GUIDANCE FOR RENDEZVOUS MANEUVERS INVOLVING NON-COOPERATIVE SPACECRAFTS USING A FLY-BY METHOD

Gilberto Arantes Jr., gilberto.arantes@zarm.uni-bremen.de
Ananth Komanduri, ananth.komanduri@zarm.uni-bremen.de
Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation - ZARM, Universität Bremen, Am Fallturm, D28359 - Bremen, Germany

Luiz S. Martins-Filho, luiz.martins@ufabc.edu.br
Universidade Federal do ABC - UFABC, Av dos Estados, 5001 - Bangu, 09210-971 - Santo André, SP, Brazil

Abstract. *Non-cooperative satellites include a vast category of spacecrafts which have lost their control or operational capabilities due to erroneous orbit injection or/and component failure. Space debris and Near-Earth Objects (NEO) belong to those classes of non-cooperating targets as well. Space missions like Orbital Express launched in 2007 open up a new era in space - on-orbit servicing - which is defined by repair, retrieval, maintenance, and rescue of satellites on orbit. The development of technologies for autonomous rendezvous and docking plays an important role for the mitigation of space debris problem. A fundamental challenge of on-orbit servicing is the safe approaching of the spacecraft to an unstable/uncontrollable target. In this case the target satellite is not able to cooperate with the service satellite during the rendezvous and capture phases. This work focuses on the guidance functions that can handle a satellite possibly rotating and lacking the ability to maintain its docking port or grasping fixture aligned with the on-orbit servicing requirements. The viability and suitability of the fly-by approach are tested through numerical simulations and preliminary sensibility analysis. The results show that the fly-by method can be an interesting guidance alternative for rendezvous and capture of non-cooperating targets.*

Keywords: *Spacecraft guidance and control, Rendezvous maneuvers, On-orbit servicing*

1. INTRODUCTION

This article aims to study a trajectory planning strategy for spacecrafts missions involving rendezvous tasks with non-cooperative targets, in the context of guidance, navigation and control (GN&C) problem. The most part of current guidance strategies is only applicable to cooperative targets, e.g. the International Space Station (ISS) that is 3-axis attitude controlled, using mainly maneuvers through straight V-bar and R-bar (considering the Hill frame axis) (Romano *et al.*, 2007). Safe and low cost in-plane maneuvers (ex: R-bar impulse) often do not suffice to meet all categories of non-cooperative targets. The non-cooperative targets include a vast category of spacecrafts which have lost their control or operational capabilities due to erroneous orbit injection or/and component failure. In other words, assets in orbit which have lost their control authority and can not convey any information concerning their states. Other classes of objects can be also considered. For instance, the space debris (parts of lost satellites and launchers), and celestial objects and asteroids NEO (Near-Earth Objects) belong to these classes of targets as well.

Space missions like Orbital Express, launched in 2007, open up a new era in space: the on-orbit servicing, which is defined by activities typified by actions of repair, re-supply, upgrade, retrieval, maintenance, and rescue of satellites on orbit (Weismuller and Leinz, 2006; Pinson, Howard and Heaton, 2008). This mission could perform autonomous rendezvous maneuvers, and accomplish tasks of capture and berthing, upgrade, refueling. It also inspected the client satellite using autonomous fly-around visual procedures (Friend, 2008). The development of technologies for autonomous rendezvous and docking (or grasping) plays an important role for the mitigation of space debris problem. A fundamental requirement of on-orbit servicing is the safe approaching of the spacecraft to an unstable/uncontrollable target. In this case, the target spacecraft is not able to cooperate with the service satellite during the rendezvous and capture phases. This technological challenge is stimulating studies and approaches propositions. For instance, an approach of multiple-spacecraft proximity control was tested with the Synchronized Position Hold Engage and Reorient Experimental Satellites (SPHERES) facility onboard the ISS (McCamish *et al.*, 2009), comprising the problem of obstacle satellite avoidance.

Missions involving scientific purposes like the study of asteroids, can also apply the proposed fly-by rendezvous strategy. In this case, the on orbit services consist of approximate, measure, observe specific features of the celestial object. An recent example of this kind of mission was the Hayabusa project, developed by the Japan Aerospace Exploration Agency (JAXA), consisting of an unmanned spacecraft aiming to return to Earth material sample from the NEO asteroid named 25143 Itokawa. In this mission, started 2003 and concluded in 2010, a challenger task was to land a probe in the asteroid to collect the surface material sample (Asphaug, 2006; Kubota *et al.*, 2006). In Brazil, a group of scientists and researcher of several institutions are preparing a deep space mission, the ASTER project, aiming a study of a triple asteroid system, and the selection of guidance and control strategy to accomplish the mission objectives has a crucial relevance (Sukhanov *et al.*, 2010).

This article focuses on the guidance functions that can handle a satellite possibly rotating and lacking the ability to maintain its docking port or grasping fixture aligned with the on-orbit servicing requirements. In the light of non-cooperative targets we study and analyze guidance schemes with time constraint (grasping time) and position constraint (grasping point). The motion of a non-cooperative target is influenced by the residual angular momentum it possesses. It can be either stabilized or rotating (angular rate < 18 deg/sec), spinning (faster angular rate > 18 deg/sec) or tumbling (angular rate changing direction). Focus is laid upon executing a fly by approach during the last phase of the mission. An elliptical fly-by strategy is chosen.

The viability and suitability of the fly-by approach are tested through numerical simulations and preliminary sensibility analysis. The results show that the fly-by method can be an interesting guidance alternative for rendezvous and capture of non-cooperating targets.

This introduction section, in addiction to the explanation of the article subject, it presents a short historic review of the rendezvous challenge. In Section 2, the problem formulation is presented, as well an analytical description of the proposed trajectory planning strategy. In Section 3, the article presents some numerical simulations in order to demonstrate the trajectories in the considered frames. The concluding remarks and the future steps of this research project close the article (Section 4).

1.1 In-plane rendezvous approaches

The origin of orbital rendezvous history can be attributed to the space race between USA and Soviet Union, in the 1960's (Woffinden and Geller, 2007). This dispute for the space hegemony stimulated the development of technological challenges like the in-orbit docking maneuvers. The improvement of these audacious programs was supported by financial resources and political sponsorship. This period gave origin to innumerable propositions and ideas since the orbital rendezvous was a challenge that had never been overcome before.

The independent initiatives, the American and the Russian efforts, originated two distinct approaches, nevertheless both were in-orbital plane. The American approach was based on manual procedures, and the Russian one consisted of an automated rendezvous methods. The complementarity of those solutions could finally converge with the end of the "cold war" to the orbital rendezvous solutions that are currently adopted, basically autonomous approaches. Four programs symbolize the first stages of this historical development: Vostok, Gemini, Soyuz, and Apollo (Woffinden and Geller, 2007).

At the present technological scenario, one of the most important rendezvous maneuvers is performed by the Space Shuttle for docking with the International Space Station (ISS). In more than two decades, the Shuttle executed five dozens of missions with different goals, like station assembly, crew exchange, and re-supply of the ISS.

A typical rendezvous scenario for the Shuttle to the ISS combines approximation phase (until 74km) planned and controlled by ground control, and a following phase calculated and controlled automatically by the Shuttle GN&C system (this phase can be also conducted manually by the Shuttle crew) (Woffinden and Geller, 2007). The terminal phase, concerning the last 15km trajectory, combine automatic and manual operations. The Fig. 1 illustrates the phases and trajectories of the Shuttle rendezvous maneuvers.

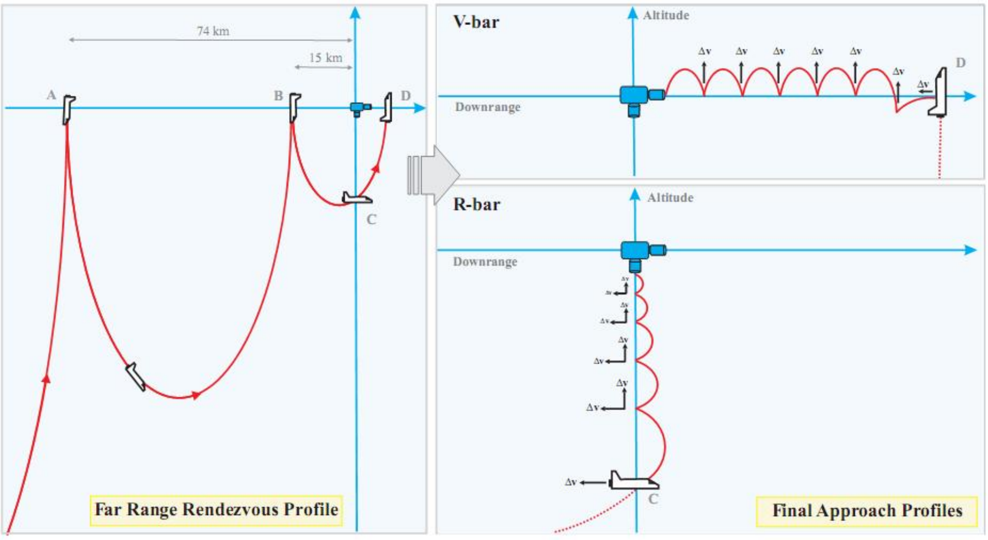

Figure 1. Example of in-plane rendezvous strategy for ISS/Shuttle (Woffinden and Geller, 2007).

The two Russians vehicles for space activities, the man-rated Soyuz and the cargo carrying Progress, were equipped with a rendezvous and docking system called Igla. The Igla system was used to docking with Mir space station. This system was upgraded in the second half of 80's to the new system called Kurs, that is used currently to docking with ISS. The main changes in the rendezvous maneuvers control are the new set of antennas that allows acquisition and maneuvering at much greater distances. The Fig. 2 shows the sequence of rendezvous maneuvers. Up to the M3 phase, the vehicle is controlled by the ground control station. From M4 to the conclusion of the docking task, the maneuvers operation is performed by the on-board control system (Woffinden and Geller, 2007). The Fig. 2 illustrates the phases and trajectories of the Soyuz/Progress rendezvous maneuvers.

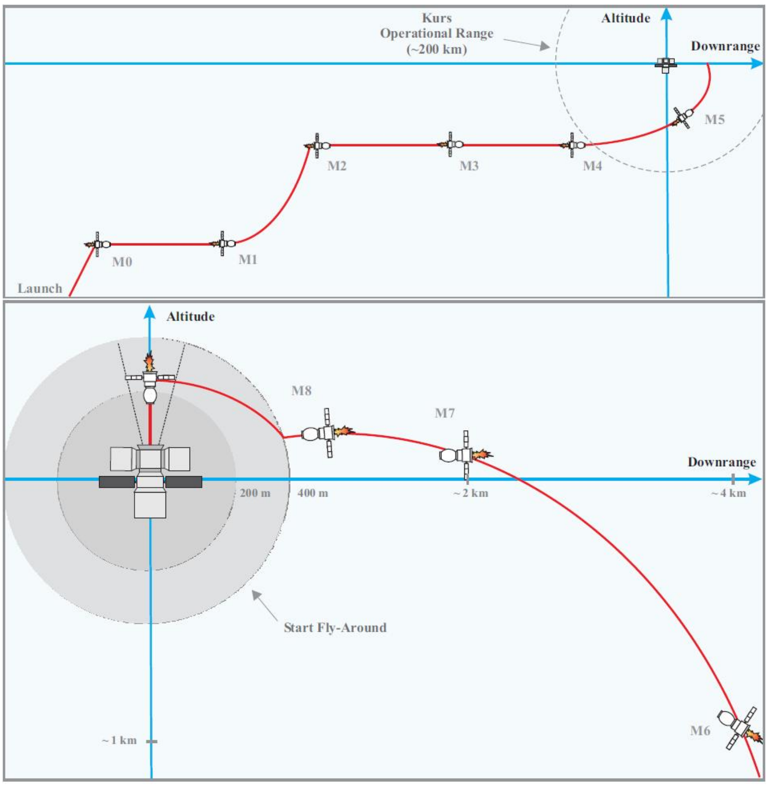

Figure 2. Example of in-plane rendezvous strategy for Soyuz/Progress (Woffinden and Geller, 2007).

2. PROBLEM FORMULATION AND FLY-BY APPROACH

In order to capture a target whose grasping fixture may be rotating or spinning in a plane which is inclined to the target's orbital plane, out of plane maneuvers are mandatory even though expensive. We have investigated an elliptical fly-by approach method to deal with those rotating targets.

2.1 The Hill frame description

The Hill frame (VHR-bar) is used to describe the relative motion between target and chaser satellite. Its origin is placed in the center of mass of the target satellite. The axis x is in the direction of the orbital velocity vector, aligned with it for a circular orbit, this axis is referred to as V-bar. The axis y is in the direction of the angular momentum vector of the orbit and it is referred to as H-bar. The axis z is pointing toward to the center of the Earth which is referred to as R-Bar. The V-bar and R-bar axes belong to the orbital plane of the target satellite. Those are depicted in Fig. (3). The Fig. 3 also illustrates the uncontrolled target's rotation motion which may not be restrained in the orbital plane, i.e VR-bar plane, therefore V and R-bar guidance schemes are unsuitable in for those satellite. The fly-by guidance schema is thus considered as an alternative for rendezvous with uncontrolled rotating targets.

We assuming that the target satellite in a near circular orbit and there is non-gravitational forces acting on it, e.g eccentricity of the target's orbit $e \cong 0$), for Earth observation satellites this assumption is valid. The equations ruling the motion are given by:

$$\ddot{\mathbf{r}}(t) = -2\mathbf{\Omega}(t) \times \dot{\mathbf{r}}(t) + n(t)^2 \begin{bmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 3 \end{bmatrix} \mathbf{r}(t) + \mathbf{u}(t) \tag{1}$$

where (x, y, z) represent the coordinates of the chaser satellite w.r.t. the target satellite (see Fig. (4)), $\mathbf{\Omega}(t) = [0 \;\; -n \;\; 0]$, $n(t) = n$ is the target orbital rate which is here constant, and $\mathbf{u}(t)$ represents the external forces (control and perturbation

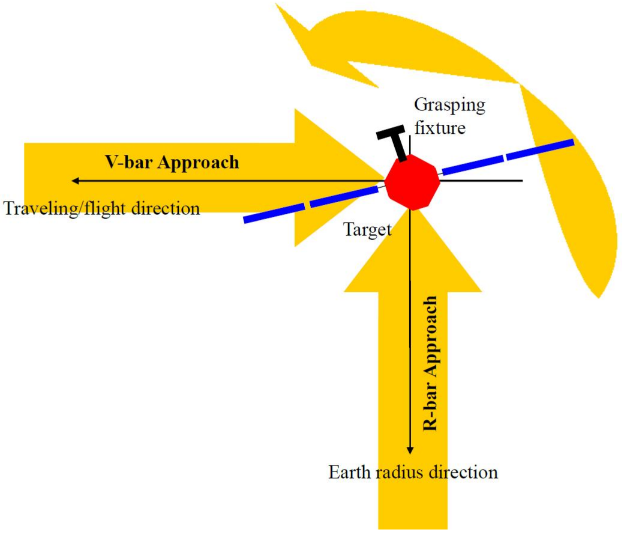

Figure 3. The problem description in Hill frame.

forces acting in the chaser satellite). Notice that the relative motion can be separately modeled as: (i) in-plane motion (xz) and, (ii) out-of-plane motion (y). The motion along x and z are coupled by $+/-2n$ which is relative small, the motion along y is unstable, e.g. a sinusoidal fashion with constant amplitude and frequency $\frac{sqrtn}{2*\pi}$ and undamped if $u_y = 0$. This turns an approach along H-bar very critical because if any failure occurs in the propulsion system of the chaser satellite the same will encounter in a collision trajectory with the target object.

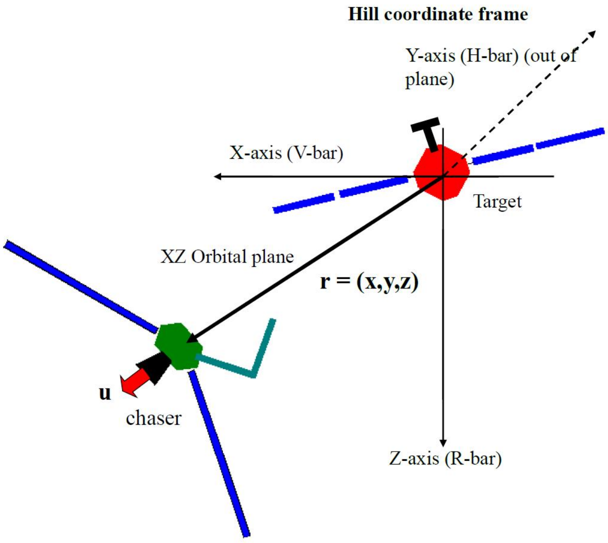

Figure 4. The relative position between chaser and target spacecrafts in Hill frame.

Regarding the safety of the fly-by approach it is compulsory a Failure Detection Isolation & Recovery (FDIR) system architect that supervise the maneuver in the portion of the guidance which is hazardous for the target and chaser. We present next the fly-by approach step by step.

2.2 The Fly-By approach

The algorithm of the fly-by guidance is summarized as follows,

Step 1: Define the fly-by plane

We define a new frame named fly-by frame ($x_a y_a z_a$) which is a reference frame defined in the fly-by plane (see

Figure 4). The transformation between the Hill's frame (xyz) and the fly-by frame is given by

$$\begin{bmatrix} x_a \\ y_a \\ z_a \end{bmatrix} = C \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{2}$$

$$C = C_y(\theta^*_{y0}) C_{xy}(\theta_x \theta_y) \tag{3}$$

$$C_{xy}(\theta_x \theta_y) = \begin{bmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\cos\theta_x \sin\theta_z & \cos\theta_x \cos\theta_z & \sin\theta_x \\ \sin\theta_x \sin\theta_z & -\sin\theta_x \cos\theta_z & \cos\theta_x \end{bmatrix} \tag{4}$$

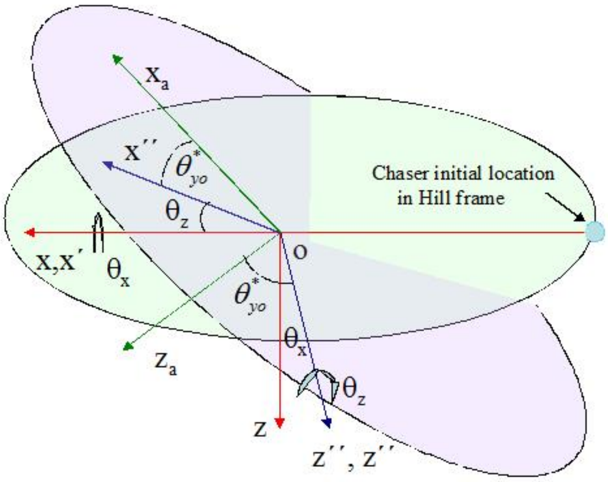

Figure 5. The frames of Fly-By approach.

Step 2: Define the grasping constraints: grasping point and grasping time

The geometry of the angles involved in fly-by approach is shown in Fig. XXX. The location of the chaser at any time t in the fly-by plane $(x_a, 0, z_a)$ is given by the eccentric angle given by:

$$\theta_y = \theta_{y0} + 2\pi(t/T) \tag{5}$$

where θ_{y0} is the initial eccentric angle at time $t = 0$.

$$\theta_{y0} = \arctan\frac{-z_a(t=0)a}{x_a(t=0)b} \tag{6}$$

Here a and b are the semi-major and semi-minor axis of the fly-by ellipse. Two important remarks about the proposed approach:

- The grasping point is define by the choices of a and b .
- The grasping time, time when the grasping point is located at fly by plane, is define by T

Thus, the guidance solution of the chaser is order to grasp the rotating target satellite is given by:

$$\mathbf{r}(t) = C^{-1} \begin{bmatrix} a\cos\theta_y(t) \\ 0 \\ -b\sin\theta_y(t) \end{bmatrix} \tag{7}$$

Some requirements must be fulfilled for the application of the proposed fly-by approach:

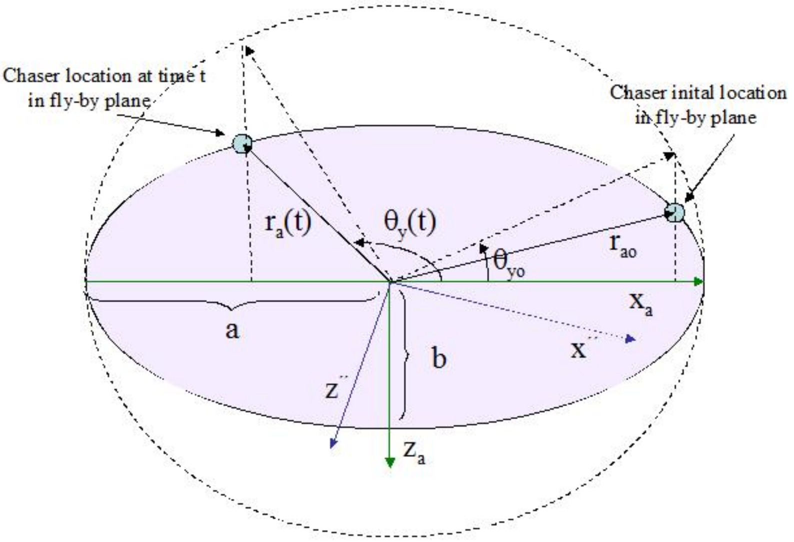

Figure 6. Description of the geometry of Fly-By approach angles.

- The navigation solution giving relative position and attitude of the target is considered as continuously made available to the chaser spacecraft navigation control by on-board relative sensors and signals processing;
- We suppose that the chaser is equipped with an agile and continuous actuation, capable to provide the adequate control actions;
- We also assume that the chaser has enough control authority during the fly-by maneuver execution, that means the on-board control hardware and software perform properly.

The fly-by approach is very general is can suit a large category of targets, we considered for the simulations a target with small eccentricity, however, there are no constraints about the target's orbit eccentricity in the fly-by approach that can be used either for satellites within elliptical orbit or near Earth objects.

3. SIMULATIONS AND RESULTS

The main ideas of the proposed rendezvous trajectories planning strategy were tested and validated through some numerical simulations. In spite of the limits of these simulations, that could not include control aspects in the present stage of this study, they can illustrate important features of the obtained solutions. They can also contribute to determine options in terms of the control approaches to be adopted.

Two scenarios were built to these numerical simulations: (I) an in-orbit plane rendezvous fly-by trajectory planning; and (ii) a out-of-orbit rendezvous fly-by trajectory planning.

In the first simulation scenario, the grasping point is rotating in-plane and the fly-by frame is coinciding with VH bar. The angles θ_x, θ_z are both zero, and $\theta_{y0} = 0$. The parameters of ellipse are $[a \;\; b] = [100 \;\; 20]$, the initial location of chaser in Hill frame is $[-100 \;\; 0 \;\; 0]$, the initial location of chaser in fly-by frame is $[-100 \;\; 0 \;\; 0]$, elliptical fly around time period (i.e. the simulation time) is 36 sec; the fly rate is 10 deg/sec. The results of this scenario simulations are shown in Fig. 7-9 (illustration of the fly-by plane, positions in Hill frame and fly-by frame, and velocities).

In the second simulation scenario, the grasping point is rotating in an inclined plane in relation to the orbital plane. This scenario imposes an out-of-plane rendezvous solution. The angles θ_x, θ_z are both 45 deg, the fly-by frame rotation with respect to the reference has the inclination $\theta_{y0} = 45$. The parameters of ellipse are $[a \;\; b] = [100 \;\; 20]$, the initial location of chaser in Hill frame is $[-66.6906 \;\; -22.2302 \;\; -31.4382]$, the initial location of chaser in fly-by frame is $[-75.8986 \;\; 0.0000 \;\; 13.0221]$, elliptical fly around time period (i.e. the simulation time) is 36 sec; the fly rate is 10 deg/sec. The results of this scenario simulations are shown in Fig. 10-12 (illustration of the fly-by plane, positions in Hill frame and fly-by frame, and velocities).

4. CONCLUSION

This article presented a fly-by strategy of spacecraft trajectory planning for the problem of rendezvous with a non-cooperative target. The proposed methodology is specially suitable when the target exhibits out of plane motions. The fly-by planning approach can facilitate the design of time unconstrained trajectories.

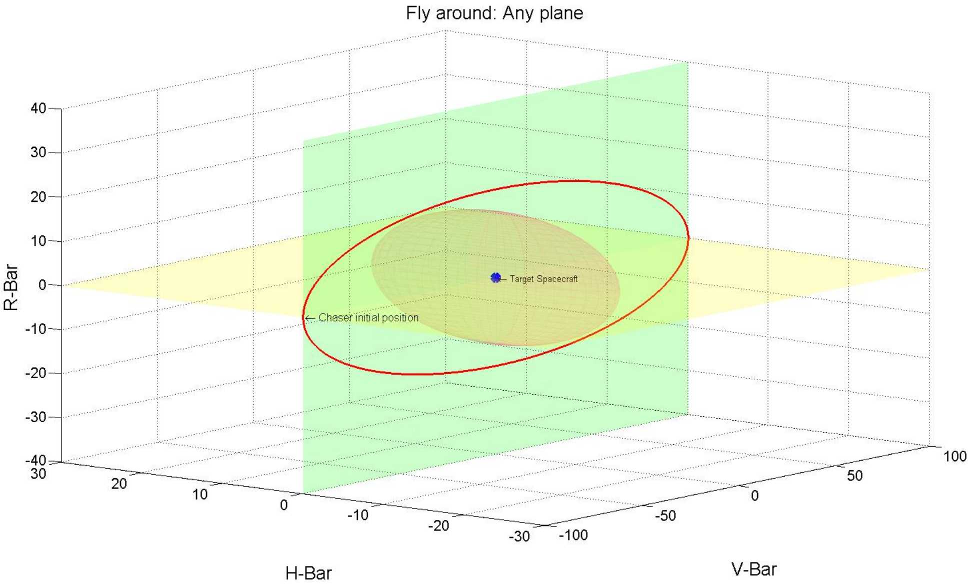

Figure 7. Illustration of the fly-by plane in the case in-plane rendezvous.

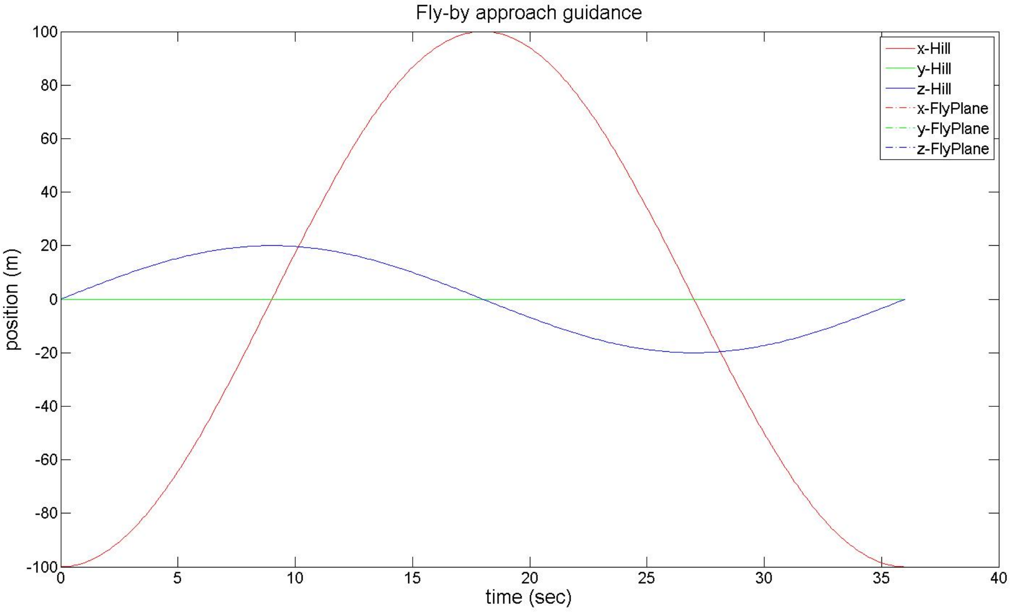

Figure 8. The planned trajectory positions in Hill frame and fly-by frame, which are coincident in this case).

If the spacecraft maneuver is designed to be executed using multiple thrust impulses, the amount of fuel spent can be obtained from the multi-pulse glide slope. The angular velocity of the chaser in the fly around plane should be chosen to be the spin rate of the target to keep the relative velocities close enough at the grasping position. In this case, this scheme works very well for targets with different spin rates.

The study, in the present developing stage, show how to determine the trajectory parameters, using a Hill coordinates frame and the relative motion description, and can provide the references to a closed loop control system, to be processed on-board of the chaser spacecraft. Evidently, this GN&C system is supposed to satisfy a number of very exigent requirements concerning sensors and actuators to be available in the spacecraft.

4.1 Future works

This research project will continue with the application of the planned trajectory for the chaser spacecraft into a closed loop control scheme. It means that the very first next step is to project the guidance control system, analyzing different control approaches in order to obtain adequate performance in terms of trajectory precision, energy consumption, and

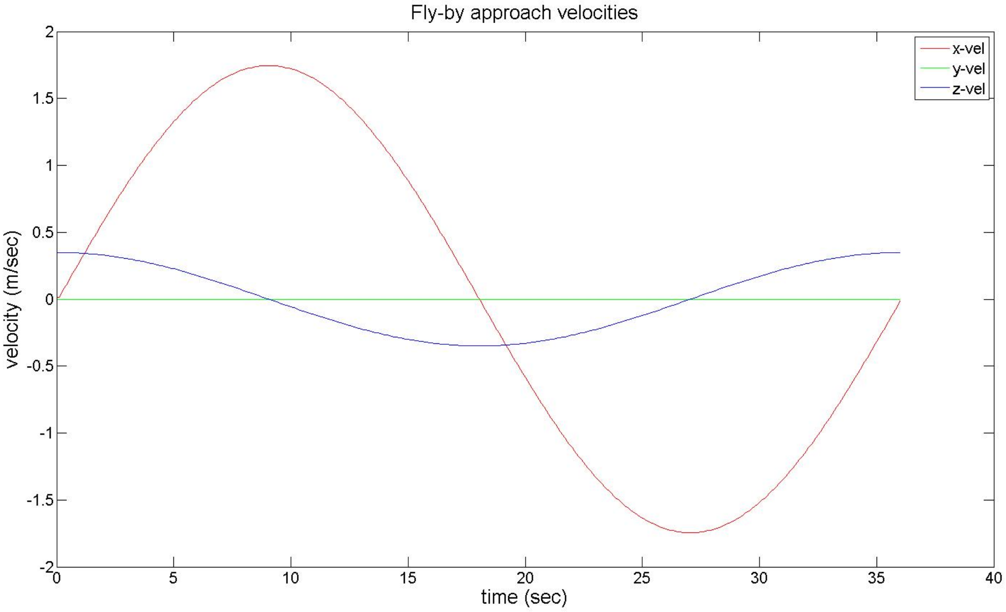

Figure 9. The planned trajectory velocities.

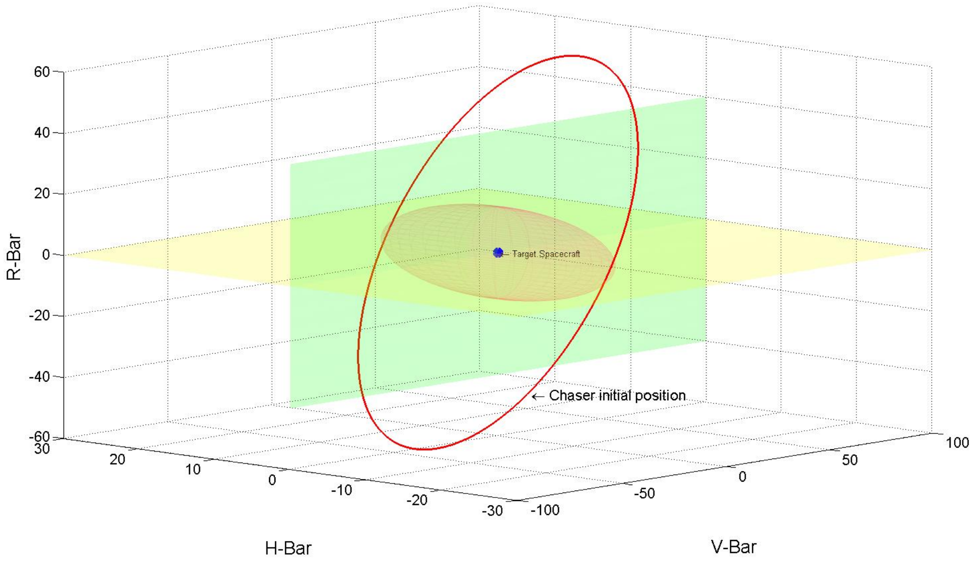

Figure 10. Illustration of the fly-by plane in the case out-of-plane rendezvous.

time optimization. These performance features can be taken into account with the model extension to include additional constraints, e.g. fuel and relative velocity constraints at the grasping position, and others. Another further investigation concerns the safety of the fly-by approach, the risks evaluation of different mission aspects. This investigation is related also to the incertitude associated to the problem modeling and the obtained navigation solution.

5. ACKNOWLEDGEMENTS

The authors acknowledge the support of ZARM (Germany) and UFABC (Brazil), *Fundação de Amparo à Pesquisa do Estado de São Paulo* – FAPESP (São Paulo, Brazil), *Conselho Nacional de Desenvolvimento Científico e Tecnológico* – CNPq (Brazil) and the cooperation program *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* – CAPES/ *Deutscher Akademischer Austauschdienst* – DAAD/ CNPq (Brazil/Germany).

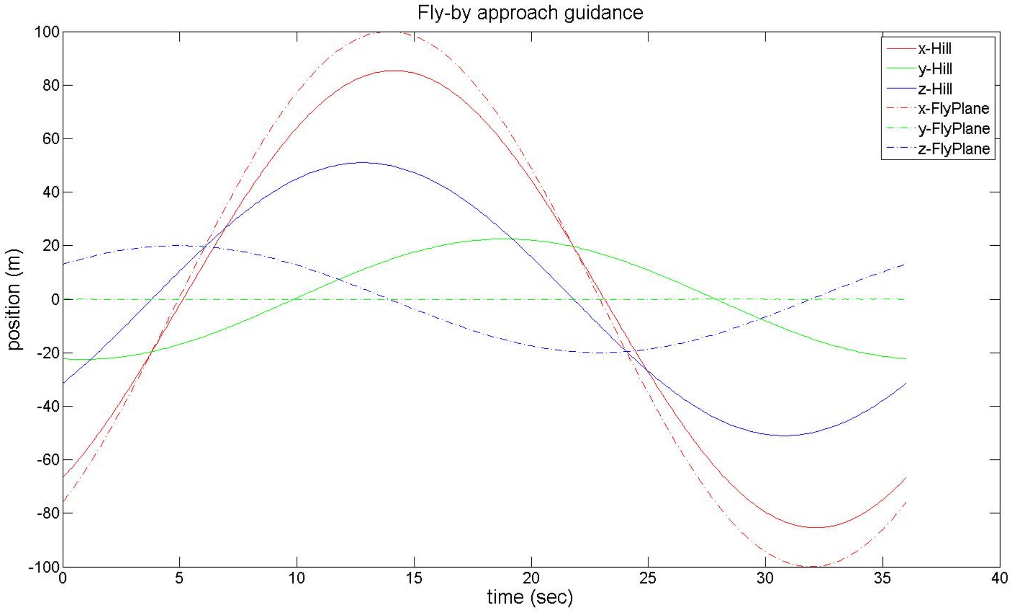

Figure 11. The planned trajectory positions in Hill frame and fly-by frame.

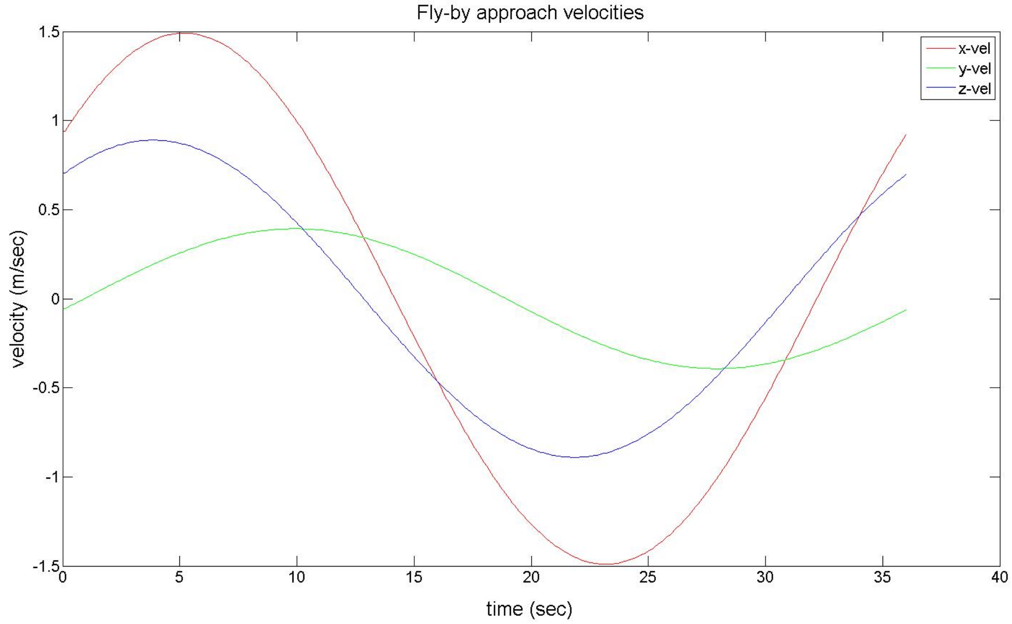

Figure 12. The planned trajectory velocities.

6. REFERENCES

Asphaug, E., 2006. “Adventures in Near-Earth Object Exploration”. *Science*, Vol. 312, No. 5778, pp. 1328–1329.

Friend, R.B., 2008. “Orbital Express program summary and mission overview”. In *SPIE, Sensors and Systems for Space Applications. II*. Orlando, Florida, USA, Vol. 6958, 695803.

Kubota, T., Otsuki, M., Hashimoto, T., Bando, N. and Yano, H., 2006. “Touchdown Dynamics for Sampling in Hayabusa Mission”. In *Proceedings of the AIAA/AAS Astrodynamics Specialist Conference and Exhibit*. Keystone, Colorado, USA, Vol. 1, pp. 1–9.

McCamish, S.B., Romano, M., Nolet, S., Edwards, C.M. and Miller, D.W., 2009 “Flight testing of multiple-spacecraft control on SPHERES during close-proximity operations”. *Journal of Spacecraft and Rockets*, Vol. 46, No. 6, pp. 1202–1213.

Pinson, R.M., Howard, R.T. and Heaton, A.F., 2008. “Orbital Express advanced video guidance sensor: ground testing, flight results and comparisons". In *Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit*. Honolulu, Hawaii, USA, Vol. 1, pp. 1–9.

Romano, M., Friedman, D.A. and Shay, T.J., 2007. "Laboratory experimentation of autonomous spacecraft approach and docking to a collaborative target". *Journal of Spacecraft and Rockets*, Vol. 44, No. 1, pp. 164–173.

Sukhanov, A.A., Velho, H.F.C., Macau, E.E.N. and Winter, O.C., 2010. "The Aster project: Flight to a near-Earth asteroid". *Cosmic Research*, Vol. 48, No. 1, pp. 443–450.

Weismuller, T.,Leinz, M., 2006. "GN&C technology demonstrated by the orbital express autonomous rendezvous and capture sensor system". In *Proceedings of the 29th Annual AAS Guidance and Control Conference*. Breckenridge, Colorado, USA, Vol. 1, pp. 1–9.

Woffinden, D.C. and Geller, D.K., 2007. "Navigating the Road to Autonomous Orbital Rendezvous". *Journal of Spacecraft and Rockets*, Vol. 44, No. 4, pp. 898–909.

7. Responsibility notice

The author(s) is (are) the only responsible for the printed material included in this paper