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Enabling design concepts for a flight-qualifiable optical delay line

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ABSTRACT

In an interferometer, an Optical Delay Line (ODL) must be able to inject a commanded pathlength change in incoming starlight as it proceeds from a collecting aperture to the beam combiner. Fringe visibility requirements for space interferometry prescribe that the optical pathlength difference between the two arms must be equal and stable to less than 5 nm RMS to a bandwidth of 1 kHz. For a space mission, an ODL must also operate in a vacuum for years, survive temperature extremes, and survive the launch environment. As part of the Interferometer Technology Program (ITP) at Jet Propulsion Laboratory, a prototype ODL was designed and built to meet typical space mission requirements. It has survived environmental testing at flight qualification levels, and control design studies indicate the 5 nm RMS pathlength stability requirement can be met. The design philosophy for this ODL was to create as many design concepts as possible which would allow *a priori* attainment of requirements, in order to minimize analysis, testing, and reliance on workmanship. Many of these concepts proved to be synergistic, and many attacked more than one requirement. This paper reviews the science and flight qualification requirements for the ITP ODL and details design concepts used to meet these requirements. Examples of hardware implementations are given, and general applicability to the field of optomechanics will be noted.

Keywords: interferometry, space, optical delay line, design, flight-qualifiable, SIM

1.0 INTRODUCTION

Michelson type interferometers have been built and operated as ground-based observing instruments for several years now. The requirements on the various active electro-optomechanical devices (delay lines, steering mirrors, etc) necessary to perform interferometry are well understood. These requirements specify active devices for optical pathlength and steering control of unprecedented dynamic range and bandwidth.

In the near future, space missions utilizing these interferometers are envisioned. To meet this challenge, the active devices comprising an interferometer must not only meet their own stringent performance requirements, but also must survive the high accelerations of the launch environment and the temperature extremes of space. In addition, they must operate in a vacuum for the duration of the mission, and they must be light weight.

1.1 Task

At JPL the Interferometer Technology Program (ITP) has been chartered to perform design validation of several selected interferometer components in an effort to mitigate risk for actual flight missions. All issues pertaining to science objectives and flight environment are addressed to some degree, but in particular any items of new technology or critical design issues must be proven. The more mundane areas of spacecraft design and assembly though, such as contamination, quality assurance, flight-trained technicians, documented procedures, etc., may be side-stepped to a large extent. This streamlines the process and allows the critical technical issues to be addressed and designs qualified without the costs typically incurred in a space flight mission. The results of this program include the qualified piece of hardware, documented performance results indicating technical goals achieved, and recommendations to flight projects for additional design, development, and qualification needed.

Under the ITP, it has been the authors' task to design, build, and test an Optical Delay Line (ODL) capable of being used in a space mission. The mission chosen to define requirements was the Space Interferometry Mission (SIM).

1.2 Definition and Requirements

An optical delay line provides optical pathlength compensation for an interferometer - that is, it equalizes optical path difference (OPD) between the two arms. It must not only compensate for the static delay caused by viewing a target off-normal from the baseline (a maximum of two meters for the proposed FOV), but also must attenuate pathlength errors caused by thermal distortions and dynamic vibrations in real time. To perform it's function then, the ODL must have one meter of mechanical stroke and sub-nanometer resolution, and have a high bandwidth (~1000 Hz) to sufficiently attenuate small amplitude vibrational disturbances. In addition, the ODL must achieve this dynamic range and bandwidth without inducing significant vibrations itself. To attain this level of performance, this ODL uses a three-tiered actuation scheme: a motor drive for the long stroke, low bandwidth motion; a piezoceramic stack for the small amplitude, high bandwidth actuation; and a voice coil / flexure stage as a mid-range to provide good overlap of dynamic ranges and bandwidths. This actuation scheme is built around a parabola - flat (or catseye) retroreflector. A schematic of ODL operation is shown in Figure 1. The complete listing of chosen functional requirements is given below.

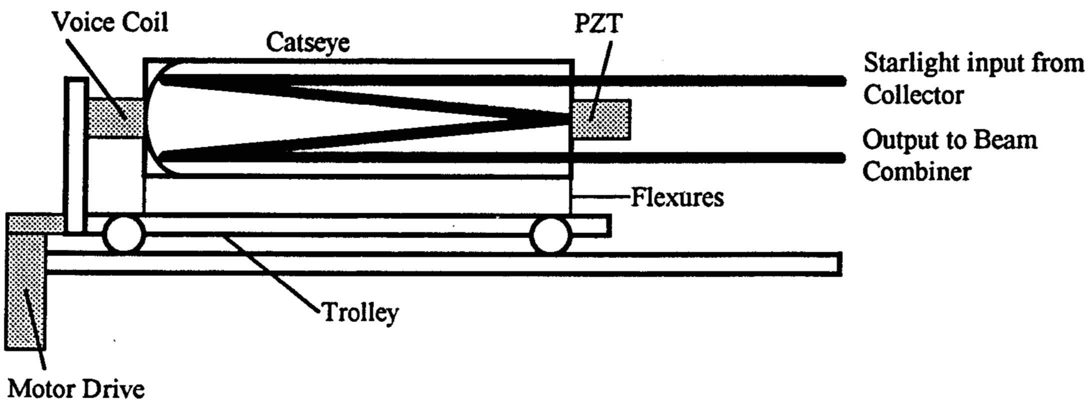

Figure 1 Optical Delay Line Operational Schematic

Table 1 Optical Delay Line Functional Requirements

1.	Science beam diameter (mm)	30
2.	Operating optical FOM p-p	λ/20
3.	Nominal optical wavelength (nm)	550
4.	Operating depth of focus p-p (μm)	20
5.	Allowable focus shift with temperature (μm/°C)	0.5
6.	Allowable deviation from straight line motion (mm)	0.1
7.	Total mechanical stroke p-p (cm)	100
8.	Voice coil stroke p-p (mm)	3.0
9.	Voice coil bandwidth (Hz)	100
10.	Piezo stroke p-p (μm)	15
11.	Piezo bandwidth (Hz)	1000
12.	Dither piezo stroke p-p (μm)	1.0
13.	Launch lock	yes
14.	Tracking rate (mm/sec)	2.0
15.	Slew rate (mm/sec)	10
16.	Operational jitter (nm, RMS, at tracking rate)	<5
17.	Home and limit switches	yes
18.	Mass (kg)	< 15
19.	Power used at device (W)	< 5
20.	Mission duration (years)	≥ 5

2.0 A NEW DESIGN PARADIGM

The stringent requirements mentioned in the introduction forced us to look carefully at all concepts typically used in optomechanical equipment design. The high loads and shock incurred during launch and separation may cause joint slippage, and hence misalignment, if not properly designed for. These same loads could cause excessive stresses in or outright failures of delicate parts. The flight regime also dictates minimum weight and power consumption, further reducing design choices. Finally, designing for a minimum mission duration of five years and many millions of cycles means dealing with fatigue and wear phenomena in a thorough fashion.

These concerns were initially addressed piecemeal for the various parts of the optical delay line, and design solutions were obtained. In the later process of formalizing the ODL design study, it was noted that many of the design concepts had a similar character or nature. The results of this design study were then not only the individual design concepts that allowed the ODL to meet performance, mass, power, and cost goals, but also a meta-concept or paradigm for design of precision systems in general.

We have termed this new paradigm "Apriori Design Concepts" (ADC). The core idea of this paradigm is that through simple logic, or at most a few simple calculations, it can be shown *apriori* that a given design concept is going to work (i.e. have the required performance / not slip or mis-align / have adequate service life / etc.). Our design process then became one which culled individual design concepts down to the point where the only ones left fit the paradigm: they were simple to understand; easy to analyze for effect or to predict results.

The ADC paradigm can also be re-stated as a number of goals, which help to focus thinking along the lines of the core idea:

1. Show apriori acceptable device performance
2. Show apriori adequate service life
3. Minimize required analysis and testing
4. Accuracy by design
5. Design for no creep or loss of alignment
6. Eliminate workmanship as a factor in manufacture, assembly, and alignment
7. Efficiency by design
8. Exploit synergism in point design choices

This list of goals should not be considered as complete, nor are these goals in any sense orthogonal to each other - there is some amount of redundancy, and there is always the underlying core idea of the paradigm. These goals are merely common-sense avenues of focus to arrive at concrete ADC paradigm point designs. The important thing is to maintain focus. When design concessions are made, backing off from the core idea of ADC, cost and complexity will increase and performance will probably decrease.

At this point these goal statements are still somewhat abstract. The best way to explain these statements is by example. This will be done in the subsequent sections.

We consider the Apriori Design Concepts paradigm essential for the proper design of spaceborne optomechanical equipment. It is also useful for designing ground based or laboratory equipment, enabling higher levels of performance than previously thought feasible.

This presentation uses the ODL design as a case study for the ADC paradigm. Depicted in Figure 2, this optical delay line was developed to meet the optomechanical, environmental, and programmatic requirements of SIM. Concrete examples of the design concepts used here (and examples of what <u>not</u> to do) will illustrate the ADC paradigm. The concepts described are not meant to be an exhaustive list, merely indicative of what ADC means and what it can do.

2.1 Applied to system architecture

The ADC paradigm can be applied to system level design issues as well as detail level ones. For the flight-qualifiable optical delay line, the highest system level design choice is which optical system to use.

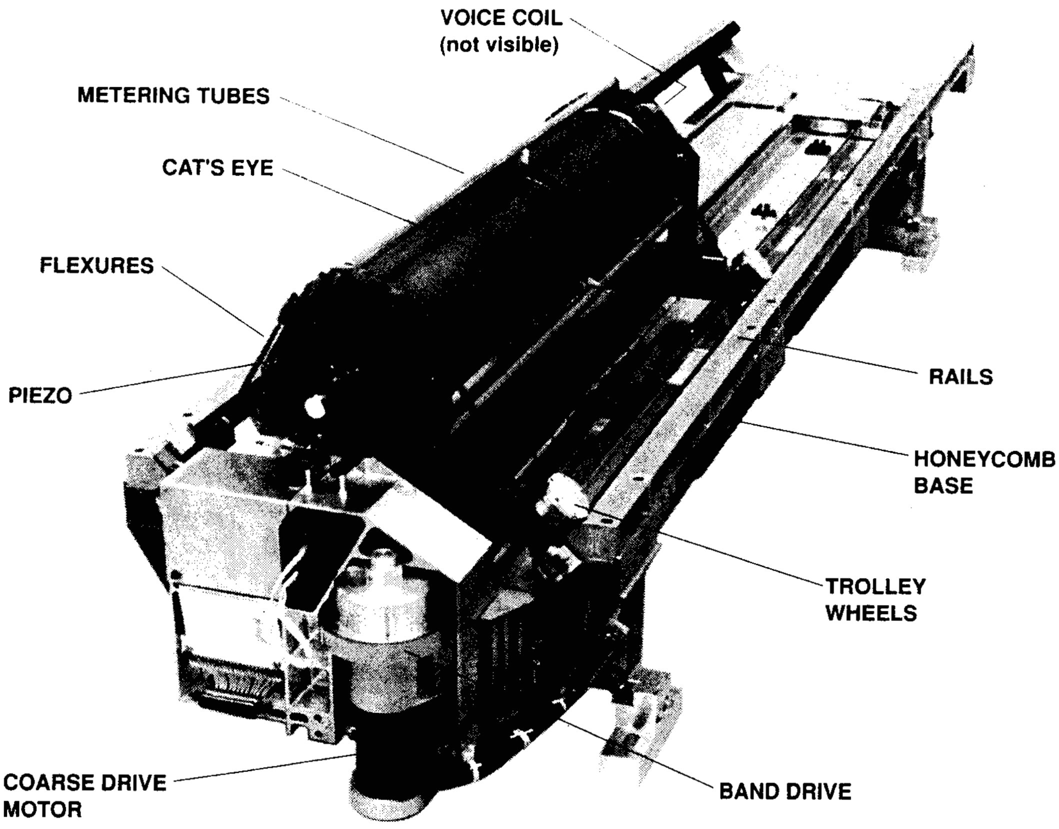

Figure 2 Flight-Qualifiable Optical Delay Line

The best way to achieve the purpose of the ODL (injecting commanded pathlength changes in the starlight beam) is to actuate some sort of retroreflector in piston. This is the simplest way to transform linear motion into pathlength change, and the most robust since rotations and lateral translations do not couple to pathlength. The ADC goal here is to maximize performance, which translates to maximizing actuator bandwidth and minimizing injected disturbances.

The prevalent ODL design in the field of interferometry (heritage from the original Navy Research Laboratory (NRL) design) utilizes a parabola-flat type retroreflector (also called a catseye). This optical architecture lends itself to the three-tiered actuation scheme (see section 1.2): a piezoceramic actuator can drive the arbitrarily small secondary flat to form the fine stage, while the succeeding coarser stage actuators drive progressively higher masses at lower bandwidths. This means that the fine stage can drive a very small mass, allowing the use of a small (and hence high resonant frequency and bandwidth) actuator. Driving a very small mass also means generating only very small reaction forces - minimizing disturbances. Furthermore, the geometric layout allows the fine stage to be reactuated at its point of attachment; that is, a duplicate fine stage pointed in the opposite direction is attached "back-to-back" with the working fine stage and driven in identical fashion, providing near perfect cancellation of induced disturbances.

The two coarser stages, the voice coil and motor drive, are not currently reactuated. However, their closed loop bandwidths (and hence induced disturbances) are far lower than the highest closed loop frequency of the ODL, and can also be below any structural resonances. This means the control loop will efficiently reject their disturbances (attenuate by several orders of magnitude), and no amplification due to resonance excitation will occur.

Other options considered during the system level design phase could not match the projected performance of the catseye. The NRL architecture definitely embodies the ADC philosophy.

2.2 Applied to structures and assembly

The field of aerospace structural design is highly evolved. The needs to minimize weight and maximize reliability or usable life have driven the development of sophisticated analysis techniques and empirical data bases. We will not attempt to encompass this vast knowledge base here, but will focus on specific areas of the highest utility to optomechanical devices.

To illustrate these areas of design epitomizing the Apriori Design Concepts philosophy, Figure 3 depicts two designs of a catseye. One utilizes typical design features that are opposed to the ADC paradigm and could harm the performance of optomechanical devices. The other embodies several ADC preferred design features.

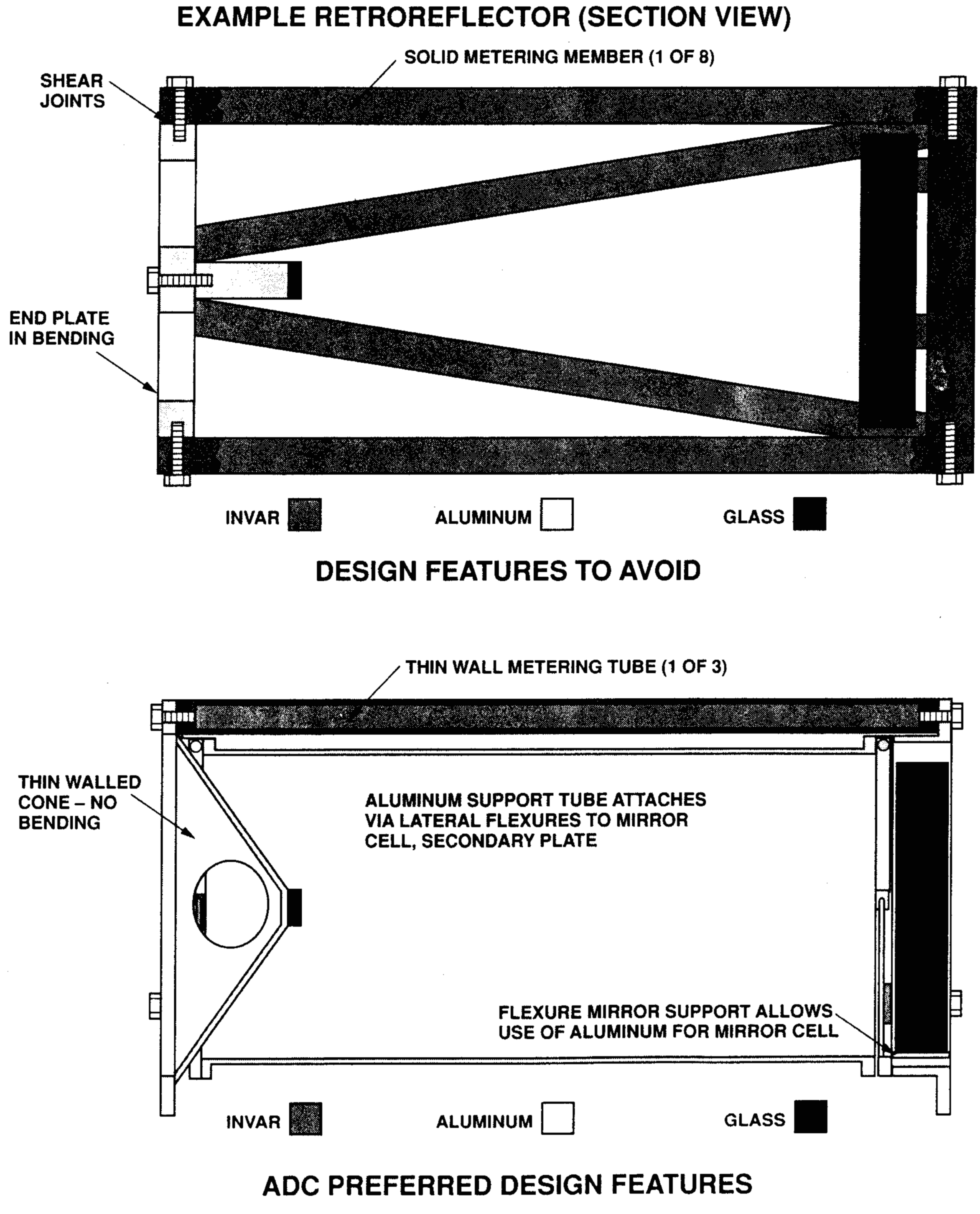

Figure 3 Structural Design Example

2.2.1 Choice of structural configuration

Modern optomechanical devices can be extremely complex, but a simple statement can be made concerning the mechanical structure: it is that portion of the device which supports and holds in alignment the various optical and electrical sub-components, and provides physical attachment to the outside world. An efficient structural configuration, according to the ADC paradigm, would be one that is rigid and light weight. These two qualities would allow the best maintenance of alignment, the highest structural resonant frequencies for the highest usable actuator bandwidth, and the lowest mass for the lowest possible actuator power consumption. For laboratory equipment, this last advantage could be re-cast as: the lowest mass which allows the use of the smallest actuator, which typically has the fastest time constant, for the quickest response.

To arrive at an efficient structural configuration, keep the following ideas in mind:

1) Use structure in tension / compression - avoid bending members if possible
2) Where bending members are necessary, use deep, light-weighted sections
3) Consider separating the function of structural support and metering
4) Keep precision adjustments and mechanisms out of main load path
5) Coefficients of thermal expansion (CTE) between components do not necessarily have to match; determinate supports can be used
6) Utilize determinate supports to minimize distortion and creep
7) Low assembly CTEs can be attained with common materials

The lower catseye in Figure 3 illustrates all of these ideas. The first two ideas are fairly basic and need no explanation. The third idea allows a minimum weight structure to be generated where metering is to be accomplished with Invar or glass. As depicted in Figure 3, the lower catseye accomplishes its metering by controlling piston between the primary and secondary in only three places, here using thin walled Invar tubes for minimum mass. Lateral motions of the primary and secondary are controlled by flexured attachments to a thin-walled aluminum support tube. To address the fourth point: structural connections to the outside world (in the case of the ODL, the flexures that allow axial motion of the entire catseye as the mid-range motion stage) also attach at the support tube, isolating the optical elements and their precision alignment stages from the main load path.

The fifth point deals with determinate, or so-called kinematic attachments between components. In the lower illustration in Figure 3, the mirror cell is attached to the mirror through a set of flexures. This set of flexures is designed to support the mirror in all its degrees of freedom without overconstraining it. This in turn means that dimensional changes in the mirror cell relative to the mirror are accommodated without inducing stresses / deformations in the mirror. Thus the mirror cell can be made of inexpensive, light-weight aluminum, and its high CTE does not affect the mirror quality. More discussion of this concept for optical element support is found in section 2.4.

The sixth point is a more general statement of the fifth point. A determinate support, that is one that controls only the six motion degrees of freedom necessary between two bodies, will minimize induced forces due to thermal distortion, assembly errors and other dimensional changes. Keeping interface forces small not only means low stress and distortion in sensitive components, it also means creep type deformations (resulting in change / loss of alignment) are unlikely to occur.

These two points both deal with a very important fundamental of optomechanical design: knowledge of, and control over support (or motion) degrees of freedom (DOF). The six DOF mentioned above are the three translations and three rotations that can exist between two bodies. Controlling these six DOF, and only these six, results in a determinate support. Controlling fewer DOF results in free motion of the remaining DOF - important for motion stages in an active device. Controlling more DOF results in overconstraint of the interface, possibly leading to distortion and creep. In an ideal world, any time two components are bolted together, their interface would be determinate.

The final point deals with a useful design trick: it is possible to create a low effective CTE in an assembly by using longer metering rods than necessary and "back-stacking" to the support point with a higher CTE material. In effect, the assembly CTE is the length-ratioed difference in CTEs of the two materials used. This is illustrated in the lower half of Figure 3, where the secondary mirror is attached to an aluminum cone whose base is supported by the metering rods. The effective CTE of this arrangement is: metering rod CTE times its length, <u>minus</u> cone CTE times its length, divided by the distance between the mirrors. This trick can be used to easily attain assembly CTEs of 20% of the metering rod CTE. Lower assembly CTEs would require actual measurement of component material CTEs for matching purposes.

2.2.2 Choice of materials

One of the mandates of the ITP was to design for minimum cost. An early decision in the design process was then to avoid the use of composite materials if possible. This has proved to be no great hardship: aluminum has always been the workhorse of the aerospace industry - it is inexpensive and light weight; and the trick of "back-stacking" mentioned above allows acceptably low assembly CTEs using the combination of Invar metering tubes and aluminum back-structure. The temporal instability of aluminum was not a serious issue either because the ODL design is insensitive to perturbations of this order.

In a few places of the design, aluminum was not acceptable because of strength or fatigue considerations. Here, high strength steels were used. These materials have comparable specific strengths to composites, and much more empirical data on fatigue and failure.

All of the above adheres to the ADC paradigm: we utilized materials that are well-characterized to avoid reliance on testing and analysis to prove the design.

Many of the design concepts mentioned in this paper could be accomplished using composite materials. However, it is likely that use of composites would lead to entirely different optimal design concepts from those presented here. Some of these concepts may be geometrically simpler than those presented here, but would require more analysis and testing. This extra work, coupled with the ITP cost and schedule mandates and a desire to avoid outgassing issues, are what led us to avoid composites. Basically, current use of composites is somewhat at odds with the ADC paradigm.

2.2.3 Design of joints and interfaces

The quality of rigidity mentioned in section 2.2.1 really has two components: stiffness, which is a materials and geometry issue; and lack of creep, which depends on the proper design of the mechanical interface between components. The best design for a bolted joint or interface in a high precision optomechanical device is: don't have one at all. Design for a monolithic device if possible. If not, design using the minimum possible number of interfaces. Many of the causes of alignment changes in an instrument stem from slip or creep in joints.

Where joints between components are required, strive to make it a determinate (kinematic) connection, as described in section 2.2.1. Beyond this, try to make the local interface plane or mounting surface normal to any loads carried through that point, and, of course, orient bolts normal to the interface. Avoid the use of shear joints - that is, interfaces that carry loads parallel to the mounting surface. Employing these ideas will reduce creep to a minimum. See section 2.3.x for more on this subject.

Additional reasons to use kinematic interfaces are ease of manufacture and assembly. If an interface is kinematic, there will be fewer tight tolerances on its machining, and assembly is simply a matter of bolting together: there should be no cut-and-try or complex shimming.

2.3 Applied to motion control and moving elements

This area is perhaps the most important for the ODL, with its high dynamic range of motion. It is crucial that the coarser stages not contaminate the finer stages with any sort of jump or uneven motion. This section describes applications of the ADC paradigm to the motion control concerns of the ODL, and optomechanical systems in general.

2.3.1 Choice of motion stage

We use the broadest possible definition here: any place on the device where relative motion between components can occur will be termed a motion stage. This would then include not only the driven stages of the ODL (fine: piezo, mid-range: voice coil, coarse: motor), but also the metering rods for the catseye, the lateral supports for the tip/tilt motion of the mirror cell, and the preloading mechanism for the band drive of the coarse stage.

The following guidelines can assist in the definition of a motion stage:

1) Avoid sliding contacts - prefer rolling contact
2) Prefer flexured stages over rolling contact stages - for linear motions less than 1 cm or rotary motions less than 10 degrees, always consider flexures

3) Minimize number of moving parts to maximize life

The first point should be obvious to most - any motion stage designed as a slider will exhibit hysteresis (stick/slip), generally high operating friction (requiring high actuator power), and wear. What may not be obvious is that this statement also applies to such things as preloading mechanisms: a coil spring or belleville washer preloaded against a surface will exhibit hysteresis and wear under motion normal to the surface. These problems may yield to sufficient analysis and testing, but it would be best to avoid them altogether.

Barring the use of magnetic levitation, the next best option for long stroke motion (>1 cm) is rolling contact. Wheels with anti-friction (rolling element) bearings operate reliably with minimal friction and wear. Contact stresses are easily calculable, enabling reliable life predictions. In particular, angular contact bearings can be preloaded together (giving a known load for life calculations) to run quietly with no play, ensuring repeatable rotary motion of a wheel or stage. For linear motion, the wheels should also be preloaded against their running surfaces to avoid lateral gapping or chatter, and the arrangement of the wheels should form a determinate connection.

The optical delay line actually uses eight wheels arranged in four pairs for its coarse motion stage. The pairs run on V-shaped rails and are preloaded against them by adjusting the lateral spacing between pairs. This forms an indeterminate or overconstrained connection with the rails, but this was done on purpose to provide load equalization throughout the trolley. The overconstraint is removed by the elasticity of the rails and a special pair of flexures in the trolley.

Although bearings are good at linear and rotary motion, there are drawbacks. There is some stick/slip and running torque variation observable in rolling elements, some amount of incalculable wear, and tolerances on balls and races allow for small but measurable amounts of runout and noise. To avoid these problems, flexures should always be considered for motions within their capability. The ranges mentioned above are not hard limits to the use of flexures, but do indicate the point at which flexures become more easy to design for devices the size of the ODL.

Finally, strive to minimize the number of moving parts (a moving part being defined as anything that rolls or slips on another part). The smaller the number of moving parts, the fewer the contacting surfaces for wear to occur or debris to jam. This will maximize life and reliability.

2.3.2 Flexure Stages

If an optical delay line can be considered a typical optomechanical device, most motion stages can be accommodated with flexures. For the ODL, there is the one coarse stage utilizing wheels on rails, and all the rest (voice coil stage, piezo stage and its reactuator, primary and secondary tip/tilt stages, band drive preloading mechanism, trolley torsional flexures, and base kinematic mount) are handled with flexures. In all, there are 36 different flexures in the ODL.

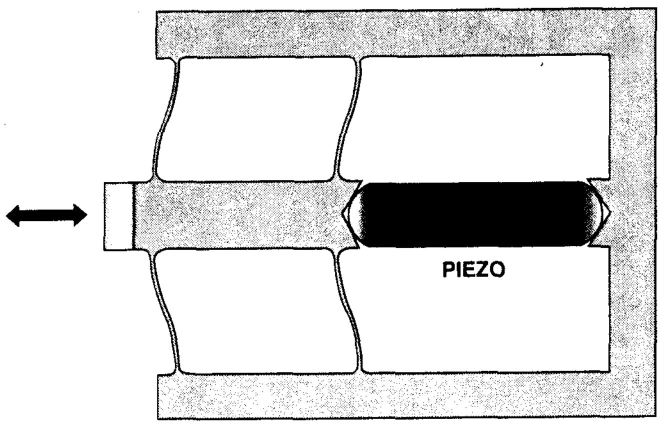

Figure 4 Schematic of ODL Fine Motion Stage

Figure 4 shows a schematic of one of the prominent uses of a flexure stage on the ODL - the piezo driven fine motion stage. This figure illustrates some of the benefits of using flexures. First off, note the simplicity. The mirror holder (moving part), flexures, and base are all one part (some simplification here - the conical pit portion of the base is actually a separate part, to allow installation of the piezo). As a monolithic structure, there is no worry of tolerance stack-up on parts, no assembly headaches and no possibility of creep. Fatigue in this situation is perfectly calculable. As with all types of flexures, there is no friction or wear and the motion is perfectly repeatable.

Secondly, note the synergism in the design. The four flexure blades form a parallel motion set, enforcing true straight line motion of the stage. As a consequence of this they also resist bending moments due to lateral loads of the secondary mirror, allowing the piezo element to be de-coupled in those degrees of freedom (bending stress is fatal to these brittle materials). Finally, the flexure elements can be deformed some amount on assembly, generating a definite preload that places the piezo safely into compression.

The last significant design features of this piezo stage are the hemispherical end caps on the piezo and the conical pits they ride in. These features allow the piezo to be simply inserted into the base for assembly with no regard for parallelism of the mating surfaces, no concern for assembly-induced stresses, and (in conjunction with the preloading) no need for bonding.

Of course, it is usually impractical to make an entire device monolithic. Flexure stages, though, perform admirably even when composed of separate pieces. Figure 5 shows three different executions of a flexure designed to accommodate lateral motion of the upper mounting plate. All three of these concepts were used on the ODL. The left hand version is the simplest to implement and the least expensive to manufacture. It performs its function well (stiff along its axis, compliant in the transverse direction), but may creep slightly under high loads. The middle version is slightly more difficult to make, but the spherical end cap and conical pit combination means virtually no creep under loads and allows the flexure to accommodate larger angular misalignments. The monolithic version, for comparison, is the most expensive to fabricate, but does not creep and has the highest reliability.

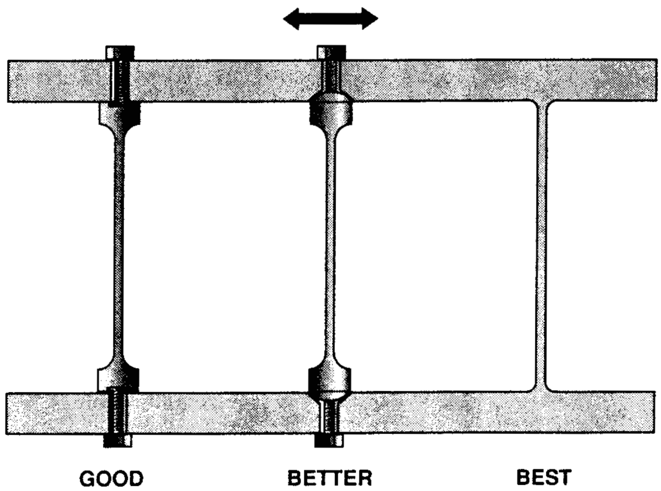

Figure 5 Different Flexure Design Executions

To recapitulate, flexure stages are highly repeatable, exhibiting no friction, hysteresis or deadband. Their usable lives are easily calculable, being subject only to fatigue due to bending stresses: there is no wear mechanism. . They can be used synergistically to provide constant preloading and dynamic load relief for the actuator in addition to motion control. All of these qualities make flexures an important tool in optomechanical design and the ADC paradigm.

2.4 Applied to optical element mounting and alignment

Since the ODL uses only reflective optical elements, a mirror will be used as the example in this section. The mounting design presented, though, is directly applicable to some types of transmissive optics.

To apply Apriori Design Concepts to optics mounting and alignment, first establish the important performance parameters:

1) Support the optic and maintain alignment through all loading and thermal conditions
2) Provide for relatively easy and accurate alignment adjustment
3) Simplify and eliminate workmanship, guesswork

Supporting the optic for the ODL means surviving launch vibration and shock without damage to the mirror or cell. For the mirror, this means mounting it in such a way so as to avoid point or line contacts, which would produce excessive stresses in the mirror. For the cell, survival is simply a matter of designing in enough strength for the specified environment.

The real challenge is maintaining alignment through the launch an thermal environments. Please note that the vibration environment typically produces hundreds of g forces response, the shock produces thousands of g forces (albeit at very high frequencies), and the thermal survival levels were +/- 40°C excursions around room temperature. How does one design for these extreme requirements?

First, determine the possible causes of shifts in alignment. From section 2.2.3, one primary cause is creep in structural joints. Other contributors may be material creep in elastomerics (if these are used for optic support and thermal compensation), creep of preloading mechanisms or mounting threads, or gap tolerances of sliding fit mounts.

The Apriori Design Concepts solution for these problems is to simply remove them. As suggested in section 2.2.3, removing joints is the best way of removing creep, and this applies to structural joints, mounting threads, preloading mechanisms and just about everything else. Figure 6 below depicts the mirror cell solution for the ODL. Here we show the mounting scheme, the adjustment detail is given in a later figure. Here we have gone almost totally monolithic: the outer framework of the mirror cell and the flexures that support the mirror are all one piece. This removes most sources of creep and makes the unit extremely simple. To actually connect to the mirror, Invar tabs are bonded to the rim with epoxy. These tabs have relatively large bonding areas to keep stresses to a minimum. The only bolted joints, then, are between the mirror tabs and flexures. Looking at the schematic on the left, the interface planes for these joints are oriented in the plane of the page so that creep out of the page, and hence tip / tilt / piston creep, is minimized.

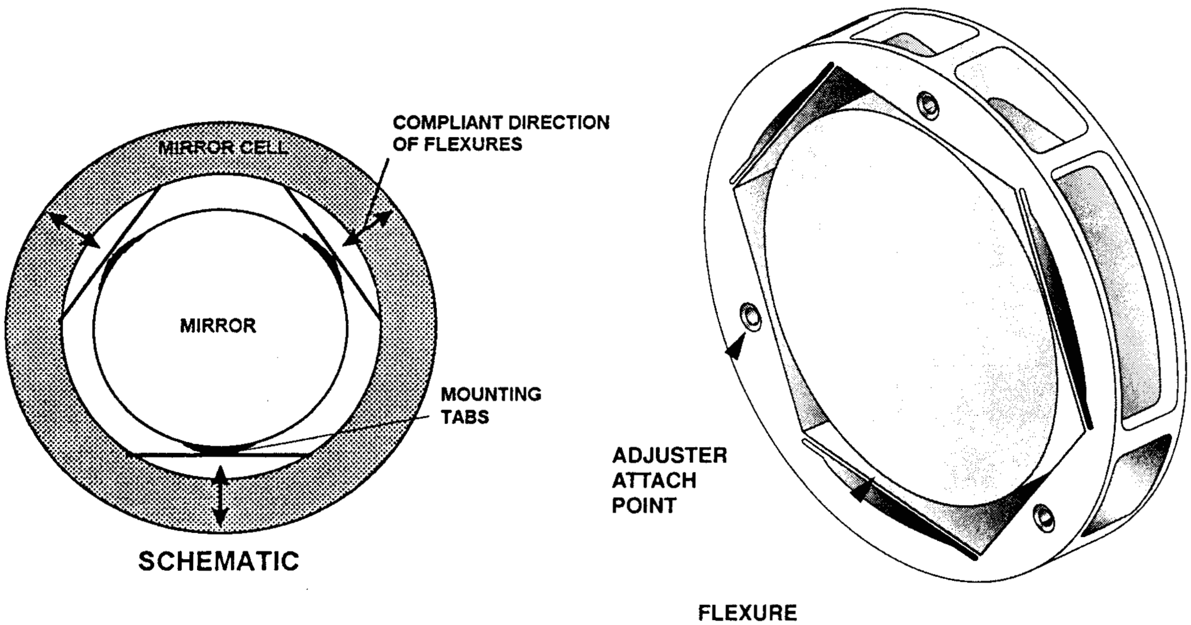

Figure 6 ODL Mirror Cell

The flexure arrangement used to support the mirror is pseudo-kinematic. The degree of determinacy is such that there is no need to match CTE between the glass and cell, i.e. the flexures are compliant in directions (see schematic) such that mechanical or thermal distortions are not transmitted to the mirror. This gives us the freedom to use aluminum for the mirror cell, and then remove unnecessary material to produce an extremely stiff, light weight structure.

The adjustment scheme for the mirror cell is shown in Figure 7. Three threaded rods pass through the mirror cell. Two nuts are used on each rod, above and below the cell, to cage it and provide positive vertical adjustment. Three lateral flexures (not shown) control the remaining degrees of freedom. So far this is a fairly standard design. Improved functionality is obtained, however, from the use of a cone-and-ball interface for the adjustment nuts. The spherical end on a nut riding in a conical recess on the mirror cell removes a level of positioning ambiguity, and prevents lateral creep of the nut. These two features make the three adjustment rods an exceptionally stable tip/tilt/piston stage.

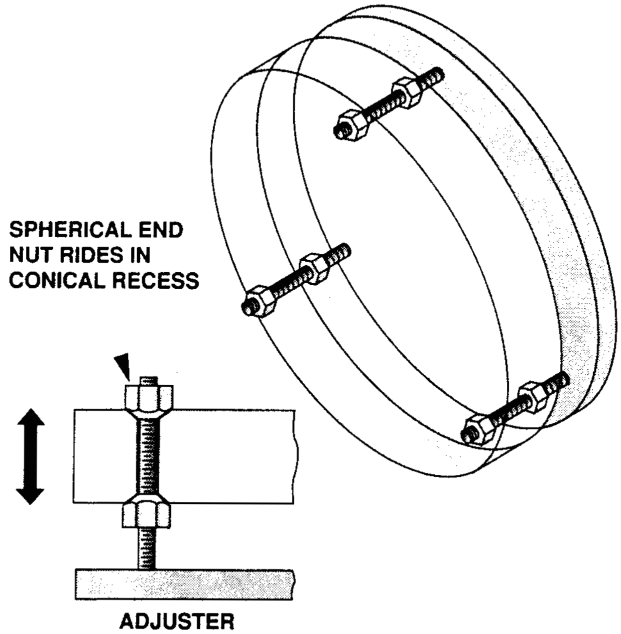

Figure 7 Mirror Cell Adjustment Stage

The rods and nuts use a relatively coarse thread, and one would think the corresponding adjustment capability equally coarse. As it turns out though, the combination of two nuts on a rod has a sort of built-in vernier stage. Once both nuts are seated, torquing down on one nut will create minute elastic deformations in the threads of the nuts and rod. These deformations are much smaller than the displacements caused by controllable nut rotation, effectively giving this simple stage sub-micron and sub-arcsecond positioning capability.

A separate test article using this adjustment concept exhibited an alignment shift of less than an arcsecond after being subjected to flight-equivalent random vibration.

2.5 Applied to motors and drive mechanisms

In this section we discuss the major criteria that led to the choice of the specific motion mechanisms for each stage of the ODL. Illustrating the selection process and indicating some alternatives makes it more applicable to optomechanical systems in general.

2.5.1 Coarse Stage

The key requirements for the ODL coarse stage motor and drive were to have minimum mass and power consumption, to induce a minimum of vibrational and electromagnetic disturbance, and to have maximum reliability. The required slew and tracking rates are 10 mm/sec and 2 mm/sec respectively. An additional benefit would be to have the drive be as "stiff" as possible; that is, it should track commanded position very well in the presence of fluctuating forces such as variances in wheel running torque, imperfections in the track, etc.

There are many types of motors and drives that could accomplish the one meter stroke and slew and tracking speed requirements of the coarse stage. Some examples are: DC brush motors, linear and rotary stepper motors, and linear and rotary DC brushless motors. The rotary motors need a rotary-to-linear conversion drive such as a lead screw, ball screw, belt drive or friction wheel drive. There is a further choice of using the rotary motor directly (hard-coupled), or through a reduction stage such as a gear head, harmonic drive, or friction wheel reducer.

Some of these choices could be discounted almost immediately: brush motors and lead screws involve sliding contacts that create wear / reliability concerns; linear motors are heavy; and gear heads are noisy (on the scales we care about).

The final choice was a DC brushless motor, through a 100:1 harmonic reducer drive, to a belt drive (belt-on-pulley). The DC brushless motor has no contacting moving parts in itself (good reliability) and the best torque-to-weight ratio of the motors mentioned (low mass and power consumption). The harmonic drive provided enough reduction to allow the use of a small motor (lower power consumption, electromagnetic interference), yet allowed it to rotate slowly at tracking speeds (vibrational disturbances low, and kept at low frequencies). This level of reduction also provided sufficient inertial "stiffness" passively; that is, without the need for augmentation by high bandwidth feedback. The belt drive is one of the lowest mass choices, and separates the motor from the trolley (lower vibrational disturbances).

2.5.2 Mid-range stage

The requirements for the mid-range stage are the same as for the coarse stage, with one important exception: it would be a benefit here to have the stage be as "soft" as possible; that is, isolate the catseye from axial coarse stage and outside disturbances as much as possible. From Table 1, the required stroke is 3 mm and the maximum usable bandwidth should be 100 Hz.

The desired stroke of the mid-range allows the use of flexures, so we immediately went to this solution. The flexure stage also provides the desired isolation since the catseye on flexures forms a low frequency oscillator with a second order roll-off.

Choices for motor devices are the same here as for the coarse stage, with the modification that linear brushless DC motors include voice coils, a more efficient but small stroke conformation. The benefit of the soft flexure stage would be lost however, if the motor or drive introduced any spring or inertial stiffness. This precludes the use of any rotary motor (the conversion drives introduce spring and/or inertial stiffness) and the linear stepper (because of magnetic detent force), leaving the voice coil as the best candidate.

The synergism of motor, drive, and motion control stage is evident in the descriptions of both the coarse stage and the mid-range. Additional synergisms for increased performance are found by comparing the driven mass of the stages to their motors. The ADC goal of minimizing mass and maximizing stiffness (for maximum resonant frequency and hence performance) has carry over to motor performance. For the mid-range stage, lower mass means lower drive force, which means a smaller actuator with a shorter time constant. This means a higher possible bandwidth or, as in the case of the ODL where that bandwidth was far in excess of the requirement, a trade to a finer coil winding which lengthens the time constant but increases the force constant (i.e. reduces current and hence feed line power dissipation and electromagnetic interference). This trading-off of excess bandwidth can be continued: a somewhat larger voice coil can be used, thereby obtaining a better motor constant (lower device power consumption) at the expense of a longer time constant.

2.5.3 Fine stage

The ODL fine stage has the same requirements as the coarse stage, with a desired stroke of 15 microns and a usable bandwidth of 1000 Hz.

To attain the bandwidth requirement, a high resonant frequency is necessary. This means the motor unit must be a solid brick of some electrodynamic material: either piezoelectric, electrostrictor, or magnetostrictor. Our choice was the piezoelectric because of its low mass, fast response time and ready availability.

The motion control portion of the stage utilized flexures, as described in section 2.3.2.

3.0 OPTICAL DELAY LINE PERFORMANCE SUMMARY

The tangible result of this design effort was a flight-qualifiable optical delay line. The previous sections have detailed the structural, mechanical, and electrical point designs used in creating the ODL, and how the Apriori Design Concepts paradigm provided an overall guiding philosophy. Summarized below are the ratings of key functional requirements, significant design features, and the results of performance and environmental testing.

Table 2 Optical Delay Line Performance Results

1. Majority of structure is aluminum
2. Maintains chosen optical figure of merit
3. Usable depth of focus calculated at 25 μm
4. Retroreflector is athermalized to 0.25 μm/°C
5. Deviation from straight line motion of coarse stage can be adjusted to less than 0.03 mm
6. Voice coil stage break frequency of 3.5 Hz
7. Slew rate greater than 10 cm/sec
8. Measured pathlength jitter at tracking speed is less than 5.0 nm RMS DC to 1.0 kHz
9. Mass is 13.06 kg
10. Power consumption at device estimated to be less than 2.5 W
11. Survived random vibration test - over 200 g's response
12. Survived shock test - input up to 3000 g's
13. Demonstrated operation in vacuum, survival of temperature extremes

4.0 CONCLUSIONS

At the most fundamental level, we have developed or re-stated concepts useful for high performance optomechanical design. On a higher level, we have demonstrated a multi-disciplinary design philosophy that, at least for the optical delay line, generates even better performance from the synergy of the individual design concepts.

5.0 ACKNOWLEDGEMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.