Fast reconfiguration maneuvers of a micro-satellite constellation based on a hybrid rocket engine

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Abstract. In this work, the formation flight of the CubeSat cluster RODiO (Radar for Earth Observation by synthetic aperture DIstributed on a cluster of cubesats equipped with high-technology micro-propellers for new Operative services [1]) with respect to a small satellite in LEO (Low Earth Orbit) has been analyzed. RODiO is an innovative mission concept funded by the Italian Space Agency (ASI) in the context of the Alcor program [2]. The small satellite is equipped with an antenna that allows it to function as a transmitter, whereas RODiO functions as a receiver. The extension of the virtual *SAR (Synthetic Aperture Radar) antenna* can be achieved by establishing an along-track baseline performing an orbital coplanar maneuver (a phasing maneuver). Another interesting scenario is the possibility to create a cross-track baseline performing an inclination change maneuver, useful for stereoradargrammetric applications. Such formation reconfiguration maneuvers can be achieved in relatively short times only by use of a high-thrust propulsion system, i.e. based on conventional chemical technologies. From the study of maneuvers, it is possible to identify the required ΔV, which represents an input parameter for the design of propulsion system. Among the different kinds of propulsion systems, a *Hybrid Rocket Engine* was chosen for its safety, compactness and re-ignition and throttle capabilities.

Introduction

In recent years, the use of CubeSats has become increasingly popular due to their simplicity of construction, cost and reduced production time compared to conventional satellites. These miniaturized satellites are well suited to formation flight for telecommunication and imaging purposes. In this study, the formation flight of a 16U CubeSat constellation (RODiO, consisting of four micro-satellites) was analyzed with respect to a LEO-satellite. The objective is to perform maneuvers to extend the virtual *SAR antenna*. The LEO-satellite is moving on a quasi-circular Sun-Synchronous Orbit (eccentricity ≈ 10^{-3}, inclination ≈ 97°) at a mean altitude of ≈ 400 km (World Geodetic System-84), and RODiO cluster follows it on this orbit.

In the following sections the *orbital maneuvers* considered were described. Using *GMAT (General Mission Analysis Tool)* an estimation of the maneuvers ΔV budget was obtained. Identified the maneuvers costs, a preliminary design of the *Hybrid Rocket Engine* for the CubeSat was carried out, complying with the requirements for propulsion unit volume (<1.5U) and mass (<2kg).

Phasing maneuver

In this maneuver, the objective is to bring one of the satellites of the RODiO cluster, which follows the LEO-satellite in its orbit, from a distance in the range [-90 km, -50 km], to a distance in the range [+50 km, +90 km]. In this way a *multistatic SAR data collection* with a triplet of acquisitions over the same area at three different observation angles is possible.

To this aim, a ΔV in the opposite direction of the motion must be applied. In this way the satellite RODiO reaches an elliptical orbit with an orbital period smaller than the period of the initial orbit and, after one orbit, the RODiO satellite reduces the along-track distance. After few orbits, the RODiO satellite reaches a new position beyond LEO-satellite and, at this point, a ΔV in the motion direction must be applied to establish a constant *along-track baseline*. The challenging point of this mission is the need to apply two ΔV but in opposite direction and evaluating the re-ignition capability of the propulsion system.

To study the relative motion between two satellites, the Hill reference frame defined in [3] was used, assuming that the LEO-satellite is the chief, while RODiO is the deputy. Combining the equations for the Hohmann transfer reported in [4] (under the assumptions of Keplerian mechanics), it is possible to write Eq. 1, which provides an initial estimate of the along-track baseline variation per orbit (ΔY_{orbit}):

$$\Delta Y_{orbit} = (\tau_{ci} - \tau_e)\, V_{ci} \tag{1}$$

where “τ_{ci}” is the orbital period of initial circular orbit, “τ_e” is the period of elliptical orbit, and “V_{ci}” is the velocity on the initial circular orbit. In Table 1 different cases are presented, and a simulation of relative motion using *GMAT* considering the presence of the atmosphere (*Jacchia-Roberts* model), the non-sphericity of the earth (*Earth Geopotential Model 96*), and solar radiation pressure, has been performed (results in Fig.1).

Table 1: Possible phasing maneuvers in the along-track distance ranges considered for different ΔV. (Y_i is the initial distance between a RODiO satellite and the LEO-satellite, Y_f is the final distance).

ΔV of single burn [m/s]	Y_i [km]	ΔY_{orbit} [km]	Number of orbits	Y_f [km]
2.5	-62.25	41.5	3	+62.25
3	-75	50	3	+75

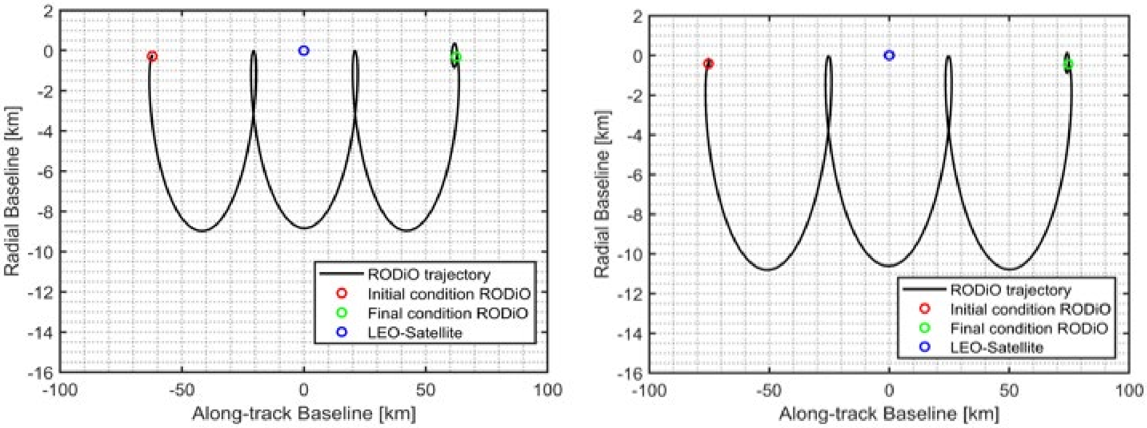

Fig. 1: RODiO trajectory in Hill reference frame with respect to LEO-Satellite (on the left, first case indicated in Table 1, on the right, second case indicated in Table 1).

Inclination change maneuver

The purpose of this maneuver is to change the inclination of the orbit of a satellite of the RODiO constellation by applying a normal ΔV to the orbital plane when the satellite arrives in the ascending node. In this way a relative drift of the nodes starts, and, after a certain time, a *cross-*

track baseline is established. Applying an impulsive burn in the same direction but where the satellite reaches the descending node, the *cross-track baseline* remains constant. An advantage of this maneuver is that the direction of ΔV does not change.

In *GMAT* the study of relative motion between two satellites of RODiO cluster has been analyzed (RODiO-1 is the chief, RODiO-2 is the deputy). Under the assumptions of a quasi-circular orbit, considering J2 effect, it is possible to simplify the equations of relative motion reported in [3] and calculate the *cross-track baseline* from Eq. 2:

$$z \approx a\delta\Omega \sin i \tag{2}$$

where "z" is the *cross-track baseline*, "a" is the semi-major axis, "δΩ" is the relative drift of ascending node consequent to the inclination change, and "i" is the inclination. In the Fig.2 the results obtained by *GMAT* for a ΔV = 3 m/s (that yields a Δi of 0.02 deg [4]) for each burn and a waiting time of 15 days are shown.

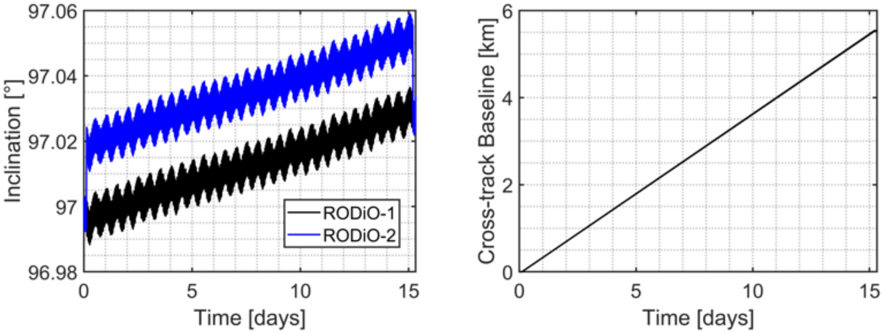

Fig. 2: Trend of inclination (on the left) and trend of cross-track baseline (on the right) with respect to mission time for ΔV = 3 m/s.

Hybrid Rocket Engine preliminary design

A mixture with *Hydrogen Peroxide* as oxidant (*91wt%*) and *ABS (Acrylonitrile Butadiene Styrene)* as fuel grain is selected to evaluate the performance of the *Hybrid Rocket Engine*. In first approximation, the regression rate for a hybrid rocket motor is related to oxidizer mass flux (Eq.3):

$$\dot{r} = a\,(G_{ox})^n \tag{3}$$

where "a" and "n" are experimental coefficients which change for each couple of propellants. Using the procedure described in [5] and considering experimental value of "a" and "n" obtained from test conducted on this engine scale, an estimate of the performance of the thrust chamber was performed. Considering an oxidant flow rate of 3.5 g/s, a circular port fuel grain with an initial port diameter of 10 mm, a nozzle throat diameter of 2 mm and an Area Ratio of 15, the performance of the propulsion system in terms of thrust and specific impulse can be evaluated. The mass of the CubeSat is 22 kg, but for an initial estimation of the performance and sizing of the rocket, a 10 kg margin on the mass budget (total mass of 32 kg) and a 100% margin on the ΔV (total ΔV required for maneuvers 12 m/s instead of 6 m/s) are considered. Table 2 shows the performance of the *Hybrid Rocket Engine*. The *Hydrogen Peroxide* total mass required is 106.75 g. From the performance analysis, it is possible to preliminarily size the propulsion system, in particular the thrust chamber, which will include a case containing the fuel grain and nozzle. Fig. 3 shows a sectional view of the thrust chamber with all dimensions of interest indicated from which it is possible to observe a pre-combustion chamber (upstream to fuel grain) of 10 mm length, a postcombustion chamber (downstream of the fuel grain) consisting of a cylindrical section (10 mm long) and the converging nozzle section (10 mm long). The pre- and post-chamber lengths shall be better defined by a more accurate study of the rocket's internal thermo-fluid dynamics. Considering graphite as material, the conical nozzle has a mass of 55 g. To reduce the length of the diverging section, a bell-shaped nozzle can be considered. In first approximation, the external case made up of steel, and its mass is 179 g. The mass of ABS fuel grain is 46 g. Since the dimensions of the thrust chamber are considerably smaller than the imposed limits (1.5 U, 10 cm x 10 cm x 15), it is reasonable to assume that there is sufficient space for the feed line, tanks, and catalytic chamber. With an appropriate choice of materials, the total mass requirement (<2kg) is also satisfied.

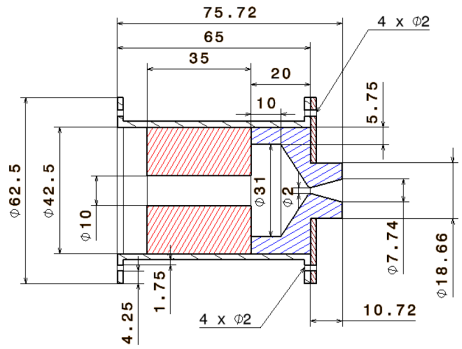

Fig. 3: CAD model section of thrust chamber (dimensions in mm). In blue the conical nozzle, in red the fuel grain, in black the external case, in brown a closing flange (wall thickness flange and case: 2 mm).

Table 2: Summary of mixture performance H_2O_2 (%wt 91) - ABS. Average values of regression rate, OF, vacuum thrust, specific vacuum impulse, fuel flow rate, chamber pressure, chamber temperature, and final grain diameter were reported (combustion efficiency and nozzle efficiency about 95%. Overall efficiency 90.25%).

t_b [s]	$\dot{r}$[mm/s]	OF	T_{vac}[N]	Isp_{vac}[s]	$\dot{m}_f$[g/s]	P_c [bar]	T_c [K]	D_{final} [mm]
30.5	0.53	2.31	12.6	255	1.53	22.6	1930	42.5

Concluding remarks

From numerical *GMAT* simulations it is possible to conclude that the *along-track baseline* variations are possible to move one RODiO satellite from the original position to a final position in few orbits, whereas a *cross-track baseline* variations up to few kilometers are possible with maneuvers duration of the orders of few days. Future developments could include a detailed design of the other main subsystems, numerical analysis of fluid dynamic, thermal and structural aspects, and the possibility of developing breadboards for ground testing of the propulsion unit.

References

[1] A. Renga, et al., Design considerations and performance analysis for RODiO distributed SAR mission, Acta Astronautica, Volume 210, September 2023, Pages 474-482. https://doi.org/10.1016/j.actaastro.2023.04.001

[2] G. Leccese, et al., Overview and Roadmap of Italian Space Agency Activities in the Micro- and Nano-Satellite Domain, 73rd IAC, Paris, France, 2022, 18 – 22 September.

[3] M. D'Errico (ed.), Distributed Space Missions for Earth System Monitoring, Space Technology Library, Springer Science Business Media, New York 2013, pp. 125-162. https://doi.org/10.1007/978-1-4614-4541-8_3

[4] D.A. Vallado, Fundamentals of Astrodynamics and Applications, Space Technology Library, Springer Dordrecht, edition 2, pp. 317-422.

[5] S. Mungiguerra, et al., Characterization of novel ceramic composites for rocket nozzles in high-temperature harsh environments, International Journal of Heat and Mass Transfer, 163 (2020) 120492. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120492