MAE 468/568
Elements of Spacecraft Design

Ch. 11 – Attitude Determination and Control

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Class Agenda

- Control modes and requirements
- Selection of spacecraft control type
- Quantify the disturbance environment
- Select and size ADCS hardware

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Attitude Determination and Control

- ADCS stabilizes vehicle and orients it in desired directions during mission despite external disturbance torques acting on it
- Requires vehicle to determine its attitude, using sensors, and control it using actuators
- Works with propulsion and navigation subsystems
- Need to know mass properties of spacecraft
  - Location of CG
  - Moments and products of inertia

Need to know how these change over time

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Attitude Determination and Control

- Disturbance torques are small, but persistent in space
- Torque types
  - Cyclic – varying in a sinusoidal manner during orbit
  - Secular – accumulating with time
- ADCS resists torques either passively or actively
- Spinning spacecraft resist disturbance torques – call gyroscopic stiffness

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Attitude Determination and Control

- ADCS must reorient vehicle (slew maneuvers) to repoint payload, solar arrays, or antennas
- External reference (Sun, Earth's IR horizon, local magnetic field direction, and stars) used to determine the vehicle's absolute attitude to orient vehicle
- Inertial sensors carried to provide short-term attitude reference

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Control System Design Process

Step	Inputs	Outputs
1a. Define control modes 1b. Define or derive system-level requirements by control mode	Mission requirements, mission profile, type of insertion for launch vehicle	List of different control modes during mission Requirements and constraints
2. Select type of spacecraft control by attitude control mode	Payload, thermal, and power needs Orbit, point direction Disturbance environment	Method for stabilizing and control; 3-axis, spinning, or gravity gradient
3. Quantify disturbance environment	Spacecraft geometry, orbit, solar/magnetic models, mission profile	Value for forces from gravity gradient, magnetic, aerodynamics, solar pressure, internal disturbances, and powered flight effects on control

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Control System Design Process

Step	Inputs	Outputs
4. Select and size ADCS hardware	Spacecraft geometry, pointing accuracy, orbit conditions, mission requirements, lifetime, orbit, pointing direction, slew rates	Sensor suite: Earth, Sun, inertial, or other sensing devices Control actuators (reactions wheels, thrusters, or magnetic torquers) Data processing electronics
5. Define determination and control algorithms	All of above	Algorithms, parameters, and logic for each determination and control mode
6. Iterate and document	All of above	Refined requirements and design Subsystem specification

Typical Attitude Control Modes

Mode	Description
Orbit Insertion	Period during and after boost while spacecraft is brought to final orbit. Options include no spacecraft control, simple spin stabilization of solid rocket motor, and full spacecraft control using liquid propulsion system
Acquisition	Initial determination of attitude and stabilization of vehicle. Also may be used to recover from power upsets or emergencies
Normal On-Station	Use for vast majority of mission. Requirements for this mode should derive system design
Slew	Reorienting the vehicle when required
Contingency or safe	Used in emergencies if regular mode fails or is disabled. May use less power or sacrifice normal operation to meet power or thermal constraints
Special	Requirements may be different for special targets or time periods, such as eclipses

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ADCS Requirements

Area	Definition
DETERMINATION	
Accuracy	How well a vehicle's orientation with respect to an absolute reference is known
Range	Range of angular motion over which accuracy must be met
CONTROL	
Accuracy	How ell the vehicle attitude can be controlled with respect to a commanded direction
Range	Range of angular motion over which control performance must be met
Jitter	A specified angle bound or angular rate limit on short-term, high-frequency motion
Drift	A limit on slow, low-frequency motion. Usually expressed as angle/time
Settling Time	Specifies allowed time to recover from maneuvers or upsets

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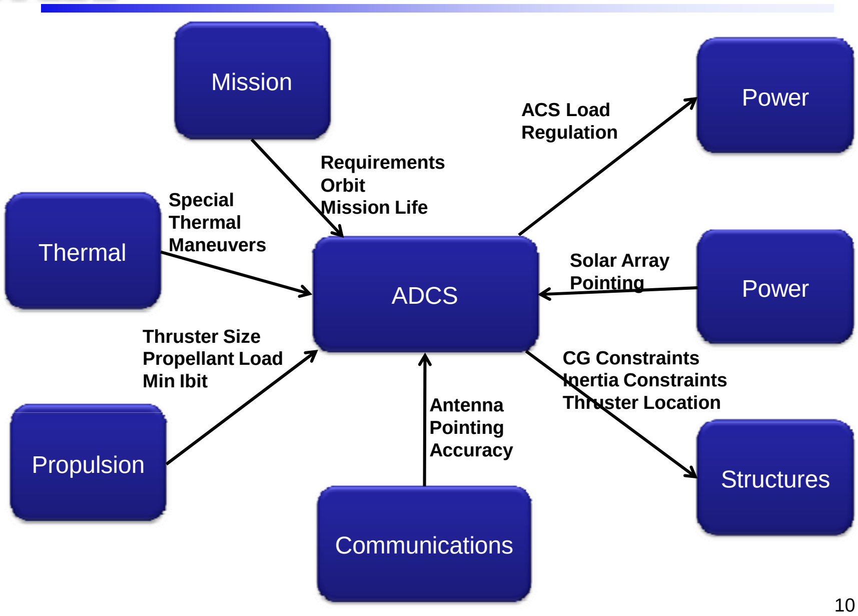
Requirements for ADCS



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Selection of Spacecraft Control Type

- Passive control techniques
  - Gravity-gradient control – uses inertial properties of vehicle to keep it pointed toward Earth; used on simple spacecraft in near-Earth orbits without yaw orientation requirements
  - Magnets – forces alignment along the Earth's magnetic field; most effective in near-equatorial orbits where field orientation stays almost constant

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Selection of Spacecraft Control Type

- Spin control techniques
  - Spin stabilization – entire spacecraft rotates so that its angular momentum vector remains approximately fixed in inertial space; employ gyroscopic stability to passively resist disturbance torques about two axes; spinning motion is stable if vehicle is spinning about axis having largest moment of inertia; disadvantages – mass properties must be controlled to ensure stability & requires more fuel to reorient – bad for repointed payloads
  - Dual-spin – two sections spinning at different rates about same axis

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Selection of Spacecraft Control Type

- Three-axis control techniques
  - More common today
  - Maneuver and can be stable and accurate
  - More expensive and more complex
  - Methods
    - Momentum wheels
    - Reaction wheels
    - Control moment gyros
    - Thrusters
    - Magnetic torquers

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Quantify the Disturbance Environment

- Need to size the external torques the ADCS must tolerate
- Types
  - Gravity-gradient effects
  - Magnetic-field torques
  - Impingement by solar radiation
  - Aerodynamics (for low altitude orbits)

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Gravity Gradient

- Constant torque for Earth-oriented vehicle

$$T_g = \frac{3\mu}{2R^3}\left|I_z - I_y\right|\sin(2\theta)$$

- T_g = max gravity torque (N-m)
- μ = Earth's gravity constant (3.986 X 10^{14} m^3/s^2)
- R = orbit radius (m)
- θ = maximum deviation of Z-axis from vertical
- I_z, I_y = moments of inertia

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Solar Radiation

- Cyclic torque on Earth-oriented vehicle, constant for solar-oriented vehicle

$$T_{sp} = F\left(c_{ps} - cg\right)$$

$$F = \frac{F_s}{c} A_s (1+q)\cos i$$

- F_s = solar constant (1,367 W/m^2)
- c = speed of light (3 X 10^8 m/s)
- A_s = surface area
- c_{ps} = location of center of solar pressure
- cg = center of gravity
- q = reflectance factor (0 to 1)
- i = angle of incidence of Sun

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Magnetic Field

- Cyclic

$$T_m = DB$$

- Tm = magnetic torque on spacecraft
- D = residual dipole of vehicle (A-m^2)
- B = Earth's magnetic field in tesla

$$B \approx \frac{2M}{R^3} \quad \text{(polar)} \qquad\qquad B \approx \frac{M}{R^3} \quad \text{(equatorial)}$$

- M = 7.96 X 10^{15} tesla-m^3
- R = radius from center to spacecraft (m)

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Aerodynamic

- Atmospheric density for low orbits varies significantly with solar activity

$$T_a = F\left(c_{pa} - cg\right)$$

$$F = 0.5\left[\rho C_d A V^2\right]$$

- F = force
- C_d = drag coefficient
- ρ = atmospheric density
- A = surface area
- V = spacecraft velocity
- c_{pa} = center of aerodynamic pressure
- cg = center of gravity

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Select and Size ADCS Hardware

- Reaction wheels – torque motors with high-inertia rotors; can spin in either direction and provide one axis control for each wheel
- Momentum wheels – reaction wheels with a nominal spin rate above zero to provide nearly constant angular momentum – provides gyroscopic stiffness to two axes
- For 3-axis control at least three wheels are required with their spin axes not coplanar
- Control-moment gyros – wheels spinning at a constant speed (high torque applications)
- Magnetic torquers – electromagnets to generate magnetic dipole moments

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Thruster Sizing

- Thruster force level sizing for external disturbances

$$F = T_D L$$

- F = thruster force
- T_D = worst-case disturbance torques
- L = thruster's moment arm

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Thruster Sizing

- Sizing force level to meet slew rates
  - Determine highest slew rate required in mission profile
  - Develop profile that accelerates vehicle to that rate, coasts, then decelerates

$$T = FL = I\ddot{\theta} \qquad \ddot{\theta} = \frac{\dot{\theta}}{t}$$

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Thruster Sizing

- Sizing force level for slewing a momentum-bias vehicle

$$T = FLd = h\omega$$

- F = average thruster force
- L = momentum arm
- d = thrust duty cycle (fraction of spin period)
- h = angular momentum
- ω = slew rate

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Thruster Sizing

- Sizing force level for momentum dumping

$$F = \frac{h}{Lt}$$

- h = stored angular momentum
- L = moment arm
- t = burn time

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Angular Momentum Storage

$$T \times \frac{P}{4} = h\theta_a$$

- T = torque
- h = angular momentum
- P = orbit period
- θ_a = allowable motion

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Propellant

$$M_p = \frac{Ft}{Isp \bullet g_O}$$

- Mp = propellant mass (kg)
- F = force (N)
- t = burn time
- Isp = specific impulse
- g_O = Earth gravity (9.81 m/s^2)

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ADCS Sensors

Sensor	Typical Performance Range	Mass Range (kg)	Power (W)
Inertial Measurement Unit (Gyros & Accelerometers)	Gyro drift rate = 0.003 deg/hr to 1 deg/hr Accel linearity = 1 to 5 X 10^{-6} g/g^2 over range of 20 to 60 g	1 to 15	10 to 200
Sun Sensors	Accuracy = 0.005 deg to 3 deg	0.1 to 2	0 to 3
Star Sensors	Attitude accuracy = 1 arc sec to 1 arc min (0.0003 deg to 0.01 deg)	2 to 5	5 to 20
Horizon Sensors Scanner/Pipper Fixed Head	Attitude accuracy: 0.1 deg to 1 deg (LEO) < 0.1 deg to 0.25 deg	 1 to 4 0.5 to 3.5	 5 to 10 0.3 to 5
Magnetometer	Attitude accuracy = 0.5 deg to 3 deg	0.3 to 1.2	<1

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