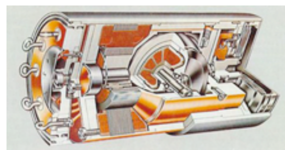
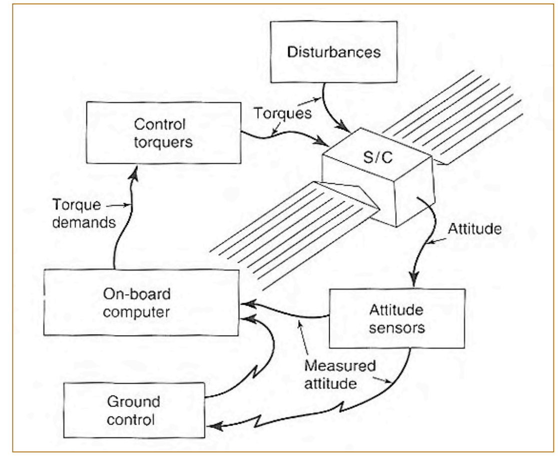
Spacecraft Sensors and Actuators

Space System Design, MAE 342, Princeton University
Robert Stengel

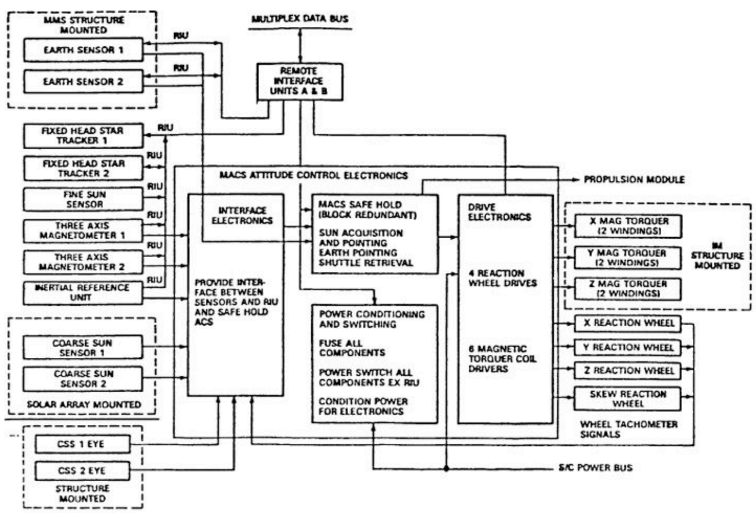
- Attitude Measurements
- Attitude Actuators
- Translational Measurements
- Mechanical Devices



Attitude Control System



UARS Attitude Control System



Attitude Measurements

- Measurement of an angle or angular rate of the spacecraft with respect to a reference frame, e.g.,
  - Earth's magnetic field
    - Magnetometer
  - Direction to the sun
    - Sun sensor
  - Earth's shape
    - Earth horizon sensor
  - Inertial frame of the universe
    - Star sensor
    - Gyroscopes
- Mission requirements dictate spacecraft sensor configuration

Potential Accuracies of Attitude Measurements

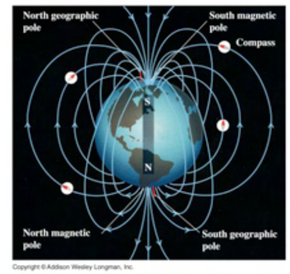
Reference object	Potential accuracy
Stars	1 arc second
Sun	1 arc minute
Earth (horizon)	6 arc minutes
RF beacon	1 arc minute
Magnetometer	30 arc minutes
Narstar Global Positioning System (GPS)	6 arc minutes

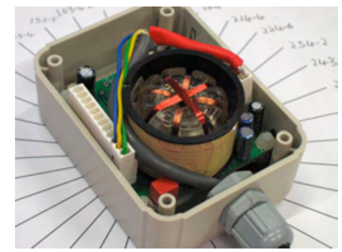
Note: This table gives only a guideline. The GPS estimate depends upon the 'baseline' used (see text).

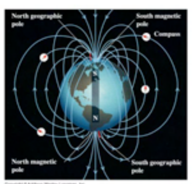
Fortescue

Magnetometer

- **Flux gate magnetometer**
  - **Alternating current passed through one coil**
  - **Permalloy core alternately magnitized by electromagnetic field**
  - **Corresponding magnetic field sensed by second coil**
  - **Distortion of oscillating field is a measure of one component of the Earth's magnetic field**
- **Three magnetometers required to determine Earth's magnetic field vector**





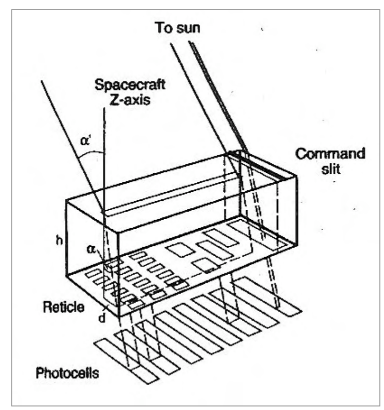


Body Orientation from Magnetometer

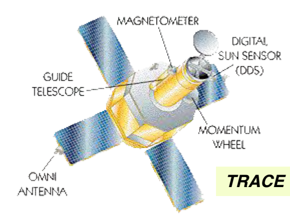
- **Earth's magnetic field vector, b_I, function of spacecraft position, (*x, y, z*)**
- **Body orientation vector, b_B, related to b_I by rotation matrix, *C*, from inertial to body frame and calibration rotation matrix, *S***

$$
\begin{aligned}
&\mathbf{b}_B = \mathbf{C}\mathbf{b}_I \\
&\mathbf{b}_B = \mathbf{S}_{mag}\mathbf{b}_{mag} \\
&\mathbf{b}_B = C\mathbf{b}_I(x,y,z) + error \\
&\mathbf{S}_{mag}(\varepsilon_1,\varepsilon_2,\varepsilon_3) = calibration\ rotation\ matrix \\
&\mathbf{C}(\psi,\theta,\phi) = inertial\ to\ body\ rotation\ matrix \\
&\qquad \equiv direction\ cosine\ matrix
\end{aligned}
$$

- **Estimation of yaw, ψ, pitch, θ, and roll, ϕ, angles requires additional information**
  - **Equation has 2 degrees of freedom, but there are 3 unknowns**



Sun Sensor

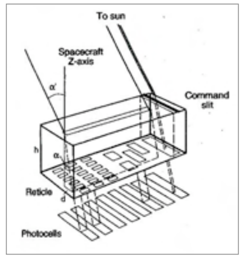


- **Transparent block of material with known refractive index, *n*, coated with opaque material**
- **Slit etched in top, receptive areas etched in bottom**
- **Light from sun passing through slit forms a line over photodetectors**

Sun Sensor

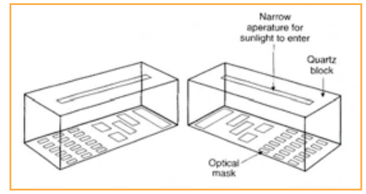
- Distance from centerline measured by sensed pattern, which determines angle, α
- With index of refraction, *n*, angle to sun, α', is determined
- Photodetectors may provide digital (coarse) or analog (fine) outputs

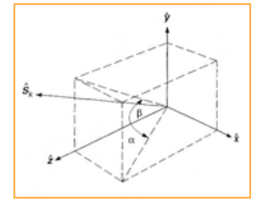
$$\tan\alpha = d/h$$
$$\sin\alpha' = n\sin\alpha \quad (Snell's\ law)$$
$$n = index\ of\ refraction$$



Dual Sun Sensors

- Orthogonal sun sensors determine direction (two angles) to the sun



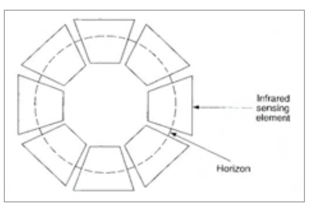


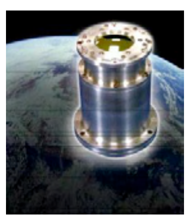
$$\mathbf{s}_{Sun} = \frac{1}{\sqrt{1+\tan^2\alpha+\tan^2\beta}}\begin{bmatrix}\tan\alpha \\ \tan\beta \\ 1\end{bmatrix}$$
$$\mathbf{s}_B = \mathbf{S}_{Sun}\mathbf{s}_{Sun}$$
$$\mathbf{s}_B = \mathbf{C}(\psi,\theta,\phi)\mathbf{s}_I + error$$

- Two measurements, three unknowns
- Three-axis attitude determination requires additional information

Static Earth Horizon Sensor

- Infrared sensing to reduce optical error
- Static horizon sensor has field of view larger than the entire earth's edge (limb)
- Provides orientation with respect to the nadir





Goodrich Multi-Mission Horizon Sensor

Characteristics

Infrared spectral band: 14 to 16 µm

Detectors: Micro-machined (MEMS) thermopiles

Total field-of-view: 16° long by 10° wide

Spacecraft keep-out-zone: 15° cone around aperture

GEO Performance (redundant, 2-telescope assembly)

Pitch accuracy (E-W): +/- 0.013°, 3-σ for either telescope

Roll accuracy (N-S): +/- 0.030°, 3-σ for either telescope

(Above is RSS accuracy at null, based on 30°C long-term thermal drift and 18° peak-to-peak diurnal)

Operating range: +/- 6° fine pitch measurement

+/- 2° fine roll measurement

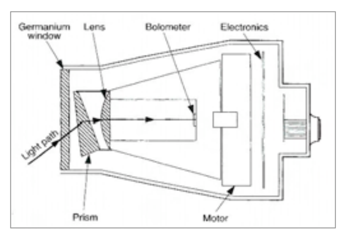
Acquisition range: 16° maximum Earth detection

Scanning Earth Horizon Sensor

- Spinning assembly identifies light and dark areas (infrared)
- Width of light area identifies spacecraft roll angle, ϕ

$$\cos\rho = \cos\gamma\cos\phi + \sin\gamma\sin\phi\cos(\Omega/2)$$
$$\rho: \quad Earth\ angular\ radius$$
$$\gamma: \quad Half-cone\ angle$$

$$\Omega = \omega_{scanner}(t_{LOS} - t_{AOS})$$
$$t_{LOS/AOS}: \quad Time\ of\ loss/acquisition\ of\ signal$$



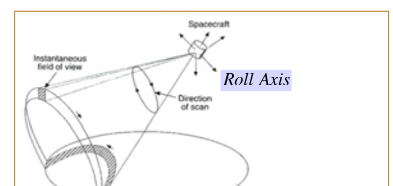


Figure 5.10 Scan cone geometry.

Star Sensor/Tracker

- Instrument has narrow field of view
- Star location catalog helps identify target
- Instrument must have low angular velocity
- *x* and *y* location of star on focal plane determines angles to the star

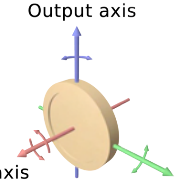
Goodrich Star Tracker

Performance Category	*Narrow FOV*	*Wide FOV*
Field of View Magnitude Sensitivity Power (avg. at +45°C)	8° x 8° +6.5 10W	20° circular +5.1 10W
Weight (with lightshade) Update Rate Stars Simultaneously Tracked	8.5 lb 6 Hz 6	7.5 lb 2 Hz 6
Overall Accuracy -Pitch/Yaw, rms -Roll, rms	 2 arc sec 40 arc sec	 5 arc sec 40 arc sec

Typical Spacecraft Sensor Configurations

- Most precise measurements (e.g., scientific satellites)
  - star trackers
- Moderate accuracy requirements
  - coarse digital sun sensors
  - horizon sensors
  - magnetometers
- Spinning satellites
  - single-axis sun sensors
  - magnetometers
  - horizon sensors
- High-altitude (e.g., geosynchronous) satellites
  - optical sensors
  - gyroscopes
  - magnetic field too weak for use

Mechanical Gyroscopes



- Body-axis moment equation

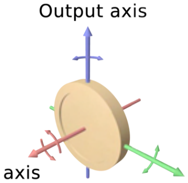
$$\mathbf{M}_B = \dot{\mathbf{h}}_B + \tilde{\omega}_B \mathbf{h}_B$$

Angular momentum: $\mathbf{h}_B = \boldsymbol{I}_B \boldsymbol{\omega}_B$

$$\boxed{\dot{\boldsymbol{\omega}}_B = \boldsymbol{I}_B^{-1}\left(M_B - \tilde{\boldsymbol{\omega}}_B \boldsymbol{I}_B \boldsymbol{\omega}_B\right)}$$

- Assumptions
  - Constant nominal spin rate, *n*, about *z* axis
  - $I_{xx} = I_{yy} << I_{zz}$
  - Small perturbations in ω_x and ω_y

Gyroscope Equations of Motion



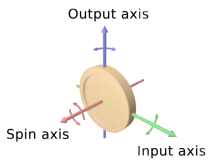
- Linearized equations of angular rate change

$$\begin{bmatrix} \Delta\dot{\omega}_x \\ \Delta\dot{\omega}_y \\ 0 \end{bmatrix} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}^{-1} \left[\begin{bmatrix} M_x \\ M_y \\ 0 \end{bmatrix} - \begin{pmatrix} 0 & -n & \Delta\omega_y \\ n & 0 & -\Delta\omega_x \\ -\Delta\omega_y & \Delta\omega_x & 0 \end{pmatrix} \begin{pmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{pmatrix} \begin{pmatrix} \Delta\omega_x \\ \Delta\omega_y \\ n \end{pmatrix} \right]$$

$$\begin{bmatrix} \Delta\dot{\omega}_x \\ \Delta\dot{\omega}_y \\ 0 \end{bmatrix} = \begin{bmatrix} \left[M_x - n\left(I_{zz} - I_{yy}\right)\Delta\omega_y\right]/I_{xx} \\ \left[M_y - n\left(I_{xx} - I_{zz}\right)\Delta\omega_x\right]/I_{yy} \\ 0 \end{bmatrix}$$

- or

$$\boxed{\begin{bmatrix} \Delta\dot{\omega}_x \\ \Delta\dot{\omega}_y \end{bmatrix} = \begin{bmatrix} 0 & n\left(I_{yy} - I_{zz}\right)/I_{xx} \\ n\left(I_{zz} - I_{xx}\right)/I_{yy} & 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_x \\ \Delta\omega_y \end{bmatrix} + \begin{bmatrix} M_x/I_{xx} \\ M_y/I_{yy} \end{bmatrix}}$$



Gyroscope Natural Frequency

- **Laplace transform of dynamic equation**

$$\begin{bmatrix} s & -n\left(I_{yy}-I_{zz}\right)/I_{xx} \\ -n\left(I_{zz}-I_{xx}\right)/I_{yy} & s \end{bmatrix}\begin{bmatrix}\Delta\omega_y(s) \\ \Delta\omega_y(s)\end{bmatrix} = \begin{bmatrix} M_x(s)/I_{xx} \\ M_y(s)/I_{yy}\end{bmatrix}$$

- **Characteristic equation**

$$\boxed{\Delta(s) = s^2 + n^2\left(\frac{I_{zz}}{I_{xx}}-1\right)^2 = 0}$$

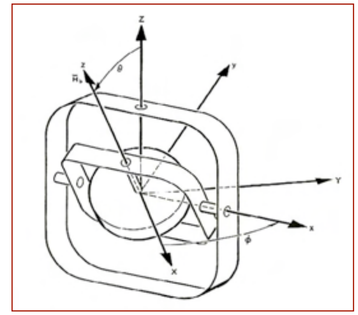
- **Natural frequency, ω_n, of small perturbations**

$$\boxed{\omega_n = n\left(\frac{I_{zz}}{I_{xx}}-1\right) \quad rad/\mathrm{sec}}$$

- **Example**

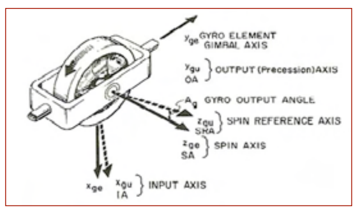
$$\boxed{\begin{array}{l} n = 36{,}000\ rpm = 3{,}770\ rad/sec \\ Thin\ disk: \dfrac{I_{zz}}{I_{xx}} = 2 \\ \omega_n = 3{,}770\ rad/sec = 600\ Hz \end{array}}$$

Two-Degree of Freedom Gyroscope



- **Free gyro mounted on a gimbaled platform**
- **Gyro "stores" reference direction in space**
- **Angle pickoffs on gimbal axes measure pitch and yaw angles**
- **Direction can be precessed by applying a torque**

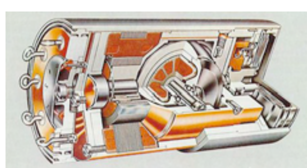
Single-Degree of Freedom Gyroscope



- **Gyro axis, θ, constrained to rotate in its case with respect to the output axis, *y*, only**

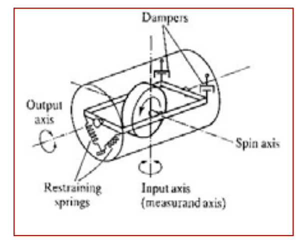
$$\begin{bmatrix}\Delta\dot{\theta} \\ \Delta\dot{\omega}_y\end{bmatrix} = \begin{bmatrix}\Delta\omega_y \\ \left(h_{rotor}\Delta\omega_x + M_{y_{control}}\right)/I_{yy}\end{bmatrix}$$

- **"Synchro" measures axis rotation, and "torquer" to keep θ small**
- **Torque applied is a measure of the input about the *x* axis**



$$M_{y_{control}} = k_\theta\Delta\theta + k_\omega\Delta\omega_y + k_c\Delta u_c$$

Rate and Integrating Gyroscopes



- **Large angle feedback produces a rate gyro**
  - Analogous to a mechanical spring restraint

$$\Delta\dot{\omega}_{y_{SS}} = 0 = \left(h_{rotor}\Delta\omega_{x_{SS}} + k_\theta\Delta\theta_{SS}\right)/I_{yy}$$

$$\Delta\theta_{SS} = -\frac{h_{rotor}}{k_\theta}\Delta\omega_{x_{SS}}$$

- **Large rate feedback produces an integrating gyro**
  - Analogous to a mechanical damper restraint

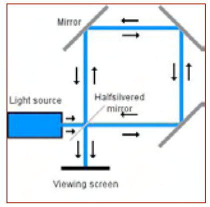
$$\Delta\dot{\omega}_{y_{SS}} = 0 = \left(h_{rotor}\Delta\omega_{x_{SS}} + k_\omega\Delta\omega_{y_{SS}}\right)/I_{yy}$$

$$\Delta\omega_{y_{SS}} = -\frac{h_{rotor}}{k_\omega}\Delta\omega_{x_{SS}}$$

$$\Delta\theta_{SS} = \Delta\phi_{SS}$$

Optical Gyroscopes

- Sagnac interferometer measures rotational rate, Ω
  - $\Omega = 0$, photons traveling in opposite directions complete the circuit in the same time
  - $\Omega \neq 0$, travel length and time are different
- On a circular path of radius R:



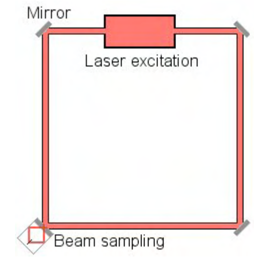
$$t_{CCW} = \frac{2\pi R}{c}\left(1 - \frac{R\Omega}{c}\right); \quad t_{CW} = \frac{2\pi R}{c}\left(1 + \frac{R\Omega}{c}\right)$$

$$\Delta t = t_{CW} - t_{CCW} = \frac{4\pi R^2}{c^2}\Omega = \frac{4A}{c^2}\Omega$$

c : speed of light
R : radius
A : area

Ring Laser Gyro

- Laser in optical path creates photon resonance at wavelength λ
- Frequency change in cavity is proportional to angular rate
- Three RLGs needed to measure three angular rates



$$\Delta f = \frac{4A}{\lambda P}\Omega$$

P : perimeter length

Fiber Optic Gyro

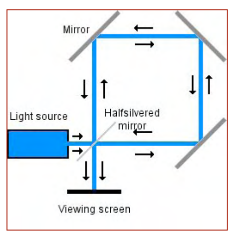
- Long length of fiber cable wrapped in a circle
- Photon source and sensor are external to the fiber optics
- Length difference for opposite beams is

$$\Delta L = \frac{4AN}{c}\Omega$$

A : included area
N : number of turns

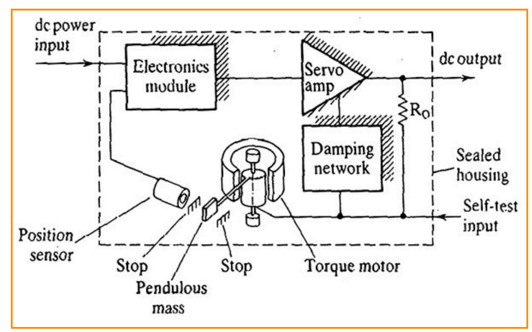
- Phase difference is proportional to angular rate

$$\Delta\varphi = \frac{8\pi AN}{\lambda c}\Omega$$



Force Rebalance Accelerometer

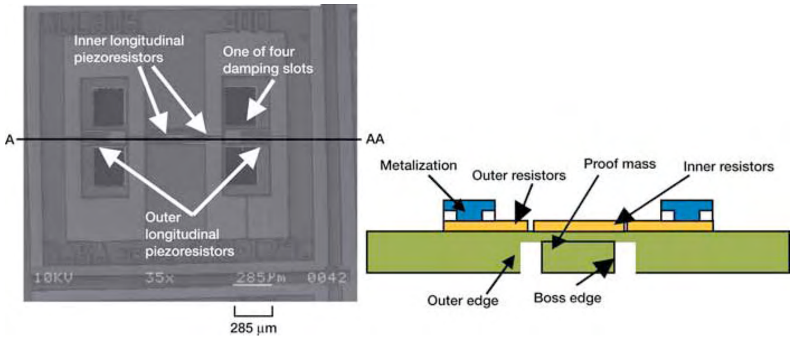
$$f = ma$$



$$\Delta\ddot{x} = f_x/m = \left(-k_d\Delta\dot{x} - k_s\Delta x\right)/m$$

- Voltage required to re-center the proof mass becomes the measure of acceleration

MicroElectroMechanical System (MEMS)Accelerometer



Inertial Measurement Units

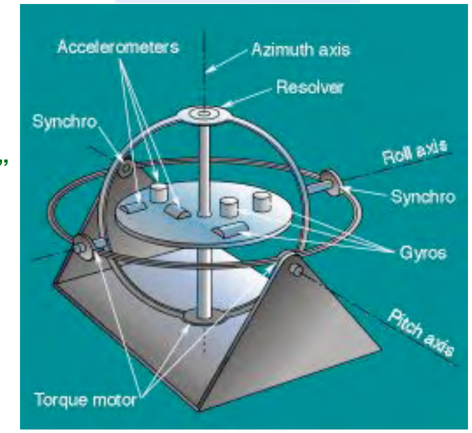
$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} \to \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} \to \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \to \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}$$

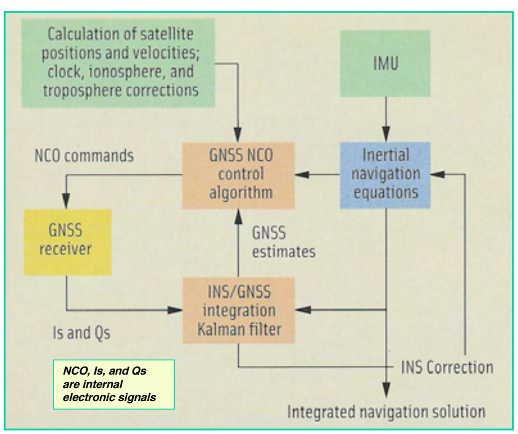
- 3 accelerometers
- 3 rate or rate-integrating gyroscopes
- Platform orientation “fixed” in space
- Vehicle rotates about the platform

- Need for high precision
- Drift due to errors and constants of integration
- Platform re-oriented with external data (e.g., GPS)

Gimbaled Physical Platform



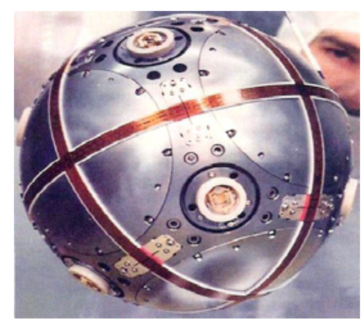
Integrated Inertial Navigation/GPS System



Gimbal-less Physical Platform

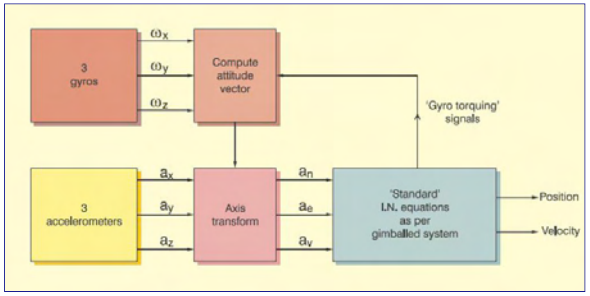
- Peacekeeper IMU*
- Reduced errors due to hydraulic suspension
- Instruments subjected to low dynamic range, allowing high precision

Servo-driven reference frame



*IEEE Control Systems Magazine, 2/08

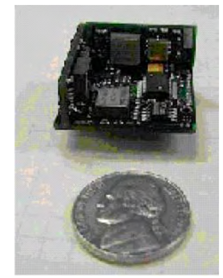
Strapdown Inertial Measurement Units



- Rate gyros and accelerometers rotate with the vehicle
- High dynamic range of instruments is required
- Inertial reference frame is computed rather than physical
- Use of direction cosine matrix and quaternions for attitude reference

MicroElectroMechanical (MEMS) Strapdown Inertial Measurement Units

- Less accurate than precision physical platform
- High drift rates
- Acceptable short-term accuracy
- Inexpensive
- Updated with GPS

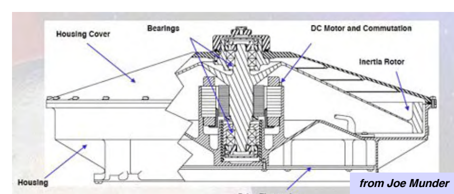


Angular Attitude Actuators

- Momentum/reaction wheels
- Control moment gyroscope
- Magnetic coils
- Thrusters
- Nutation dampers
- Solar radiation pressure

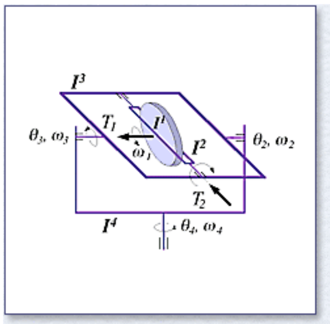
Momentum/ Reaction Wheels

- Flywheel on a motor shaft
- Momentum wheel operates at high rpm and provides spin stability
- Reaction wheel rpm is varied to trade angular momentum with the spacecraft for control
  - Three orthogonal wheels vary all components of angular momentum
  - Fourth wheel at oblique angle provides redundancy



Control Moment Gyroscope

- Control moment gyros operate at constant rpm
- Small torque on input axis produces large torque on output axis, modifying spacecraft momentum
- One or two degrees of freedom



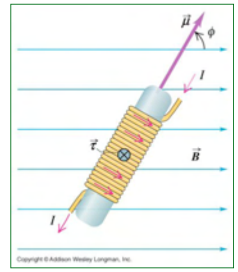
International Space Station
Control Moment Gyros

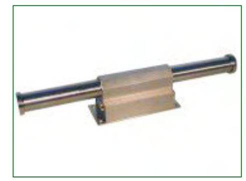
Magnetic Torquers

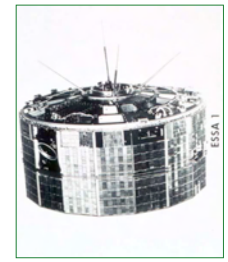
- Current flowing through a loop generates a magnetic torque through interaction with the Earth's magnetic field
  - Torque rods
  - Loops around spacecraft exterior (e.g., TIROS-2)

$$\boxed{\mathbf{m} = NIA(\mathbf{i} \times \mathbf{B})}$$

N: number of loops
I: current
A: included area of loops
i: unit vector along coil axis
B: local flux density





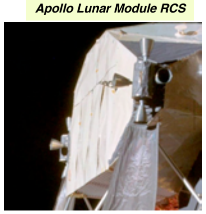


Reaction Control Thrusters

- Direct control of angular rate
- Unloading momentum wheels or control-moment gyros
- Reaction control thrusters are typically on-off devices using
  - Cold gas
  - Hypergolic propellants
  - Catalytic propellant
  - Ion/plasma rockets
- Thrusters commanded in pairs to cancel velocity change

> - **Issues**
>   - Specific impulse
>   - Propellant mass
>   - Expendability

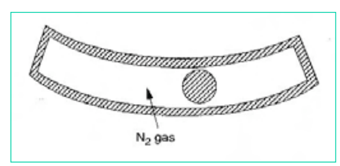
Apollo Lunar Module RCS

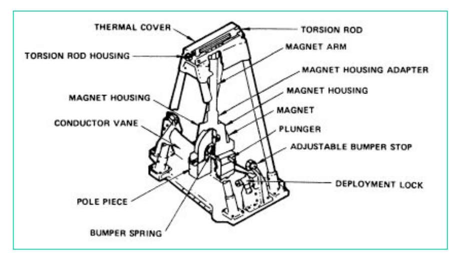


Space Shuttle RCS

Nutation Dampers

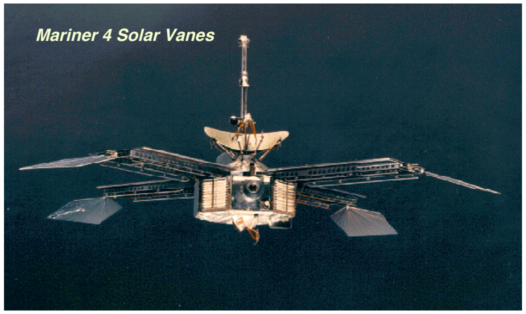
- Nutation dampers dissipate angular energy, damping angular oscillations
  - Mass moving in a gas or viscous fluid
  - Eddy current on a conducting pendulum in a magnetic field





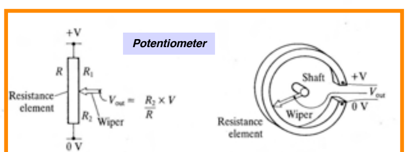
Solar Radiation Pressure Control Panels

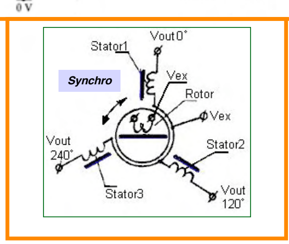
- Solar radiation pressure
- Vanes deflected differentially
- Long moment arm from center of mass

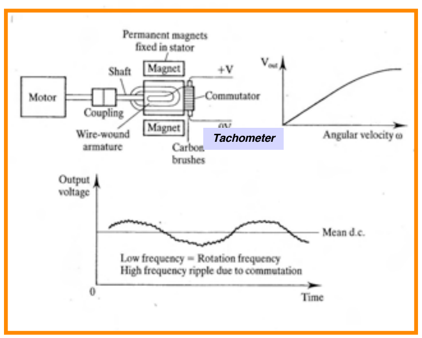


Sensors and Actuators for Spacecraft Mechanisms

Potentiometer, Synchro, and Tachometer

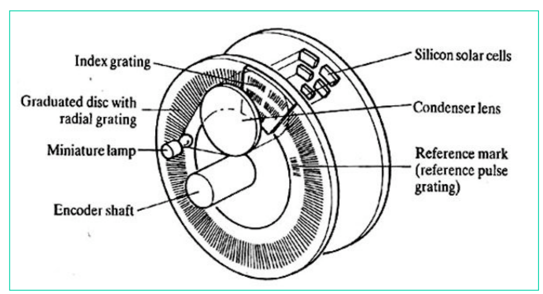


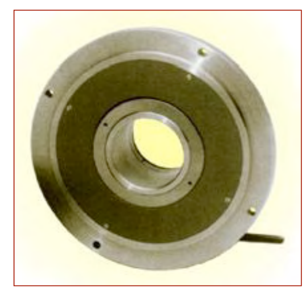




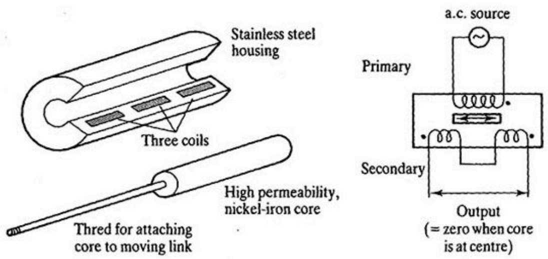
Attitude Encoder

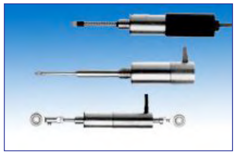
- Rotary pulse generator

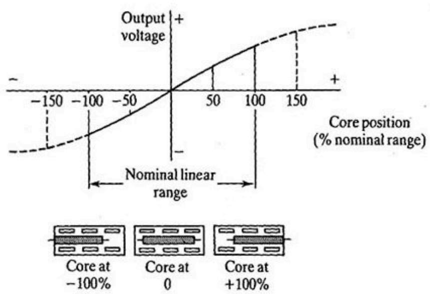




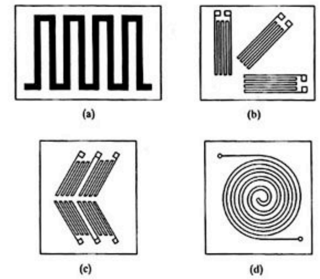
Linear Variable Differential Transformer



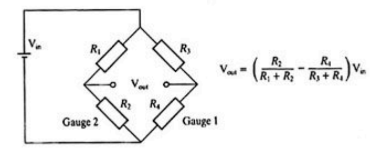


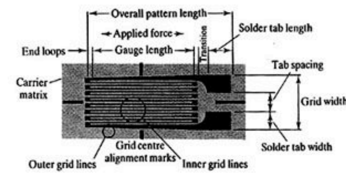


Strain Gage



Wheatstone Bridge

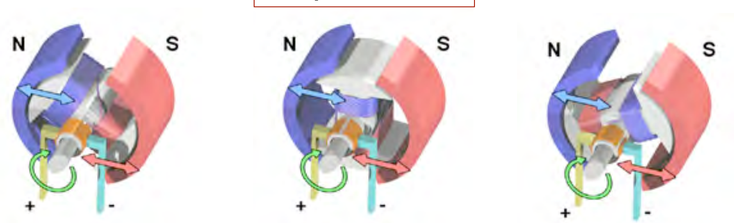




$$\varepsilon = \frac{\left(\frac{\Delta R}{R_o}\right)}{Gage\ Factor}$$

Electric Actuator: Brushed DC Motor

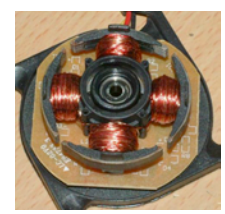
Two-pole DC Motor

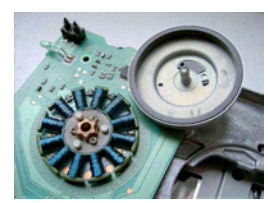


- Current flowing through armature generates a magnetic field
- Permanent magnets torque the armature
- When armature is aligned with magnets, commutator reverses current and magnetic field
- Multiple poles added to allow motor to smooth output torque and to start from any position

Electric Actuator: Brushless DC Motor

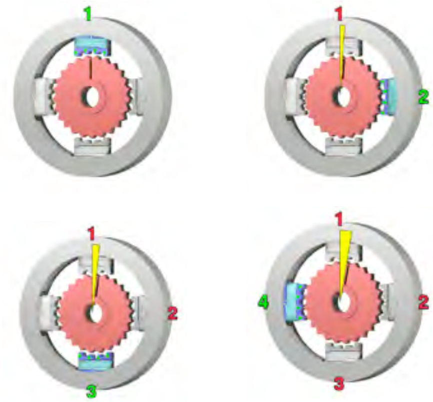
- Armature is fixed, and permanent magnets rotate
- Electronic controller commutates the electromagnetic force, providing a rotating field
- Advantages
  - Efficiency
  - Noise
  - Lifetime
  - Reduced EMI
  - Cooling



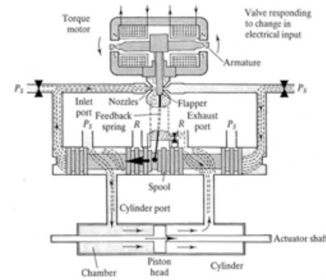


Electric Actuator: Stepper Motor

- **Brushless, synchronous motor that moves in discrete steps**
- **Precise quantized control without feedback**
- **Armature teeth offset to induce rotary motion**



Hydraulic Actuator



- **Used principally for launch vehicle thrust vector and propellant control**
- **Not widely used on spacecraft**

Next Time: Attitude Control