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Master of Aerospace Engineering Research Project

Optimal control of Trajectory of reusable launcher in OpenMDAO/dymos

Short Note

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Duration: 14 Months

1 Three months achievements

1.1 Description of the Work

The activity of this research project is focused on numerical simulation using OpenMDAO/dymos. In particular, dymos offers two intresting transcription methods to convert a continuous time control problem into a non-linear programming problem (NLP) that can be solved by specific libraries provided by SciPy package.
In order to run a simulation with these tools, the user is asked to provide different inputs:

1. State variables and controls with their relative unit of measurement
2. Equations of motion (EOMs)
3. Jacobian of the outputs respect to the inputs of the EOMs
4. Initial and final boundary conditions
5. Path constraints
6. Initial guesses on state variables, controls and time of flight
7. Degree of the interpolating polynomials and number of segments in time in which the whole trajectory is split and analysed
8. Design parameters such as spacecraft mass, specific impulse (ISP) and thrust

From the obtained results, it is possible to retrieve information about the fuel mass consumed, the time of flight and the evolution in time of the state variables and controls.

1.2 Results until the S2 Progress presentation

Referring to the previous description of work, various simulations have been carried out.

1. First of all, a constant thrust ascent trajectory to a LLO has been evaluated with different ISP and thrust values in order to compare these results with the ones obtained by one of the supervisors through an indirect method. The results obtained through the direct transcription match almost perfectly with the second approach, thus validating the solution method proposed for this research project.

2. The next step has been to relax the constant thrust assumption and consider the trajectory divided in three different phases: powered ascent, coasting and insertion in the final orbit (LLO). With this design the problem was not solvable by the open-source NLP solver provided by ScyPy (SLSQP).
   Thus, a new control variable throttle has been introduced in order to redesign the trajectory as a unique phase with varying thrust. As expected, the final optimal trajectory closely approximate a *switch-on/switch-off* control scheme that resembles the three phases mentioned above.

3. Lastly, after an accurate bibliography review regarding different landing trajectories on the Moon surface, two main simulations have been carried out to reproduce the results obtained by Ramanan and Remesh. The solutions proposed by the authors were obtained using

genetic algorithms, whose philosophy is quite different from the one behind the method proposed for this study. However, for all the cases a common solution has been found.

1.3 Ascent trajectory with path constraints

The next task was the design of an ascent trajectory that takes into account the limitation imposed by the geographical features of the Moon. This was achieved adding path constraint that specifies the minimum thrust angle in the first phase of the ascent to avoid a collision. The trajectory was modeled as a unique phase with a variable thrust modifying the results discussed in point 2 of the previous section.
To obtain a reliable result with the ScyPy library solver, it was necessary to take as initial guess the accurate solution of the unconstrained simulation (point 2 previous sec.) otherwise the results were not physically feasible.

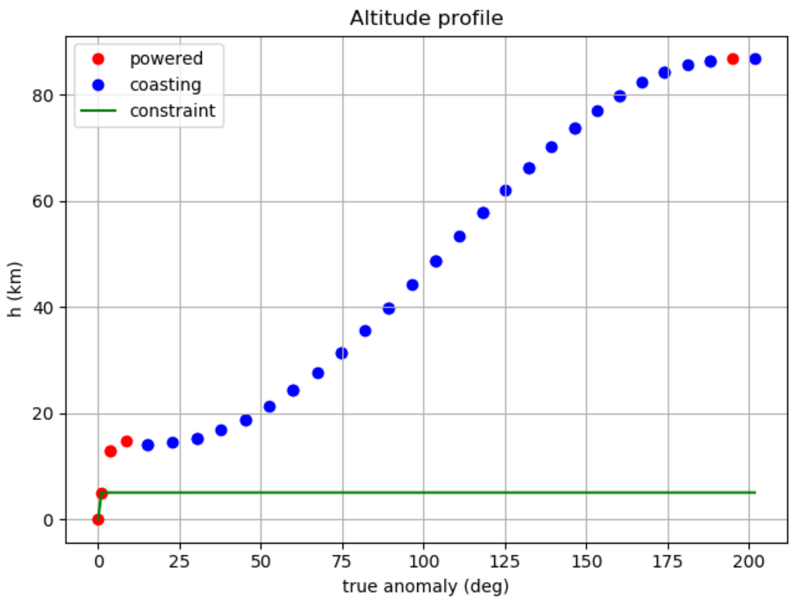

Figure 1.1: Ascent trajectory with path constraint

For this reason, multiple issues have been underlined regarding the reliability of the ScyPy library. In fact, many times it was not able to converge or it gave different results depending on the transcription used for the problem. This brought to the decision of using PyOptSparse library, that requested great effort to be properly compiled. With the NLP solver present in this library such as IPOPT and SLSQP, new results were achieved, in particular:

1. A feasible solution for the ascent trajectory simulation with the path constraint was obtained without the need to compute an accurate guess. It is sufficient to linearly interpolate the boundary conditions and set that as the first iteration of the problem.

2. An ideal trajectory was modeled in order to compare the optimization results with an analytical solution from this simplified model. The assumption was to split the trajectory in three phases considering the first as an hedgehop at Moon radius to acquire the necessary tangential velocity for an Hohmann transfer up to the final orbit radius. Finally, an impulsive burn was added to model the insertion. The result of the comparison are compatible.

3. Different trajectories were solved using different initial guesses and solvers, both from ScyPy and PyOptSparse packages. In particular, the initial points were taken from the ideal trajec-

tory explained in the previous point, from the unconstrained trajectory and from the linear interpolation of the boundaries. IPOPT, SLSQP and PSQP were taken as solvers.
For the specific transcription that allows to reach a feasible solution, all the results were comparable to the ideal one.