Trajectory Module for Launcher MDAO

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1. Introduction

The goal:

- To develop a trajectory module for LAST (Launcher Analysis and Sizing Tool).

The tools:

- Multidisciplinary Design, Analysis and Optimization (MDAO).
- Pseudospectral methods for trajectory optimization.

The questions:

- Can these tools be integrated?
- Can the proposed integration overcome the sensitivity of pseudospectral methods to the initial guess?

Our answer:

- To use a single level, partially decoupled MDAO architecture. Based on an All-at-Once (AAO) approach.

2. Methods

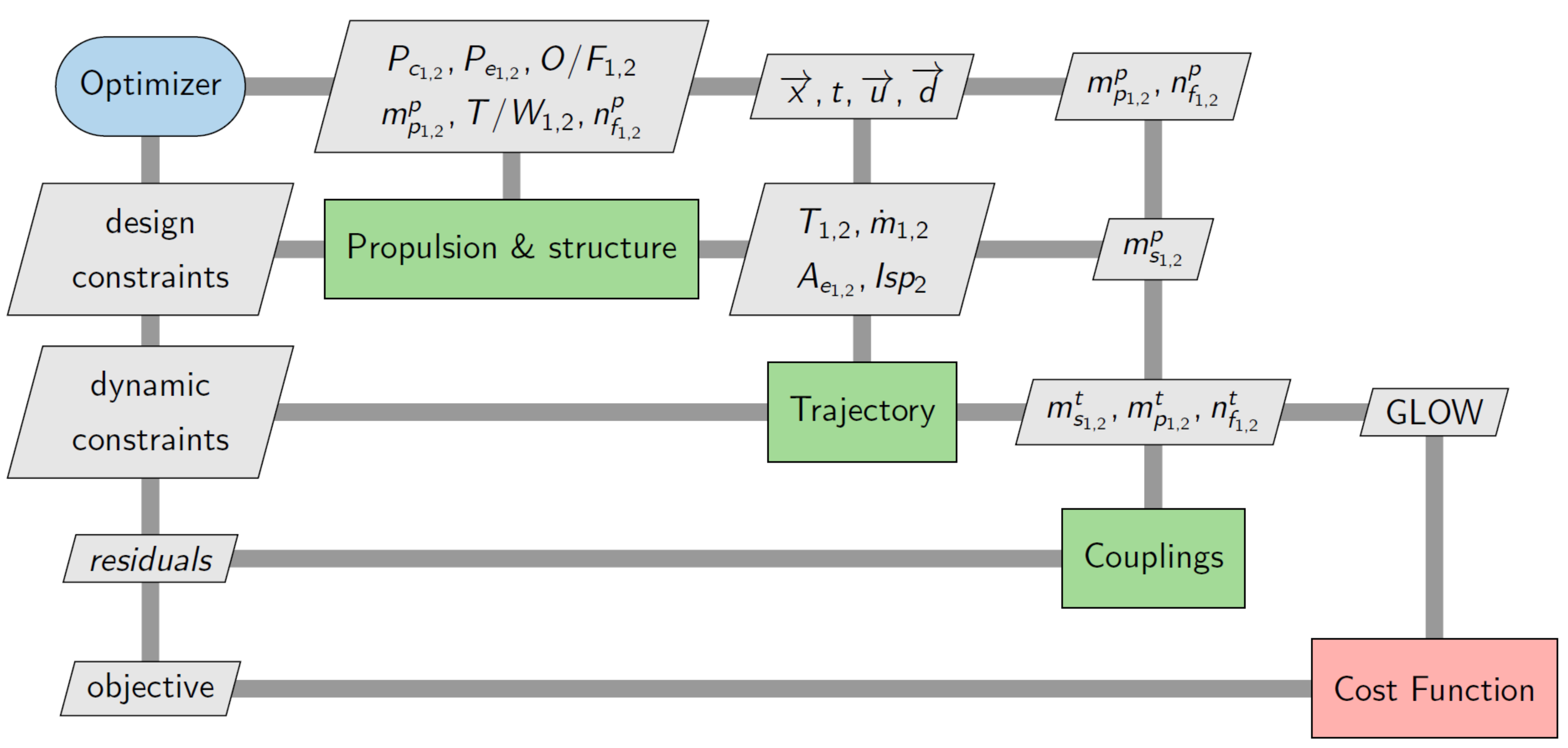
Trajectory:

- 2D polar coordinates.
- Two-Stage-to-Orbit (TSTO) launcher.
- U.S. Standard Atmosphere.
- Variable drag coefficient.
- Pitch angle guidance program.
- Hohmann Transfer Ascent.
- Constraints on heat flux and dynamic pressure.

Propulsion and structures:

- Propellants: Liquid Oxygen and kerosene.
- Chemical equilibrium modelled with interpolation of Rocket CEA outputs
- Constant throttle.
- Structural mass as a function of propellant mass and load factor.

All-at-Once based MDO architecture using Dymos and OpenMDAO:



$\vec{x}$: *State var. vector*	P_c : *Chamber pressure*	T : *Thrust*
t : *time*	P_e : *Exit pressure*	$\dot{m}$: *Mass flow rate*
$\vec{u}$: *Dynamic control*	O/F : *Ratio oxidizer / fuel*	A_e: *Exit Area nozzle*
$\vec{d}$: *Design parameters*	T/W: *Ratio thrust / weight*	I_{sp}: *Specific impulse*
$GLOW$: *Gross liftoff weight*	m_p : *Propellant mass*	m_s: *Structural mass*

Pseudospectral optimal control:

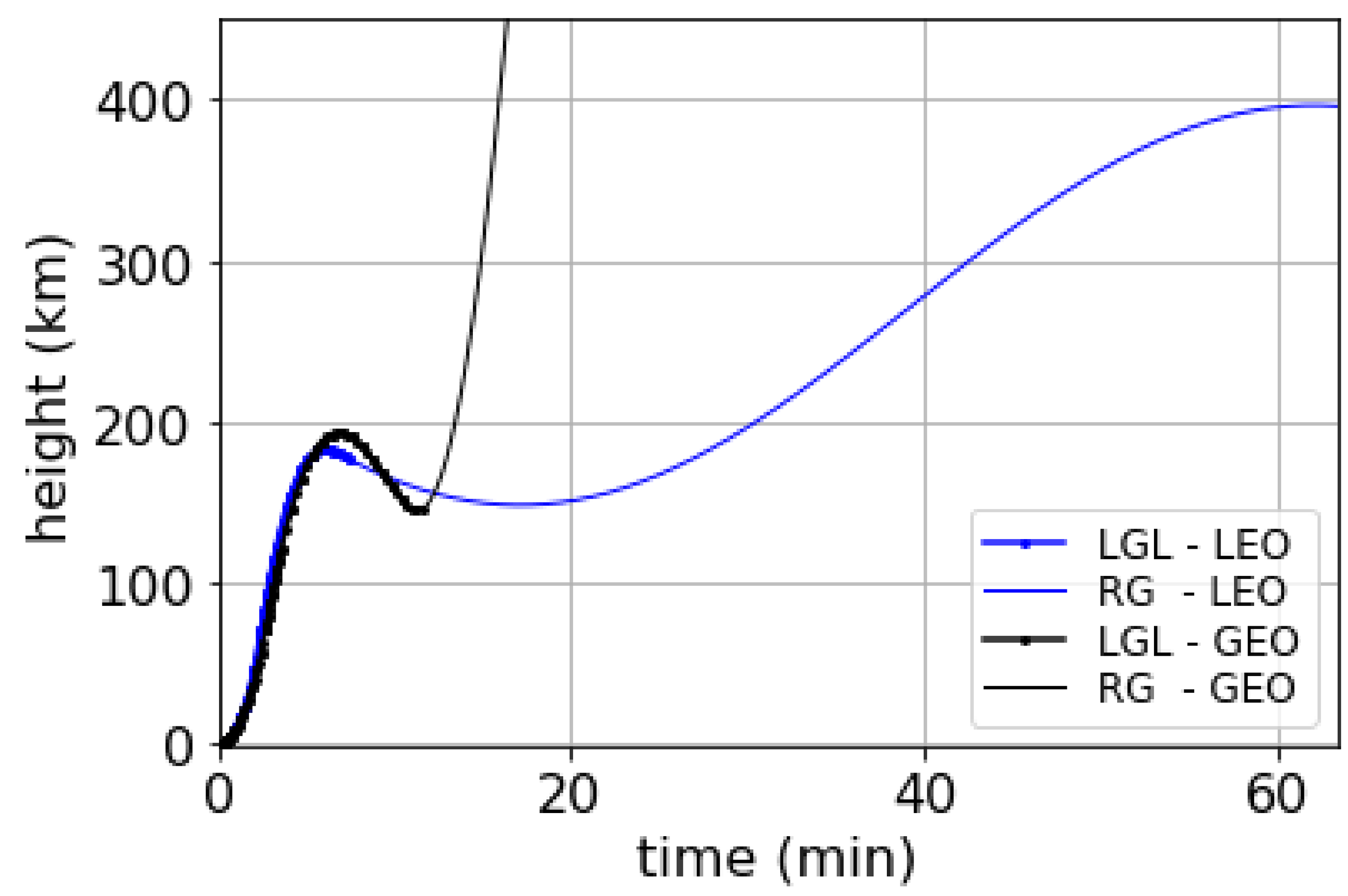
- Legendre-Gauss-Lobatto (LGL) transcription of order 3.
- 2 optimization variables per segment. 5 states discretized in 56 segments each. 4 boundary conditions. $\rightarrow \vec{x} \in \mathbb{R}^{556}$
- SLSQP NLP solver fed with analytic derivatives.

3. Results

Two vehicles with different missions were optimized along with their trajectories using the same initial guess.

	LEO Mission	GEO Mission
Height (km)	400	35786
Payload (tons)	11	3

- The LGL pseudospectral method was used to optimize the trajectory up to the insertion into the transfer orbit (TO).
- A Runge-Kutta (RG) method was used to verify the results and further propagate the trajectory up to the apogee of the TO.



Parameter	LEO Mission	GEO Mission
$Thrust_1$ (tons)	484,7	580,0
$Specific\ Impulse_1$(s)	298,4	294,1
T/W_1	1,6	1,5
$Thrust_2$ (tons)	46,5	23,3
$Specific\ Impulse_2$(s)	339,0	345,2
T/W_2	0,8	0,5
$GLOW$ (tons)	292,4	434,6
Optimization time	**3’49’’**	**7’15’’**

4. Conclusions and Future Work

- A 2D trajectory optimization module for TSTO launchers was developed using an LGL pseudospectral optimal control method.
- A new methodology to perform MDO of launchers was proposed by integrating pseudospectral methods in a AAO based architecture.
- The robustness of such methodology was assessed by optimizing launchers for a GEO and a LEO mission using the same initial guess.
- Future work could include the optimization of more disciplines, the extension to 3D trajectories, the optimal control of pitch angle and throttle and the study of different order transcriptions and recovery scenarios.

5. Selected References

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[3] R. D. Falck and J. S. Gray, “Optimal Control within the Context of Multidisciplinary Design, Analysis, and Optimization," in AIAA *Scitech 2019 Forum*, American Institute of Aeronautics and Astronautics, 2019.