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High-Fidelity Orbital Simulator for Testing Guidance and Control strategies in Target Inspection Maneuvers

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Abstract: This paper present the six-degree-of-freedom orbital simulator developed by the students within the course "Dynamics and Control of Aerospace Vehicles". The paper outlines the rationale and objectives of the course, including the introduction of students to a practical experience in Guidance Navigation and Control (GNC) systems through the use of the orbital simulator to perform a Rendezvous and Docking (RVD) maneuver. The simulator models the relative motion of a chaser spacecraft with respect to a target spacecraft in Low Earth Orbit (LEO), enabling the implementation and testing of diverse GNC algorithms, components, and architectures within the Matlab/Simulink environment. Also, the paper presents a recent master's thesis demonstrating the soundness of the simulator as a basis for advanced research purposes. In this thesis, an autonomous proximity inspection maneuver targeting an uncooperative spacecraft was executed. The study compared the performance of Proportional-Integral-Derivative (PID) and Sliding Mode Control (SMC) strategies in tracking a reference trajectory generated by the Lyapunov Guidance Vector Field (LGVF). Furthermore, the impact of different sensor configurations on control performance was evaluated. The results demonstrate the proposed GNC strategy's capability for autonomous maneuver execution, establishing the simulator as a valuable platform for academic and research purposes in the GNC field.

Keywords: Autonomous control, Sliding-mode control, PID controller, Simulation, Lyapunov Guidance Vector, Satellite control, Path planning

1. INTRODUCTION

Nowadays, we can observe a rapid increase of space missions in which several satellites co-operate in close proximity to each other for activities such as formation flying, active debris removal and in-orbit servicing. These activities are part of Rendezvous and Proximity Operations (RPOs), a very timely topic for space companies due to the recent technological advancement (Li et al., 2019; Curzi et al., 2020). RPOs include space maneuvers that aim to manipulate the relative states between two (or more) satellites in roughly the same orbit, thus involving peculiar conditions for the intersatellite distances and speeds (on the order of kilometers and meters per second). The on-board Guidance, Navigation and Control (GNC) system plays a critical role in the success of the RPOs, as it is responsible for properly handling the spacecraft position and attitude dynamics (Flores-Abad et al., 2014). The GNC system consists of: (i) sensors for measuring the states of the spacecraft (position, orientation, linear and angular velocities), (ii) the navigation function for estimating the actual states from sensor's data, (iii) the guidance function for determining the desired trajectory and orientation of the spacecraft, (iv) the control function for calculating the control forces and torques required to track the guidance output, and (v) the actuators which physically realise the control actions (Schulte and Spencer, 2016). Within RPOs, GNC system must meet strict requirements regarding relative position and relative orientation of the satellites. Indeed, the success of this type of missions requires high precision while keeping the satellites in the correct configuration. Furthermore, GNC system must ensure adequate separation among the satellites for the safety of the space mission. Given its critical importance, the GNC system must be carefully designed and validated through extensive numerical simulations in a proper orbital simulator. Within this context are the objectives of the "Dynamics and Control of Aerospace Vehicles" course taught by prof. Elisa Capello within the master's program in aerospace engineering at the Polytechnic University of Turin. This course aims to introduce the students to dynamics and control of attitude and trajectory of autonomous space vehicles, with special focus on RPOs. In order to provide students with hands-on experience in aerospace education, the course requires students to complete a project in which they must build and test an orbital simulator for rendezvous and docking (RVD) maneuvers. In order to complete this task, students take advantage of hands-on laboratory classes scheduled at regular intervals during the academic semester. During these hours, students build the simulator step by step by implementing the various modules with the assistance of teaching staff. After completing the course, the students have acquired practical skills such as familiarity with the Matlab/Simulink environment, implementation of dynamic systems and actuator models, and design of guidance and control algorithms. In addition, they dispose of an orbital simulator providing a solid base for master's students with a strong interest in pursuing a master's thesis on GNC algorithms for RPOs.

During the 5-year life of the course, the orbital simulator proved to be an ideal educational tool for both introductory academic purposes and advanced research. It enables students to implement various GNC strategies through a hands-on approach that improves their understanding of the design and testing aspects of the algorithms. In addition, the hands-on approach of simulator construction effectively engages students, bringing them closer to the fields of simulation and control and preparing them for the advanced research tasks they undertake in their master's thesis. To provide a practical example, part of this

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article discusses a recent master's thesis pursued by two students that enhanced the orbital simulator built during the course. This enhancement aimed to develop a guidance strategy for inspection maneuvers of an uncooperative satellite, to compare the results obtained from two different position controllers, and to evaluate the attitude errors associated with different sensors.

The paper is organised as follows. Section 2 describes the academic course from which the simulator was obtained. Section 3 shows the improvements made during the thesis work and the algorithms used in the treated case. Section 4 describes the numerical example and presents the results obtained. Finally, some concluding remarks are in Section 5.

2. TEACHING PURPOSE

This Section details the organization of the course "Dynamics and Control of Aerospace Vehicles" and describes the orbital simulator developed by the students during the academic semester to reproduce the motion of small satellites (30-150 kg). During the 40-hours lecture period, students acquire the theoretical basis of the reference frames and equations to describe spacecraft attitude and orbital dynamics, with a special focus on the relative dynamics w.r.t. a target in a circular orbit. In addition, lectures address the space environment and its effects on position and attitude dynamics. Also, students receive insight about RVD missions and the orbital maneuvers required to complete them. Then, students learn the fundamentals of GNC system by studying its algorithms, actuators, and sensors. A variety of both open-loop and closed-loop guidance algorithms are introduced, detailing the theoretical foundations of these algorithms and suggesting their potential applications. The course also addresses real actuators models, including "Pulse Width Pulse Frequency"(Krovel, 2005) for on-off thrusters and the modelling of a pyramidal cluster of reaction wheels with filters and saturations constraints. This allows students to evaluate the differences in system response when compared to an ideal actuator. The theoretical lectures also give an introduction to onboard sensor technology for close proximity missions. It provides details regarding the application and operation of these sensors, as well as the potential implications they may have on the system's response. The rest of the theoretical course is about automatic control. First, the lectures review basic notions and concepts, starting from the general definition of the control problem and the theory of dynamical systems (state variables, system linearity, equilibria, stability, linearization and frequency response). Then, the design of feedback control systems is addressed in terms of stability, dynamic and static performance. The course includes lectures dedicated to analyzing the main algorithms discussed in the literature, covering essential control techniques such as state feedback control with pole placement, PID and LQR. Also, the course includes lectures dedicated to analyzing modern control techniques such as SMC.

Beside theoretical lectures, the course offers 20 hours of practical classes where students, with the support of PhD candidates and researchers, are encouraged to develop their own orbital simulator for RVD maneuvers. Throughout the semester, students progressively construct the simulator in Matlab/Simulink environment. Initially, they implement the Hill and Euler equations to model the position and attitude dynamics of the satellite relative to a target. This allows to reproduce the dynamics considering relative motion w.r.t the target, which is assumed to be in a circular orbit. Therefore, Hill's equations are used to describe the spacecraft translation dynamics w.r.t. the origin of the LVLH frame centered on the target, while Euler's equations are used to describe the 3-dimensional rotation dynamics of the body frame (attached to the spacecraft) w.r.t. the LVLH frame. A complete derivation of the models for position and attitude dynamics is given in (Fehse, 2003). Following this, they develop models for the actuators, i.e. thrusters for position dynamics and cluster of pyramidal reaction wheels for attitude dynamics. In particular, they implement a PWPF modulator to manage the thrusters activation/deactivation logic and saturation modules to mimic the realist behaviour of the wheels. Furthermore, the project includes external input disturbances typically affecting position and attitude dynamics in LEO environment. These disturbances are modelled as described in (Fehse, 2003) and are mainly due to solar pressure, atmospheric drag, J2 effect, gravity gradient and magnetic torque. Also, students implement the guidance and control algorithms necessary for conducting a specific RVD mission as follows. The simulated mission includes several key phases: an initial transfer to the target orbit using a Hohmann maneuver, which positions the chaser few kilometers behind the target. Then, the relative distance is reduced to few hundreds meters through a radial boost maneuver. Finally, a final approach within the safety cone using a straight-line V-bar approach leads the chaser to the immediate proximity of the target. When implementing this simulated RVD mission, students have free choice to implement open-loop or closed-loop maneuvers and, in the latter case, choose which guidance and control algorithm to implement. Students are encouraged to implement both open-loop and closed-loop maneuvers and to compare the results obtained in the ideal case and with disturbances and real actuators in the closed-loop. This practical approach helps the students to effectively compare open-loop and closed-loop control systems and to understand the differences between a nominal dynamics and a perturbed one. In addition, students must implement closed-loop attitude control so that the chaser is coordinated with the target throughout the mission. Also, the simulator includes the coupling between position and attitude dynamics, as it allows to rotate the control force exerted by the thrusters (supplied in body frame) in LVLH coordinates to properly fit Hill's equations. For the final evaluation, students are required to produce a report detailing the results of the simulations, as well as the design choices made during the development of the simulator. The practical part of the course not only serves as an evaluation tool but also deeply engages students by allowing them to experiment with controller tuning, evaluate guidance strategies, and enhance their software knowledge. This hands-on application provides an early and comprehensive introduction to the GNC field.

3. MASTER'S THESIS STUDY

This section summarises the master thesis work carried out in (Sarvadon, 2024) and details the improvements made to the orbital simulator designed during the master's degree course. The final architecture of the proposed 6-degree-of-freedom simulator is presented in Figure 1. First, the orbital simulator was improved with the inclusion of the navigation system, providing attitude and position estimation. Typical LEO missions sensors and algorithms necessary to measure and to evaluate position, velocity, orientation, and angular rate of the spacecraft were included in the simulator. Additionally, a data filtering process was implemented using an Extended Kalman Filter (EKF) combined with an initial data fusion process. These improvements resulted in a more sophisticated simulator that accounts for errors in estimating the actual states of the satellite.

The master's thesis objective was the design of guidance and control algorithms to perform autonomous inspection maneuvers. In particular, the chaser spacecraft has to track a circular reference orbit around a non-cooperative target while pointing at it. For this purpose, the students designed and implemented a guidance algorithm based on LGVF (Lawrence et al., 2008). This allows the instantaneous generation of the reference path leading the spacecraft to the desired circular trajectory around the target. LGVF computes the reference trajectory as a function of the spacecraft's position relative to the target, and shows strong convergence properties on the three dimensions. Furthermore, LGVF imposes a constant velocity (in module), which is chosen arbitrarily by the user to ensure safety in compliance with mission requirements. With regard to attitude, the students designed a guidance algorithm giving the reference attitude as a function of the sensor axis (to be pointed to the target) and the position of the chaser w.r.t. the target. Two different position

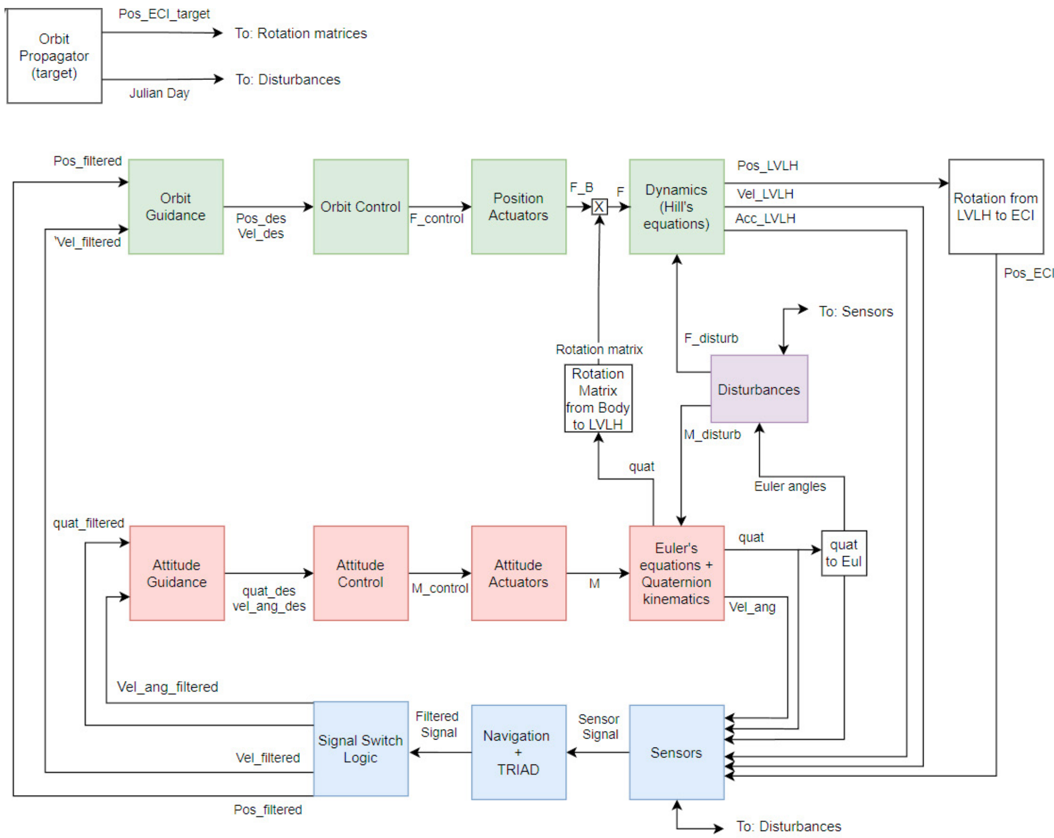

Fig. 1. Simulator architecture scheme.

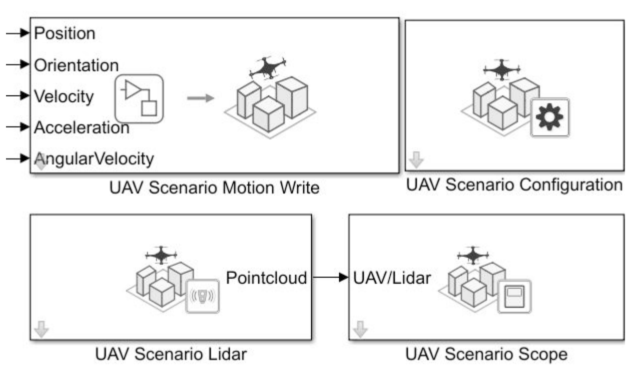

Fig. 2. UAV Toolbox.

controllers (PID and SMC (Utkin, 1992)) are included in the simulator. The PID is included as standard approach for space applications, while the SMC algorithm is an enhanced version w.r.t. the ones implemented during the hands-on lectures. In particular, the students used the boundary-layer SMC (Slotine and Sastry, 1983) to avoid high-frequency oscillations in the closed-loop dynamics (chattering) and the Integral SMC (ISMC) to improve the robustness of the control system (Utkin and Shi, 1996). Instead, the attitude controller is a standard PID. The other components of the 6-degree-of-freedom simulator (Figure 1) are implemented thanks to the expertise given during classes: Hill's equations and Euler's equations are used to describe the dynamics of the chaser relative to the target (assumed to be in LEO circular orbit). The actuators are on-off thruster and pyramidal cluster of reaction wheels and are modeled as indicated in Section 2. Although for the sake of conciseness of the article we propose a limited variety of GNC strategies, the partitioning of the simulator allows, with a minimal implementation effort, to select and test other algorithms to perform each GNC function. The rest of this Section gives the technical detail of the GNC strategy developed in the master thesis.

3.1 Navigation algorithms

Navigation capabilities were integrated into the simulation. This integration involved the incorporation of both absolute and relative sensors, as well as the introduction of data fusion techniques. Specifically, models from the Simulink library were utilized to simulate the behavior of GPS, IMU, and LIDAR sensors (UAV toolbox Figure 2). Please note that the UAV toolbox in Figure 2 has been adapted to the Local Vertical Local Horizontal (LVLH) system to account for both the dynamics and attitude of the chaser within the appropriate reference frame. For other sensors, including the Startracker, RGB camera, Earth Horizon Sensor, Sun Sensor and Magnetometer, Gaussian noise was applied as described in the literature (Blomqvist, 2010), to achieve realistic sensor accuracy. The sensor outputs were subsequently processed using the TRIAD algorithm (John L. Crassidis, 2014) and an EKF designed according to (Garcia, 2024), resulting in enhanced signal quality and effective data fusion. This process not only improved the accuracy and reliability of the sensor data but also provided a comprehensive framework for evaluating the performance of various navigation systems in a simulated environment. Through this approach, students gained practical experience in sensor integration, data fusion, and the application of advanced filtering techniques, contributing to a deeper understanding of the complexities involved in modern navigation systems.

3.2 Guidance algorithm

Here, the guidance algorithm to generate reference trajectory and attitude adequate for the mission objective are discussed. The reference trajectory is a circular orbit around the target perpendicular to the target orbital plane, and is generated using a guidance algorithm based on LGVF (Yao et al., 2015). The algorithm consists in the definition of a velocity field satisfying Lyapunov conditions for finite-time convergence. Following the procedure from (Lawrence et al., 2007, 2008), the velocity field is defined as

$$v^* = \begin{bmatrix} v_x^* \\ v_y^* \\ v_z^* \end{bmatrix} = B \begin{bmatrix} -x_r(r-R) - y_r(\gamma \cdot r) \\ -y_r(r-R) + x_r(\gamma \cdot r) \\ -\lambda r \cdot (h_r - H) \end{bmatrix}, \tag{1}$$

where

$$r = \sqrt{x_r^2 + y_r^2}, \tag{2}$$

$$h_r = z_r, \tag{3}$$

$$B = \frac{U_0}{r\sqrt{\lambda^2(h_r-H)^2 + R^2\gamma^2}}, \tag{4}$$

U_0 is the modulus of the desired relative speed, R and H are the nominal relative radius and height of the trajectory, and $\lambda,\gamma > 0$ are constant gains that regulate the convergence rate in the vertical and horizontal plane, respectively. Considering the Lyapunov candidate function

$$V = \frac{1}{2}(r^2 - R^2)^2 + \frac{1}{2}(h^2 - H^2)^2, \tag{5}$$

the variation rate is evaluated along the desired velocity field. It is given as

$$\dot{V} = \begin{bmatrix} \frac{\partial V}{\partial x} & \frac{\partial V}{\partial y} & \frac{\partial V}{\partial z} \end{bmatrix} \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \tag{6}$$

$$= -2B(r^2 - R^2)(r-R)r^2 +$$
$$-2B(h_r^2 + H^2)(h_r - H)\lambda r h_r.$$

Considering $H = 0$ (as in our case), it is verified that $\dot{V} \leq 0$ in every point. In particular, $\dot{V} = 0$ only when $r = R$ and $h_r = H$. Therefore, according to the Lasalle invariance principle (Lamberto Cesari, 1976), if the velocity field of the chaser is as in Eqs. (1)-(4), the chaser trajectories converge to the desired trajectory ($r = R$ and $h = H$) in finite time.

With regard to attitude, the mission objective requires the boresight vector of the sensor used for the inspection to be steadily pointed towards the target. Then, the guidance algorithm gives the reference attitude as a function of the sensor axis (fixed in body frame) and the position of the chaser w.r.t. the target. If the velocity field of the chaser mirrors Eqs. (1)-(4), it follows a circular orbit around the target at a constant relative velocity. In this case, the desired attitude is depicted by a sinusoidal reference with a period equal to the orbital period.

3.3 Control algorithms

Here, the position and attitude control algorithms used to properly handle the bounded uncertainties and disturbances affecting the spacecraft dynamics are presented. The position control problem is to track the velocity field in Eqs. (1)-(4), while the attitude control problem is to keep the sensor axis pointed to the target according to the guidance output. In this study, two position control strategies (PID and SMC) are proposed and compared in simulation environments. In both cases, attitude dynamics is handled with PID controllers.

PID A PID controller is used for each coordinate of the 3-dimensional spacecraft position dynamics. The input of each PID controller is the error $e(t)$ given by the difference between the reference speed v_i^* (given by the LGVF algorithm) and the estimated speed on the corresponding axis $\hat{v}_i$ (given by the EKF), i.e. $e_i = v_i^* - \hat{v}_i$ with $i = x,y,z$. The PID provides the corrective control force F_i to achieve the desired velocity along the associated axis according to the following equation:

$$F_i = K_{P_i} e_i + K_{I_i} \int e_i \, dt + K_{D_i} \frac{de_i}{dt}, \quad i = x,y,z. \tag{7}$$

Similar to position control, the 3-dimensional attitude dynamics is manipulated through three PID with the same structure of Eq. (7). However, the input for each PID attitude controller is the vectorial part of quaternions error $\tilde{q}_{v_i}$ on the corresponding axis $i = x,y,z$. The quaternions error is computed as $\tilde{q} = \overline{q_d} \otimes \hat{q} = [\tilde{q}_s, \tilde{q}_v{}^T]^T$, where $\otimes$ denotes the quaternions moltiplication, $\overline{q_d}$ is the conjugate of the desired quaternion q_d, and $\hat{q}$ is the estimated quaternion. Instead, the output of the PID attitude controllers are the control torques T_i ($i = x,y,z$) to achieve the desired orientation.

SMC The second controller used for the maneuver consists of an ISMC where the sliding surface for each axis is based on proportional and integral term of the speed error as follows:

$$\sigma_i = v_i^* - \hat{v}_i, \; S_i = \sigma_i + \lambda_i \sigma_i^I, \; \dot{\sigma}_i^I = \sigma_i, \; \lambda_i > 0, \; i = x,y,z \tag{8}$$

with $\sigma_i^I(t=0) = -{}^{\sigma_i(t=0)}/_{\lambda_i}$ to realise $S_i(t=0) = 0$, i.e. the system is in sliding mode from the very beginning of the control process. The asymptotic stability of the sliding dynamics under the condition $\lambda_i > 0$ is proven in the following. $S_i = 0$ yields $\sigma_i = \dot{\sigma}_i^I = -\lambda \sigma_i^I$, which realises $\sigma_i^I \to 0$ as $t \to \infty$. For $S_i = 0$, $\sigma_i^I \to 0$ implies $\sigma_i \to 0$, therefore $v_i \to v_i^*$ as $t \to \infty$, i.e. the errors converge asymptotically when the system is in sliding motion. The classical SMC law is of the type $F_i = K_i \mathrm{sign}(S_i)$, and ensures that the subset $S_i = 0$ is finite-time stable for the closed-loop system under proper selections of $K_i > 0$. However, it is well known that the discontinuity across $S_i = 0$ induces high-frequency oscillations near the sliding surface, and hence at the equilibrium point. In this work, the boundary layer SMC approach is proposed to avoid chattering. It consists in smoothing out the discontinuity of the *sign* function within a boundary layer of width $\overline{S}$ surrounding the sliding surface. The boundary layer SMC law uses a linear function to replace the discontinuity within the set $\{(i,v_i) \in \mathbb{R}^2, \, |S_i| < \overline{S_i}\}$ ($i = x,y,z$) as follows:

$$F_i = K_i \mathrm{sat}({}^{S_i}/_{\overline{S_i}}), \; K_i > 0, \quad i = x,y,z$$
$$\mathrm{sat}({}^{S_i}/_{\overline{S_i}}) = \begin{cases} 1 & \text{if } S_i > \overline{S_i} \\ {}^{S_i}/_{\overline{S_i}} & \text{if } S_i \in (-\overline{S_i}, \overline{S_i}) \\ -1 & \text{if } S_i < -\overline{S_i} \end{cases} \tag{9}$$

The chattering reduction through the boundary layer approach leads to deterioration of the steady-state error. Through Lyapunov analysis, it is found that the asymptotic stability of $\sigma_i = 0$ cannot be assured, however it can be proven that $\sigma_i \in [-2\overline{S_i}, 2\overline{S_i}]$ for $t \to \infty$($Fenget\ al.$, 2013).

4. SIMULATION RESULTS

This section shows the results of numerical simulations performed via Matlab/Simulink implementation of the orbital simulator. The simulation scenario is a target inspection maneuver as described in Section 3.2: the chaser has to move on a circular orbit around the target, perpendicular to the target orbital plane, while keeping the sensor axis steadily pointed at the target. The reference trajectory is generated according to Eqs. (1)-(4) with $R = 80\ m$, $\lambda = 0.01$, $\gamma = 0.09$, and $U_0 = 0.1$. Instead, the sensor axis is directed along the $X-$ body axis of the chaser. If the reference trajectory is perfectly tracked, the chaser must rotate at a constant angular velocity around the $Z-$body axis to maintain pointing at the target as described in Section 3.2. The PID (Eq. 7) and the SMC (Eqs. 8-9) are used in different numerical simulations to track the reference trajectory and the results are compared by considering several performance indexes. The gains of the two controllers are obtained via trial and error, and the values are reported in Table 1. Also, Table 1 gives the gains of the PID attitude controllers.

The effectiveness of the proposed guidance algorithm, with respect to the one proposed in (Yao et al., 2015), is shown in Figure 3. It reports the time history of the distance from the target, proving that the closed-loop system allows trajectory tracking, while satisfying safety requirements on both distance and velocity errors (within 1.5 m and 2 cm/s , respectively). The trajectory is reported in Figure 4, where the grey arrows show the velocity field

Table 1. Controllers gains.

SMC		PID			
		Pos.		Att.	
So_x	0.0361				
So_y	0.0361	K_{Px}	24.75	K_{Px}	0.539
So_z	0.015	K_{Px}	24.75	K_{Py}	0.539
λ_x	10^{-6}	K_{Pz}	275.62	K_{Pz}	0.539
λ_y	10^{-6}	K_{Iz}	0.1	K_D	4,375
λ_z	0.01				

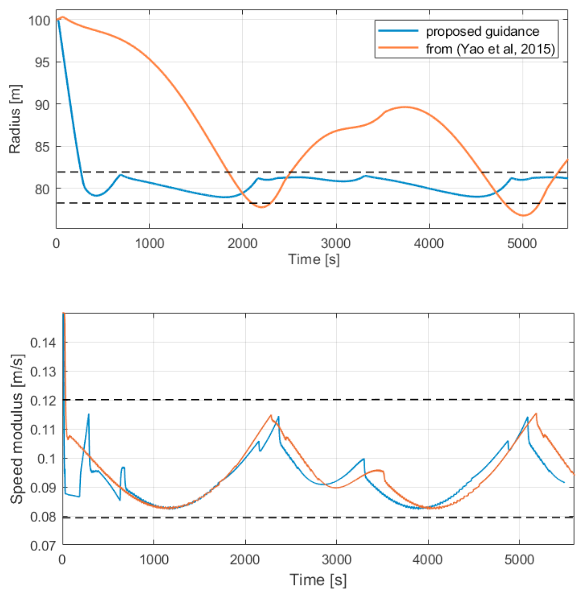

Fig. 3. Chaser spacecraft: distance from target (**top**) and relative velocity (**bottom**). The dotted lines represent the safety bounds.

given by Equation (1). Figures 3 and 4 are obtained with PID strategy starting from $h=0\ m$, $r=100\ m$ and $\|v\|=0.15\ {}^{m}/_{s}$ in the LVLH frame, where $\|v\|$ is the L^2-norm of v. The figures corresponding to the SMC controller are qualitatively similar and are not included in the article, but a numerical comparison of the two control strategies reveals that SMC allows to reduce 1.2% of fuel consumption and 4.9% of control effort with respect to PID controller. The control effort is evaluated as $\int_0^{t_f} \|F\|^2 dt$, where $F \in \mathbb{R}^3$ is the control force and t_f is the simulation time.

The sensor axis for target inspection is denoted by red arrows in Figure 4, which proves the effectiveness of the attitude controller to keep pointing at the target. Since the position controller tracks the reference trajectory with high precision, the attitude maneuver (Fig. 5) closely resembles the one described above: $\omega_z \approx {}^{2\pi}/_{T} = 0.0011\ {}^{rad}/_{s}$, and $\omega_x, \omega_y \approx 0\ {}^{rad}/_{s}$ ($T=5600\ s$ orbital period of the chaser orbit around the target). The oscillations around these values (Figure 5) are related to the non-perfect tracking along the orbit, which causes local accelerations-decelerations behaviour.

Given the versatility of the proposed simulator, pointing accuracy is evaluated for different set of sensors. Pointing accuracy is evaluated by the Root-Mean-Square-Error (RMSE), and it is reported in Figure 6, where the sensors are referred by the following acronyms: Startracker (STR), Earth Horizon Sensor (EHS), combination of Sun-sensor and Magnetometer (TRIAD), and Gyroscope (IMU). Performance depends on the EKF design, but there is an improvement with the combination of more sensors. The combination with the EHS affects RMSE, because of the lower sensor accuracy.

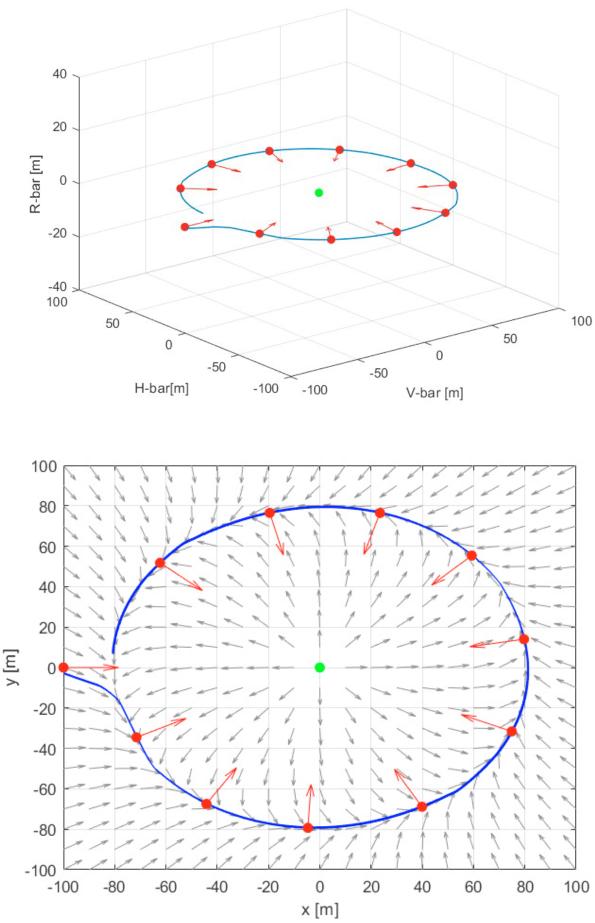

Fig. 4. Target inspection maneuver: trajectory and velocity field.

Furthermore, numerical simulations are carried out to evaluate closed-loop system behaviour for different initial conditions w.r.t. the ones used in Figures 3-5. In these simulations, the control gains are the same as in Table 1. The simulations with both PID and SMC revealed that the convergence performances in V-bar/H-bar are only slightly affected by the initial conditions. However, the PID controller for R-bar proved susceptible to a change in initial conditions, possibly showing the need to re-tune the controller to guarantee satisfactory performance. As an example, Figure 7 shows the results of a numerical simulation with initial conditions $r=100\ m$, $h=0\ m$, $v=[0.5, 0.15, 1]\ {}^{m}/_{s}$ and the control gains of Table 1. In this case, the response of the closed-loop system with SMC tends to have higher overshoot with respect to PID controller, but it significantly improves the settling time, especially for R-bar.

5. CONCLUSION

This work summarises the educational experience offered to students during the course "Dynamics and Control of Aerospace Vehicles", which provides students with practical experience to effectively understand orbit and attitude dynamics, proximity maneuvers, relative motions, GNC algorithms and components. The article details the process that gradually leads students to build an orbital simulator for RVD maneuver in Matlab/Simulink, and how teachers promote its use to gain an in-depth understanding of the subject. Also, The paper presents the creation and evolution of a student-implemented six-degree-of-freedom orbital simulator, designed to support varied architectures and scenarios within RPO missions. A practical example is provided through a target inspection maneuver using a circular trajectory, guided by the LGVF algorithm combined with PID and SMC control strategies.The simulator's versatility

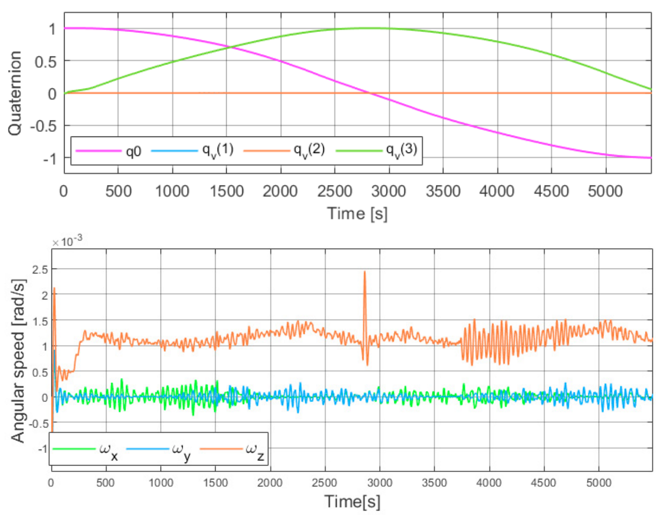

Fig. 5. Attitude and angular velocity time evolution during target inspection.

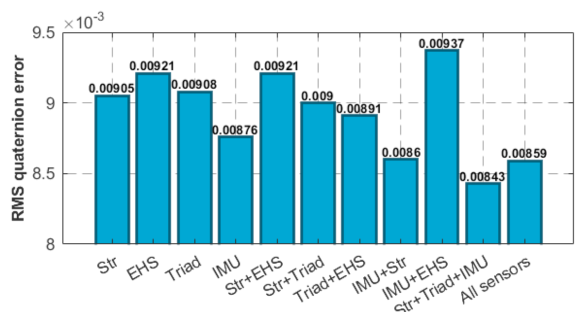

Fig. 6. Pointing accuracy (RMSE).

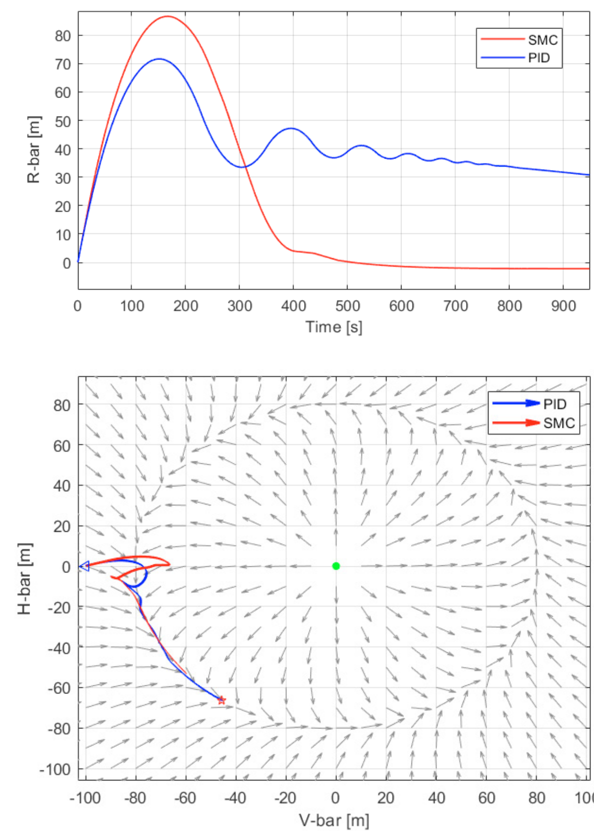

Fig. 7. Trajectory evolution with critical initial conditions.

is demonstrated through a series of numerical simulations with different sensor configurations and initial conditions. Results show that the closed-loop system trajectories successfully converge to desired paths with both PID and SMC, meeting safety requirements. SMC performs better when initial conditions differ from the nominal value, especially with large initial velocity errors.These findings validate the proposed GNC approach for the maneuver and confirm the simulator's value as an academic and educational tool, highlighting its effectiveness for research.

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