Attitude Determination and Control

Mark Campbell

AA420 Space Design

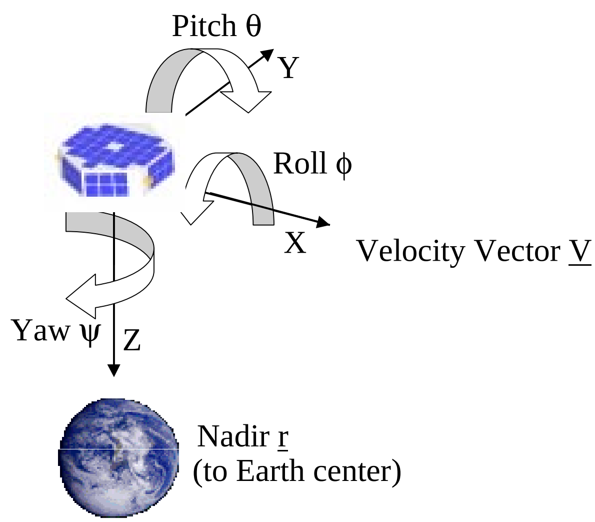
Outline

- Driving Issues and Requirements
  - Modes of Operation
  - Disturbances
  - Others
- Passive Options
  - Gravity Gradient, Spin stabilized, permanent magnets, radiometer spin
- Active Options
  - actuators (wheels, torque coils and rods, thrusters)
  - sensors (magnetometer, gyro, star tracker, horizon and sun sensors)
- Design Approach
- References:
  - Sections 10.4, 11.1 of Larson and Wertz
  - Wertz, J. ed. *Spacecraft Attitude Determination and Control*, D. Reidel Publishing Company, Dordrecht, Holland, 1978.
  - Griffin, M.D., and French, J.R., *Space Vehicle Design*, American Institute of Aeronautics and Astronautics, 1991.

Attitude Determination and Control

- Spacecraft Attitude is the angular orientation of a spacecraft body vector with respect to an external reference frame
- Attitude is concerned with angles only; all vectors may be reduced to unit length for ease of use.
- The external reference frame may be inertial or non-inertial.

Basic Reference Frame



Modes of Operation

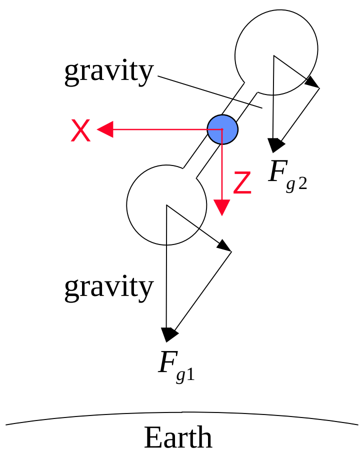
- Control requirements differ during different operations
- Modes of Operation
  - Launch
  - Detumble - reduce rotation rates to near zero (from separation, fault)
  - Attitude Acquisition - Find sun, Earth, Stars, etc by sweeping
  - Flight - normal operation such as pointing for science
  - Delta V - propulsive maneuver for orbit change (sharing of resources)
  - Formation Flight - propulsive maneuver for relative position change
  - Communication - periodic pointing of antenna at Earth
  - Safe - response to a fault, stable state in which to wait for commands
    - May include transition to Detumble or Attitude Acquisition
- System must be designed to allow smooth switching between control modes.
  - Mode switching problems may be fatal in flight.

Disturbance Environment

- External disturbances (can be cyclic or constant)
  - Gravity gradient
  - Magnetic moment
  - Atmospheric drag
  - Solar radiation and pressure
- Internal disturbances (constant or dynamic)
  - Actuator misalignment (thruster, wheel, etc.)
  - Sensor misalignment (gyro, magnetometer, etc.)
  - Uncertainty in center of mass (cg)
  - Structural dynamics (such as arrays)
  - Thermal shows (entering/leaving eclipse)
  - Fluid slosh
- See Tables 11-9a and 11-10.

Gravity Gradient

- A constant disturbance torque for Earth oriented satellites
- A cyclic disturbance torque for inertially oriented satellites
- Can be used for “control” as well



- Gravitational force on mass *m*:

$$F_g = -\frac{\mu m}{R^2}$$

- A resulting torque occurs when

$$F_{g1} > F_{g2}$$

- In general, the gravitational torque can be expressed as

$$T_{gX} = \frac{3\mu}{2R^3}\left|I_Z - I_Y\right|\sin(2\theta_Y)$$

$$T_{gY} = \frac{3\mu}{2R^3}\left|I_Z - I_X\right|\sin(2\theta_X)$$

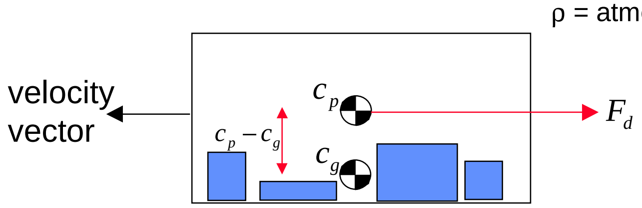
Atmospheric Drag

- Different parts of a satellite have different drag coefficients
- This produces a net torque on the system that is
  - constant for Earth oriented vehicles
  - variable for inertially oriented vehicles
  - Example: a low CG because of placing most components on the bottom of the satellite

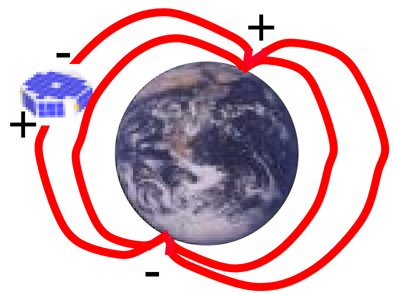
$$T_d = F_d\left(c_p - c_g\right)$$

$$F_d = \frac{1}{2}\left(\rho C_d A V^2\right)$$

C_d = drag coefficient
c_p = center of aero pressure
A = surface area
V = velocity
ρ = atmospheric density



Magnetic Moment



- Charge builds up on a spacecraft because of interactions with the ionosphere.
- This charge creates a “magnet” that interacts with the magnetic field, much like a compass

Solar Radiation and Pressure

$$T_s = F_s\left(c_s - c_g\right)$$

$$F_s = \frac{1358\mathrm{W/m^2}}{c} A(1+q)\cos i$$

c = speed of light
c_s = center of solar pressure
A = surface area
q = reflectance (0 - 1)
I = angle of incidence

- Tiny photons strike the satellite and transfer momentum
- Different parts of a satellite have different reflectivity, shape
- This produces a net torque on the system that is
  - cyclic for Earth oriented vehicles
  - constant for solar oriented vehicles
- Magnitude of disturbance is most easily reduced by minimizing the distance from the body cg to the cp.
- Disturbances due to solar radiation pressure may be of very significant concern if a boom or other long element is involved.
- Can also be used for spin

UW PRIMEX AEROSPACE COMPANY

Other Driving Issues and Requirements

- Mass/Inertia
- Flexible frequency
- Power
- Safety
- Cost

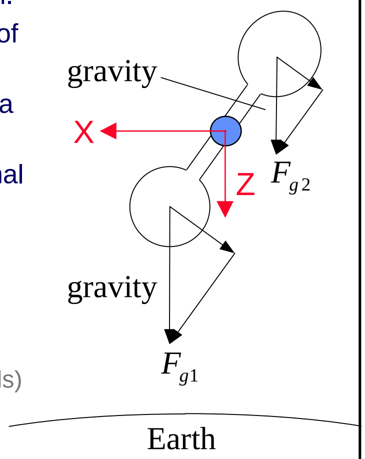
UW PRIMEX AEROSPACE COMPANY

Attitude Control Summary

Method	Accuracy (deg)	Axes	Notes
Spin stabilization	0.1-1.0	2	Passive, simple, cheap, inertially oriented
Gravity gradient	1-5	2	Passive, simple, cheap, central body oriented
RCS	0.01-1	3	Expensive, quick response, consumables
Mag torquers	1-2	2	Cheap, slow, lightweight LEO only
Momentum wheel	0.1-1	2	Expensive, similar to dual spin
Reaction wheels	0.001-1	3	Expensive, precise faster slew
CMG	0.001-1	3	Expensive, heavy, quick for fast slew, 3-axes

Gravity Gradient

- Can control two axes passively by design.
- Iz must be much less than the moments of inertia about the other two axes (Ix or Iy)
- This is often accomplished by extending a boom with a tip mass.
- Libration are oscillations about the nominal attitude caused by other disturbances (solar pressure, drag, internal, etc.)
- Passive damping is often used to damp these disturbances
  - viscous dampers
  - mag hysteresis rods (similar to torque rods)
  - eddy current dampers
- Problems with booms
  - can have very flexible frequencies
  - Solar pressure may cause significant, time-varying disturbances.

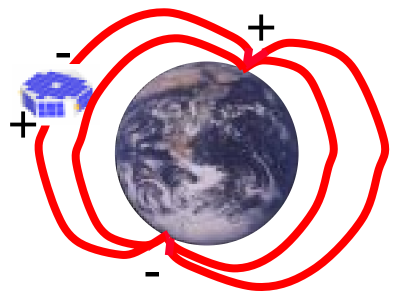


Radiometer Spin

- Caused by a difference in the amount of solar pressure exerted on each side of the spin axis.
- Radiometer spin may be achieved by painting extrusions in alternating black and white patterns.
- Solar pressure produces a greater force on the white sections than on the black sections, creating a small but constant torque.
- This torque causes a slowly increasing spin rate, which may be useful for both stabilization and thermal control.

- Sapphire, Stanford University Performance
  - ½ RPM after 3 weeks in orbit

Permanent Magnetic



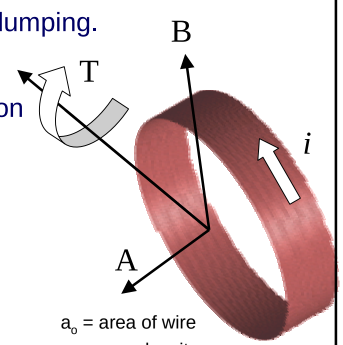
- Add large permanent magnets to the satellite to create a "charge".
- This charge creates a "magnet" that interacts with the magnetic field, much like a compass

Torque Coils and Rods

- Magnetic Torquer (coils or rods) use a current through wires that interacts with the Earth's magnetic field to produce a torque.
- Useful for two-axis control and momentum dumping.
- Does not have to be circular, can be square
- The magnetic dipole moment (M) is a function of the number of turns, current, and area

$$M = NiA$$

$$T = M \times B_{Earth}$$



- The mass, resistance, and power loss are given as

$$m = Nla_0\gamma$$

$$R = \frac{Nl\rho}{a_0}$$

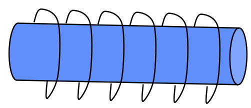
$$P = i^2 R$$

i = Electric current	a_o = area of wire
N = Number of loops	γ = mass density
A = cross-sectional area	m = total mass
B = Earth's magnetic field	R = resistance
l = length of wire	P = power loss

- Requires magnetometer to find sign of magnetic field

Torque Coils and Rods

- The magnitude of B is inversely proportional to r^3, so magnetic torquer control is only feasible in LEO.
- Typical values at 200 km for small s/c are
  - $B = 3\times10^{-5}$ Tesla,
  - $M = 0.1$ Atm^2 (amp-turn-meter^2), and
  - $T = 3 \times10^{-6}$ Nm
- Torque rods are similar, but very thin:



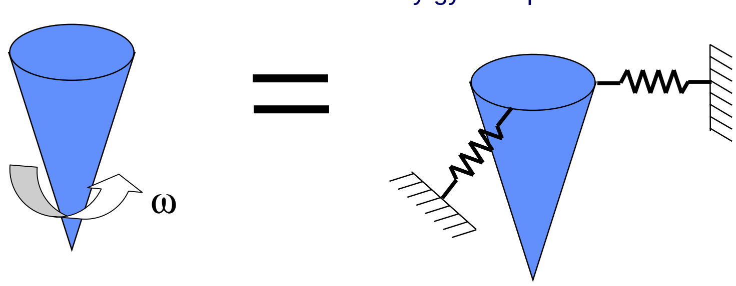
- The magnetic dipole comes from two sources:
  - "solenoid" effect (same as coils)
  - "magnet" effect - a ferromagnetic inner core creates a magnet when charged

Momentum from Spinning

- Many attitude control approaches utilize momentum from spinning concepts
- Consider a spinning top, pinned at the bottom
- For a constant spin rate, the momentum is constant

$$\vec{H} = I\vec{\Omega}$$

which "stiffens" the two cross-axes by gyroscopic effects

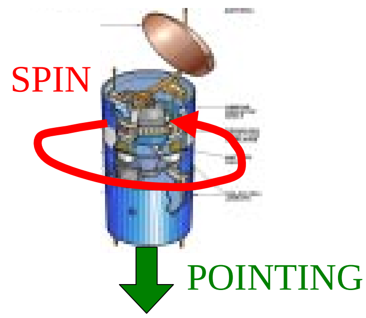


- When external torques are added, the momentum changes (Newton)

$$\vec{T} = \dot{\vec{H}} = I\dot{\vec{\Omega}} = I\vec{\alpha}$$

Spin Stabilized

- S/C is spun about an axis with high moment of inertia.
  - The system is unstable if spun around a lower moment of inertia
- Cannot achieve nadir pointing!
- Controls two axes, with the third in constant rotation
- Nutation angles may be introduced during spin-up or from an internal or external disturbance.
- These angles may be removed within minutes or even seconds by an energy damper (viscous, rods)
- Usually accompanied by a thruster or magnetic coils to keep the satellite spinning

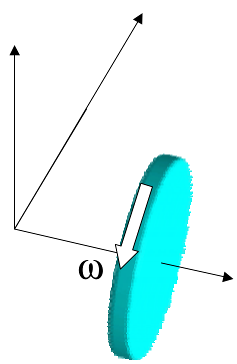


Momentum Wheels

- There are several types of momentum wheels:
- A single biased momentum wheel - stabilizes in two axes using very high speeds

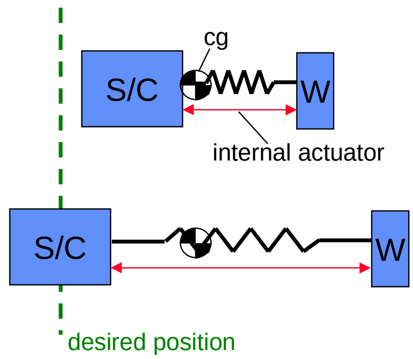
$$\vec{H} = I\vec{\Omega}$$

  this is exactly like the spin stabilized approach
- A zero momentum wheel - stabilizes one axis by changing the rotational rate to produce a torque
- Reaction wheels - three or four (for redundancy) zero momentum wheels
- Control moment gyro (CMG) - one or more wheels on gimbals that rotate



Momentum Dumping

- All wheels produce *internal* torques, which can usually reject the internal disturbances.
- But, the total momentum is never changed by the wheels, only the direction is changed
- Example: Two mass system with a linear internal actuator:

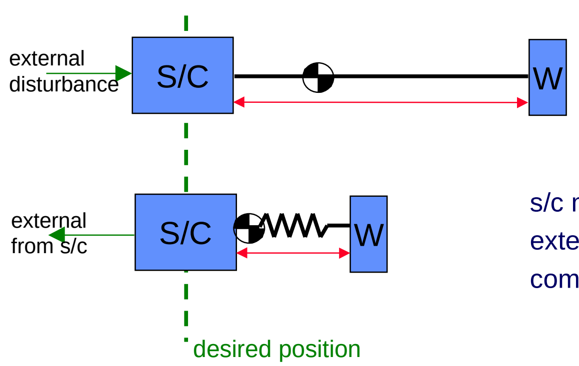


when the s/c position requires change, the internal wheel compensates

note that the cg does not move

Momentum Dumping

- All external disturbances *change* the total momentum, which causes the wheels to spin up to saturation
- Therefore, all wheels must dump this extra momentum periodically, usually using an inertial torque
  - torque coils or rods
  - thrusters

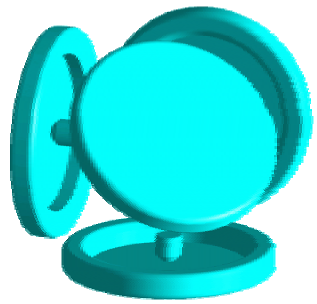


saturation caused by external disturbance

s/c must use an external force to compensate

Reaction Wheels

- Reaction and Momentum Wheels
- Usually at least three zero momentum wheels aligned with each axis
- A fourth is usually includes that is at an odd angle for redundancy

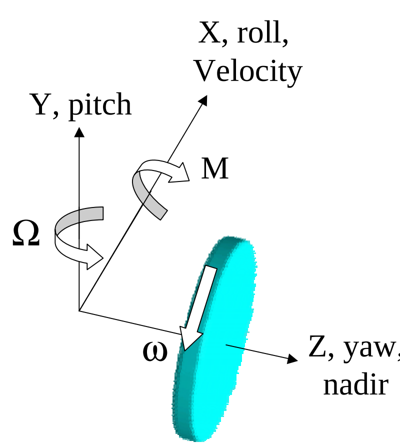


- Good points
  - Precision control
  - No consumables
- Bad points
  - System mass and complexity
  - Gyroscopic effect
  - Momentum dumping

Gyroscopic effect of Momentum Wheel

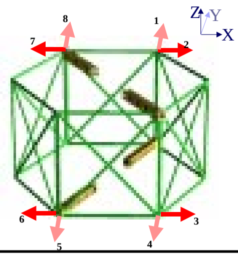
- $M = \Omega \times I\omega$
  - Pitch angular velocity Ω.
    - To remain Earth-pointed.
  - Reaction wheel about yaw.
    - Has angular velocity ω.
- A moment results about the roll axis.
  - Acts to rotate the wheel into the pitch axis, into the orbital plane

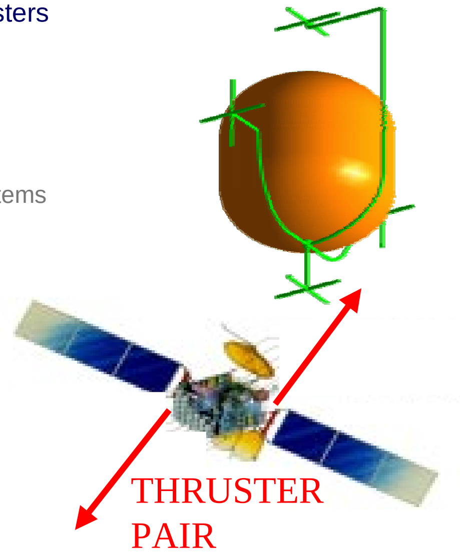
- This can be a disturbance
- or can be used for control (CMG)



Reaction Control System (RCS)

- Active control using multiple thrusters
- Tightly coupled with Propulsion.
  - Propellant and control
- Good points
  - High control authority
  - Reduces number of different systems
- Bad points
  - Consumable propellant
  - Mass of system
  - deadband from on-off type thrust



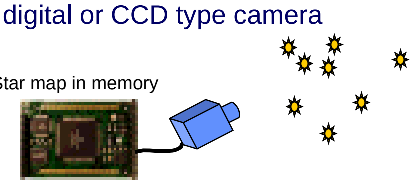


Attitude Determination Summary

Sensor	Accuracy (deg)	Axes	Notes
Sun Sensor	0.1	2	Cheap, simple, reliable, intermittent use.
Horizon Scanner	0.03	2	Expensive, orbit dependant, poor in yaw.
Magnetometer	1	2-3	Cheap, low altitude only, continuous coverage.
Star Tracker	0.001	3	Expensive, heavy, complex, very accurate.
Gyroscope	0.01/hour	3 (vel)	Expensive, drifts with time.

Star Tracker

- Usually a digital or CCD type camera

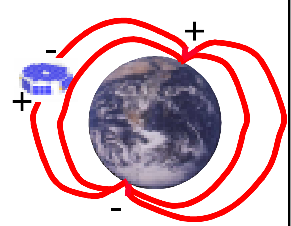


- Locks on to bright stars.
  - Star map in held in computer memory
  - Requires computer time to process map algorithm, match picture with map
  - Provides amazingly accurate pointing knowledge.
- One star identified:
  - Provides two-axis knowledge
- Three or more stars identified:
  - Provide three-axis knowledge
- Sensitive to sun and moon

Magnetometer

- Measures direction of Earth's magnetic field
- Provides good two-axis knowledge, ok with the third axis
- Can use a three axis magnetometer, but is usually only accurate in two axes
- One approach
  - Measure location using GPS
  - Using a Magnetic field model and location, find the model based field
  - Using rotation matrices, find the three angular rotations
- Second approach
  - Couple with initial launch conditions, gyro, and model to find attitude.

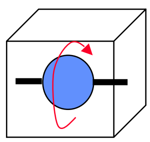
$$\begin{bmatrix} B_{E1} \\ B_{E2} \\ B_{E3} \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta & \\ \cos\theta & \sin\theta & \\ & & 1 \end{bmatrix} \begin{bmatrix} \sin\phi & & -\cos\phi \\ & 1 & \\ \cos\phi & & \sin\phi \end{bmatrix} \begin{bmatrix} 1 & & \\ & \sin\psi & -\cos\psi \\ & \cos\psi & \sin\psi \end{bmatrix} \begin{bmatrix} B_{M1} \\ B_{M2} \\ B_{M3} \end{bmatrix}$$



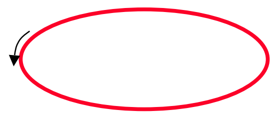
Gyroscope

- Senses rotation rate, not attitude
- Sometimes called inertial measurement units (as are accels)
- Can use three gyros for three axis measurements
- Rate is integrated over time to determine changes in attitude.

- But, gyros drift with time and thus have bias errors
  - Small rates are seen even if none exist.
  - Must be periodically zeroed out by another *inertial* sensor
- Very useful for Detumble and burns
- Examples:



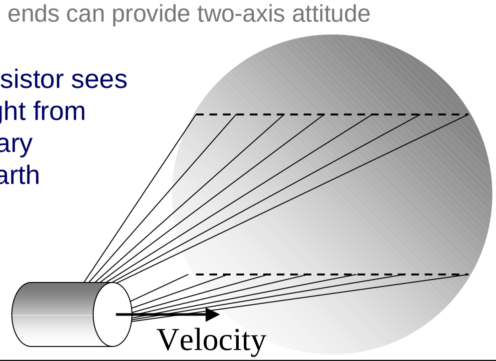
mass on gimbal



ring laser gyro,
where time around
loop and speed of light
are used to calculate rate

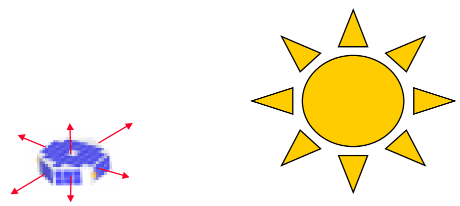
Earth/Horizon sensor

- Distinguishes Earth's horizon, usually by its IR transition or horizon
- Can usually only provide two-axis knowledge
  - Very poor in yaw
- There are multiple types of horizon sensors.
- In a scanning sensor, two beams scan across the Earth, as shown below.
  - The difference in time, the absolute time, and the s/c relative angles at which the scan begins and ends can provide two-axis attitude knowledge.
- An Earth-sensing phototransistor sees the visual and/or infrared light from the Earth and outputs a binary trigger, tripping when the Earth is within the field of view.



Sun Sensors

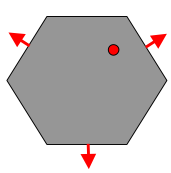
- Determines direction/vector to the Sun
- Provides extremely accurate two-axis pointing knowledge.
  - But: Sun is not always visible in most orbits
- Simplest Example:
  Multiple Photocells give 1 if they see the sun and 0 if they do not

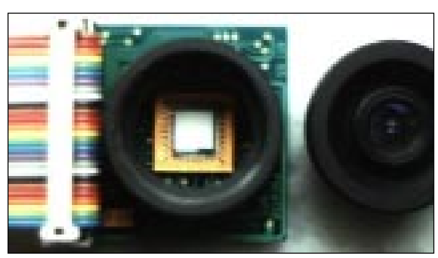


- Solar panels may be used as sun sensors by comparing the voltages produced in panels that are skewed with respect to each other.

Dawgstar: Horizon & Sun Sensors

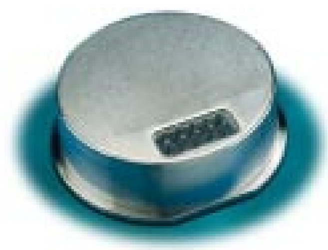
Use four small, cheap digital CMOS cameras
Image horizon and sun

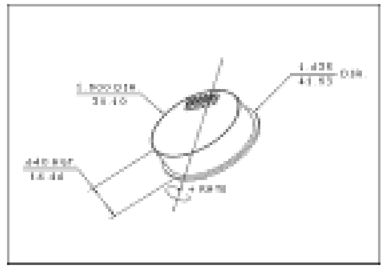




Manufacturer	IMEC Company
Model	Fuga 15d Matrix Sensor
Mass	60 g
Power Consumption	50 mW
Dimensions	45 x 45 x 40 mm

Dawgstar Gyroscope

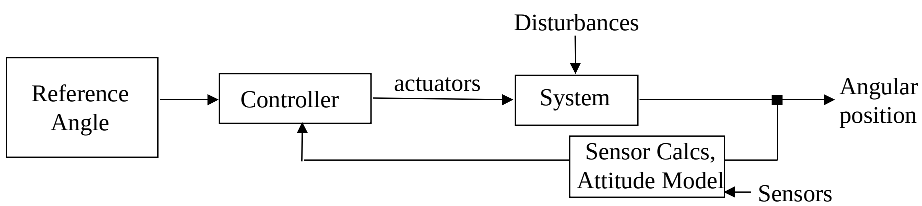




Manufacturer	Systron Donner
Model	QRS - 11
Mass	60 g
Power Consumption	0.3 W
Dimensions	16.46 x 41.53 x 41.53 mm

Control Loop

- For pointing and slow slew maneuvers, the system is modeled as a linear plant.
- Typically use a servo control loop:



- For slow movements, can be designed using three separate axes, linear models
- Nonlinearities, fluid slosh, flexibility must be taken into account for fast slews (and high bandwidth)
  - usually use a Kalman Filter (model based system to estimate “state”)
- Pointing maneuvers are simply that the RefAng = constant
- Slew maneuvers give RefAng as a function of time

Design Approach

1. Define all control modes for all mission modes
2. For each control mode, derive requirements on pointing/maneuvering
3. Quantify the disturbance environment (torques) for each control mode, as well as if they are cyclic or constant
4. Select type of spacecraft control based on system and control mode requirements, disturbance environment
5. Select and size ADCS hardware
6. Define determination and control algorithms