DRAFT

PRECISION MECHANISMS FOR SPACE INTERFEROMETERS
A TUTORIAL

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OUTLINE

1. MOTIVATION

20 ACTUATOR COMPONENTS

3. DESIGN EXAMPLES

4. TIPS FOR SPECIFYING ACTUATORS
1. MOTIVATION

- There is a strong correlation between the quantity and quality of science from space-born interferometers, and the number of moving parts on the spacecraft.
  - More baselines (and trolleys) = more star comparisons
  - Steerable mirrors enables better pointing accuracy, fainter targets
  - Articulated solar panel enables greater sky coverage.

- New NASA philosophy: “It’s the price, stupid.”

- Moving parts are expensive, and therefore not strongly compatible with this philosophy.

- To maximize salability, spaceborne interferometer designs must minimize actuator cost while maximizing science quality and quantity.

- Interferometer designers must have the knowledge to design a system with the simplest, most reliable, and least expensive actuators possible.
2. ACTUATOR COMPONENTS
ACTUATOR COMPONENTS

2.1 BEARINGS

- Devices which *predictably* constrain motion in some axes, allow motion in others.

- The best, most commonly used bearings for precision space applications are:
  - Angular-contact ball bearings
  - Flexures

- The most promising future bearing technology is:
  - Magnetic suspensions
2.1.1 Angular Contact Ball Bearings

- Duplex pair before preload
- Preloaded Back-to-Back, or DB: Resists cross-axis moment
- Preloaded Face-to-Face, or DF: Does not resist cross-axis moment
2.1.1 Angular Contact Ball Bearings

Insert drawing of Dahl Friction

Equation

Rules of hysteresis loops.
2.1.2 Flexures

insert drawing
## 2.1 Bearing Comparison

<table>
<thead>
<tr>
<th></th>
<th>Ball Bearing</th>
<th>Flexure</th>
<th>Magnetic Suspension</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range of motion</strong></td>
<td>Continuous</td>
<td>&lt;±10°</td>
<td>Continuous</td>
</tr>
<tr>
<td><strong>Stiffness of constrained axes</strong></td>
<td>Highest, predictable</td>
<td>Predictable</td>
<td>High but bandwidth-limited, predictable</td>
</tr>
<tr>
<td><strong>Axis of rotation precision</strong></td>
<td>Runout as small as 0.0001&quot;</td>
<td>Moves with rotation</td>
<td>Equivalent to ball bearing</td>
</tr>
<tr>
<td><strong>Friction, torsional stiffness</strong></td>
<td>Dahl friction, difficult to predict</td>
<td>Predictable torsional stiffness, increases with load capability.</td>
<td>Virtually zero friction and torsional stiffness</td>
</tr>
<tr>
<td><strong>Life</strong></td>
<td>Prediction based on previous experience</td>
<td>Can be designed for infinite life</td>
<td>Limited by electronics only</td>
</tr>
<tr>
<td><strong>Temperature range</strong></td>
<td>Limited</td>
<td>Widest</td>
<td>Wide</td>
</tr>
<tr>
<td><strong>Contamination</strong></td>
<td>Lubricant must be contained</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Wide variety of sizes, configurations</td>
<td>Generally requires custom design</td>
<td>No NASA flight heritage</td>
</tr>
</tbody>
</table>
2.2 Prime Movers

- Common prime movers for precision flight actuators:
  - DC brushless motor
  - Stepper motor
  - Voice coil
  - “Smart Materials” (piezoelectric, electrostrictive, etc.)
2.2.1 DC Brushless Motors

**Square-Wave Commutation**

\[ \tau_{\text{total}} \approx I_1 K_T \cos(\theta) + I_2 K_T \sin(\theta) \]

**Sinusoidal Commutation**

\[ l_1 = I \cos(\theta), \quad l_2 = I \sin(\theta) \]

\[ \tau \approx I K_T \]

High resolution angle knowledge required, Torque ripple \( \approx 0 \)

\( \theta \)
## 2.2 Motor Comparison

<table>
<thead>
<tr>
<th></th>
<th>Brushless motor</th>
<th>Stepper motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion increment</td>
<td>Continuous</td>
<td>1.6 rads to 26 mrads per mechanical step, 125 urad per microstep</td>
</tr>
<tr>
<td>Power efficiency</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Holding torque</td>
<td>Requires power</td>
<td>Passive detents at mechanical steps</td>
</tr>
<tr>
<td>Rate stability</td>
<td>Smooth</td>
<td>Inherently poor</td>
</tr>
<tr>
<td>Torque modelability</td>
<td>Easy to model</td>
<td>Difficult to model</td>
</tr>
<tr>
<td>Open-loop operation</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Mechanical impedance</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Electronic Complexity</td>
<td>Complex</td>
<td>Simple</td>
</tr>
</tbody>
</table>
2.3 Displacement Sensors

Common displacement sensors for precision flight actuators:

- Resolver
- Inductosyn™
- Optical encoder
- Potentiometer
- Linear (or Rotary)-Variable Differentiator Transformer (LVDT / RVDT)
2.3.1 Resolver, Inductosyn™, and LVDT

An Inductosyn is a multi-pole “pancake” resolver with printed windings.

- Up to 1024 poles/rev available.
- Absolute knowledge obtained with an additional single pole winding, or correlation between an N-pole and an N-1 pole winding.

An LVDT is similar to a resolver, with a moving core and fixed windings.
### 2.3 Sensor Comparison

<table>
<thead>
<tr>
<th></th>
<th>Resolver</th>
<th>Inductosyn™</th>
<th>Encoder</th>
<th>Potentiometer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>&lt;100 μrad</td>
<td>&lt;1 μrad</td>
<td>25 μrad</td>
<td>10 mrad</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>Highest</td>
<td>Low</td>
<td>High</td>
<td>Lowest</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>High</td>
<td>Highest</td>
<td>Low</td>
<td>Lowest</td>
</tr>
<tr>
<td><strong>Integration with motor</strong></td>
<td>Simplest</td>
<td>Requires tighter alignment than resolver</td>
<td>Separate assembly connected by flexible coupling</td>
<td>Separate assembly connected by flexible coupling</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>High</td>
<td>High</td>
<td>Limited by LED</td>
<td>Subject to electrical noise and wear</td>
</tr>
<tr>
<td><strong>Signal transfer</strong></td>
<td>Requires rotary transformer or leads</td>
<td>Requires rotary transformer or leads</td>
<td>None</td>
<td>Requires brushes</td>
</tr>
<tr>
<td><strong>output</strong></td>
<td>Analog sine &amp; cosine or digital word</td>
<td>Digital word</td>
<td>Digital word or quadrature pulses</td>
<td>Analog</td>
</tr>
<tr>
<td><strong>Electronics complexity</strong></td>
<td>Complex</td>
<td>Most complex</td>
<td>Simple</td>
<td>Simplest</td>
</tr>
</tbody>
</table>
Actuator Components

2.4 Transmissions

- Common mechanical transmissions for precision flight actuators:
  - Spur gears
  - Planetary gears
  - Harmonic drive
  - Ball screw/roller screw
  - Band drive (rotary to linear, rotary to rotary)
2.4.1 Harmonic Drive

Actuator Components

Flex Spline (output) with N-2 teeth

45° rotation of Wave Generator

180° rotation of Wave Generator

Circle Spline (fixed) with N teeth

Wave Generator (input)

Characteristic Error

Frequency: Twice per input revolution

Hundreds of mrads

1 output revolution

Gear Ratio = -N/2 :1

Flex Spline rotates 1 tooth in opposite direction for 180° of Wave Generator rotation
2.4.2 Ball and Roller Screws

Actuator Components

Figures courtesy of SKF
2.4.3 Band Drive
### Actuator Components

#### 2.4 Comparison of Transmissions

<table>
<thead>
<tr>
<th></th>
<th>Gear train</th>
<th>Harmonic Drive</th>
<th>Ball/roller screw</th>
<th>Band drive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Advantage</strong></td>
<td>Nearly any ratio</td>
<td>60:1 to 200:1</td>
<td>up to 2 mm/rev for ball screw, up to 1 mm/rev for roller screw</td>
<td>Not much greater than 10:1</td>
</tr>
<tr>
<td><strong>Lost motion</strong></td>
<td>Anti-backlash gears available</td>
<td>Gear error</td>
<td>Thread error, Can be preloaded to eliminate backlash</td>
<td>Vitually none</td>
</tr>
<tr>
<td><strong>Fr ct on</strong></td>
<td>Depends on ratio, no. of Passes.</td>
<td>-0.05 Nm</td>
<td>Depends on preload</td>
<td>Extremely low</td>
</tr>
<tr>
<td><strong>Life</strong></td>
<td>Decreases with mechanical advantage</td>
<td>Slightly less than that of ball bearing</td>
<td>Comparable to that of ball bearings</td>
<td>Limited by bearings</td>
</tr>
</tbody>
</table>
Actuator Components

2.5 Signal Transfer

Signal Transfer Devices:
- Cable service loop
- Flex tape assembly
- Slip ring assembly
- Roll ring assembly
- Rotary transformer
## 2.5 Signal Transfer Comparison

<table>
<thead>
<tr>
<th></th>
<th>Cable</th>
<th>Flex-tape</th>
<th>Slip rings</th>
<th>Rotary transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range of motion</strong></td>
<td>&lt;180°</td>
<td>&lt;360°</td>
<td>continuous</td>
<td>continuous</td>
</tr>
<tr>
<td><strong>Mechanical impedance</strong></td>
<td>Non-linear stiffness, hysteresis</td>
<td>Low non-linear stiffness, hysteresis</td>
<td>Coulomb friction</td>
<td>No mechanical contact</td>
</tr>
<tr>
<td><strong>Life</strong></td>
<td>Limited by fatigue</td>
<td>Limited by fatigue, &gt;$10^7$ cycles</td>
<td>Limited by wear, &gt;$10^7$ cycles</td>
<td>Unlimited</td>
</tr>
<tr>
<td><strong>Signal compatibility</strong></td>
<td>Unlimited</td>
<td>Unlimited</td>
<td>Best for low-bandwidth analog signals</td>
<td>Inefficient for power transfer. Limited to narrow frequency range</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>Stiffness difficult to predict, can hang up</td>
<td>High</td>
<td>Wear debris can cause shorts</td>
<td>High</td>
</tr>
</tbody>
</table>
3. Actuator Examples

- Direct drive
- Stepper/harmonic drive
- Motor/roller screw
- Linear motion band drive
3.1 Direct Drive

- Low mechanical impedance ideal for disturbance isolation, inertial pointing.

- Used on Galileo (with encoder), proposed for Cassini scan platforms.

- Gyro on scan platform used for control, resolver used for commutation & spacecraft pointing

- Pointing stability: 10μrad over 0.5 sec at rate

- Cost: >$1 million
Actuator Examples

3.2 Stepper motor with Harmonic Drive

- High mechanical impedance for body-relative pointing.
- Used for Magellan and TOPEX solar array drives. Proposed for POINTS solar array drive.
- Several standard sizes available from several vendors
- Output bearing is independent of actuator for ease of integration.
- Cost: $1 million
3.3 Linear Actuator for POINTS Interferometer Articulation

- High mechanical advantage for extreme accuracy.
- Passive holding force to withstand launch loads, flexure torsional stiffness.
- Reliability maximized by minimizing stages.
- Based on Viking & Cassini engine gimbal actuator.
- Range: \(\pm 3^\circ\)
- Accuracy: 2.4 \(\mu\)rad with interferometer feedback
- Cost: \(< 1\) million

![Diagram of linear actuator for interferometer articulation]

- Face-to-face bearing pair
- Roller screw, 1 mm/rev
- Brushless motor with Hall-sensor feedback
- Labyrinth seal
- Bearing pair
- LVDT
- Hard point on fixed optical bench
- Face-to-face bearing pair

Accuracy: 2.4 \(\mu\)rad with interferometer feedback

Cost: \(< 1\) million

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3.4 Linear Band Drive

Proposed for Tropospheric Emission Spectrometer delay line actuation.

- Bearings and motor thermally isolated from -123°C optics.

Breadboard to be tested this summer

- Requirements
  - Range: 17 cm+ turn-around
  - Rate: 2 cm/s
  - Rate stability: ±5%
  - Life: 1 million cycles,

- cost: > $1 million
4. Tips on Specifying Actuators

Rules of Thumb:
- Get actuator engineer involved early in the design phase.
- Try to accommodate devices, or at least major components with heritage.
- Don’t specify a device with heritage unless you thoroughly understand its capabilities.
- Use components with predictable behavior; tests and analyses to prove compliance with requirements as major cost drivers.
- Keep is simple; complexity = cost.

Requirement Tips:

Position and rate performance
- Define terms precisely, and preferably with graphics.

Disturbance spectrum
- Requires integrated structural-optical model of spacecraft.

Launch loads
- Launch loads, not operating loads, size most mechanisms.
- Deployable structures are usually over-constrained when stowed, complicating loads analysis.
- Caging mechanisms are not trivial.

Resource allocation (mass, power, cost)
- Most mechanisms can trade mass for power.