ESTCube-2 Nanosatellite Attitude Control for Interplanetary Missions

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Introduction

2 Satellite Dynamics
   • Linearization

3 Attitude Control Designs
   • Attitude Modes
   • Controller Designs

4 Simulation Results

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   • Conclusion
ESTCube-2 Mission

3U CubeSat

Scientific objective:

Demonstrate plasma brake deorbiting experiment

Earth observations

Coating resistant experiment

ESTCube-3 platform
Linearization with Reaction Wheels

From Satellite dynamics with reaction wheels

\[ J\dot{\omega}_i = T_d + T_c - \Omega(\omega_i)(J\omega_i + H) \quad (1) \]
\[ J\dot{\omega}_i = T_d + T_c + f(\omega, \omega^B) \quad (2) \]

Assumptions for nadir pointing of the satellite,
- angular velocity rate \( \omega \approx 0 \)
- both frames be aligned with very little error \( q_1, q_2, q_3 = 0 \).

The state space linearized form of \( \dot{x} = Ax + BT_c \)

\[
\begin{bmatrix}
\dot{q} \\
\dot{\omega}_i
\end{bmatrix} =
\begin{bmatrix}
0_3 & \frac{1}{2}(I_3) \\
f_3 & f_3
\end{bmatrix}
\begin{bmatrix}
q \\
\omega_i
\end{bmatrix} +
\begin{bmatrix}
0_3 \\
I_3
\end{bmatrix}(T_c)
\quad (3)
\]
The magnetic field $b$ is expressed based on the dipole model described as

$$
\begin{align*}
b &= \begin{bmatrix}
b_1(t) \\
b_2(t) \\
b_3(t)
\end{bmatrix} = \frac{\mu_f}{a^3} \begin{bmatrix}
\cos \omega_0 t \sin \theta \\
- \cos \theta \\
2 \sin \omega_0 t \sin \theta
\end{bmatrix}
\end{align*}
$$

where $\theta$ is the inclination

- $a$ is the orbit’s semi major axis
- $\omega_0$ is the orbit angular velocity
- $\mu_f$ is the magnetic field’s dipole strength in $Wb \cdot m.$
Attitude Modes

- **Detumbling** to stabilize the angular rate of the satellite after orbital insertion. Spin rate to 0.1 deg/s
**Attitude Modes**

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- **Pointing** A fundamental attitude control task to be used to fulfill the following tasks (0.25 deg accuracy, 0.125 deg/s stability)
  - Sun pointing
  - Ground location tracking
  - Nadir pointing

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Attitude Modes

- **Detumbling** to stabilize the angular rate of the satellite after orbital insertion. Spin rate to 0.1 deg/s

- **Pointing** A fundamental attitude control task to be used to fulfill the following tasks (0.25 deg accuracy, 0.125deg/s stability)
  - Sun pointing,
  - Ground location tracking,
  - Nadir pointing

- **Spin-up** to generate angular momentum for tether deployment (E-sail and Plasma brake Experiment)
  - Spin axis must be pointed with accuracy of 2 degrees
  - Magnetic coils + Reaction wheels (LEO)
  - Reaction wheels + Cold-gas thrusters (Lunar Orbit)
Attitude Modes

Control Structure

\[ \text{Error signal} \rightarrow \Sigma \rightarrow \text{Control Algorithm} \rightarrow T_c \rightarrow \text{Actuator} \rightarrow \Sigma \rightarrow \text{Spacecraft Attitude Dynamics} \rightarrow \text{Attitude (} \Phi, \theta, \psi \text{)} \]

\[ \text{External disturbance torque} \rightarrow T_d \]

\[ \text{Feedback} \rightarrow \text{Sensor} \]
Controller Designs

Bdot Algorithm

In order to decrease the kinetic energy of the spacecraft the control torque $\tau$ has to be proportional to $-\omega$

The magnetic moment needs to be perpendicular to $\omega \times B$ as no torque will be produced if it were parallel.

$$m = -k \cdot (\omega_i \times B) \quad (5)$$

The simple Bdot control law is based on

$$m = -k \dot{B} \quad (6)$$
Controller Designs

Cross Product Law

\[
\begin{bmatrix}
T_{cx} \\
T_{cy} \\
T_{cz}
\end{bmatrix}
= 
\begin{bmatrix}
k_\omega \omega_i + k_q q_e
\end{bmatrix}
\quad (7)
\]

\[
m = -\frac{k}{(\|B\|)^2}[B \times h_e]
\quad (8)
\]

where

- \(T_c\) is the control torque from the reaction wheels
- \(m\) is the magnetorquer dipole moment vector
- \(k, k_\omega, k_q\) are controller gains
- \(h_e\) is the angular momentum error of the wheels.
Controller Designs

Introduction

Satellite Dynamics

Attitude Control Designs

Simulation Results

Conclusion

Controller Designs

Linear Quadratic Regulator

The design begins from the basic state space model

\[ \dot{x} = Ax + Bu \]  

(9)

and the controller aims to implement a basic feedback control \( u \) for optimization,

\[ u = -Kx \]  

(10)

where \( K \) is the feedback gain matrix calculated to minimize the Linear Quadratic cost function

\[ J = \int_0^\infty [x^T Q x + u^T R u] dt \]  

(11)
Controller Designs

Linear Quadratic Regulator

where the basic feedback control $u$ is further expressed as

$$u = -R^{-1}B^TPx$$

(12)

where $P$ is a symmetric positive semi-definite solution of the Algebraic Riccati Equation (ARE) given below

$$0 = PA + A^TP + Q - PBR^{-1}BP$$

(13)
Controller Designs

LQR Algorithm

1. Define Control outputs
2. Identify the Control Variables
3. Define Performance Index or Specifications
4. Obtain Spacecraft model with actuator
5. Specify Parameters for LQR controller
6. Optimize parameters for effective performance gain
7. Check if Specifications and requirements achieved?
   - YES: Implement the design
   - NO: Go back to step 5

- Attitude requirement in quaternions
- $q_1, q_2, q_3$
- Settling time, accuracy
- From linearized satellite dynamics

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Angular Rate Control

Simplified control law for x-axis spin rate control for tether deployment

\[
m = -\frac{k}{(\|B\|)^2}[B \times (h_e + k_1 h_{e1} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + k_2 S\omega)]
\]  

- where \( m \) is the magnetorquer dipole moment vector in SBRF
- \( k, k_1, k_2 \) are control law gains.
- \( S \) represents the axes selection matrix.
Bdot Detumbling Result

![B-dot Angular Velocity Detumbling](image1)

![Quaternion Attitude error with Bdot](image2)

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Cross Product Law Result

Angular Velocity

Quaternion Attitude Error
Cross Product Law Result (Angular momentum)
LQR-Magnetic Result (Angular Velocity)
LQR-Reaction wheels Result (Angular Velocity)

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Spin up Result (Angular Velocity -360deg/s )

![Magnetic SpinUp Angular velocity graph](image_url)
Future Work

The controllers designed are implemented in MATLAB environment, however these control algorithms would have to be written in c language and tested in simulation.

- Magnetic controllers gain optimization
- Angular rate spin controller with Reaction wheels
- Thruster Pulse width modulation control
- Fault detection and isolation based on Neuro-fuzzy scheme