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SPACECRAFT PROPULSION FOR ORBITAL MANEUVERS AND STATION KEEPING

By rishabh ,
IIMT UNIVERSITY, India

ABSTRACT

Orbital maneuvers and station keeping are crucial aspects of spacecraft operations, requiring precise and efficient propulsion systems. This paper provides a comprehensive review of spacecraft propulsion technologies, focusing on their applications in orbital maneuvers and station keeping. We discuss the fundamentals of spacecraft propulsion, including thrust principles, propulsion systems, and performance metrics. We also examine various propulsion technologies, such as chemical propulsion, electric propulsion, and advanced propulsion systems, highlighting their advantages and limitations. Furthermore, we discuss the challenges and future directions in spacecraft propulsion for orbital maneuvers and station keeping. We also explore the potential of swarm propulsion, in-orbit refueling, and advanced life support systems for enhanced mission flexibility and efficiency. Our analysis shows that these advanced propulsion systems can significantly improve fuel efficiency, mission duration, and overall spacecraft performance, enabling more sustainable and ambitious space exploration missions. The findings of this research have important implications for future space missions, including deep space exploration, satellite constellations, and space stations, and provide a foundation for further research and development in this field.

INTRODUCTION

Spacecraft propulsion plays a vital role in enabling spacecraft to perform various tasks, including Earth observation, communication, navigation, and exploration. Orbital maneuvers and station keeping are essential for spacecraft to maintain their desired orbits, perform rendezvous and docking, and conduct scientific experiments. The selection of a suitable propulsion system depends on the specific mission requirements, including the type of orbit, mission duration, and payload capacity.Spacecraft propulsion systems play a vital role in enabling spacecraft to achieve and maintain desired orbits, perform orbital maneuvers, and execute station-keeping tasks. The efficient and reliable operation of these systems is crucial for the success of various space missions, including Earth observation, communication, navigation, scientific exploration, and national security. As space agencies and private companies continue to push the boundaries of space exploration and development, the demand for advanced propulsion systems capable of delivering high performance, efficiency, and flexibility is growing.

Fundamentals of Spacecraft Propulsion:

Thrust Principles:Thrust is generated by expelling propellant in the opposite direction of motion. The fundamental principles of thrust include conservation of momentum, Newton’s third law, and the ideal rocket equation.

Propulsion Systems:Chemical propulsion systems use liquid or solid propellants, while electric propulsion systems utilize electrical energy to accelerate charged particles. Hybrid Propulsion systems combine chemical and electric Propulsion.

Performance Metrics: Specific impulse, thrust-to-power ratio, and propellant efficiency are crucial performance metrics for evaluating spacecraft propulsion systems.

Chemical Propulsion: Chemical propulsion systems are widely used for orbital maneuvers and station keeping due to their high thrust-to-weight ratio and fast response time. However, they have limited propellant efficiency and specific impulse.

Electric Propulsion: Electric propulsion systems offer high propellant efficiency and specific impulse, making them suitable for long-duration missions and station keeping. However, they have lower thrust levels and longer response times.

B. REFERENCE MISSION

The objective of the reference mission is to maintain the nominal orbit and attitude of a small ,Remote sensing satellite, with given accuracy and lifetime requirements, through a suitable a AI based spacecraft propulsion for orbital maneuvers and station keeping. . In the following, details of the mission, navigation requirements, and Spacecraft configuration, are provided.

Al-Optimized Propulsion Control: Develop Al algorithms to optimize propulsion system performance, efficiency, and reliability for orbital maneuvers and station keeping.

Autonomous Fault Detection and Recovery: Design Al-based systems to detect and recover from propulsion system faults, ensuring continued spacecraft operation and mission success.

Al-Driven Propulsion System Design: Use Al techniques (e.g., generative design, topology optimization) to design innovative propulsion systems and components for improved performance and efficiency.

Machine Learning for Propulsion System Modeling:

Develop machine learning models to predict propulsion system behavior, enabling more accurate simulation and optimization of orbital maneuvers and station keeping.

Al-Based Station Keeping Strategies: Investigate Al-developed strategies for efficient station keeping, considering factors like fuel efficiency, mission requirements, and spacecraft constraints.

Orbit Determination and Prediction using Al: Develop Al algorithms to accurately determine and predict spacecraft orbits, enabling more precise orbital maneuvers and station keeping.

Al-Enhanced Propulsion System Integration: Explore Al-based approaches for integrating propulsion systems with other spacecraft subsystems, optimizing overall spacecraft performance and efficiency.

Human-Al Collaboration for Propulsion Decision Making: Design interfaces and systems enabling effective human-Al collaboration for propulsion-related decision making, leveraging the strengths of both humans and Al.

Al-Driven Propulsion System Health Management: Develop Al-based systems for monitoring and managing propulsion system health, enabling predictive maintenance and minimizing downtime.

Al-Based Mission Planning and Optimization: Use Al techniques to optimize mission planning, including propulsion system performance, for efficient and effective orbital maneuvers and station keeping.

ORBIT AND ATTITUDE

Orbit Determination and Prediction:

x(t) = x0 + vot + (1/2)at^2 where x(t) is the position at time t, x0 is the initial position, vo is the initial velocity, and a is the acceleration.

1. Altitude Control and Maintenance:

$$h(t) = ho + v_ht + (1/2)g_ht^2$$

where $h(t)$ is the altitude at time t, ho is the initial altitude, v_h is the vertical velocity, and g_h is the vertical acceleration due to gravity.

1. Orbit Correction and Maneuver Planning:

$$Av = sqrt((2*Ah)/m)$$

where Av is the required velocity change, Ah is the required altitude change, and m is the spacecraft mass.

1. Fuel Efficiency and Optimization:

$$m_f = (m_p/(1- (\Delta v/v_e)))$$

where m_f is the fuel mass, m_p is the payload mass, Av is the velocity change, and v_e is the exhaust velocity.

1. Orbit Stability and Perturbation Analysis:

$$dx/dt = f(x, t)$$

where x is the state vector (position, velocity, etc.), and f is the perturbation function.

1. Altitude and Orbit Estimation Uncertainty:

$$\sigma_x = sqrt((\sigma_p^2 + \sigma_v^2) / 2)$$

where o_x is the uncertainty in position, o_p is the uncertainty in position measurement, and σ_v is the uncertainty in velocity measurement.

Al-Driven Propulsion System Sizing:

$$T = (m_p/(2 * \eta * g_0 * I_{sp}))$$

Where T is the thrust, m_p is the payload mass, η is the efficiency, g_0 is the standard gravity, and I_{sp} is the specific impulse.

1. Orbit and Altitude Control during Anomalies:

$$X(t) = x0 + vot + (1/2)at^2 + 8x(t)$$

Where 8x(t) is the anomaly-induced position error.

1. Comparison with Traditional Methods:

$$N_{Al} = (m_p/m_f) / (\eta_T / (1 - (\Delta v/v_e)))$$

Where n_{Al} is the Al-based propulsion efficiency, n_T is the traditional propulsion efficiency, and other variables are as defined earlier.

1. Robustness and Fault Tolerance Analysis:

$R = (\sigma.\chi / x) + (\sigma\alpha\nu / \nu)$

Where R is the robustness metric, σ_x and σ_v are the uncertainties in position and velocity, and x and v are the nominal values.

NAVIGATION AND CONTROL REQUIREMENTS

Orbit Determination:

$X = r \cos(0)$

$Y = r \sin(0)$

$Z = 0$

Where (x, y, z) is the position vector, r is the radial distance, and e is the true anomaly.

1. Velocity Control:

$V = \sqrt{(2 * \mu / r)}$

Where v is the velocity, u is the gravitational parameter, and r is the radial distance.

1. Attitude Control:

$\Omega = \Omega + \delta\omega$

Where w is the angular velocity, Q is the nominal angular velocity, and δω is the attitude error.

1. Orbit Correction:

Av = v_e * In(r_f/r_i)

Where Av is the required velocity change, v_e is the exhaust velocity, r_f is the final radial distance, and r_i is the initial radial distance.

1. Station Keeping:

Av v_e/r)*(1-c =(2*v_e/r) * (1- cos(10))

Where Av is the required velocity change, v_e is the exhaust velocity, r is the radial distance, and A0 is the angular separation.

1. Navigation:

$$P = [x, y, z, v_x, v_y, v_z]$$

Where p is the navigation state vector, (x, y, z) is the position, and (v_x, v_y, v_z) is the velocity.

1. Control:

$$U = [F_x, F_y, F_z, T_x, T_y, T_z]$$

Where u is the control input vector, (F_x, F_y, F_z) is the force, and (T_x, T_y, T_z) is the torque.

1. State Estimation:

$$X_{hat} = x + 6x$$

Where x_hat is the estimated state, x is the true state, and ox is the estimation error.

1. Kalman Filter:

$$X_k = A x_{k-1} + B u_k + w_k$$

Where x_k is the state at time step k, A is the state transition matrix, B is the control input matrix, u_k is the control input, and w_k is the process noise.

SPACECRAFT DYNAMICS

The simulation model state is a 14-dimensional vector which includes the inertial position r And velocity v, the quaternion qIB defining the orientation of the spacecraft with respect to the Inertial frame, the spacecraft angular rate ωB defined in the spacecraft body reference frame, and The spacecraft mass m. The equations which describe the dynamics of the state vector are:

Equations of Motion:

$$dx/dt = v$$

$$dv/dt = F/m$$

where x is position, v is velocity, F is force, and m is mass.

1. Orbital Mechanics:

v = √(2 μ/r) r = a_(1-e^2)/(1 + e*cos(0))

where v is velocity, u is gravitational parameter, r is radial distance, a is semi-major axis, e is eccentricity, and e is true anomaly.

1. Attitude Dynamics:

ω = Ω + δω dw/dt = (M/I) + (ω x lw)/1

where w is angular velocity, Q is nominal angular velocity, δω is attitude error, M is moment, I is moment of inertia, and x denotes cross product.

1. Euler's Equations:

dwx/dt = (Mx/lx) + (wy_wz_(ly - Iz))/lx dwy/dt = (My/ly) + (wz_wx_(lz-Ix))/ly dwz/dt = (Mz/lz) + (wx_wy_(lx-ly))/Iz

where wx, wy, wz are angular velocities, Mx, My, Mz are moments, and lx, ly, Iz are moments of inertia.

1. Kinematics:

$v = Rw$

$x = Rx$

where v is velocity, R is rotation matrix, w is angular velocity, x is position, and x' is position in body-fixed frame.

Earth’s non-spherical gravity field: A spherical harmonic expansion EGM96 [21] up to degree b And order 24 for the disturbance acceleration and a spherical mass distribution for the gravity Gradient torque computation are considered.

- Atmospheric drag: The Jacchia-71 model [22] is employed to approximate the atmospheric Density. High solar activity (F10.7 = 220) is considered, providing a worst-case scenario for the Simulation. The drag force acting on the satellite is computed using the mean cross-sectional

Area, while the aerodynamic torque depends on the satellite layout and orientation [23].

- Solar radiation pressure: The solar radiation pressure value accounts for the Earth’s orbit Eccentricity and eclipse conditions [24]. A Cannonball model is employed for the translational Dynamics while the solar radiation torque is related to the offset between the satellite center Of pressure and center of mass.

- Earth’s magnetic field: Magnetic disturbance torques result from the interaction of the space-Craft residual magnetic field and the geomagnetic field, described by the IGRF95 model trun-Cated to degree and order 9.

- Luni-solar attraction: Disturbance accelerations due to lunar and solar point mass gravity Field are considered. The position of the Sun and the Moon is obtained through precise Ephemerides .

CONCLUSION

Spacecraft propulsion for orbital maneuvers and station keeping requires careful selection and optimization of propulsion systems. This paper provides a comprehensive review of spacecraft propulsion technologies, highlighting their advantages and limitations. Future research should focus on developing advanced propulsion systems and innovative mission architectures to enable more efficient and sustainable spacecraft.

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