1st APSCO & ISSI-BJ Space Science School

Satellite System Engineering

-- Attitude and Orbit Control System

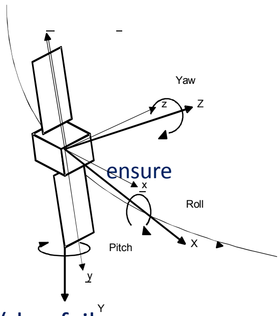
Prof Dr Shufan Wu
Chinese Academy of Science (CAS)
Shanghai Engineering Centre for Microsatellite
Haike Road 99, Shanghai, China
Email: shufan.wu@mail.sim.ac.cn

Introduction

- **Content:**
  - AOCS main requirements and drivers
  - What is considered to be AOCS
  - Process for AOCS design
  - Focus on AOCS Hardware
  - H/W Sizing and Accommodation
  - Miscellaneous

microsat

AOCS requirements & drivers



- **Typical AOCS requirements:**
  - Guarantee pointing control on the 3 SC axes.
    - In order to: perform mission; point SA toward Sun; ensure communication; thermal balance…
  - Guarantee Spacecraft survival after reconfiguration (due failure or anomaly) and after Launcher separation.
    - Avoid batteries discharge (rough Sun pointing); ensure thermal balance…
  - Provide a ΔV to the spacecraft (orbit variation).

microsat

AOCS requirements & drivers

- **Mission specific AOCS requirements (1/2):**
  - Pointing performances *(*)*
    - **APE** Absolute Performance Error → SC absolute pointing error.
    - **AKE** Absolute Knowledge Error → Absolute attitude knowledge error (on board or on ground).
    - **RPE** Relative Performance Error → max SC pointing error vs. mean error over a time interval (pointing stability, microvibration, bending modes).
    - **RKE** Relative Knowledge Error → max SC pointing knowledge error vs. mean error over a time interval.

(*) For further description of pointing error to be considered: see ECSS-E-ST-60-10C (15 November 2008)

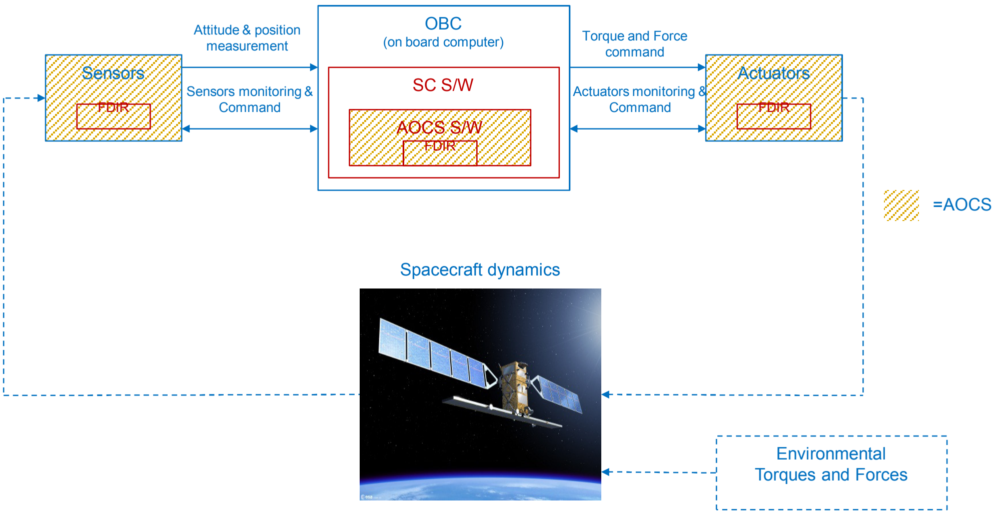
AOCS requirements & drivers

- **Mission specific AOCS requirements (2/2):**
  - Agility performances
    - Perform a rotation of a given amplitude in a given time frame. Pointing performances shall be met at end of rotation. Typical for military SC.
  - Sun Avoidance
    - AOCS shall guarantee a minimum separation angle between payload and Sun direction. → Significant impact on Safe mode approach.
  - ΔV characteristics
    - Total impulse, minimum thrust force, etc.

AOCS requirements & drivers

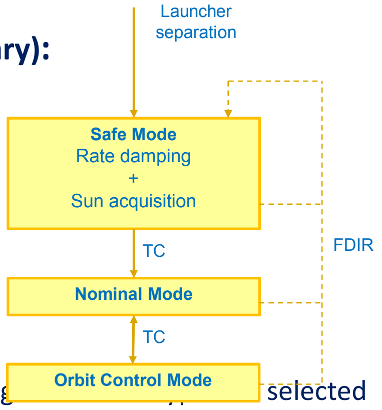
- **AOCS key parameters:**
  - Spacecraft Inertia
    - Impact on external torques (gravity gradient disturbance).
    - Affects dynamics (agility).
  - Orbit
    - Affects external disturbances, eclipse time, magnetic field availability, …
  - Mission lifetime
    - Affects hardware selection

What is considered to be AOCS



Process for AOCS design

- **1. Modes definition (preliminary):**
  - Typical mode architecture:



  - Modes may be added depending … selected hardware (second iteration).

Process for AOCS design

- **2.1 Hardware selection: Nominal mode sensors (1/2)**

Attitude

- Star Tracker (STR) is the preferred choice
  - Best Absolute knowledge performance **<10 arcsec**.
  - Stand alone no other sensor needed (3 axes inertial measurement).
- High accuracy Gyroscope (FOG)
  - In case of stringent RPE/RKE requirement a high accuracy gyro may be selected in addition to STR → gyro vs. gyroless tradeoff to be performed.
  - Gyro improves STR performances only for timeframes **0.1 – 600 sec**

Process for AOCS design

- **2.1 Hardware selection: Nominal mode sensors (2/2)**

- Other sensors
  - Recent improvements in STR robustness (radiation, moon blinding,..) reduced advantages to adopt other sensing architectures (e.g. Earth sensor + Fine Sun sensor + gyroscope).

Position

- GNSS receiver (e.g. GPS)
  - Only for LEO Spacecrafts

Process for AOCS design

- **2.2 Hardware selection: Nominal mode actuators**
  - Reaction Wheel (RW) is the preferred choice
    - Provides accurate torque. Does not provide external torque (*)
  - Control Moment Gyro (CMG) (*)
    - More complex and expensive, generate higher torques than RW with lower mass.
    - For mission with stringent agility requirements → Tradeoff RW vs. GMG.
  - Cold gas Thrusters
    - Limited lifetime, allows very low torque generation with no microvibration
    - For mission with high RPE/RKE requirements → tradeoff RW vs. cold gas

(*) Provide torque storing angular momentum → Unloaded with chemical thrusters or Magnetotorquers (LEO)

Process for AOCS design

- **2.3 Hardware selection: Safe mode sensors**
  - Sun sensor is nearly an obliged choice
    - Allows to determine SC attitude vs Sun direction (2axes inertial meas.).
    - Used for SC and SA Sun pointing.
    - Tradeoff between Coarse Sun Sensor (2axes) vs multiple Cosine Sun sensors (1 axis).
  - Rate sensor
    - Allows to determinate SC angular rate (to be added to the Sun sensor).
    - Used to de tumble the satellite.
    - Outside LEO orbit → Coarse rate Gyro
    - LEO orbit (magnetic field is stronger) → tradeoff Magnetometer vs. gyro.

Process for AOCS design

- **2.4 Hardware selection: Safe mode actuators**
  - Thusters (THR)
    - Preferred choice outside LEO orbit, where magnetic field is weak.
    - Chemical THR:
      - Provides high torque → allows to quickly damp high angular momentum
      - Preferred choice (outside LEO) if control during OCM is performed also with chemical THR.
      - If chemical THR are chosen for Safe mode → a coarse gyro is strongly recommended.
    - Cold Gas THR :
      - Interesting for non LEO satellites using only Electric propulsion for OCM (same tank).
  - Magnetotorquers (MTQ)
    - Preferred choice in LEO, simple and robust architecture.
    - If high inertia or angular rate → Tradeoff 3 MTQ vs. chemical THR

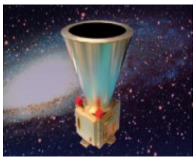
Process for AOCS design

- **2.5 Hardware selection: Orbit control mode Sensors**
  - Same as Nominal Mode
    - If Nom mode uses only STR and a coarse Gyro is used in safe mode
      → gyro can be used for failure detection in OCM

Process for AOCS design

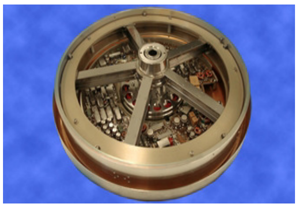
- **2.6 Hardware selection: Orbit control mode actuators**
  - This is a system tradeoff
  - Possible options
    - Perform ΔV with 4 small Chemical THR (1-5 N)
      - 2 options for Attitude control:
        - » THR off-modulation (Switching off a THR provides a torque to the SC)
        - » Use RW → Limited OCM duration (RW saturation), or unload RW with THR off-modulation.
    - Perform ΔV with Electric THR (0.02 – 0.3 N)
      - Attitude control with RW + unloading with THR off-modulation or gimbal on THR nozzle.
    - Perform ΔV with 1 Chemical THR (20 - 400 N)
      - Attitude control with small chemical THR used on-modulation. → GEO telecom
    - Many other options..
  - Choice of OCM actuators affects Safe mode architecture!

AOCS hardware



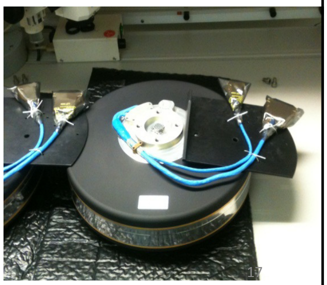
- **Star tracker**
  - Optical Heads (OH) detect Stars → Electronic unit S/W recognizes star pattern and determines inertial attitude.
    - One acquisition mode for initial "lost in space" attitude determination
    - One tracking mode for high-accuracy measurement at high frame rate
  - Absolute knowledge performance **<10 arcsec** (<5 if bias calibration).
  - One OH is sufficient to provide 3 axis measurement, however the bosesight axis is less accurate → 2 OH give best results.
  - If STR is stand alone → 3 STR or at least 3 OH
  - Today STR uses Active Pixel Sensors, which are robust to Moon blinding and radiation (against protons "false stars"). Still blinded by Earth and Sun.

AOCS hardware



- **Reaction Wheel**
  - Provides a torque to the SC around its rotation axis. Receives an equal but opposite torque. Therefore SC and RW accelerate in opposite directions.

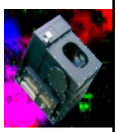
→ RW does not provide an external torque to the system SC + RW
→ The total angular momentum does not change.

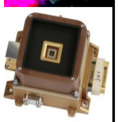


  - Torque: 0.075 - 0.3 Nm
  - Momentum storage: 8 – 60 Nms
  - Weight 5 – 10 Kg

AOCS hardware

- **Other Sensors**
  - Earth Sensor
    - Earth direction measurement (2 axes: Roll pitch). Accuracy: ~0.03° (GEO) - 0.1° (LEO)
  - Sun Sensor
    - Earth direction measurement. Fine Sun Sensor (2 axes) / Coarse Sun sensor (1 or 2 axes).
    - Accuracy: 0.01° - 3°
  - Magnetometer
    - Magnetic field measurement (2 axes). Accuracy: ~0.1° – 1°
  - Gyro
    - Measures angular rate around 1 or more axes
    - Different types: Mechanical gyro, HRG, FOG, MEMS → Very different performances
  - GPS Receiver
    - Filtered position accuracy ~ 10 m





AOCS hardware

- **Other Actuators**
  - Control Moment Gyro (CMG)
    - Based on gyroscopic effect
    - Max Torque 6 - 45 Nm (SC + CMG torque = 0)
    - Angular momentum storage < 15 Nms

$$\vec{T} = \vec{\Omega} \wedge \vec{H}$$

  - Magetotorquers (MTQ)
    - Creates an External Torque by interaction with Earth magnetic field:
    - n = MTQ magnetic moment e.g. 100 Am2
    - B = Earth magnetic field e.g. 10-7 T

    } Torque = 10-5 Nm

$$\vec{T} = \vec{n} \wedge \vec{B}$$

    - Used to control SC in safe mode and unload RW in Nom mode (momentum management)
  - Thrusters → See Propulsion presentation.

Actuators Sizing

- **External perturbation torques: 10^{-6} – 10^{-2} Nm**
  - Gravity gradient
    - Proportional to the difference between the 3 principal axes of inertia
    - Higher values in LEO
  - Solar pressure
    - Depends on distance between centre of pressure and CoG
    - Most important perturbation source for GEO and interplanetary SC
  - Air Drag
    - Depends on distance between centre of pressure and CoG
    - Only in LEO
  - Magnetic
    - Interaction between magnetic field and SC magnetic moment
    - Higher values in LEO

Actuators Sizing

- **Reaction wheel**
  - Typical configuration: 4 RW (1 hot redundancy) → Sizing on 3 RW conf.
  - RW shall be able to:
    - Counteract perturbation torques (10^{-6} – 10^{-2} Nm)

      $T_{RW} >> T_{Pert}$

    - Store angular momentum generated by perturbation during at least 1 orbit

      $H_{RW} > H_{pert\_1orbit}$

    - Provide capability to follow guidance (Yaw steering, slew manoeuvres)

      $H_{RW} > Inertia_{SC} \cdot Max\_angular\_rate_{SC}$

      $T_{RW} > 4\ Inertia_{SC} \cdot Slew\_angle / Max\_Slew\_time^2$

Actuators Sizing

- **Magnetotorquer (MTQ)**
  - Typical configuration: 3MTQ internally redounded
  - In Safe mode:
    - Counteract perturbation torques $T_{MTQ} > T_{Pert}$
    - Damp initial angular rate $T_{MTQ} > Inertia_{SC} \cdot Max\_ang\_rate_{SC} / Damp\_time$
  - In Nom mode (for RW unloading):
    - Integral of T_{MTQ} over 1 orbit > angular momentum generate by perturbation during 1 orbit
- **THR**
  - Thrusters accommodation and sizing is mission specific.

Sensors Accommodation

- **STR accommodation constrains:**
  - Typical configuration: 3 STR (1 hot redundancy) → Accommodation shall take into account the case one STR failure.
  - During converged Safe mode the STR shall be able to see clear sky in order to acquire a measurement.
  - Given Nominal mode guidance, STR Sun and Earth blinding shall be minimized (or even avoided).
  - OCM guidance shall be taken into account as well.
  - A minimum angle (~50°) between the different optical heads shall be guaranteed in order to improve overall AKE performances.

Miscellaneous

- **Controller**
  - Controller architecture has low impact at system level as far as performance requirements are met.
  - Basic rules
    - Structural bending modes (SA, antennas, etc) and tank sloshing with frequency <1 Hz may have an impact on controller design.
    - Agile spacecraft require high frequency controller → can hardly cope with low frequency bending modes.
- **Pointing budget**
    - Typically AOCS pointing budget refers to the STR mechanical interface.
    - Thermoelastic, bias and microvibration between STR and Payload interfaces should be handled at system level.