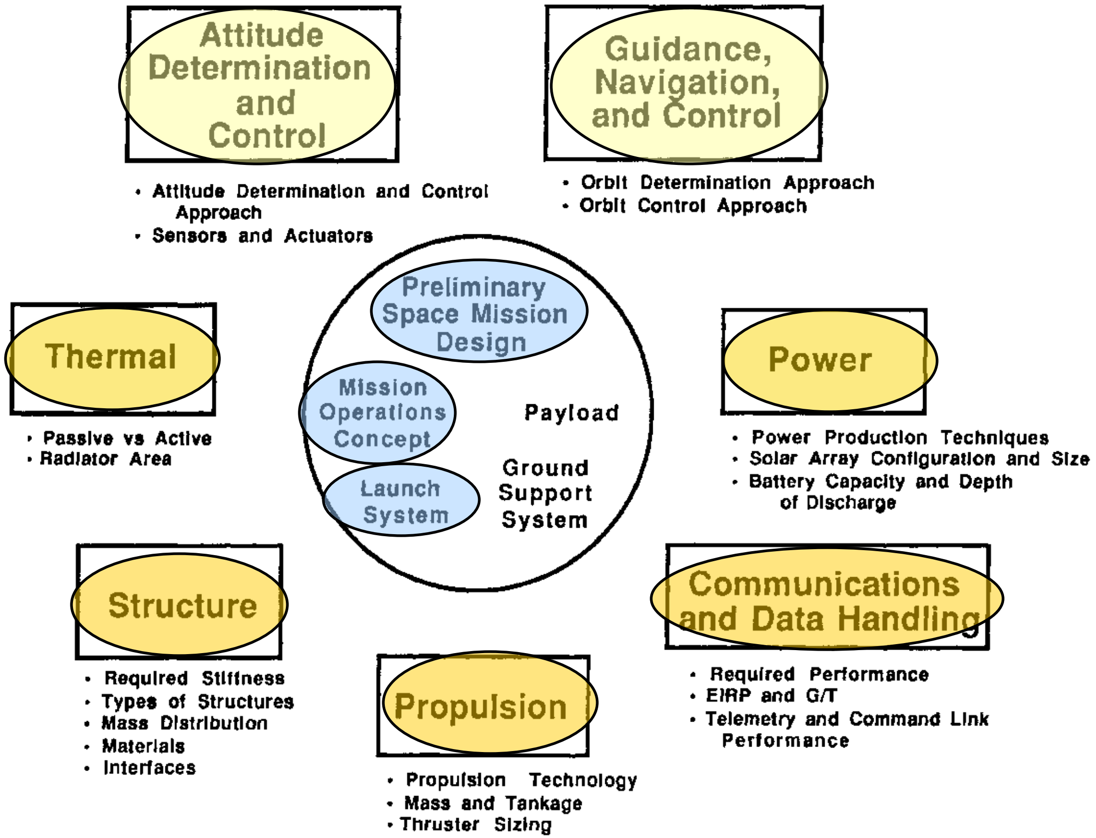
Il sistema di controllo di assetto di un satellite

SOTTO-SISTEMI



Determinazione e Controllo Assetto 1/5

A satellite must maintain a certain attitude while in orbit
- to allow **precise pointing** of an antenna toward the Earth,
- to allow the **accurate orientation** of observation instruments toward the object being observed,
- and to **direct solar panels** toward the Sun.

But the satellite receives **interference** from such phenomena as the **Earth's gravitational and magnetic fields, and the solar wind**. These phenomena tend to disturb the satellite's attitude, so it is necessary to control attitude to keep the satellite stable.

http://spaceinfo.jaxa.jp/

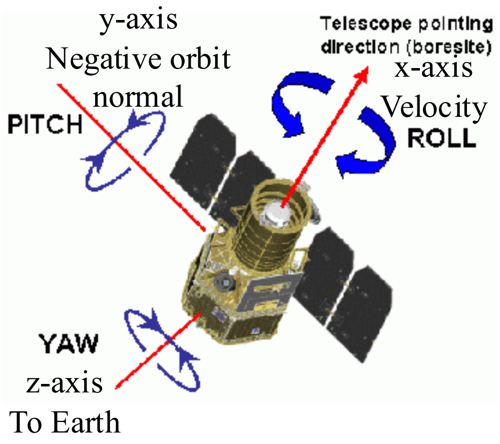
Determinazione e Controllo Assetto 2/5

- The spacecraft needs an Attitude Determination and Control System (ADCS)
- To do the determination function requires knowledge of kinematics
- Attitude is determined using sensors
- To do the control function requires knowledge of kinetics and kinematics (dynamics)
- Attitude is controlled using actuators

Determinazione e Controllo Assetto 3/5

Modi operativi:

- Inserzione in orbita
- Acquisizione iniziale
- Normale
- Slew
- Contingency
- Speciale



$M = 215$ kg
$I_x = I_y = 90$ kg m^2
$I_y = 60$ kg m^2
Orbite attitude = 800 km, circular
Slew rate < 0.1° / s
Pointing accuracy = 0.1°
Mission is earth looking, except one operational manoeuver per month to a target of opportunity

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	Used for the vast majority of the mission. Requirements for this mode should drive 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.

Determinazione e Controllo Assetto 4/5

Parametri e requisiti

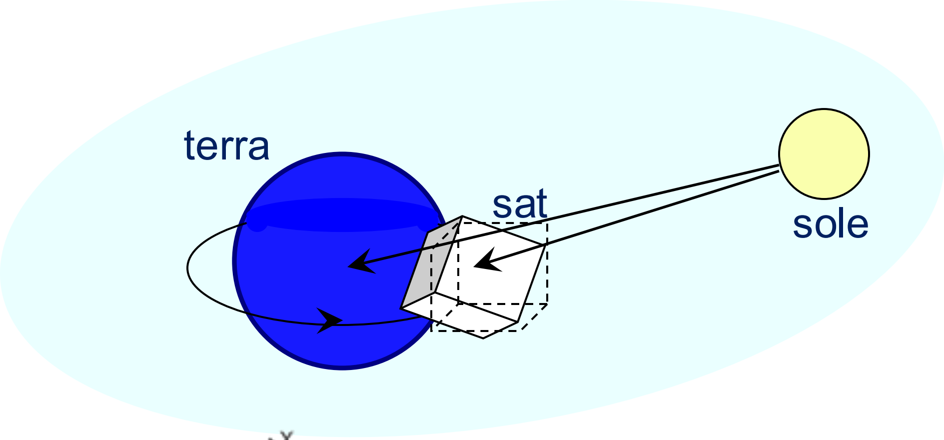
determinazione & controllo

- *Accuracy*
  - quanto bene misuro/controllo orientazione S/C (0.25° su 3 assi)
- *Range*
  - intervallo angolare entro cui devo garantire *accuracy* (30° dal nadir)

controllo

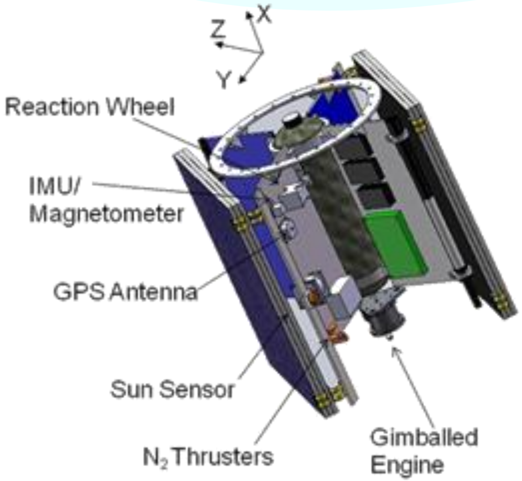
- *Jitter*
  - velocità angolare a breve termine, moto alta frequenza (1° s^{-1})
- *Drift*
  - velocità angolare a lungo termine, moto bassa frequenza (1° hr^{-1})
- *Settling time*
  - tempo limite per riprendere il controllo dopo una manovra

Determinazione e Controllo Assetto 5/5



CONTROLLO:

SISTEMI ATTIVI
SISTEMI PASSIVI



DETERMINAZIONE:
SENSORI

GPS
CELLE SOLARI,
FOTODIODI
MAGNETOMETRO

Tecniche di Controllo 2/3

CONTROLLO PASSIVO

- Gravity gradient control
- Controllo tramite magneti permanenti
- Tecniche di controllo dello spin

CONTROLLO ATTIVO

- Controllo tramite bobine magnetiche
- Sistemi a zero momentum
- Sistemi a momentum bias
- Thrusters

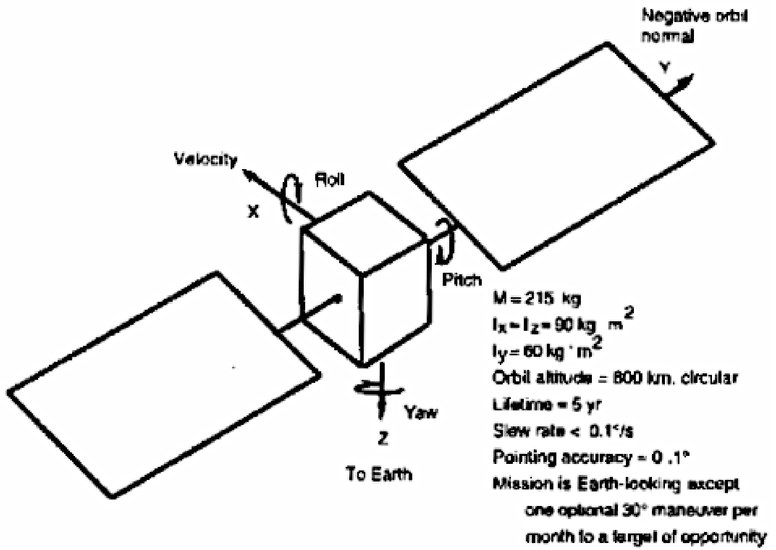
Control Algorithms

- Control Algorithms are computer programs that receive input data from vehicle sensors and derive the appropriate torque commands to the actuators to rotate the vehicle to the desired attitude

Tecniche di Controllo 3/3

Equazione di Eulero

- $d\underline{L} / dt = \underline{T} = \Sigma \underline{M}_i$ $\quad$ $(\underline{M}_i = \underline{r}_i \times \underline{F}_i)$
- $\underline{L} = \underline{\underline{I}} \cdot \underline{\omega}$ $\quad$ $\underline{T} = \underline{\underline{I}} \cdot d\underline{\omega}/dt \; (\ldots + \underline{\omega} \times \underline{\underline{I}} \cdot \underline{\omega} \ldots)$



Tecniche di Controllo 3/3

CONTROLLO PASSIVO

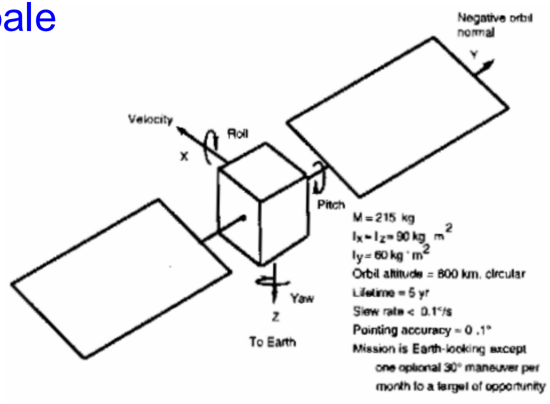
- $f(I_x, I_y, I_z, \omega_x, \omega_y, \omega_z) = M_{dx}$ $(\ldots M_{dy}, M_{dz})$
- $I_x \dot{\omega}_x + [(I_z - I_y)\, \omega_y\, \omega_z] = M_{dx}$
- $I_y \dot{\omega}_y + [(I_x - I_z)\, \omega_z\, \omega_x] = M_{dy}$
- $I_z \dot{\omega}_z + [(I_y - I_x)\, \omega_x\, \omega_y] = M_{dz}$

Matrice nel sistema di riferimento fisso col corpo

Sistema di riferimento principale

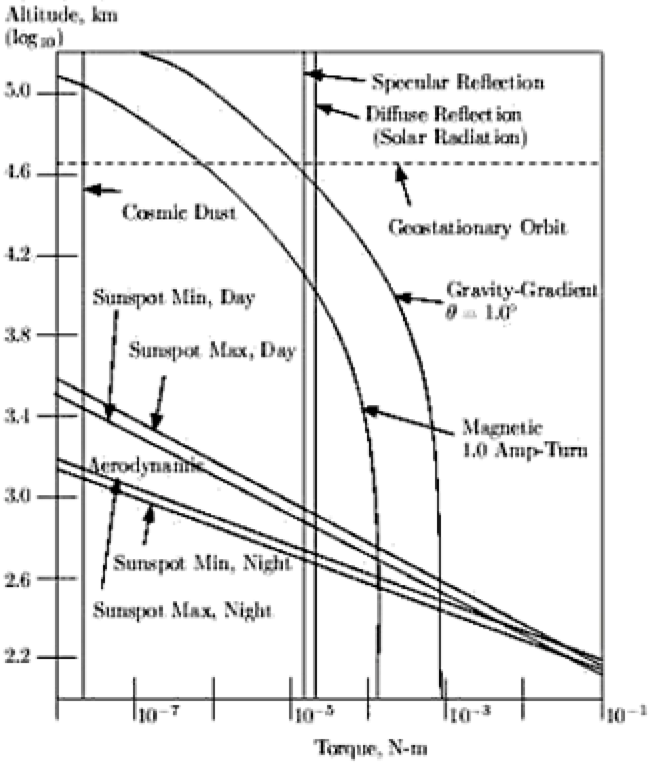
CONTROLLO ATTIVO

- $I_x \dot{\omega}_x + (I_z - I_y)\, \omega_y\, \omega_z = M_{dx} + M_{cx}$
- $I_y \dot{\omega}_y + (I_x - I_z)\, \omega_z\, \omega_x = M_{dy} + M_{cy}$
- $I_z \dot{\omega}_z + (I_y - I_x)\, \omega_x\, \omega_y = M_{dz} + M_{cz}$

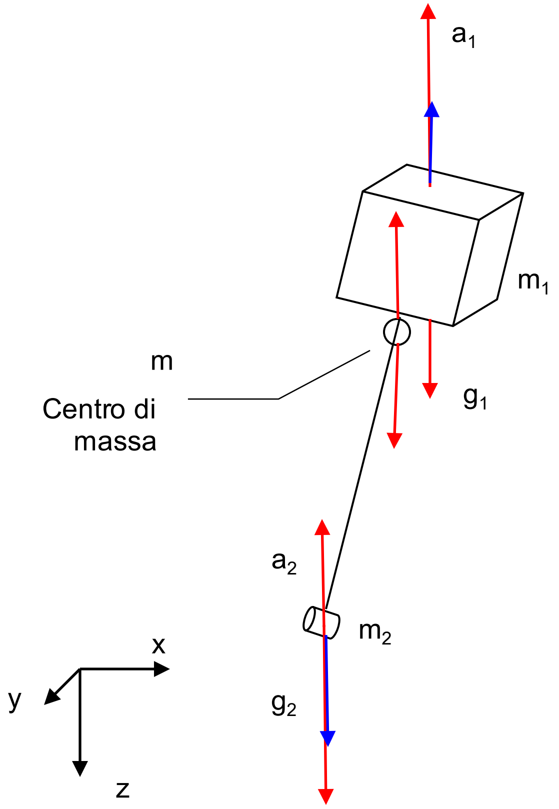


Disturbi Ambientali

39800 km →
6310 km →
1000 km →
158 km →



BOOM: Gradiente di Gravità



DIMENSIONAMENTO DEL BOOM

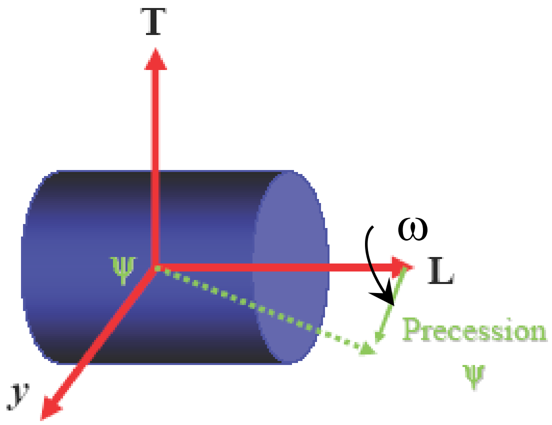
- CdM:
  - $F_0 = m\mu / R^2 = m\omega^2_o R$
- m_1:
  - $F_{g,1} = m_1\mu / R_1^2 < m_1\omega^2_o R_1$
- m_2:
  - $F_{g,2} = m_2\mu / R_2^2 > m_2\omega^2_o R_2$

$(\omega^2_o = \mu/R^3)$

$$T_G = \frac{3\mu}{2a^3}\left|I_Z - I_{MIN}\right| sen(2\theta)$$

Stabilizzazione a Spin 1/2

RIGIDITA' GIROSCOPICA



$L = I\omega$

ω velocità angolare, I momento d'inerzia,

$\Rightarrow$ L momento angolare (>>)

Perturbazione $\Rightarrow$ Forza $\Rightarrow$ T (torsione),

$\Rightarrow$ direzione di L varia di $d\psi$ (precessione)

$\Rightarrow$ piccola torsione T:

$\Rightarrow d\psi/dt$ piccolo

$$\frac{d\psi}{dt} \simeq \frac{T}{L}$$

$\Rightarrow$ per una data torsione T:

$\Rightarrow$(L >>) $d\psi/dt$ <<

$$\mathbf{T} = \frac{d\boldsymbol{\psi}}{dt} \times \mathbf{L}$$

Stabilizzazione a Spin 2/2

Valori tipici: 1 rivoluzione al secondo

Svantaggi:

- pannelli solari ridotti
- orientamento antenne e strumenti richiedono ulteriori manovre (de-spinning)

I diversi tipi di attuatori

- Propulsori e gas jet
- Ruote di reazione e di momento
- Control moment gyro
- Magnetic torquer

Actuator	Typical Performance Range	Weight (kg)	Power (W)	Suppliers
Thrusters • Hot gas (hydrazine) • Cold gas	0.5 to 9,000 N* < 5 N*	Variable† Variable†	N/A † N/A†	Rocket Research, Hamilton Standard, TRW, Marquardt, Walter Kidde, Hughes
Reaction & momentum wheels	0.4 to 400 N·m·s for momentum wheels at 1200 to 5000 rpm: max torques from 0.01 to 1 N·m	2 to 20	10 to 110	Bendix, GE, Honeywell
Control moment gyros (CMG)	25 to 500 N·m of torque	> 40	90 to 150	Bendix, Honeywell
Magnetic torquers	1 to 4000 $A \cdot m^2$ ‡	0.4 to 50	0.6 to 16	Ithaco, Hughes, Lockheed, McDonnell Douglas

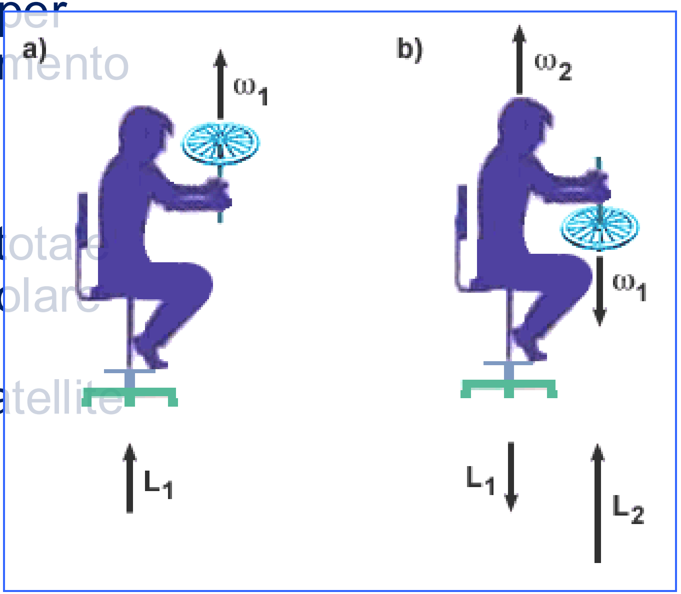
Ruote 1/4

Momentum o Reaction Wheel

Dischi (rotori) che ruotano grazie a un motore elettrico

Quando il motore applica un momento di torsione per accelerare o rallentare il rotore, produce un momento di torsione di reazione sul corpo del satellite

Essendo un sistema chiuso, il momento angolare totale e' costante ⇒ qls variazione del momento angolare di una ruota comporta una variazione uguale e opposta del momento angolare del corpo del satellite



Ruote 2/4

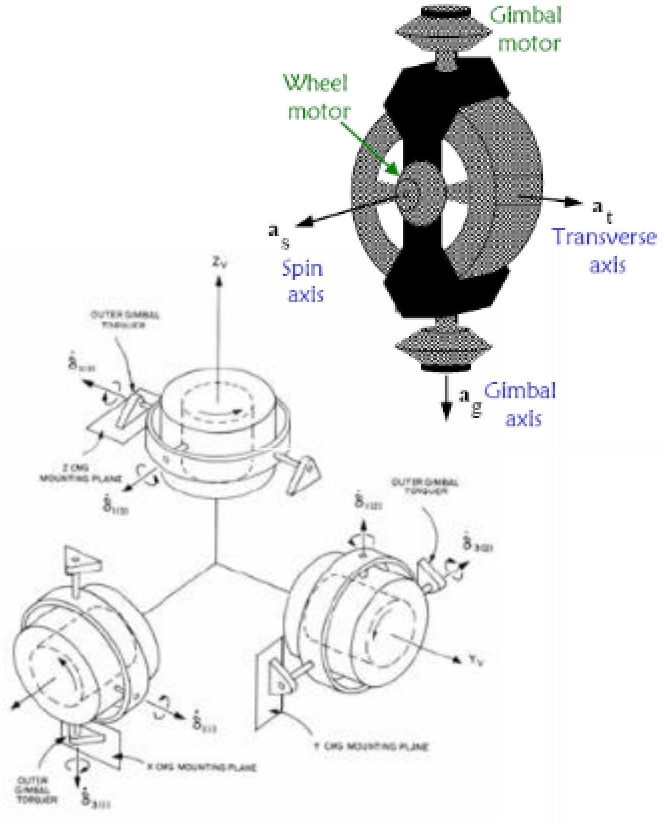
- Asse di gimbal: fisso nel sistema rif. corpo
- Asse di spin controllato dal motore di gimbal
- Velocita’ di spin controllata dal motore della ruota
- Angoli di gimbal fissi:

  “momentum wheel” (MW)

  “reaction wheel” (RW)
- Velocita’ di ruota fissa:

  “control moment gyro” (CMG)

L’asse di rotazione fissato per ogni ruota $\Rightarrow$ una ruota puo’ agire solo su un asse $\Rightarrow$ almeno tre ruote per controllare il satellite su tre assi

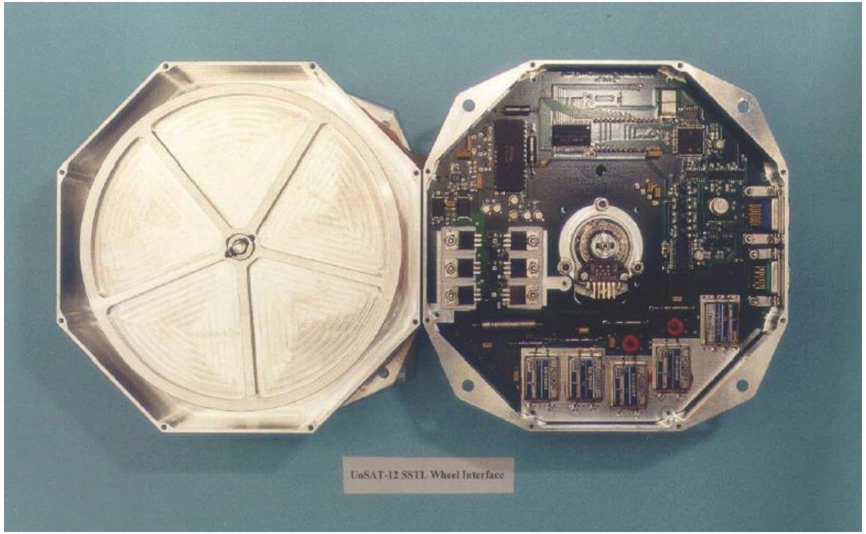


Ruote 3/4

Se le ruote sono usate ripetutamente per contrastare una torsione sempre nello stesso senso, le ruote possono superare la loro velocità massima ⇒ devono essere "dumpate" (thrusters or magnetic torquers)

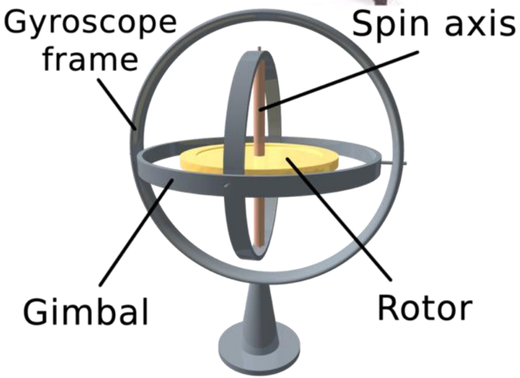
- Ruote di reazione: velocità nominale zero
  - Il motore elettrico fa ruotare la RW per torcere la S/C
  - Risposta veloce
  - Saturazione puo' essere un problema
  - Usate quando la torsione e' richiesta periodicamente
- Ruote di momento: velocità nominale alta (~6000 rpm) per fornire rigidità giroscopica
  - Range permesso: +/- 10% della velocita' media

Ruote 4/4



Giroscopi

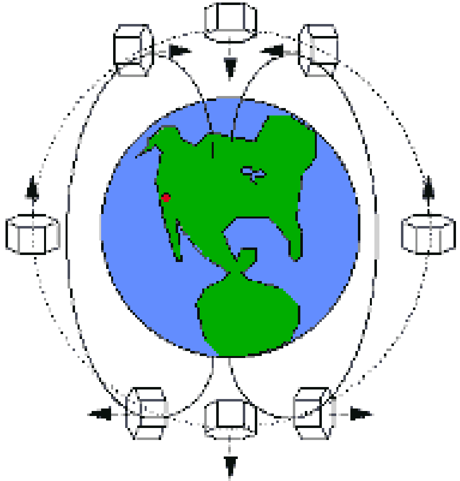
- Forniscono alti livelli di controllo (100x ruote convenzionali)
- Il sistema di controllo molto più complesso delle ruote convenzionali
- Pesanti, alti consumi, rumorosi, vibrazioni



Magnetic Torquer 1/2

Il campo magnetico della S/C (momento di dipolo **m**) interagisce con quello della Terra (**B**) producendo un momento di torsione **T**:

$$\mathbf{T} = \mathbf{m} \times \mathbf{B}$$

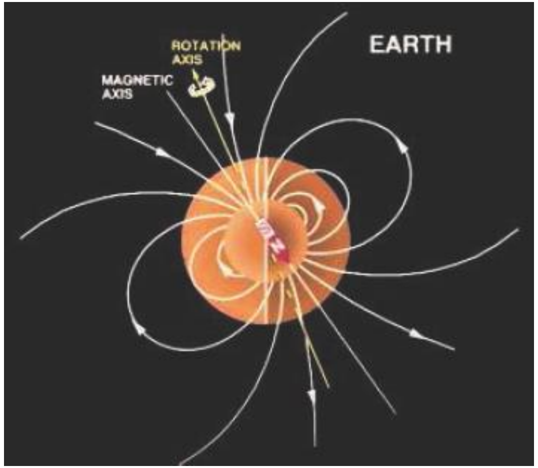


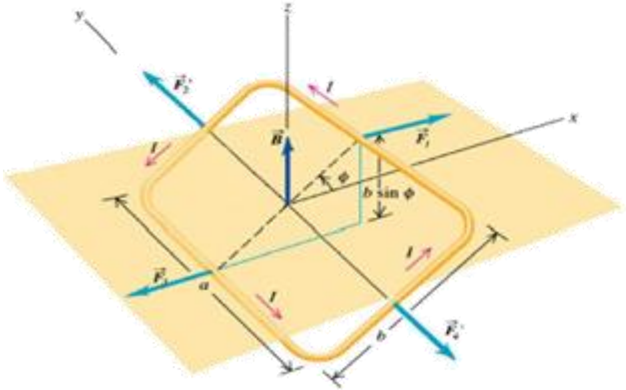
Torque rods: bobine scelte e posizionate opportunamente, percorse da correnti variabili per controllare l'assetto

$$\mathbf{T} = nIA\,(\mathbf{c} \times \mathbf{B})$$

n=no. di spire, I = corrente, A = sezione trasversale della bobina, **c** = versore dell'asse della bobina

Magnetic Torquer 2/2





- Magnetic torquers sono efficaci anche fino alle GEO, ma il CM della Terra decresce velocemente con l’altezza
- Questi sistemi non richiedono carburante e sono controllabili (ma sistema di controllo complesso) e devono essere posizionati accuratamente
- Sono utilizzati anche per “momentum dumping”…

Momenti

Sommario
p. 366 SMAD
(tab. 11-9A)

Disturbance	Type	Influenced Primarily by	Formula
Gravity-gradient	Constant torque for Earth-oriented vehicle, cyclic for inertially oriented vehicle	• Spacecraft inertias • Orbit altitude	$$T_g = \frac{3\mu}{2R^3}\lvert I_z - I_y\rvert \sin(2\theta)$$ where T_g is the max gravity torque; μ is the Earth's gravity constant (3.986×10^{14} m^3/s^2); 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 $kg \cdot m^2$.
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/m^2, 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.
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·m^2 ($A \cdot m^2$), 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·m^3, 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.

I diversi tipi di sensori 1/2

- Sensori solari
  - o Analogici
  - o Di presenza
  - o Digitali
- Sensori stellari (star tracker)
- Sensori di orizzonte
  - o Terra (IR / V)
  - o Luna (IR / V)
- Magnetometri
- Ricevitori GPS
- Giroscopi

sole/terra ~ 400

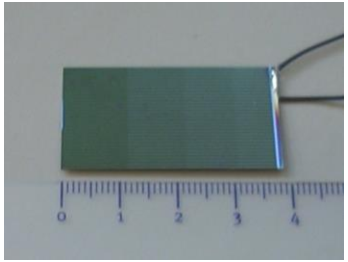
sole/terra ~ 30000

Sensor	Typical Performance Range	Wt Range (kg)	Power (W)	Some Typical Suppliers
Inertial measurement unit (gyros & accelerometers)	Gyro drift rate = 0.003°/hr to 1°/hr, accel. linearity = 1 to 5 x 10^{-6} g/g^2 over range of 20 to 60 g	3 to 25	10 to 200	Northrop, Bendix, Kearfott, Honeywell, Hamilton Standard, Litton, Teledyne
Sun sensors	Accuracy = 0.005° to 3°	0.5 to 2	0 to 3	Adcole, TRW, Ball Aerospace
Star sensors (scanners & mappers)	Attitude accuracy = 1 arc sec to 1 arc min 0.0003° to 0.01°	3 to 7	5 to 20	Ball Aerospace, Bendix, Honeywell, Hughes
Horizon sensors • Scanner/Pipper • Fixed head (static)	Attitude accuracy: 0.1° to 1° (LEO) <0.1° to 0.25°	 2 to 5 2.5 to 3.5	 5 to 10 0.3 to 5	Barnes, Ithaco, Lockheed Barnes, Lockheed
Magnetometer	Attitude accuracy = 0.5 to 3°	0.6 to 1.2	<1	Schonstedt, Develco

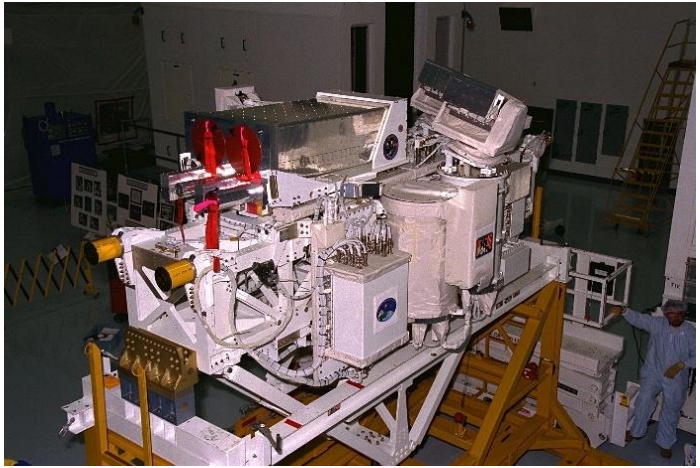
I diversi tipi di sensori 2/2

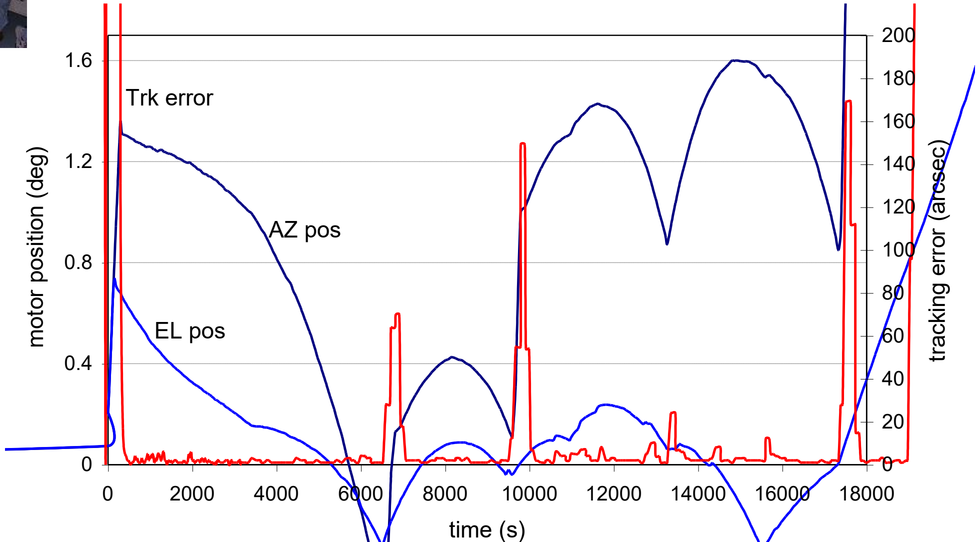
Sensori stellari

Sensori solari



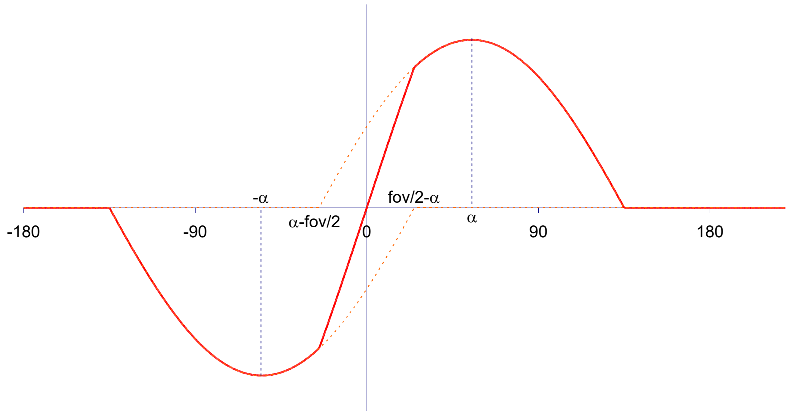
Star Trackers

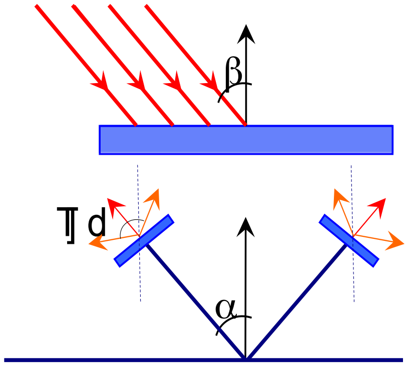




Sensori Solari Analogici

Celle solari: $I(\beta) = I_o \cos \beta$

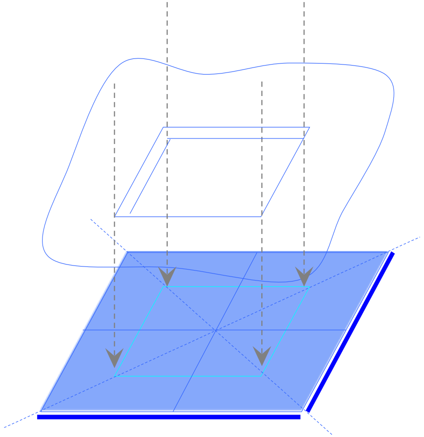


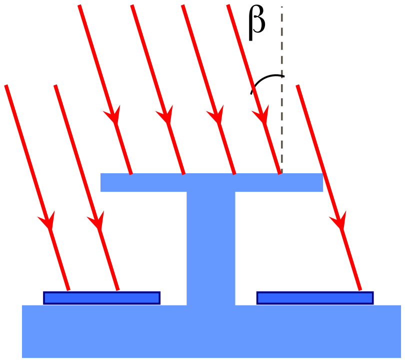


$\alpha = 55^o$

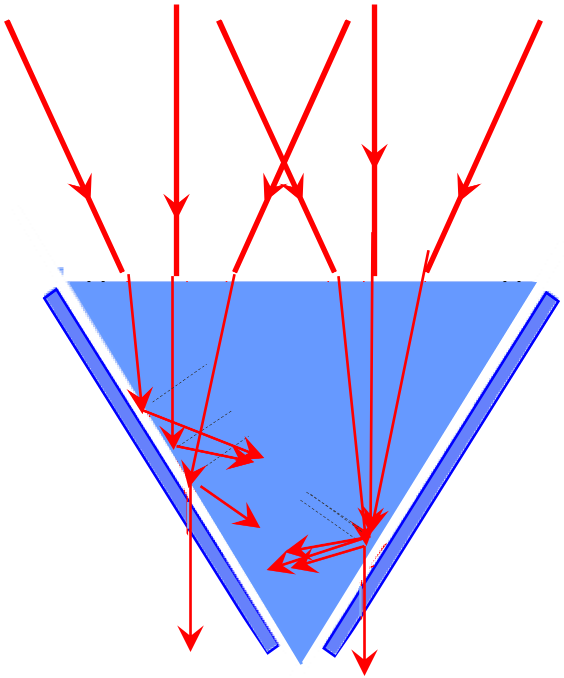
$fov=160^o$

Sensori Solari Analogici



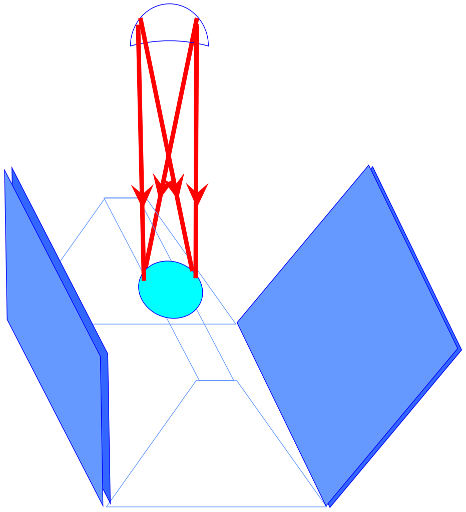


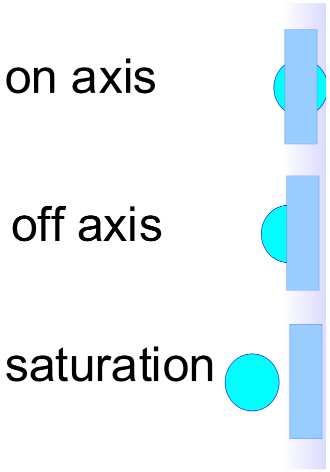
Sensori Solari di Presenza



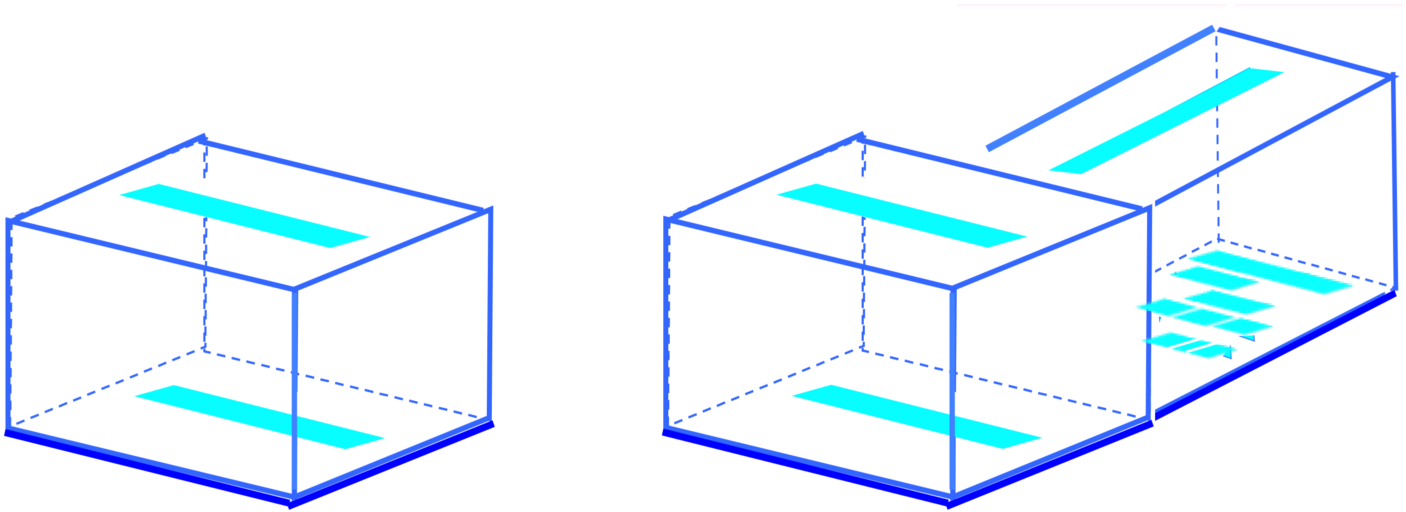
$n \sin \gamma = 1$

Sensori Solari di Presenza

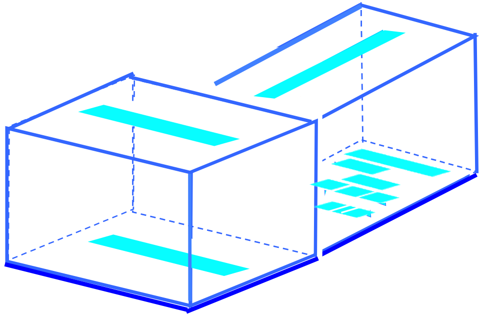




Sensori Solari di Presenza

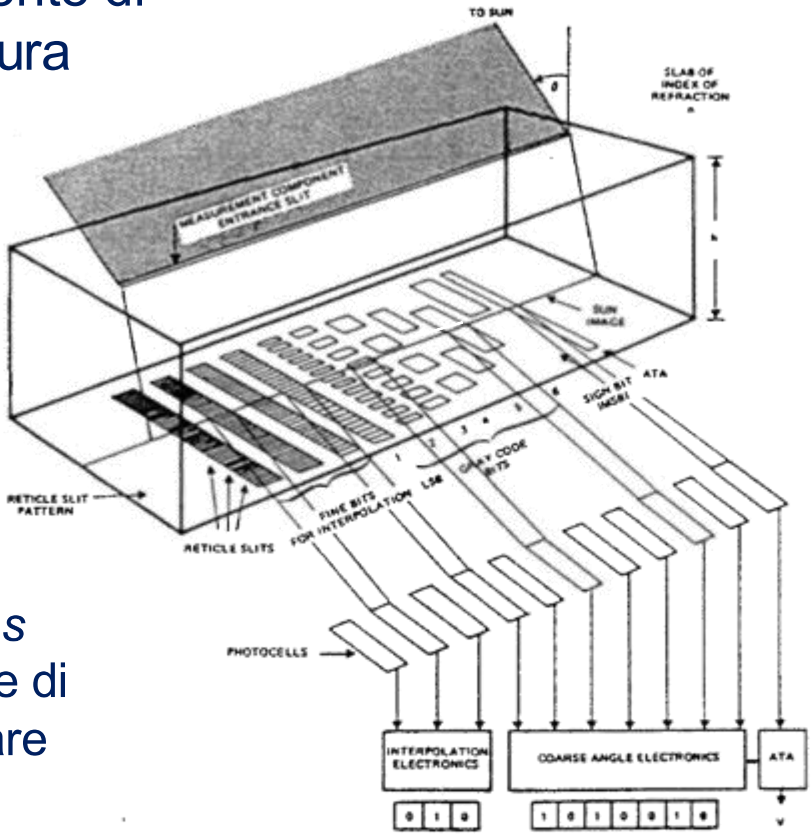


Sensori Solari Digitali



Componente di misura

Componente di comando



Codice Gray

codice binario a lunghezza fissa s costituito da tutte le 2^s sequenze di s bit e consente di rappresentare tutti gli interi da 0 a $2^s - 1$

SMAD tab. 11-12

Parameter	Simplified Equations	Application to FireSat Example
Torque from Reaction Wheel for Disturbance Rejection	Reaction-wheel torque must equal worst-case anticipated disturbance torque plus some margin: $T_{RW} = (T_D)$ (Margin Factor)	For the example spacecraft, $T_D = 4.5 \times 10^{-5}$ N·m (Table 11-9). This is below almost all candidate reaction wheels. We will select a wheel based on storage requirements or slew torque, not disturbance rejection. See below.
Slew Torque for Reaction Wheels	For max-acceleration slews (1/2 distance in 1/2 time): $\frac{\theta}{2} = \frac{1}{2}\frac{T}{I}\left(\frac{t}{2}\right)^2$	For the 30-deg slews of the 90 kg·m² spacecraft (Fig. 11-1) in 10 min, this becomes: $T = 4\theta\frac{I}{t^2} = \frac{4 \times 30\ \text{deg} \times (\pi / 180\ \text{deg}) \times 90\ \text{kg}\cdot\text{m}^2}{(600\ \text{sec})^2}$ $= 5.2 \times 10^{-4}\ \text{N}\cdot\text{m}$ This is also a small value.
Momentum Storage in Reaction Wheel	One approach to estimating wheel momentum, h, is to integrate the worst-case disturbance torque, T_D, over a full orbit. If the disturbance is gravity gradient, the maximum disturbance accumulates in 1/4 of an orbit. A simplified expression for such a sinusoidal disturbance is: $h = (T_D)\frac{\textit{Orbital Period}}{4}(0.707)$ where 0.707 is the rms average of a sinusoidal function.	For $T_D = 4.5 \times 10^{-5}$ N·m (Table 11-9B) and a 700-km orbital period of 98.8 min $h = (4.5 \times 10^{-5}\ \text{N}\cdot\text{m})\left(\frac{98.8\ \text{min}}{4}\right)\left(\frac{60\ \text{sec}}{\text{min}}\right)(0.707)$ $= 4.7 \times 10^{-2}\ \text{N}\cdot\text{m}\cdot\text{s}$ A small reaction wheel which gives us storage of 0.4 N·m·s would be sufficient. It provides a margin of > 9 in storage for the worst-case torques.
Momentum Storage in Momentum Wheel	Roll and yaw accuracy depend on the wheel's momentum and the external disturbance torque. A simplified expression for the required momentum storage is: $T \times \frac{P}{4} = h\theta_a$ T = torque, P = orbit period, h = angular momentum, θ_a = allowable motion	The value of h for a 0.1 deg yaw accuracy would be $h = \frac{(4.5 \times 10^{-5}\ \text{N}\cdot\text{m}) \times 1482\ \text{sec}}{0.1 \times \frac{\pi}{180\ \text{deg}}}$ $= 38.2\ \text{N}\cdot\text{m}\cdot\text{s}$ T_D is from Table 11-9A. For a 1 deg accuracy, we would need only 3.8 N·m·s
Momentum Storage in Spinner	Same as for a momentum wheel, but with the spin rate: $\omega_s = \frac{h}{I}$	For the 0.1 deg accuracy, the spin rate is: $\omega_s = \frac{(37.3)\ \text{N}\cdot\text{m}\cdot\text{s}}{90\ \text{kg}\cdot\text{m}^2} = 0.42\ \text{rad / sec} = 4.1\ \text{rpm}$
Torque from Magnetic Torquers	Magnetic torquers use the Earth's magnetic field, B, and electrical current through the torquer to create a magnetic dipole (D) that results in torque (T) on the vehicle: $D = \frac{T}{B}$ Magnets used for momentum dumping must equal the peak disturbance + margin to compensate for the lack of complete directional control.	Table 11-9B estimates the worst-case Earth field, B, to be 4.5×10^{-5} tesla. We calculate the torque rod's magnetic torquing ability (dipole) to counteract the worst-case gravity gradient disturbance, T_D, of 4.5×10^{-5} N·m as $D = \frac{T}{B} = \frac{4.5 \times 10^{-5}\ \text{N}\cdot\text{m}}{4.5 \times 10^{-5}\ \text{tesla}} = 1\ \text{A}\cdot\text{m}^2$ which is a small actuator. The Earth's field is cyclic at twice orbital frequency; thus, maximum torque is available only twice per orbit. A torquer of 3 to 10 A·m² capacity should provide sufficient margin.

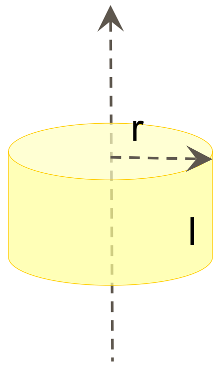
Esercizio 1/2

SMAD tab. 11-12

- Stimare i momenti di torsione esterni (di disturbo) che agiscono sulla S/C
- Supponendo di avere un sistema di 3 RW (R=0.075 m, vel. spin=1000 rpm), stimare quale debba essere la capacita' di immagazzinamento di momento (L=Torsione x tempo accumulo) e la massa di ciascuna RW
- Suggerimenti tab 11.12 smad
  - $I_{cilindro} = \frac{1}{2} mr^2$
    (lungo l'asse longitudinale)
  - $I_{cilindro} = m(r^2/4+l^2/12)$
    (lungo l'asse trasversale)
  - $L = 0.707\ T_D\ (t/4)$ RW
  - $L \cdot \theta = T_D\ (t/4)$ MW

    T_D = torsione di disturbo

    t = periodo orbitale



S/C characteristics		
mass	2089	kg
length	4	m
diameter	2.6	m
coeff. reflectivity	0.6	
magnetic dipole	2.5	A m2
drag coeff.	2.5	
diff. center pressure / center gravity	0.40	m

Operational characteristics		
orbit altitude	600	km
max angular dev. from local vertical	1	deg
mission lifetime	5	years

Risultati

INPUTS:		
S/C characteristics		
mass	2089	kg
cylinder length	4	m
cylinder diameter	2,6	m
min mom. inertia	1765,2	kg m2
max mom. inertia	3667,9	kg m2
coeff. reflectivity	0,6	
magnetic dipole	2,5	A m2
drag coeff.	2,5	
diff. center pressure / center gravity	0,4	m
area to Sun	5,3	m2
area to atmosphere	16,3	m2
max area	10,4	
v2	57121351	m2/s2
v	7557,9	m/s
operational characteristics		
orbit altitude	600	km
max angular dev. from local vertical	1	deg
	0,017	rad
mission lifetime	5	years
	157680000	s
orbit radius	6978	km
period	5801,2	s
	1,6	hr
numero orbite 1 day	14,9	

TORQUES		
gravity gradient	1,17E-04	N m
solar radiation	3,04E-05	N m
	7,59E-05	N
magnetic field	1,17E-04	N m
magn. f.	4,69E-05	tesla
aerodynamic	1,45E-04	N m
	3,63E-04	
TOTAL (QUADRATIC SUM)	2,22E-04	N m
TOTAL (SUM)	4,10E-04	N m

Risultati

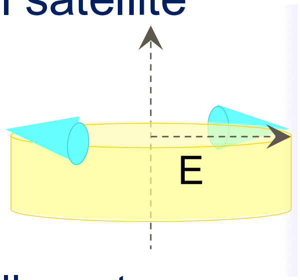
	sum	quadr sum (indip)		
REACTION WHEEL				
Storage	4,2E-01	2,3E-01	N.m.s	1 orbit
	1,1E+04	1,1E+04	N.m.s	lifetime
storage 1 day tot	6,3E+00	3,4E+00	N.m.s	
/wheel	2,1E+00	1,1E+00	N.m.s	
ω	1000		rpm	
	104,7		rad/s	
m	21,2	0,8	kg	1 day
		3,8	kg	/wheel

	sum	quadr sum (indip)		
MOMENTUM WHEEL				
θ	1		deg	
Storage	34,0	18,5	N.m.s	1 orbit
m	115,6	62,7	kg	1 orbit
		20,9		/wheel

- $I_{cilindro} = \frac{1}{2} mr^2$
- $L = I\,\omega$
- $L = 0.707\, T_D\, (t/4)$ RW
- $L \cdot \theta = T_D\, (t/4)$ MW

Esercizio 2/2

- Supponendo di avere un sistema di 2 thruster (posti ai bordi del cilindro in posizione opposta) per smorzare ogni RW (una volta al giorno, Δt=1 s, I_{sp}=320 s), valutare:
  - la spinta di ciascun thrust
  - Il numero totale di impulsi per tutta la vita del satellite
  - il propellente necessario



- Suggerimenti:
  - $F = L / (\ell \, \Delta t)$

    F=thrust, L=momento immagazzinato dalla ruota, ℓ =braccio, Δt=tempo di accensione thruster
  - Impulso totale = $F \, \Delta t$
  - $I_{sp} = F / (g \, \Delta M / \Delta t)$

Risultati

THRUSTER (RW - sum)	1 Wheel	
storage 1 day tot	6,3E+00	N.m.s
Δt	1	s
thrust	41,7	N
impulso	20,8	N.s
Isp	320,0	s
Mp	0,0133	kg
numero tot/wheel	1825	
numero tot	5475	
Mp/wheel	48,5	kg
Mp tot	145,4	kg

- $F = L / (\ell \, \Delta t)$
- Impulso totale = $F \, \Delta t$
- $I_{sp} = F / (g \, \Delta M/\Delta t)$