Launch Vehicle Trajectory Module For Multidisciplinary Design Analysis and Optimization

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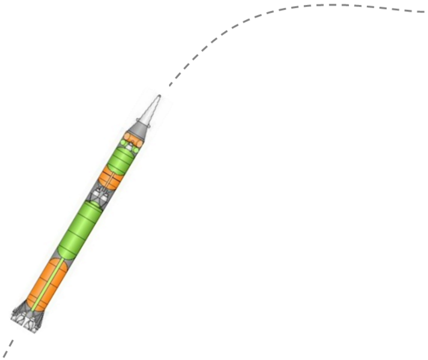
March 29, 2021

- Optimization of the launcher and its trajectory



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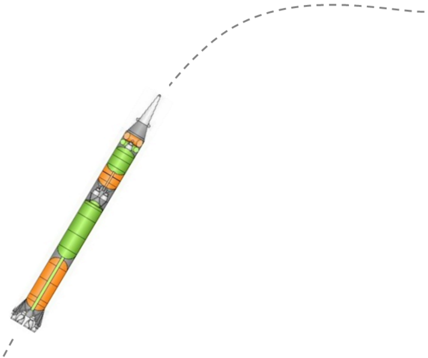
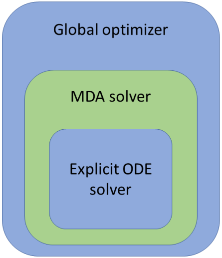
- Using Multidisciplinary Design, Analysis and Optimization (MDAO)



Introduction

- Optimization of the launcher and its trajectory
- Using Multidisciplinary Design, Analysis and Optimization (MDAO)
- The most common methods involve 3 solvers. Costly Multidisciplinary Analysis (MDA)



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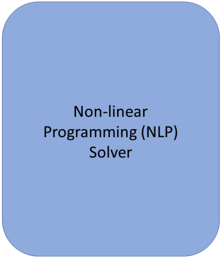
- We propose an approach with 1 solver



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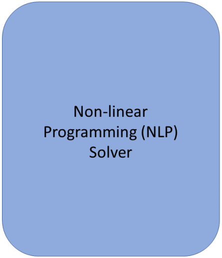
- We propose an approach with 1 solver
- Two-stage-to-orbit (TSTO)



Content of the presentation

- To integrate a trajectory optimization module using a pseudospectral method into the MDAO of a launch vehicle

Objectives

- To integrate a trajectory optimization module using a pseudospectral method into the MDAO of a launch vehicle
- To develop the trajectory module using gradient-based optimization with analytic derivatives

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- To develop the trajectory module using gradient-based optimization with analytic derivatives
- To evaluate the performance of the optimization process and compare it against an existing method

Plan

Multiple disciplines coupled with complex interactions. For example:

- Trajectory
- Propulsion
- Sizing

[1] Balesdent et al. 2012.

MDAO

Multiple disciplines coupled with complex interactions. For example:

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Single-level architectures of our interest:

- Multi-Discipline Feasible (MDF):
  - Coupled approach. Requires MDA
  - The most used in launch vehicle design[1]
- All-At-Once (AAO)
  - Decoupled approach. No MDA

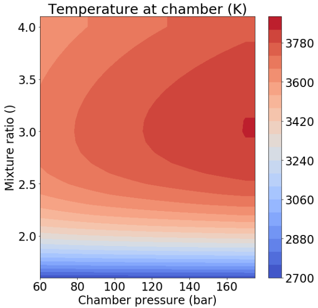
[1] Balesdent et al. 2012.

Plan

Design variables:

- Pressure at combustion chamber (P_c)
- Pressure at nozzle exit (P_e)
- Mixture ratio (O/F)
- Thrust at vacuum (T_{Vac})

$$\boldsymbol{z_p} = \begin{bmatrix} P_{c_1} \\ P_{c_2} \\ P_{e_1} \\ P_{e_2} \\ O/F_1 \\ O/F_2 \\ T_{vac_1} \\ T_{vac_2} \end{bmatrix}$$



Methods:
Rocket CEA[2] with bivariate interpolation

[2] Sanford and McBride 1994.

Design variables:

- Mass of propellants (m_p)
- Stage diameter (D)
- Mixture ratio (O/F)
- Thrust at vacuum (T_{vac})

$$\boldsymbol{z_m} = \begin{bmatrix} m_{p_1} \\ m_{p_2} \\ D \end{bmatrix}$$

Feedback couplings:

- Max. load factor (n_{max})
- Max. dynamic pressure (q_{max})

$$\boldsymbol{y_{fb}} = \begin{bmatrix} n_{max} \\ q_{max} \end{bmatrix}$$

Methods:

Regressions on existing launchers[3]

[3] Castellini 2012.

Methods:

- 2D polar coordinates

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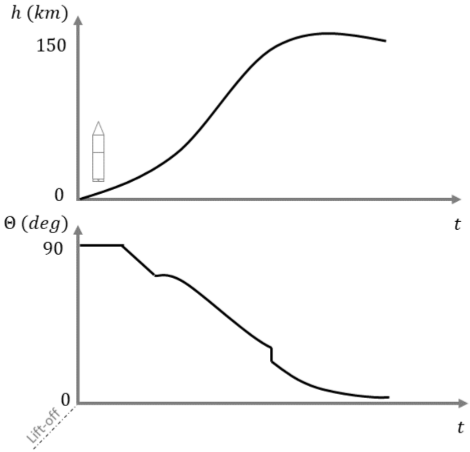

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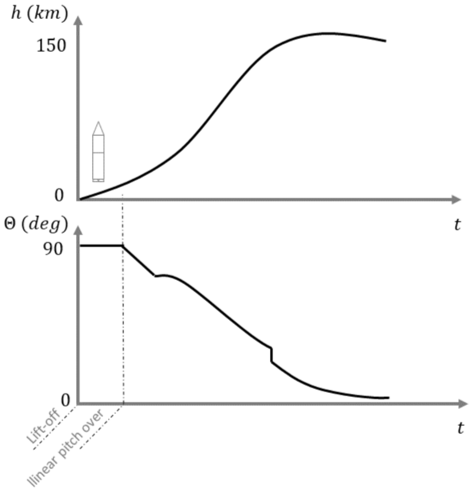

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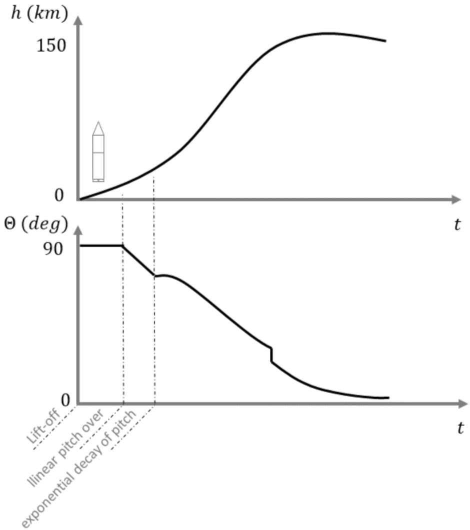

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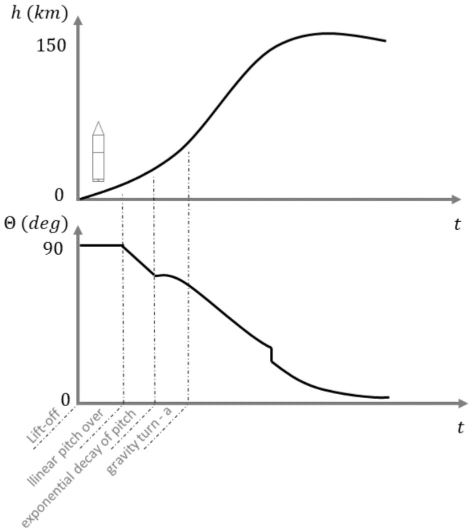

Description of disciplines

Trajectory

Methods:

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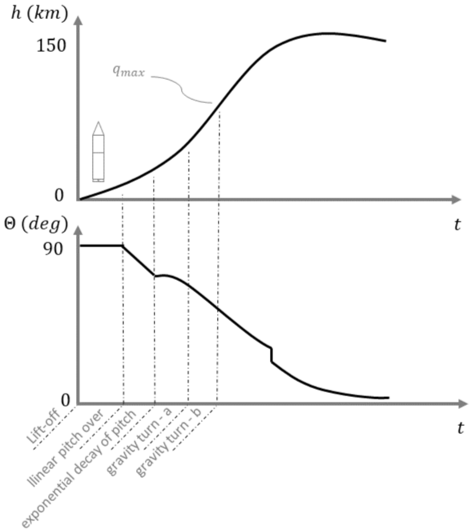
- Hohmann transfer ascent



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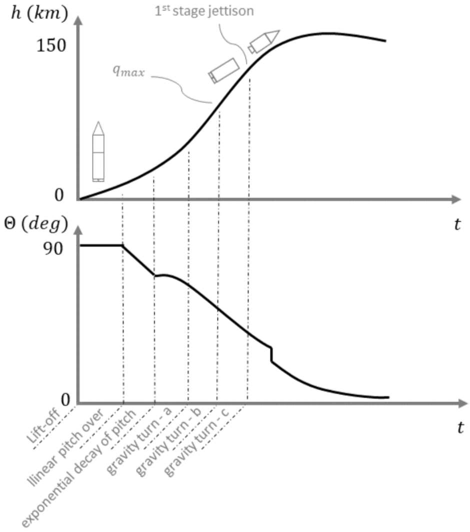

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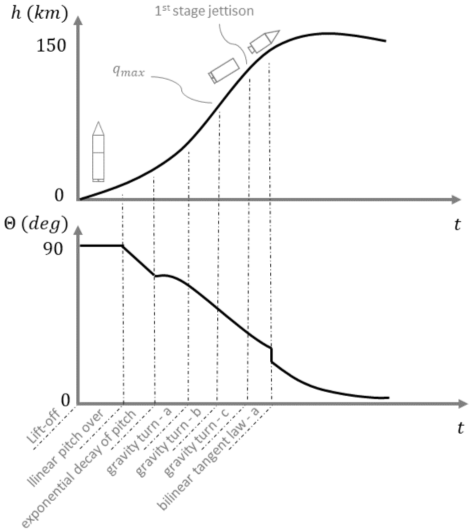

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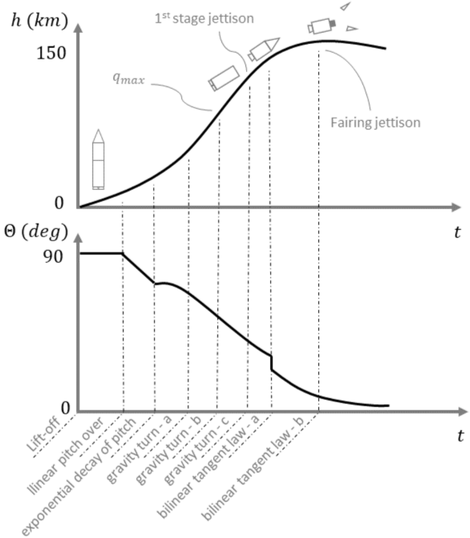

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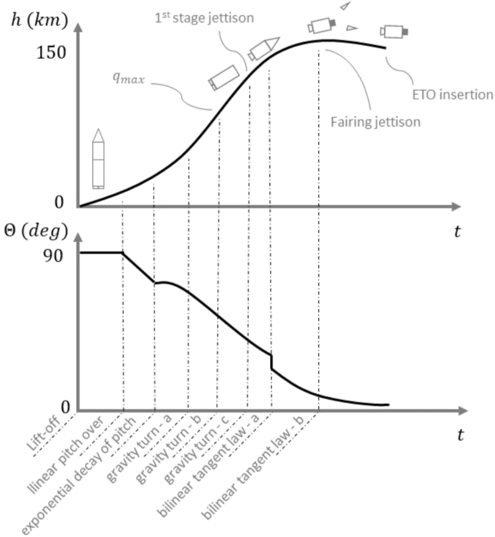


Design variables:

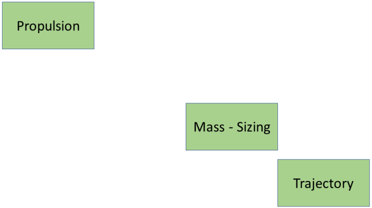
- Pitch angle guidance variables
    - Change in pitch angle during pitch over ($\Delta\theta_{lpo}$)
    - Change in pitch angle during bilinear tangent law ($\Delta\theta_{btl}$)
    - Final pitch angle (θ_{btl_f})
    - Shape parameter bilinear tangent law (ξ)
- Time variables ($\boldsymbol{t}$)

$$\boldsymbol{z_t} = \begin{bmatrix} \Delta\theta_{lpo} \\ \Delta\theta_{btl} \\ \theta_{btl_f} \\ \xi \end{bmatrix}$$

Plan

Description of Benchmark method

Onera's FELIN[4] - "MDF-like" formulation



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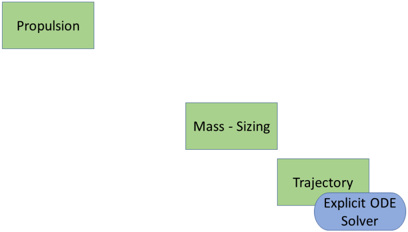
- Explicit ODE Solver.
  Runge-Kutta.



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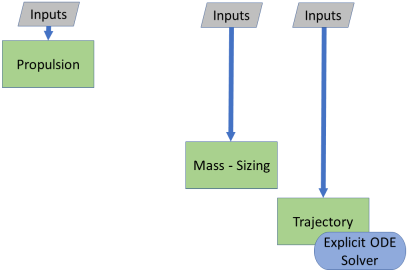

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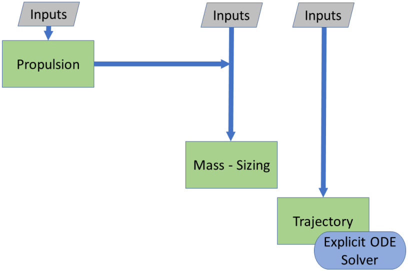

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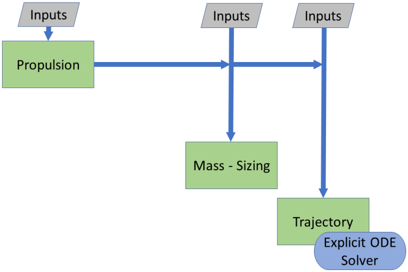

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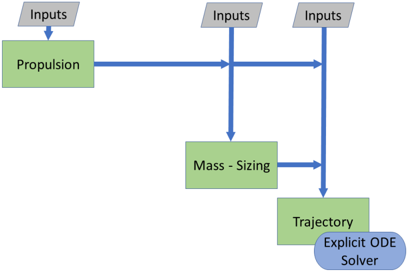

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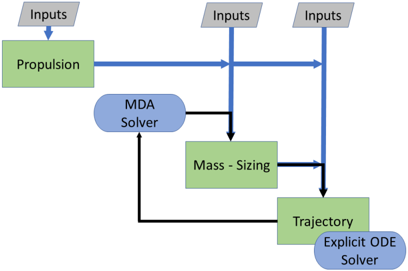
- Feedback couplings.
  Fixed point iteration.



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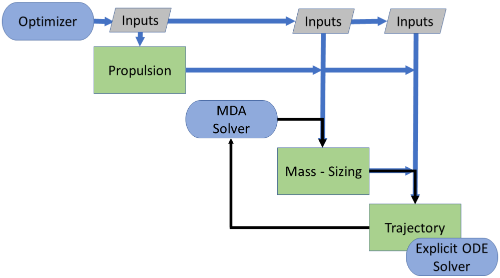

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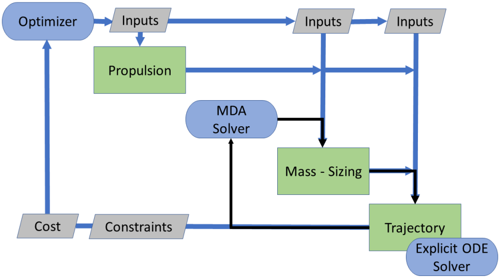

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Plan

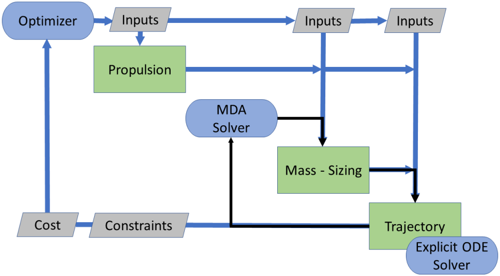
Proposed optimization method

Main features

- Pseudospectral transcription for the optimal control problem using Dymos[5]
- Replacement of feedback couplings in an ”AAO-like” fashion
- Analytic gradient calculation for all disciplines
- Chain rule with OpenMDAO[6]

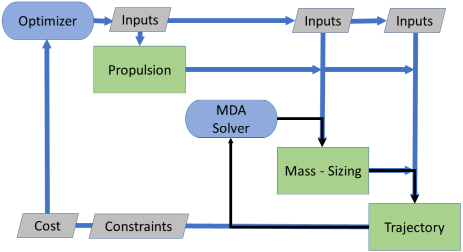
[5] Falck and Gray 2019.
[6] Gray et al. 2019.

Proposed optimization method



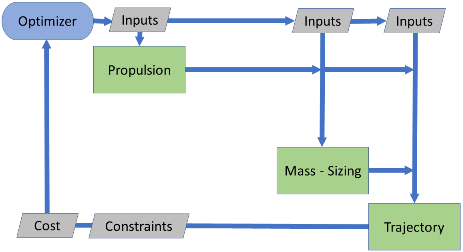
Proposed optimization method

- Remove explicit ODE solver



Proposed optimization method

- Remove explicit ODE solver
- Remove MDA solver



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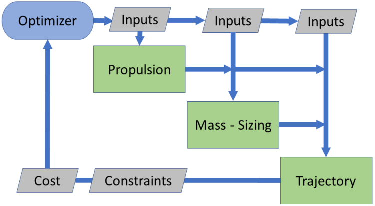
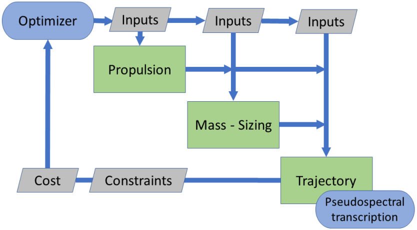


- Remove explicit ODE solver
- Remove MDA solver
- Use of pseudospectral transcription



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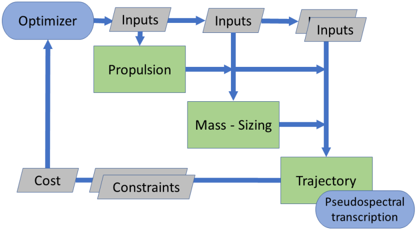
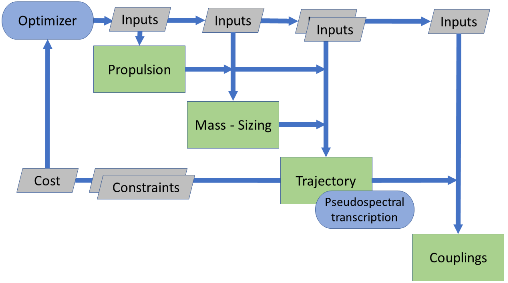


- Remove explicit ODE solver
- Remove MDA solver
- Use of pseudospectral transcription
- Duplicated variables for feedback couplings



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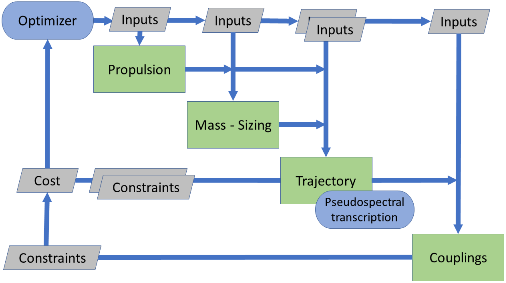

Proposed optimization method

- Remove explicit ODE solver
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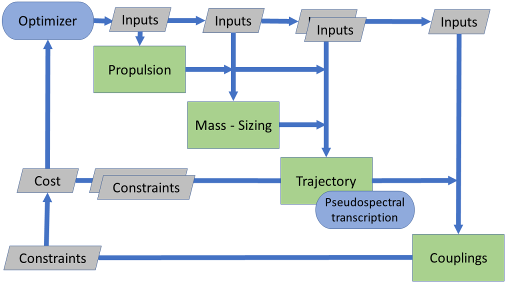
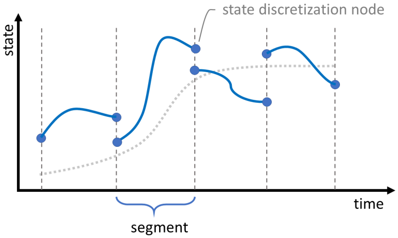
- Duplicated variables for feedback couplings
- Optimizer: Sequential Least Squares Programming (SLSQP)



Legendre-Gauss-Lobatto - Order 3

- 5 states
- 56 segments
- 560 state discretization nodes ($\boldsymbol{x}_t$)
- 15 time variables ($\boldsymbol{t}$)
- 566 equality constraints



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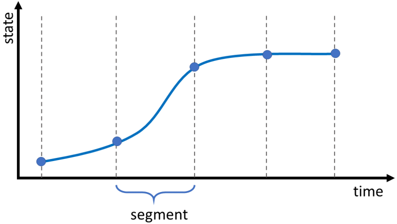
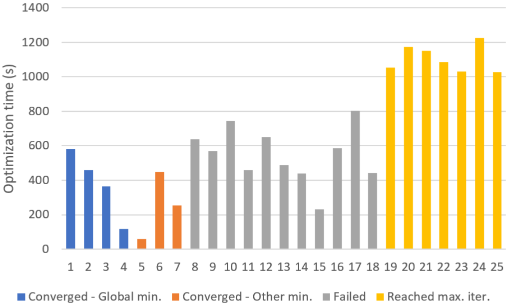


$$
\begin{aligned}
\text{minimize} &: \text{Gross lift-off weight (GLOW)} \\
\text{with respect to} &: [\boldsymbol{x}_t, \boldsymbol{t}, \boldsymbol{y}_{fb}, \boldsymbol{z}_p, \boldsymbol{z}_m, \boldsymbol{z}_t] \in \mathbb{R}^{592} \\
\text{subject to} & \\
\text{equality constraints} &: \boldsymbol{h}(\boldsymbol{x}_t, \boldsymbol{t}, \boldsymbol{y}_{fb}, \boldsymbol{z}_p, \boldsymbol{z}_m, \boldsymbol{z}_t) = \boldsymbol{0} \quad , \quad \boldsymbol{h} \in \mathbb{R}^{567} \\
\text{inequality constraints} &: \boldsymbol{g}(\boldsymbol{x}_t, \boldsymbol{t}, \boldsymbol{y}_{fb}, \boldsymbol{z}_p, \boldsymbol{z}_m, \boldsymbol{z}_t) \leq \boldsymbol{0} \quad , \quad \boldsymbol{g} \in \mathbb{R}^{13}
\end{aligned}
$$

The NLP solver SLSQP drives the whole problem

Plan

- SLSQP is a local optimizer
- 25 runs with partially random initialization
- 4 runs converged to the global minimum

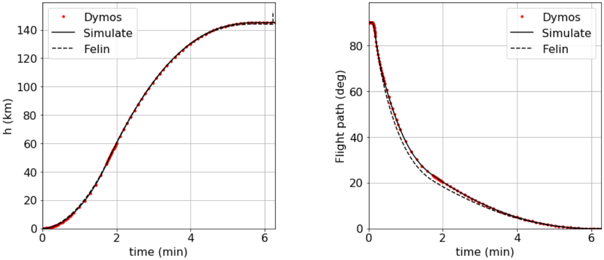


Dymos:
Proposed method

Felin:
Benchmark method

Simulate:
Test for discretization

Coast test:
Orbit verification



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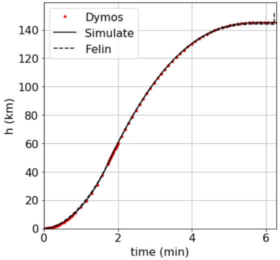

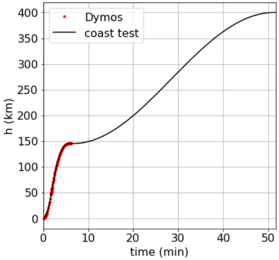

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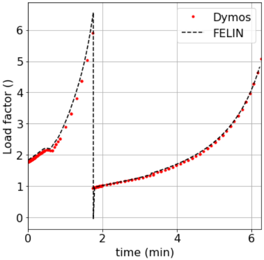
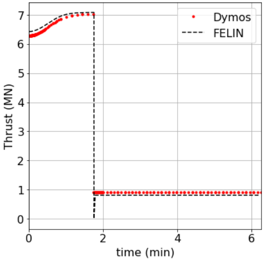


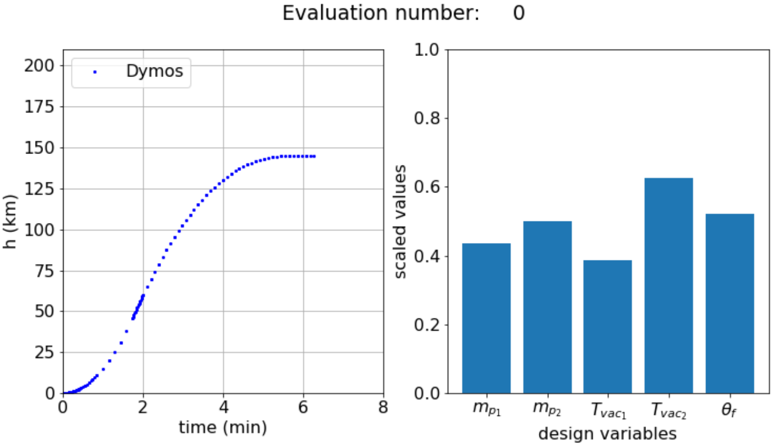


	Dymos Global optimum Best run	Dymos 25 runs	Felin Unique run
GLOW (tons)	359.08	359.08	355.6
Function evaluations	169	31 035	51 019
Optimization time (h)	0.03	4.4	1.88

Design Variables				
Discipline	Variable	Dymos	Felin	Error
Propulsion	T_{vac_1}	7 026 653.2	7 084 316.2	8.14×10^{-3}
	T_{vac_2}	911 354.5	804 667.2	1.33×10^{-1}
	O/F_1	2.3026	2.3298	1.17×10^{-2}
	O/F_2	2.3445	2.3556	4.71×10^{-3}
	P_{c_1}	10 000 000.0	9 953 515.2	4.67×10^{-3}
	P_{c_2}	10 000 000.0	9 999 345.6	6.54×10^{-5}
	P_{e_1}	53 760.9	62 725.4	1.43×10^{-1}
	P_{e_2}	3 540.8	3 439.2	2.95×10^{-2}
Mass/Sizing	m_{p_1}	238 461.2	244 349.4	2.41×10^{-2}
	m_{p_2}	74 853.7	65 174.2	1.49×10^{-1}
	D	3.8066	3.6189	5.19×10^{-2}
Trajectory	$\Delta\theta_{lpo}$	7.9985	9.2866	1.39×10^{-1}
	$\Delta\theta_{btl}$	2.1142	-	-
	θ_{btlf}	0.8422	0.77	9.38×10^{-2}
	ξ	-0.152	-0.286	4.69×10^{-1}

Average error in design variables between global optimum in Dymos and Felin : 4%

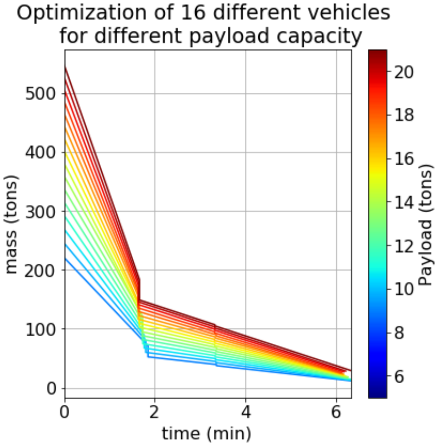
Use of existing solution as initial guess



Optimization time: 222 s

Use of obtained results as initial guess to optimize vehicles with different payloads.

- 93% convergence rate
- Total optimization time 0.8 h.



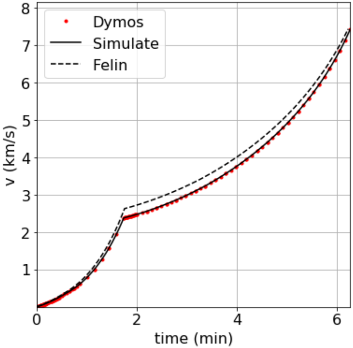
- A new methodology for the MDAO of launch vehicles was proposed using a pseudospectral method for optimal control.
- The current model is sensitive to random initialization.
- A comparison with a existing methodology was done to verify the accuracy of the new methodology.

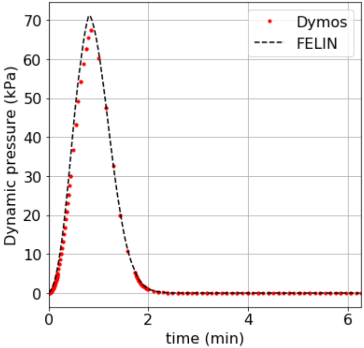
- Improve the models to reduce the sensitivity to random initialization
- Use more performant optimizers like SNOPT with bounds on state discretization nodes
- This work will be presented in the 14th World Congress on Structural and Multidisciplinary Optimization in June 2021

- Balesdent, Mathieu et al. (May 2012). “A Survey of Multidisciplinary Design Optimization Methods in Launch Vehicle Design”. en. In: *Struct Multidisc Optim* 45.5, pp. 619–642. ISSN: 1615-1488. DOI: 10.1007/s00158-011-0701-4.
- Brevault, Loic and Mathieu Balesdent. *Framework for Evolutive Launcher optImizatioN*. https://github.com/l-brevault/FELIN.
- Castellini, Francesco (2012). “MULTIDISCIPLINARY DESIGN OPTIMIZATION FOR EXPENDABLE LAUNCH VEHICLES”. en. In:
- Falck, Robert D. and Justin S. Gray (2019). “Optimal Control within the Context of Multidisciplinary Design, Analysis, and Optimization”. In: *AIAA Scitech 2019 Forum*. American Institute of Aeronautics and Astronautics.
- Gray, Justin S. et al. (Apr. 2019). “OpenMDAO: An Open-Source Framework for Multidisciplinary Design, Analysis, and Optimization”. en. In: *Struct Multidisc Optim*. ISSN: 1615-1488. DOI: 10.1007/s00158-019-02211-z.

Sanford, Gordon and Bonnie J. McBride (Oct. 1994). *Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. Part 1: Analysis*.

more results I





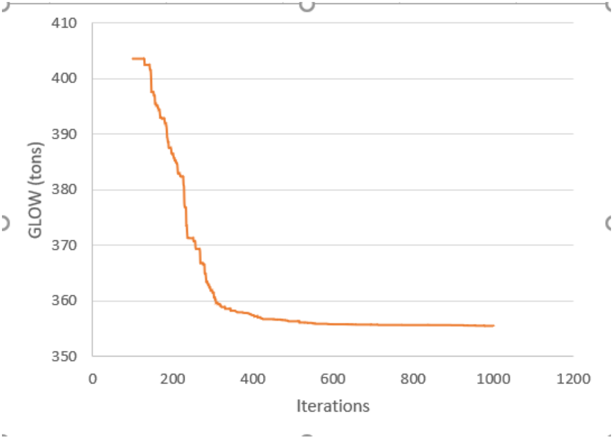
```
=============================================================================
========================== Optimization Report ==========================
=============================================================================

Design parameters: All values in standard SI units. Angles in radians.
Design parameters marked with (***) are close to their bounds or violate them
Name                                     lower          value          upper
-----------------------------------------------------------------------------
lift_off.t_duration                      1.0            5.912          100.0
pitch_over_linear.t_duration (***)       5.0            5.0            10.0
pitch_over_exponential.t_duration        1.0            11.2118        100.0
gravity_turn.t_duration                  1.0            27.6856        150.0
gravity_turn_b.t_duration                1.0            50.7093        150.0
gravity_turn_c.t_duration                1.0            58.1435        150.0
exoatmos_a_t_duration                    1.0            39.6573        250.0
exoatmos_b_t_duration                    1.0            174.6421       250.0
delta_theta_pitch_over                   0.0175         0.1735         0.1745
xi                                       -1.0           -0.1038        1.0
delta_theta_exoatmos                     -1.0472        0.0439         1.0472
theta_f                                  -0.3491        0.0141         0.3491
P_c_stage_2 (***)                        6000000.0      10000000.0     10000000.0
P_e_stage_2                              1.0            3572.0683      10000.0
o_f_stage_2                              2.0            2.3442         4.0
thrust_vac_stage_2                       100000.0       911856.4145    1400000.0
mp_2 (***)                               50000.0        75000.0        75000.0
P_c_stage_1 (***)                        6000000.0      10000000.0     10000000.0
P_e_stage_1                              40530.0        56464.0449     200000.0
o_f_stage_1                              2.0            2.3016         4.0
thrust_vac_stage_1                       5000000.0      7234644.1341   15000000.0
mp_1                                     230000.0       237753.0767    280000.0
max_n_f_1                                1.0            6.0468         10.0
max_q_dyn_1                              10.0           71880.9436     100000.0
D_stage_1                                1.0            3.7947         5.0
```

```
Constraints:  All values in standard SI units. Angles in radians.
Name                                     lower          value          upper
-----------------------------------------------------------------------------
Jettison.residual_ms_1                   0.0            -0.0           1e+30
Jettison.residual_mplf                   0.0            -0.0           1e+30
Jettison.residual_m_final                0.0            -0.0           1e+30
ExitArea.residual_area_1                 0.0            -0.0           1e+30
ExitArea.residual_area_2                 0.0            -0.0           1e+30
DynamicPressure.residual_max_q_dyn       0.0            -0.0           1e+30
Propellants.residual_mp_1                0.0            -0.0           1e+30
Propellants.residual_mp_2                0.0            -0.0           1e+30
LoadFactor.residual_max_n_f_1            0.0            0.0            1e+30
lift_off.final_value:r                   6378285.0      6378285.0      6380135.0
gravity_turn.final_value:qDot            -1e+30         -0.0           1e+30
gravity_turn_c.final_value:q_dyn         -1e+21         10.5702        1000.0
exoatmos_a.final_value:q_heat            -1e+21         1135.0         1135.0
exoatmos_b.final_value:ra                6778135.0      6778135.0004   6798135.0
exoatmos_b.final_value:rp                6523135.0      6523134.9996   1e+21
```

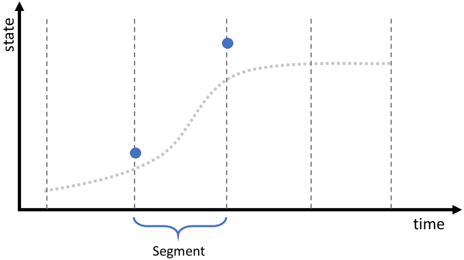
```
Vehicle paramaters
--------------------------------------------------------------------------------
Payload mass (kg):                      11000.0
Fairing mass (kg):                      1900.0
Aux mass first stage (kg):              3000.0
Propulsion type ():                     LOx + RP_1
First stage:
    Structural mass (kg):               26499.14
    Propellants mass (kg):              237753.08
    Structural coef ():                 0.1
    Thrust (N):                         7234644.13
    Isp (vac) (s):                      311.9
    number of engines ():               9
    Ae_t (m^2):                         7.24
Second stage:
    Structural mass (kg):               6928.2
    Propellants mass (kg):              75000.0
    Structural coef ():                 0.08
    Thrust (N):                         911856.41
    Isp (vac) (s):                      339.59
    number of engines ():               1
    Ae_t (m^2):                         7.24
First stage flight with fairing:
    Tw_ratio ():                        2.05
Second stage flight with fairing:
    Tw_ratio ():                        0.98
```

Convergence FELIN I



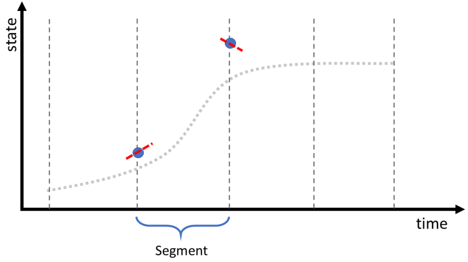
Legendre-Gauss-Lobatto - Order 3

- Time discretization



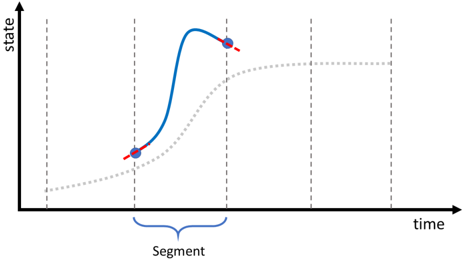
Legendre-Gauss-Lobatto - Order 3

- Time discretization
- ODE evaluation



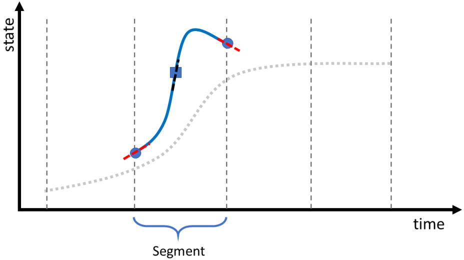
Legendre-Gauss-Lobatto - Order 3

- Time discretization
- ODE evaluation
- Interpolation



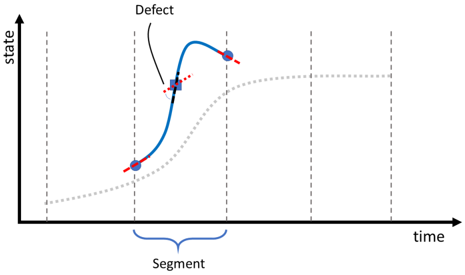
Legendre-Gauss-Lobatto - Order 3

- Time discretization
- ODE evaluation
- Interpolation
- Polynomial derivative



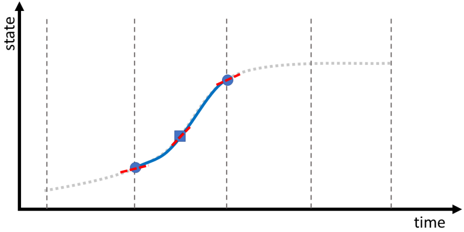
Legendre-Gauss-Lobatto - Order 3

- Time discretization
- ODE evaluation
- Interpolation
- Polynomial derivative
- ODE evaluation



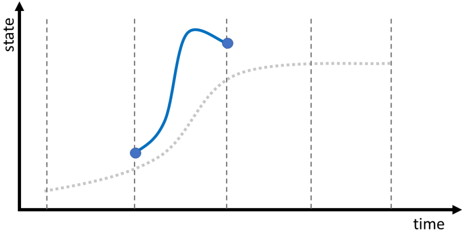
Legendre-Gauss-Lobatto - Order 3

- Time discretization
- ODE evaluation
- Interpolation
- Polynomial derivative
- ODE evaluation
- NLP optimizer



Legendre-Gauss-Lobatto - Order 3

- Time discretization
- ODE evaluation
- Interpolation
- Polynomial derivative
- ODE evaluation
- NLP optimizer



Legendre-Gauss-Lobatto - Order 3

- Time discretization
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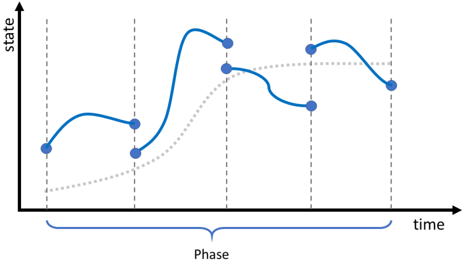

Legendre-Gauss-Lobatto - Order 3

- Time discretization
- ODE evaluation
- Interpolation
- Polynomial derivative
- ODE evaluation
- NLP optimizer