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ITASAT-2: Formation flying maneuver and control considering J_2 disturbances and differential drag

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Abstract – **Studies have shown that the Brazilian region has several unique features in its geospatial. In this context, the ITASAT-2 mission, plans to launch three satellites in formation flying, in order to improve the knowledge that we have today about the phenomenology of space plasma. The objective is also to capture the signal to provide the geolocation service. This work aims to use simulation and movement control techniques to verify and evaluate the behavior of the following vehicles using different phase angles in detachment and rendezvous maneuvers in relation to the movement of the chief CubeSat considering two orbital disturbances: the J_2 term of the gradient disturbance of gravity due to the inhomogeneity of the Earth and the disturbance due to the differential aerodynamic drag of the satellites. For that, the linear model in Cartesian coordinates called Clohessy-Wiltshire Equations and the optimal control approach described by the Linear Quadratic Regulator (LQR) were used.**

Key-Words – **CubeSat, Formation Flying, ITASAT-2.**

I. INTRODUCTION

In 1976, optical observations of the ionosphere over the region of Cachoeira Paulista [1], a city in the interior of the state of São Paulo, under the coordination of researchers José Humberto Sobral, from INPE (National Institute for Space Research,"Instituto Nacional de Pesquisas Espaciais"), and Mangalathayil Abdu, from ITA (Aeronautics Institute of Technology, "Instituto Tecnológico de Aeronáutica" in Portuguese) showed the first indications that the brazilian region presents singularities in its geospatial environment that require attention. Later, in 2006, the discovery took place simultaneously in other parts of the globe by foreign researchers [2].

Studies have shown that Brazil has several unique characteristics in its geospace, such as the distinct configuration of the lines of the geomagnetic field, which have a high declination (difference between the geographic and geomagnetic axes), the intense reduction of its magnitude (Magnetic Anomaly of the Atlantic South) and the frequent occurrence of large-scale depletion in plasma ionospheric density, also called plasma bubbles, whose effect occurs most strongly between October and March, and their frequency decreases until reaching a minimum around June or July [2].

As a consequence, plasma bubbles can lead to disturbances that affect the propagation of radio and telecommunication signals that can cause the interruption or malfunction of essential communication, navigation, and other services.

Therefore, specifically for the study of the ionosphere, there are phenomena not yet fully understood by man, but whose effects can cause irreparable damage. More detailed development is needed for the temporal resolution of ionosphere measurements and to advance the understanding of the nature and evolution of ionospheric structures around the sunset, related to the space climate.

In this context, the ITASAT-2 project has been proposed as a space mission in a joint effort by ITA and with the collaboration of Brazilian research institutions that have joined the recent technological-scientific efforts made by Brazil in the scope of development of CubeSats. It is worth mentioning that the scientific community is very interested in better understanding the ionosphere, so that the ITASAT-2 space climate mission becomes a continuation of the ongoing project called SPORT (Scintillation Prediction Observation Research Task) [3] - a subsequent mission space climate, the result of an international cooperation between ITA, NASA and INPE.

In order to improve the temporal resolution of the scientific data collected, the ITASAT-2 mission plans to launch three satellites in a formation flying operation, in order to make possible multipoint measurements of significant quantities of the ionosphere in much shorter timescales than the orbital period of a single satellite. The objective of this mission is also to capture the signal from the formation flying to provide the geolocation service.

The concept of space missions called formation flying is defined as a set of more than one satellite whose dynamic states are coupled through a common control law. At least one member of the set must track a desired state relative to another member, and the tracking control law must make use of the state of at least one of other members [4].

Formation flying has potential applications with emphasis on the Earth-observing, interferometry, on-orbit service, deep space, Synthetic Aperture Radar (SAR) and human exploration. In this context, different space missions using this approach have been developed since the 2000s. For example, the mission called TanDEM-X/TerraSAR-X [5] was launched on June 2010 and its purpose was to capture high-resolution and wide-area radar images independent of the weather conditions. The mission uses two satellites in formation flying that have a unique geometric accuracy that is unmatched by any other spaceborne sensor. Both satellites are almost identical and operate in six alternate operating modes for a wide range of applications in Earth observation. It can also be highlighted the mission called Magnetospheric Multiscale Mission (MMS) [6] launched on March 13, 2015 formed by four identical spacecraft in a variably spaced tetrahedron (1 km to several Earth radii), with a planned two-year mission lifetime. Its purpose is to measure magnetic and electric fields using electron and ion plasma spectrometers, providing high temporal and spatial resolution.

ITASAT-2, the second mission of the ITASAT program, will consist of three identical 8U standard CubeSats, designed and integrated by ITA. Its development will be based on the SPORT platform [3], becoming the second mission to use this type of platform from the institution. ITA proposes to make this study using payload composed of sensors for measurements of the ionosphere with commercial components and some with its own development.

As the ionosphere is floating in time and in spatial coordinates, so that the drifting ionosphere can be probed by multipoint measurements in different spatial and time coordinates, it is appropriate to consider that the formation flying of the three satellites has the ability to alter both its angular separation as well as the separation in along-track direction by using propellants. However, the main current challenge for satellite formation flying is the limited resources of the current sensor and actuator technologies, so it is necessary to provide a maintenance control of the formation from an orbital control system for the three satellites of the ITASAT-2 mission.

In the context of studying the behavior of controllers for the ITASAT-2 mission and the positioning of the following vehicles relative to the chief, this paper aims to use simulation and movement control techniques to verify and evaluate the behavior of the following vehicles using different phase angles in detachment and rendezvous maneuvers in relation to the movement of the chief CubeSat. For that, the relative motion of a chase spacecraft with respect to a target spacecraft that is on a circular orbit about a central body, considered a point mass, was described by the linear model in Cartesian coordinates called Clohessy-Wiltshire Equations (CW) [7]. The control technique used in this work is the Linear Quadratic Regulator (LQR) [8] which is a well-known method that provides optimally controlled feedback gains to enable the closed-loop stable and high-performance design of systems.

To support the choice of altitude parameters used in the simulation, it is important to highlight that the expected useful life for accomplishing the mission is at least 1 year and the re-entry into the atmosphere (de-orbit) with a significant margin in fulfilling the requirement for space debris mitigation, which establishes that in less than 25 years [9] after the operational mission satellite must re-enter the atmosphere. It is also important to note that the plasma bubbles begin to rise at an altitude of 300 km, so the choice of altitude must be adequate for scientific fulfillment of the mission. Thus, the orbital requirement of ITASAT-2 requires a circular orbit with an insertion of nominal orbital altitude in the range of 350 to 450 km.

To meet scientific data in order to guarantee wide coverage in the equatorial range, which is of interest for observing the formation of plasma bubbles and SAMA, the mission also requires an orbital inclination for the satellite in the range of 45 to 55 degrees [3], because it considers, thus, a possible launch by the International Space Station. Since the satellites will have low orbits, it is desirable to increase the life of the mission by reducing the CubeSat drag areas. It is noteworthy, then, that special attention should be paid to the attitude control subsystem, as it will have to guarantee the desired note throughout the operation of the satellite to fulfill the mission.

In addition to the training flight challenges presented, it is also necessary to consider environmental disturbances that can induce CubeSats to move away very quickly from each other if not properly controlled. Then, this paper considers two orbital disturbances: the J_2 term of the gradient disturbance of gravity due to the inhomogeneity of the Earth and the disturbance due to the aerodynamic drag of the satellites.

Finally, this paper is divided into: introduction, segmented methodology in Clohessy-Wiltshire Equations and Linear Quadratic Regulator (LQR), results and discussion, conclusion, acknowledgment and references.

II. METODOLOGY

In this context, this work aims to use simulation and movement control techniques of the formation flying to verify and evaluate the behavior of the deputies vehicles in detachment and rendezvous maneuvers in relation to the movement of the chief CubeSat considering two orbital perturbations: the J_2 term of the perturbation of the gravity gradient due to the inhomogeneity in mass distribution of the Earth and the disturbance due to the differential aerodynamic drag of the satellites.

For that, the linear model in Cartesian coordinates called Clohessy-Wiltshire Equations and the optimal control approach described by the Linear Quadratic Regulator (LQR) were used.

A. Clohessy-Wiltshire Equations

The Attitude Reference frame defines the coordinate system that the spacecraft's attitude is referenced to. In the expressions to be presented, the LVLH [9] (Local Vertical, Local Horizontal) reference system was used whose origin is determined by the satellite's center of mass. The Z-axis is oriented in the direction to center of Earth (Vertical Location), Y-axis is negative to the normal orbit and X-axis is perpendicular to Y and Z, forming a right-handed coordinate system (Horizontal Location).

Expressions for the components of the J_2 induced perturbing acceleration vector are derived for circular orbits ($e_0 = 0$) by retrofitting a modified set of Clohessy-Wiltshire equations to the analytical solutions [4]. The established equations are given by:

$$\ddot{x} - 2\dot{\bar{M}}_0\dot{y} - 3\dot{\bar{M}}_0^{\,2}x = -3n_0^{\,2}x_{bias} + u_x + p_x \tag{1.a}$$

$$\ddot{y} + 2\dot{\bar{M}}_0\dot{x} = u_y + p_y \tag{1.b}$$

$$\ddot{z} + (\dot{\bar{M}}_0^{\,2} + 2n_0\dot{\bar{\omega}}_0)z = -2\rho(0)kn_0\sin^2(\bar{\iota}_0)\sin(\bar{\lambda}_0)\cos(\alpha(0)) + u_z + p_z \tag{1.c}$$

In which x, y and z are the respective relative position components; $\dot{x}$, $\dot{y}$ and $\dot{z}$ are the respective relative velocity components and $\ddot{x}$, $\ddot{y}$, $\ddot{z}$ are the respective relative acceleration components. The u_x , u_y and u_z are the control acceleration inputs and p_x, p_y and p_z are the inputs for the external disturbance exerted by the differential aerodynamic drag. Finally, α is the phase angle of the formation; ρ is the relative position; $\bar{\iota}_0$ is the inclination of the chief; n_0 is the chief's mean motion and the constant $k = -1.5J_2n_0\left(\frac{R_e}{\bar{a}_0}\right)^2$, where R_e is the radius of the Earth and $\bar{a}_0$ is the semimajor axis.

The equations for evaluating the mean drift rates for mean anomaly and perigee argument are given below for each satellite in the formation [4]:

$$\bar{M}_0 = M_0 + \dot{\bar{M}}_0 t \tag{2}$$

$$\bar{\omega}_0 = \omega_0 + \dot{\bar{\omega}}_0 t \tag{3}$$

where:

$$\dot{\bar{\omega}}_0 = 0.75 J_2 \left(\frac{R_e}{\bar{a}_0}\right)^2 n_0 \left(5\cos^2(\bar{\iota}_0) - 1\right) \tag{4}$$

$$\dot{\bar{M}}_0 = n_0 \left\{1 + 0.75 J_2 \left(\frac{R_e}{\bar{a}_0}\right)^2 \left(3\cos^2(\bar{\iota}_0) - 1\right)\right\} \tag{5}$$

Now, define the mean argument of latitude as:

$$\bar{\lambda}_0 = \bar{M}_0 + \bar{\omega}_0 \tag{6}$$

And the differential aerodynamic drag can be described for each deputy vehicle by [10]:

$$\Delta\boldsymbol{\gamma}_{D2} = -\frac{\rho_\infty}{2}\boldsymbol{v}^2 \frac{1}{C_{B2}}\left(1 - \frac{C_{B2}}{C_{B1}}\right) \tag{7}$$

$$\Delta\boldsymbol{\gamma}_{D3} = -\frac{\rho_\infty}{2}\boldsymbol{v}^2 \frac{1}{C_{B3}}\left(1 - \frac{C_{B3}}{C_{B1}}\right) \tag{8}$$

where:

$$C_{Bi} = \frac{m}{C_D A} \tag{9}$$

The relation C_{Bi} is called ballistic coefficient; m is the mass of the spacecraft; C_D is the drag coefficient; A is the cross-sectional area; and the indices 1, 2 and 3 denote target, first chaser and second chaser, respectively. Lastly, ρ_∞ is the atmospheric density and $\boldsymbol{v}$ is the velocity vector relative to terrestrial atmosphere.

Then the differential aerodynamic drag for the formation flying is:

$$\boldsymbol{p} = \Delta\boldsymbol{\gamma}_{D2} + \Delta\boldsymbol{\gamma}_{D3} \tag{10}$$

The position and velocity vector is created by:

$$\boldsymbol{x} = [x\ y\ z\ \dot{x}\ \dot{y}\ \dot{z}]^{\boldsymbol{T}} = [x\ y\ z\ \boldsymbol{v}]^{\boldsymbol{T}} \tag{11}$$

In the formation flying shown in Fig. 1, the chief vehicle 0 is at the center, of an ideal PCO formation at the ascending node. Follower 1 has $\alpha = 0°$ and it will require the maximum fuel to mitigate the effects of differential nodal precession because it has the maximum δi and $\delta\Omega = 0$. The Follower 2 ($\alpha = 90°$) will require the least fuel for orbit maintenance, it presents the maximum $\delta\Omega$ and δi $= 0$.

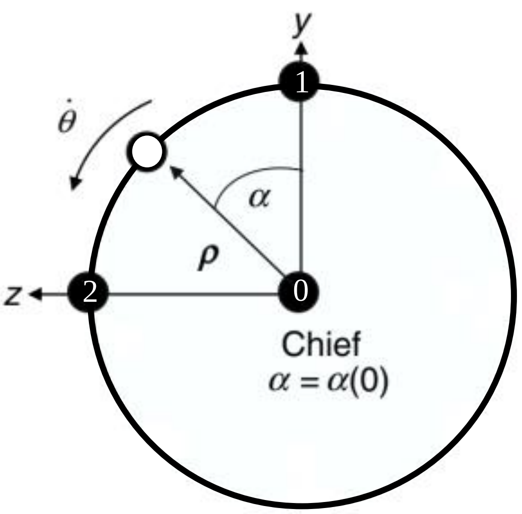

Fig. 1. Chief vehicle and two deputies layout (adapted of [4]).

Gradually, each deputy will spend equal time in good and bad locations, thereby balancing the fuel required for formation maintenance among the deputies.

The variation of the phase angles for each satellite is given by:

$$\alpha = \alpha(0) + \dot{\alpha}t \tag{12}$$

The following reference trajectories are selected to estimate the control requirements for formation maintenance [4]:

$$x_r = 0.5\left(1 + \frac{0.5\dot{\alpha}}{n_0}\right)\rho(0)\sin(\bar{\lambda}_0(0) + \alpha(0) + (\dot{\bar{M}}_0 + \dot{\alpha})t) + x_{bias} \tag{13.a}$$

$$y_r = \rho(0)\cos(\bar{\lambda}_0(0) + \alpha(0) + (\dot{\bar{M}}_0 + \dot{\alpha})t) \tag{13.b}$$

$$z_r = \rho(0)\sin(\bar{\lambda}_0(0) + \alpha(0) + (\dot{\bar{M}}_0 + \dot{\alpha})t) \tag{13.c}$$

where:

$$x_{bias} \approx -\frac{5}{4}J_2\rho(0)\left(\frac{R_e}{\bar{a}_0}\right)^2 \sin(2)\cos(\alpha(0)) \tag{14}$$

The reference trajectories require velocities equal to zero, thus the vector of reference has:

$$\boldsymbol{x_r} = [x_r\ y_r\ z_r\ 0\ 0\ 0]^T \tag{15}$$

And, the reference controls are:

$$u_{xr} = 0 \tag{16.a}$$

$$u_{yr} \approx -\rho(0)n_0\dot{\alpha}\cos(\bar{\lambda}_0(0) + \alpha(0) + (\dot{\bar{M}}_0 + \dot{\alpha})t) \tag{16.b}$$

$$u_{zr} \approx 2n_0(\dot{\bar{\omega}}_0 - \dot{\alpha})\rho(0)\sin\left(\bar{\lambda}_0(0) + \alpha(0) + \left(\dot{\bar{M}}_0 + \dot{\alpha}\right)t\right) + 2\rho(0)kn_0\sin^2(\bar{\iota}_0)\cos(\alpha(0))\sin(\bar{\lambda}_0) \tag{16.c}$$

It is worth mentioning that radial thrust is inefficient for formation maintenance near a circular orbit, as shown in (16.a). Fortunately, the CW model is controllable with only the along-track and cross-track control components (16.b and 16.c).

B. Linear Quadratic Regulator (LQR)

LQR is an optimal control technique in which allows to operate the dynamic system at minimal cost based on a linear approximation of a dynamical system of the form [8]:

$$\dot{\boldsymbol{x}} = [A]\boldsymbol{x} + [B]\boldsymbol{u} \tag{17}$$

where $[A]$ and $[B]$ are matrices of appropriate dimensions.

The control law for $\boldsymbol{u}$ is obtained in this approach in (17) by minimizing the following performance index [8]:

$$\mathcal{J} = 0.5\int_0^{t_f}(\boldsymbol{x}^{\boldsymbol{T}}[Q]\boldsymbol{x} + \boldsymbol{x}^{\boldsymbol{T}}[R]\boldsymbol{x})\, dt \tag{18}$$

where t_f is the final time and the matrices [Q] and [R] are parameters used to penalize each state or control action differently, thus determining the action of the controller. Both matrices are semi-definite positive and square.

For an autonomous system, constant weight matrices, and $t_f \rightarrow \infty$, the minimization of (18) is achieved by the following control law:

$$\boldsymbol{u} = -[K]\boldsymbol{x} \tag{19}$$

where $[K] = [R]^{-1}[B]^T[S]\boldsymbol{x}$ and [S] satisfies the Algebraic Riccati Equation [11]:

$$[S][A] + [A]^T[S] - [S][B][R]^{-1}[B]^T[S] + [Q] = 0 \tag{20}$$

whose solution is positive definite if the pair $([A],[B])$ is controllable and the pair $([A],[Q]^{0.5})$ is observable [11]. Positive definiteness of $[S]$ guarantees closed loop stability, i.e., asymptotic stability of the system:

$$\dot{\boldsymbol{x}} = ([A] - [B][K])\boldsymbol{x} \tag{21}$$

Important to note that radial thrust is inefficient for formation maintenance near a circular orbit [12][13]. Fortunately, the CW model is controllable with only the along track and cross track control components.

Hence the six-dimensional error vector, $\boldsymbol{e} = \boldsymbol{x} - \boldsymbol{x_r}$, satisfies:

$$\dot{\boldsymbol{e}} = [A]\boldsymbol{e} + [B]\begin{bmatrix} u_x \\ u_y - u_{yr} \\ u_z - u_{zr} \end{bmatrix} \tag{22}$$

where,

$$[A] = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 3\dot{\bar{M}}_0^{\,2} & 0 & 0 & 0 & 2\dot{\bar{M}}_0 & 0 \\ 0 & 0 & 0 & -2\dot{\bar{M}}_0 & 0 & 0 \\ 0 & 0 & -\dot{\bar{M}}_0^{\,2} - 2n_0\dot{\bar{\omega}}_0 & 0 & 0 & 0 \end{bmatrix} \tag{23}$$

$$[B] = \begin{bmatrix} 0_{3x3} \\ I_{3x3} \end{bmatrix} \tag{24}$$

III. RESULTS AND DISCUSSION

First, for the simulation, a PCO-type orbit with an altitude of 400 km and a 45° inclination is considered. The simulation time considered is four orbital periods of the formation flying (4T). The movement to be controlled is the distance between the deputies vehicles and the chief satellite initially at $\rho(0_-) = 1$ km to $\rho(0_+) = 6$ km at the start time, creating a detachment maneuver and, after two orbital periods $\rho(2T) = 3$ km, a rendezvous maneuver.

It is important to note that the three satellites are considered to be 8U CubeSats of equal mass, 10.5 kg each. And the cross-sectional areas are the same in all directions for 8U type satellites, i.e., 0.04 m². It is also considered here that all satellites are three-axis stabilized in attitude.

Lastly, the Earth's atmospheric density is computed according to the U.S. Standard Atmosphere Model [14] up to an altitude of 400 km and the drag coefficient is set equal to 2.2. The initial conditions of the simulation can be found in TABLE I.

TABLE I. INITIAL CONDITIONS OF THE SIMULATION

Parameter	***Value***
A	0.04 m²
$\bar{a}_0$	6378.14 + 400 km
C_D	2.2
$\bar{e}_0$	0
$\bar{\iota}_0$	45°
J_2	0.001082
m	10.5 kg
M_0	0°
ω_0	0°
$\rho(0_-)$	1 km
$\rho(0_+)$	6 km
$\rho(2T)$	3 km
ρ_∞	216.65 kg/m³

In Fig. 2, the space of along-track, radial and cross-track coordinates in 2 and 3 dimensions can be observed for the Follower 1 with initial phase angle of 0 degrees and the Follower 2 with 90 degrees.

The beginning of the movement is marked by a red asterisk. It is possible to observe that for all followers the correction movements from 1 km to 6 km begin in the same coordinates due to the instantaneous positioning error related to the ideal state identified by the LQR controller, reaching 6 km using the angle nominal phase of each satellite. Subsequently, at the time of two orbital periods, the followers satellites perform a rendezvous maneuver to reach 3 km of relative position.

It is possible to verify that the existence of different phase angles in the formation flying causes the followers satellites to enter different positions in the orbit with greater ρ, therefore it is important to consider the possibility of maneuvering at different times for each of the satellites.

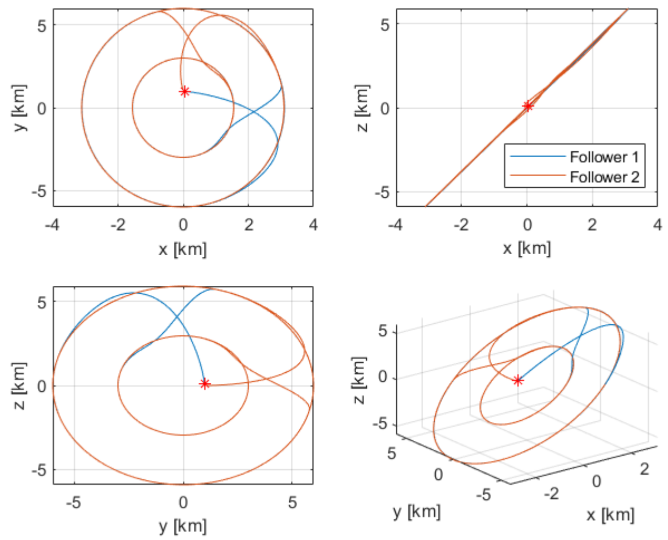

Fig. 2. Along-track, Radial and Cross-track coordinate in 2 and 3 dimensions

The Fig. 3 shows the behavior of the x, y, z coordinates as a function of time for all followers. It is possible to observe the decrease in the positions in x, y and z when going from 6 km of relative position to 3 km.

Fig. 4 shows the control acceleration of the three components, as a function of time. Finally, Fig. 5 shows the velocity increments as a function of time.

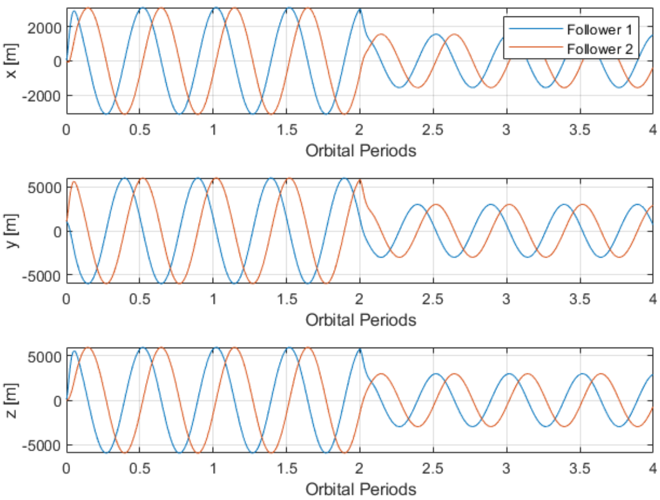

Fig. 3. x, y, z coordinates as a function of time.

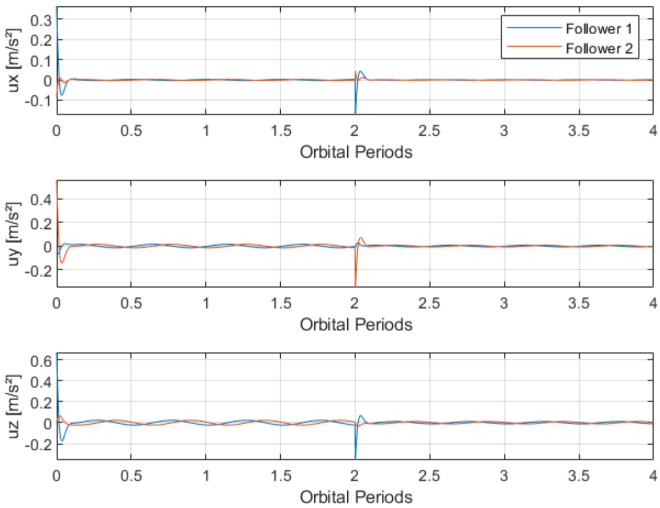

Fig. 4. Control acceleration, **u**, as a function of time.

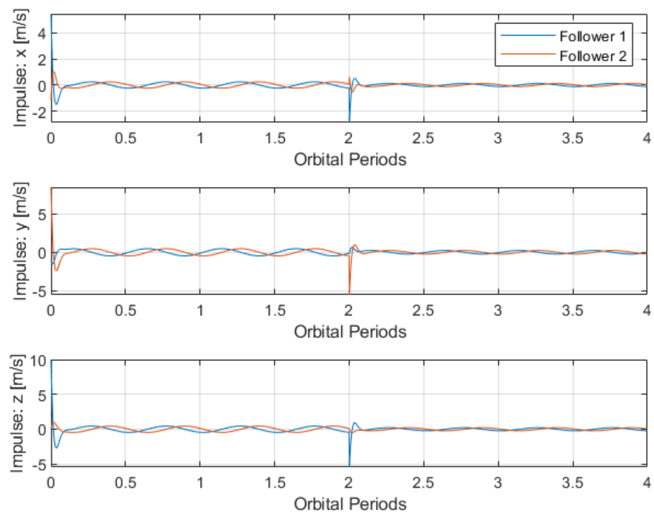

Fig. 5. Speed increments, delta-V, as a function of time.

Looking at Fig. 4 and 5, it is possible to notice that Follower 1 requires, at the beginning of the simulation period, a greater performance of the signal from controller **u**, and consequently a greater amount of impulse with respect to Follower 2, as shown in TABLE 2.

The total Delta-V consumption of the Follower 1 to perform the detachment maneuver was 11.4948 m/s and the Follower 2 was 8.4853 m/s. For the rendezvous maneuver, the Follower 1 consumed 6.2161 m/s of Delta-V and the Follower 2 consumed 5.5608 m/s. So, as expected, a phase angle of 90º tends to decrease the consumption for carrying out the maneuver.

TABLE II. DELTA-V ANALYSIS.

Followers	***Delta-V of detachment maneuver***	***Delta-V of rendezvous maneuver***	***Delta-V Total***
1 (α = 0°)	11.4948 m/s	8.4853 m/s	19.9801 m/s
2 (α = 90°)	6.2161 m/s	5.5608 m/s	11.7769 m/s
Total amount	17.7109 m/s	14.0461 m/s	31.7570 m/s

After carrying out the both maneuvers, the controller only becomes corrective, in order to compensate for the orbital disturbances existing in the nominal movement of the formation flying, so the control signal and the impulse tend to zero. So, the LQR controller proved to be efficient for controlling formation flying maintenance and performing maneuvers.

IV. CONCLUSION

The LQR controller applied to the linear model in Cartesian coordinates called Clohessy-Wiltshire Equations proved to be efficient to control the CubeSats' distance maneuver and also to maintain the required training position despite the disturbances of the J_2 term of the gradient disturbance of gravity due to the inhomogeneity of the Earth and the disturbance due to the differential aerodynamic drag of the satellites.

It was also found, as expected, that the phase angle of the following satellites directly interferes in the consumption for carrying out the formation flying maneuvers.

This paper was intended to contribute to the conceptual project of the ITASAT-2 mission by providing controlled maneuver analysis that should be studied to enable the acquisition of data relating to plasma bubbles and the geolocation service.

As a future work, we propose the development of LQR control of the same maneuvers covered in this paper. However, in addition to the CW model already presented, a technique that describes relative movement using Quaternions will also be used. It is a non-linear propagation method without singularities from the orbital elements of the formation vehicles.

In this way, it will be possible to compare the feasibility (advantages and disadvantages) of each movement simulation approach, in terms of the accuracy of the positioning of the satellites during the mission, in addition to the computational time required.

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REFERENCES

[1] Abdu, M. A., Batista, I. S., Carrasco, A. J., Brum, C. G. M., “South Atlantic magnetic anomaly ionization: A review and a new focus on electrodynamic effects in the equatorial ionosphere”. Journal of Atmospheric and Solar-Terrestrial Physics, v. 67, p. 1633-1657, 2005.

[2] Leithold, A. A, “Um breve resumo da Atmosfera e Ionosfera da Terra”, 2006.

[3] J. Spann, C. Swenson, O. Durao, L. Loures, R. Heelis, R. Bishop, G. Le, M. Abdu, L. Krause, C. Denardin, et al., “The Scintillation Prediction Observations Research Task: An International Science Mission using a CubeSat,” 31st Annual AIAA/USU Conference.

[4] Alfriend, K. T., et al. “Spacecraft Formation Flying: dynamics, control and navigation”. Elsevier Astrodynamics Series, Elsevier, 382 p., 2010.

[5] ESA Earth Online 2000. TerraSAR-X/TanDEM-X Mission. Online in: https://earth.esa.int/web/guest/missions/3rd-party-missions/current-missions/terrasar-x. Accessed on: July 4, 2020.

[6] Fuselier, S. A., et al. “Magnetospheric multiscale science mission profile and operations”. Space Sci Rev 1-27, 2014.

[7] Clohessy, W. and Wiltshire, R., “Terminal Guidance System for Satellite Rendezvous”, Journal of the Astronautical Sciences, Vol. 27, No. 9, 1960, pp. 653–678.

[8] Kalman, R.E., "Contributions to the theory of optimal control,"Bol. Soc. Mat. Mexicana, vol. 5, pp. 102-119, 1960.

[9] Wertz, J. R., “Spacecraft Attitude Determination and Control”, Kluwer, 1997.

[10] W. Fehse, “Automated rendezvous and docking of spacecraft”. United Kingdom: Cambridge University Press, 2003.

[11] Lewis, F. L. and Syrmos, V. L. L., “Optimal Control”, 2nd ed., 1995.

[12] Vadali, S. R., et al., “A New Concept for Controlling Formation Flying Satellite Constellations”, Advances in the Astronautical Sciences, Vol. 108, No. 2, February 2001, pp. 1631–1648. Also, Paper AAS 01-218 of the AAS/AIAA Space Flight Mechanics Meeting.

[13] Starin, S. R., et al., “Spacecraft Formation Flying Maneuvers Using Linear Quadratic Regulation with No Radial Axis Inputs”, AIAA Guidance, Navigation and Control Conference and Exhibit, No. AIAA-2001-4029, AIAA, Montreal, Canada, August 2001.

[14] NASA, “U.S. Standard Atmosphere Model”, 1976.