ASTE 585: Spacecraft Attitude Control

Summer Session 2020

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The objective of this course is to introduce the student to various methods of designing attitude control of systems for a spacecraft performing a variety of tasks and operating under different mission imposed conditions. First, topics in kinematic and dynamic modeling of spacecraft relevant to control system development will be reviewed. Classical and modern techniques of attitude stabilization will be explained and applied to different modes of spacecraft operation. Control system design methods will include Laplace domain techniques, frequency domain methods, and design in state-space. Techniques that use earth's environment for spacecraft control, such as gravity gradient stabilization and control via magnetic torquers, will be discussed. A number of methods for development of large angle attitude maneuvers will be introduced. These approaches will include control with momentum exchange devices, magnetic attitude control, momentum unloading techniques and momentum minimization, momentum-biased attitude stabilization, and control with reaction thrusters. Influence of spacecraft structural flexibility on the control system performance will be also discussed. The implementation of the control laws on flight hardware will be also introduced. When appropriate the operation of the devices used for the implementation of the attitude control system will be explained. The devices will include attitude determination sensors such as earth, sun, and star sensors, rate and rate integrating sensors, and magnetometers, and attitude control actuators such as reaction wheels, control moment gyros, and magnetic torque rods.

Grading: The grade will be determined by three small projects (homeworks).

Prerequisites: At least one course in control, understanding of kinematics and dynamics.

Textbook: Marcel J. Sidi *Spacecraft Dynamics and Control*, Cambridge Aerospace Series, Latest edition.

Outline

In the following outline the acronyms of the references for the various sections are as follows:

(MS) M. J. Sidi: *Spacecraft Dynamics and Control: A Practical Engineering Approach,* Cambridge Aerospace Series, 2000

(BW) B. Wie: *Space Vehicle Dynamics and Control,* AIAA Educational Series, 1998.

(AB) A. E. Bryson: *Control of Spacecraft and Aircraft,* Princeton University Press, 1994.

(MC) F. L. Markley and J. L. Crassidis, *Fundamentals of Spacecraft Attitude Determination and Control,* Springer, 2014

(DDF) A. H. J. De Ruiter, C. J. Damaren and J. R. Forbes: *Spacecraft Dynamics and Control, An Introduction,* Wiley, 2013

1. Introduction *(Notes)*
    (a) Example spacecraft
    (b) Control problem formulation
    (c) Actuators
    (d) Open-loop control
    (e) Disturbances and modeling errors
    (f) Closed-loop control
    (g) Control problem statement
    (h) Spacecraft model
2. Review of Orbital Mechanics *(Notes)*
    (a) Two body problem
    (b) Kepler's laws
    (c) Conic sections
    (d) Orbital parameters
3. Attitude Kinematics
    (a) Rotation matrix and direction cosines *(BW 5.1, MS A.2)*
    (b) Parametrization of the attitude
        i. Euler's axis rotation *(BW 5.3, MS A.4.2, MC 3.2.5)*
        ii. Quaternions *(BW 5.4, MS A.4.1, MC 3.2.1)*
        iii. Rodrigues parameters *(MC 3.2.2)*
        iv. Euler angles *(BW 5.2, MS A.3, MC 3.2.5)*
    (c) Differential kinematic *(BW 5.5, MS 4.7)*

i. Derivative of the rotation matrix
ii. Angular velocities in different parametrizations

(d) Basic frames *(Notes, MC 2.6)*

i. ECI (Earth-Centered Inertial)
ii. ECEF (Earth-Centered Earth-Fixed)
iii. Orbital (Roll, pitch, yaw)
iv. Body (Rigidly attached to main s/c body)
v. Geomagnetic

4. Attitude Estimation

(a) The TRIAD algorithm *(MC 5.1, DDR 25.2.4)*

(b) Wahba's problem *(MC 5.2, DDR 25.2.1)*

(c) Quaternion solution of Wahba problem

i. Davenport's q method *(MC 5.3.1, DDR 25.2.2)*
ii. Quaternion estimator (QUEST) *(MC 5.3.2, DDR 25.2.2)*

5. Attitude Dynamics

(a) Rate change of a vector in a rotating frame *(BW 1.2.3, MS88)*

(b) Angular momentum and kinetic energy of a rigid body *(BW6-1,6-2,MS 4.2-4.3)*

(c) Principal axesv*(BW6-3, MS4.4)*

(d) Euler's equations *(BW 6.4, MS 4.5)*

(e) Torque free motion of an axisymmetric rigid body *(BW 6-5, MS 4.5.1)*

(f) Stability of a general torque free motion *(BW6.6, MS 4.5.2)*

(g) Nutation of a spinning body (MS 4.6.1)

(h) Nutation destabilization *(MS 4.6.2)*

6. Earth Satellite in Circular Orbits

(a) General equations *(BW 6.10, MS 4.8.2, AB 1.4.1-3)*

(b) Linearized equations (*BW 6.10.1, MS 4.8.3, AB 1.4.4)*

7. Disturbance Torques

(a) Magnetic torques

i. Magnetic field models
ii. Dipole model

(b) Solar pressure torques

i. Solar pressure model

(c) Aerodynamic torques

    i. Atmospheric density model

  (d) Gravity gradient torques

8. Gravity gradient stabilization

   (a) Linear stability analysis of passively controlled satellite *(BW 6.10.2 MS 5.3.2, AB 1.4.5-7).*
   (b) Gravity gradient (pitch) stabilization with passive damping *(MS 5.3.3).*
   (c) Gravity gradient (pitch) stabilization with active damping using magnetic torques *(MS 5.3.4).*
   (d) Gravity gradient three-axis stabilization with active damping using magnetic torques *(MS 5.3.5).*

9. Attitude Stabilization with a Spin

   (a) Spin stabilization *(MS 6.1, AB 5.1)*
   (b) Nutation of a rigid body
      i. Torque-free motion of a symmetric rigid body *(BW 6.5, MS 4.5.1, 4.6.1, AB 5.1.1)*
      ii. Stability of torque-free an asymmetric body *(BW 6.7, MS 4.5.2).*
      iii. Nutation destabilization due to energy dissipation *(BW 6.7, MS 4.6.2)*
   (c) Spin-up maneuver *(BW 7.1.2)*
   (d) Attitude stabilization during *spinup (MS 6.2, AB 5.1)*
   (e) Single-spin nutation damping *(MS 6.6, AB 5.2)*
   (f) Active wheel nutation damping *(MS 6.6.2, AB Problem 5.2.1)*
   (g) Dual spin stabilization *(MS 6.7, AB 5.3)*

10. Large angle maneuvers

   (a) Using direction cosine matrix *(MS 7.2.1)*
   (b) Using Euler axis of rotation *(BW 7.3.2, MS 7.2.2)*
   (c) Using quaternion errors *(BW 7.3.1, MS 7.2.3)*

11. Attitude control using momentum exchange devices

   (a) Control modes using momentum exchange devices *(Notes)*
   (b) Model of momentum exchange device *(BW 7.5, MS 7.3.1, AB 4.1, Notes)*
   (c) Fast attitude control
      i. Control law *(MS 7.3.2, AB 4.1, Notes)*
      ii. Momentum accumulation and its dumping *(MS 7.3.3)*
      iii. Momentum wheel commands *(MS 7.3.4, Notes 37-39)*
      iv. Momentum management during a maneuver *(MS 7.3.5)*
      v. Magnetic attitude control *(MS 7.4)*
      vi. Magnetic unloading *(MS 7.5)*
   (d) Slow attitude control using gravity gradient unloading

      i. Pitch control law *(AB 4.2)*
      ii. Roll/yaw control law *(AB 4.3)*

12. Momentum-biased stabilization
    (a) Dynamic equations *(MS 8.2, Notes)*
    (b) Intuitive explanation
    (c) Stabilization without active control *(MS 8.2)*
    (d) Roll/yaw stabilization with active control *(MS 8.3)*
        i. Stabilization with yaw measurement *(MS 8.3.1)*
        ii. Stabilization without yaw measurement
            A. Control law derivation *(MS 8.3.2, Notes)*
            B. Implementation using reaction thrusters *(MS 8.8.2, AB 3.3.3, Notes)*
            C. Magnetic rods implementation *(MS 8.4)*
    (e) Control using two wheels *(MS 8.7.1-2, Notes)*
    (f) Momentum unloading using thrusters *(MS 8.7.4, Notes)*

13. Reaction thruster attitude control
    (a) Set-up of reaction thruster control *(MS 9.2)*
    (b) On-off control *(AB 3.3.1-2)*
    (c) Attitude control using PWPF modulators *(BW 7.7, MS 9.3.2, AB 3.3.3, Notes)*