Spacecraft Mechanisms

Space System Design, MAE 342, Princeton University

Robert Stengel

- One-shot Devices
- Deployable Structures
- Continuous and Intermittently Operating Devices
- Components
- Materials
- Tribology
- Testing and Verification

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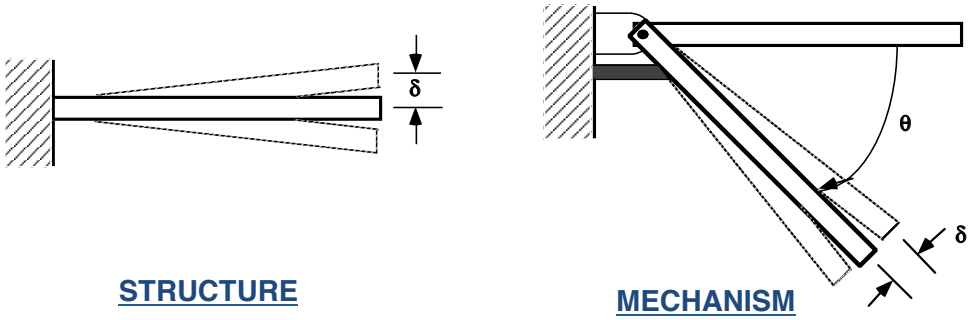
http://www.princeton.edu/~stengel/MAE342.html

Mechanism Functions

- Any device that is required to move, rotate, slide or separate
- Characterized by displacements vs. small displacements of structures
- Scale: quite small ($^1/_4$ inch or less) to very large (100+ ft)
- Often a mechanism functions as structural member prior to, during, or after deployment



STRUCTURE MECHANISM

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When Do Mechanisms Function?

AT LAUNCH
- Electrical and fluid disconnects

DURING ASCENT
- Fairing jettison
- Spacecraft and sub-satellite separation
- Ion thruster gimbals

AFTER ACHIEVING ORBIT
- Doors and covers that open or close
- Solar array, boom and antenna deployments and unfurlments

THROUGHOUT MISSION
- Solar array sun tracking
- Pointing antennas and instruments
- Active doors and shields
- Gyroscopes and reaction wheels
- Fast steering mirrors, optical delay lines

PRIOR TO RE-ENTRY
- Dampers for re-entry and landing forces

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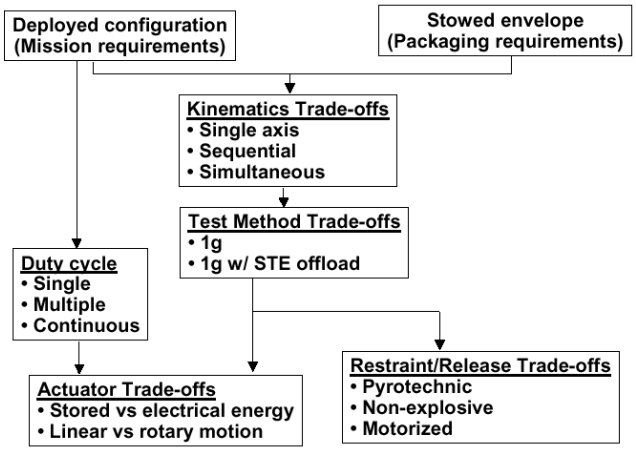
Mechanism Design Guidelines & Selection

- Build in redundancy
- Provide high force/torque margin
- Design to preclude improper assembly or installation
- Allow for visual inspection
- Thermal considerations (materials, clearance, preload)
- Vacuum considerations (outgassing, cold welding, heat dissipation, lube)
- Vibration considerations (potting, positive locking, preload change, wear)
- Cycle life, including ground testing
- Design for ease of analysis and test



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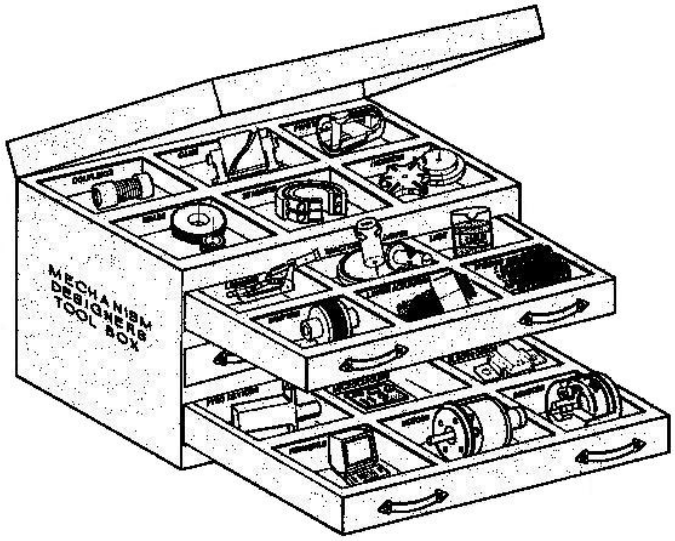
Mechanism Parts

- Bearings
- Lubrication
- Force/Torque
  - Application
  - Multipliers
  - Dampers & Load Absorbers
- Release Devices
- Power & Signal Transfer
- Telemetry Devices
- Extension Devices



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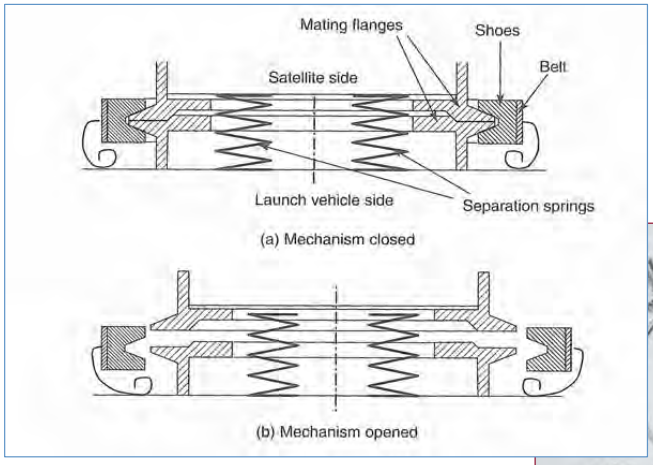
Separation Mechanisms

Marmon clamp



Release Devices

PYROTECHNIC (EXPLOSIVE)

- Cable and Bolt cutters
- Pinpullers and pinpushers

OTHER

- Motor-driven latch
- Non-explosive initiators
  - Pinpullers and pinpushers (non-pyro)
    - Paraffin
    - Shape Memory Alloy

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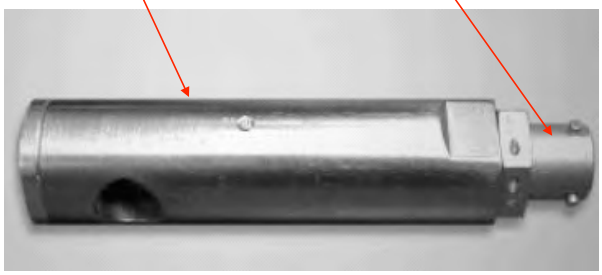
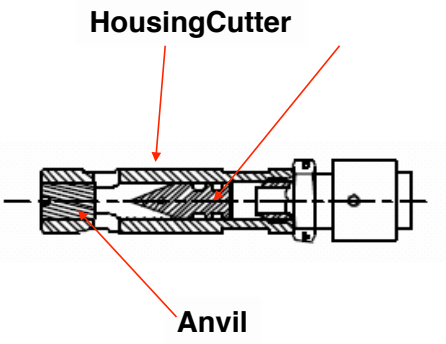
Pyrotechnic Cable and Bolt Cutters

Power Cartridge propels Cutter through the target and into the Anvil

- Cutter Assembly with Power Cartridge





Advantages: fast actuation, high load capability, low weight, simple design

Disadvantages: high shock, safety

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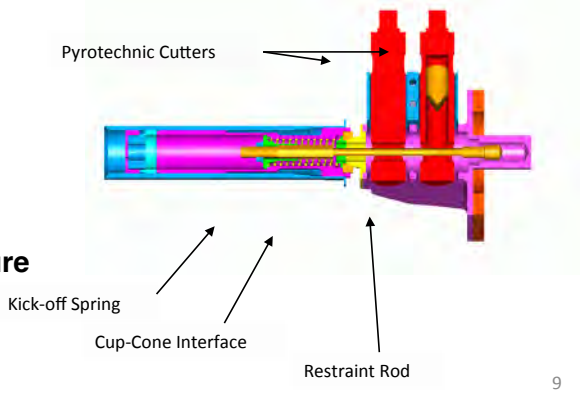
Shear-Tie Release Mechanism

- **Key Features:**
- **Utilized in sets of 3 minimum**
- **Preloaded steel rods and cables prevent gapping of cup-cone interface during ascent**
- **Relative motion between spacecraft and reflector is prevented by cup-cone shear tie seats which react in-plane loads**
- **Redundant pyrotechnic actuated cutters are used to sever restraint rods for deployment**
- **Kick-off washers/springs at each cup-cone interface ensure separation**



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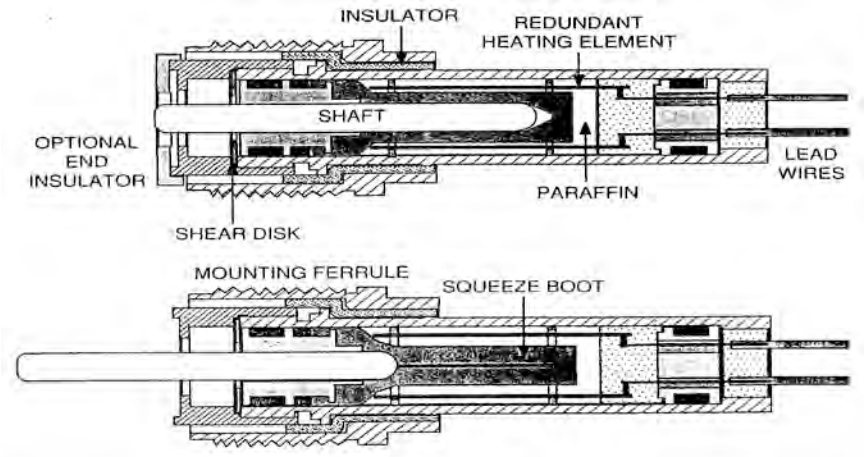
Paraffin/Wax Release



- **Advantages: resettable low weight, uses heater circuit**
- **Disadvantages: low force output and capability, slow actuation, overtemp self actuation**

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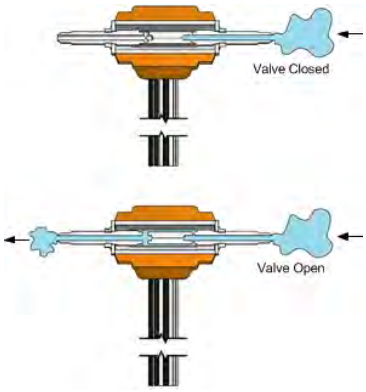
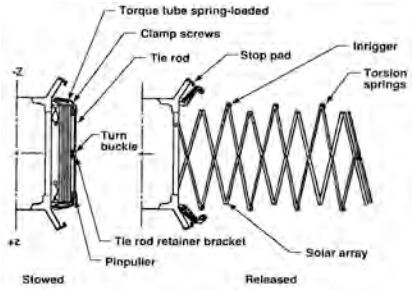
Frangibolt

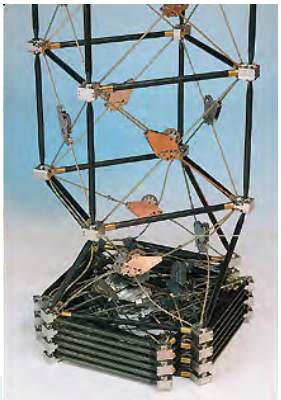
Non-pyrotechnic separation device (for valving)
Use of shape-memory alloy



Extension Devices

- LAZY TONGS
- EXTENDIBLE REEL
- COILABLE MAST
- TELESCOPIC
- INFLATABLE





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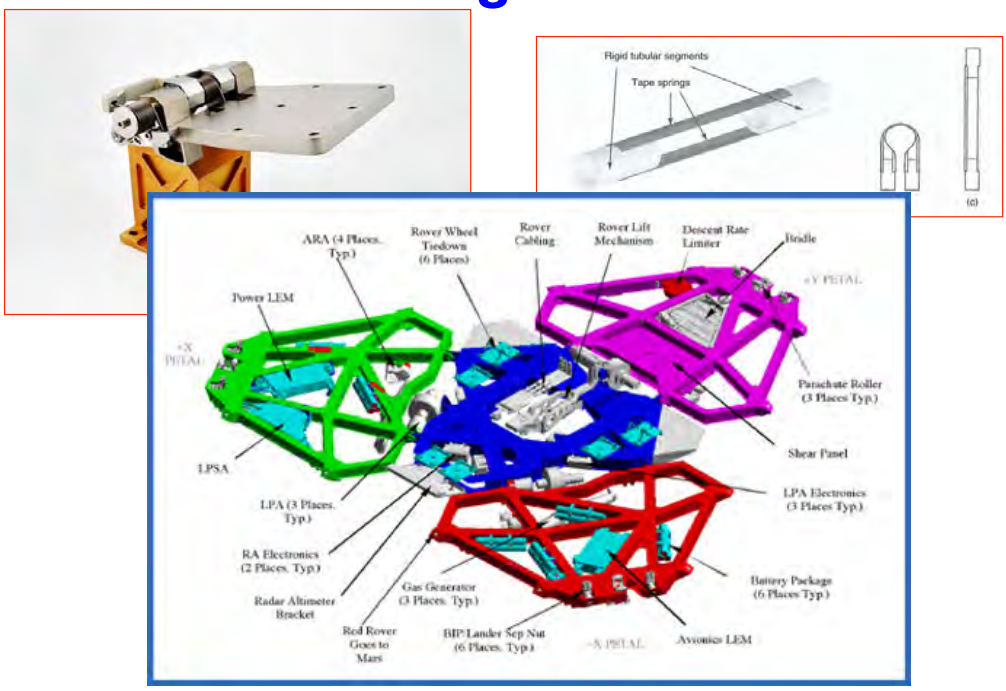
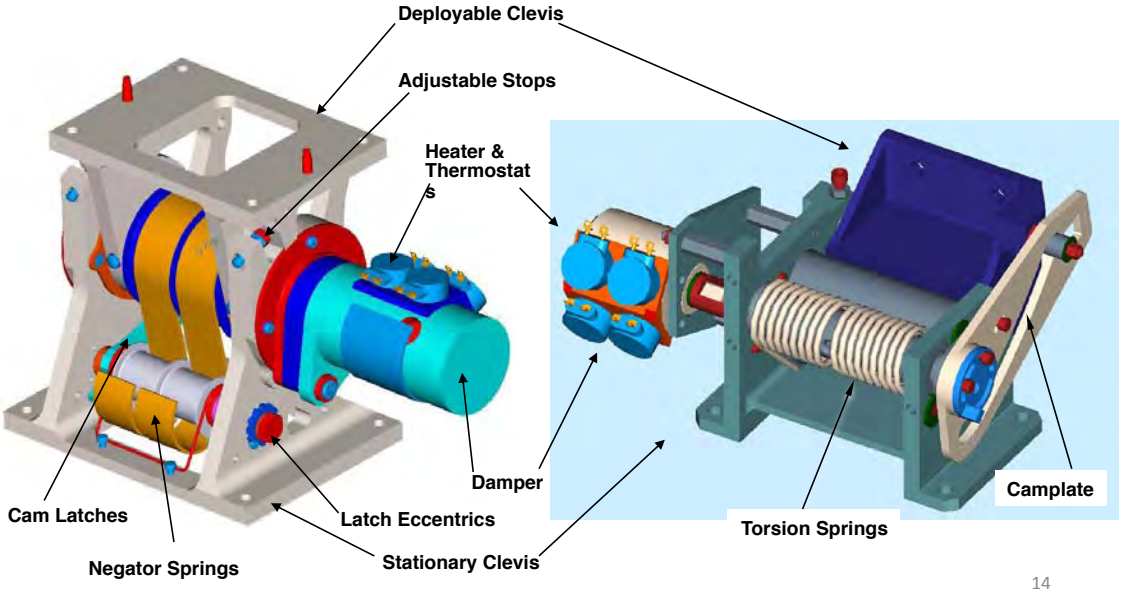
Hinges

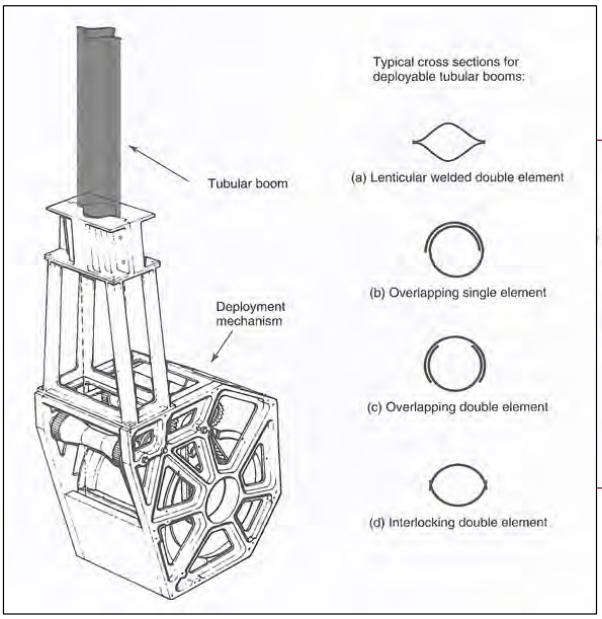


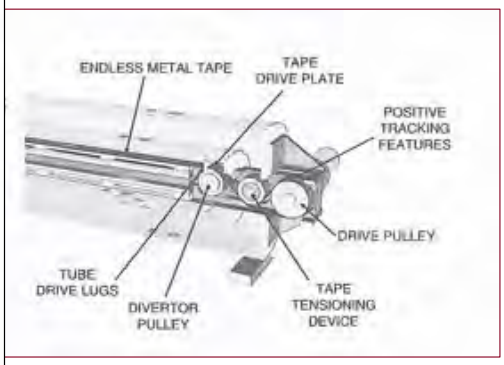
Deployment Hinges

- Redundant spring driven
- Heated viscous damper for rate control
- Preloaded ball bearings or journal bearings
- Hard stops and latches on a large radius for improved deployed repeatability

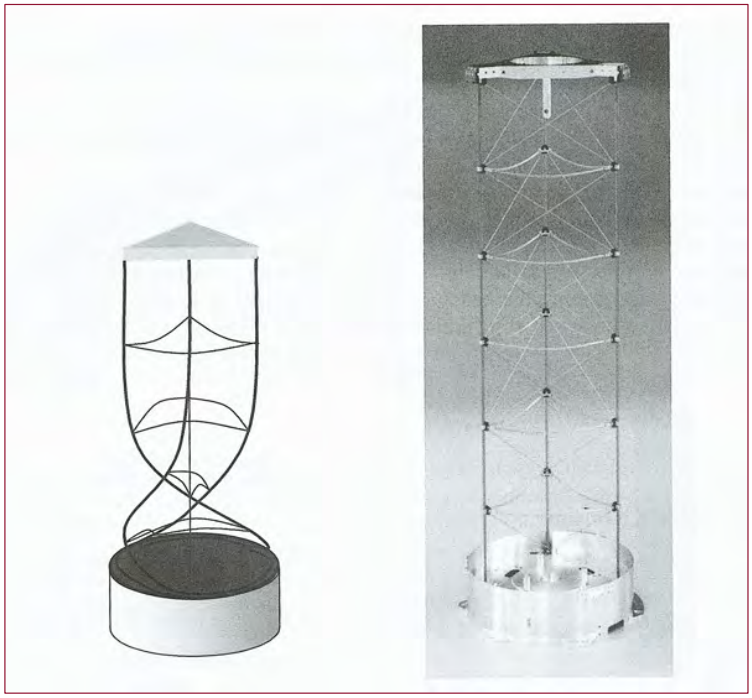


Extendible Tube Mast

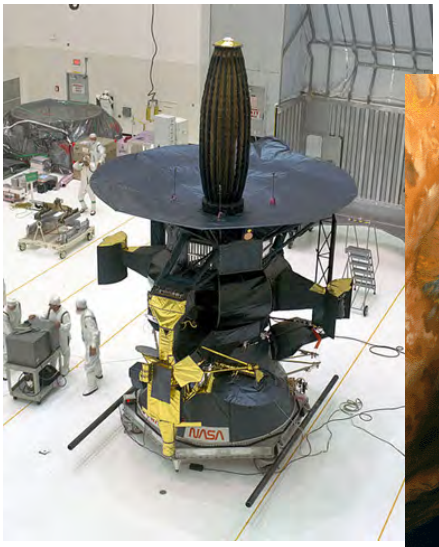




Deployable Camera Mast



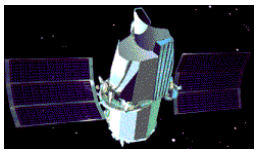
Umbrella Antenna
Galileo Spacecraft

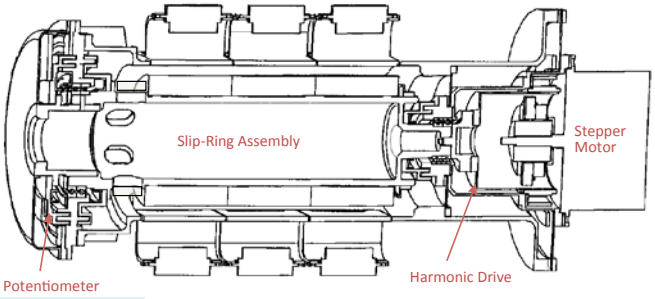


Solar Array Drive Assembly

Usage on S/C:
- 1 location per solar array wing

Key Features:
- Provides precision stepping rotation for sun tracking in forward and reverse directions.
- Provides power transfer across rotating interface between the solar array and spacecraft
- Tracking rate 1 rev/day
- Consisting of:
  - Stepper Motor with redundant windings
  - Harmonic Drive Assembly
  - Fiber Brush Slip Ring Assembly
  - Redundant Potentiometers provide telemetry





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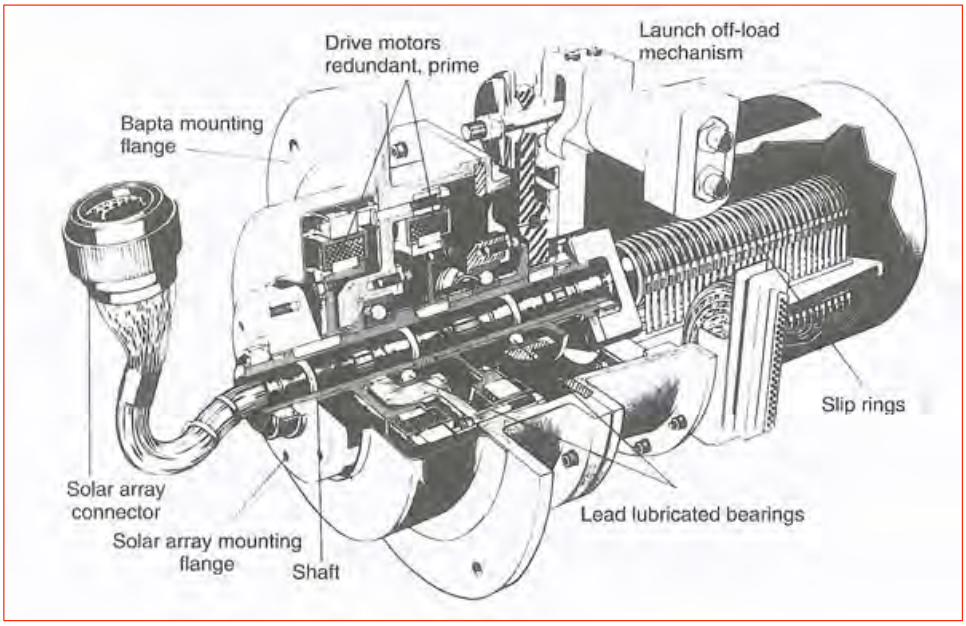
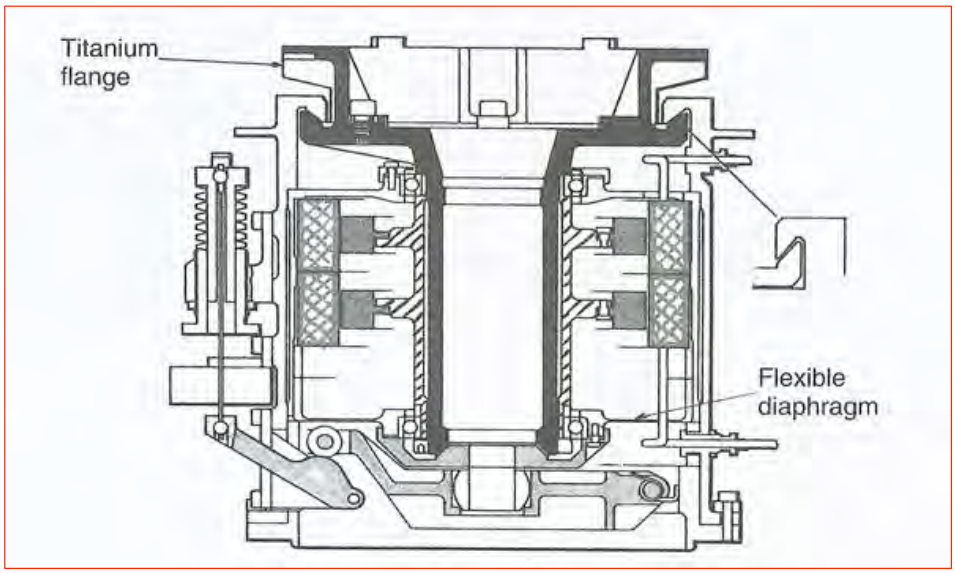
Solar Array Drive



Giotto De-Spin Mechanism

Dual-spin spacecraft



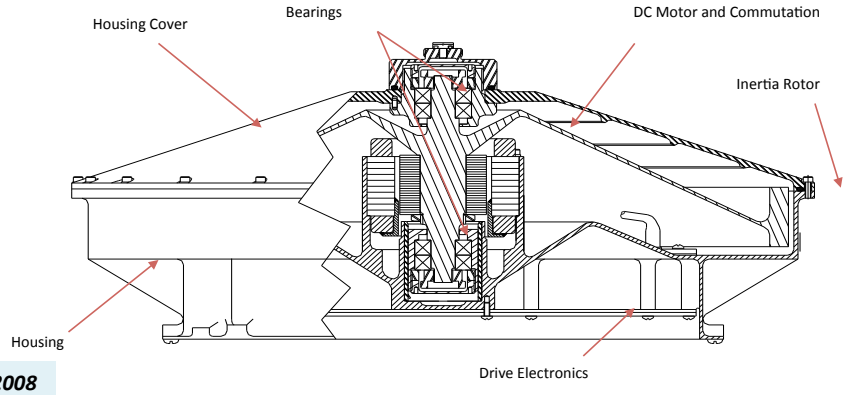
Reaction Wheel Assembly

Usage on S/C:

- Qty (4) per Spacecraft, internally mounted

Key Features:

- Function:
  - Apply reaction torque for three-axis attitude control
  - Bi-directional angular momentum storage
  - Operates at x1000 rpm
- Consist of
  - Drive electronics, brushless motor, and a inertia rotor enclosed within the housing.



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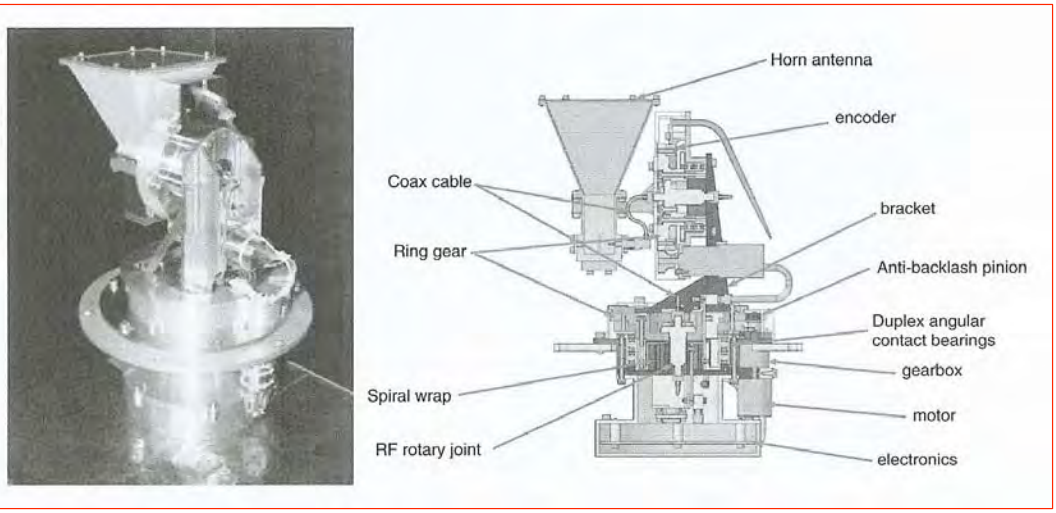
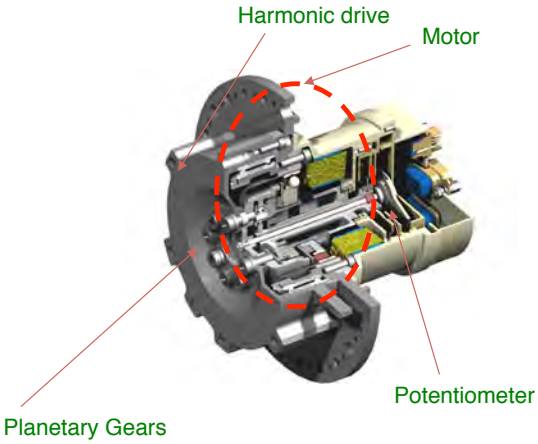
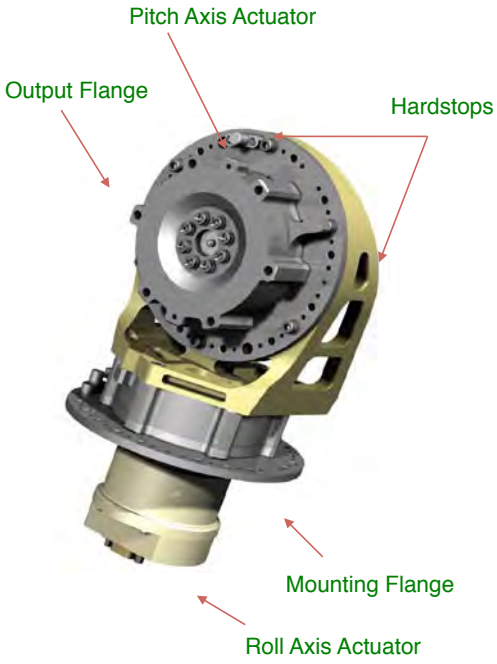
X-Band Antenna Pointing Mechanism



Antenna Gimbal

- **Key Features:**
- **Contains two nearly identical, orthogonally mounted drive mechanisms**
- **Each drive consists of a stepper motor with redundant windings that is coupled to a drive transmission**
- **Redundant course and fine potentiometers for angle telemetry**
- **Heaters and thermal tape on housings**

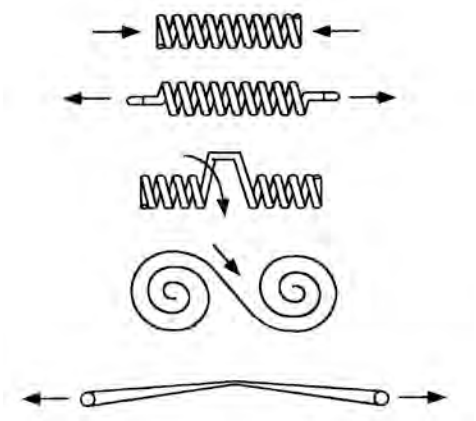


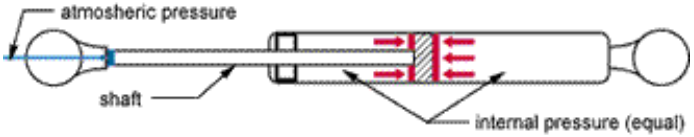


Force/Torque Application

STORED ENERGY
- **Compression spring**
- **Tension spring (not usually used due to its failure mode)**
- **Torsion spring**
- **Constant-force spring (Ne'gator)**
- **Lenticular strut (Carpenter Tape)**
- **Gas pressure – Gas Springs**

ELECTRICAL ENERGY
- **Motors**
- **Solenoids**





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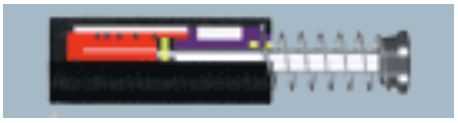
Dampers and Load Absorbers

F = ma; without control, loads would be excessive

DAMPERS
- Rotary and Linear
  - Viscous fluid
  - Induced electrical current

(Eddy current)

LOAD ABSORBERS
- Elastomer Bumpers
- Friction washers – Brake Shoes
- Crushable Honeycomb



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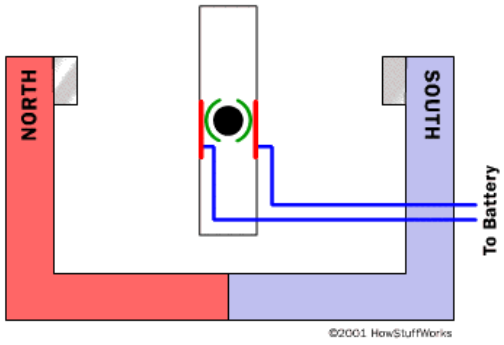
DC Brush Motor

- DC brushed motors
  - Simple electronics: two wires going to motor
  - Low cost
  - Can operate open loop (which is good and bad!)
  - Rapid wear of the brushes (especially under vacuum)
  - Need purging during ambient testing with special brushes
  - Current spikes may occur under vacuum
  - Requires EMI shielding
  - Concern about restart after storage
  - Concern about brushes during vibration
  - Shorting risks due to brush wear debris
  - Used on one-shot deployables



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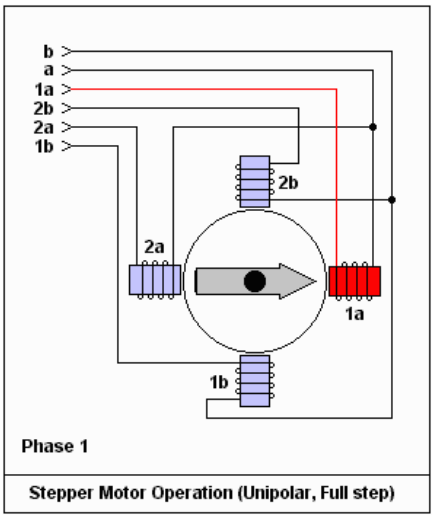
Stepper Motor

Stepper motors (DC brushless)

- –Weight
- –Few wearing parts
- –Simple construction, simple electronics
- –Can operate open loop (which is good and bad!)
- –Each step is a structural excitation - May excite modes of other equipment and structure
- –May have stability problems that depend on friction, damping, and frequency
- –Good unpowered detent torque
- –Used on Lockheed Gimbals and Solar Array Drives



Stepper Motor Operation (Unipolar, Full step)

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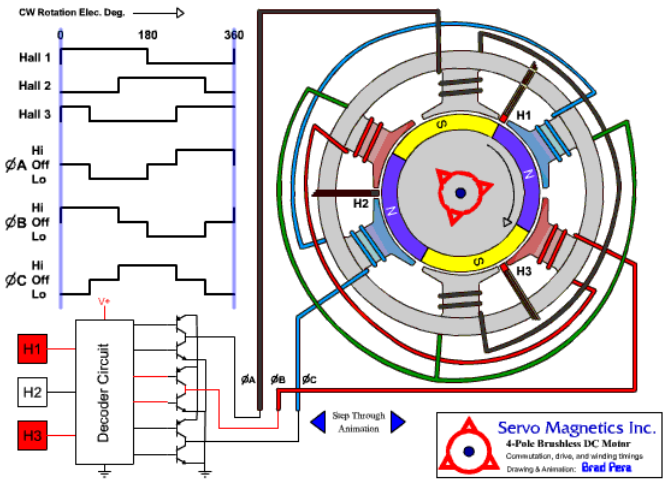
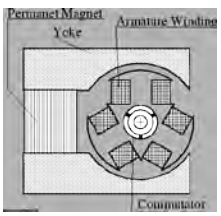
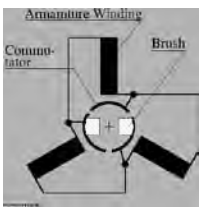
DC Brushless Motor

- **DC brushless torquer motors**
  - – Motion control, torque ripple, life are all advantages
  - – Low vibration
  - – Relatively complex electronics
  - – Commutator reliability
  - – Low unpowered detent torque
  - – Intolerant to stall condition
  - – Used on Lockheed Reaction Wheel Assemblies







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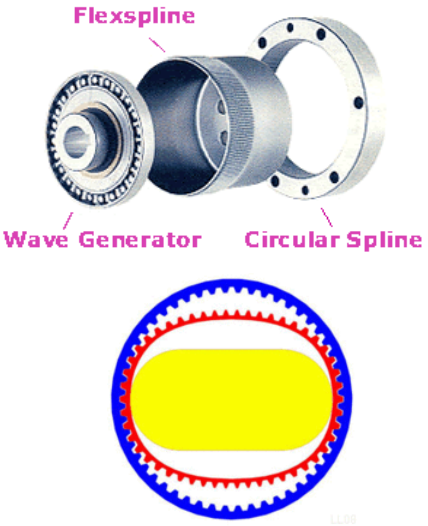
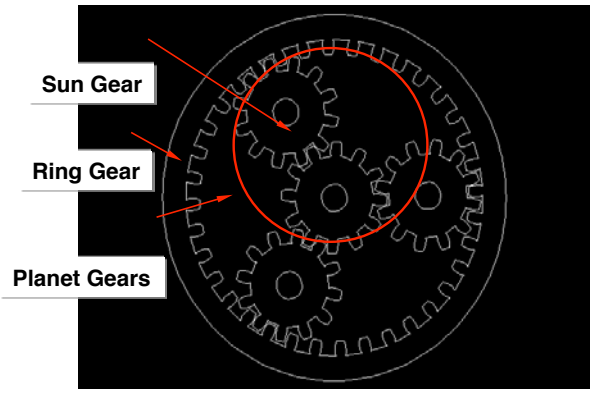
Force/Torque Multipliers

Harmonic Drive



Planetary Gears



Advantages: low backlash, high stiffness
Disadvantages: torque efficiency, torque ripple, fatigue life

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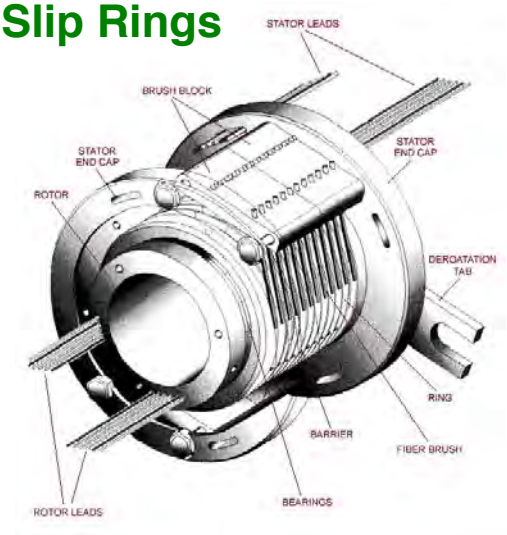
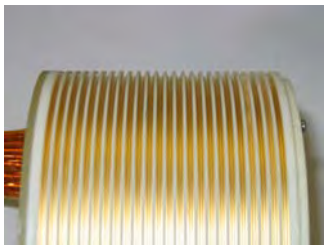
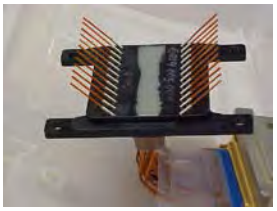
Advantages: torque capability, different gear ratios based on operation
Disadvantages: backlash, wear

Power & Signal Transfer Mechanisms

Slip Rings







Advantages: full rotation, low friction
Disadvantages: failure mode, lubrication issues for long life, signal noise

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Bearing Choices

Bearings (in some form) are used in almost all mechanisms to provide for smooth relative motion

- Journal: Shaft in round or square hole
- Advantages: simple
- Disadvantages: susceptible to small changes in lubrication
- Flex pivot: Beam in bending
- Advantages: low friction, no wear, environment insensitive
- Disadvantages: ± 30° rotation, center shift, low radial load capability
- Rolling element: Ball, Roller, Linear
- Advantages: low friction, combined radial and thrust capability
- Disadvantages: more packaging space radially, expensive

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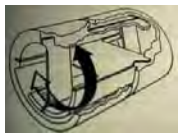
Bearing Choices

- Magnetic: Magnetic levitation
- Advantages: non-contacting, controllable stiffness
- Disadvantages: complex control, poor axial stiffness, high power req'd
- Typical Problems:
- • Torque / force required
- • Performance at temperature and loads
- • Instability
- • Lubrication
- • Strength / fatigue life
- • Stiffness / deadband



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Lubrication

- **Solid films** how applied: bonded (thick), impinged (thin), sputtered (control thin)
  - MoS_2
  - Graphite
  - Tungsten Disulfide
- **Composites & Transfer film**
  - PTFE (Teflon, glass reinforced)
  - Polyimide (Vespel)
  - Polyacetal (Delrin)
  - Polyimide-imide (Torlon)
- **Soft Metals** (ion-plated, ion sputtered)
  - Gold
  - Silver
  - Lead

Issues
Migration
Outgassing
Life
Friction
-Temperature Range

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Lubrication

- **Oils/Greases**
  - Mineral oil (KG-80)
  - Silicones (F-50)
  - Perfluoropolyalkylether (PFPE) (Bray, Krytox, Fomblin)
  - Trialkylated cyclopentane (TAC) (Pennzane)
  - Poly-*α*-olefin (PAO) (Nye 179A)

Issues
Migration
Outgassing
Life
Friction
-Temperature Range

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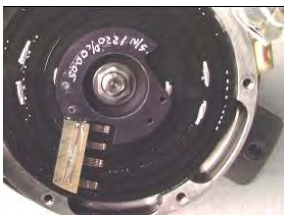
Sensors for Telemetry

- **Potentiometer**
  - small size, weight, easy electronics
  - can be unreliable for large number of cycles
  - single-turn potentiometer
    - multi-turn potentiometer not used often
    - carbon pot (actually graphite in a plastic matrix) essentially infinite resolution, low inductance
  - thermal stability, stair-step linearity (less precise)
- **Resolver**
  - Rotary transformers that provide voltage output proportional to rotation angle
  - No sliding or rubbing parts and low voltage mean high reliability
  - Electronics to drive and interpret resolver can be expensive
- **Encoder**
  - small size, weight (sometimes)
  - low power requirements (but more than a potentiometer)
  - High accuracy / cost

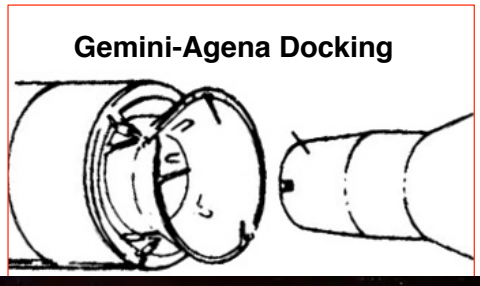


Test of Deployment Mechanisms

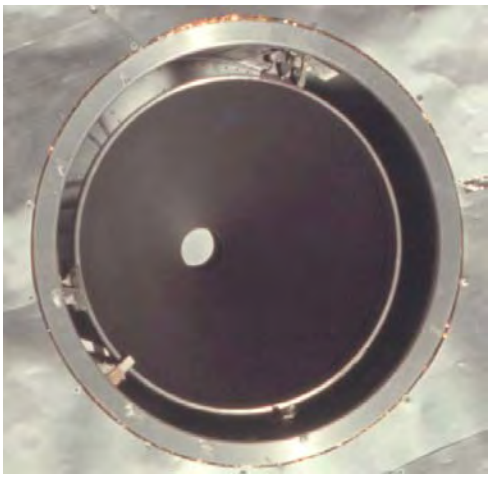
- BALLOONS
  - reflector deployments
- OVERHEAD TRACK
  - solar arrays
- CABLE AND SPRING
  - jettison, booms
- CONICAL PENDULUM
  - booms
- ROCKING BEAM
  - separation
- BALANCE BEAM
  - separation, deployments
- WATER FLOATS
  - masts
- AIR BEARING
  - large deployments
- SERVO-CONTROLLED SUSPENSION
  - unusual motions

Progress and Dragon Docking and Berthing with ISS

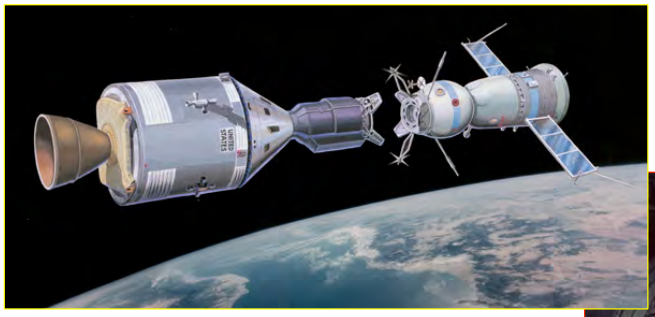
Docking and Berthing Mechanisms

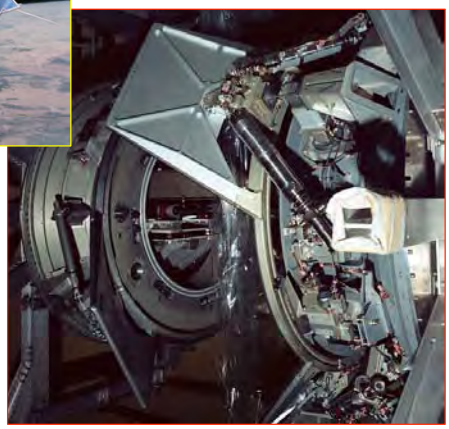


Apollo Probe and Drogue Docking Mechanism

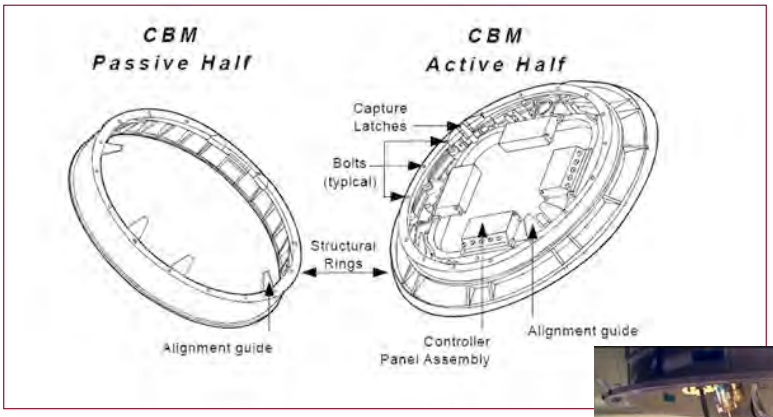


Apollo-Soyuz Docking Mechanism





Future NASA Common Berthing Mechanism



Next Time: Space Robotics