McLean seminar

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6.4. MECHANICAL DESIGN

optical design → mechanical layout

all the optical components are properly mounted, aligned, and stable
→much more difficult than expect

Several issues:

・choice of lens and mirror-mounting schemes
・mechanical and thermal stress on the optics
・alignment of the optics
・flexure and stability under gravity if the instrument moves with the telescope
・ method of attaching to the telescope
・stray light baffles and light-tight enclosures
・moving parts such as focus drives, filter wheel, and shutter mechanisms
・ ease of handling, assembly, and disassembly
・integration of electrical wiring
・cooling systems, thermal paths, and thermal mass

6.4. MECHANICAL DESIGN

Astronomical instruments show various sizes, weights, complexity
→ difficult to generalize
First step = draw a rough layout around the optical components
→ assign real thicknesses and dimensions to support structure (e.g. lens barrel, mirror mounts, filter wheels…)
→ look for "first order" problems (e.g. collisions between components and vignetting)

Example of "first look"

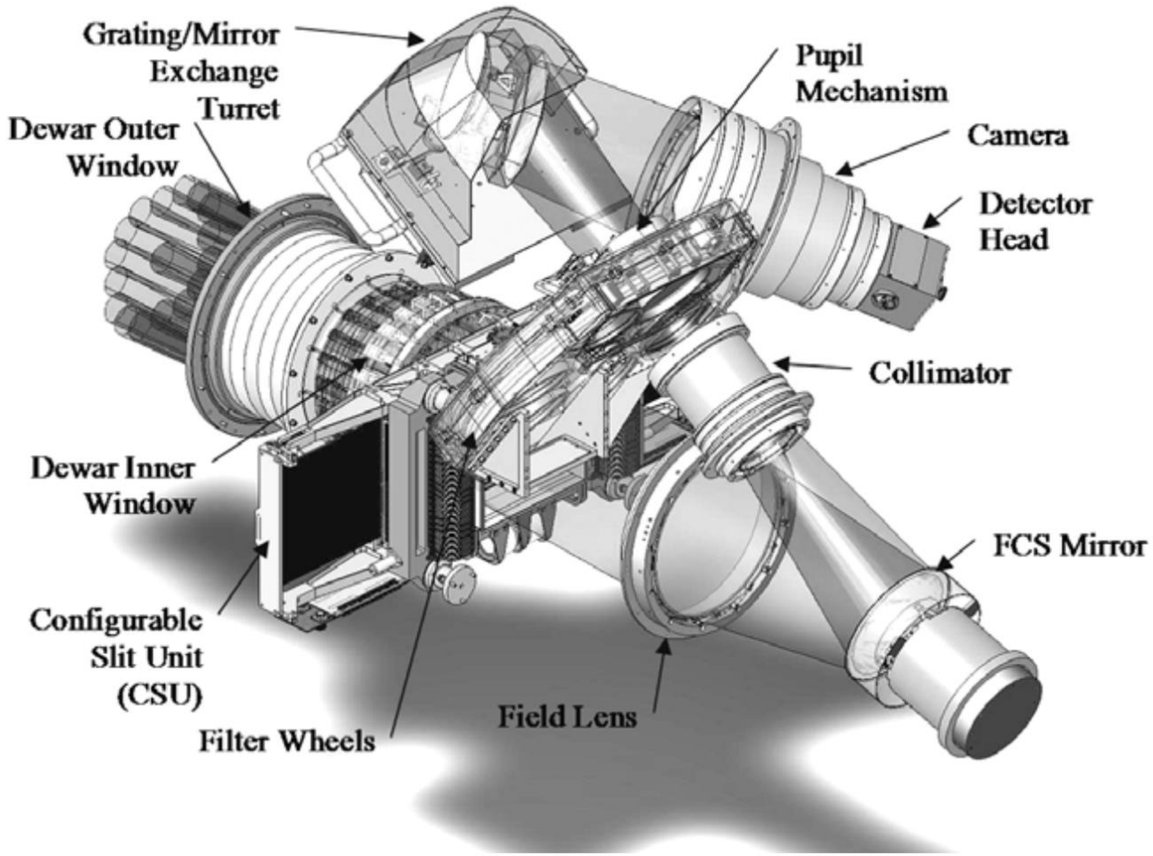
・Estimate the location of the center of mass of the whole instrument.
・Look for poor design arrangements such as a heavy component supported by a horizontal rod which is either too thin or lacks a triangular support strut.
・Try to understand what might bend (flex) as the telescope carries the instrument around.
・Three-point (ball/groove/flat)"kinematic" mounting schemes maybe required to minimize stress and to enable units to be removed and put back in exactly the same place.

6.4. MECHANICAL DESIGN

Affter the first look, a detailed mechanical design can be developed!!

With careful assessment of the dimensions and properties of walls, struts, wheels, bearings, and other support components required to meet specifications on strength, flexure, load bearing, heat flow, and so on.

3-D drawing tools; AutoCad, Solidworks + ray-tracing packages; ZEMAX
→ build the mechanical design around the optical rays and surfaces.



Keck/MOSFIRE
NIR, MOS

6.4.1 Materials and properties

Aluminium → save weight
Steel → handling frame + large rotating bearing
copper, brass, stainless steel, fiberglass materials (G10), and some plastics (Delrin)

total weight limit + "moment" limit (e.g. 227 kg at 1 m from the mounting flange)

How telescope bend/flex as the telescope points to the different parts of sky?
→ important

Instrument not fully enclosed in vacuum chamber → "space frame" (3-D trass) structure is ideal

Box-like strucutres tongued and grooved light-tight fitting joints and triangular gussets and buttresses for added stiffness.

Surface Treatments: External surfaces are anodized for durability, while internal surfaces are black anodized or painted matte black to minimize reflections.

6.4.1 Materials and properties

・basic properties of the materials:

density, coefficient of thermal expansion, Young's modulus, yield strength compression strength, shear strength, heat treatment, hardness, specific heat, emissivity

→ many properties are a function of temperature

→ understanding the range of applicability and an "integrated" effect over the required temperature range is required

6.4.1 Materials and properties

・Stress and Strain Calculations:

Use elementary physics to estimate tensile (stretching) and shear (tangential) stresses (F/A: force per unit area) on various components.

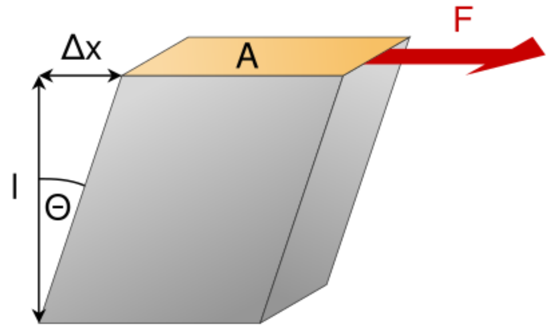
Compare these values with tabulated limits for yield strength and breaking strength.

Yield strength indicates the point beyond which a material will not return to its original shape after force removal.

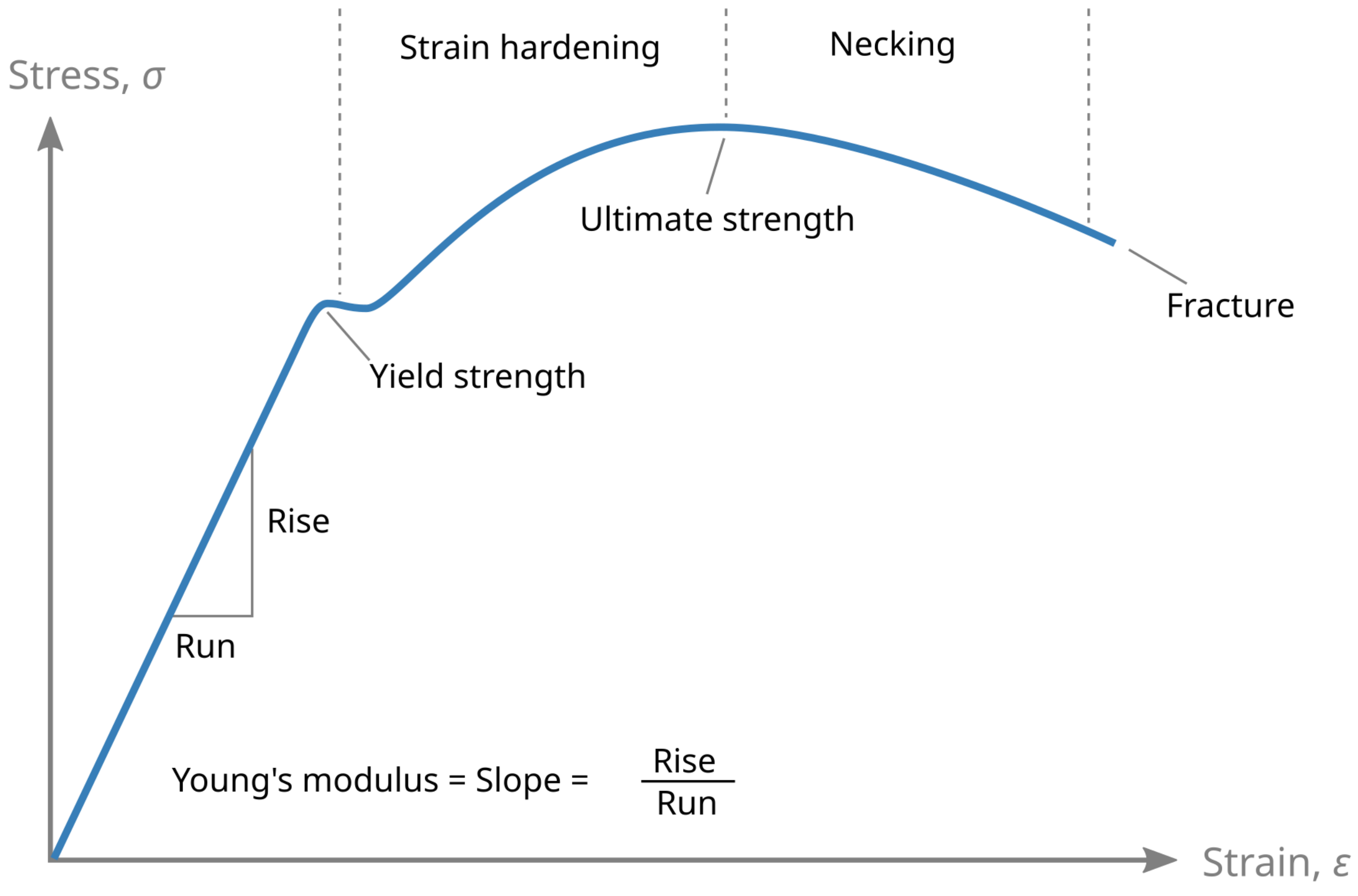
Young's modulus (ヤング率：E), shear modulus (せん断弾性係数、剛性率: S)

$$F = EA\frac{\Delta L}{L}, \qquad F = SA\frac{\Delta x}{h}$$

→ strain ΔL/L and displacement



https://ja.wikipedia.org/wiki/剛性率



https://en.wikipedia.org/wiki/Stress–strain_curve

6.4.1 Materials and properties

・Units of Measurement:
Stress (same unit as pressure) measured in N/m^2 or Pa in the SI system, and in pounds per square inch (psi) in the U.S.

・Finite Element Analysis (有限要素解析、FEA):
Necessary for complex structures;
divides the structure into small elements to simulate stress, strain, and other factors.

・Vibrations: concern for sensitive equipment on a telescope
Hooke's Law: stress is linearly proportional to strain

$$F = kx$$

For a mass m → frequency of harmonic motion $\sqrt{(k/m)}$

Avoid resonance effects by ensuring that the fundamental frequency of the instrument is not close to natural vibration due to closed-cycle refrigerators or other vibration-producing systems

6.4.1 Materials and properties

Aluminum:

・Density: One-third that of steel.
・Electrical Conductivity: 60% of copper's conductivity.
・Specified by four digits and a suffix (T for heat treatment, H for hardness).
  1100-T0: Nearly pure, very soft aluminum.
  6061-T6: Hard, easily machinable, commonly available.
・Welding（溶接）: Heliarc welding (Arc welding in an insert atomosphere) or electron-beam welding（電子ビーム溶接）.
  →Metal weakens near the weld.

Heat Treatments:

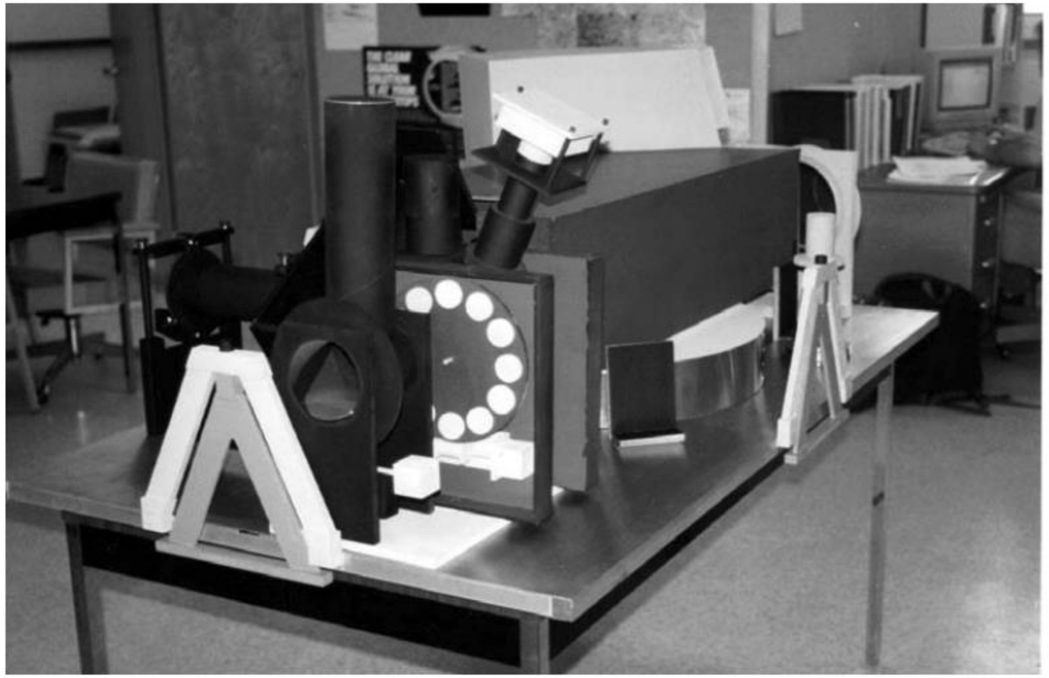
・Annealing（焼きなまし）: Heating and slow cooling.
・Quenching: Rapid cooling.
・Tempering: Reheating to relieve stresses.
・parts to be used at cryogenic temperatures must be "thermally cycleld"
  → to release stresses and eliminate small changes in dimensions "micro-creep"

6.4.1 Materials and properties

Other Materials Used:
・Stainless Steel: Iron, chromium, nickel alloy, non-magnetic, common in the 300 series.
・Invar: Iron-nickel alloy, very low thermal expansion.
・Copper: Soft, but best thermal and electrical conductor
→thermal heat sink/ cold block for the chip in cooled CCD
→OFHC (oxygen-free high conductivity) copper is preferred.
・Brass: Copper-zinc alloy, limited use in modern instruments.
・Fiberglass (G-10): Used for thermal isolation in vacuum-cryogenic applications.
・Dupont （デュポン社）plastic（Vespel）: impregnated with molybdenum disulfide (MoS_2).

6.4.1 Materials and properties

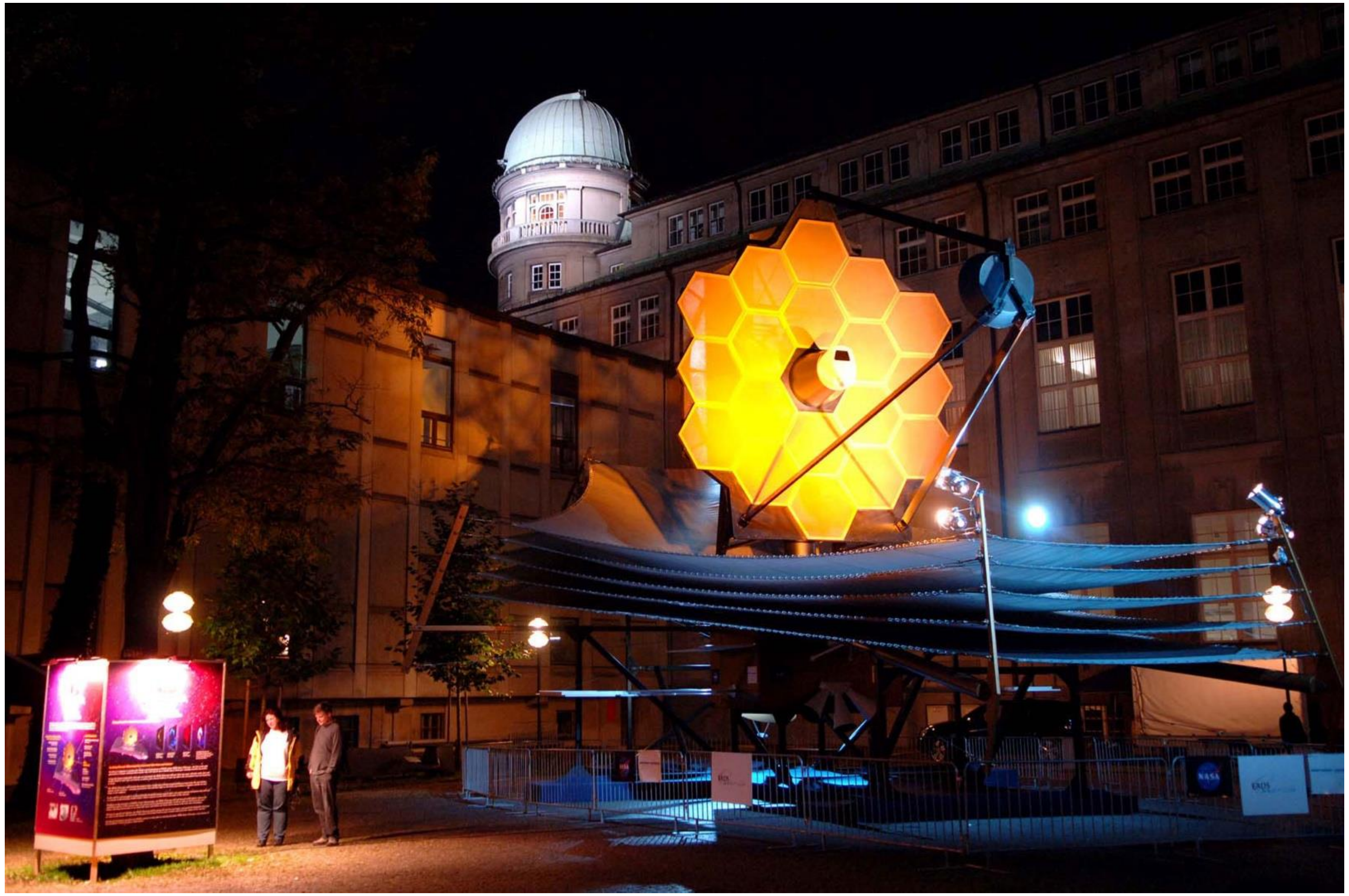
Modeling Techniques:
・3D Modeling Software: Visualizes how parts fit together.
・Space Models: Full-size replicas using lightweight materials to identify design flaws and assembly challenges.
・Example: NIRSPEC instrument model for the Keck telescope.



Problems
(i) the order of assembly
(ii) optical alignment and verification
(iii) location and installation of baffles
(iv) electrical wiring and connectors
(v) cooling paths
(vi) general handling fixtures.

James Webb Space Telescope full-scale model in Dublin, Ireland, in June 2007.

https://hubblesite.org/contents/media/images/2013/10/3158-Image.html?news=true



6.4.1 Mechanisms

Filter wheel

・Filters are located in a parallel beam close to to the pupil

→ minimize size, reduce influence of dust/scratches on filter, eliminate any focus shift

・Filters placed in divergent beams

→ larger, optical path (nd) need to be balanced to ensure no change in focus

・N filters → minimum diameter of wheel ~ ND_pupil / π

・How to drive filter wheel? → There are 2 methods

1. Direct drive shaft through the center of the wheel

→ require intermediate gearing to yield some mechanical advantage

2. Edge drive using gear around the perimeter

→ using warm gear, very large mechanical advantage (gear-ratio)

6.4.1 Mechanisms

Rotating shaft can be driven by DC servo motor or stepper motor（ステッピングモーター）

・DC servo motor runs continuously until stopped

・Stepper motor only moves when commanded to do so by receiving a pulse

→can be operated "open loop" (= non-feedback) and position of wheel can be determined by counting pulse

・dealing with "backlash" → rotate one direction / mechanically spring-loaded (pre-loaded)

6.4.1 Mechanisms

Worm-Driven Wheel:

•**Stepper Motor and Worm Shaft:**

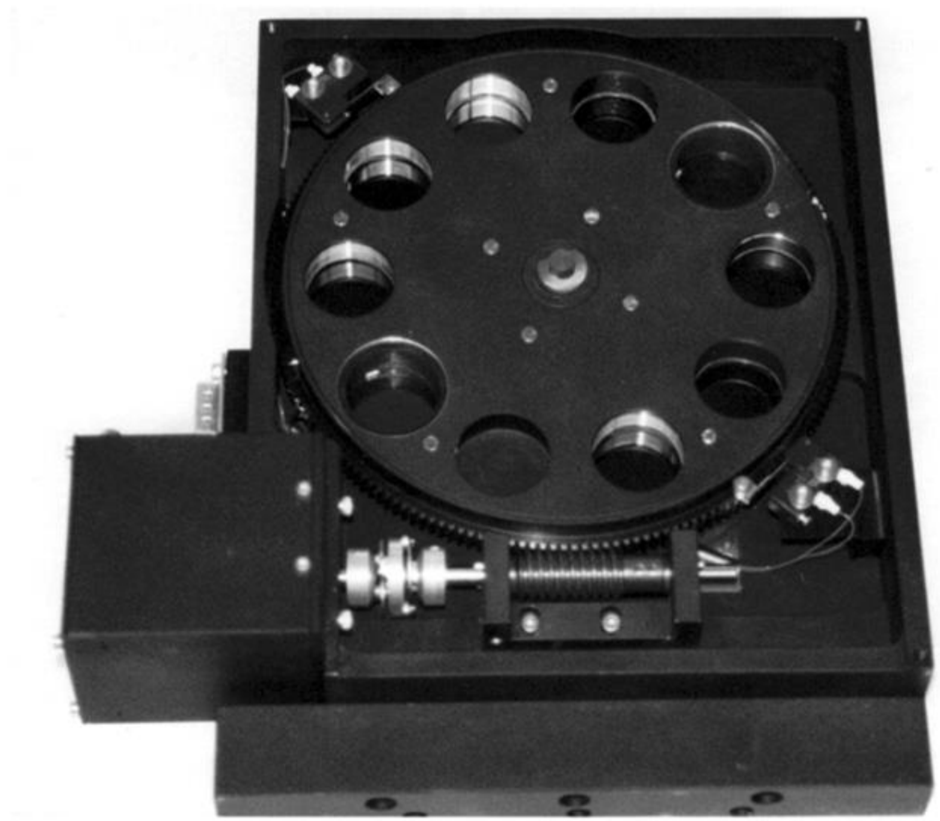
- Stepper motor shaft is attached to the worm shaft via a flexible wafer coupling. This compensates for misalignment and differential thermal contraction.

•**Gear Ratio and Resolution:**

- Worm threads have a small pitch, preventing rotation by turning the wheel, making it safe to switch off the motor without losing position.
- When driven in "half-step" mode (400 steps per turn), a motor directly attached to the filter wheel hub moves the filter center by 0.016R per step.
- For a worm-driven wheel with 180 teeth, the motor achieves a finer resolution, with 72,000 steps per full turn (0.004° or 4 microns per step for R = 50 mm).

•**Closed-Loop System:** Uses continuous absolute position encoders or discrete encoding (e.g., micro-switches) for precise positioning.

•**Open-Loop System:** Relies on step counting from a reference ("datum") position, suitable for cryogenic conditions but requires multiple datum points for reliability.



6.4.1 Mechanisms

Challenges in Infrared Instruments:
Cryogenic Temperatures:

- All components, not just the detector, are cooled.
- Differential contraction of plastic and metal mounts can cause alignment issues.
- Stainless steel ball and roller bearings must be degreased; a dry lubricant (e.g., molybdenum disulphide, MoS_2) is burnished onto bearings.

Degreasing Process:

1. Pop the seal on bearings.
2. Place in a beaker of ethyl alcohol for 5 minutes to loosen grease.
3. Use an ultrasound bath for 30 minutes to dissolve grease.
4. Rinse individually with alcohol, dry with dry nitrogen gas, and store in sealed plastic bags to maintain cleanliness.

- **Handling Considerations:**
  - Design instruments with built-in handles and feet for safety.
  - Plan for lifting mechanisms and appropriate storage containers to prevent damage and ensure ease of transport.

These slides condense the information into key points, making it easier for the audience to grasp the complexities involved in designing and operating worm-driven wheels and handling infrared instruments.