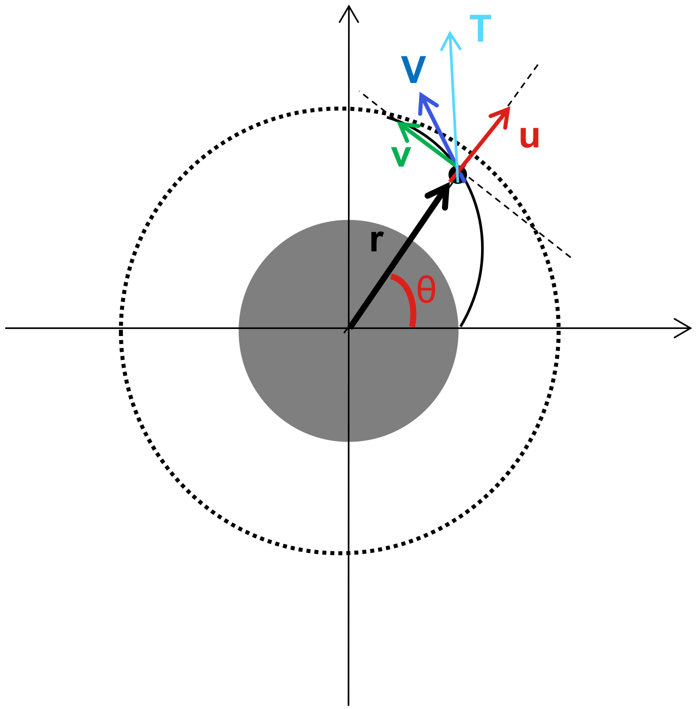
Minimize:

$$J = \phi(t_f, \boldsymbol{x}_f) + \int_{t_0}^{t_f} L(t, \boldsymbol{x}, \boldsymbol{u})dt$$

Subject to:

$\dot{\boldsymbol{x}} = \boldsymbol{f}(t, \boldsymbol{x}, \boldsymbol{u})$	dynamics
$\boldsymbol{x}(t_0) = \boldsymbol{x}_0$	initial conditions
$\boldsymbol{u} \in U$	controls
$\boldsymbol{\Psi}(t_f, \boldsymbol{x}_f) = \boldsymbol{0}$	terminal constraints
$S(\boldsymbol{x}) \geq 0$	path constraints

Equations of Motion



$$\dot{r} = u$$

$$\dot{\theta} = \frac{v}{r}$$

$$\dot{u} = -\frac{\mu}{r^2} + \frac{v^2}{r} + \frac{T}{m}\sin\alpha$$

$$\dot{v} = -\frac{uv}{r} + \frac{T}{m}\cos\alpha$$

$$\dot{m} = -\frac{T}{Isp\ g_0}$$

legend:

r: radial distance

θ: swept angle

u: radial velocity

v: tangential velocity

m: mass

T: thrust magnitude

α: thrust direction

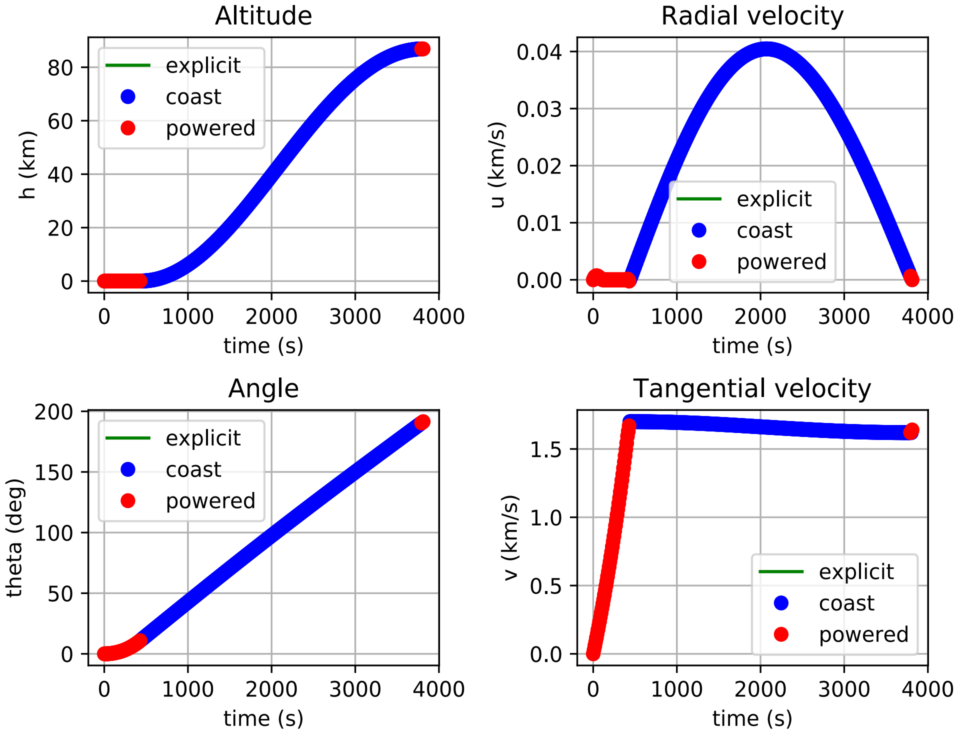
Isp: specific impulse

g_0: standard gravitational acceleration

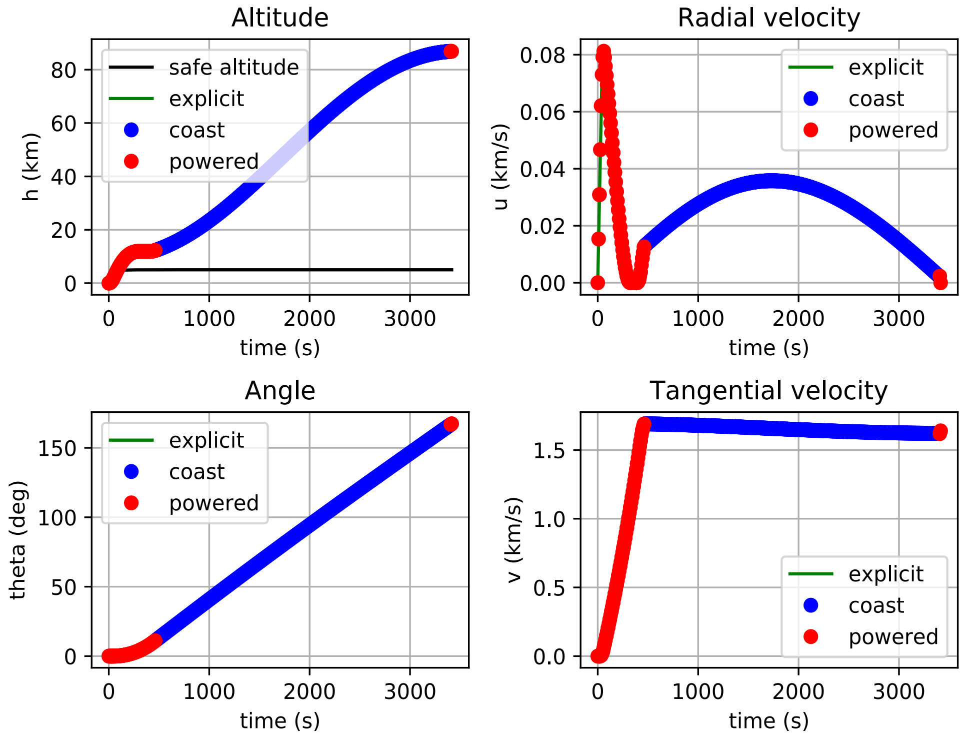
μ: Moon standard gravitational parameter

Achievements of Semester 2

Ascent with variable thrust



Ascent with variable thrust and minimum safe altitude

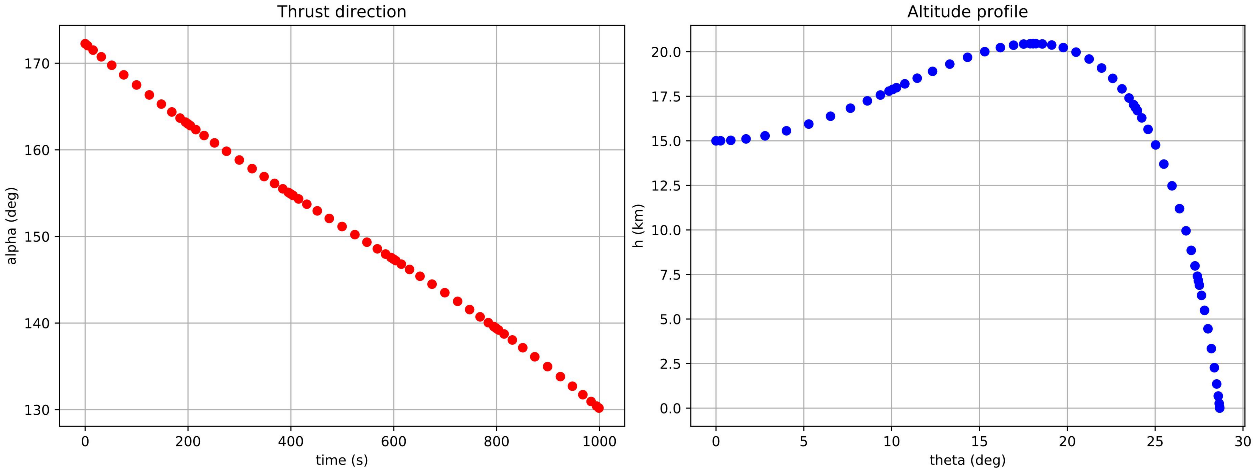


Parameters	
h	86.87 km
Isp	450 s
twr	2.1

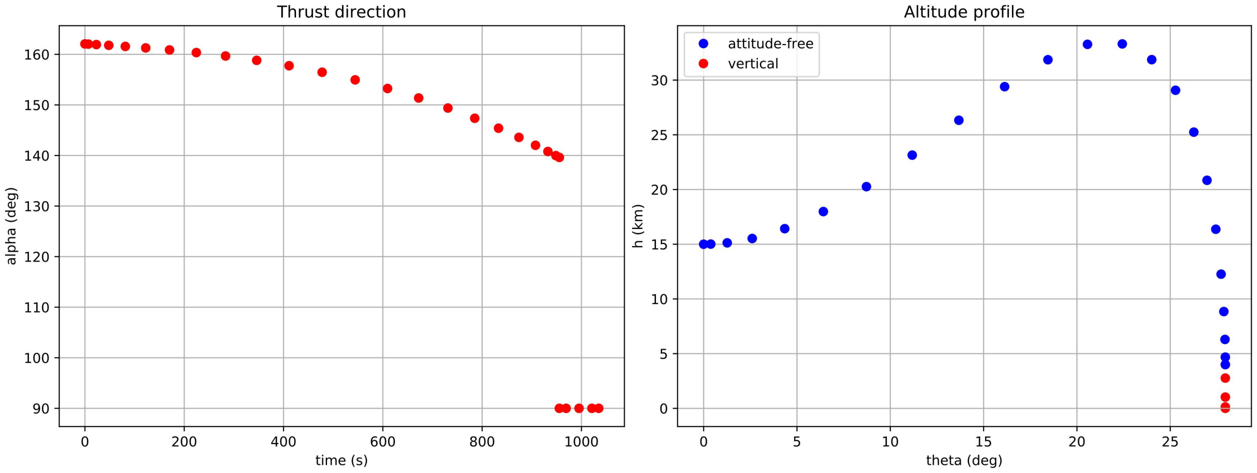
Ascent Trajectory	Time of Flight	Propellant consumption
Constant Thrust	476.13 s	36.80%
Variable Thrust	3697.56 s	33.64%
Variable Thrust, Minimum safe altitude	3367.77 s	35.50%

Achievements of Semester 2

Descent Trajectory without final constraints



Descent Trajectory with final constraints



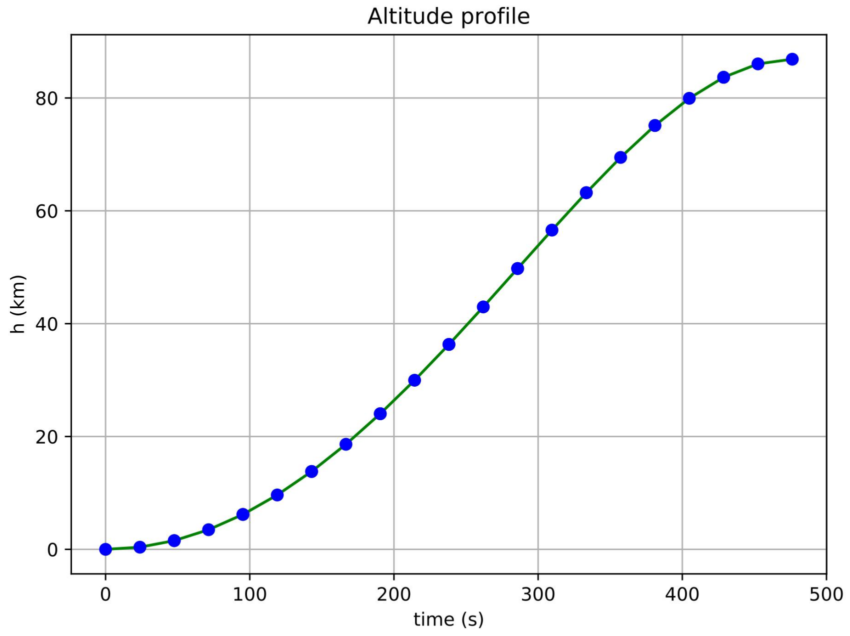
Parking orbit altitude	100 km
Powered descent phase initial altitude	15 km
Vertical phase initial altitude	4 km

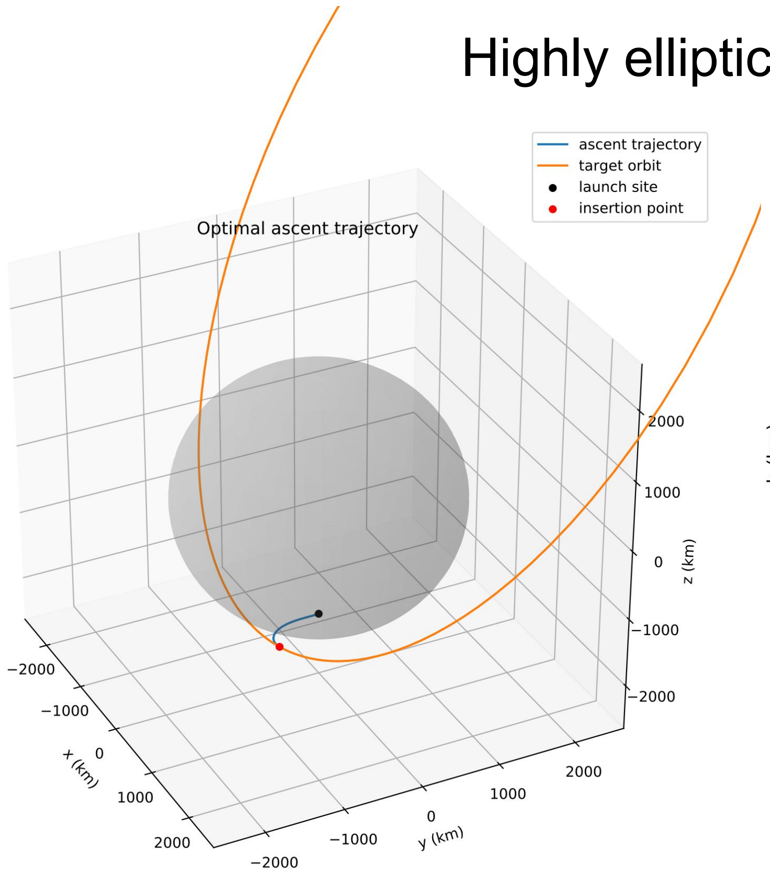
Parameters	
Isp	310s
twr	0.9

	Time of Flight	Propellant consumption
Free	999.05 s	48.51%
Vertical constrained	1034.77 s	50.24%

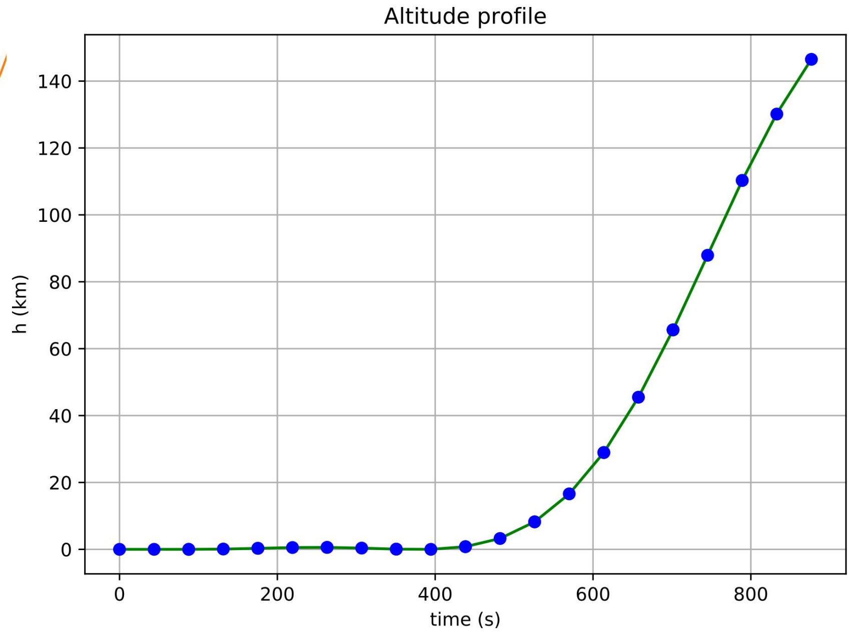
Achievements of Semester 2

Polar orbit - coplanar transfer





Highly elliptical orbit - out-of-plane maneuver



Type of orbit	Eccentricity	Inclination	Argument of periapsis	Semimajor axis	Time of flight	Propellant consumption
Polar	0	90°	-	1824.27 km	476.29 s	36.81%
Highly elliptical	0.7	60°	270°	6080.90 km	876.73 s	67.76%

2D Descent: Optimal control problem

Minimize:

$$J = -m(t_f)$$

Subject to:

$\dot{\boldsymbol{x}} = \boldsymbol{f}(t, \boldsymbol{x}, \boldsymbol{u})$	dynamics
$\boldsymbol{x} = [r, \theta, u, v, m]$	state variables
$\boldsymbol{u} = [T, \alpha]$	controls
$\boldsymbol{x}(t_0) = \boldsymbol{x}_0$	initial conditions
$\boldsymbol{\Psi}(t_f, \boldsymbol{x}_f) = \boldsymbol{0}$	terminal constraints
$S(\boldsymbol{x}) \geq 0$	path constraints

Initial conditions $\boldsymbol{x}_0$ and terminal constraints $\Psi(t_f, \boldsymbol{x}_f)$:

$$\begin{cases} t_0 = 0 \\ r(t_0) = R + H \\ \theta(t_0) = free \\ u(t_0) = 0 \\ v(t_0) = \sqrt{\mu/(R+H)} \\ m(t_0) = m_0 \end{cases} \qquad \begin{cases} t_f = free \\ r(t_f) = R \\ \theta(t_f) = \theta_f \\ u(t_f) = 0 \\ v(t_f) = 0 \\ m(t_f) = free \end{cases}$$

Path constraints $S(\boldsymbol{x})$:

$$\begin{cases} r(t) > R \\ m(t) > m_{dry} \\ T_{min} < T(t) < T_{max} \\ r(t) > R + \dfrac{h_{min} \cdot R \cdot \theta(t)}{R \cdot \theta(t) + h_{min}/s} \end{cases}$$

legend:

R: Moon radius

H: target orbit altitude

m_0: initial spacecraft mass

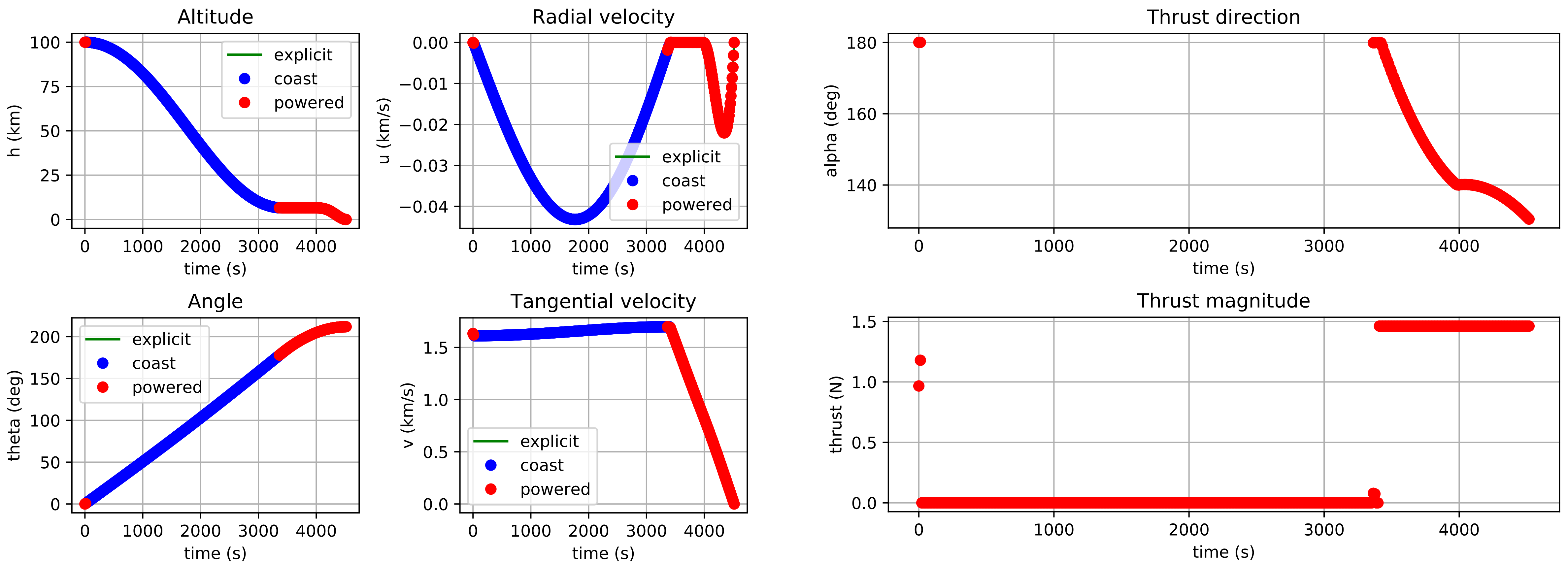
m_{dry}: spacecraft dry mass

T_{min}, T_{max}: minimum and maximum thrust magnitude

h_{min}: safe altitude

s: constraint slope

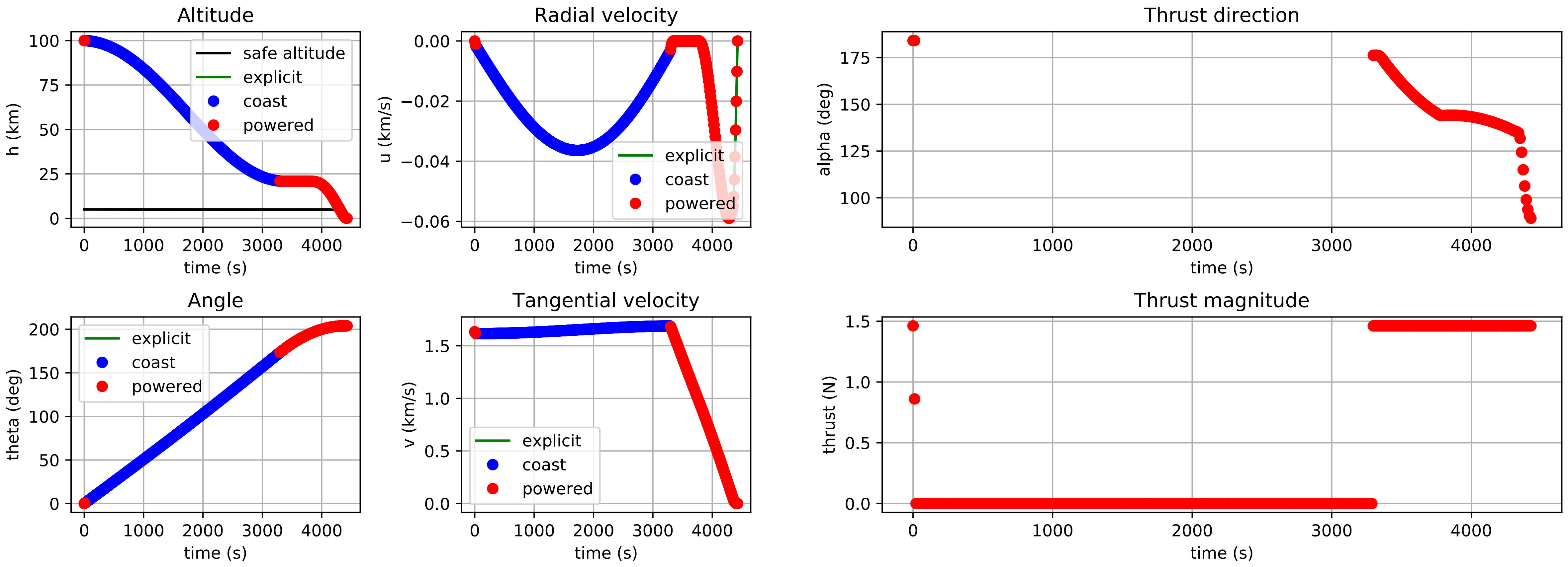
2D Descent: Variable thrust



h	Isp	twr
100 km	400 s	0.9

Time of Flight	Propellant consumption
4516.7708 s	41.97%

2D Descent: Minimum safe altitude



h	Isp	twr	h min	s
100 km	400 s	0.9	5 km	-5

Time of Flight	Propellant consumption
4426.9527 s	42.67%

LLO to HEO: Optimal control problem

Minimize:

$$J = -m(t_f)$$

Subject to:

$\dot{\boldsymbol{x}} = \boldsymbol{f}(t, \boldsymbol{x}, \boldsymbol{u})$	dynamics
$\boldsymbol{x} = [r, \theta, u, v, m]$	state variables
$\boldsymbol{u} = [T, \alpha]$	controls
$\boldsymbol{x}(t_0) = \boldsymbol{x}_0$	initial conditions
$\boldsymbol{\Psi}(t_f, \boldsymbol{x}_f) = \boldsymbol{0}$	terminal constraints
$S(\boldsymbol{x}) \geq 0$	path constraints

legend:

R: Moon radius

H: target orbit altitude

v_{LLO}: LLO circular velocity

m_0: initial spacecraft mass

a_{HEO}: HEO semi-major axis

h_{HEO}: HEO angular momentum vector

r_a: HEO apoapsis radius

Initial conditions $\boldsymbol{x}_0$:

$$\begin{cases} t_0 = 0 \\ r(t_0) = R + H \\ \theta(t_0) = \theta_0 \\ u(t_0) = 0 \\ v(t_0) = v_{LLO} \\ m(t_0) = m_0 \end{cases}$$

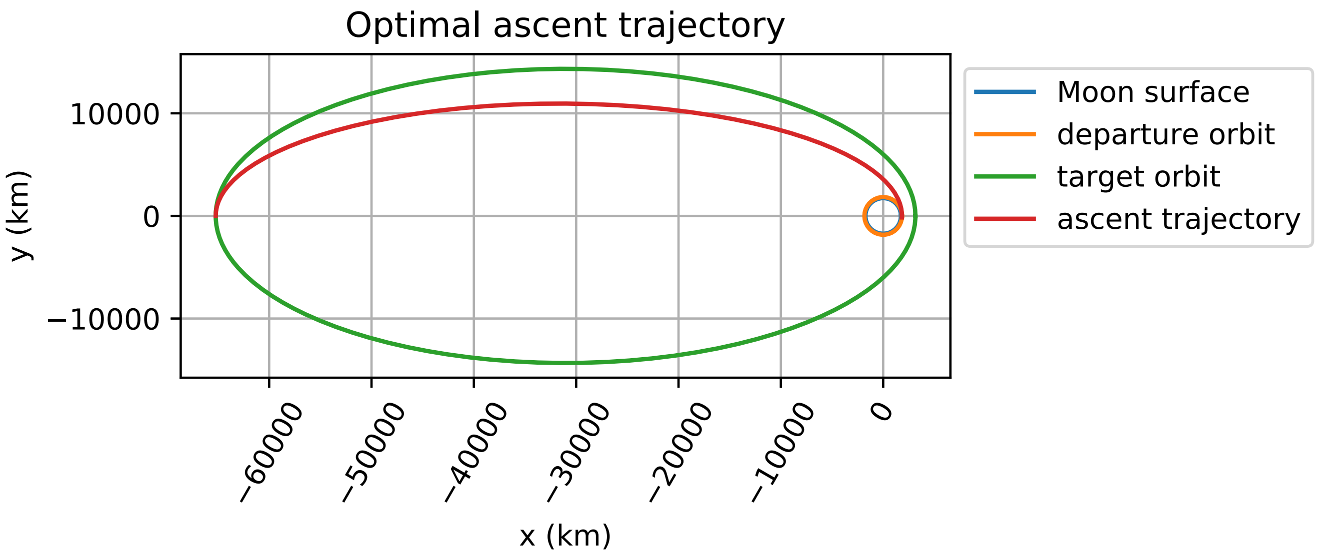
Terminal constraint $\Psi(t_f, \boldsymbol{x}_f)$ (three phases):

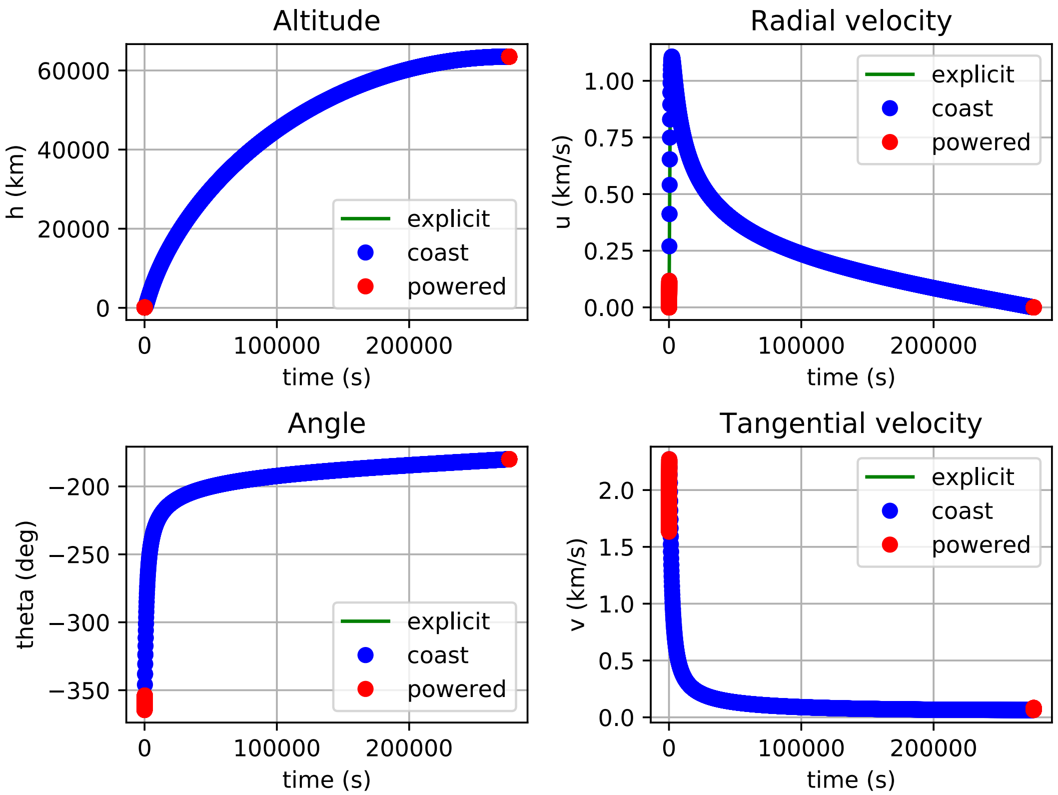
$$\begin{cases} \dfrac{\mu r}{2\mu - r \cdot (u^2 + v^2)} - a_{HEO} = 0 \\ r \cdot v - h_{HEO} = 0 \end{cases}$$

Terminal constraint $\Psi(t_f, \boldsymbol{x}_f)$ (escape burn):

$$\Psi(r, u, v, r_a) = r_a - \frac{r\left[\mu + \sqrt{(rv^2 - \mu)^2 + (ruv)^2}\ \right]}{2\mu - r(u^2 + v^2)} = 0$$

LLO to HEO: Three-phases transfer



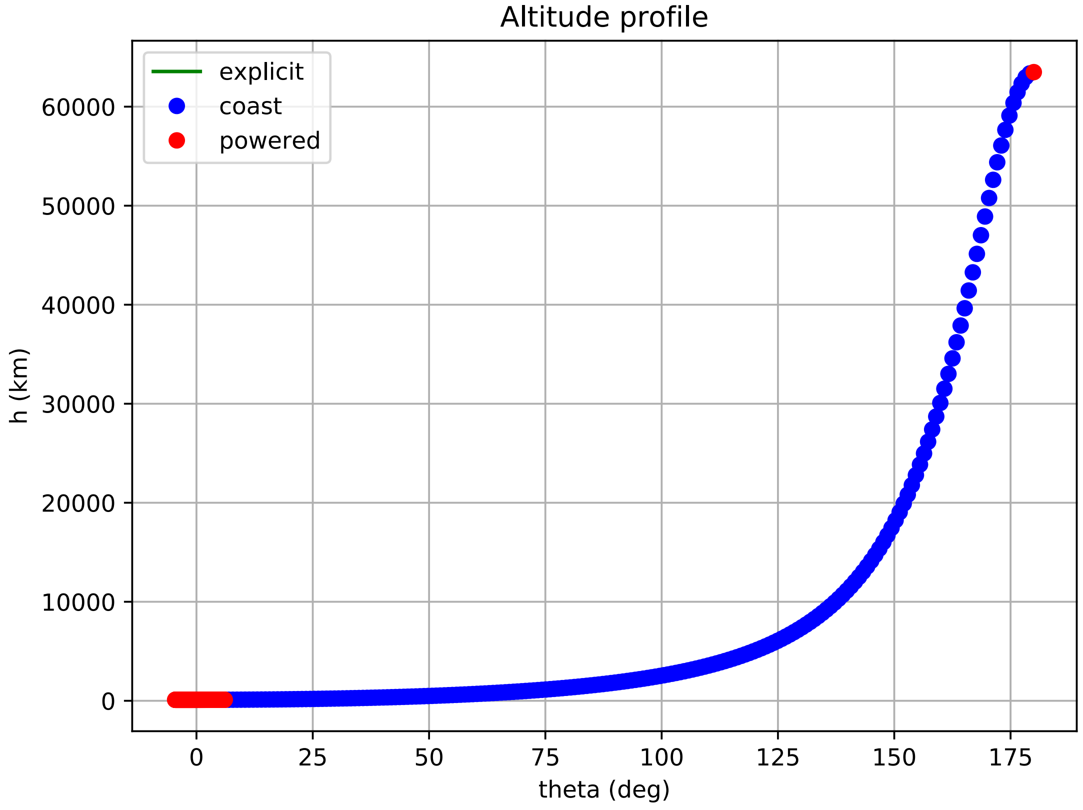


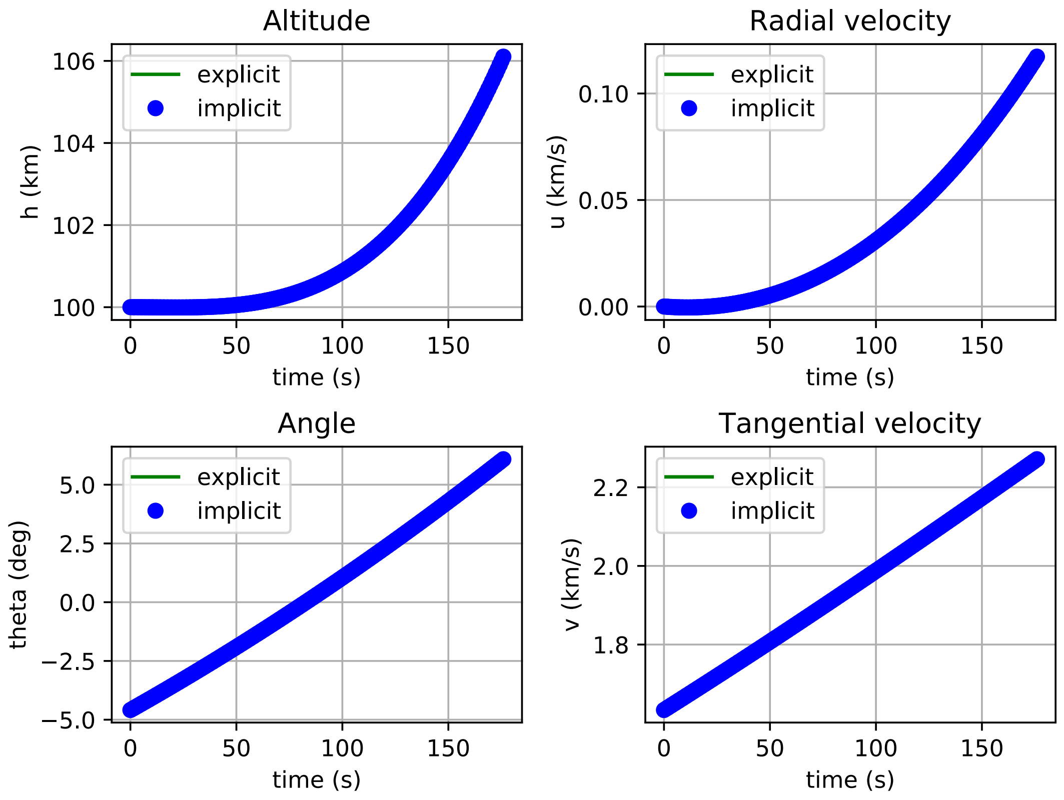
	LLO	HEO
a	1837.4 km	34188.7 km
e	0.0	0.9079

Isp	twr
450 s	2.1

Time of Flight	Propellant consumption
3.1907 days	13.97%

LLO to HEO: Finite Escape Burn





	LLO	HEO
a	1837.4 km	34188.7 km
e	0.0	0.9079

Isp	twr
450 s	2.1

Time of Flight	Propellant consumption
3.1898 days	13.97%

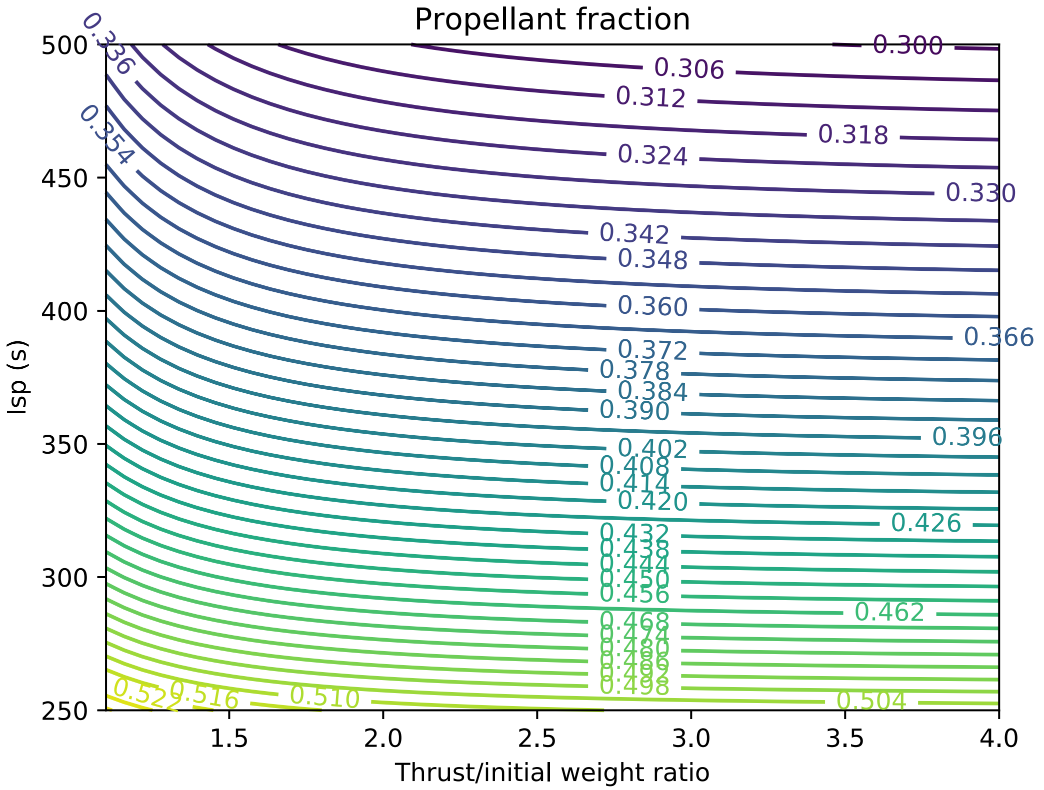
Surrogate Models - Tools

	Sampling	Prediction	Results
Surrogate Modelling Toolbox[9] (SMT)	Latin Hypercube, Full-Factorial	Kriging, Least-Squares, 2nd-order Polynomial	Non-smooth derivatives
OpenMDAO MetaModel StructuredComp	Regular grid, provided	Polynomial splines, 1st to 5th order	Smooth interpolation, direct integration in MDO

Maximum Prediction Error					
SMT	Kriging + LHS	5.0e-4	MMSC	Scipy_cubic	1.0e-5
	QP + FF	1.3e-2		Scipy_quintic	1.4e-6

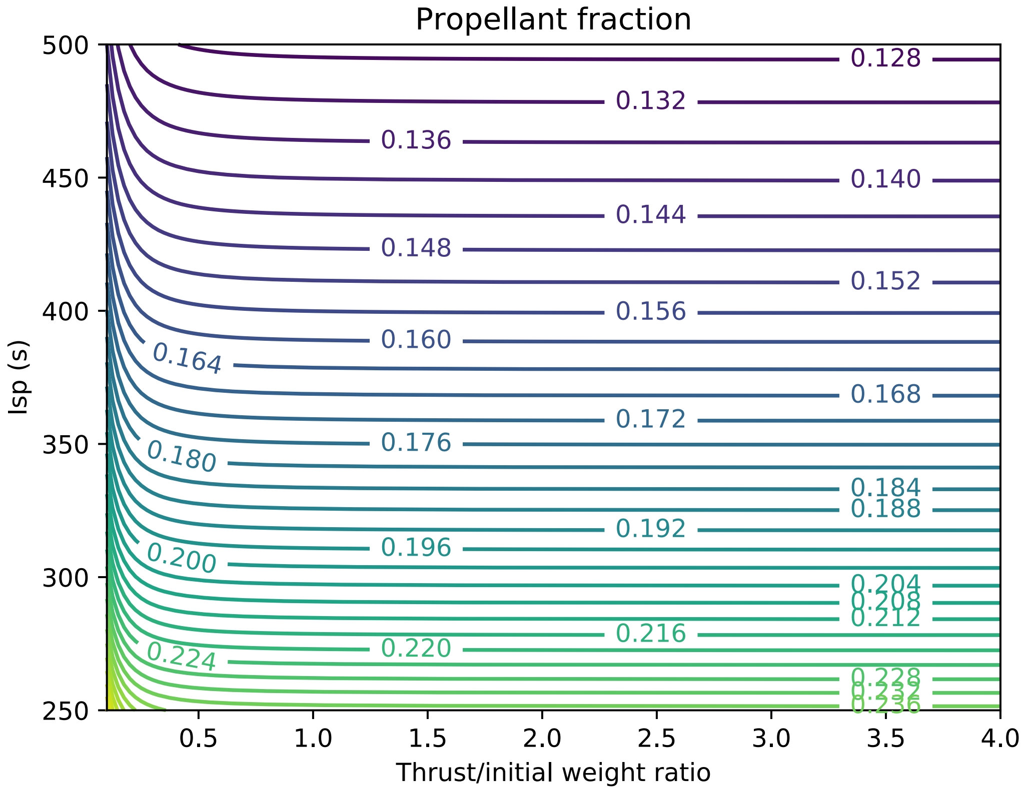
[9]Bouhlel et al. “A Python Surrogate Modeling Framework with Derivatives.” Advances in Engineering Software (2019)

Surrogate Models - Examples



Descent trajectory with variable thrust

Isp	twr
[250 s, 500 s]	[1.0, 4.0]

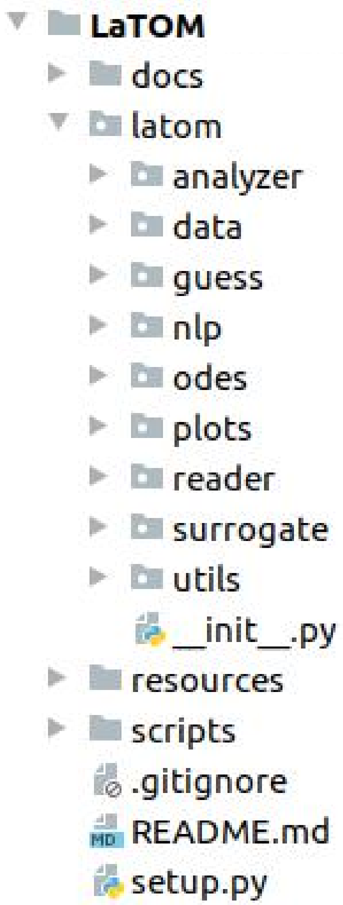


LLO to HEO transfer

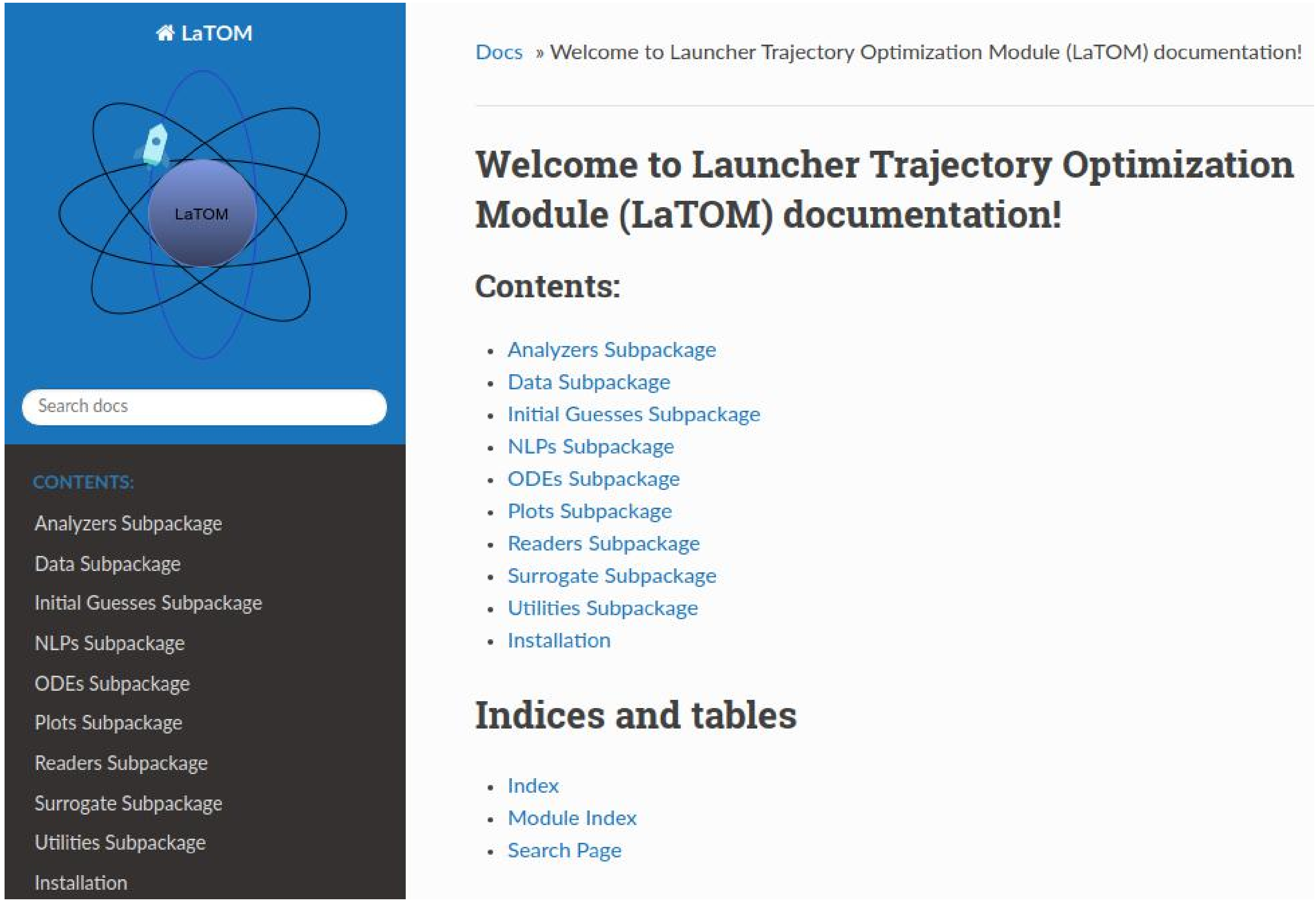
Isp	twr
[250 s, 500 s]	[0.1, 4.0]

LaTOM Software Package

Launcher
Trajectory
Optimization
Module



Package architecture



Package documentation in HTML format

Conclusions & Future achievements

Current achievements:

- 2D ascent/descent Moon to LLO
- 2D ascent LLO to HEO
- 3D ascent Moon to LLO
- Surrogate models for 2D cases

Future developments:

- 3D trajectories improvements
- CR3BP for LLO to NRHO
- High fidelity gravity model
- Solar Radiation Pressure

Main issues:

- CR3BP implementation
- Selection for appropriate Surrogate Model library
- Memory required for 3-phases LLO to HEO simulation
- Simulations with very small twr values

Solutions:

- Two-Body Problem approximation
- Error comparison
- Computations on Supercomputer
- Continuation method

Selected bibliography

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Thank you for your attention

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