Design Considerations for Optical Pointing and Scanning Mechanisms

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ABSTRACT:

Optical pointing and scanning mechanisms require inter-related optical, mechanical and electrical engineering and manufacturing disciplines. Such devices are employed in extremely diversified fields of photographic imaging, laser projection displays (LPD), remote sensing for weather prediction, mapping, and earth resources study, and free space laser telecom. The degrees of freedom commonly applied include rotary scanning, raster and vector scanning, and limited angle gimbals. Support systems include flexures, ball bearings, and gas bearings. The performance of the optical payload supported by the pointing or scanning mechanism is paramount and dominates the process of materials selection, structural analysis, actuator selection, and control system development. This paper introduces the tradeoffs among range and type of motion, actuator types, angular sensor types, bearing types, and control systems applied to these types of systems. Actual product design and performance data is presented for a high-speed rotary scanner, a fast "nodding" scanner, a flexure supported fast steering mirror (FSM), and several ball bearing and a gas bearing gimbal designs.

Keywords: FSM, LPD, RGB, gimbal, ball bearings, gas bearings, flexures, resolver, torquer, metal mirrors, beryllium, structural efficiency

1.0 INTRODUCTION:

The basic elements of pointing and scanning mechanisms are the optical payload, bearings, actuators, angular position sensors, and structural embodiment. Optical payloads vary considerably in type, size, and shape and include flat mirrors, telescopes, de-rotators, polygon mirrors, etc. The performance of the optical payload and its pointing and scanning accuracy requirements dominate the system design process. Flexures, ball bearings, and gas bearings are common means to sustain means of support for an optical payload and allocate desired compliance and constraint of motion among the six degrees of freedom. Moving coil motors and piezoelectric actuators are commonly coupled with flexure spring suspension systems for highly responsive, limited angle, and small sized pointing mechanisms. Ball bearings, torque motors, and resolvers or optical encoders are suited to less agile, larger sized mechanisms with large angular excursions. Self-acting and externally pressurized, gas lubricated bearings can be used in many specialized contexts where exceptionally high speeds, low friction, and accuracy are required.

2.0 DISCUSSION:

An outline of a variety of bearings, actuators, angular sensor types, and structure design tradeoffs is presented herein. This discussion forms the basis for the presentation of a number of examples that illustrate the successful use of these elements in a wide variety of actual optical pointing and scanning mechanisms.

2.1 Optical Payload Integration:

The opto-mechanical engineer is faced with the challenge to embody the optical payload that has been defined for a pointing or scanning mechanism without compromise to the optical, electrical and mechanical sub-system requirements. Common payloads included gimbaled telescopes, mirrors, and rotating single facet and polygon mirrors, The optical requirements are generally expressed in terms of aperture size, effective focal length (EFL), field of view (FOV) and transmitted wavefront error (WFE). The aperture size is a function of the size of the beams that must be accepted plus a reasonable allowance for mirror manufacture (such as edge roll-off) and misalignment error stack-ups within the entire product. The WFE tolerance relates to design residual errors and degradation of the beam due to imperfections in the surface accuracy of reflective and/or refractive surfaces within the optical payload under both static and dynamic conditions transmitted by the pointing mechanism.

Mounting of the optical payload within the scanning and pointing mechanism is critical. Generally, balance of the optical payload under static and dynamic conditions, and a high natural frequency of vibration is desired. Dissimilar coefficients of expansion among the optical payload, bearings, and support structure must be reconciled to avoid torque and pointing accuracy anomalies, and degradation of WFE performance upon changes in temperature. Metal mirrors and telescope assemblies are readily designed for direct (no adhesives) fastening to the pointing or scanning system. Metal mirrors may even be designed integral to the shafts of scanners and gimbals and may be structurally contiguous in operation.

2.2 Bearing support systems

Once the desired payload and the required range, rate, type and accuracy of motion for a pointing or scanning mechanism is defined, the bearing support system of choice can be selected. Flexures can only be used over a limited range of motion and for limited mass but are simple and very repeatable. Ball bearings have large load capacity and infinite angular range but require careful fitting, specialized lubrication, and protection from shock loading. Gas bearings have superb accuracy, range of motion, and very low friction but require an external or internally generated source of gas pressure. Roller, needle, and oil film bearings have high load capacity and stiffness but suffer from significant frictional effects and lubricant containment issues that are detrimental to many scanning and pointing mechanisms. The following discussion is limited to flexures, ball bearings, and gas bearings.

2.2.1 Flexure Spring Design: Spring design and material selection is vital criteria to the design of flexure mounted optical payloads. Spring rate in both the compliant and non-compliant directions must be considered simultaneously. An ideal flexure system has the following attributes:

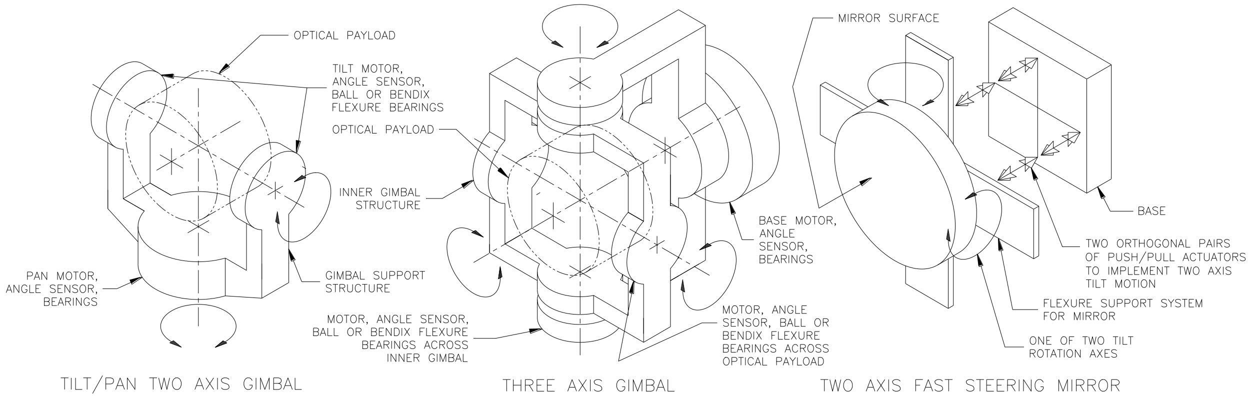
- Very low stiffness to resist the desired directions of motion
- Very high stiffness in the constrained directions of motion
- Controlled location of the virtual pivot of flexure system
- Near-perfect elastic response in the desired directions of motion
- Low mechanical hysteresis
- Very high resistance to metal creep and fatigue
- Compatible coefficient of thermal expansion with the optical payload and support structure

A wide selection of spring materials, spring types and associated manufacturing technologies are available for flexure designs. Also, mature flexure designs such as “Bendix flex pivot” rotary types are commercially available. Beryllium copper is particularly well suited for flexure designs and may be formed in a wide variety of shapes when cut or stamped from varying thickness of commercially available sheet stock. Integrally machined flexures in mirrors fabricated from aluminum or beryllium are also feasible so long as metal fatigue thresholds are not approached and features having high stress concentration factors are avoided. Generally, attempts are made to conserve energy and reduce actuator force requirements by minimizing the spring rate of the flexure in the compliant directions. This minimizes the holding force that the actuator must express to maintain a commanded position against the resistance of the flexure. Conversely, it is desirable to maintain very high spring rates for constrained degrees of freedom. The appropriate balance of spring rate and range of motion for all of the six degrees of freedom must be accommodated in the flexure design process.

2.2.2 Precision ball bearings: Ball bearings are the most common bearing technology applied to pointing and scanning mechanisms. The technology is very mature, there are excellent reference materials and technical support resources available, and a wide variety of off-shelf ball bearing products are commercially available. Optical pointing and scanning mechanisms tend to present many challenges for accuracy, limited angles, high acceleration and lubrication that push the envelope for ball bearings. Poor design practices, or inadequate geometrical accuracy of the bearing housings can result in wear, accuracy, or torque anomalies in the operation of otherwise high quality ball bearings. Limited angles result in uneven wear and distribution of lubricant. Ball bearing selection and assembly tolerances are critical for smoothness, low torque, life, adaptation to temperature changes, and structural stiffness. A pair of axially separated, preloaded duplex bearings is common practice for pointing mechanisms. Duplex bearings allow highly controlled, angular contact, ball preload to be established at the bearing manufacturer. One duplex bearing is fixed and the second widely spaced bearing will have axial “float” to prevent binding of the assembly. Lapped interfaces, interference fits, and compliance are often necessary to ensure that the bearing mounting geometry is retained and such that there is no axial or radial “shake” over temperature. Requirements for fit, geometry of flatness, squareness, and cylindricity, and bearing preload are all essential to the accuracy, smoothness, stiffness and life of duplex bearing operation. Refinements to the hone of bearing raceways, custom grinding and lapping for setting preload, sorting of balls for size matching and geometry, and customized lubrication are essential requirements for many high accuracy space applications. Vacuum applications necessitate the use of low out-gas lubricants or no lubrication within the bearing. Since a primary cause of bearing failure is “brinneling” or dinging of the bearing races by the balls, extreme attention to assembly processes, anticipation of peak shock and vibration, and handling of the completed mechanisms is extremely critical. Tightly toleranced crash prevention features or caging mechanisms can be designed into the bearings or support structure to prevent brinneling of the balls under extreme shock and vibration conditions.

General Rules of Thumb: Ball bearing mechanisms

- Preload: minimize for reduced torque but must be maintained under all environmental conditions
- Duplex bearings are best for controlled preload and accuracy
- Ball Geometry: Roundness of 0.000001-0.000025”
- Race Geometry: 0.000010-0.000100” in contact band
- Accuracy: Approximately 2X geometry errors divided by the separation of the radial bearings
- Surface finish: less than 8 micro-inches RMS per surface
- Stiffness, running torque: proportional to preload, number of balls, race diameter
- Anticipate effects of differential expansion over the operating temperature range



TILT/PAN TWO AXIS GIMBAL THREE AXIS GIMBAL TWO AXIS FAST STEERING MIRROR

Figure 1: Common design configurations for pointing mechanisms that employ ball bearings or flexures:

<u>2.2.3 Externally pressurized (aka hydrostatic, aerostatic) gas lubricated bearings:</u> This type of bearing is very similar to the pressurized oil bearings used in internal combustion engines and other types of high load bearing rotating machinery. A pressurized gas, rather than oil, is introduced into a network of air passages leading to small orifices at the junction between the opposing surfaces. The gas emerges from the orifices at high velocity, impinges upon the opposing surfaces and produces a significant gas film pressure upon the exhaustion of the kinetic energy of the gas stream. Since no sliding contact occurs, mechanical errors in geometry and surface finish between surfaces separated by the gas film, are averaged, resulting in exceptional accuracy of motion. The averaging effect is particularly important to note when comparing ball bearings to gas film bearings. Although bearing surface finishes and geometry for pressurized gas bearings are similar to those instilled in ball bearings, it is common that the gas bearing will perform with 10-100+ times greater precision due to the respective differences between averaging and continuous contact error effects.

The externally pressurized gas bearing can be used in the context of rotating shafts, linear slides, and spherical balls that may be both rotated in all directions. Rotating shafts can be operated from static to dynamic conditions reaching velocities in excess of 100,000 RPM. In general the stiffness of this type of bearing is related to the number of orifices, gas film thickness (gap) supply pressure, gas viscosity, and bearing surface area. Air passages, fittings, small drilled holes, and sometimes bearing sleeves are required for externally pressurized bearings. Self-acting gas bearings do not require these features. The figures below are generally applicable to both gas bearing types.

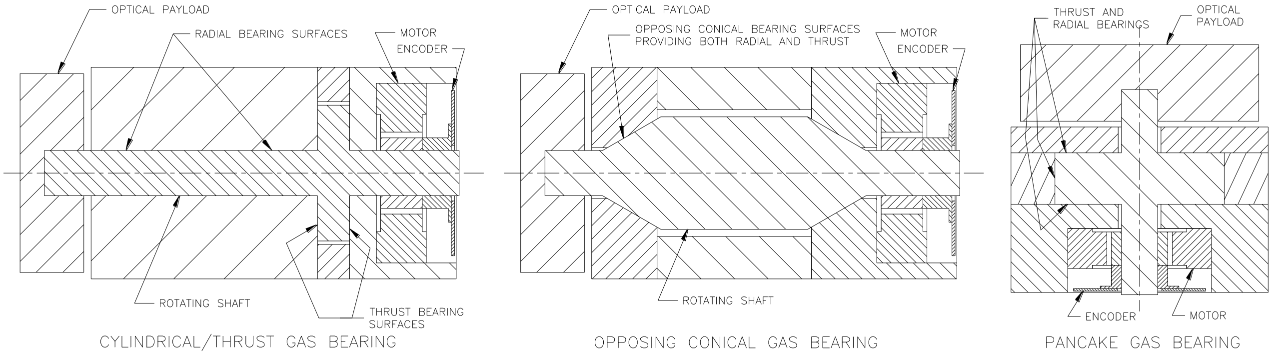


Figure 2: Three common configurations for rotating gas bearings: both self-acting and externally pressurized

General Rules of Thumb: Externally pressurized gas Bearings

- Gap: 0.00025-0.00060”
- Geometry: (roundness, cylindricity, sphericity, conical profile, etc): 1/10 Gap
- Accuracy: less than 1/10 geometry divided by the separation of the radial bearings
- Surface finish: less than 8 micro-inches RMS per surface
- Orifice diameter: 0.003-0.020” diameter depending on gas pressure and viscosity
- Stiffness: directly proportional to supply pressure, effective surface area, 1/gap
- Eccentricity: less than 30% of gap
- Gas consumption: proportional to $(\text{gap})^3$
- Power consumption: increases/decreases proportional to $(\text{gap})^2$

2.2.4 Self acting (aka hydrodynamic, aerodynamic) gas lubricated bearings: This bearing produces a gas film pressure by use of pump patterns integral to the thrust and radial bearing surfaces. Initially the rotating and stationary surfaces are in sliding contact, then, as the shaft gains speed, “lifts off” occurs. The pressure of the gas film then increases steadily as the shaft accelerates to operating speeds. This type of bearing was originally optimized for use in high speed gyroscopes for navigation systems. Although its use in inertial guidance systems has waned due to emergence of other technologies such as GPS and ring laser gyros, this device commands an important role in high speed rotary scanners used for digital imaging of photographic film and plates, and laser projection displays (LPD). Like the externally pressurized gas bearing, principal advantages of the self acting gas bearing are low friction, high speed, superb accuracy, and long life. Its disadvantages include very tight tolerances and sliding contact until sufficient film pressure is developed for “lift-off”. Its major advantages over its cousin, the externally pressurized gas bearing, is the elimination of an external source of pressurized gas and the associated passages and manifolds required to route the gas to orifices. The self-acting gas bearing can also be operated as a completely closed and sealed system independent of adverse or vacuum environments. Its relative disadvantage is its requirement for high speed, and range of motion limited to one rotational degree of freedom, and generally one direction. The use of his type of bearing is limited to modest payloads due to the initial sliding contact condition. Because of the tight tolerances involved, outside contamination or particulates from wear of the sliding surfaces can result in bearing failure. Selection of sliding surface treatments and controlled filtering of gas flow is critical. Some additional payload can be reconciled by the use of magnetic or mechanical force to assist lift off while the bearing spins up. For exceptionally high speed applications, the bearing can be sealed in low viscosity gas medium such as helium.

General Rules of Thumb: Self-acting gas lubricated bearings

- Gap Range: 0.000070-0.0004”, Pump pattern depth: 1.0-2.5x Gap
- Materials: Ceramic or ceramic glazed aluminum and beryllium
- Geometry: (roundness, cylindricity): 1/10 Gap
- Angular accuracy: less than 1/10 geometry divided by the separation of the radial bearings
- Surface finish: less than 8 micro-inches RMS per surface
- Stiffness: increases proportional to effective surface area, rotating velocity, and1/gap
- Eccentricity: less than 30% of gap
- Power consumption at speed: increases proportional to angular rate, 1/Gap, surface area

2.3 Actuator Choices:

There is a tremendous range of actuator choices for pointing and scanning mechanisms dependent on range of travel, accuracy, and frequency response. An introductory summary including PZT's, moving coil motors, brush and brushless torqers, and stepper type motors is as follows:

2.3.1 Piezoelectric actuators (PZT's): PZTs typically consist of laminated stacks of piezoelectric material encased in a steel cylinder. By application of a modulated high voltage input to the PZT, small increments of motion result. When compared to other actuator types, PZT's can produce tremendous force, at great frequency response, for a small package size. However, PZTs suffer from very limited range of travel, hysteresis, and they must be mechanically preloaded in compression to prevent de-lamination and to provide a restorative spring force. PZT's are often used in conjunction with mechanical flexures. PZT mechanisms can also be procured as micro stepper rotary devices.

2.3.2 Moving coil (aka voice coil) actuators: These devices consist of a coil of wire and a permanent magnet. By modulating the amplitude, frequency and direction of the current flowing through the coil, a precisely metered push or pull effect can be realized. Although most typically used as a linear actuator, the magnet and coil can be curved to allow rotational actuation about a virtual pivot point or axis. In this manner expanded ranges of tilt can be achieved. The coil and magnet must be guided by bearings or flexures to maintain alignment over the range of travel. Generally the efficiency of the voice coil degrades as the clearance between the coil and the magnet is increased. Moving coil actuators have advantages of large travel excursion, moderate frequency response and the potential for finely metered increments of motion. These actuators are very effective in conjunction with flexures for moderate angle FSM's.

2.3.3 Brushless and brush type DC direct drive torque motors: Brushless motors are the actuator of choice for many gimbaled pointing mechanisms. They are also satisfactory for many rotary scanning applications requiring high speed and can often fill the niche of the hysteresis synchronous motor. Since there are no brushes, a source of contamination, friction, and reliability problems is eliminated. These motors typically consist of a high performance permanent magnet such as samarium cobalt and wound copper coil. Commutation of the motor is achieved by including Hall Effect sensors or by reliance upon an external angle sensing device such as a resolver. These devices are efficient and reliable with extensive heritage within pointing and scanning mechanisms for commercial, and space systems. Redundant windings and wiring terminations and generous performance margins are also common practices on space flight hardware to increase reliability. Both primary and back-up windings on a resolver can also be used to commutate the motor as replacement or back-up to the more common approach using Hall effect sensors. Brush type motors are also still in common use, even though there are performance drawbacks, based on heritage and since the control system electronics tend to be simpler and less costly.

2.3.4 Stepper Motors: Stepper motors are widely used in commercial, and aerospace applications and are often coupled to speed reducer gear heads to increase torque and subdivide steps. While similar to DC brushless motors in that a permanent magnet rotor follows a rotating field generated by the stator windings, stepper motors have several unique features that are well suited for positioning applications. The chief advantage of a stepper motor is that the rotor position may be incremented in concise "steps" by appropriately energizing the stator windings. No commutation sensor is required for continuous rotation and the relative shaft position may be determined by counting the number of steps from a known angle. Stepper motors produce high torque at low speeds and also have the ability to hold position without applied power to the windings. The inherent simplicity of the motor contributes to its high reliability.

2.4 Angular Position Sensors:

Widely varied position sensor technologies are available to the system design engineer. Some of the more common sensor types for rotary operation include potentiometer, capacitive, optical, and inductive devices. Linear position sensors are commonly implemented in the same technologies as the rotary types except for the capacitance sensor that is inherently rotary. Most high reliability applications utilize inductive or optical position sensors. Inductive analog devices include resolvers and inductosyns while optical sensors may be analog (such as continuous area position sensors) or digital (such as incremental encoders). The inherent accuracy and repeatability of these devices is also coupled to the accuracy of the bearings that define the degrees of freedom. Each sensor technology has unique characteristics and advantages that may be desirable for a given application. Some examples include:

2.4.1 Resolver: This rotary inductive position sensor has no active electronic components and is able to operate over a very wide temperature range. It is an ideal position sensor for harsh environments and is essentially immune to high-level radiation. This sensor is available in many sizes and is easily adaptable for large bore applications. An input excitation signal (typically 60Hz, 400Hz, or 10KHz) is required while the two output signals are amplitude modulated and vary as the sine and cosine of the rotor angle. The resolution of the output is essentially infinite while the accuracy may range from arc-minutes to arc-seconds. The output signals may be used in analog form or converted to digital for subsequent processing. For resolvers designed to operate at 60Hz or 400Hz, the processing electronics may be located at a significant distance from the sensor.

2.4.2 Inductosyn: This inductive position sensor may be manufactured for rotary or linear position sensing. The technology is similar to resolvers in that an AC excitation is applied to the device and amplitude modulated sine-cosine signals are recovered from the output. Inductosyns are unique in that the sensing elements consist of printed circuit patterns etched into a substrate rather than wire wound around a laminated metal core. Inductosyns, like resolvers, have infinite resolution and are capable of achieving high accuracy but are not as rugged or environment tolerant as resolvers. In addition, the processing electronics must be located close to the sensor elements and will likely be subjected to the same environments.

2.4.3 Optical encoders: Optical encoders are popular rotary and linear position sensing devices that have been in use for many years. Chief advantages of this type of sensor include lower cost, self-contained processing electronics (except for high accuracy units), and good thermal stability and repeatability. Drawbacks include sensitivity to radiation, finite resolution, and other environmental issues.

Figure 3 AVHRR/3 Scan Mirror motor sub-assembly

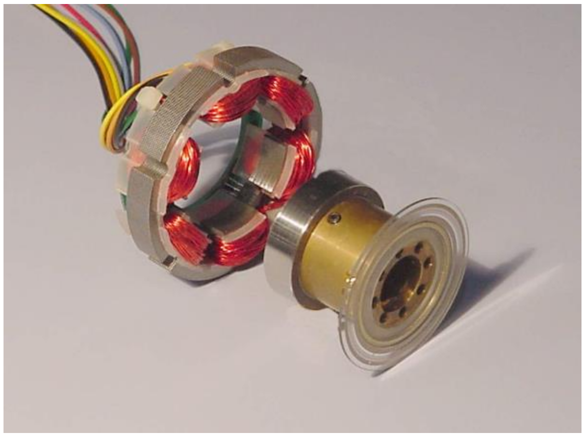


Figure 4: High Speed Brushless DC motor and optical encoder

2.5.1 Example #1: Development of AVHRR/3 Orbiting Scan Motor Assembly

The Advanced Very High Resolution Radiometer (AVHRR) is a broad-band, multiple channel scanner, sensing in the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum. This sensor is carried on the National Oceanic and Atmospheric Administration's (NOAA's) Polar Orbiting Environmental Satellites (POES). Earlier versions of the scan motor used AC hysteresis-synchronous motors that have a limited torque margin (running load compared to applied load before loss of sync). An updated scan motor assembly was recently developed that consists of a 10-pole DC brushless motor, dual redundant encoders, a duplex bearing up front and a single radial bearing in the back preloaded by a "spider" flexure spring assembly. The bearing design was required to provide smooth and low torque while at the same time sustaining launch loads and a broad operating temperature range. The bearing housing was manufactured from beryllium due to its low mass, stiffness and reasonably matched CTE to that of the steel bearings and shaft. The scan mirror was also beryllium for minimized mass, rotating inertia and optical figure deformation under the influences of centrifugal forces. A photo of the AVHRR/3 can be seen above.

Performance Criteria: AVHRR/3

Mechanical

- Dimensions: 9" wide X 7" tall X 6" long (approximate)
- Housing material : Beryllium
- Shaft & mechanical components: Stainless steel
- Weight: 7 lbs.
- Operating Speed: 360 RPM
- Payload: 8.25 in. x 11.6 in. elliptical, beryllium mirror
- Vibration Environment: Up to 22g RMS
- Operating Temperature: 0C to +35C
- Low outgassing design

Three Phase Brushless DC motor

- Peak torque:125 oz-in
- Running Torque: 8 oz-in
- Magnet Type: samarium-cobalt
- Number of poles: 10
- Commutation: Hall sensor
- Cogging Torque: 2.0 oz-in max.
- Maximum Winding Temperature: 200C

Optical Encoders

- Dual redundant read heads
- Format: Incremental
- Outputs: A, B, INDEX (each section)
- Disk: Chrome pattern on glass

System Performance

- Power consumption: <8 Watts
- Time to speed: <12 seconds
- Running torque: <8 oz-in
- Speed jitter < 2us standard deviation (100 scans) at 360RPM, (12 PPM)

2.5.2 Example #2: Fast Retrace Nodding Scanners:

Figure 5 Photo of nodding mirror

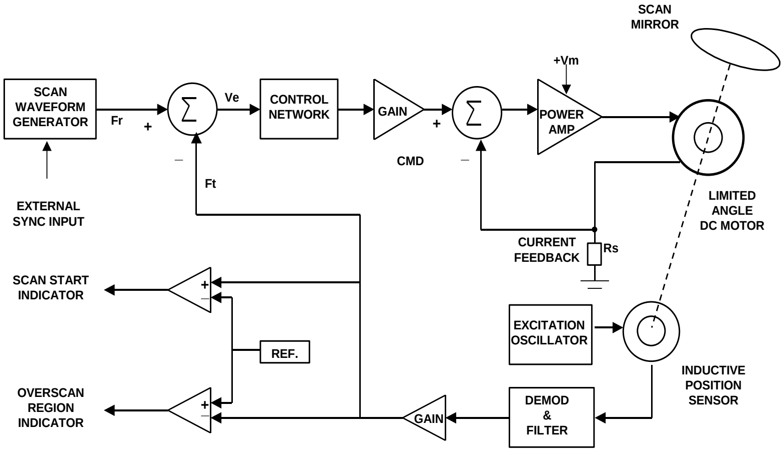


Figure 6 Nodding Scanner simplified block diagram

Performance Criteria: Nodding Mirror

- Scan rate: DC to 60Hz
- Scan angles: to ±12.5°
- Cross-scan error: < 50μrad,
- Scan jitter: < 50μrad,
- Ball bearings, steel shaft
- 1.75” x 1.25” Be mirror
- Scan profiles: Ramp, Triangle, Sawtooth
- High scan efficiency: 75% at 50Hz
- Mid scan linearity error: < 0.25%.
- Control outputs: SOS, Position, EOS
- power: 8 Watts at 50Hz.
- Operating temp. range: -30°C to +90°C
- Drift: 100ppm (-30°C to +90°C)
- motor: limited angle brushless DC

An important class of optical scanning systems involves the generation of still and video raster images composed by stacking equal length horizontal scan lines. The completed image is commonly known as a frame, and the rate at which a new image may be generated is known as the frame rate or refresh rate. In the case of video images, the frame rate is generally required to be 50-60 Hertz to preclude “flicker” effects associated with human eye response to motion pictures. The above photograph and technical data describes a “nodding mirror” scanner that produces the vertical or slow scan component of a system such as for laser projection display (LPD). The nodding mirror moves at constant velocity to index the horizontal scan lines in the slow vertical scan direction until the frame is complete and then it must rapidly return and settle to start the slow scan component of the next frame. A polygon scanner is used to provide the fast horizontal scan line component. A combination of ball bearings, limited angle DC torque motor, beryllium mirror, resolver, and control system, synchronized to the prescribed video display format, provides a compact and effective design solution.

2.5.3 Example #3: High Performance, Self Acting Gas Bearing Scanner:

High speed polygon scan engines are now being used as part of laser projection displays (LPD) as low cost, high powered red, green, and blue (RGB) lasers are being developed. LPD's hold the prospect to provide life-like saturated color, resolution, large format, and brightness under nearly all ambient lighting conditions. In order to meet the requirements for 1000+ vertical lines of resolution and 50+ Hertz frame rate, a specification requiring a polygon scanner with 35 facets and a rate of rotation of 81,000 RPM was developed. The high speed, high accuracy and moderate cost goals for the scanner immediately suggested the use of a self- acting gas bearing. In order to minimize viscous drag, power consumption and over-heating, a self contained hermetically sealed environment of fractional atmosphere pressure Helium gas was chosen to lubricate the bearings. In addition, and although more difficult to manufacture, the use of an opposing conical bearing design provided further efficiency compared to cylindrical/thrust bearing designs. The resulting design runs cool and has less than 0.25 arc second facet to facet and less than 5.0 arc seconds of cross scan error. Combined RGB laser beams are introduced into the scanner via a window. A photo of the scanner and a schematic of the RGB laser projector it was built for can be seen below. A nodding mirror is also used in the complete LPD system to provide the slow scan raster component.

Figure 7 Photo of 81,000 RPM Polygon Scanner Unit

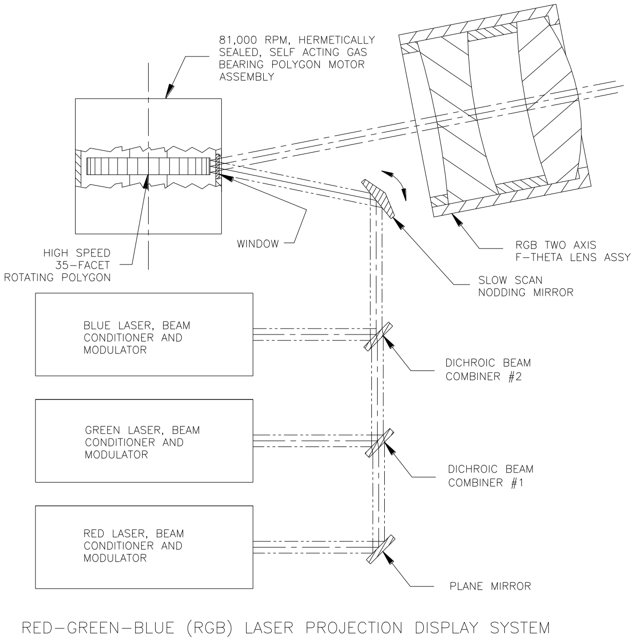


Figure 8 Diagram of RGB Laser Projection Display

2.5.4 Example #4: Two Axis Fast Steering Mirror (FSM) for Free Space Laser Telecom:

Free space laser telecommunication systems entail propagation of modulated laser signals across open atmosphere or the vacuum of space rather than through fiber optic cable. A common path laser emitter and receiver are positioned opposite each other, often at large separation distances. A Fast Steering Mirror (FSM) within each module compensates for any drift in the optimal co-alignment of the two systems. The requirements for low cost and moderate angles of excursion resulted in the development of a two axis flexure supported FSM driven by moving coil linear actuators. Angular positioning of the FSM is enabled by an outside “null seeking” sensor system and optical transducers sensing the back of the mirror. A picture of a two axis tilt FSM and a schematic of a laser telecom link are shown below. FSM’s can also used for a variety of vector scanner applications including laser cutting, welding, and marking.

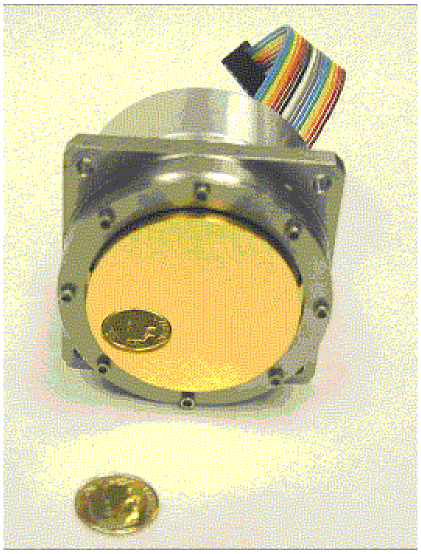


Figure 9 Photo of 40 mm Fast Steering Mirror

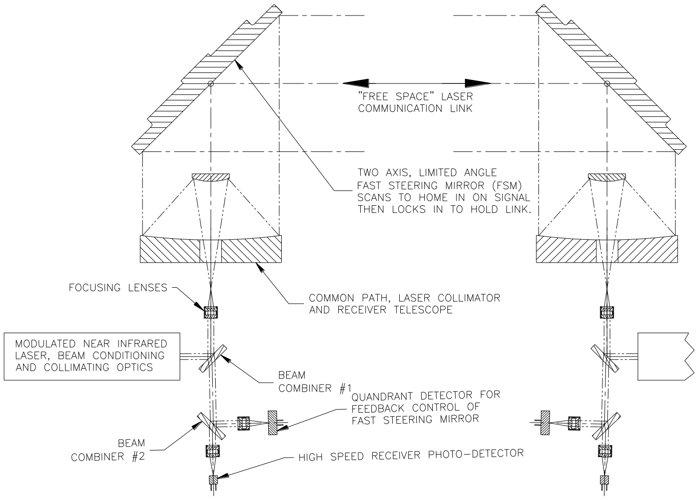


Figure 10 Diagram of a free space laser telecom system

2.5.5 Example #5: Rate Gimbal Platform for Orbiting Nano-g Accelerometer

Inertial navigation systems on aircraft and spacecraft are required to provide precise feedback on angular position, velocity, and acceleration relative to a frame of reference commonly defined in terms of pitch, yaw, and roll. Industry is constantly pressured to enhance the accuracy of such devices while simultaneously reducing the cost, size, and weight. A two axis rate table gimbal, known as the Orbital Accelerometer Research Experiment (OARE) was developed for the space shuttle to test accelerometers with nano-g precision in the absence of gravity. By rotating the instrument platform at a very controlled angular velocity, and at a controlled radius, calibrated centripetal acceleration is created. The rate gimbal consists of a light-weighted aluminum structure with ball bearings, tightly controlled orthogonality between rotating axes and very precisely controlled rate table with a large dynamic range. Particular challenges for the design of this project were to define and successfully mount, low friction, high accuracy ball bearings in the contexts of broad operating temperature and an aluminum structure. To solve these problems, duplex ball bearings and special lubrication, matched CTE beryllium bearing housings, sub-micron geometry and fits for assembly of the bearings, and membrane flexures were used to achieve optimal bearing performance over temperature.

OARE Performance Summary:

- Position accuracy: 20 arc sec
- Repeatability: +/- 20 arc sec
- Rates: 0.01 to 2.0 rad/sec
- Rate accuracy: 0.1%
- Acceleration: 25 rad/sec^2
- Bandwidth: 30 Hz
- Average power consumption: 13 Watts
- Encoders: 16-bit absolute
- Structure: aluminum frame, beryllium bearing housings
- Ball bearings: Duplex pairs, special lubrication
- Orthogonality: 10 microradians

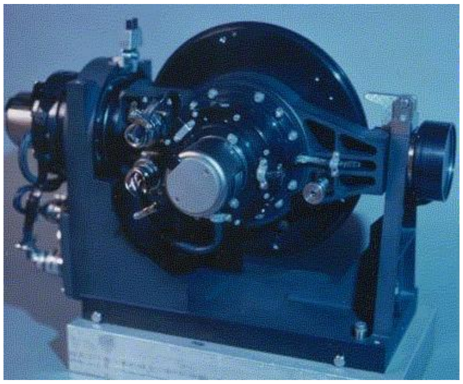


Figure 11 Photo of OARE Rate Table Assy.

2.5.6 Example #6: Externally Pressurized Three Axis Gas Bearing Gimbal

A commonly applied mechanism to provide three axes of tilt is a ball in a socket. By applying the principles of an optimized, externally pressurized gas bearing, a compact, high stiffness 3-axis gimbal, with very low friction can be designed. In one case (figure at left below) a hollowed out ball is encased between two stationary hemispherical sockets. Air passages connect a network of high velocity orifices. By introducing compressed gas into the air passages, the ball is floated between the two shells and can be rotated with negligible friction in all three rotational degrees of freedom. The optical payload is mounted and balanced on the ball and can be tilted or rotated by the action of control tendons or electro-magnetic forces. Alternatively, the ball may be fitted to one hemispherical socket (center figure below) and harnessed by control tendons to oppose the gas bearing. This design is compact but lacks the stiffness and load capacity of the enclosed ball. As discussed above, optimal stiffness and least gas consumption of the bearing will occur when the gap is minimized and sphericity is tightly controlled. Single point diamond machining processes and specialized coatings are commonly used to achieve precise specifications for size and geometry while at the same time providing a hard durable surface. The photograph at the lower right illustrates a hemispherical shell being measured for sphericity on an air bearing rotary/tilt table. A 16" diameter spherical air bearing such as that shown in figure 12 was successfully used for the Kuiper airborne observatory (KAO). A 48" diameter spherical air bearing was also considered in early investigations for the SOFIA (Stratospheric Observatory For Infrared Astronomy).

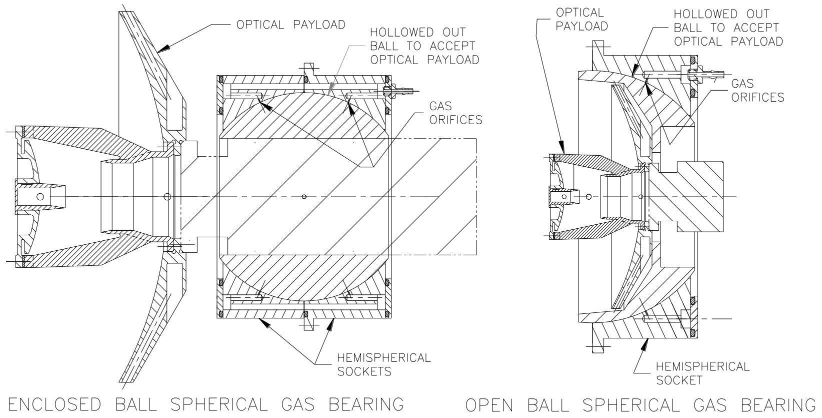


Figure 12 Spherical externally pressurized gas bearing design configurations

Figure 13 Spherical Bearing under test

2.5.7 Examples #7: Structural Considerations for Large, High Performance Pointing Mechanisms:

The support structures for pointing mechanisms used to direct mirrors and telescopes are required to be highly stiff and accurate. When compared to ground systems, mechanisms used on aircraft or spacecraft are also additionally required to be much less massive and higher in natural frequency while preserving stiffness and accuracy in the presence of harsh launch, maneuvering, and landing accelerations. The structure that houses the payload, bearings, motors and angular position sensors is thus essential to sustain performance. An additional consideration is that a lighter and stiffer payload and/or first tier structure cascades into smaller bearings, motors, electronics, power requirements and second tier support structures. Beryllium and beryllium aluminum alloys are outstanding for stiffness, mass reduction, compatibility to manufacture metal mirrors and to house steel ball bearings with well matched coefficient of thermal expansion. These materials are often considered as a last resort due to perceived cost and delivery considerations, however the significant overall mass reductions that are realizable often more than compensate. The following examples illustrate the use of beryllium to reconcile three pointing mechanism design problems:

2.5.7.1 Example 7a: NASA at JPL required a replacement mirror for a system upgrade to AVIRIS (Airborne Visible/Infrared Imaging Spectrometer). This system employs a large, 14" major axis "whisk broom" scan mirror that contributes the fast axis raster scan component while aircraft motion provides the slow scan component. Because of the large mirror aperture, high scan rate, and high acceleration at the ends of scan, a specialized design was required to minimize wavefront degradation. The end result was a beryllium mirror with closed back at its center accomplished by deep wire EDM processes and a separate beryllium shaft passing through the mirror at the neutral axis. The remainder of the backside of the mirror was light-weighted via isogrid triangular pockets tapering off in depth out to the mirror edges. The bearings, motor, and angular position sensor were directly attached to the beryllium shaft. The shaft was locally plated with electroless nickel to improve the producibility and lubricity for fitting of the bearings to the shaft. The shaft was separate from the mirror so that the non-beryllium gimbal support structure could be designed as stiff and as close to the edges of the mirror as possible for maximum structural efficiency and also to minimize the opportunity to impart mechanical strain into the flatness of the optical surface. See figure 12 below.

2.5.7.2 Example 7b: An optimal structure for minimizing the mass while at the same time maximizing the stiffness of bending and torsion for a pointing mechanism structure is realized when triangular or square machined pockets are "skinned" over to create a close cell space frame. The use of beryllium for such a structure results in a stiffness/mass advantage of over 6X, and natural frequency increase of about 2.5X compared to magnesium, aluminum, titanium, and steel all other factors held consistent. Aluminum beryllium alloy materials such as AlBeMet are signifantly lower in cost and provide reduced, but still impressive gains, for stiffness/mass and natural frequency of over 3.0X and 1.7X respectively. The use of fasteners or adhesives to attach skin panels results in significant manufacturing compromises and stiffness reduction. Brazing and welding can also be use to achieve improved structural integrity. A large, closed cell beryllium gimbal structure (shown below in figure example 13 below) was fabricated by using an aluminum alloy brazing process. The skin panels were self-fixtured for brazing with beryllium screws and pins and the braze joint thickness is so thin that negligible bi-metallic effects occur over temperature. The beryllium distorts very little since its melting point is so much higher than that of aluminum. Electron beam (EB) welding is also being introduced to compose closed cell aluminum beryllium structures for pointing mechanisms. EB welding imparts little excess heat outside the weld zone so stress and deformation are minimized.

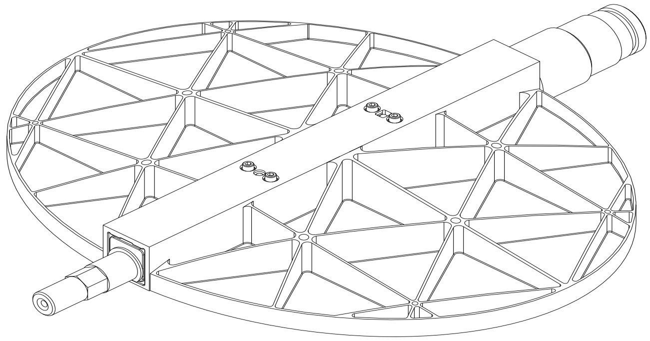


Figure 12: AVIRIS beryllium Scan mirror and Shaft Assembly

Figure 13: Brazed beryllium closed cell gimbal

2.5.7.3 Example 7c: An additional dilemma faced by the pointing system structural designer is whether or not to utilize the optical payload as part of the load path in the optimization of the pointing mechanism structure. Although it is generally best to isolate the sensitive optical payload from the load paths of the pointing system, there are cases where this is difficult or impossible to achieve. A prime example is an 18", two axis gimbaled mirror system, discussed below. The acceleration of the gimbal, particularly in azimuth, was relatively severe. In order to minimize the requirements for the structure connecting the azimuth gimbal to the elevation, the solid beryllium mirror was designed to be structurally contiguous. Besides being beryllium, the mirror was oriented at approximately 45 degrees relative to both the azimuth and elevation axes and so was profoundly stiff in bending for these directions. The yoke shaped frame of the gimbal was designed and fabricated from a closed, semi-tubular, and tapered iron casting for reasonable structural efficiency and cost and matched CTE to the steel duplex bearings and steel support housings. General performance specifications and a photo of this device can be seen below:

18" Gimballed Mirror Performance Summary

- Constant velocity tracking: 5 rad/sec; zero position error; both axes simultaneously
- Constant acceleration tracking: 16 rad/sec2;
- 1 milli-rad position error; both axes simultaneously
- Step velocity response: +/- 1 rad/sec velocity step; 5 milli-rad position error
- Orthogonality: 10 microrads
- Azimuth excursion: +/- 60 degrees
- Elevation excursion: +/- 35 degrees
- Fundamental resonant frequency: >200 Hz
- Duplex ball bearings

Figure 14 18" beryllium gimbal mirror assembly

3.0 SUMMARY:

General descriptions and application design rules for various actuators, position sensors, bearing types, and structures have been presented and then discussed in the context of several commercial, scientific, and aerospace applications.

Mechanisms for scanning and pointing systems are essential to the performance of a wide variety of optical devices in commercial, aerospace and spacecraft contexts. In general the type and range of motion, dynamic response, aperture, and tolerances on the performance of the optical payload define the solution space for development of the bearing support system, actuator type and characteristics, mechanism structure, and control system requirements. Smooth, repeatable, low friction, high stiffness and uncoupled motion of the mechanism degrees of freedom are highly desired for equipment life, accuracy, control system performance, and minimized power consumption.

Ball bearings and gas bearings require very demanding tolerances for fit and geometry. It is often overlooked that the supporting structures that house the bearings need to be manufactured to similar tolerances and have matching or compensating CTE. Optimal bearing performance also enhances the accuracy and repeatability of the angular position sensor(s) and overall control system performance. Caging and crash protection features can protect bearings and flexures from damage during extreme environmental conditions experience in launch, operation, and transport.

Although often considered the material of last resort by many mechanical designers, beryllium and its alloys offer mass and performance advantages that are un-matched by other materials for high speed scanners, spacecraft, and high performance military equipment. Specialized construction techniques including EDM, brazing, and electron beam welding can be applied to further enhance the performance of beryllium structures while reducing material cost and fabrication risks. Reduction of mass and moments of inertia at the optical payload cascades into reduced mass of motors, support structure, bearings, and secondary support structure tied to an aircraft or spacecraft.

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