Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Modeling and analysis for reaction control thruster used for station-keeping maneuvers of a GEO satellite

To cite this article: M K Ashraf *et al* 2023 *J. Phys.: Conf. Ser.* **2616** 012026

View the article online for updates and enhancements.

You may also like

- Formation of molecular ions by radiative association of cold trapped atoms and ions
  Humberto da Silva Jr, Maurice Raoult, Mireille Aymar et al.
- Contribution of BDS-3 observations to the precise orbit determination of LEO satellites: a case study of TJU-01
  Kai Wei, Min Li, Tianhe Xu et al.
- Fibrous structures in augmentation for rotator cuff repair: an experimental comparison
  Tânia Peixoto, Fábio A M Pereira, Paula L Silva et al.


PRIME PACIFIC RIM MEETING ON ELECTROCHEMICAL AND SOLID STATE SCIENCE
HONOLULU, HI
Oct 6–11, 2024
Abstract submission deadline:
April 12, 2024
Learn more and submit!
Joint Meeting of
The Electrochemical Society
•
The Electrochemical Society of Japan
•
Korea Electrochemical Society

This content was downloaded from IP address 195.43.0.86 on 12/03/2024 at 07:41

Modeling and analysis for reaction control thruster used for station-keeping maneuvers of a GEO satellite

M K Ashraf[1], H Hendy[2], A F Sallam[3], M M Ashry[4], and Y Z Elhalwagy[5]

[1]Electrical Engineering Department, MTC, Egypt, [2]Dr. of Electrical Engineering, MTC, Egypt, [3]Dr. of Mechanical Engineering, Space Technology Center, Egypt, [4]Professor of Electrical Engineering, MTC, Egypt, [5]Professor of Electrical and Computer Engineering, MTC, Egypt.

E-mail: `kareem.ashraf@hotmail.com`

Abstract. This paper introduces a theoretical description, force, and torque analysis of a Reaction Control Thruster (RCT) used as an actuator in Attitude Determination and Control Subsystem (ADCS). Mathematical formalization, realization, and implementation are offered to implement the RCT model using Matlab-Simulink. Furthermore, this paper proposes an accurate RCT Simulink model to control the orientation and stabilizes the Geostationary Earth Orbit (GEO) satellite within its orbit. Finally, a comparative analysis is carried out with an existing satellite platform (Eurostar-3000) based on the Root Mean Square Error (RMSE) for the delta velocity (delta-$\mathcal{V}$) parameter. The outcomes of the model simulation validated the effectiveness of the proposed approach.

1 Introduction

Satellites with the same orbital period as the earth's rotation are called GEO satellites. After each sidereal day, when the earth spins 360 degrees (approximately 23 hours 56 minutes 4 seconds), they return to the same position. Orbits of GEO satellites are along a path parallel to the earth's rotation and lie over the equator [1]. Therefore, they seem fixed as they move at the same angular velocity as the earth. They are pointed at a particular place on the ground to provide coverage to that area. They can cover about one-third of the globe. GEO satellites are located at about 36,000 km and have a ten to fifteen years lifespan [1].

GEO satellites are exposed to various non-Keplerian forces and disturbance torques, resulting in a deviation from the desired orbital position of the satellite. For satellites in GEO, the fundamental perturbations are solar and lunar gravitational attractions that induce drift in orbital inclination and solar radiation pressure that affects orbit eccentricity [2]. Station-keeping (SK) maneuvers include a series of planned and unplanned correction maneuvers implemented by RCT to counteract these perturbations while maintaining satellite attitude [3]. Planned SK maneuvers were executed to keep the satellite in a predefined window at a required fixed orbital slot and have the antennas point to a defined footprint. Two kinds of orbital correction maneuvers perform SK. First, the North/South (N/S) adjusts the inclination. Second, the

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

East/West (E/W) adjusts the longitude and eccentricity. Otherwise, these perturbations would drive the satellite out of its assigned slot. In addition, the growing number of controlled and uncontrolled space objects increases the risk of space collisions [4, 5]. Therefore, most agencies emphasize this issue after numerous collision incidents, such as the Iridium-Cosmos collision in 2009 produced roughly 1850 debris pieces greater than 10 cm [6]. Therefore, unplanned collision avoidance maneuvers are required to prevent collision with debris. Hence, Satellite Control Centers (SCC) must maintain a high level of awareness to avoid collisions with debris.

In [2] Daily North/South (NS) SK method for a GEO satellite is proposed to improve the NS-SK strategy, which not only reduces the drift accumulation but also reduces the period of the inclination oscillation to consume minimum delta velocity. The proposed model of the satellite in [7] has internal and external actuators employed in tandem to control the satellite orbit and attitude by using six chemical thrusters and four reaction wheels. The fuel consumption is reduced by maintaining the satellite in a nadir-pointing (pointing perpendicular to the earth precisely underneath the satellite) attitude configuration. At the same time, it is reducing the usage of the RCT. The proposed method in [8] optimizes the thrust and torque directions the thrusters produce. As a result, the total of the control forces and torques generated about the body-fixed frame is specified as a cost function in terms of the positions and orientations of the thrusters. It is demonstrated by a few numerical examples of how to successfully determine the most fault-tolerant fixed thruster topologies to improve the fault tolerance of the actuators. In [9], a control strategy is developed to perform station-keeping for a GEO satellite powered by electric propulsion while consuming the least amount of fuel possible. By keeping the satellite inside its station-keeping window, which is a rectangle with specified geographic longitude and latitude limits. The station-keeping maneuver is carried out as soon as the satellite gets close to the edge of its station-keeping window. The author of [10] performed station-keeping maneuvers of a nadir-pointing GEO satellite equipped with electric thrusters using a Model Predictive Controller (MPC) that predicted environmental perturbing accelerations. It was demonstrated that the technique considerably decreased the ((delta-$\mathcal{V}$)) needed to maintain the GEO satellite in the intended orbit. The station-keeping problem of a GEO satellite under the influence of various environmental perturbing accelerations was solved using an effective control method in [11]. The suggested control approach is based on calculating the accelerations needed to execute the correction maneuver relative to the satellite position and translating those corrections into commands for turning on-off the thrusters. A fuzzy control system was used in [11] to actuate the thrusters and a genetic optimization method to calculate the on-time duration of the maneuver period.

This paper aims to develop a general RCT model that gives extensions and alterations flexibility. Furthermore, the model can use the same architecture for several satellites after modifying the initial parameter for each one.

The arrangement of the remaining paper sections is as follows. First, section II gives a quick summary of the attitude determination and control subsystem. Then in section III, the discussion of the RCT model is detailed, including frame definition, RCT configuration, and force and torque analysis. The handling of the MATLAB-Simulink simulation, implementation, numerical outcomes, and real case comparisons are calculated in Section IV to validate the work between the existing platform and the suggested model for maneuver delta-$\mathcal{V}$ outputs. Finally, section V is the paper's conclusion.

2 Attitude determination and control subsystem (ADCS)

The attitude determination and control subsystem (ADCS) is in charge of the satellite stabilization and keeps it pointed in the appropriate direction throughout the mission [12]. ADCS will be highlighted in this section, which consists of many blocks, as presented in figure 1. First, the satellite dynamic block defines the motion of the satellite concerning the disturbance torques that affect it (gravity, aerodynamics, solar radiation, and magnetic field). Second, the Satellite kinematic block defines the trajectory of the satellite and the necessary maneuvers acting on it. Third, the orbital parameters block describes the orientation of the spacecraft. Then, the Navigation and guidance algorithm block determines the spacecraft's location and velocity at a given time. Finally, the orientation sensors to determine the position of the satellite consist of (a sun sensor, star tracker, earth sensor, magnetometer, angular momentum sensor, and gyroscope). Furthermore, the actuators to control the position of the satellite consisted of (reaction wheels, momentum wheels, magnetic torques, and a reaction control thruster). [13, 14].

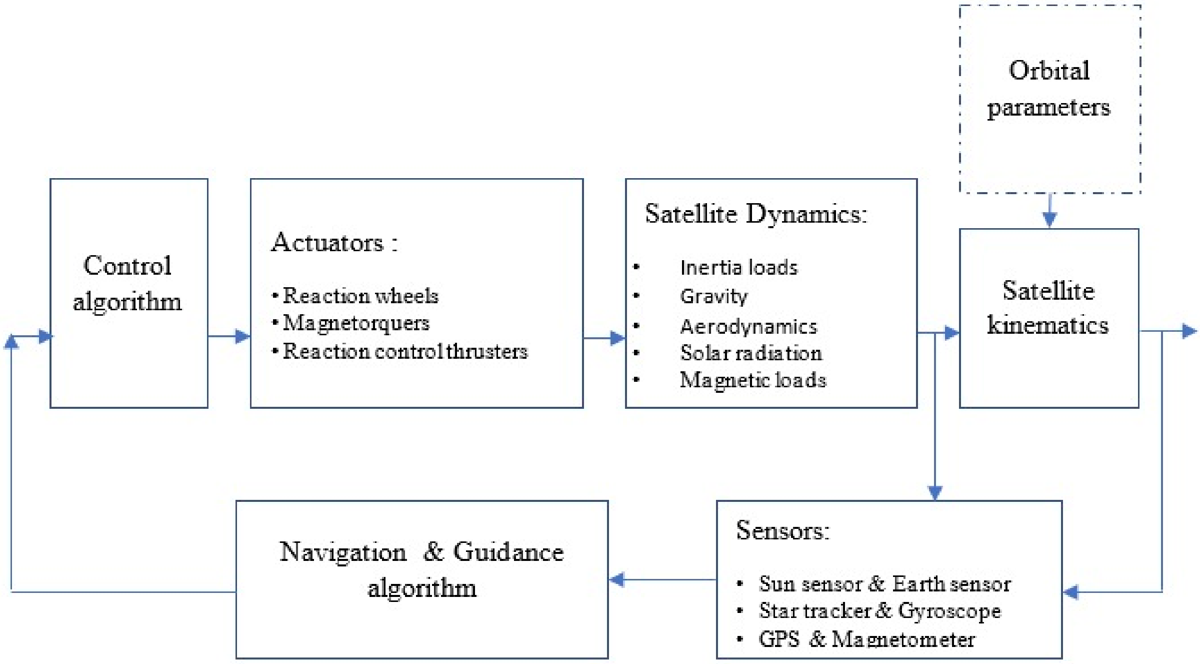

Figure 1: ADCS block diagram

ADCS is in charge of activating the RCT actuator, which is chemical, electrical, or hybrid. RCT is a small rocket engine able to perform SK and collision avoidance maneuvers by generating tiny amounts of force in any direction or combination of directions to counteract the large disturbance torques. The RCT model and MATLAB Simulink results will be illustrated in the following sections.

3 Reaction control thruster model

The proposed RCT model is presented in this section. The model structure consists of three main blocks and operates in the time domain, as shown in figure 2 and 3. The input block consists of RCT configuration, the mass flow rate calculation to update the initial mass before each maneuver, and the force components to calculate the required delta-$\mathcal{V}$. The inputs for any equation are in this block for flexibility and to be generalized for any spacecraft to use the same architecture for several satellites. Another two blocks, one for the torque calculation and the other for the algorithms of the acceleration and delta-$\mathcal{V}$ needed for the correction maneuver.

This section is arranged as follows. The first subsection defines the appropriate coordinate reference frames. The second one defines the RCT configuration for the force and torque

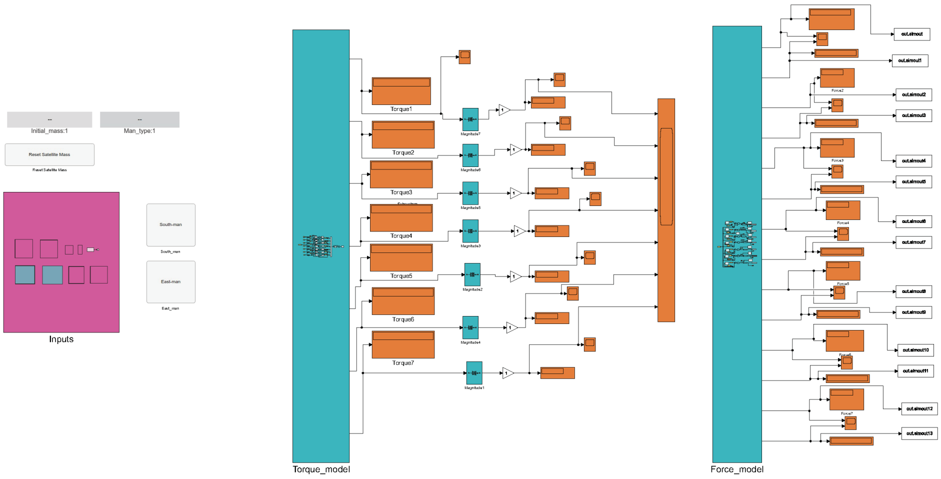

Figure 2: RCT model

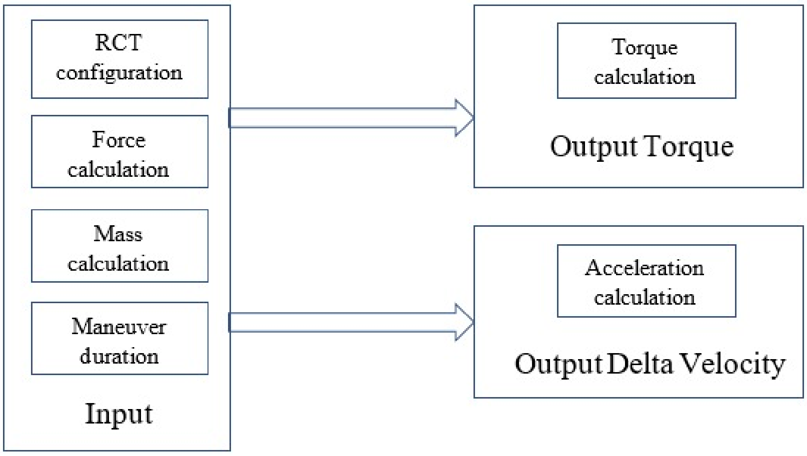

Figure 3: Schematic of RCT model

calculations. Finally, the last subsection describes the equations of the delta-$\mathcal{V}$ and torque calculations.

3.1 Frame definition

3.1.1 Satellite orbital reference frame The orientations of the RCT are defined with respect to the satellite orbital reference frame with orthonormal X, Y, and Z axes. The frame three axes are shown in figure 4, and its origin is at the satellite center of mass. The main axis is the

X-axis, which is aligned with the velocity vector. The Z-axis is perpendicular to the main axis and points toward the earth. Finally, the Y-axis is normal to the orbit plane and southwards oriented. The X, Y, and Z axes are also called the roll, pitch, and yaw axes, respectively [15, 16].

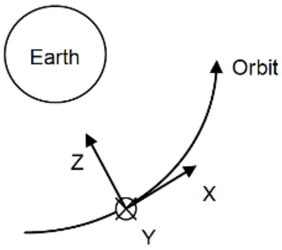

Figure 4: Satellite orbital reference frame

3.1.2 Local orbit frame The coordinate system used for describing the delta-$\mathcal{V}$ of the satellite is the radial, tangential and normal frame with orthonormal R, T, and N axes, also called the local orbital frame, shown in figure 5. The R-axis is oriented from the earth's center toward the spacecraft and is equal to the negative Z-axis. The T-axis is aligned with the velocity vector in the direction of the satellite movement and in the same direction as the X-axis. Finally, the N-axis is normal to the orbit plane, northwards oriented, and equal to the negative Y-axis [15, 16].

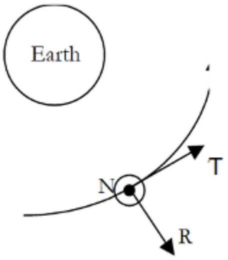

Figure 5: Local orbital frame

3.2 RCT configuration

This subsection defines the configuration of the seven thrusters on the satellite structure, as depicted in figure 6. The placement of the first three thrusters used to perform delta-$\mathcal{V}_N$ (Normal) for applying the south maneuver. Thrusters four and five perform delta-$\mathcal{V}_T$ (Tangential) to apply the east and west maneuvers. Finally, thrusters six and seven perform delta-$\mathcal{V}_R$ (Radial) for attitude control during the maneuver.

The configuration of the seven thrusters allows the torque to be applied in any direction. Moreover, it permits the force to be involved in the direction of +X by thruster number four, -X by thruster number five, +Y by thrusters one, two, and three, and +Z by thrusters six and seven. Thus, orbital correction is planned regarding the available force directions. The torque calculations depend on the position and orientation of the thrusters from the center of mass and the force vector in the three axes provided in table 1.

From table 1, the thrust force vector required for the south maneuver is presented in equations (1), (2), and (3). F_X, F_Y, and F_Z are the force directions in the X, Y, and Z axes. F is the

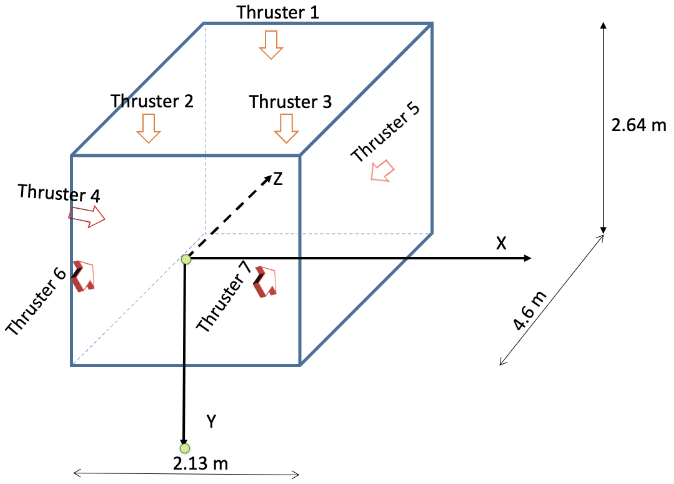

Figure 6: RCT configuration

Table 1: Thruster configuration

Function	Thruster number	Orientation		Position		
		Beta (β) (degree)	Alpha (α) (degree)	r$_x$($meter$)	r$_y$($meter$)	r$_z$($meter$)
South maneuver	One	-12.5	0.2	0.02	-1.3	2.5
	Two	-12.5	-133	-1.3	-1.2	-1.1
	Three	-12.5	133	1.3	-1.2	-1.1
East maneuver	Four	-1.5	30	-1.1	0.04	0.7
West maneuver	Five	5	31	1.1	-0.01	0.7
Attitude control	Six	-2.5	8	-1.1	-0.01	-1.5
	Seven	1	8	1.1	0.05	-1.5

thrust force level. Alpha (α) is the elevation angle that defines the rotation of the thruster about the Z-axis, and the rotation about the Y-axis of the thruster defines the azimuth angle beta (β).

$$F_X = Fcos\beta \ sin\alpha \tag{1}$$

$$F_Y = Fcos\beta \tag{2}$$

$$F_Z = Fsin\beta \ cos\alpha \tag{3}$$

The components of the thrust force vector to achieve the east and west maneuvers are calculated as in equations (4), (5), and (6).

$$F_X = (\pm)Fcos\beta \ cos\alpha \tag{4}$$

$$F_Y = Fsin\beta \tag{5}$$

$$F_Z = -Fcos\beta \ sin\alpha \tag{6}$$

The thrust force vector required for the attitude control during the maneuver is calculated as in equations (7), (8), and (9).

$$F_X = (\pm) F cos\beta\ sin\alpha \tag{7}$$

$$F_Y = (\pm) F sin\beta \tag{8}$$

$$F_Z = F cos\alpha \tag{9}$$

3.3 Force and Torque analysis

3.3.1 Force analysis The amount of the propellant forced out with an exhaust velocity $\mathcal{C}_e$ from the nozzle of each thruster is defined as the RCT force (F) and is expressed in equation (10) [1].

$$F = \mathcal{C}_e \dot{m} + \mathcal{A}_n(\mathcal{P}_g - \mathcal{P}_a) = C\dot{m} \tag{10}$$

Where $(\dot{m})$ is the mass flow rate of propellant, (A_n) denotes the cross-sectional area of the nozzle exit, and (P_g and P_a) are the gas and the ambient pressure, respectively. Parameter (C) is the effective exhaust velocity of the forced-out mass concerning the satellite. In station-keeping mode, the satellite uses on-off chemical thrusters as actuators for position control. The spacecraft acceleration (a_t) is a result of the thrust (F) over the mass of the spacecraft (m(t)) and is calculated as in equation (11) [1,17].

$$a_t = dv/dt = F/m(t) = C(\dot{m}/m(t)) \tag{11}$$

The station-keeping maneuver is performed by adding or subtracting delta velocity from the satellite's velocity. Equation (12, 13) provides the required delta velocity to achieve the maneuver [17].

$$\Delta V = \int_{lt_0}^{t_0+\Delta t} a_t dt, \tag{12}$$

or

$$\Delta V = (-F/m).ln(1 - (\dot{m}\Delta t/m_0) \tag{13}$$

It is clear that the spacecraft mass (m(t)) decreases during its lifetime due to the consumed propellant after each maneuver and is calculated as in equation (14) [1,17].

$$m(t) = m_0 - \dot{m}t \tag{14}$$

where (m_0) is the spacecraft's initial mass and (t) is the time of the applied maneuver.

The RCT specific impulse (I_{sp})indicates how efficiently the propellant is transformed into proper thrust. The total specific impulse is calculated as in equation (15) [17].

$$I_{sp} = F/(g * \dot{m}) = C/g \tag{15}$$

Whereas the earth's gravitational g = 9.80665 m/s^2. The values of the RCT specific impulse (I_{sp}), mass flow rate $(\dot{m})$, ejection velocity (C), and thrust force (F) are shown in table 2 [1,17].

From Table 2 and substitution in equations (1-9). The force components F_X, F_Y, and F_Z have the most significant value from the thrust force for thrusters (1, 2, and 3), thrusters (4 and 5), and thrusters (6 and 7), respectively, as shown in Table 3.

Table 2: Thrust specification force F and the mass flow rate of RCT systems

Propulsion system type	F	C	I_{sp}	m_0
`Chemical station keeping thruster`	10 N	3500 m/s	300 s	3.57 g/s

Table 3: Thruster force components

Thruster number	F_X (N)	F_Y (N)	F_Z (N)
`One`	-0.01	9.8	-2.2
`Two`	1.6	9.8	1.4
`Three`	-1.6	9.8	1.4
`Four`	8.7	-0.3	-4.9
`Five`	-8.5	0.8	-5.1
`Six`	-1.4	0.3	9.8
`Seven`	1.4	-0.2	9.9

3.3.2 Torque analysis The torque about the center mass of the spacecraft is calculated by multiplying the thruster force vector with the position vector from the center mass of the satellite as in equation (16) [18].

$$T = \begin{bmatrix} T_X \\ T_Y \\ T_Z \end{bmatrix} = r * F = \begin{bmatrix} (r_y.F_Z) - (r_z.F_Y) \\ (r_z.F_X) - (r_x.F_Z) \\ (r_x.F_Y) - (r_y.F_X) \end{bmatrix}. \tag{16}$$

Where $r = [r_x r_y r_z]^T$ is the distance components in X, Y and Z directions of the thruster from the center mass of the spacecraft, and the thrust force vector F is equal to $[F_x F_y F_z]^T$ [18]. Hence, the component of the torque vector of each thruster and the total torque applied on the satellite due to the thruster firing is calculated and represented in table 4. The actual RCT design accepts the total torque computation from the suggested RCT model.

Table 4: Thruster torque components

Thruster	T_X (N_m)	T_Y (N_m)	T_Z (N_m)
`One`	-20.1	0.04	0.2
`Two`	9.5	0.09	-11.16
`Three`	9.5	-0.10	10.78
`Four`	0.002	0.75	-0.038
`Fife`	-0.98	-0.72	0.045
`Six`	-0.38	13.32	-0.62
`Seven`	0.17	-13.14	-0.25
`Total Torque`	-2.3	0.22	-0.98

4 MATLAB-Simulink simulation results

Simulations of the proposed RCT model and the numerical results are presented in this section. Considering a GEO satellite with a mass of 3476 kg and equipped with seven on-off chemical

Table 5: $\Delta V_{X}, _{Y}, _{Z}$ and ΔV_t for south, east and west maneuvers

Type	Thruster number	Duration (sec)	System	ΔV_X (m/s)	ΔV_Y (m/s)	ΔV_Z (m/s)	ΔV_{total} (m/s)
South Maneuver	One	213.473	Real	-0.001	0.61	-0.139	0.62
			Proposed	-0.0005	0.63	-0.14	0.64
	Two	260.369	Real	0.13	0.72	0.116	0.74
			Proposed	0.12	0.77	0.113	0.73
	Three	253.627	Real	0.13	0.71	0.115	0.76
			Proposed	-0.119	0.75	0.112	0.72
East Maneuver	Four	24.768	Real	0.063	-0.00203	-0.036	0.072
			Proposed	0.065	-0.00209	-0.037	0.074
West Maneuver	Five	27.606	Real	0.069	0.0068	-0.041	0.081
			Proposed	-0.071	0.0070	-0.042	0.083

thrusters whose maximum thrust is 10 N, the satellite's total mass is changed during the station-keeping maneuver with time and updated before performing the new maneuver. The output delta-$\mathcal{V}$ from the model for each maneuver is calculated and compared with the actual output delta-$\mathcal{V}$ of the existing platform Eurostar-3000, which is designed and manufactured by Airbus Defence and Space. The Eurostar-3000 platform is known for its reliability, flexibility, and high performance. It has been used by several satellite operators worldwide, such as Arabsat 6B, to provide commercial GEO satellite services.

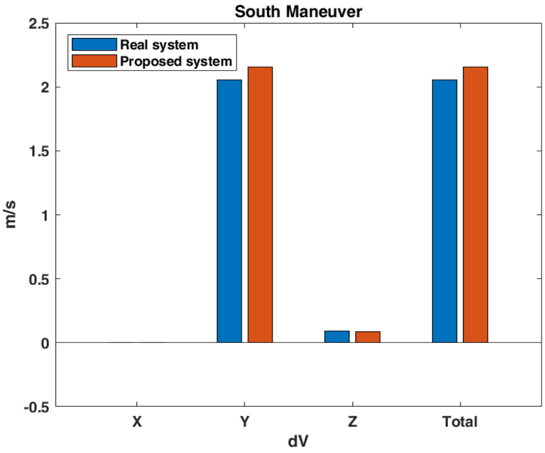

Figure 7: South maneuver $\Delta V_{X}, _{Y}, _{Z}$ and ΔV_{total}

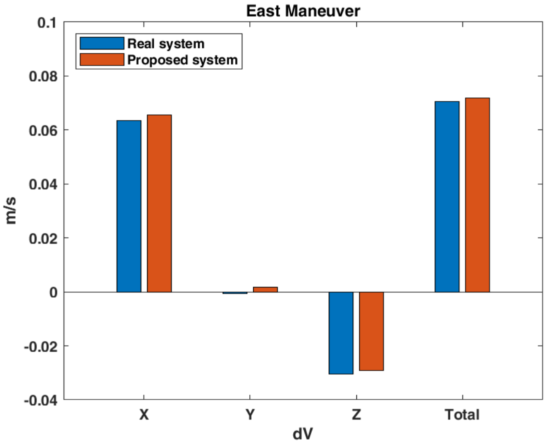

Figure 8: East maneuver $\Delta V_{X}, _{Y}, _{Z}$ and ΔV_{total}

The Root Mean Square Error (RMSE) is a crucial performance indicator for assessing a model, which determines the usual discrepancy between the output values of the proposed model and the actual values. The simulation results evaluate the efficiency of the proposed RCT model to compare the model results with the existing actual spacecraft results. The simulation results match the actual results of the existing platform for a specific south, east and west maneuver. The output delta-$\mathcal{V}$ in (X, Y, and Z) components and the total delta-$\mathcal{V}$ are given in table 5 and figures 7, 8, and 9.

RMSE determines the ability of the model to forecast the target values. The suggested RCT

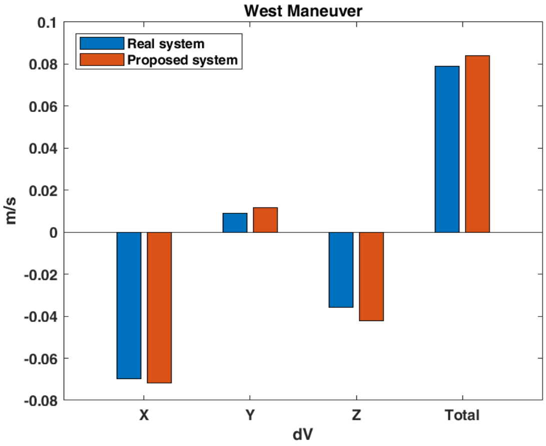

Figure 9: West maneuver $\Delta V_{X},_{Y},_{Z}$ and ΔV_{total}

Table 6: RMSE of the system

Maneuver Type	Duration(s)	Actual ΔV(m/s)	Proposed ΔV(m/s)	RMSE
`South`	727.97	2.055	2.156	0.10036
`East`	28.694	0.0705	0.0719	0.001
`West`	31.613	0.078	0.084	0.005

model matches the existing platform, according to the RMSE values in Table 6. These values range from (0.001 to 0.1) depending on the maneuver type, which indicates a better match and high accuracy of the proposed model.

5 Conclusion

This paper proposed a mathematical RCT model of the GEO satellite. The model architecture gives extensions and alterations flexibility. Furthermore, the model can be generalized to any spacecraft using the same architecture for several satellites. The proposed RCT model output delta-$\mathcal{V}$ successfully achieves maneuvers with different initial states in three cases (south, east, and west). The outcomes of the model simulation validated the effectiveness of the suggested approach. The model RMSE fits the actual data with high accuracy values. Additionally, the simulation outcomes in the paper could be helpful for similar system development. Future work will focus on applying the proposed RCT model to a simulated model of a geostationary satellite to compare the classical orbital elements of the desired position of the proposed model with the existing system.

References

[1] Losa D 2007 *High vs Low Thrust Station Keeping Maneuver Planning for Geostationary Satellites* (Doctoral dissertation, École Nationale Supérieure des Mines de Paris)
[2] Huang X, Yang B, Li S and Wang Z 2021 Efficient high-accuracy north-south station-keeping strategy for geostationary satellites *Science China Technological Sciences* **64**(11) pp 2415-2426
[3] Zou H, Song J, Wang J, Zhang L and Huang Y 2020 Geostationary station keeping using relative orbital elements with model predictive control *Chinese Control and Decision Conf.* **2020** pp 4437-4442
[4] Hamed AR, Badawy A, Omer AA, Ashry M and Hussein WM 2019 Multiple debris orbital collision avoidance *IEEE Aerospace Conf.* **2019** pp 1-8
[5] Mancini M, Bloise N, Capello E and Punta E 2019 Sliding mode control techniques and artificial potential field for dynamic collision avoidance in rendezvous maneuvers *IEEE Control Systems Letters* **4**(2) pp 313-318

[6] Hamed AR, Omer AA, Ashry M and Badawy A 2020 Optimized curvilinear potential field based multi-objective satellite collision avoidance maneuver *IEEE Aerospace Conf.* **2020** pp 1-9
[7] Emri KÜ and Cihan O 2021 Control allocation of a GEO satellite for station-keeping and momentum management by using thrusters and reaction wheels *Avrupa Bilim ve Teknoloji Dergisi* (26) pp 374-382
[8] Yoshimura Y and Kojima H 2018 Optimization of fault-tolerant thruster configurations for satellite control *Advances in Space Research* **61**(6) pp 1617-1625
[9] Gazzino C, Arzelier D, Cerri L, Losa D, Louembet C and Pittet C 2019 A three-step decomposition method for solving the minimum-fuel geostationary station keeping of satellites equipped with electric propulsion *Acta Astronautica* **158** pp 12-22
[10] Weiss A, Kalabić UV and Di Cairano 2018 Station keeping and momentum management of low-thrust satellites using MPC *Aerospace Science and Technology* **78** pp 229-241
[11] Maghsoudi H, Kosari A, Fakoor M and Khoshsima M 2019 A hierarchical fuzzy-optimal strategy for station-keeping maneuver of a GEO satellite *IEEE Transactions on Aerospace and Electronic Systems* **56**(3) pp 2212-2227
[12] Markley FL and Crassidis JL 2014 *Attitude Kinematics and Dynamics Fundamentals of Spacecraft Attitude Determination and Control* vol 1286 (New York, USA: Springer New York)
[13] Wertz JR 2012 *Spacecraft Attitude Determination and Control* vol 73 (London, England: Springer Science and Business Media)
[14] Mancini M and Capello E 2021 Reaching law-based SMC for spacecraft applications with actuators constraints *IEEE Control Systems Letters* **6** pp 2036-2041
[15] Chobotov VA 2002 *Orbital Mechanics* (Virginia, USA: American Institute of Aeronautics and Astronautics)
[16] Vallado DA 2001 *Fundamentals of Astrodynamics and Applications* vol 12 (Boston, USA: Springer Science and Business Media)
[17] Montenbruck O and Gill EKA 2014 *Models, Methods and Applications in Satellite Orbits* (Berlin, Germany: Springer) pp 293-318
[18] Sidi MJ 1997 *Spacecraft Dynamics and Control: a Practical Engineering Approach* vol 7 (New York, USA: Cambridge university press)