Space Station OS

AOCS System: Orbital Motion, Attitude Dynamics & Controller

Design, Simulation, and Performance

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Date: March 10, 2025

Overview

Agenda:

- Project Background & Objectives
- Orbital Motion Dynamics
- AOCS System Overview
- Simulation Setup & Results
- Challenges & Future Work

Project Background & Objectives

Our focus is on developing an Attitude and Orbit Control System (AOCS) that ensures both precise orientation and stable orbital dynamics.

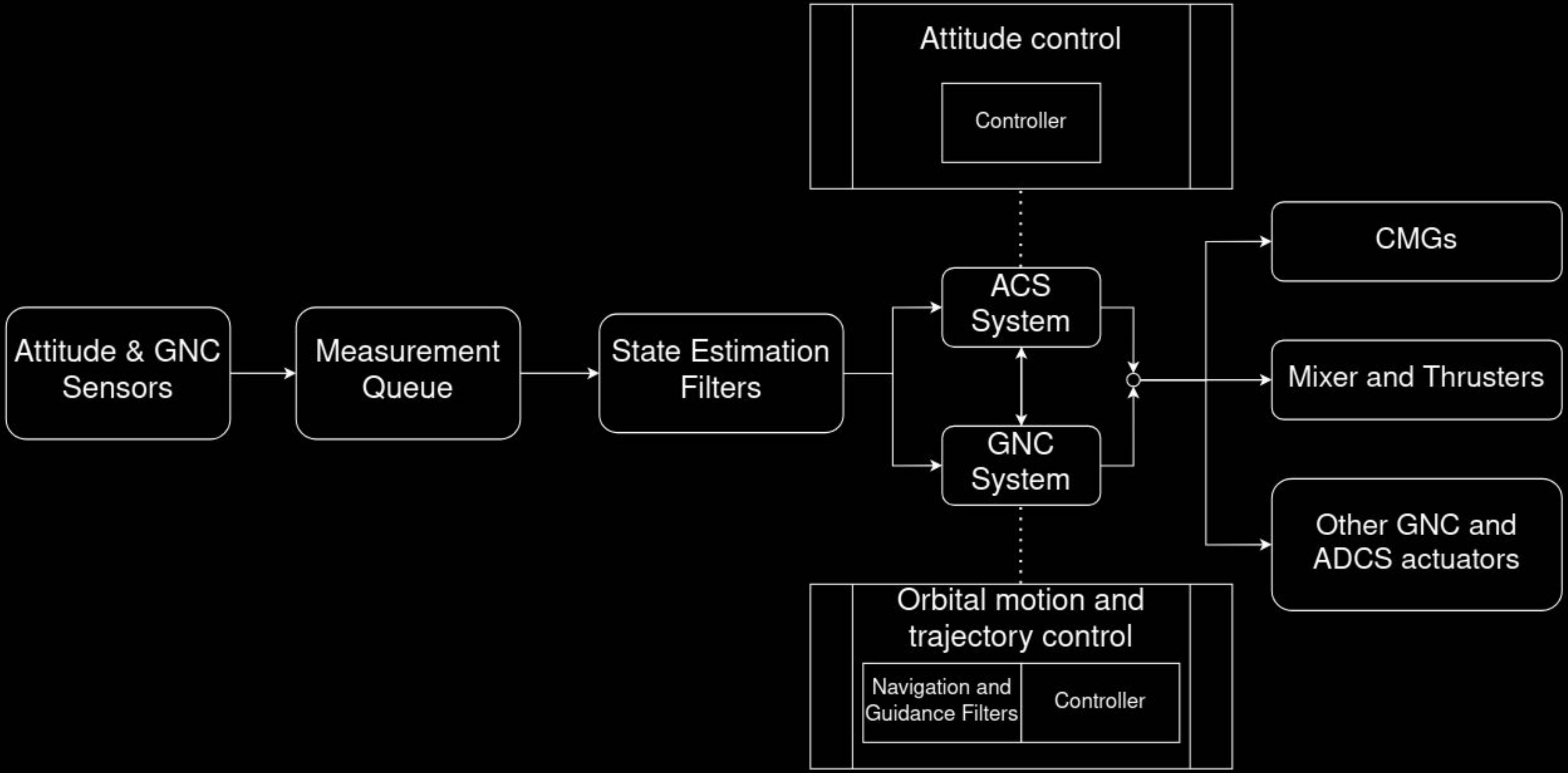
Key Objectives:

- Design system model and control architecture
- Optimize energy consumption through efficient control algorithms
- Achieve high-precision attitude and orbital control under varying conditions

Milestones:

- Successful integration of physics and AOCS subsystem components
- Completion of simulation validations
- Integration phase

Architecture

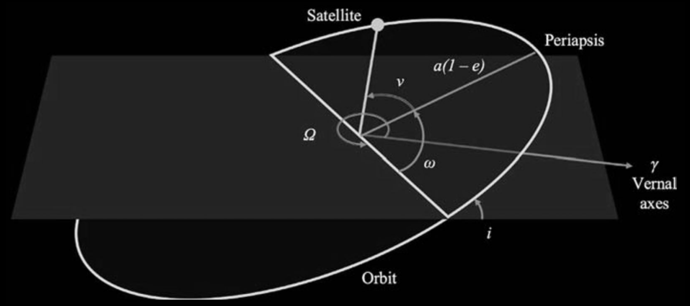


Orbital and Attitude Dynamics

Orbital and attitude model dynamics are written to help with simulation of the AOCS system and help designing the optimal controller & state estimation algorithms.

Key Components:

- Non-linear 1st order differential equations for attitude dynamics and orbital dynamics
- Kepler’s Law, two-body problem and Euler-Newton law
- 6 states orbital dynamics and 10 states attitude dynamics
- Perturbation Forces and Torques considered for the currently dynamics:
  - Atmospheric Drag
  - Microgravity
  - Gravity Gradient
  - CMG’s dynamics



$$\mathbf{x} = \begin{bmatrix} x \\ y \\ z \\ v_x \\ v_y \\ v_z \end{bmatrix} \qquad \mathbf{x} = \begin{bmatrix} p \\ q \\ r \\ \phi \\ \theta \\ \psi \\ \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \end{bmatrix}$$

AOCS System Overview

The Attitude and Orbit Control System (AOCS) is the core system that maintains the space station's correct orientation and trajectory in orbit.

Key Components:

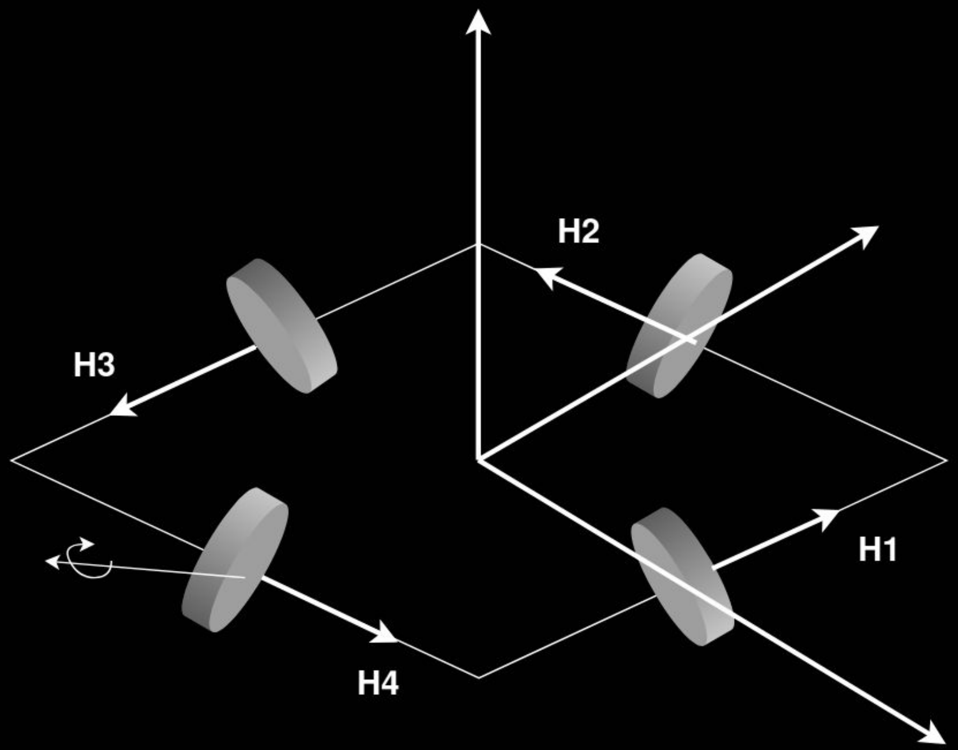
- Attitude Control Actuators: Single Gimballed CMGs, Thrusters & Engines
- Orbital Control Actuators: Thrusters & Engines
- Attitude Control System: PD Controller, NMPC Optimal Control*
- Orbital Control System: PID Controller with actuator mapping & H_∞ controller(in-progress)*

Single Gimballed CMGs

- This design employs four single gimballed CMGs arranged in a pyramid formation, with each CMG positioned on one edge of the pyramid.

- This configuration ensures effective distribution of control torques across all three axes, allowing controllability of the attitude.

- The pyramid model is great for minimizing singularities and improves responsiveness.



Simulation setup - Initial Conditions

State Variables

$$p_0 = 0.0, \quad q_0 = 0.001, \quad r_0 = 0.0$$
$$\phi_0 = 0.0, \quad \theta_0 = 0.0, \quad \psi_0 = 0.0$$
$$\boldsymbol{\delta}_s = \mathbf{0}_{4\times 1} \quad \text{(Zero vector of size 4)}$$

Spacecraft and Environmental Parameters

$$I_{xx} = 10.0, \quad I_{yy} = 12.0, \quad I_{zz} = 9.0$$
$$I_{xy} = 0.0, \quad I_{xz} = 0.0, \quad I_{yz} = 0.0$$
$$\mu = 3.986 \times 10^{14}\ \mathrm{m^3/s^2} \quad \text{(Gravitational parameter)}$$
$$r_{\text{orbit}} = 7.0 \times 10^6\ \mathrm{m} \quad \text{(Orbit radius)}$$
$$\boldsymbol{T}_{\text{cmg}} = \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \quad \text{(CMG torque)}$$

Initial Position and Velocity

$$x_0 = 0.0, \quad y_0 = 0.0, \quad z_0 = 7.0 \times 10^6\ \mathrm{m}$$
$$v_{\text{circ}} = \sqrt{\frac{\mu}{r_{\text{orbit}}}} \quad \text{(Circular orbit speed)}$$
$$v_{\text{elip}} = \sqrt{\mu\left(\frac{2}{r_{\text{orbit}}} - \frac{1}{7.5 \times 10^{-6}}\right)} \quad \text{(Elliptical orbit speed)}$$
$$v_{x_0} = v_{\text{circ}}\cos(0.3), \quad v_{y_0} = v_{\text{circ}}\sin(0.3), \quad v_{z_0} = 0.0$$

Atmospheric and Spacecraft Properties

$$C_d = 2.2 \quad \text{(Drag coefficient)}$$
$$A = 4\ \mathrm{m^2} \quad \text{(Cross-sectional area)}$$
$$m = 500\ \mathrm{kg} \quad \text{(Mass of spacecraft)}$$
$$P = 1.57 \times 10^{-5} \quad \text{(Atmospheric pressure)}$$
$$T_{\text{atm}} = 2000\ \mathrm{K} \quad \text{(Atmospheric temperature)}$$

Thermospheric Parameters

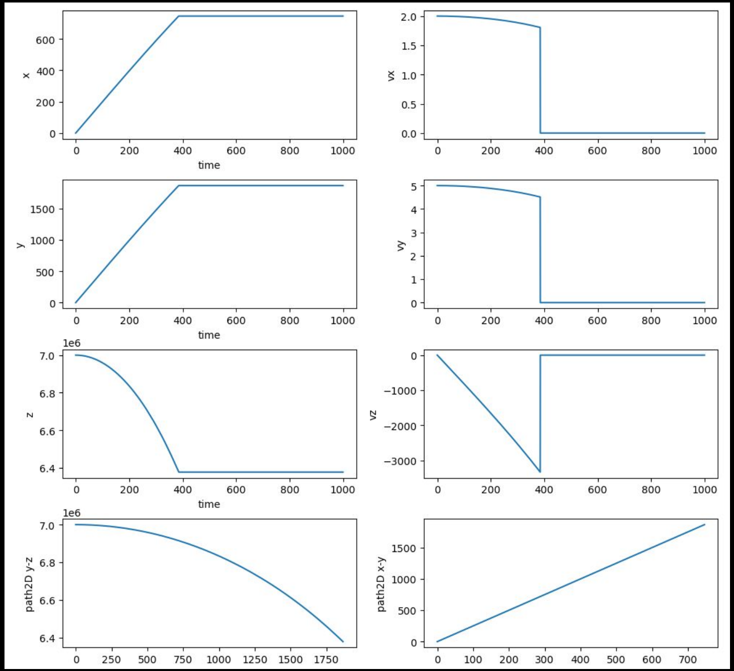
$$m_{\text{mol}} = 2.66 \times 10^{-26}\ \mathrm{kg} \quad \text{(Molecular mass)}$$
$$k_B = 1.380649 \times 10^{-23}\ \mathrm{J/K} \quad \text{(Boltzmann constant)}$$
$$\rho_{\text{therm}} = 4 \times 10^{-10}\ \mathrm{kg/m^3} \quad \text{(Density)}$$
$$h_0 = 400\ \mathrm{km}, \quad H = 70\ \mathrm{km} \quad \text{(Scale height)}$$

Integration Settings

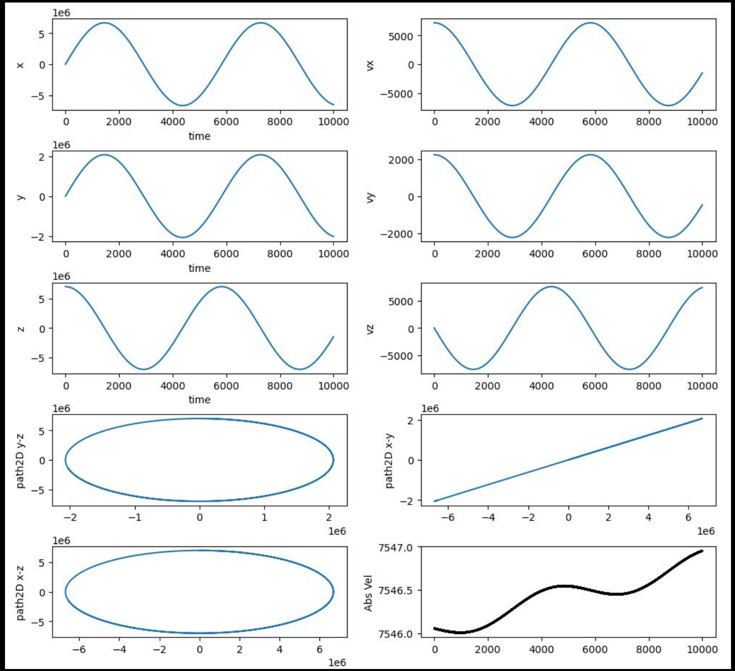
$$\Delta t = 0.1\ \mathrm{s} \quad \text{(Time step)}$$
$$N_{\text{steps}} = 100000 \quad \text{(Number of integration steps)}$$

Simulation results - 1

Orbital dynamics



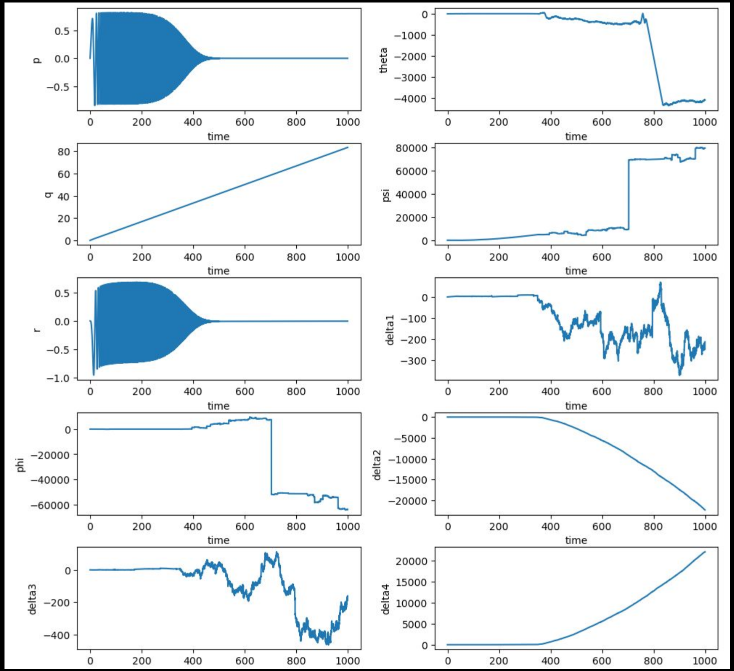
Negligible tangential velocity, free fall



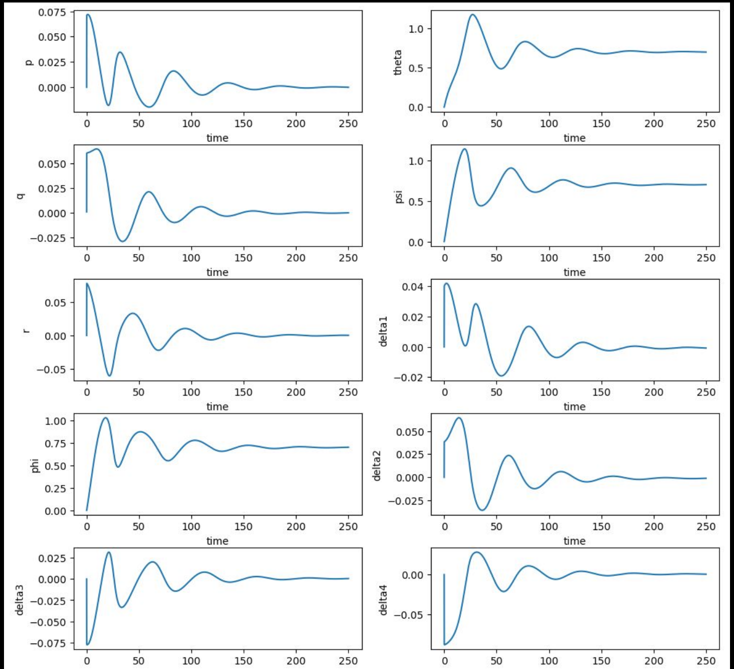
Balanced initial orbital velocity, elliptical orbit

Simulation results - 2

Attitude dynamics and PD controller



No controller, static initial conditions



PD controller, untuned

Considerations and TODOs

Considerations:

Attitude System:

- Modeled with a static inertial frame and constant atmospheric conditions (fixed pressure and density).
- Torques and dynamics are referenced to both the body frame and LVLH frame.

Orbital System:

- Modeled using a static inertial Earth frame with a constant atmospheric model.
- Forces and dynamics are expressed in the inertial frame with outputs in Cartesian coordinates.

Future Enhancements (TODO):

Perturbations:

- Incorporate additional effects such as aerodynamic/magnetic torques, solar radiation pressure, and Gaussian noise.

Simulation & Visualization:

- Shift to ROS2 for real-time, live visualization as the solver processes the equations.

Model Complexity:

- Consider more complex body shapes and inertia parameters; include rotational inertial frames for both systems.

Controller Improvements:

- Add an NMPC controller for attitude adjustments using CMGs (and later thrusters).
- Implement a controller for orbital altitude regulation once thrusters/engines are integrated.
- Merge attitude dynamics with orbital models for comprehensive control.

Control System Tuning:

- Use root-locus and bode-plot analyses to design compensators and fine-tune PID controller performance.

Thank You