ROSSONERO: A TOOL FOR PRELIMINARY RENDEZVOUS MISSION DESIGN IN THE RESTRICTED THREE-BODY PROBLEM

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ABSTRACT

ROSSONERO (Rendezvous Operations Simulation Software on Near Rectilinear Orbit) is a realistic simulation tool developed in MATLAB/Simulink for preliminary design of rendezvous/docking/berthing maneuvers between two spacecraft in three-body problem scenarios, with particular focus on the Earth-Moon system and development of a space station in cis-lunar space. The peculiarity of the lunar environment, and the critical aspects of the rendezvous operations require the availability of dedicated predictive simulation tools, for dynamics and control analysis as well as overall mission assessment. ROSSONERO is based on a complete set of 6-DOF relative motion equations expressed in the *local-vertical local-horizon* (LVLH) frame and under *elliptic restricted three-body problem* (ER3BP) hypothesis. A graphical user interface allows the user to set up the simulation, define the mission and simulate the mission execution, as well as analyze and plot the results. In this paper, we present the tool structure and we show its effectiveness by showing the results for two examples of rendezvous mission in lunar orbit.

***Index Terms*—** Relative Dynamics, Rendezvous Operations, Three-Body Problem, Earth-Moon System.

1. INTRODUCTION

The current international cooperation scenario for robotic and human space exploration is focusing on mission architectures that revolve around building and exploiting a crew-tended cis-lunar space station, known as *Lunar Orbital Platform-Gateway* (LOPG). Candidate orbits for this station are the family of *near rectilinear halo orbit* (NRHO). Therefore, the capability to inject in NRHO and to perform rendezvous and docking or berthing maneuvers with a station in NRHO is key to many future exploration missions.

The aim of ROSSONERO (Rendezvous Operations Simulation Software on Near Rectilinear Orbit) is to provide a tool for preliminary design and assessment of rendezvous trajectories in NRHO and, more in general, in a restricted three-body problem scenario. ROSSONERO was developed under ESA/EXPRO contract, and it serves also as support to the proposed HERACLES mission. In fact, ESA is working with the Canadian and Japanese space agencies to prepare the HERACLES robotic mission to the Moon in the mid-to-late-2020s. Using the LOPG as a halfway point, a robotic rover will scout the terrain in preparation for the future arrival of astronauts, and deliver lunar samples to Earth. More specifically, A small lander with a rover inside weighing around $1800\,\mathrm{kg}$ in total will land and will be monitored by astronauts from the space gateway. An ascent module will take off from the surface and return to the gateway with samples taken by the rover. When the ascent module carrying the sample container arrives, the gateway's robotic arm will capture and berth it with the outpost's airlock for unpacking and transfer of the container to Orion and subsequent flight to Earth with returning astronauts. Hence, rendezvous operations will be a critical point of the mission and ROSSONERO can help in the preliminary evaluation of rendezvous trajectories and maneuvers planning.

The tool is developed in MATLAB/Simulink environment and the dynamic behavior is based on the equations of relative motion proposed in [1]. Unlike other sets of equations proposed in the past for relative motion in the restricted three-body problem, the equations describe the dynamics of chaser spacecraft with respect to a target in the LVLH, a local frame centered on the target generally adopted for rendezvous analysis [2]. Rotational dynamics was added, based on [3] to perform a complete 6-DOF dynamic motion analysis.

A general rendezvous mission description consists of the definition of a set of waypoints or *hold points* in the LVLH, that the chaser must reach during its approach to the target. The number and location of the waypoints is selectable by the user, and provides the opportunity of removing position and attitude errors, changing sensor suite, and thrust profiles. Two types of maneuvers can be used for transferring from a waypoint to the next one: impulsive or continuous. Maneuver computation is performed by propagation of translational lin-

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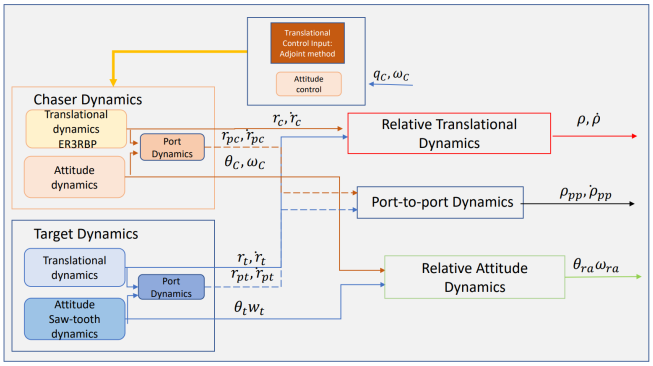
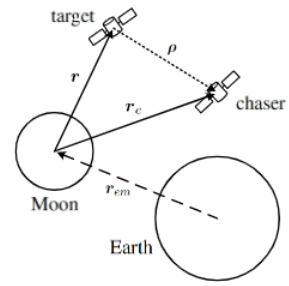
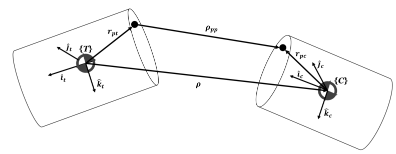


Fig. 1: Dynamics simulation flow chart.



(a) Spacecraft in the three-body system.



(b) Port-to-port vector.

Fig. 2: Target and chaser relative dynamics geometry.

earized equations of relative motion by means of the *adjoint method theory* as shown in [4, 5]. In these references, the use of two different sets of equations was analyzed, obtained by linearizing the exact relative dynamics and using two different assumptions for the primary body motion: elliptical and circular. The tool gives the user the option to choose between these two sets for maneuver computation at each transfer arc. Overall mission analysis is then performed by means of key performance indexes such as maneuver execution error and propellant consumption.

The paper is organized as follows: Section 2 presents a brief overview on the different equations set used for translational and rotational dynamics simulation, Section 3 discuss the tool structure and main components, Section 4 provides two examples of rendezvous mission executed with ROSSONERO, Section 5 concludes the paper with final remarks and current activities aimed at improving the tool.

2. ROSSONERO EQUATIONS OF MOTION FOR RELATIVE DYNAMICS SIMULATION

A brief discussion about the equation set for dynamics simulation is provided in this section. For further reference the reader can refer to [1] and [4] where a more detailed discussion about the relative dynamics in the general three-body problem is provided.

2.1. Translational and Rotational Dynamics

The simulation structure is described graphically in Figure 1. The translational and rotational dynamics is first simulated, and the results are then used for propagating the relative dynamics.

The target is considered as an autonomous system following a prescribed orbit and with attitude that oscillates around the LVLH frame with a saw tooth profile of maximum amplitude of $1\,\text{deg}$ as, for instance, in [3].

The chaser, is moving under ER3BP dynamics. In ROSSONERO the Earth-Moon system is considered. Its attitude dynamics with respect to the LVLH frame is driven by the standard kinematics and dynamic equations expressed in the chaser body frame [6]:

$$\dot{\boldsymbol{q}}_{c/l} = \frac{1}{2}\begin{bmatrix} 0 & -\boldsymbol{\omega}_{c/l}^T \\ \boldsymbol{\omega}_{c/l} & -[\boldsymbol{\omega}_{c/l}]^\times \end{bmatrix} \boldsymbol{q}_{c/l}$$

$$\mathbb{I}_c\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \mathbb{I}_c\boldsymbol{\omega} = \boldsymbol{N}$$

where $\boldsymbol{q}_{c/l}$ and $\boldsymbol{\omega}_{c/l}$ denote the quaternion describing the chaser attitude and its angular velocity with respect to the LVLH frame, $\mathbb{I}_c$ is the chaser rotational inertia, and $\boldsymbol{N}$ represents the torques applied on the chaser.

The relative attitude $\boldsymbol{q}_{t/c}$ and angular velocity $\boldsymbol{\omega}_{t/c}$ of the target with respect to the chaser are then computed as follows [7]:

$$\boldsymbol{q}_{t/c} = \boldsymbol{q}^*_{c/l} \otimes \mathbf{q}_{t/l}, \quad \boldsymbol{\omega}_{t/c} = \boldsymbol{\omega}_{c/l} - \boldsymbol{R}_{cl}(\mathbf{q}_{c/l})\boldsymbol{\omega}_{t/l}$$

where the operator $\otimes$ and the superscript $*$ denote the quaternions product and the conjugate operation, respectively, $\mathbf{q}_{t/l}$ and $\boldsymbol{\omega}_{t/l}$ are the target attitude and angular with respect to the LVLH frame, and $\boldsymbol{R}_{cl}(\mathbf{q}_{c/l})$ represents the rotation matrix between the LVLH frame and the chaser body frame.

All the quantities are normalized during the simulation in improve the numerical conditioning.

The relative translational dynamics is instead given by the following equation [1, 4]:

$$\begin{aligned}\left[\ddot{\boldsymbol{\rho}}\right]_{\mathcal{L}} = &-2[\boldsymbol{\omega}_{l/i}]^\times\left[\dot{\boldsymbol{\rho}}\right]_{\mathcal{L}} - \left(\left[\dot{\boldsymbol{\omega}}_{l/i}\right]^\times_{\mathcal{L}} + ([\boldsymbol{\omega}_{l/i}]^\times)^2\right)\boldsymbol{\rho} \\ &+ \mu\left(\frac{\boldsymbol{r}}{r^3} - \frac{\boldsymbol{r}+\boldsymbol{\rho}}{\|\boldsymbol{r}+\boldsymbol{\rho}\|^3}\right) \\ &+ (1-\mu)\left(\frac{\boldsymbol{r}+\boldsymbol{r}_{em}}{\|\boldsymbol{r}+\boldsymbol{r}_{em}\|^3} - \frac{\boldsymbol{r}+\boldsymbol{\rho}+\boldsymbol{r}_{em}}{\|\boldsymbol{r}+\boldsymbol{\rho}+\boldsymbol{r}_{em}\|^3}\right)\end{aligned}$$

where the superscript $\times$ denotes the skew symmetric matrix, $[\boldsymbol{\rho}]_{\mathcal{L}}$, $[\dot{\boldsymbol{\rho}}]_{\mathcal{L}}$, and $[\ddot{\boldsymbol{\rho}}]_{\mathcal{L}}$ denote the relative position, velocity and acceleration of the chaser with respect to the target in the LVLH frame, $\boldsymbol{r}$ is the target position in the orbit and r its norm, $\boldsymbol{r}_{em}$ is the position of the Moon with respect to the Earth, $\boldsymbol{\omega}_{l/i}$ and $[\dot{\boldsymbol{\omega}}_{l/i}]_{\mathcal{L}}$ denote the LVLH angular velocity and acceleration with respect to an inertial frame, as seen in the LVLH frame (see Figure 2a). The latter can be obtained as follows:

$$\boldsymbol{\omega}_{l/i} = \boldsymbol{\omega}_{l/m} + \boldsymbol{\omega}_{m/i}$$

$$[\dot{\boldsymbol{\omega}}_{l/i}]_{\mathcal{L}} = [\dot{\boldsymbol{\omega}}_{l/m}]_{\mathcal{L}} + [\dot{\boldsymbol{\omega}}_{m/i}]_{\mathcal{M}} - \boldsymbol{\omega}_{l/m} \times \boldsymbol{\omega}_{m/i}$$

with $\boldsymbol{\omega}_{l/m}$ denoting the angular velocity of the LVLH frame with respect to the Moon, and $[\dot{\boldsymbol{\omega}}_{l/m}]_{\mathcal{L}}$ representing the angular acceleration of the LVLH with respect to the Moon, derived in the LVLH frame.

The port-to-port position is then computed as follows:

$$\boldsymbol{\rho}_{pp} = \boldsymbol{\rho} + \boldsymbol{r}_{pc} - \boldsymbol{r}_{pt}$$

where $\boldsymbol{r}_{pc}$ and $\boldsymbol{r}_{pt}$ are the positions of the chaser and target berthing ports (see Figure 2b).

2.2. Control Input

The chaser attitude control is performed in closed loop, it takes as input the relative attitude and angular velocity of the chaser with respect to the LVLH frame and produces the torques necessary to impose an user-defined profile. The profile is defined by the user, as a sequence of angles, one for each hold-point, expressed using the Euler angles (3,2,1) transformation.

The translational guidance is computed a-priori by the means of the *adjoint method*. Two-impulse and continuous thrust maneuvers can be computed using two sets of linearized equations: the *elliptic linear equations of relative motion* (ELERM) or the *circular linear equations of relative motion* (CLERM) equations. ELERM are obtained from the general nonlinear equations 2.1 under the hypothesis of ER3BP for the primaries, and the gravitational acceleration linearization. Similarly CLERM are obtained considering the *circular restricted three-body problem* (CR3BP) and linearizing the gravitational acceleration.

Discussion about the different linearized representation available for the relative dynamics and the maneuver computation is out of the scope of the present paper. The interested reader can refer to [1, 4, 5] where the analytical derivation of the linearized equation sets and the computation of the maneuvers is discussed in detail.

3. SOFTWARE STRUCTURE

ROSSONERO is composed by three main elements: the *graphical user interface* (GUI), a set of MATLAB scripts for mission initialization, maneuver computation, etc., and a set of Simulink models for dynamics simulation. The overall tool composition and the relationships between the different elements are shown in Figure 3 and are discussed in the following.

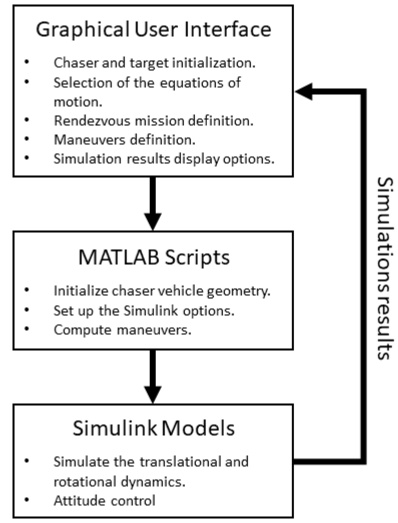


Fig. 3: ROSSONERO flow chart.

3.1. Graphical User Interface

Through the ROSSONERO GUI the user can define the mission and select the degree of fidelity for dynamics simulation. A screenshot of the GUI is shown in 4.

The user can initialize chaser and target initial states and select a list of *hold points* composing the rendezvous trajectory. The hold points are are defined in the LVLH frame and must be reached by the chaser with a prescribed relative velocity and attitude. Due to the specific nature of the motion (no ascent or early phasing) it is possible to chose a maximum of 10 hold points. For each of them, it is necessary to define the velocity in the LVLH and the relative attitude with respect to the LVLH frame the chaser must achieve there.

In addition, the user can select the type of maneuver the chaser will execute to move from a hold point to the next. Two-impulse and continuous thrust maneuvers are available, which can be computed using either the ELERM or the CLERM equations set. The user can specify the maneuver duration or *time of flight* (TOF), the firing direction (tangential, radial, normal or all directions) and the firing times.

The GUI is completed by different options for displaying the results. Plots for showing the evolution of position, velocity, attitude, thrust magnitude and firings can be generated. Several mission statistics are also provided, such as maneuvers ΔVs and errors. The GUI allows the user also to select whether plots and results must be showed for the single maneuver or for the overall mission. Results are expressed in the

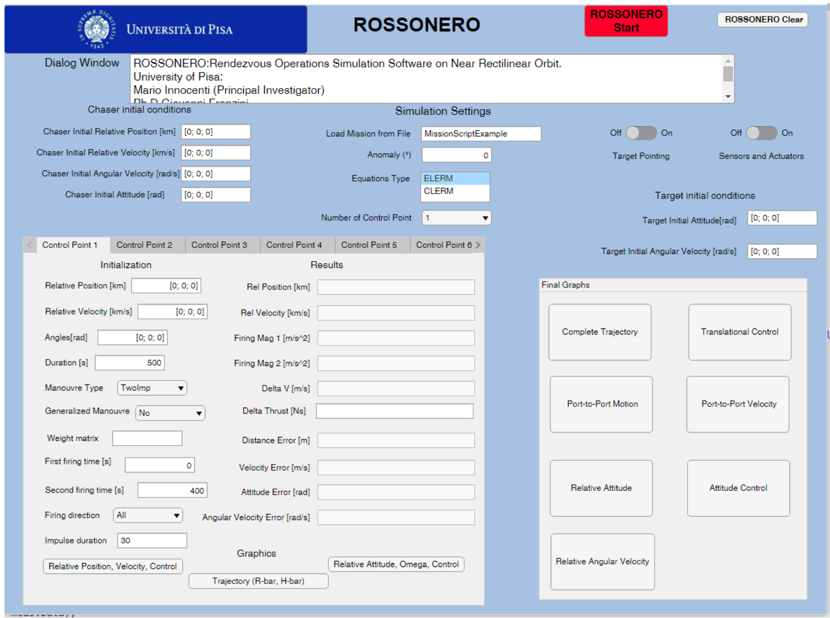


Fig. 4: Screenshot of the ROSSONERO graphical user interface.

LVLH frame for the translational motion, whereas the attitude is displayed as Euler angles (3,2,1) with respect to the LVLH frame.

ROSSONERO interface also allows the user to load input data from file, to speed-up simulation setup procedure.

3.2. MATLAB Scripts

MATLAB scripts are used to initialize and simulate the mission, as well as define chaser spacecraft properties and compute the maneuver to perform between the hold points. In particular, the scripts collect the information from the GUI and initialize the mission simulation. Chaser geometry, dimensions, mass distribution, inertia moments and berthing port position are defined. For the target, berthing port position and motion characteristics are defined as well. More specifically, a target orbit is loaded from the data sets available and a an approximated see-saw evolution in the target body frame around each axis of the LVLH frame is defined for the attitude.

Two-impulse and continuous thrust maneuvers are computed using the *adjoint method theory*, using ELERM or CLERM equations, according to the selection made by the user during the mission definition.

3.3. Simulink Models

Simulink models are used for translational and dynamics equations propagation. A standard attitude stabilizing controller is implemented in Simulink, and controls the chaser attitude during the maneuvers. The maneuvers computed for the chaser by the script are applied during dynamics simulations.

4. RENDEZVOUS MISSION EXAMPLES

In this section two examples of mission simulated using ROSSONERO are presented.

In both examples, the lunar NRHO in Figure 5a was selected for the target. The orbit is characterized by a mean period $T = 6.9867\,\mathrm{d}$. The *aposelene* is located at approximately $70\,000\,\mathrm{km}$ from the Moon, whereas the *periselene* at approximately $7000\,\mathrm{km}$. This orbit represents a potential candidate for the LOPG, as discussed in [8]. In particular, in Figure 5a, the potential region for rendezvous with the LOPG around the aposelene is highlighted in red.

The chaser is modeled as a cylinder with height $0.9\,\mathrm{m}$, radius $1.3\,\mathrm{m}$, constant mass $1231\,\mathrm{kg}$ and inertia equal to:

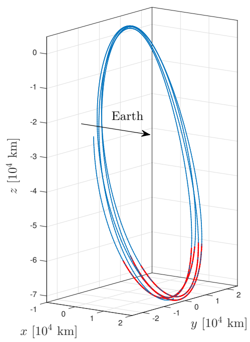
$$\mathbb{I}_c = \mathrm{diag}\,\{1080.6, 623.3861, 623.3861\}\,\mathrm{kg\,m^2}$$

Target berthing point is located at $5\,\mathrm{m}$ on the LVLH z-axis (Figure 5b), whereas in chaser this is located on the surface, along the positive direction of the body frame x-axis (Figure 5c). The settings for dynamics simulation are as follows: MATLAB solver ode45, absolute tolerance 10^{-20}, relative tolerance 10^{-13}, maximum integration step $T/10^{-4}$.

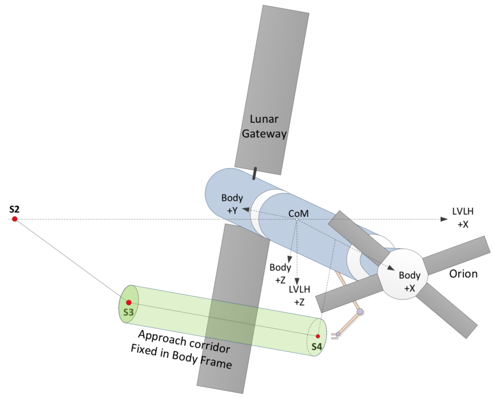
4.1. Example 1: Rendezvous at the Aposelene

In this first example the rendezvous trajectory is divided into four segments. The hold points and the desired attitude for the chaser at the points are:

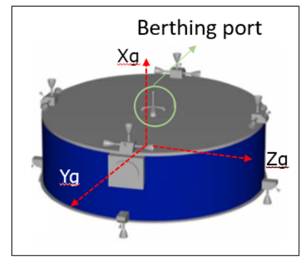
- $\boldsymbol{\rho}_1 = [-10, 0, 0]$ km, attitude $[0, 0, 0]$, with time of flight $3\,\mathrm{h}$;



(a) Reference Earth-Moon L_1 south NRHO orbit for target. In red the rendezvous zone.



(b) Target architecture and approach corridor.



(c) Chaser architecture and berthing port position.

Fig. 5: Chaser and target architectures.

- $\boldsymbol{\rho}_2 = [-1, 0, 0]$ km, attitude $[0, 0.1, 0]$ rad, with time of flight 2 h;
- $\boldsymbol{\rho}_3 = [-0.1, 0, 0]$ km, attitude $[0, 0, -0.3]$ rad, with time of flight 2 h;
- $\boldsymbol{\rho}_4 = [0; 0; 0]$, attitude $[0, 0, 0]$, with time of flight 1 h;

At all the control points the chaser must have zero translational and angular velocities. The mission starts at $\boldsymbol{\rho}(t_0) = [-2; 0; 0]$ km with initial attitude $(0, 0, 0)$, and zero translational and angular velocities. The target is initialized with non zero initial attitude $[0.01, -0.03, 0]$ rad, and angular velocity $[0, 0, 0.001]$ rad/s.

The overall rendezvous trajectory and the translational control evolution are shown in Figures 6a and 6b. The relative attitude evolution and the relative control signal are shown in Figures 6c and 6d. The target starts its motion at the aposelene.

4.2. Example 2: Rendezvous at the Periselene

In this second example, a rendezvous mission close to the periselene is shown. This represents a more challenging situation, given the high velocities reached in this region by the spacecraft. Nevertheless, the maneuvers computed by the tool are characterized by a great accuracy, proving the effectiveness of ROSSONERO.

The rendezvous trajectory is divided into four segments by defining four control points:

- $\boldsymbol{\rho}_1 = [0, 0, 1]$ km, attitude $[0, 0, 0]$;
- $\boldsymbol{\rho}_2 = [2, 0, 0]$ km, attitude $[0, 0.1, 0]$ rad;
- $\boldsymbol{\rho}_3 = [1, 0, 0]$ km, attitude $[0, 0, -0.3]$ rad;
- $\boldsymbol{\rho}_4 = [0; 0; 0]$, attitude $[0, 0, 0]$.

All the maneuvers have a time of flight of 1 h. At all the control points the chaser must have zero translational and angular velocities. The mission starts at $\boldsymbol{\rho}(t_0) = [0; 0; 2]$ km with initial attitude $[0, 0, 0]$, and zero translational and angular velocities. In this example the target attitude is fixed in the LVLH frame.

The overall rendezvous trajectory is shown in Figure 7a. It is possible to notice how the high speeds "bend" the trajectory and the rectilinear nature of the motion close to the aposelene is no longer verified. The translational control, the relative angles and the attitude control effort are shown in Figures 7b, 7c and 7d, respectively.

4.3. Comments on the Simulation Results

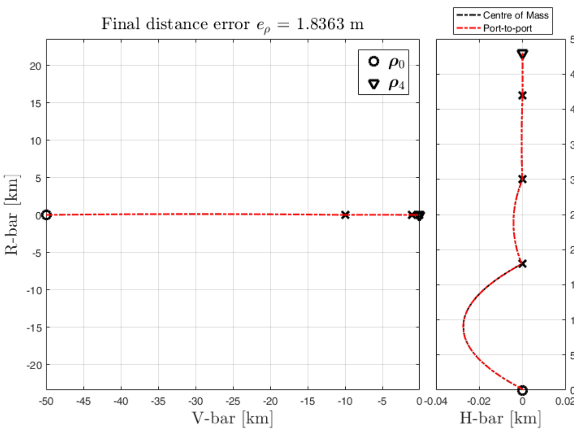
The simulation results show that the final position error provided by the maneuver computed using the adjoint method is small, taking also into account that the executed maneuver is open-loop.

The influence of the non linearities is evident at periselene, that is the reason of the curvature of the trajectory, nevertheless the amount of ΔV is limited.

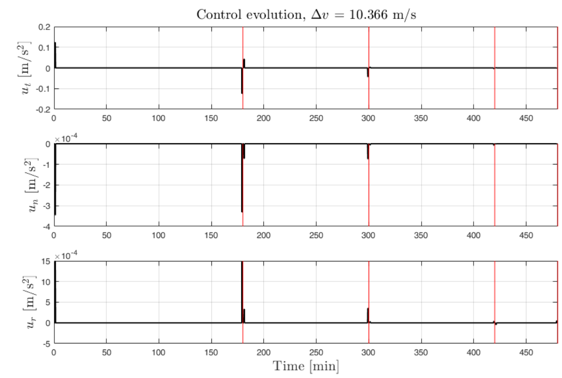
The attitude controller is able to force the vehicle to follow the user-desired profile. Recall that the controller is not optimized, so in the future better performance can be achieved for the attitude control (e.g. low thrust consumption or capability to keep the chaser pointing to the target).

5. CONCLUSIONS AND CURRENT WORK

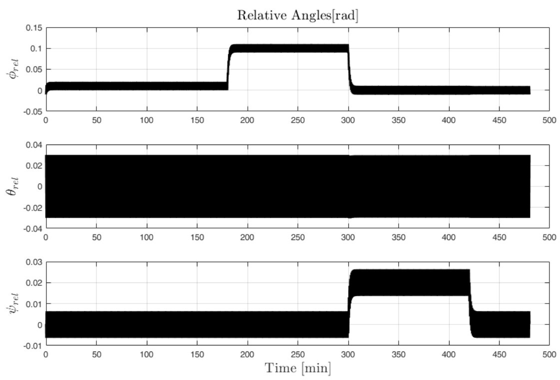
A simulation tool, ROSSONERO, was developed for analyzing and performing preliminary design of the rendezvous missions with a target in a three-body problem scenario, such as a cislunar space station in the Earth-Moon system. The tool simulates the nonlinear relative dynamics of two spacecraft in



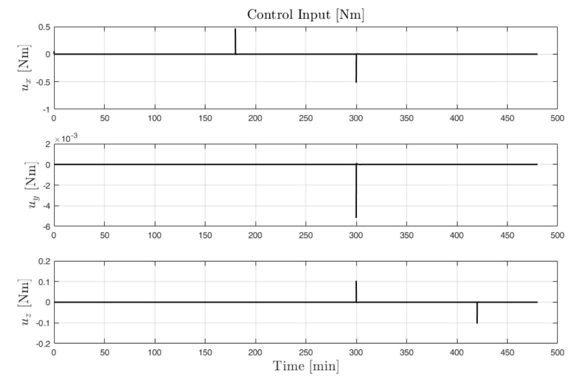
(a) Rendezvous trajectory.



(b) Translational control in the LVLH frame.



(c) Relative attitude evolution.



(d) Chaser attitude control signal in the body frame.

Fig. 6: Example 1 simulation results.

presence of non negligible third-body perturbation, and computes two-impulse or continuous thrust maneuvers to be executed for moving from a hold point to another during the approach to the target. ROSSONERO offers an intuitive user interface that allows the user to easily configure the maneuvers and efficiently analyze the results.

Our current work is focused on the introduction of several features for improving the degree of fidelity of the simulation and increase the configurable properties for the chaser vehicle. For instance, inclusion of sensors and actuator models is currently investigated. In particular, a suite of sensors/actuators for rendezvous will be provided by the tool and the user will select the combination to use for the mission. In this way, a preliminary analysis of the payload will be performed easily and different trade-offs can be explored effectively. Control allocation will also be addressed, according to the thrusters configuration selected. Finally, the possibility of designing the closed loop guidance design for the rendezvous terminal phase (relative distance below 1 km) will be offered.

6. ACKNOWLEDGMENTS

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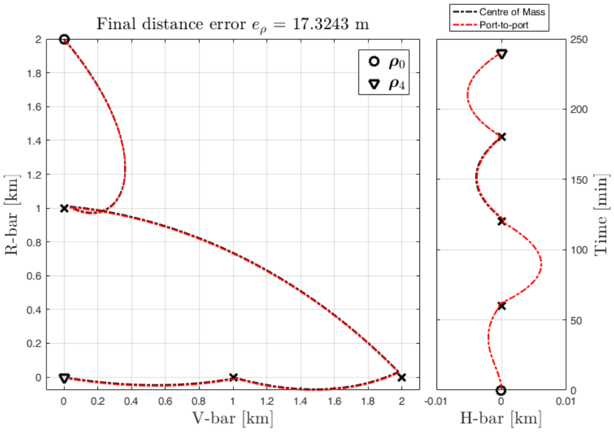
7. REFERENCES

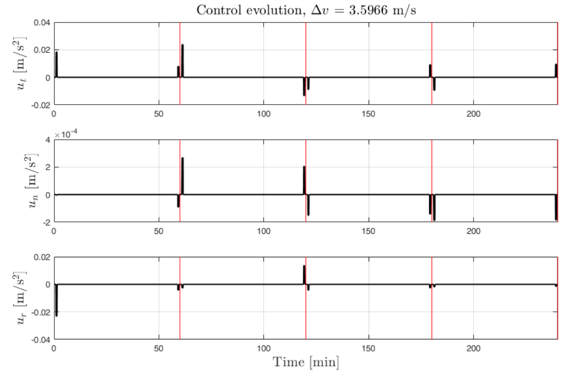
[1] G. Franzini and M. Innocenti, “Relative motion equations in the local-vertical local-horizon frame for rendezvous in lunar orbits,” in *Proc. 2017 AAS/AIAA Astrodynamics Specialist Conference*, Stevenson, WA, USA, Aug. 2017, Paper AAS 17-641.

[2] W. Fehse, *Automated Rendezvous and Docking of Spacecraft*. New York: Cambridge University Press, 2003.

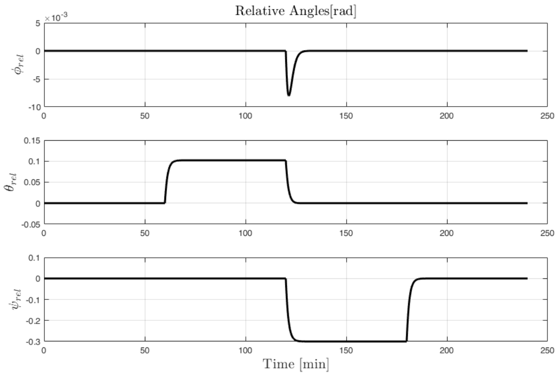
[3] F. Ankersen, “Guidance, navigation, control and relative dynamics for spacecraft proximity maneuvers,” Ph.D. dissertation, Aalborg University, 2011.



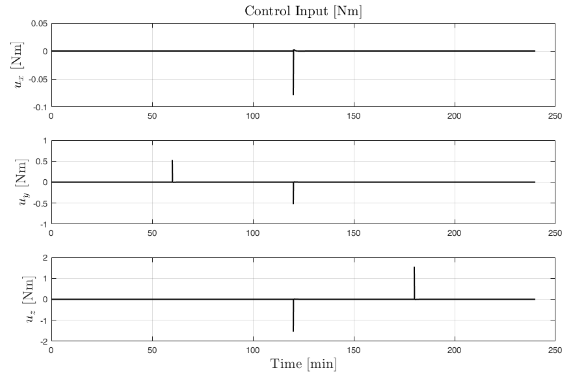
(a) Rendezvous trajectory.



(b) Translational control in the LVLH axes.



(c) Relative attitude evolution.



(d) Chaser attitude control signal in the body frame.

Fig. 7: Example 2 simulation results.

[4] G. Franzini, "Relative dynamics and control in the two-body and in the restricted three-body problems," Ph.D. dissertation, University of Pisa, 2018.

[5] G. Franzini, M. Innocenti, and M. Casasco, "Impulsive rendezvous maneuvers in the restricted three-body problem," in *Proc. 2019 AIAA Guidance, Navigation and Control Conference*, San Diego, CA, USA, Jan. 2019, (to appear).

[6] S. Segal and P. Gurfil, "Effect of kinematic rotation-translation coupling on relative spacecraft translational dynamics," *Journal of Guidance, Control, and Dynamics*, vol. 32, no. 3, pp. 1045–1050, 2009.

[7] H. Dong, Q. Hu, and M. R. Akella, "Dual-quaternion-based spacecraft autonomous rendezvous and docking under six-degree-of-freedom motion constraints," *Journal of Guidance, Control, and Dynamics*, vol. 41, no. 5, pp. 1150–1162, 2017.

[8] F. Renk, M. Landgraf, and M. Roedelsperger, "Operational aspects and low thrust transfers for human-robotic exploration architectures in the Earth-Moon system and beyond," in *Proc. 2017 AAS/AIAA Astrodynamics Specialst Conference*, Stevenson, WA, USA, Aug. 2017, Paper AAS 17-586.