Master of Aerospace Engineering Research Project

Optimal control of Trajectory of reusable launcher in OpenMDAO/dymos

S2 Progress Report

Authors:
Alberto Fossà
Giuliana Elena Miceli

Tutors:
Laurent Beauregard
Joseph Morlier
Stéphanie Lizy-Destrez

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Duration: 14 Months

Contents

1 Goal of the project

This study is focused on the analysis of new ascent and descent trajectories from the Moon surface to different possible lunar orbits, such as Low Lunar Orbits (LLO) and Near Rectilinear Halo Orbits (NRHO). The objective is to provide a possible answer to the questions arisen after the renewed interest in the Moon exploration and *in-situ* resources exploitation, as demonstrated by the current development of the Lunar Orbital Platform-Gateway (LOP-G) and the Space Launch System (SLS).

The main objective is to determine the most fuel-efficient trajectory for a given final orbit suitable for a crewed reusable launcher, for which different constraints and safety requirements must be taken into account. The principal tools used to achieve the final goal are OpenMDAO and Dymos, two Python libraries that provide a *user-friendly* and powerful interface for solving optimal control problems through different numerical techniques.

2 Project issues

The project issues are mainly related to the usage of OpenMDAO and Dymos tools and the integration of this work within a bigger framework that includes the development of all the subsystems of which the launcher is constituted.

In the first case, it has been necessary to deeply read the documentation and run the different examples to have a better understanding of the processes behind the mentioned libraries. Moreover, to fully take advantage of the potential of OpenMDAO, a proprietary software package for solving non-linear optimization problems is to be preferred instead of the open-source alternative already included in the library. Due to its unavailability, to obtain a reliable solution the problem has to be tackled with a different approach and the trajectories have to be designed relaxing some constraints and simplifying the dynamic models.

Secondly, since all the parts of the project are being developed simultaneously, many parameters required to properly set up the optimization problem are missed, such as the initial spacecraft mass and the engines performances. As a consequence, to be already able to carry out the simulations different assumptions have been done and some analysis have been conducted to understand the impact of the different parameter choices.

3 Main bibliography and State of the Art

Before starting with the actual implementation of the optimization framework, different sources have been consulted to gain knowledge about the optimal control theory, the transcription methods available to numerically solve the problem and the solutions already proposed for ascent and descent trajectories from the Moon surface.
For the mathematical theory behind optimal control most of the concepts were explained by one of the supervisor in a dedicated lecture, while the numerical implementation refers mainly to the work published by Garg [2] and Shirazi [6].
Than, the work of Cho [1], Ramanam [4], Remesh [5] and Sostaric [7] have been studied to reconstruct the actual *state-of-the-art* for the descent trajectories on the Moon surface. These papers have provided a better understanding of the dynamic behind a possible lunar landing and also important numerical results that have been used to test the earliest simulations.
Similarly as before, in the case of ascent trajectories two main papers, written by Ma [3] and Zhang [8], have been referenced and compared to the first obtained data.

4 Milestones of the project

The workload has been divided into several goals that will be sequentially achieved during the whole project duration. A brief outline of the different steps is presented below:

1. Gain the required knowledge of the mathematical theory behind optimal control
2. Review of the *state-of-the-art* algorithms available to solve an optimal control problem and understanding of the OpenMDAO/dymos framework
3. Analysis and comparison of the results already published by different authors concerning optimal ascent and descent trajectories from the lunar surface
4. Simulation of descent and ascent trajectories from a Low Lunar Orbit in the simplified context of the restricted two-body problem
5. Development of a dynamic model that takes into account the rocket attitude and inertia
6. Inclusion of the orbital perturbations models in the simulations
7. Analysis of the transfer trajectories from the Moon South Pole to the proposed NRHO for the future LOP-G
8. Development of a control algorithm for the reusable launcher
9. Integration of the conducted work in the global optimization framework

5 Task 1

5.1 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.

5.2 Technical Progress: two months achievements

Referring to the previous description of work, various simulations have already been carried out. 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 Figure 5.1 (a) shows that the results obtained through the direct transcription match almost perfectly with the second approach, thus validating the solution method proposed for this research project.

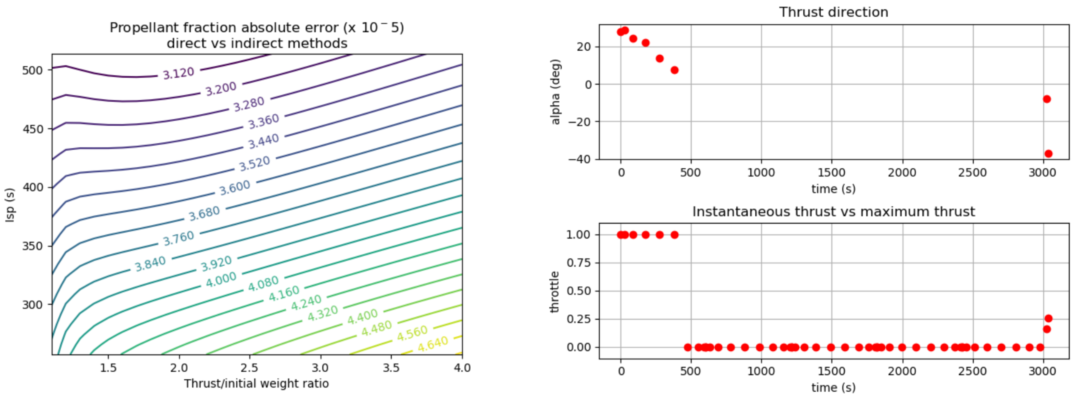

Figure 5.1: (a) Propellant fraction error - (b) Thrust direction and throttle

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 currently used, as already mentioned in chapter 2. 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 (Figure 5.1 (b)).

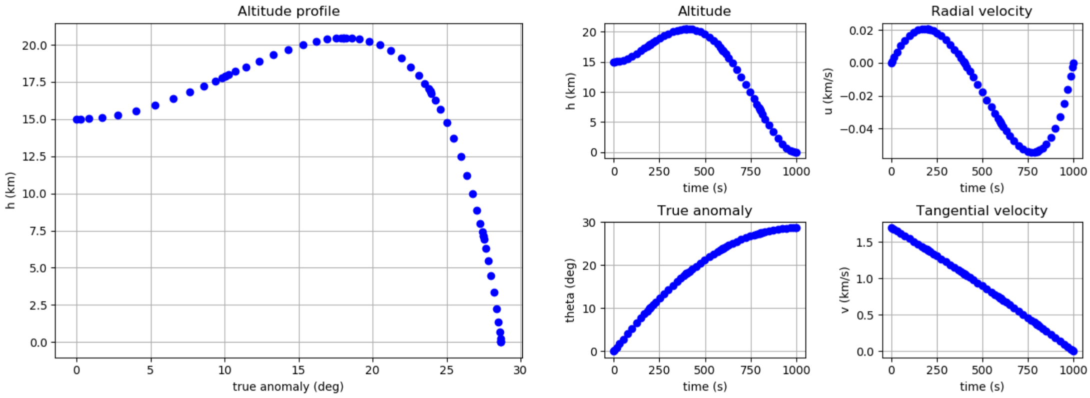

Figure 5.2: (a) Altitude vs true anomaly - (b) State variables

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 [4] and Remesh [5]. 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.

5.3 Plan versus achievements

Conceiving the initial plan proposed for the project, the work proceeds as expected.

5.4 Planned work for the next three months

The first improvement planned for the next months will take into account the geographical constraints imposed by the landing site, such as the presence of lunar mountains and hills. The design of such trajectory will be accomplished in two separate stages:

1. Impose a vertical-rise phase for a specified height or time interval during the ascent trajectory
2. Introduce a vertical final path on the landing trajectory
3. Define path constraints to maintain a minimum distance from the lunar highlands both in the ascent and descent phases

Starting from the work already done, the next tasks will be to develop a complete model of the launcher that considers both its attitude and inertia. This will allow to study 3D trajectories, impose appropriate limits on the attitude rates and derive a control law for the rocket.
Finally, new orbits will be considered to match the one proposed for LOP-G.

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