IAC-21-A3.2C.3

Enhancing Technologies and Operations for Service Transportation in Cislunar Environment

Andrea Colagrossi[a]*, Michèle Lavagna[a]

[a] *Department of Aerospace Science and Technology, Politecnico di Milano, Via La Masa, 34*, 20156, Milano - Italy
* Corresponding Author

Abstract

Future space exploration missions are intended to exploit cislunar environment as effective outpost to advance technology readiness in view of human presence beyond Earth. The forthcoming space projects entail modular large space infrastructures to be available in non-Keplerian orbits, in the Moon vicinity, to run manned and robotic activities. The realization of such a complex space system will require enhanced technologies and operations for the service transportation vehicles, which will be involved as cargo and Earth-Moon transfer spacecrafts. The paper discusses the peculiarities and the novelties of service missions in Cislunar space, compared to analogous service missions in Low-Earth Orbits (LEO). In fact, the operational orbit in the new space scenario is going to be a Near Rectilinear Halo Orbit (NRHO), which is dynamically distinct from any existing Keplerian trajectory. Thus, figures of merit of the future service missions are much different from the ones that are known from International Space Station (ISS) heritage. The discussion will be particularly focused on the proximity phases of service transportation missions, including the phasing with the target's staging orbit. Time and ΔV budgets will be presented and compared to those of LEO missions, such as Soyuz, ATV and Dragon. The terminal rendezvous phase will be described, highlighting the sequence of required operations to approach the Cislunar space station. A section of the paper will be analysing the undocking phase, with the subsequent departure from the target and its NRHO. This sequence of proximity operations is peculiar and somehow different from the approaching one, especially considering the natural Cislunar dynamics that may be leveraged to support the undocking and departure operations. The discussion is also considering the enabling technologies to support the proposed Cislunar operations. The service transportation system architecture and design are considered, discussing some preliminary requirements for the GNC and the Propulsion subsystems.

Keywords: Cislunar Space; NRHO; Service Transportation Mission; Phasing; Rendezvous; Undocking.

Acronyms/Abbreviations

Collision Avoidance Manoeuvres (CAM)
Guidance Navigation and Control (GNC)
International Space Station (ISS)
Low Earth Orbit (LEO)
Lunar Orbital Platform Gateway (LOP-G)
Near Rectilinear Halo Orbit (NRHO)
Rough Order of Magnitude (ROM)
Time of Flight (TOF)

1. Introduction

Cislunar space has a renewed interest in the space community, since it is the ideal location to host an advanced space outpost beyond Earth orbit: the Lunar Orbital Platform Gateway (LOP-G), proposed in the Global Exploration Roadmap by the International Space Exploration Coordination Group [1]. In fact, recent works suggested a Near Rectilinear Halo Orbit (NRHO), in the Earth-Moon Lagrangian Point 2 (L2), as ideal location to stage the human-robotic outpost [2]. This orbit guarantees a low pericenter over the lunar poles, favourable orbital stability, and eclipsing properties, as well as numerous transfer options to and from the Earth or the lunar surface.

The LOP-G project is based on a modular large space infrastructures to be continuously available in such a non-Keplerian NRHO in Moon vicinity. The purpose is to guarantee a stable human presence beyond Earth orbits, facilitate access and re-entry from the Moon surface and support advanced deep space mission and future space explorations. The realization of this complex space system will require enhanced technologies and operations for the service transportation vehicles, which will be involved as cargo and Earth-Moon transfer spacecrafts.

The LOP-G missions will exploit existing heritage of the International Space Station (ISS), but the operational scenario is dramatically different from the one existing in Low Earth Orbit (LEO). For instance, the dynamical regime existing along a NRHO will influence many figures of merit of the future service missions and operations. This is particularly true, for the proximity phases of service transportation missions, including the phasing with the target's staging orbit.

Space agencies and industries are working to design a proper service infrastructure to support the LOP-G assembly and maintenance, considering both cargo and refuelling capabilities [3]. Thus, versatility to cope with various gateway requirements, and large payload capacity are sought. In these regards, the European Space Agency proposed a Cislunar Transfer Vehicle (CLTV) to satisfy these technological and operational requests. Based on previous experience of ATV, Soyuz, Cygnus, Dragon, the system design must satisfy the evolved mission requirements and maximize the exploitation of the Cislunar space characteristics.

This paper discusses the peculiarities and the novelties of this kind of service missions in Cislunar space, compared to analogous one in LEO. The discussion is particularly focused on the proximity phases of service transportation missions, including the phasing with the target's staging orbit and the rendezvous with the LOP-G. A section of the paper analyses the undocking phase, with the subsequent departure from the target and its NRHO. This sequence of proximity operations is peculiar and somehow different from the approaching one, especially considering the natural Cislunar dynamics that may be leveraged to support the undocking and departure operations. Time and ΔV budgets are presented and compared to those of LEO missions, such as Soyuz, ATV and Dragon.

The service transportation system architecture and design are considered, discussing some preliminary requirements for the GNC and the Propulsion subsystems.

2. Cislunar Space

Cislunar space is the region of outer space lying between the Earth and the Moon. Its dynamics can be described exploiting a restricted n-body problem modelling approach, which considers a spacecraft, with mass m, under the influence of the Earth, with mass m_E, and the Moon, with mass m_M, assuming $m \ll m_E, m_M$. The perturbations of Cislunar space are mainly due to the presence of the Sun and to the real motion of Earth and Moon. Accurate investigation about Cislunar operations shall consider these perturbing effects [4]. Thus, the absolute and relative orbital and attitude dynamics in Cislunar space need to be modelled exploiting a Full Ephemeris Restricted 4-Body Problem (FER4BP) [5, 6].

Despite classic 3-body models provide a useful support to perform preliminary analyses, they shall be discarded whenever high-fidelity modelling is sought and the goal of the investigation is a practical application on system design. The weak points of the classic restricted 3-body models may be summarized as follows:

• null or constant eccentricity, which has an effect on the apocenter location [7];

• lack the Sun's gravity, which influences the inclination of the "line of orbit apses" [8].

2.1 Invariant Manifolds

Invariant manifolds are defined in dynamical system studies as a topological *n*-dimensional space that is invariant under the action of the dynamical system. Their theoretical description can be found in many literature sources [9], but their notable relevance in transportation mission studies is due to their exploitation as natural relative dynamics trajectories. Thus, they may be leveraged to accomplish free drift approaching or departing trajectories. Moreover, they also allow natural hovering/fly-around in proximity of a certain relative position with respect to a target. This is possible since NRHOs have stable, unstable, and centre manifolds, which guarantee the aforementioned natural relative dynamics trajectories. Fig. 1 reports examples of various natural invariant manifolds relative trajectories, with respect to a target flying on an example L2 NRHO, which is shown in Fig. 2.

Unstable and centre manifolds are applied to service transportation studies, since they respectively guarantee natural exponential motion away from the target, for passive safety, and motion along the same orbit, for hovering phases [4]. Stable manifolds are not applied for practical applications, since it will asymptotically approach the target, leading eventually to a collision in case of engine malfunction or misfiring.

Natural trajectories allow to reduce ΔV budget of cislunar operations by exploiting the natural stability properties of NRHOs.

3. Transfer and Phasing to NRHO

Service transportation missions to LOP-G shall run on convenient and versatile transfer trajectories to/from Earth orbits. In fact, considering many transfer strategies allow to increase the versatility of the whole system. Fast and costly direct transfer may be exploited for human

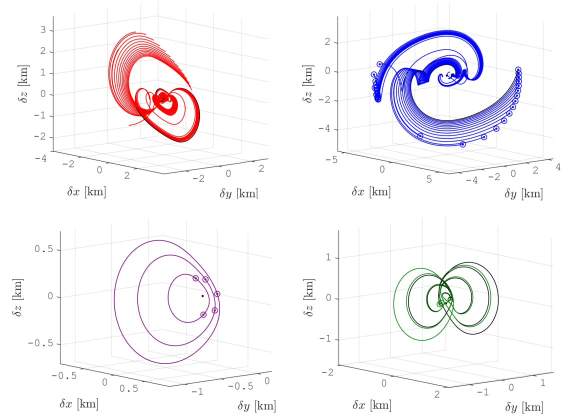

Figure 1: NRHO Invariant Manifolds Relative Dynamics (From top left, clockwise: unstable manifold - departure, stable manifold - approach, centre manifold - hovering, centre/periodic manifold - fly around).

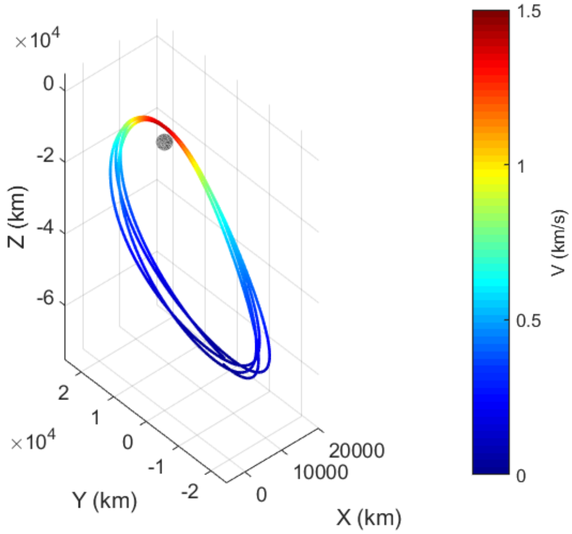

Figure 2: Earth-Moon L2 NRHO Example.

transportation, while slow and economic non-Keplerian trajectories may serve cargo and refuelling missions. To have a first estimation of time and cost involved, Tab.1 reports Rough Order of Magnitude (ROM) estimation for ΔV and Time of Flight (TOF) in different transfer alternatives from Earth to NRHO.

Table 1: ROM ΔV and TOF for Transfer Strategy Alternatives between Earth and NRHO.

Transfer Strategy	**ΔV [m/s]** **(ROM)**	**TOF [d]** **(ROM)**
Direct transfer	1000	5
Lunar gravity assist	600	10
Weak stability boundary	200	>100

As evident from Tab. 1, direct transfer allows very fast transfer but high ΔV, while the exploitation of lunar gravity assist can reduce transfer costs by increasing TOF of just few days. Weak stability boundary transfers have positive ΔV performances, but extremely long time is required. Moreover, they increase complexity of the system for the required navigation accuracy [10].

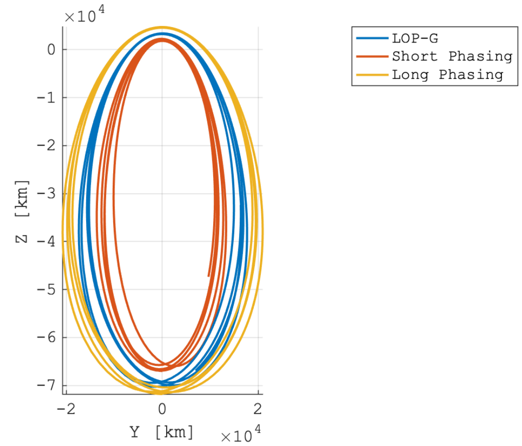

Figure 3: LOP-G, Short and Long Phasing Orbits.

Numerous transfer opportunities are another key point to improve the design of space transportation systems in cislunar environment. In fact, the availability of frequent launch windows is fundamental to have an effective service to the LOP-G. Then, a phasing orbit may be added to increase the number of launch opportunities. The phasing with the LOP-G can be included after the transfer phase, accounting for additional time on the overall transfer time.

Two different phasing orbits are analysed as possible scenario alternatives. The first has a period of 6 d, and it is referred as Short Phasing; the second has a period of 7 d, and it is referred as Long Phasing. This choice is motivated since the two phasing orbits have a period that is respectively shorter and longer than the LOP-G nominal orbit (~6.5d). The phasing orbits, and the gateway reference trajectory are shown in Fig. 3. Moreover, two different phasing strategy alternatives are studied:

- phasing with a time constraint, with TOF shorter than 14 d;
- phasing with no time constraint.

Table 2: ROM ΔV and TOF for Phasing Strategy Alternatives.

Phasing Strategy	**ΔV [m/s]** **(ROM)**	**TOF [d]** **(ROM)**
Constrained Time	100	5
Unconstrained Time	35	25

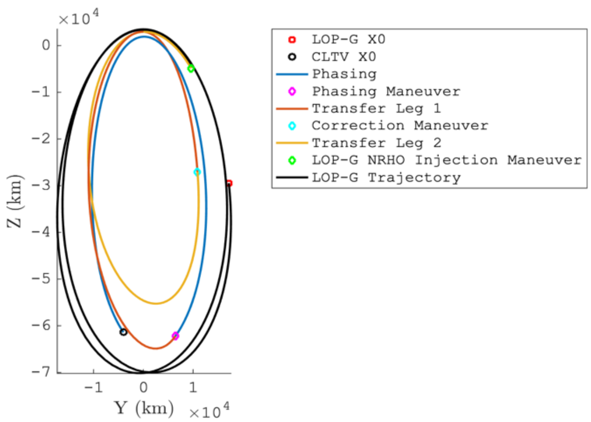

Figure 4: Example NRHO Phasing Solution.

NRHO phasing could require a time between 5d and 25d. The typical Δv for the transfer to the final NRHO is in the order of ~ 30 - 100 m/s. The phasing NRHO can be selected optimizing the Δv for the overall transfer cost to the target NRHO, and it is concluded with the injection in the LOP-G NRHO, which should be performed at ~100 km from the LOP-G; after this point, rendezvous phase with relative GNC takes place. Tab. 2 resumes the ROM estimates for the phasing budget, while Fig. 4 shows an example phasing solution.

4. Rendezvous with LOP-G

Rendezvous operations with the LOP-G can be designed exploiting at maximum the dynamical regime existing in Cislunar space, as proposed in previous works of the authors [4, 5]. The rendezvous phases are divided in many holding points, as from the ISS experience. The location of these points is being selected according to the stability features of the invariant manifolds. In this way, as discussed in the previous section, the natural relative dynamics is leveraged to improve the rendezvous performance.

The rendezvous phase begins at the first holding point, S1, which can be situated approximately 100 km away from the LOP-G in the negative along-track direction. S1 lies on the central manifold of the NRHO. This allows, in case of misfiring or no firing at all, remaining at about ~100 km from the LOP-G, without getting in proximity, to have subsequent opportunities to perform the transfer or to perform abort/contingency manoeuvres. The central manifold selection for holding points location is applied in the entire far-range rendezvous phase, i.e., outside the 2 km approach sphere. On the other hand, getting in proximity of the LOP-G, passive safety is more relevant than natural hovering characteristic. Thus, close-range rendezvous holding points are designed on the unstable manifold. In this way, if the manoeuvres to approach/depart the passively safe holding points are not performed, or misfired, the service transportation system will start safely drifting away from the LOP-G.

The entire rendezvous phase shall occur in the apocenter location of the NRHO. Nominally, in a time window of 5 days (i.e. ±2.5 d) around the apocenter crossing epoch. The pericenter location is characterized by fast dynamics, potentially disturbing the marginally stable motion on the NRHO. Thus, it is not suitable to execute rendezvous and proximity operations.

Rendezvous manoeuvres can be computed as open-loop impulsive operations, or as continuous thrust closed-loop ones. The service transportation system shall be capable autonomously handle the previously described proximity operations. Moreover, it must also compute and perform active safety Collision Avoidance Manoeuvres (CAM) to minimize any residual risk of collision with the LOP-G.

4.1 Example Rendezvous Solution

An example rendezvous solution is discussed in this section to highlight the sequence of required operations to approach the Cislunar gateway. A rendezvous phase starting at 100 km from the target and divided in 5 holding points is considered. As said, natural hovering is guaranteed at far-range, while passive safety is enforced on the close-range holding points. Fig. 5 and Fig. 6 show the example rendezvous trajectories, while Tab. 3 reports the summary of time and ΔV budgets for the proposed solution.

Table 3: ΔV and TOF for Rendezvous Example Solution.

Rendezvous Phase	**ΔV [m/s]**	**TOF [h]**
Far Range (100-2 km)	6.59	13
Close Range (2-0 km)	1.36	6
Total	**7.95**	**19**

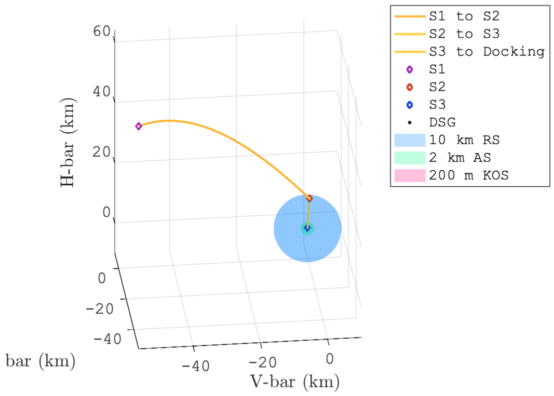

Figure 5: Example Rendezvous Far-range Trajectories.

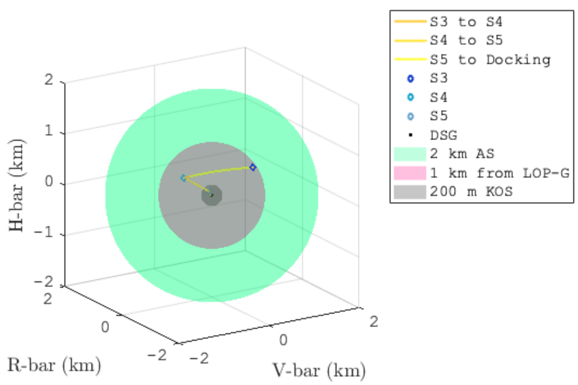

Figure 6: Example Rendezvous Close-range Trajectories.

5. Undocking and NRHO Departure

Service transportation missions will be frequently operated with transfers between Earth and NRHO and between Moon and NRHO. Thus, not only autonomous rendezvous and docking is required to the transportation system, but also autonomous undocking and NRHO departure capabilities may be implemented. In this way, cycler autonomous missions may be realized.

Natural dynamics can be exploited also in this phase, by using departure properties of the unstable NRHO manifold. The injection of the service transportation system in the unstable manifold state guarantees free departure from the NRHO, with minimal ΔV budget to undock and reach the manifold insertion location, which can be targeted by a forced straight line translation manoeuvre. Then, an exponential free drift away from the LOP-G guarantees to reach a safe location (e.g. ~3 km) in 2 NRHO orbital periods (e.g. ~ 15 days). Fig. 7 and Tab. 4 show the natural NRHO departure trajectory and summarize the figures of merit for this phase.

Table 4: ΔV and TOF for Undocking and NRHO Departure Example Solution

Departure Phase	ΔV [m/s]	TOF [h]
Undocking (0 - 0.2 km)	0.03	3
NRHO Departure (0.2 - 3 km)	0	360 (~15 d)

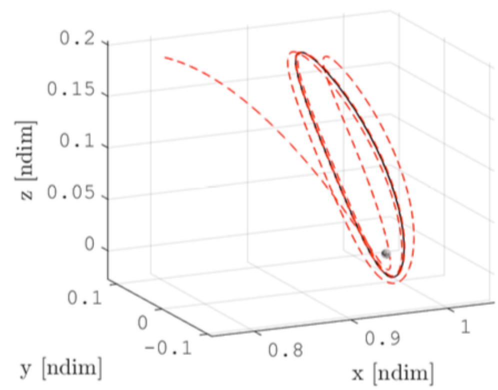

Figure 7: Example NRHO Free Departure Trajectory.

6. Service Transportation System

Service transportation system design is going to be characterised with the peculiarities of Cislunar space, especially when compared with existing systems operating LEO. In fact, figures of merit of typical ISS/LEO service transportation missions (e.g. ATV, Progress, Dragon, Cygnus) are much different from those needed for future cislunar service transportation missions. As highlighted in the previous sections, transfer, phasing and rendezvous with the LOP-G on NRHO, are characterized by longer TOFs and smaller ΔVs. In particular, the elemental manoeuvring ΔV bits are much smaller than in LEO, being much lower than 1 m/s.

The dynamical environment governing the motion is completely different, leading to different on-board functions, with the requirement to store Earth, Moon and Sun ephemerides data as Chebyshev polynomials or time-based look-up tables. In addition, the system is required to handle non-linear dynamical models and have the on-board manifold computation capability, for autonomous mission re-planning.

The manoeuvres need to be computed both as open-loop and closed-loop, where the models' knowledge is fundamental for their correct execution. In these regards, the propulsion shall cope with the small impulse bits, while guaranteeing high thrust for large control authority required by the CAM execution. Moreover, the manifold insertion requires high accuracy, and the error budget cannot be all spent on the actuation side.

Finally, operations have different time scales compared with the one for ISS service missions. This has an impact also on the ground segment with longer operation shifts and continuous communication coverage duties.

7. Conclusion

The Cislunar gateway, or Lunar Orbital Platform – Gateway (LOP-G), will be a complex infrastructure to be assembled, maintained, and refuelled on-orbit. The staging orbit will be a Near Rectilinear Halo Orbit (NRHO), which is a non-Keplerian multi-body orbit, existing in the vicinity on the Moon, belonging to the Lagrangian Point L2 of the Earth-Moon system. This detail will strongly influence the dynamical environment where the operations supporting the Cislunar gateway will occur. Hence, the service transportation missions that will operate in this framework need to be designed accordingly, in terms of operations and technologies.

Transfer and phasing to NRHO shall be investigated and analysed to guarantee many launch alternative strategies over several launch windows. Similarly, the proximity operations shall be designed exploiting the positive features offered by non-Keplerian dynamics, such as the invariant manifold trajectories. Dedicated strategies for undocking and NRHO departure shall be foreseen for autonomous Earth re-entry or to enable cycler service transportation systems between Earth, Moon and NRHO. The system design is analogously affected; in particular, GNC and propulsion subsystems requirements shall be tailored in accordance with the Cislunar features and peculiarities.

Acknowledgements

The authors want to acknowledge Thales Alenia Space – France and Thales Alenia Space – Italy for their fruitful collaboration along the Cis-Lunar Transfer Vehicle (CLTV) – Phase A/B1 study, which was financed under an ESA contract issued with the invitation to tender AO10413. Special thanks are owed to Nicolas Thiry, Davide Casu and Sébastien Herbiniere for their positive collaboration during the project.

References

[1] International Space Exploration Coordination Group. (ISECG), The Global Exploration Roadmap, Tech. rep., ISECG, 2018.

[2] R. Whitley, R. Martinez, Options for staging orbits in cislunar space, in: 2016 IEEE Aerospace Conference, Big Sky, Montana, USA, 5–12 March, 2016, pp. 1–9.

[3] A. Carlson. The Logistics Development of a cis-Lunar Transfer Vehicle, in: AIAA SPACE 2011 Conference & Exposition, 2011.

[4] A. Colagrossi, V. Pesce, L. Bucci et al., Guidance, navigation and control for 6DOF rendezvous in Cislunar multi-body environment, Aerospace Science and Technology 114, 106751, 2021.

[5] A. Colagrossi, M. Lavagna, Cislunar non-keplerian orbits rendezvous & docking: 6DOF guidance and control, in: 69th International Astronautical Congress, Bremen, Germany 1-5 October, 2018, pp. 1–18, 2018.

[6] A. Colagrossi, M. Lavagna, Preliminary results on the dynamics of large and flexible space structures in Halo orbits, Acta Astronaut. 134, pp. 355–367, 2017.

[7] L. Bucci, M. Lavagna, R. Jehn, et al., Station keeping techniques for near rectilinear orbits in the Earth-Moon system, in: 10th International ESA Conference on Guidance, Navigation & Control Systems (GNC 2017), Salzburg, Austria, 29 May-2 June, 2017, pp. 1–17, 2017.

[8] D. Guzzetti, E.M. Zimovan, K.C. Howell, D.C. Davis, Stationkeeping analysis for spacecraft in lunar near rectilinear halo orbits, in: 27th AAS/AIAA Space Flight Mechanics Meeting, San Antonio, Texas, USA, 5–9 February, 2017, pp. 1–24, 2017.

[9] V. Szebehely, Theory of Orbits: The Restricted Problem of Three Bodies, Academic Press inc., New York, 1967.

[10] E.A. Belbruno, J.P. Carrico, Calculations of weak stability boundary ballistic lunar transfer trajectories, in: AAS/AIAA Astrodynamics Specialist Conference, Denver, Colorado, USA, 14-17 August, 2000.