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A. Colagrossi, M. Lavagna
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Rendezvous in Lunar Near Rectilinear Halo Orbits

Lorenzo Bucci[1]*, Andrea Colagrossi[1], Michèle Lavagna[1]

[1] *Department of Aerospace Science and Technology, Politecnico di Milano, via La Masa 34, 20156 Milano, Italy.*
lorenzo.bucci@polimi.it, andrea.colagrossi@polimi.it, michelle.lavagna@polimi.it
* Corresponding Author

Abstract

Near Rectilinear Halo Orbits (NRHO) have been recently identified as suitable location for a cislunar space station, to orbit in the Earth Moon vicinity and offer long term infrastructural services to manned and unmanned missions to the Moon and further. Indeed, to reliably perform rendezvous and docking/undocking phases between space vehicles orbiting on highly non-Keplerian orbits, such as NRHOs, represents a fundamental key technology. Rendezvous is well-known for Earth centred missions, while no mission ever performed it on non-Keplerian orbits. The paper critically discusses the adopted approach and the obtained results in modelling the non-Keplerian relative dynamics and in synthetizing the guidance, to safely rendezvous and dock on NRHOs. The entire study is strongly driven by engineering constraints and mission requirements which lead the practical implementation. The dynamics intrinsic non-linearity - which makes the trajectories highly sensitive to small deviations - is here exploited to benefit both rendezvous operations and safety. The paper shows the relative trajectories, designed in a way that both NRHO central and unstable manifolds are used: the former to ensure the chaser relative orbit to be periodic with respect to the target, the latter to answer the passive safety philosophy here preferred. In fact, chaser deviation from target is naturally obtained, whenever on an unstable direction. Along the approaching trajectory, 2 holding points are assumed: on the central manifold the farthest, at about 100 km from the target, to prepare for the final approach; if a no-go is commanded, the spacecraft hovers on the central manifold, waiting for the next approach opportunity. The closest holding point is designed to lay on the unstable manifold direction, to privilege risk mitigation through passive safety, since if no active control occurs, the chaser - now just meters away from the target - naturally drifts away. The relative trajectory and approach strategy design, driven by the guidance and mission operations definition in nominal and non-nominal scenarios, is discussed in the paper: the simulations and the analyses that led to the approach corridor shape, Keep-Out Zones (KOZ) radius and Collision Avoidance Manoeuvres (CAM) settling are here reported. The practical case of the cislunar space gateway servicing is here exploited to present the proposed rendezvous and approach techniques for non-Keplerian scenarios and to highlight the GRANO software tool – developed by the authors at Politecnico di Milano, ASTRA Team – flexibility for general application in the n-body framework.

Keywords: Rendezvous; Near Rectilinear Halo Orbits; Passive Safety; Cislunar Space Gateway

Acronyms/Abbreviations

- Near Rectilinear Halo Orbits (NRHO)
- Rendezvous (RDV)
- Keep-Out Zones (KOZ)
- Collision Avoidance Manoeuvres (CAM)
- State Transition Matrix (STM)

1. Introduction

The problem of rendezvous in non-Keplerian orbit is a recent topic in space systems engineering and astrodynamics. Future exploration missions are devised by many space Agencies, and international collaboration is fostered for new space stations and infrastructures, under the common framework of non-Keplerian orbits in lunar environment. Recently, Near Rectilinear Halo Orbits (NRHO) have been proposed by NASA for placing the Lunar Orbital Platform-Gateway (LOP-G), and such orbits have been thoroughly investigated in international literature.

The paper aims at providing a solid, analytical background for rendezvous and docking aspects in such novel environment, employing the NRHO as working example and case study, although underlining the generality of the results. First, the formulation of the equations of relative motion is analysed, comparing different models and finding their respective ranges of applicability. Then, the results are applied in a case study of a vehicle that performs rendezvous in NRHO, investigating as well, the effect of reduced, linearised models in the guidance definition. The spectral decomposition of the State Transition Matrix (STM) is employed, since the space of the eigenvectors defines the ranges of exponential decays or increase of the relative motion, deriving from the first-order variational equations; the correct targeting of the central eigenvector of such space enables trajectories that are intrinsically safe, where no corrective action is needed. The study is concluded with a recollection of the main results and recommendations for future works on the topic.

2. NRHO Absolute and Relative Dynamics

NRHO dynamics is dependent from the cislunar environment main characteristics:

- Gravitational pull of the Earth and the Moon;
- Motion of the Earth and the Moon around their common barycentre;
- Presence of the Sun in terms of 4-th body gravitation and radiation pressure.

The non-linear formulation of the NRHO absolute dynamics is here conveniently expressed in the inertial reference frame. Considering the 6DOF dynamics the equations of motion along a NRHO are:

$$\begin{aligned} a_x &= -\frac{(1-\mu)(x-x_E)}{r_{B_E}^3} - \frac{\mu(x-x_M)}{r_{B_M}^3} + a_{Sun_x} + a_{SRP_x} \\ a_y &= -\frac{(1-\mu)(y-y_E)}{r_{B_E}^3} - \frac{\mu(y-y_M)}{r_{B_M}^3} + a_{Sun_y} + a_{SRP_y} \\ a_z &= -\frac{(1-\mu)(z-z_E)}{r_{B_E}^3} - \frac{\mu(z-z_M)}{r_{B_M}^3} + a_{Sun_z} + a_{SRP_z} \end{aligned} \quad [1]$$

$$\begin{aligned} \dot{\omega}_1 &= \frac{I_3-I_2}{I_1}\left(\frac{3(1-\mu)}{r_{B_E}^5} l_2 l_3 + \frac{3\mu}{r_{B_M}^5} h_2 h_3 - \omega_2\omega_3\right) + \alpha_{Sun_1} + \alpha_{SRP_1} \\ \dot{\omega}_2 &= \frac{I_1-I_3}{I_2}\left(\frac{3(1-\mu)}{r_{B_E}^5} l_1 l_3 + \frac{3\mu}{r_{B_M}^5} h_1 h_3 - \omega_1\omega_3\right) + \alpha_{Sun_2} + \alpha_{SRP_2} \\ \dot{\omega}_3 &= \frac{I_2-I_1}{I_3}\left(\frac{3(1-\mu)}{r_{B_E}^5} l_1 l_2 + \frac{3\mu}{r_{B_M}^5} h_1 h_2 - \omega_1\omega_2\right) + \alpha_{Sun_3} + \alpha_{SRP_3} \end{aligned} \quad [2]$$

where $\mu = \frac{m_M}{m_M + m_E}$ is the 3-body gravitational parameter because the equations are in non-dimensional form. For a complete definition of the non-dimensionalisation process and of all the other quantities in equations 1 and 2, the reader can refer to [1, 7]. The kinematics equations are omitted (for conciseness) and consist of the well-known integration of dynamics equations.

This model is used with full non-linear formulation of EoM using numerical integration. The positions of the celestial bodies are in fact obtained with numerical ephemerides models available from the NASA/SPICE tool.

The translation equation 1 can be conveniently expressed also in the synodic reference frame. In this case, the position of the Earth and the Moon are fixed along the x-axis of the synodic frame and their relative distance is varying because of the eccentricity of their orbits. However, the non-inertial terms due to the rotation of the synodic reference must be added, i.e. the centrifugal and Coriolis apparent accelerations.

The attitude equations are characterized by the presence of the gravity-gradient torque of the two primaries and of the Sun. NRHO absolute attitude dynamics is particularly affected by this contribution, in particular at the perilune of the NRHO [1, 2].

The non-linear formulation of the NRHO relative dynamics can be simply obtained from the absolute dynamics previously described in inertial reference frame. In fact, the relative translational dynamics is simply obtained as:

$$\delta\ddot{r} = \ddot{r} - \ddot{r}_T \quad [3]$$

where $\ddot{r} = [a_x, a_y, a_z]$ is the chaser absolute acceleration and $\ddot{r}_T = [a_{x_T}, a_{y_T}, a_{z_T}]$ is the target – or reference – absolute acceleration.

The relative attitude dynamics (for berthing or docking) is obtained from the relative quaternion kinematics as:

$$\delta q = q \times q^{-1} \quad [4]$$

and from the relative angular acceleration expressed in the frame of the chaser as:

$$\delta\dot{\omega} = \dot{\omega} - \mathrm{A}(q)\dot{\omega}_T \quad [5]$$

where A is the relative direction cosine matrix from the target body frame to the chaser body frame, respectively.

The relative dynamics in eq. [3] can be linearised if the relative distance between target and chaser is small compared to the distance of the target from the primaries. Namely, from the simulations available, a relative distance below 100 km is fully acceptable to linearize the NRHO relative dynamics.

Using now a different notation, where $\delta r = x$ for simplicity's sake, the linearised relative dynamics in inertial frame is:

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \ddot{\boldsymbol{x}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I_3} \\ {}^{I}\boldsymbol{\Xi}(t) & \mathbf{0} \end{bmatrix} \begin{bmatrix} \boldsymbol{x} \\ \dot{\boldsymbol{x}} \end{bmatrix} \quad [6]$$

$$\begin{aligned} {}^{I}\boldsymbol{\Xi}(t) &= \left\{-(c_1(t)+c_2(t))\,\mathbf{I_3} + 3\,c_1(t)\,[\boldsymbol{e}_{1L}(t)\,\boldsymbol{e}_{1L}(t)^{\mathsf{T}}] + 3\,c_2(t)\,[\boldsymbol{e}_{2L}(t)\,\boldsymbol{e}_{2L}(t)^{\mathsf{T}}]\right\} + T_{Sun} \\ c_1(t) &= \mu_1 ||\boldsymbol{r}_{1L}(t)||^{-3} \\ c_2(t) &= \mu_2 ||\boldsymbol{r}_{2L}(t)||^{-3} \end{aligned}$$

where all the terms are introduced and explained in [3].

In synodic frame, the previous equation is modified taking into account the presence of the non-inertial terms:

$$\begin{bmatrix} {}^{R}\dot{\boldsymbol{x}} \\ {}^{R}\ddot{\boldsymbol{x}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \mathbf{I_3} \\ \{{}^{R}\boldsymbol{\Xi}(t) + [\dot{n}\times] - [n\times][n\times]\} & -2\,[n\times] \end{bmatrix} \begin{bmatrix} {}^{R}\boldsymbol{x} \\ {}^{R}\dot{\boldsymbol{x}} \end{bmatrix} \quad [7]$$

where $[n\ \mathrm{x}]$ is the cross-product matrix composed with the angular velocity components of the synodic frame. All the other quantities are now expressed in the synodic reference frame.

The relative attitude dynamics can be linearised if the relative attitude rates and the relative attitude difference are small. The linearization process is standard, and it is not reported here for conciseness.

Relative dynamics in NRHO can be analysed using different formulations and they can be compared to understand the level of accuracy of the approximated models. In fact, it is possible to study the relative dynamics between the chaser and the target with the Ephemerides restricted 4-body model (EpR4B) or the Circular restricted 4-body model (CR4B).

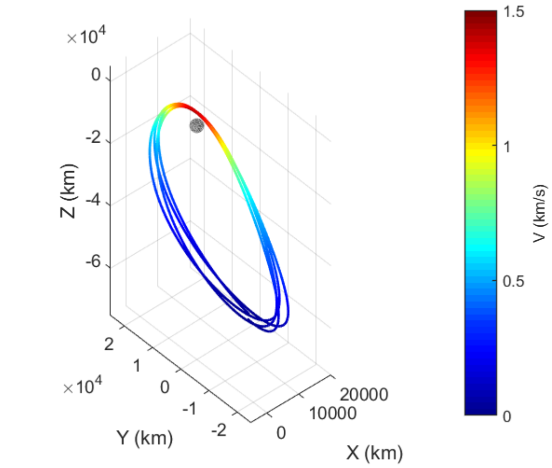

Figure ***Error! No text of specified style in document.****1: NRHO trajectory and velocity.*

CR4BP is a valuable model for preliminary analysis of non-Keplerian orbits. Nevertheless, the very peculiar regime of NRHOs, in the Earth-Moon system, requires that the true non-linear motion of the Earth and the Moon is taken into account, since their relative eccentricity is not negligible in dictating the force field that maintains the periodicity of the NRHO. Furthermore, the gravity of the Sun plays a non-negligible role as well; in fact, the periodic oscillations of the NRHO due to the Sun's gravitational pull are missed out in a CR3BP model [6].

For what concerns relative dynamics, even in the short period, the non-linear, non-analytic ephemerides 4-body model is the model to correctly represent the peculiar regime of NRHOs, in particular at the apocenter of the orbits, as reported in Figure 2. The relative dynamics approximation analysis has been performed for different NRHO families in the Earth-Moon system (e.g. L1 South NRHO, L2 North NRHO, etc.) and the outcomes are similar in all the cases.

As a final remark, the circular restricted models do not provide generally valid approximations of the relative dynamics on NRHOs in the Earth-Moon system.

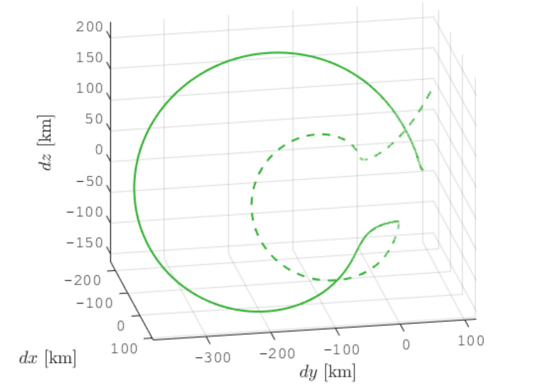

Figure 2: NRHO relative dynamics from apocenter: ephemerides 4-body (solid) and circular 4-body (dashed).

3. Rendezvous Applications in NRHO

An example rendezvous application in NRHO is shown here, assuming to begin the scenario after orbit phasing and far (>1000 km) approach. The chaser begins the rendezvous mission at the first holding point, HP1, situated 100 km away from the target, along the negative along-track direction. The shown example rendezvous mission has been completely designed with the GRANO software tool developed by the authors at Politecnico di Milano, ASTRA Team.

3.1 Rendezvous transfer

A two-impulse transfer composes the first phase from HP1 (100 km to target) to HP2 (1km to target). The following constraints hold:

- The time of flight shall be long enough to allow state determination and stabilisation of errors induced by manoeuvres;
- Passive safety shall be ensured by verifying the effect of a missed burn (especially the braking/stop manoeuvre).

Thus, the whole phase set is sized such that:

- The departure point (HP1 – purple dot in the following figures) 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 target, without getting in proximity, in order to have subsequent opportunities to perform the transfer or to perform abort/contingency manoeuvres.
- The arrival point (HP2 – red dot in the following figures) lies on the unstable manifold of the NRHO. With this strategy, if the second burn is not performed, or misfired, the chaser will safely start drifting away from the target.

The overall rendezvous trajectory is optimised to minimise the total ΔV. It is remarked that, since the manifolds of the NRHO change in time, the rendezvous analysis is strictly coupled with a related phasing trajectory analysis [5, 8, 9] (not discussed in this paper). In fact, the design of the phasing shall target HP1, which in turn is settled driven by the rendezvous design. In accordance with previous and recent works [4, 5, 8], the global rendezvous phase shall take place in arc of ±100 degrees of mean anomaly around the aposelene, setting thus a boundary for the position of HP1. The duration of the free drift transfer between HP1 and HP2 comes as output from the total ΔV minimization, and it is equal to 20h. The associated total ΔV is equal to 2.8 m/s. The related trajectory is shown in Figure 3.

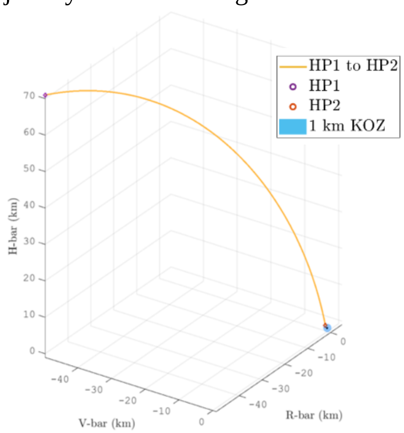

Figure 3: Relative dynamics during rendezvous in LVLH frame.

The rendezvous trajectory - yellow line in Figure 3 - starts at HP1 before the NRHO apocenter, purple circle, and is symmetric with respect to the Earth-Moon axis and ends at HP2, red circle. The chaser is approaching the target from the negative V-bar, with a free drift motion in the 3-dimensional LVLH space. This picture is relevant to understand the relative distance between chaser and target during rendezvous phase.

3.2 Passive safety

The HP2 holding point selection is driven by the preferred strategy for passive safety: the HP2 setting on the NRHO unstable manifold ensures that if the burn to stop at HP2 is not performed, or misfired, the chaser will start safely drifting away from the target.

Figure 4 depicts the resulting trajectories if a misfiring happens in HP2, if placed on the unstable manifold:

- If no braking burn occurs, the chaser will safely go away without getting closer to the target;
- If the departure burn is not performed, the chaser will slowly spiral away from the target.

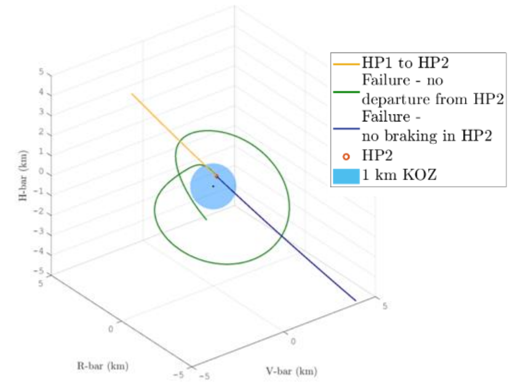

Figure 4: Passive safety in HP2.

Note that the latter condition allows not only avoiding a close proximity of the chaser to the target, but also having a subsequent chance to perform again the rendezvous transfer. In fact, the unstable manifold guarantees a safe drift away, but the time scale is slow enough to allow recovery.

The offset position of HP2 with respect to the pure V-bar holding point is defined through the unstable manifold selection, but it is also constrained by any additional requirement imposed on the approach corridor for the final approach.

3.3 Active safety

Contingency operations can be managed exploiting an active safety enforcement and, in particular, Collision Avoidance Manoeuvres (CAM) are planned to have the chaser without any residual collision risk with the target when a problem occurs. Collision avoidance manoeuvres are to be intended in addition to nominal passive safety enforcement at all time of the rendezvous and docking/berthing operations. However, if a non-nominal condition occurs, the safety of the mission can be actively guaranteed at all time: collision avoidance trajectories are computed to avoid any possibility of collision between the chaser and the target. In these cases, the chaser after the CAM execution is retreated to HP1. Typically, a CAM executed in proximity of HP2 requires a ΔV in the order of 8.5 m/s and a time of flight of 6h.

4. Conclusions

The study presented an operational scenario of rendezvous in NRHO, highlighting the drivers that led to the choices in terms of manoeuvre placement, holding points location, and approach direction. Safety of the trajectory is ensured both in a passive way, designing the holding points to be along given manifolds of the NRHO, and in an active way, inserting CAMs when in close proximity of the target. The analytical study, prior to the scenario definition, highlighted ranges of validity of reduced order models, although concluding that, for the peculiar NRHO regime, such models do not satisfy the requirements, even though coarse, of preliminary analysis and mission design.

The proposed design guidelines are valid, through general extension, for any class of non-Keplerian orbits, provided that the validation of the relative motion formulation is performed, with the proposed models and techniques, for the specific operational orbit family. Future studies are thus suggested to be devoted to the extension of these results to different class of lunar orbits, recently investigated for exploration missions (Distant Retrograde Orbits, Lyapunov Orbits, etc.), in order to define a general framework that includes common points and remarks the dynamical differences.

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