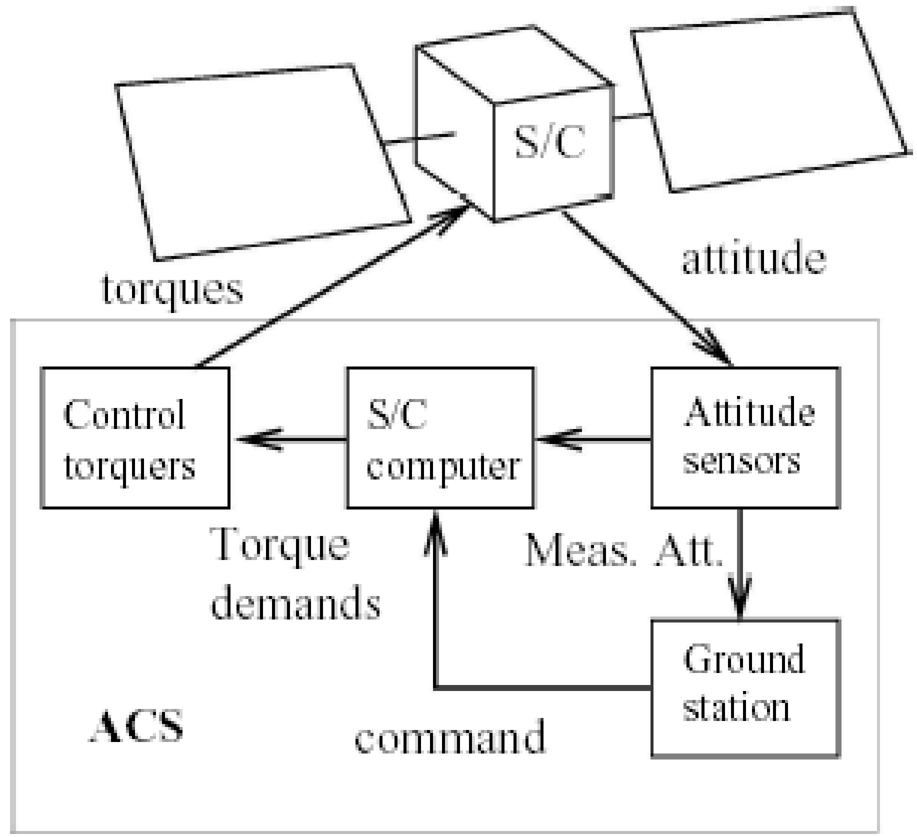
Section 7 – Spacecraft Attitude Control Subsystem overview

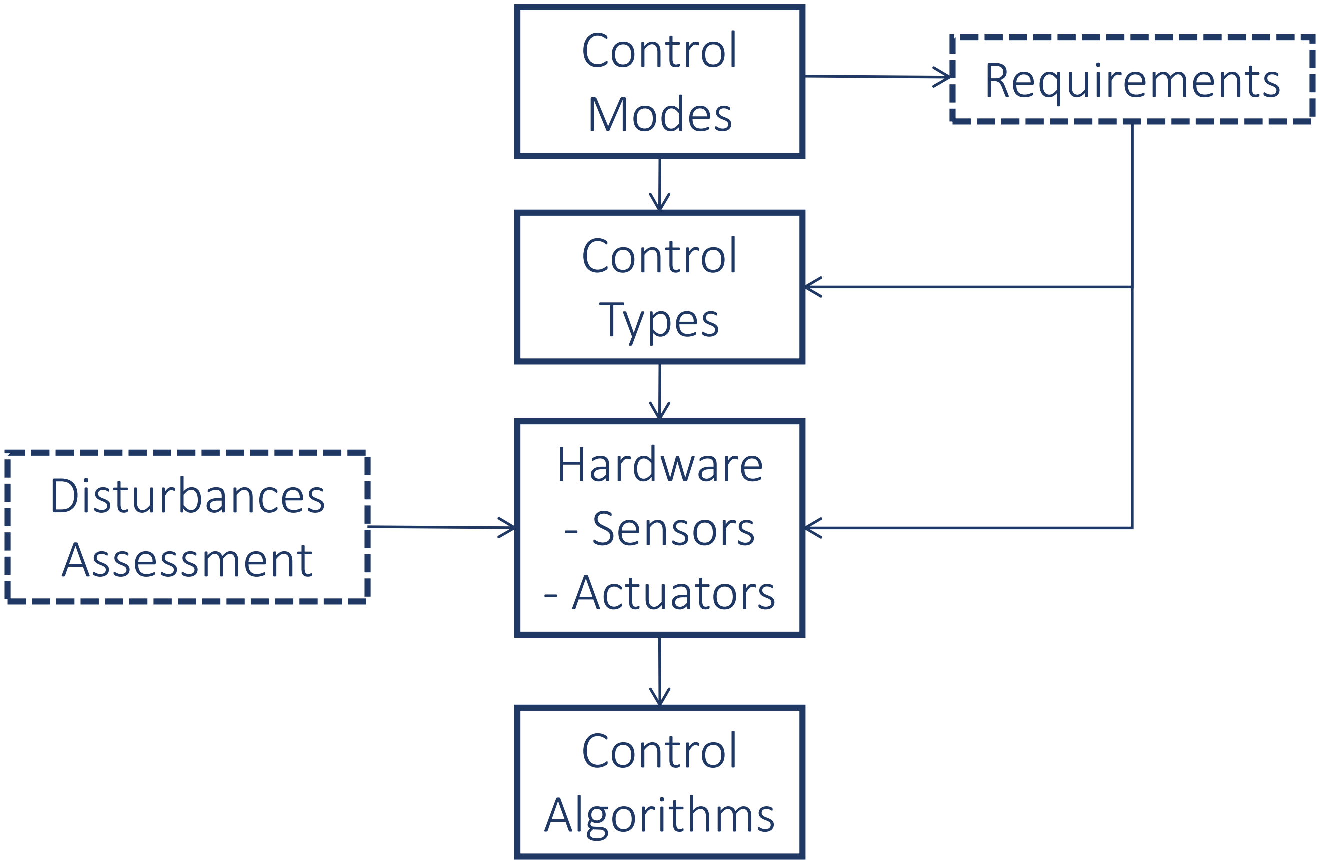
- **Objectives**
  - Provide an overview of the most important methodologies for spacecraft attitude control
- **Topics**
  - Introduction to ACS: tasks and functional diagram
  - ACS preliminary design procedure and requirements
  - Attitude control types and working principles:
    - Magnetic field passive
    - Gravity Gradient
    - Gyroscopic tenacity, momentum bias passive/active
    - Zero momentum

Introduction to ACS

- ACS tasks (objectives)
  - Ensure the **correct pointing** of **all** spacecraft subsystems and payloads
  - **Reject disturbances** which may affect the pointing accuracy and stability



Preliminary design procedure – 1/2



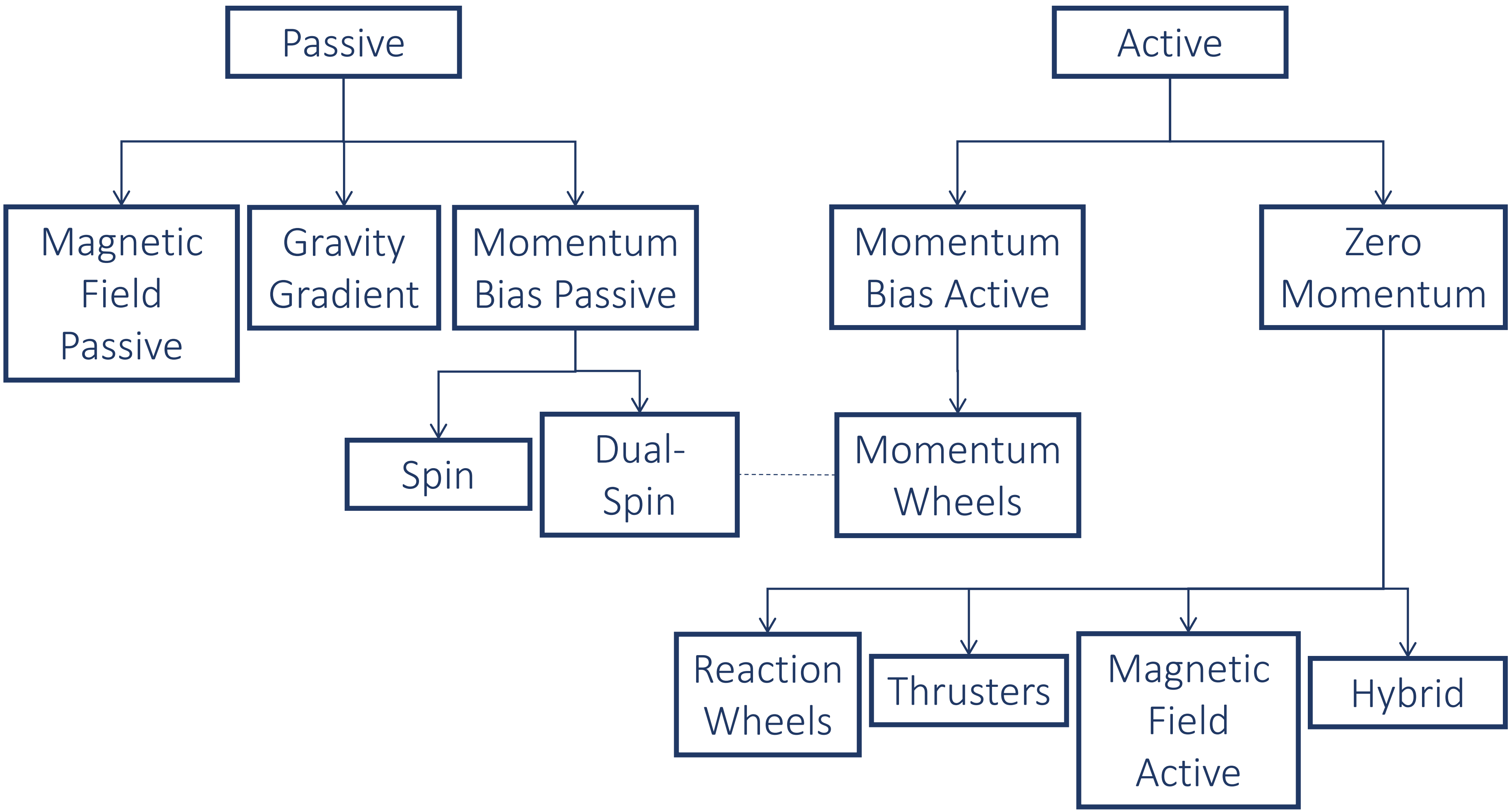
Preliminary design procedure – 2/2

- **Control modes:** mission phases during which attitude control is requested. Analysis of control modes provides (different) requirements for each mode (e.g. stabilization during major orbital maneuvers, acquisition, on-station, slew, etc.)
  - Requirements arise from both payload and bus needs
  - Requirements include pointing range, accuracy, stability, knowledge; control authority, robustness, etc.

- **Control types:** specific control configurations employing different working principles (e.g. passive vs. active – 3 axis vs. spin)

- **Attitude disturbances:** can come from the environment (**external**, e.g. gravity gradient, interaction with magnetic field, solar radiation pressure, aerodynamic) or from the vehicle (**internal**)

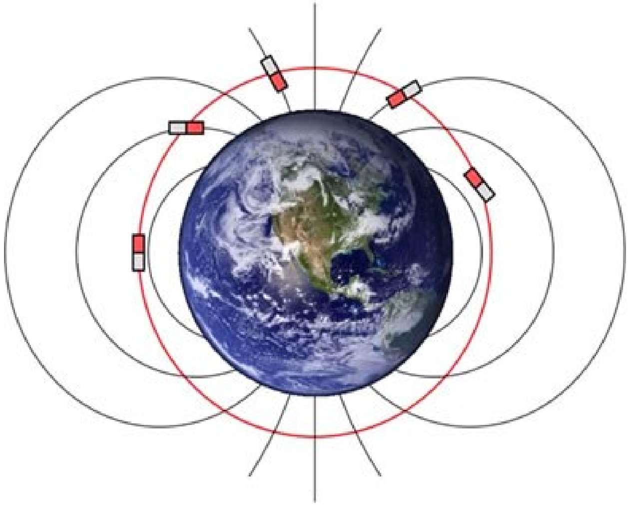
Control types (building blocks) – 1/5



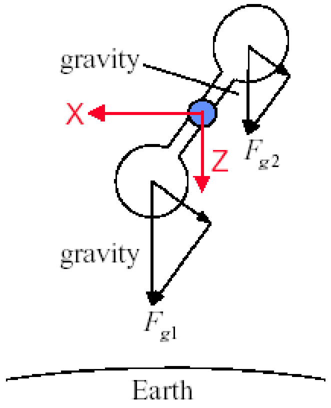
Control types (building blocks) – 2/5

- Passive techniques are simpler but provide lower **accuracy** (±0.1 - ±5°) and **authority** (< 10^{-5} Nm) than active ones (< ± 0.05°; < 5 Nm)

- **Magnetic Field passive:** residual spacecraft magnetic dipole aligns along the local magnetic field vector. **Accuracy ~±5°, authority < 10^{-5} Nm** and quickly decreases with altitude. The magnetic field does not provide a fixed reference for Earth-pointing and inertially-pointing spacecraft

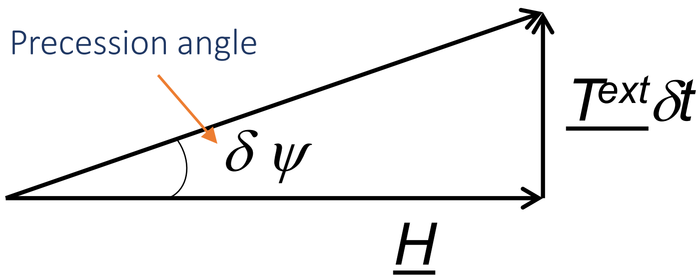


- **Gravity gradient:** body axis with minimum moment of inertia aligns along the local vertical. **Accuracy ~±5°, authority < 10^{-5} Nm** and quickly decreases with altitude. Stability requires implementation of specific body geometry



Control types (building blocks) – 3/5

- **Gyroscopic tenacity**
  - Any rigid body provided by angular momentum **H** has an inherent resistance to external disturbance torque perpendicular to the direction of H. Such tenacity is proportional to the magnitude of **H**



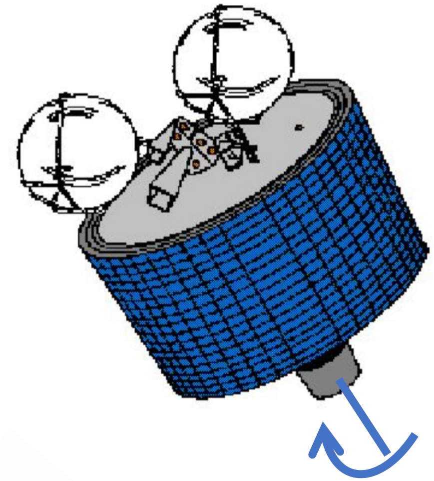
$$\delta H = T^{ext}\delta t = H\delta\psi$$

$$\Rightarrow \quad \frac{\delta\psi}{\delta t} = \frac{T}{H}$$

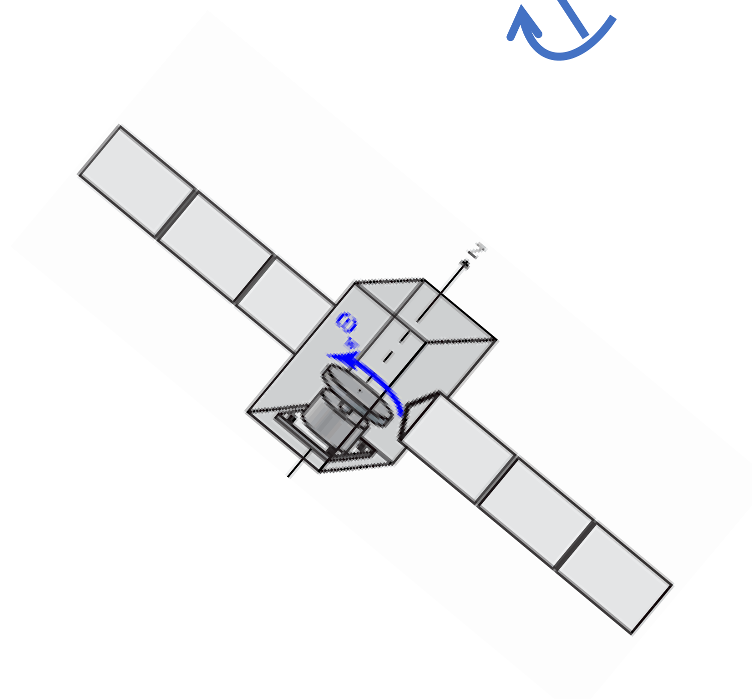
- Gyroscopic tenacity is employed as a **two-axis control principle** (no control is possible about **H**), and may be implemented in two different ways:
  - Making the whole satellite spin about a symmetry axis (**spin-stabilized spacecraft**)
  - Using an active flywheel inside a **3-axis stabilized spacecraft**

Control types (building blocks) – 4/5

- **Momentum bias passive**: gyroscopic tenacity provides an **inertially-fixed spacecraft axis**. **Accuracy <±1°, authority < 10^{-3} Nm**. Stability requires implementation of specific body geometry



- **Momentum bias active:** gyroscopic tenacity given by a momentum wheel mounted on a 3-axis stabilized platform. **Accuracy <±0.1°, authority < 10^{-3} Nm**. Stability requires control of nutation modes



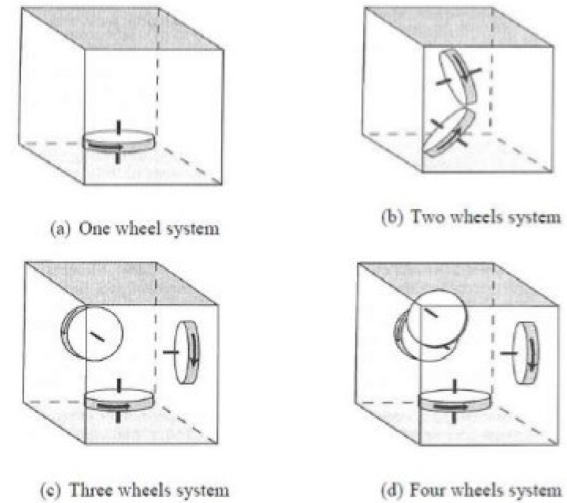
Control types (building blocks) – 5/5

- **Zero momentum**: spacecraft momentum is kept null thanks to actuators reacting to external/internal disturbances. Main choices:

– Full 3-axis control using **Reaction Wheels**. **Accuracy < ±0.05°, authority < 1 Nm**. External actuators (e.g. active magnetic torquers) requested for momentum dumping

– 2 axis active magnetic control. **Accuracy < ±0.1°, authority < 0.1 Nm**. Control impossible along local magnetic field vector

– Full 3-axis control using **thrusters**. **Accuracy <±0.05°, authority < 10 Nm**. It is requested to carry propellant on-board

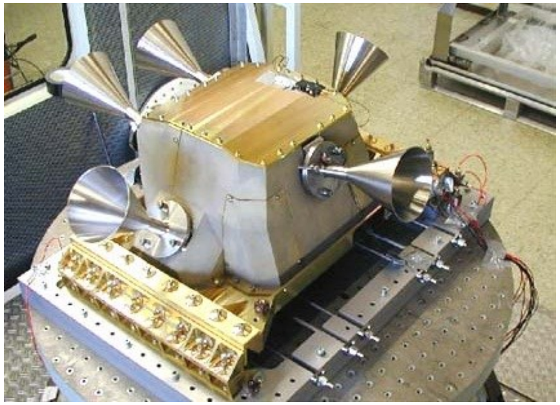


(a) One wheel system

(b) Two wheels system

(c) Three wheels system

(d) Four wheels system



Preliminary disturbances estimation

Disturbance	Type	Influenced Primarily by	Formula
Gravity-gradient	Constant torque for Earth-oriented vehicle, cyclic for inertially oriented vehicle	• Spacecraft inertias • Orbit altitude	$$T_g = \frac{3\mu}{2R^3}\left\lvert I_z - I_y \right\rvert \sin(2\theta)$$ where T_g is the max gravity torque; μ is the Earth's gravity constant (3.986×10^{14} m³/s²); R is orbit radius (m), θ is the maximum deviation of the Z-axis from local vertical in radians, and I_z and I_y are moments of inertia about z and y (or x, if smaller) axes in kg·m².
Solar Radiation	Cyclic torque on Earth-oriented vehicle, constant for solar-oriented vehicle or platform	• Spacecraft geometry • Spacecraft surface reflectivity • Spacecraft geometry and cg location	Solar radiation pressure, T_{sp}, is highly dependent on the type of surface being illuminated. A surface is either transparent, absorbent, or a reflector, but most surfaces are a combination of the three. Reflectors are classed as diffuse or specular. In general, solar arrays are absorbers and the spacecraft body is a reflector. The worst case solar radiation torque is $$T_{sp} = F(c_{ps} - cg)$$ where $F = \frac{F_s}{c} A_s (1+q)\cos i$ and F_s is the solar constant, 1,367 W/m², c is the speed of light, 3×10^8 m/s, A_s is the surface area, c_{ps} is the location of the center of solar pressure, cg is the center of gravity, q is the reflectance factor (ranging from 0 to 1, we use 0.6), and i is the angle of incidence of the Sun.

Disturbance	Type	Influenced Primarily by	Formula
Magnetic Field	Cyclic	• Orbit altitude • Residual spacecraft magnetic dipole • Orbit inclination	$$T_m = DB$$ where T_m is the magnetic torque on the spacecraft; D is the residual dipole of the vehicle in amp·turn·m² (A·m²), and B is the Earth's magnetic field in tesla. B can be approximated as $2M/R^3$ for a polar orbit to half that at the equator. M is the magnetic moment of the Earth, 7.96×10^{15} tesla·m³, and R is the radius from dipole (Earth) center to spacecraft in m.
Aerodynamic	Constant for Earth-oriented vehicles, variable for inertially oriented vehicle	• Orbit altitude • Spacecraft geometry and cg location	Atmospheric density for low orbits varies significantly with solar activity. $$T_a = F(c_{pa} - cg) = FL$$ where $F = 0.5\,[\rho\, C_d A V^2]$; F being the force; C_d the drag coefficient (usually between 2 and 2.5); ρ the atmospheric density; A, the surface area; V, the spacecraft velocity; c_{pa} the center of aerodynamic pressure; and cg the center of gravity.