Obstacle Avoidance, Guidance and Control for Rendezvous Maneuvers based on Artificial Potential Field

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The purpose of this study is to show the Artificial Potential Fields (APF) capabilities in support of obstacle avoidance on satellite maneuver. In particular, in this work an orbital simulator is developed for Rendezvous maneuver. The Rendezvous and Docking maneuvers (RVD) encounter complex systems have to be performed autonomously. The main idea of this research is based on the design of a Guidance, Navigation and Contro (GN&C) system for rendezvous phases, able to autonomously track the target and avoid obstacles. This study exploits a Sliding Mode Control (SMC) to track the gradient obtained from Artificial Potential Field method, combining a first-order SMC for the position control and a super-twisting SMC for the attitude. This strategy is applicable with an actuation system by discontinuous thruster vector and with reaction wheels. Moreover, the proposed controllers can be easily computed on-board, due to the low computational effort. Finally, the results show good performance of the proposed controllers and the Chaser can avoid the obstacle security zone.

Nomenclature

APF	=	Artificial Potential Field
e	=	error between Target position and actual position
f_a	=	attractive artificial force
f_r	=	repulsive artificial force
F_x, F_y, F_z	=	force vector components applied on Chaser in LVLH
I	=	Chaser tensor of inertia
I_{RW}	=	Reaction Wheels tensor of inertia
k_a	=	attractive gain in APF
k_r	=	repulsive gain in APF
$LVLH$	=	Local Vertical/Local Horizontal
m_c	=	Chaser mass
M_B	=	total moment vector applied on Chaser in LVLH
q	=	quaternion vector
q_x, q_y, q_z	=	quaternion vectorial components
R_0^b	=	Rotation Matrix between the Chaser body reference frame and LVLH
u	=	control input
U_a	=	attractive potential field
U_r	=	repulsive potential field
x, y, z	=	relative position components in LVLH
$\dot{x}, \dot{y}, \dot{z}$	=	relative velocity components in LVLH
$\ddot{x}, \ddot{y}, \ddot{z}$	=	relative acceleration components in LVLH
φ, θ, ψ	=	Euler angles between LVLH and Chaser body reference frame
σ_x	=	first order sliding surface
σ_ω	=	super-twisting sliding surface
η_0	=	security nominal radius of obstacles
ω	=	constant angular velocity of the circular Target orbit
ω_B	=	angular velocity of Chaser with respect to Chaser body reference frame
$\dot{\omega}_B$	=	angular acceleration of Chaser with respect to Chaser body reference frame
ω_{RW}	=	angular velocity of Reaction Wheel with respect to Chaser body reference frame
$\dot{\omega}_{RW}$	=	angular acceleration of Reaction Wheel with respect to Chaser body reference frame
$\omega_x, \omega_y, \omega_z$	=	Chaser angular velocity components with respect to body reference frame

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I. Introduction

RENDEZVOUS maneuvers are crucial for the success of space mission, explorations and research. It is every time there is a transfer of astronauts, realization of space stations, maintenance or simple refuelling. In fact, the primary purpose of this maneuver is the docking between two spacecraft (Chaser and Target). In this study, the maneuver is stopped when the Chaser is few meters far from the Target, because the docking is considered complex in terms of strict requirements. The following work provides an optimised path for the Chaser, able to avoid possible obstacles along trajectory. For this aim, its Guidance and Control algorithm is developed to guarantee a completely autonomously maneuver in the space cluttered with obstacles. The thematic of obstacle avoidance plays an increasingly significant role in the space exploration, in fact, in addition to decrease the risk of mission's failure, avoids the uncontrolled increase of space debris. In 1987, Donald J. Kessler has already suggested the NASA a scenario, baptized as Kessler's syndrome, which exposes the possibility of chain reactions generated by multiple collisions between space debris. In the worst case scenario, it would lead to entrapment in our planet, as a result of which further space missions and the function of satellite communication became impossible.[1] Nowadays, more than 500000 space debris orbit around the Earth, whether the sources be natural or artificial, and they are monitored all time, while more than a million are so small, with a diameter of less than 10 cm, for which traceability is not guaranteed.

The success of the autonomously maneuver entrusts an actuation system, consisting of thrusters, able to exercise discontinuous and constant control actions for the position control. While for the attitude spacecraft model employs reaction wheels, that apply continuously variable moments to the system. For the development of the more suitable strategy to be followed, it has relied a proposed method by V.Utkin and J.Guldner in the field of robotics. [2] They proposed Artificial Potential Field, combined with the technique of Sliding Mode Control, for motion planning between obstacles.

The paper is structured as follows. The Section II presents the rendezvous maneuver. Section III contains spacecraft model, including relative translation equations, attitude dynamics and actuator models. In Section IV is described the guidance algorithm with the method of artificial potential field. The proposed controller is illustrated in Section V, in detail the different sliding mode control strategies for position and attitude. In the Section VI is presented a simulator architecture in MATLAB/Simulink. The simulation results are in Section VII. Finally, the Section VIII contains the conclusion and future work.

II. Rendezvous Maneuver Description

A typical RVD mission can be divided in different phases, as shown in Fig.1. The trajectory strategy consists in three maneuver after the acquisition of the communication link to the Target takes place: a Hohmann transfer, in order to acquire the target orbit and reduce the relative speed, the radial boost transfer, where the Chaser approaches a few hundred meters from the target (exactly 500m). Finally, a forced motion straight line approach, to satisfy the rigid requirements of docking, ends once the spacecraft is a few centimeters from the Target. [3]

The exact solution for the realistic case of thrust maneuvres with limited thrust level and duration is given by considering each phases quasi-impulsive.

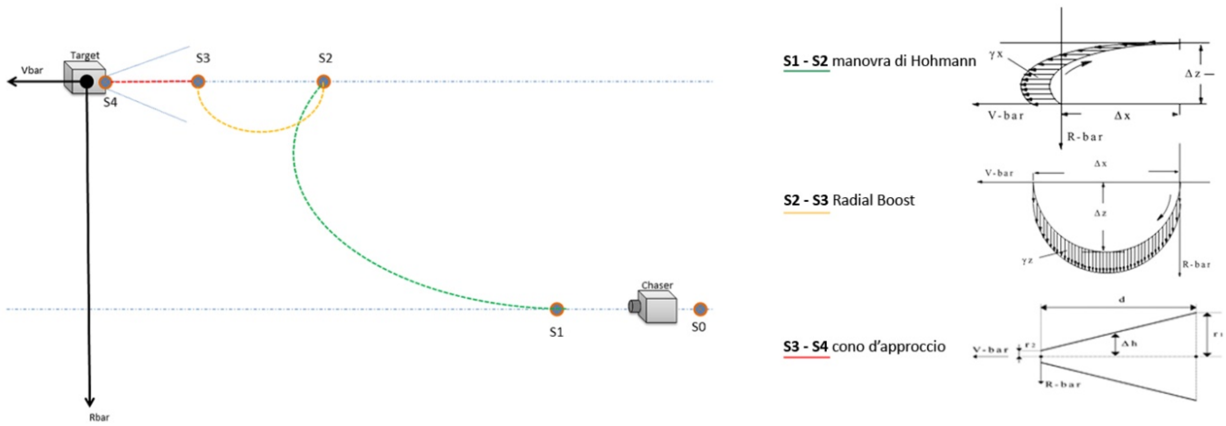


Figure 1. Three phases of rendezvous maneuver

III. Spacecraft Model

In this study, the analyzed Chaser model is a 6 degree-of-freedom model, in which an actuation system, reaction wheels and nonlinearities and external disturbances are taken into account. [4] As a result of these assumptions, it could be possible to create a simulator in Simulink, where each of these constitute a block, like that the relative dynamics, Euler and kinematic equations and the actuation model.

A. Relative dynamics equations

In RVD maneuver, where the distance between chaser and target is small compared with the distance from the center of the Earth, the relative translational dynamics are usually analyzed a local orbital frame of the target is often used to as the local-vertical/local-horizontal (LVLH) frame. [5]

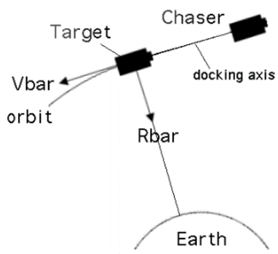


Figure 2. Definition of LVLH frame

Assuming a circular orbit, the chaser position, speed and accelerations are evaluated from the numerical integration of the Hill equations of the relative motion, derived from the W.H.Clohessy and R.S.Whiltshire equations

$$\begin{cases} \ddot{x} - 2\omega\dot{z} = \frac{1}{m_c}F_x \\ \ddot{y} + \omega^2 y = \frac{1}{m_c}F_y \\ \ddot{z} + 2\omega\dot{x} - 3\omega^2 z = \frac{1}{m_c}F_z \end{cases},$$

where $x = [x, y, z]^T$ is the Chaser vector position, $\omega = \sqrt{\mu/r_{HF}}$ is the angular frequency of the LVLH frame, r_{HF} is the distance of Earth's center, μ is the Earth gravitational constant, m_c is the Chaser mass, which is decreasing with fuel consumption, and $F = [F_x, F_y, F_z]^T$ is the total force vector, which is the sum of the forces applied by thrusters and the forces due to external environmental disturbances that act on the system,

$$F^* = F_{thr} + \Delta F_{ex}.$$

This force must be transformed from the body system to the LVLF frame through the rotation matrix, which couples the attitude and position dynamics, once the angles of Euler angles (φ, θ, ψ) are known (as we will see in the Section B)

$$F = R_0^b(\varphi, \theta, \psi)F^*.$$

B. Kinematic equations

For the attitude evaluation of the Chaser, i.e. the angular velocities and Euler angles w.r.t. the LVLH frame, the body axes frame is considered.

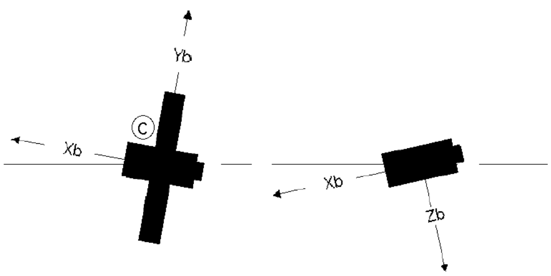


Figure 3. Definition of body axes frame

The Euler equations defines the attitude dynamics and the angular velocities as

$$\dot{\omega}_B = I^{-1}(M_B - \omega_B * (I\omega_B + I_{RW}\omega_{RW})),$$

where $\dot{\omega}_B = [p_B, q_{B,} r_B]^T \in \mathbb{R}^3$ is an angular acceleration vector of the Chaser, $I \in \mathbb{R}^{3,3}$ is the Chaser tensor of inertia (diagonal and update with a center of mass), $I_{RW}\mathbb{R}^{3,3}$ is a RW tensor of inertia (known and constant), $\omega_{RW} = [\omega_{x,RW}, \omega_{y,RW,}\omega_{z,RW}]^T \in \mathbb{R}^3$ is angular velocities of the RW and $M_B \in \mathbb{R}^3$ is an active total moment on Chaser, given by a sum of the moments of the main external disturbances, i.e. phenomena related to the gravitational and magnetic field, to solar radiation and aerodynamic resistance, plus the moments of the reaction wheels and thrusters

$$M_B = M_{thr} + \Delta M_{ex} + M_{RW}.$$

We consider the quaternion dynamics and we obtain the attitude, w.r.t. the Earth Centered Inertial (ECI) frame, by the integration of following equation

$$\dot{q} = \frac{1}{2}\sum(q)\omega_B ,$$

where $q = [q_1 q_2 q_3 q_4]^T \in \mathbb{R}^4$ is the vector of quaternions and $\sum(q) \in R^{3,4}$ is calculated as

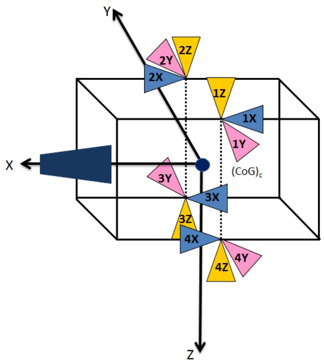
$$\sum(q) = \begin{bmatrix} q_4 I_3 + Q_{13} \\ -q_{13}^T \end{bmatrix},$$

where $q_4 \in R$ is a scalar component of quaternion, $I_3 \in R^{3,3}$ is an identity matrix and $Q_{13} \in R^{3,3}$ is skew-symmetric matrix as

$$Q_{13} = \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix}.$$

C. Actuation System

The characteristics of the actuation system strongly influence the way of controlling a spacecraft. In this model the position control is exploited by thrusters, which can use mono-directional actions along fixed direction and with a constant intensity. This means that the position and the shoot direction of the thrusters are important to obtain a robust and reliable system. See Fig.4 for the thrusters configuration check.



Forces	Thrusters	
+X	1X	3X
-X	2X	4X
+Y	2Y	3Y
-Y	1Y	4Y
+Z	3Z	4Z
-Z	2Z	1Z

Figure 4. Direction of the thrust by the ith thruster switched on at time t_0

Therefore, for each direction control are activated a pair of actuators and these thrusters coupled by direction are always switched on together by the controller to avoid a thruster moment in the zero configuration. A single thruster can provide either the maximum amount of thrust when switched on or no force when switched off.

$$T = \begin{cases} T_{max}, & if\ t \in (t_0, t_0 + \tau_{ONi}) \\ 0, & if\ t(t_0 + \tau_{ONi}, t_0 + \tau_{ONi} + \tau_{OFFi}) \end{cases},$$

where τ_{ONi} and τ_{OFFi} are known and constant. The total forces on the ith thruster is described as:

$$F_{thri} = \beta_i T_i d_{thr,i} ,$$

where $\beta \in R^{N_{thr}}$ is a Boolean vector related to the thruster switching on/off, T_i is the force applied by the ith thruster and d_{thri} is the vector representing the shoot direction of ith thruster.
Whereas for the attitude control the Chaser uses three axial reaction wheels, driven by electric motors powered by the spacecraft electrical power supply. Reaction wheels actuators produce moments M_{RW}, to determine its increased angular momentum, as studied in section B.

IV. Guidance Algorithm

As briefly said in the introduction, the aim of this research is to develop an algorithm that autonomously perform autonomously the rendezvous maneuver in the presence of obstacles. In this study the method of Artificial Potential Fields (APF), usually used for robotic systems, is proposed to avoid obstacles. This technique is based on the physical principle for which a change particle, moving in an electrostatic field, is guided towards the target due to an artificial attractive component generated by the goal, while it is rejected away from obstacles as the result of repulsive component caused by field generated by them.

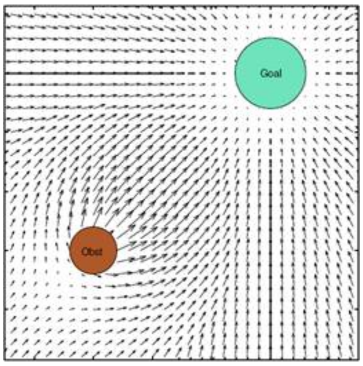


Figure 5. The artificial attractive and repulsive forces [6]

For simplicity, the case in which the obstacles are fixed with known safety radius is analyzed.
The attractive paraboloid APF are considered and is evaluated as [7]

$$U_{a1}(q) = \frac{1}{2} k_a e^T(q) e(q) = \frac{1}{2} k_a \|e(q)\|^2 \,,$$

where k_a is the proportional positive gain of the attractive gradient, $e(q)$ is the error between the final and actual position in LVLH frame. The relative force is calculated by the negative gradient of this potential, as

$$f_{a1}(q) = -\nabla U_{a1}(q) = k_a e(q) \,,$$

whereas, once the chaser is close to an obstacle and be able to avoid it, a repulsive hyperbolic APF is calculated as follows for each obstacles $(i = 1, \dots N_{obs})$

$$U_{rep,i}(q) = \begin{cases} \frac{k_{r,i}}{\gamma} \left(\frac{1}{\eta_i(q)} - \frac{1}{\eta_{0,i}} \right)^{\gamma} & if\ \eta_i(q) \le \eta_{0,i} \\ 0 & otherwise \end{cases} ,$$

where $k_{r,i}$ is the proportional positive gain of the repulsive field, $\eta_{0,i}$ is the safety radius, that is the distance of repulsive influence of obstacles, $\eta_i(q)$ is the minimum distance between the chaser and the obstacle position and $\gamma = 2$ is defined equal 2 for hyperbolic field. The repulsive force is as follows

$$f_{r,i}(q) = -\nabla U_{r,i}(q) = \begin{cases} \frac{k_{r,i}}{\eta_i^2(q)} \left(\frac{1}{\eta_i(q)} - \frac{1}{\eta_{0,i}} \right)^{\gamma - 1} \nabla \eta_i(q) & if\ \eta_i(q) \le \eta_{0,i} \\ 0 & if\ \eta_i(q) > \eta_{0,i} \end{cases} .$$

The total potential field and force is the sum of attractive and repulsive contributions as:

$$U_{tot}(q) = U_a(q) + \sum_{i=1}^{N_{obs}} U_{r,i}(q) \,,$$
$$f_t(q) = -\nabla U_t(q) = f_a(q) + \sum_{i=1}^{p} f_{r,i}(q).$$

In a second step, the total force is normalized to know the exact direction of desired speed that is needed for overcome obstacles, designed by means of a control system. The desired speed is so the maximum speed of each phase maneuver value, multiplied by unit vector derived from normalization of total force

$$E_U = \frac{f_a(x) + f_{r.i}(x)}{\|\nabla U_{tot}(x)\|}$$
$$\dot{x}_d = \dot{x}_{d,max} E_U$$

where the $\dot{x}_{d,max}$ is the maximum speed to perform the maneuver and $\dot{x}_d$ is the desired speed.

V. Control Algorithm

Since the rendezvous mission is a nonlinear maneuver from the dynamic point of view, the implemented control strategy, first of all, must comply with this requirement. Sliding Mode Controller (SMC) can be applied to nonlinear systems and is robust to model uncertainties and insensitive to noise. Moreover, a first order SMC produces a discontinuous input signal, as exploited by the thrusters. For this specific case, the system trajectory is forced to slide along a surface, called sliding surface. The only drawback of this controller is that the system becomes vulnerable during the control of the output signals: the trajectories oscillate around the same surface with amplitude the smaller than the largest is the frequency (phenomenon "chattering").

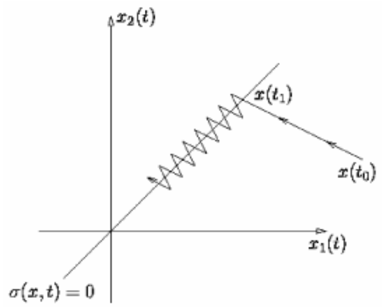


Figure 6. Sliding surface with chattering phenomena

As position control-channel of Chaser, a first order sliding mode is designed, due to the intrinsic nature of thrusters. In fact as already mentioned, these provide thrust that can not be (continuously) modulated but simply can be switched on or off.
The input vector $u_x = F_{thr} \in R^3$ is designed for the SMC as follows

$$u_x = -B_x^{-1} K \, sign\,(\sigma_x) \,,$$

where $B_x^{-1} = m_c I_3$ is the control matrix, $K = nT_{max}$ with $n = 2$ since it represents the number of thrusters that can be turned on simultaneously. σ_x is the a desired sliding output

$$\sigma_x = (\dot{x} - \dot{x}_d) + c_x(x - x_d) \,,$$

where $\dot{x}_d \in \mathbb{R}^3$ and $x_d \in \mathbb{R}^3$ are respectively desired velocity and position vector, derived from the APF guidance algorithm, $\dot{x} = [\dot{x}, \dot{y}, \dot{z}]^T \in \mathbb{R}^3$ and $x = [x, y, z]^T \in \mathbb{R}^3$ are measured at each time step through the Hill equations and c_x is a positive constant. Finally, the desired sliding surface is $\sigma_x = 0$.
For the attitude control, a second order sliding mode control, known as super-twisting (STW), is considered. This technique is suitable for the actuation system to the attitude dynamics, i.e. the reactions wheels. In fact, this controller provides a continuous action control, without frequency limitations, by which the chattering is reduced since the continuous generation of pairs of moments. [8]
The input $u_\omega = M_{RW} \in \mathbb{R}^3$ is defined in accordance with the STW sliding mode algorithm as follows

$$u_\omega = -\lambda |\sigma_\omega|^{1/2} \, sign\,(\sigma_\omega) + u_1 \,,$$

$$\dot{u}_1 = \begin{cases} -u & |u| > U_M \\ -\alpha \, sign\, \sigma_\omega & |u| \leq U_M \end{cases} ,$$

where λ and U_M is defined theoretically defined according to the dynamics analyzed. The sliding output of this controller is

$$\sigma_\omega = \omega_B + C_\omega \delta q_{13} \,,$$

where $C_\omega \in R^{3,3}$ is a positive matrix, δq_{13} is evaluated starting from the desired attitude vector $q_d = [0\ 0\ 0\ 1]^T$, that is when the LVLH frame is aligned with the body system, and is calculate as

$$\delta q_{13} = \sum\nolimits^T (q_d) q$$

where $\sum^T (q_d) \in R^{3,4}$ is defined from the matrix $\sum^T (q)$ including q_d definition.

VI. Simulator Architecture

The software tool to develop the simulator is MATALB/Simulink. The purpose of this section is to provide a complete vision of the simulator architecture. The three phases of the maneuver are separately analyzed inside the simulator. The first phase deals with the Hohmann transfer, for which the attitude is variable and where an obstacle. The second one is the radial boost, in which not only a variable attitude is considered, but also two obstacles. Finally, in the approach cone, the attitude is constant and the trajectory without obstacles, because the Chaser is close to the Target and to respect the strict docking requirements, which the Chaser aligned with the Target.
This simulator can be some main divided in blocks

- The relative dynamics with Hill equations (green block in Fig.7).
- The artificial potential algorithm as Guidance algorithm (yellow block in Fig.7).
- The first order sliding mode for the position control within the Hill equation block (green block in Fig.7)..
- The Euler and kinematic equations (light blue block in Fig.7).
- The super-twisting sliding mode for the attitude control (blue block in Fig.7).

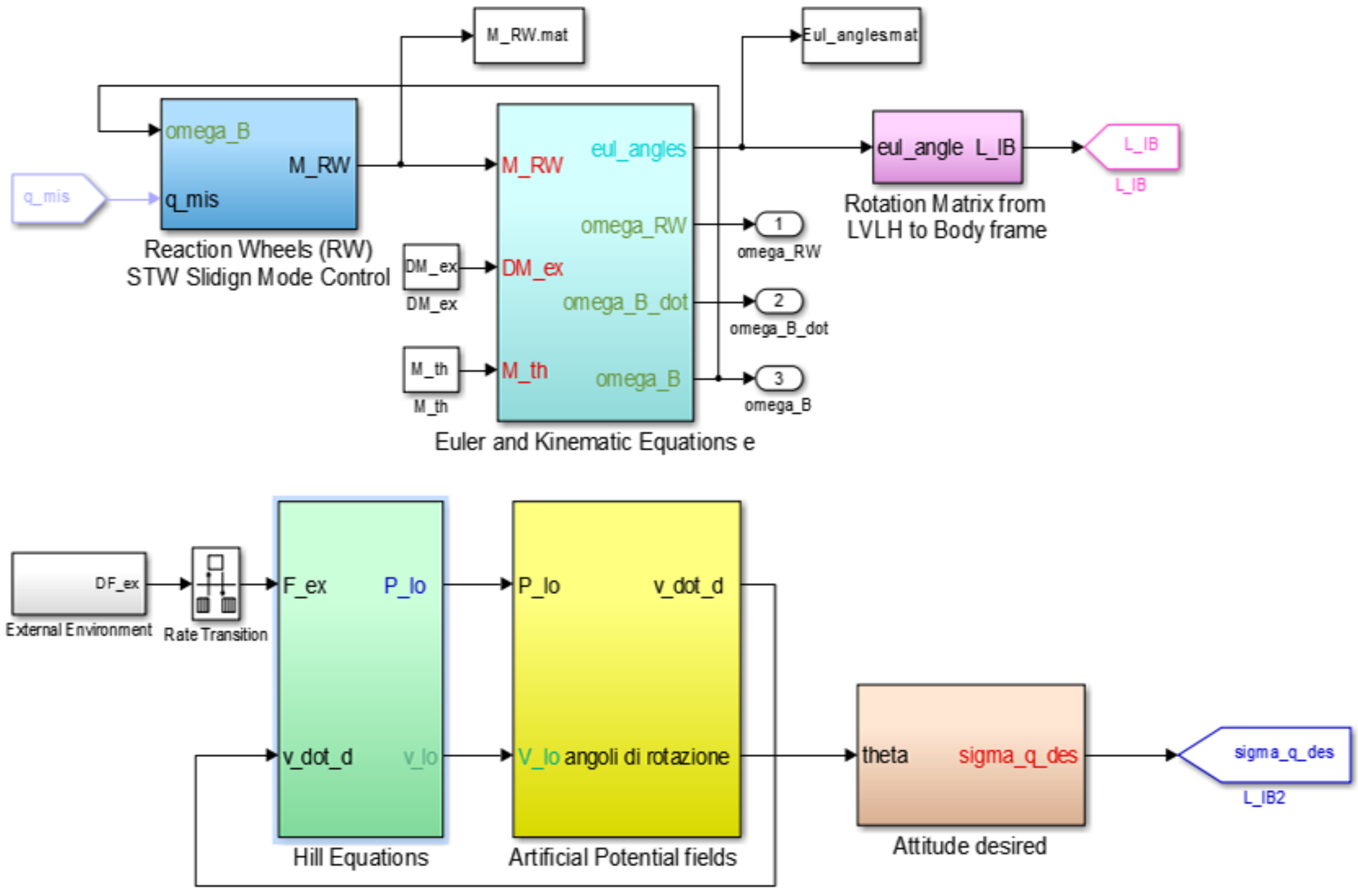


Figure 7. Main Simulink model of each three phases of Rendezvous maneuver

VII. Main results

As a simulation scenario, it is assumed that the center of mass of the Target is the origin of LVLH frame and the initial distance between Chaser and Target is 16 km. A cubic-shape Chaser (1.2 m) is considered with an initial mass of 600 kg, as in Table 1, it is variable in function of the fuel mass. As already described in the Section 2, a complete rendezvous maneuver, including Hohmann transfer, radial boost and the final has been studied. As previously described, in the last part of the maneuver, when the Chaser is approaching the Target, APF algorithm is not considered. The Chaser and orbit characteristics are shown in the following table.

Table 1. Chaser and orbit characteristics

Parameter	Symbol	Unit
Inertial mass	m_{co}	600 kg
Initial inertial tensor	J0	144 I_3 kgm^2
Altitude orbit	height	500 10^3 m
Zero shoot time of thrusters	T_{sp0}	0.02 s
Maximum thrust	T_{max}	1 N
Specific impulse of thruters	I_{sp}	220 s
RW Maximum torque	g_{max}	1 Nm
RW Inertial tensor	I_{RW}	0.1 I_3 kgm^2

The trajectory of the complete maneuver in the xz plane is shown in the Fig.9. It can be demonstrated that the artificial potential method can be used also for path planning in the orbital maneuvers with the addition of obstacles, know and static.

Table 2. Main waypoints

Waypoint	Position [m]
Initial position simulation	[-16000, 0, 3000]
Terminal position simulation	[0.02, 0, 0]
Obstacle #1 in Hohmann transfer	[-10000,0,1500]
Obstacle #2 in the radial boost	[-2800,0,0]
Obstacle #3 in the radial boost	[-2100,0,200]

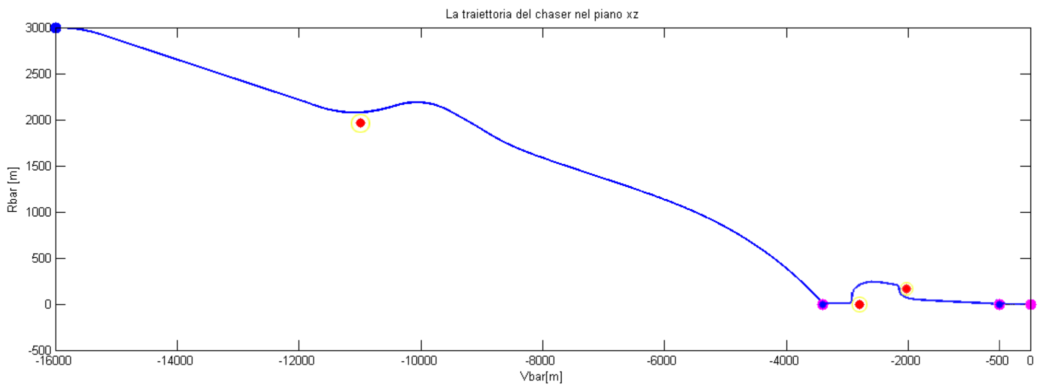


Figure 8. The complete trajectory in xz plane

In detail, we show the main results of each phases of the maneuver.

A. Hohmann transfer

For the Hohmann transfer, quasi-impulsive thrusts transfer the Chaser to a different height, reaching the Target altitude. The ending point in the LVLH frame is [-3000,0,0] m, that means 3km far than the Target. The input is the relative positions of the Chaser in LVLH frame by means of Hill equation. The output is the vector of Chaser of desired speed. The speed variation assigned by the guidance algorithm is function of the maximum thrust T_{max} and Δt, that is the guidance sample time equal to 1Hz. The sampling rate of the simulator is 100 Hz. The thruster forces are the outputs of first order SMC; it sees the upper and lower limits due to the maximum thrust value for the number of thruster that can be switched simultaneously, in our case 2. For the single obstacle, due to the high speed required to perform the maneuver, a bigger safety radius and an high elevated repulsive gain are defined to avoid it.

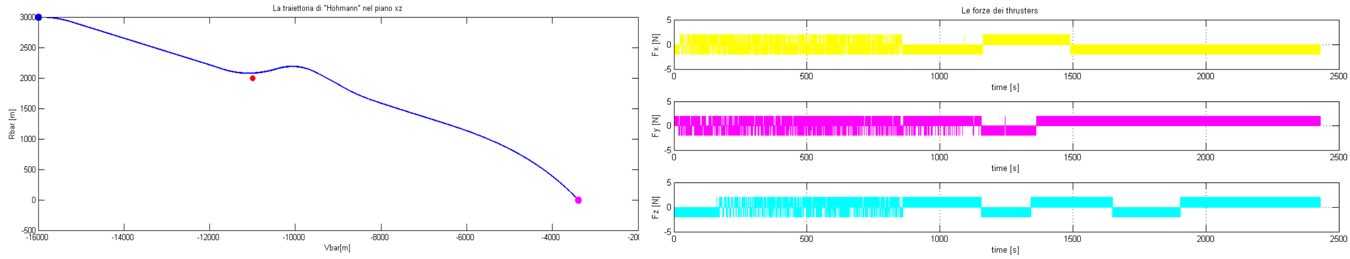


Figura 9. Trajectory and discontinous thrusters variation in the Hohmann transfer

B. Radial boost transfer

For the Radial Boost transfer, quasi-impulsive thrusts move close the Chaser towards the Target, until few meters. Precisely, the final point in the LVLH frame is [-500,0,0] m. In this maneuver, the safety radius of two obstacles and, consequently, the repulsive gain of artificial potential are changed to avoid them.

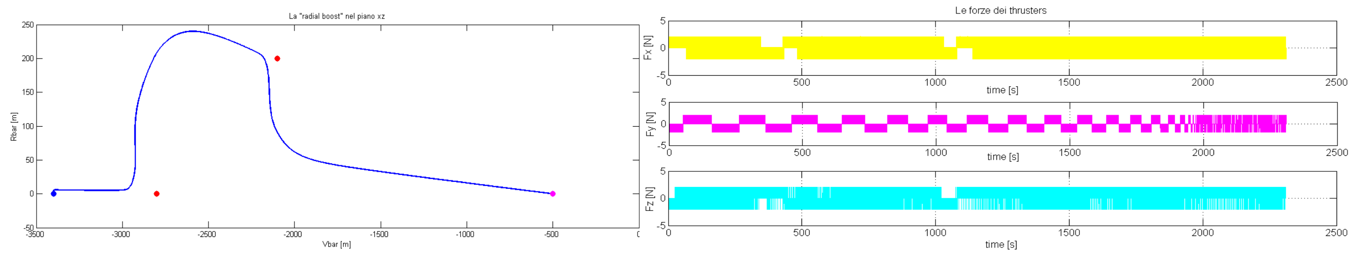


Figure 10. Trajectory and discontinous thrusters variation in the Radial Boost transfer

C. Cone approach

For the last part of the proximity operation, a proximity approach is considered in which the Chaser has to stay inside a pre-defined cone approach. The radius of the base of the cone is supposed to be 1 m and its vertex is represented by the final waypoint, a few centimeters from the Target. No obstacles are included in this last phase, because the Chaser is too close to the Target. The initial speed vectoris $\dot{x} = [0.15,0,0]$ m/s and the speed is decreased close to zero in the Target point, thanks to the SMC controller. Moreover, the sample time of the controller is increased to 50 Hz.

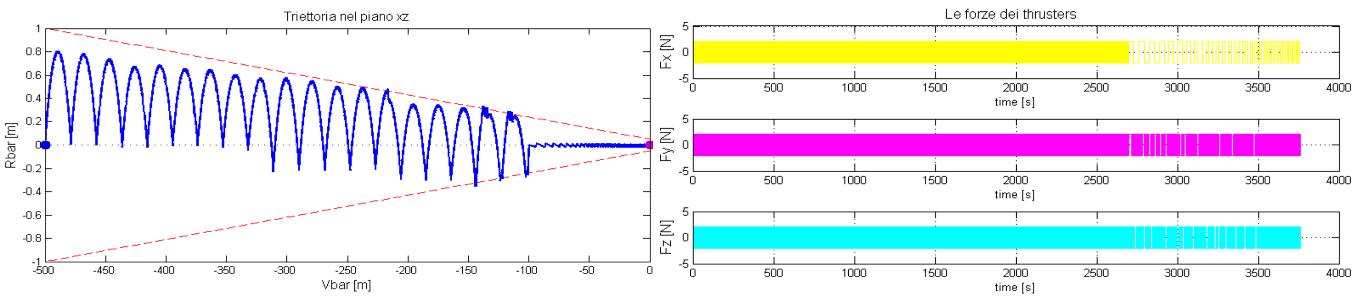


Figure 11. Trajectory and discontinous thrusters variation in the Cone Approch

VIII. Conclusions

A Guidance and Control algorithm for a Rendezvous maneuver between an active Chaser and a passive Target in circular orbit has been developed. Specifically, the focus of this study was to show how the path planning for orbital maneuver (safe, autonomous and able to avoid hypothetical obstacles) can be entrusted to the artificial potential method. The simulations demonstrate as an APF combined with sliding mode control return satisfying results. An important factor has been to create a field of vector forces appropriately weighed within the working space, in order to drive the Chaser towards its goal, respecting safety requirements. It was proven that this strategy can be easily implemented with a minimum on-board computational effort and can efficiently solve the problem of obstacle avoidance. However, it presents several problems and disadvantages that must be overcome in future works. The main problem is related to the possible appearance of local minima in the function of the constructed potential. These could arise in the event of perfect balance between the attractive and the repulsive potential, generating a cancellation of the gradient that could be seen by the chase as a "false" goal. This situation traps the satellite, which is not able to complete the desired path. Moreover, in this algorithm, the considered obstacles are in a fixed position and known a priori: we know their position and hypothesize a safety radius. In future, we could take into account the dynamics of the obstacle, as well as introducing the theme of real time collision avoidance through obstacle detection using LIDAR tools. With this change, the algorithm must be able to detect objects in its vicinity, calibrate the gains of artificial potential forces autonomously and overcome the obstacle. Additionally, a dynamic radius could be implemented, coming from this nominal, to take into account a velocity of chaser and to obtain a smoother trajectory.

Acknowledgement

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