Lunar Trajectory Example

Extendable Orbit System

an orbital mechanics matplotlib-based Python3 library

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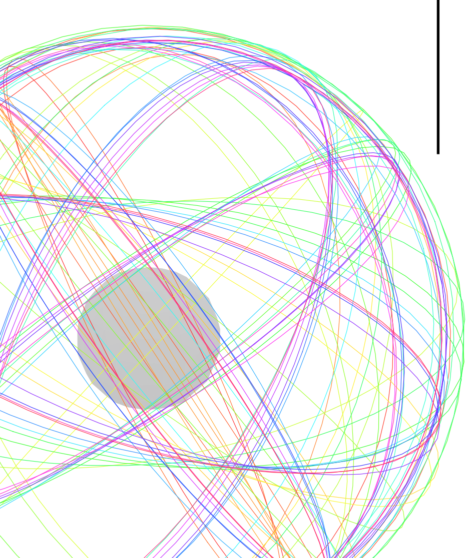

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Chapter 1

Introduction

This report has been written as part of the personal project of Delft University of Technology's Faculty of Aerospace's Engineering's Python programming course (AE1250), in which I have chosen to extend EOS with an n-body simulation class as explained in the documentation. The ultimate goal was to be able to simulate an Apollo 11-like lunar trajectory. To realize this goal, I set out to find as much data as I could on the burn program of the original Apollo 11 mission. Provided by NASA's Johnson Space Center were however only the ΔV-increments without flight path angles or burn directions [1]. This demanded for an individual research to be conducted, the results of which are posted in this document.

Chapter 2

Lunar Rendezvous

There are many factors that play a role in the planning and execution of a lunar rendezvous, and ultimately lunar orbit insertion. As mentioned by Bate et al. [2], NASA scientists and engineers have had to manually calculate suitable orbits, as there simply is no algorithm to calculate the optimum launch date or ΔV-budget. There are however several approximations that simplify the problem. These include [2]:

- Application of spheres of influence
- Neglecting lunar gravity for the coasting phase
- Rendering the Earth as stationary
- Approximating the Moon to be in the same orbital plane
- Assuming a circular lunar orbit

As the goal is to simply simulate a lunar rendezvous, the only approximation made is that of the Moon being at an angle of $0°$ with respect to the Earth's orbital frame. As the computer will take care of all calculations, application of spheres of influence, negligence of lunar gravity and assuming a circular orbit make no difference in terms of perceived complexity.

We define three impulse types in the rendezvous phase:

1. Translunar injection (TLI)
2. Midcourse corrections (MCC)
3. Lunar orbit insertion (LOI)

To simplify the simulation, it has been chosen to apply one TLI, MCC and LOI. The circular parking orbit in which the spacecraft is initially situated is the same as that of the Apollo 11 Command/Service Module (CSM), namely 100 M (nautical miles=185.2 km).

According to [2], the least-energy maneuver needed to arrive to the Moon, is one in which the angle swept by the true anomaly is $\theta = 180°$. This is in turn means that the time of flight is also the longest of all possibilities. After inserting the Moon's apsides data [3] and the spacecraft orbit data into EOS, the following plot has been produced (fig. 2.1). The lunar transfer orbit (LTO) has been set to have an apogee that is equal to the periapsis of the Moon (0.3633×10^6 km).

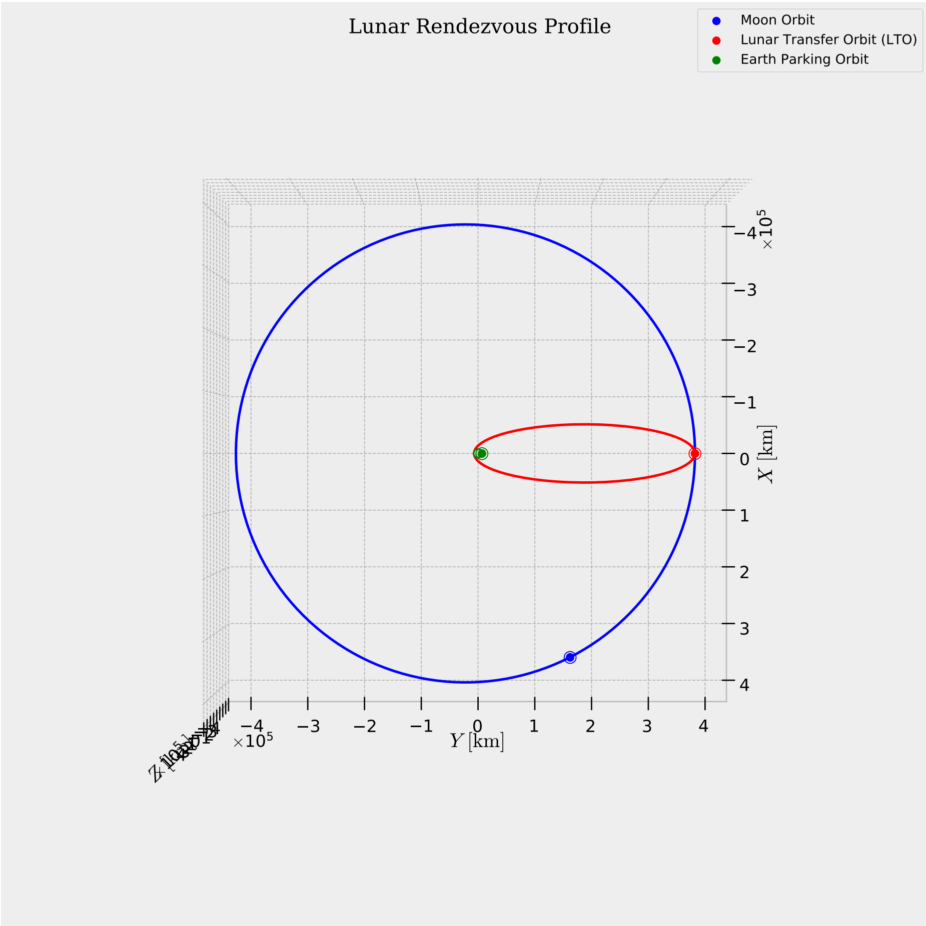


Figure 2.1: Lunar transfer profile overview

The orbit properties of the lunar transfer orbit (LTO) are as follows:

Table 2.1: Lunar transfer orbit (LTO) properties

	ORBT
Apoapsis Altitude	356922
Apoapsis Radius	363300
Apoapsis Velocity	0.197327
Argument of periapsis	180
Ascending node longitude	0
Eccentricity	0.96451
Inclination	0
Periapsis Altitude	185.2
Periapsis Radius	6563.3
Periapsis Velocity	10.9227
Period	791469
Semi-latus Rectum	12893.7
Semi-major Axis	184932
Semi-minor Axis	48830.8
Unit	km

The transfer time to the orbit's apoapsis will be equal to:

$$t_{\text{transfer}} = \frac{T}{2} \approx 110\,\text{h} \approx 4\,\text{d}14\,\text{h} \tag{2.1}$$

This is much longer that the 3 days it took for Apollo 11 to reach its final LOI burn. Finding a suitable balance between ΔV and flight time was a substantial part of the original design mission, as a longer flight time could end up with the same required propellant mass for a faster trajectory, because of the added mass of the life-support systems that need to hold for an extra 40 hours.

2.1 Simulated Burn Program

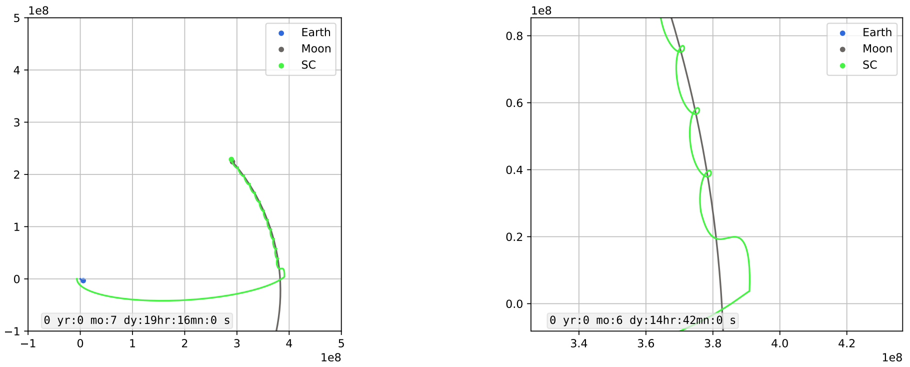
The TLI in the simulation is executed at $\theta = 0°$ at $t = 0$. The initial lunar position was obtained by calculating the Moon's position at time from periapsis $\tau = -t_{\text{transfer}}$. This is to ensure that the spacecraft reaches LTO apoapsis at the same time that the Moon reaches its periapsis, at which the two coincide.

By taking the difference between the parking orbit and the LTO perigee velocity, the required velocity change is obtained. This turned out to be $\Delta V_{\text{TLI}} = 3.13\,\text{km}\,\text{s}^{-1}$. At $t = 0$, a prograde impulse burn of ΔV_{TLI} is executed to set course to the Moon.

After a free flight of 116 h, a first midcourse correction (MCC). The velocity change for this maneuver is $\Delta V_{\text{MCC}} = 700\,\text{m}\,\text{s}^{-1}$. This causes the spacecraft to enter a gravity assist with the Moon, thereby gaining extra velocity for orbit insertion.

At $t = 128\,\mathrm{h}$, a first LOI burn is performed. This required a velocity change of $\Delta V_{\mathrm{LOI1}} = 580\,\mathrm{m\,s^{-1}}$ and enters the spacecraft in a corkscrew orbit with a period of four hours. Due to the lack of knowledge on orbit insertion and the difficulty of finding information on such a maneuver, a second lunar orbit insertion has not been attained.

When applied, the abovementioned burn program results in the following trajectory (fig. 2.2):



(a) Overall view

(b) Close-up view

Figure 2.2: Achieved lunar trajectory

Chapter 3

Conclusion

As seen from the above, interplanetary orbit planning is a very difficult task, even if only targeting the closest celestial body. The proposed translunar injection, midcourse correction and lunar orbit insertion have the following magnitudes:

Table 3.1: Proposed ΔV budget for lunar transfer and orbit insertion

Maneuver	ΔV [$\mathrm{m\,s^{-1}}$]
Translunar Injection (TLI)	3130
Midcourse Correction (MCC)	700
Lunar Orbit Insertion (LOI)	580
Total ΔV (TOT)	4410

In comparison, Apollo 11's ΔV budget for the same set of maneuvers was [1]:

Table 3.2: Apollo 11 ΔV budget for lunar transfer and orbit insertion

Maneuver	ΔV [$\mathrm{m\,s^{-1}}$]
Translunar Injection (TLI)	3185
Midcourse Correction (MCC)	0
Lunar Orbit Insertion (LOI)	939
Total ΔV (TOT)	4124

From this it may be concluded that a further ΔV optimization of at least 286 $\mathrm{m\,s^{-1}}$ may be achieved. This may be done by achieving a better timing for the lunar gravity assist, which required too high of a midcourse correction.

All in all, it seems EOS and the `Nbody` class are indeed very suitable for facilitating a true-to-life n-body simulation of an interplanetary trajectory, in this case a lunar trajectory.

Bibliography

[1] NASA Houston Manned Spacecraft Center, Flight Planning Branch, Flight Crew Support Division. Apollo 11 Flight Plan. Technical Report AS-506/CSM-107/LM-5, Houston Manned Spacecraft Center, Houston, TX, Jul 1969.

[2] R. R. Bate, D. D. Mueller, and J. E. White. *Fundamentals of ASTRODYNAMICS*. Dover Publications, Inc., New York City, NY, 1971. ISBN 0-486-60061-0.

[3] J. S. Parker and R. L. Anderson. Low-Energy Lunar Trajectory Design. Technical report, Jet Propulsion Laboratory, Pasedena, CA, Jul 2013.