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Spacecraft Attitude Dynamics

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General requirements for attitude control

Introduction

General elements

- Sensors (operation, precision, power, weight, cost)
- Actuators (operation, power, weight, cost)
- Disturbances
- Mission requirements
- Mission phases → During initial phases we need to check if all the systems are working properly
- Control logic

Disturbance torque

How to estimate the maximum value of the disturbances

External disturbances

Disturbance	Type	Main parameters	Reference formula
Gravity gradient	Constant torque for Earth pointing, cyclic for inertial pointing	- Inertia moments - Orbit altitude	$T_{max} = \frac{3Gm_t}{2R^3}\left\|I_M - I_m\right\|$
Solar radiation	Cyclic torque for Earth pointing, constant for inertial (or Sun-oriented) pointing	- Spacecraft geometry - Panel reflectivity - Position of center of mass	$T_{max} = P_s A_s (1+q)(c_{ps} - c_g)$
Magnetic field	Cyclic torque	- Orbit altitude - Orbit inclination - Residual dipole	$T_{max} = D_s B_{max}$
Aerodynamics	Constant torque for Earth pointing, variable for inertial pointing	- Orbit altitude - Geometry and position of center of mass	$T_{max} = \frac{1}{2}\rho V^2 A_s C_D (c_{pa} - c_g)$

Disturbance torque

Once we have understood the entity of external torque we should check if we have any kind of external disturbances
The internal disturbances are very difficult to model.

Internal disturbances

Disturbance	Effects on satellite	Typical values
Uncertain position of center of mass	- Unbalanced torque when using symmetric thrusters - Disturbance torque when using any single thruster	1 - 3 cm
Misaligned thrust	Same	0.1° - 0.5°
Incorrect thrust magnitude	Same	±5%
Unbalanced rotors	Torques that affect stability and pointing accuracy	Depends on rotors, can be compensated with counter-rotating rotors
Fluid slosh	Same as uncertain position of center of mass	Depends on tank shape, can be reduced with internal fins
Flexible structures	Resonance at natural frequencies, limit on control bandwidth	Depends on structure, care when mounting large panels and antennas or booms
Thermal-structural coupling	Disturbance at transition between sunlight and eclipse	Same

Requirements

Origin of the requirements for attitude control systems

Requirement	**Information needed**
e.g we want to take a picture	The instrument is seen as a payload of the space craft.
Payload requirements	
Object to point	Whole object or some parts of it such as an antenna or a radiator
Pointing direction	Target definition
Pointing area	All possible pointing directions
Pointing accuracy	Requirement on absolute angular pointing
Verification on pointing	Knowledge of the pointing direction in real time or after pointing
Pointing stability	Maximum deviation from nominal pointing
Slew maneuver	Reorientation from one direction to another in a specified time
Exclusion cones	Areas where pointing is not allowed
Other requirements	
Sun pointing	Required to generate electrical power or for thermal control
Pointing during thrust	Required for guidance system corrections
Pointing of antennas	Ground station or support satellite position

Design criteria

How can I achive the requirement? → Either the payload is fixed to the s/c and the space craft is manoeuvre or the payload can rotate freely

Design criteria for some selected pointing requirements

Requirement	System
Nadir pointing payload	Payoad fixed to the satellite using a two-axis control on the satellite to achieve Earth pointing. The third axis is used to point a horizontal axis in the direction of velocity. Use of dual spin stabilization, with spin axis in the horizontal plane (pitch axis) and payload mounted on a non-spinning platform.
Inertial pointing payload	Payoad fixed to the satellite controlled on two axes to maintain the inertial pointing of the third axis. Control of the third axis can be used to keep one side towards the Sun.
Solar panel to point the Sun	A flat panel requires two-axis control. This can be achieved with a controlled satellite axis, and a rotation of the panel. A spinning "cylindrical" panel can be used, whose axis is orthogonal to the direction of the Sun.
Pointing the telecommunication antenna	Two-axis mechanism

fixing mechanism on the inside of the s/c can be usefull

Design criteria

Types of attitude control

Control mode	Type of control
Control during thrust phase	
Spin stabilisation	Option 1) Spin axis aligned with the direction of thrust, continuous thrust Option 2) Spin axis orthogonal to direction of thrust, thrust with short impulses synchronous to spin rate
Three-axis control	Control torques controlled by sensors. Torques can also be generated by thrusters, with modulated thrust (on / off) or tilted to control the thrust direction.
Control without thrust	
Spin stability to control precession	The spin direction is controlled by applying precession torques with offset rockets.
Dual spin	Spin stabilisation with despun platform
Three-axis control	Control using sensors and actuators

↳ most demanding in terms of sensors and actuators

Design criteria

Effect of pointing requirements on control type

Requirement	**Effetct**
Control during apogee kick	Preference for spin stability
Coarse control (> 10°)	Spin stabilisation or passive control with gravity gradient
Low-precision pointing (> 0.1°)	Dual spin or three-axis control
Precise pointing (< 0.1°)	Three-axis control
Low power control (< 1 kW)	Tilting solar panel or body-mounted panel on spinning spacecraft
High power control (> 1 kW)	Tilting solar panel
Multiple pointing requirements	Three-axis control
Slew maneuvers	Three-axis control with sufficient control torques

Design criteria

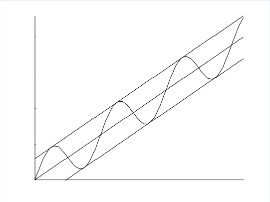
Estimation of control torques

what are the control torque the set of the actuators need to provide

Disturbance	Reference formula	Reference quantities
"Capture"	$T = \frac{1}{2}\omega_t^2\left(\frac{I_s}{\theta_{max}}\right)$	- Angular velocity at release - Inertia moment around the axis of rotation - Maximum rotation allowed
Maneuver	$T = 4\theta_{man} I_s / t_{man}$	- Maneuver time - Maneuver angle → Estimation of torque required
Misaligned thrust		- Thrust magnitude - Thruster location
Aerodynamics	$T = \frac{1}{2}\rho V^2 A_s C_D\left(c_{pa} - c_g\right)$	- Atmospheric density - Satellite drag coefficient - Exposed surface - Relative speed - Distance between center of mass and center of pressure
Gravity gradient	$T = \frac{3Gm_t}{R^3}\left\|I_1 - I_2\right\| c_1 c_2$	- Inertia moments - Distance from ground - Misalignment w.r.t. LVLH
Magnetic field	$T = D_s B$	- Distance from groung - Residual dipole
Solar radiation	$T = P_s A_s (1+q)\left(c_{ps} - c_g\right)$	- Absorption and reflection coefficients - Exposed surface - Direction of the Sun - Distance between center of mass and center of pressure

Design criteria

Estimation of angular momentum requirements

Step	Operations and Comments
1. Estimation of disturbance torque	→ Done then we need to do step 2
2. Estimation of the integral over time of the disturbance torque for each axis	$h_x = \int \lvert T_{dx} \rvert dt$ $h_y = \int \lvert T_{dy} \rvert dt$ $h_z = \int \lvert T_{dz} \rvert dt$ It would be complicated to do
3. Separate cyclic components from secular components	 cyclic component have a net contribution equal to zero. secular component are important to consider the effect of the secular component → important to decide if we need a desaturation mechanism
4. Sizing of actuators	For cyclical components, inertia, reaction or CMG wheels can be used, for secular components rocket or magnetic systems for reaction wheel. because they are continuously accelerating due to secular component.
5. If thrusters are used, evaluate the integral over time of the disturbance magnitude for each axis	$h_x = \int T_{dx} dt$ $h_y = \int T_{dy} dt$ $h_z = \int T_{dz} dt$ → gives us an idea on the amount of propellant required.

Design criteria

Steps in the design of the attitude control system

Step	Input	Output
1) Definition of control modes	Mission requirements, mission profile, conditions for orbit injection	List of mission control modes Requirements and constraints
2) Selection of control type	Payload, thermal and power requirements, type of orbit and pointing, disturbances	Methods of stabilization and control (three-axis, gravity gradient, spin)
3) Quantify disturbances	Satellite geometry, mission profile, magnetic and orbit model	Values of gravity gradient torque, magnetic, aerodynamic, solar pressure, thrust, internal
4) Choice and sizing of hardware	Satellite geometry, pointing accuracy, maneuvering speed, operational life, pointing direction	Type of sensors Type of actuators Signal processing
5) Definition of attitude determination and control algorithms	All the above	Algorithms and logic of each control mode
6) Iterate the design	All the above	Subsystem specifications

Design criteria

Typical control modes

Mode	Description
Orbit insertion	Period during and after the final phase of the launch, insertion into orbit. The satellite may not be controlled, be spinned with the apogee thruster, or controlled by a thruster system
Attitude acquisition	Initial attitude determination and stabilization. It can be used to correct small orbit injection errors
Normal	Used for most part of the mission. The system is primarily sized for this phase
Slew maneuver	Satellite re-orientation
Emergency	If the normal system does not work or if it is deactivated. It may require less power or sacrifice performance to meet thermal and / or power requirements
Special	With particular requirements for particular phases of the mission

Design criteria

Requirements of the attitude determination and control system

Requirement	Definition	Example / Comments
Determination		
Accuracy	Accuracy of information on the attitude with respect to an inertial system	Information available in real-time onboard or processed on ground
Amplitude	Angular interval for which the accuracy must be maintained	In a cone of 30° around nadir
Control		
Accuracy	Accuracy achievable with respect to an imposed command	Contains errors in both control and determination of the attitude
Amplitude	Angular interval for which the control accuracy must be maintained	
Oscillation	Limit on angles or angular velocities for high frequency transient motions	It is usually specified so as not to confuse sensor data. 0.1° in one minute, 1°/s between 1 and 20 Hz.
Drift	Limit for low frequency transient motion	1°/hour, max. 5°. This is to avoid frequent system resets
Response time	Specifies the time available to complete maneuvers or corrections after disturbances	

Design criteria

Effects of required precision on the attitude control architecture

Precision	Effects on spacecraft	Effects on control system
>5°	- Allows use of gravity gradient - Cheap system	- No sensor needed for gravity gradient, just need a boom motor, damper and momentum wheel - Accuracy of Earth sensors and magnetometers are sufficient - For better precision, Sun and / or star sensors are needed
1° - 5°	- Gravity gradient not suitable - Spin stability is possible if pointing is inertial - De-spun platform might be required - Three-axis stability is suitable	- Sun and Earth sensors might be enough for a spinner - Three-axis stabilization requires a system of RWs or CMGs, saving propellant for long missions - For a spinning platform, thrusters and nutation dampers are good - An all-magnetic system might be fine for certain orbits
0.1° - 1°	- Dual-spin or three-axis systems are suitable	- Accurate reference needed, star sensors or gyroscopes and Earth sensors - Wheel systems with thrusters for coarse control and desaturation - A magnetic system could also be fine for small satellites
<0.1°	- Three-axis control is required - Individual payloads might be isolated, articulated and autonomous in pointing	- You need a very precise star sensor or gyroscope - Control laws and computational load are complex - Flexible parts must be taken into account in the model

Interaction with other subsystems

Mission
- Earth pointing or inertial pointing ?
- Control during orbit correction maneuvers ?
- Payload on separate platform ?
- Availability of on-board navigation data ?
- Pointing stability and accuracy required ?
- Slew maneuvers required ?
- Orbit ?
- Autonomy ?
- Mission lifetime ?

Structure
- Limits on position of center of mass
- Constraints on inertia moments
- Effects of structural flexibility
- Thruster position
- Sensor position

Propulsion
- Thruster sizing
- Propellant volume
- Minimum impulse

inputs of the attitude control

output control system

Thermal
- Special maneuvers required ?

Communication
- Pointing precision of antenna

ADCS system design
- Spin or passive stability or three-axis active control
- On board data processing vs ground control
- Sensor selection
- Actuator selection
- Architecture of data processing system

Power
- Solar panel pointing requirements

Power
- Power needed for ADCS