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Rendezvous in Low-Lunar-Orbit from Gateway via Low-Thrust Nonlinear Control

Edoardo Maria LEONARDI[1,a *], Mauro PONTANI[1,b] and Paolo TEOFILATTO[1,c]

[1]Via Salaria 851, 00138, Rome, Italy

[a]edoardomaria.leonardi@uniroma1.it, [b]mauro.pontani@uniroma1.it, [c]paolo.teofilatto@uniroma1.it

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Abstract. This research investigates low-thrust nonlinear control for rendezvous in lunar orbit, in a high-fidelity dynamical model and in the presence of nonnominal conditions. The feedback control law is based on Lyapunov stability theory and is capable of tracking time-varying orbital elements, including the true anomaly. Monte Carlo campaigns are run to assess the performance of the control strategy, with regard to both a controlled and an uncontrolled target vehicle (i.e. subject to free dynamics). Results show that the proposed low-thrust feedback controller is capable of driving the spacecraft to a safe distance from the target vehicle, with minimal residual velocity, without relying on any reference trajectory nor numerical integration, making it suitable for onboard implementation.

Introduction

The Artemis program led by NASA foresees the deployment of the space station Gateway along a Near-Rectilinear-Halo-Orbit around the collinear exterior point of the Earth-Moon system. Establishing a long-term human presence on the Moon will require the development of autonomous and reliable transportation systems between Earth, Moon and Gateway. As part of ESA's Explore 2040 strategy, the Argonaut spacecraft will carry cargo from and to the lunar surface, proving a versatile access to the lunar surface [1]. In this context, the development of efficient and lightweight guidance and control strategies for autonomous rendezvous in Low-Lunar-Orbit (LLO) is an area of doubtless interest among researchers.

The design of optimal trajectories in cislunar space usually leverages dynamical system theory or two-body approximations to generate initial guess solutions, to combine with differential corrections and optimization techniques. In this field, optimal trajectories from Gateway to LLO have been identified through either direct and indirect methods, with both high thrust and low thrust [2, 3]. Instead, other studies focus on guidance and control strategies for rendezvous in cislunar space. However approaches based on direct and indirect optimization methods [4, 5] involve a higher computational load. Recently, the application of machine learning has been investigated for efficient guidance schemes in rendezvous scenarios, though demanding extensive training. In contrast, nonlinear control does not require any offline design process, apart from tuning the control gains. The objective of this research is to assess low-thrust nonlinear control as a viable strategy for rendezvous in lunar orbit, in a high-fidelity dynamical framework and in the presence of nonnominal conditions. Specifically, the study case considers a spacecraft equipped with a low-thrust propulsion system that departs from Gateway and is directed toward a target vehicle in LLO, to rendezvous with minimal residual relative velocity. Modified Equinoctial Elements (MEE) are employed as state variables for dynamics modeling, which includes third-body perturbations from Earth and Sun, as well as the relevant harmonics of the selenopotential. The positions of Sun and Earth are taken from NASA ephemeris, which also provides the state of Gateway at initial time. To drive the spacecraft from Gateway toward the target, a nonlinear controller is being proposed. Specifically, the feedback control law at hand is based on Lyapunov

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stability theory and is capable of tracking time-varying orbital elements, including the true anomaly, while enjoying quasi-global stability [6]. Two different scenarios are being considered:

a) the target vehicle flies a circular and polar LLO at an altitude of 100 km, with constant orbital elements except for the true anomaly;
b) the target spacecraft is subject to an uncontrolled dynamics; its initial orbit is identical to case (a), but the orbital elements vary under the effect of perturbing accelerations.

Monte Carlo campaigns are intended to assess the performance of the control strategy in the high-fidelity model, in the presence of several nonnominal situations, namely (i) time delays on the departure from Gateway, (ii) thrust misalignment, (iii) temporary thrust unavailability and (iv) noise on the measured perturbing accelerations.

Orbit dynamics

In this research, Modified Equinoctial Elements (MEE) are adopted as state variables since they exhibit no singularities, apart from retrograde equatorial orbits [7], which are rarely encountered. The set of MEEs is denoted as $x = [x_1, x_2, x_3, x_4, x_5, x_6]^T$. Through MEEs, the dynamical equations of a spacecraft orbiting around a primary body (with gravitational parameter μ) can be expressed in a compact form,

$$\dot{\boldsymbol{x}} = \mathbf{G}(\boldsymbol{x})\boldsymbol{a} + \boldsymbol{f}, \tag{1}$$

Where $\boldsymbol{f} = \left[0_{1x5} \quad \sqrt{\mu/x_1^3}(1 + x_2 \cos x_6 + x_3 \sin x_6)^2\right]^T$, while $\mathbf{G}$ is a 6x3 matrix depending on the state $\boldsymbol{x}$. Finally, $\boldsymbol{a}$ collects the components of the vector $\vec{\boldsymbol{a}}$ of non-Keplerian accelerations in the Local-Vertical-Local-Horizontal frame [8]. This vector includes the contribution of (i) the perturbing acceleration $\vec{\boldsymbol{a}}_P$ and (ii) the thrust acceleration $\vec{\boldsymbol{a}}_T$.

Perturbing acceleration. The term $\vec{\boldsymbol{a}}_P$ includes the perturbing acceleration $\vec{\boldsymbol{a}}_g$ due to the harmonics of the gravitational potential (i.e. excluding the Keplerian term) and the gravitational acceleration $\vec{\boldsymbol{a}}_{3B}$ due to the third-body effects of both Earth and Sun. The acceleration $\vec{\boldsymbol{a}}_g$ can be expressed as the gradient of the gravitational potential, conveniently described in terms of multipole series of spherical harmonics functions. In this research, the corresponding coefficients are taken from the Lunar Prospector LP100K model for the lunar gravitational field [9]. However, only the relevant harmonics associated with coefficients $|J_{lm}| > 5 \cdot 10^{-6}$ are retained in the dynamical model. Instead, the gravitational acceleration $\vec{\boldsymbol{a}}_{3B}$ due to a generic third body can be expressed in terms of its gravitational parameter and position vector in the inertial frame [6], taken from NASA ephemeris.

Thrust acceleration. The spacecraft is equipped with a low-thrust engine, which is assumed to be steerable and throttleable, and provides the thrust acceleration $\vec{\boldsymbol{u}}_T = x_7\vec{\boldsymbol{a}}_T$, where x_7 is the mass ratio. The thrust acceleration magnitude $u_T = |\vec{\boldsymbol{u}}_T|$ can be modulated from 0 up to a maximum value u_{Tmax}. Therefore, the dynamical state of the spacecraft includes its mass ratio, whose time derivative is given by $\dot{x}_7(t) = -u_T/c$, where c is the effective exhaust velocity.

Nonlinear orbit control

Rendezvous is achieved through a nonlinear feedback control law, which in a previous work was proven to enjoy global asymptotic stability despite time-variable desired MEEs, including the true anomaly [6]. As a preliminary step, the state of the target vehicle is expressed in terms of MEEs, $\boldsymbol{x}_d = [x_{1d}, x_{2d}, x_{3d}, x_{4d}, x_{5d}, x_{6d}]^T$. Then, the target state is enforced as a nonlinear constraint,

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$$\boldsymbol{\Psi}(\boldsymbol{x},t)=\begin{bmatrix}(1-\cos(x_6-x_{6d}))x_1\\(x_2-x_{2d})^2+(x_3-x_{3d})^2\\(x_4-x_{4d})^2+(x_5-x_{5d})^2\\(x_1-x_{1d})^2(1+x_2\sin x_6-x_3\cos x_6)\end{bmatrix}. \quad (2)$$

The formulation in Equation (2) allows to track all time-varying orbital elements of the virtual target, including the true anomaly. The instantaneous thrust acceleration is expressed as [6]

$$\boldsymbol{a}_T=-\frac{u_T}{x_7}\frac{\boldsymbol{b}+\boldsymbol{d}}{|\boldsymbol{b}+\boldsymbol{d}|},\qquad u_T=\begin{cases}x_7|\boldsymbol{b}+\boldsymbol{d}|, & \text{if } x_7|\boldsymbol{b}+\boldsymbol{d}|\le u_{Tmax}\\0, & \text{if } x_7|\boldsymbol{b}+\boldsymbol{d}|>u_{Tmax} \text{ and } \boldsymbol{b}^{\boldsymbol{T}}(\boldsymbol{b}+\boldsymbol{d})<0\\u_{Tmax} & \text{if } x_7|\boldsymbol{b}+\boldsymbol{d}|>u_{Tmax} \text{ and } \boldsymbol{b}^{\boldsymbol{T}}(\boldsymbol{b}+\boldsymbol{d})\ge 0\end{cases} \quad (3)$$

with $\boldsymbol{b}$ and $\boldsymbol{d}$ defined as

$$\boldsymbol{b}=\mathbf{A}^{\mathrm{T}}\boldsymbol{\Lambda}\boldsymbol{\Psi},\qquad \boldsymbol{d}=\boldsymbol{a}_P+\ \mathbf{A}^{\mathrm{T}}(\mathbf{A}\mathbf{A}^{\mathrm{T}})^{-1}\left(\frac{\partial\boldsymbol{\Psi}}{\partial\boldsymbol{x}}\boldsymbol{f}+\frac{\partial\boldsymbol{\Psi}}{\partial\boldsymbol{x}_d}\dot{\boldsymbol{x}}_d\right), \quad (4)$$

where $\mathbf{A}=\left(\frac{\partial\boldsymbol{\Psi}}{\partial\boldsymbol{x}}\mathbf{G}\right)$, while $\boldsymbol{\Lambda}$ is a diagonal and positive definite matrix, namely $\boldsymbol{\Lambda}=\mathrm{diag}\{\lambda_1,\lambda_2,\lambda_3,\lambda_4\}$.

Nonlinear orbit control

For each scenario, a Monte Carlo campaign comprising 100 simulations is run to assess the performance of the control strategy at hand in the high-fidelity model. The initial reference epoch is set to 25/05/2025 @14:06:08. The low-thrust propulsion system has effective exhaust velocity c = 30 km/s and maximum thrust acceleration $u_{Tmax}=4.91\cdot10^{-4}$ m/s^2. The control gains are tuned to $\lambda_1=10^2$, $\lambda_2=10^8$, $\lambda_3=10^8$, $\lambda_4=10^5$ and $\lambda_1=10^5$, $\lambda_2=10^{11}$, $\lambda_3=10^{10}$, $\lambda_4=10^{11}$ respectively for scenarios (a) and (b). Furthermore, canonical units are used throughout for numerical convenience: the distance unit (DU) is set to 10000 km, and the time unit (TU) is defined to yield a unit gravitational parameter.

The nonnominal conditions include (i) time delays on the departure from Gateway, (ii) thrust misalignment, (iii) temporary thrust unavailability, and (iv) noise on the measured perturbing accelerations. Further details on the modeling of these effects can be found in [6]. The integration is stopped when the final state corresponds to a safe distance $||\delta\vec{\boldsymbol{r}}||$ < 1.5 km from the target, where close-range rendezvous can be addressed as in recent contributions [10]. The performance of the strategy is analyzed in terms of final mass ratio (m_{Rf}), time of flight (ToF) and dispersions on $||\delta\vec{\boldsymbol{v}}||$, i.e. the magnitude of the spacecraft velocity relative to the target.

Table 1 collects the results of the Monte Carlo campaigns. The analysis of the results shows that the feedback control law drives the chaser to a safety distance from the target vehicle, with limited dispersion on the relative velocity, even when the spacecraft must rendezvous with the uncontrolled target. This is confirmed by inspection of Figure 1, which points out how the relative distance from the target is gradually reduced during each orbit. Rendezvous is achieved within an average of 65 days, with a modest fuel expenditure. Figures 2 and 3 show the time histories of the right ascension of the ascending node Ω, confirming the capability of the control law to track either constant or time-varying orbital elements. In particular, the zoom on the last days highlights the effectiveness of the feedback control law to track time-varying orbit elements induced by perturbations in the LLO environment.

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Table 1: Results of the Monte Carlo campaign for scenarios (a) and (b).

Parameter	Scenario (a)		Scenario (b)	
	Mean value	Standard deviation	Mean value	Standard deviation
$\|\|\delta\vec{\boldsymbol{r}}\|\|$ [m]	1477.64	17.00	1471.96	22.03
$\|\|\delta\vec{\boldsymbol{v}}\|\|$ [m/s]	1.17	0.18	1.14	0.36
ToF [days]	65.26	5.37	64.60	0.99
m_{Rf}	0.897	$3.01 \cdot 10^{-3}$	0.912	$1.10 \cdot 10^{-3}$

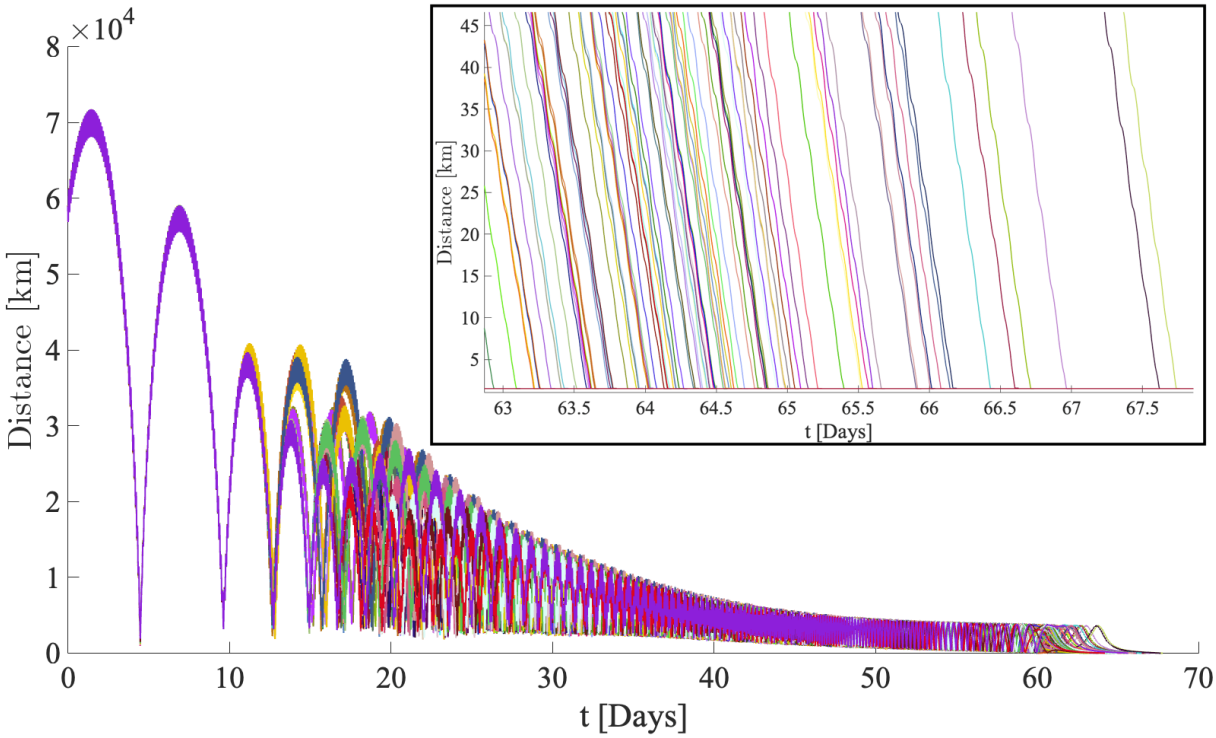


Figure 1: Scenario (b): time histories of the distance from the target across 100 Monte Carlo simulations with nonnominal conditions (in the insets, zoom on the last days).

Concluding remarks

The development of autonomous guidance and control techniques represents a key factor in ensuring the success of future lunar missions. This research addresses low-thrust nonlinear control as an effective guidance strategy for rendezvous from Gateway to LLO. A high-fidelity framework is employed for numerical simulations, including all relevant perturbations and nonnominal conditions associated with delays on the initial injection time, misalignment errors, thrust unavailability, and noise on measured accelerations. Moreover, low-thrust nonlinear control is employed to drive a spacecraft from Gateway toward rendezvous in LLO. The feedback law is capable to achieve rendezvous with either a controlled vehicle flying a Keplerian orbit or an uncontrolled target subject to natural (perturbed) dynamics. Remarkably, this strategy operates without the need for offline data or pre-computed trajectories, nor numerical integration, yielding a significantly lower computational cost compared to solutions based on optimal control theory. The low-thrust feedback controller requires only proper gain tuning, yet it is capable of autonomously generating trajectories online, making it suitable for onboard implementation.

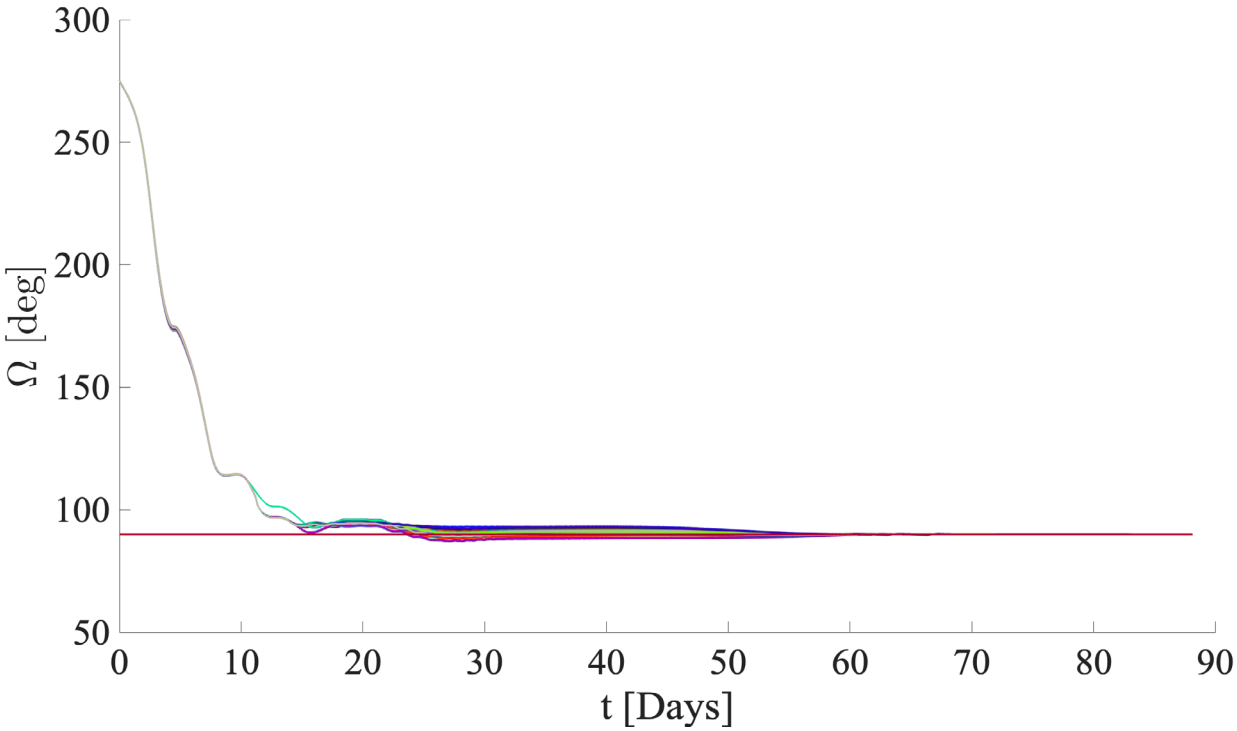


Figure 2: Scenario (a): time histories of Ω across 100 Monte Carlo simulations with non-nominal conditions.

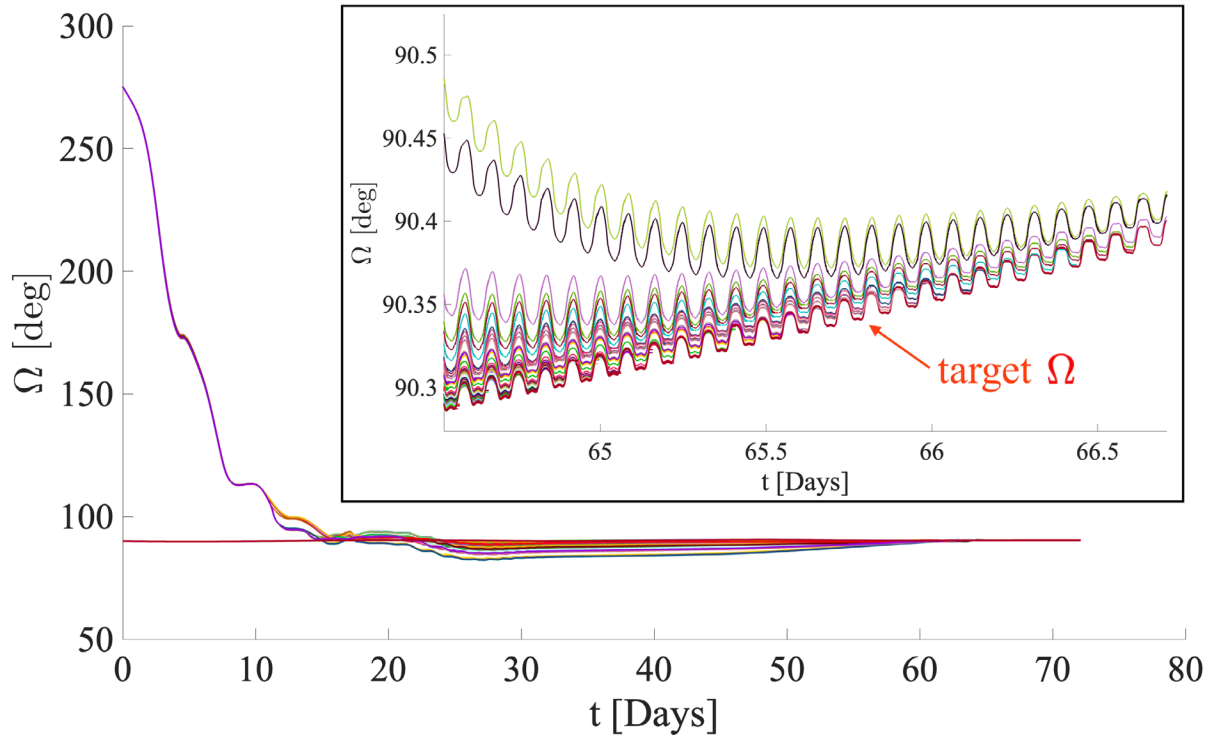


Figure 3: Scenario (b): time histories of Ω across 100 Monte Carlo simulations with non-nominal conditions (in the insets, zoom on the last days).

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