Summary of the CELT Mirror Segment Actuator Survey

February 20, 2001
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I. Overview and Summary of Requirements

The California Extremely Large Telescope (CELT) will require in the neighborhood of 4000 linear actuators for the control of the primary mirror segments, including spares . The requirements for the actuators are summarized in the table below.

Table 1: Actuator Requirements

Total Stroke	≥ 1.2 mm
Commandable Positioning Resolution	≤ 4 nm
Incremental Positioning Accuracy	the larger of ±4 nm or ±10% of Incremental Move (note 1)
Tracking Accuracy (note 2)	≤ 7 nm RMS for errors above 0.2 Hz in Frequency
Tracking Rate (note 3)	0 to 170 nm/sec
Command Rate (note 4)	≥10 Hz
Slew Rate (note 5)	≥ 10 μm/sec
Axial Load Capacity	≥300 N
Transverse Load Capacity	≥> 5 N
Axial Stiffness	≥ 10 N/μm
Transverse Stiffness	≥ 0.1 N/μm
Average Power Dissipation (note 6)	≤ 2 watts
Operating Temperature Range	2 ±8 °C
Survival Temperature Range	5 ±25 °C
Operating Humidity	0 to condensing
Cost (note 7)	≤ $2000

Notes:

1. For example, if an acuator starts at a zero position and is commanded to move 30 nm, the final position should be between 26 nm and 34 nm. If it were commanded to move 100 nm, the final position should be between 90 nm and 110 nm.
2. This is the accuracy when following a trajectory. We presume that there is an external closed-loop around the position of a mirror segment that can sufficiently attenuate any errors below 0.2 Hz.
3. This is the rate at which the tracking accuracy must be met.
4. This is the rate at which the actuator will accept and execute position commands from an external source.
5. This is the maximum rate for actuator travel. No particular accuracy requirements must be met when moving at this rate.
6. Power includes electronics.
7. This is the cost for the entire acutator and electronics in large quantities and in a plug-and-play condition. For the purposes of the survey, potential vendors were told that the acutator must cost less than $1800. This 10% reduction is based on the observation that in preliminary surveys interfacing details are often overlooked.

In addition to the requirments above, there are other criteria that the actuator must meet which are more difficult to quantify for the purposes of a design specification. Nevertheless they are important. These include:

> Lifetime and Reliability: At the end of 10 years of operation, we desire a less than 1:2000 chance that any particular actuator will fail in the following year.
>
> Environmental Suitability: The actuator should not be susceptible to damage from the sort of conditions found in telescope operation. These conditions can include
>
> --years of accumulated dust and grit,
> --exposure to magnetic fields such as from large electric motors, transfomers, and welding equipment,
> --exposure to electric fields generated by devices such as high voltage arc lamps or piezoelectric drivers,
> --exposure to other sources of interference such as 60 cycle fields from the utility power and RFI generated by reasonably shielded—but not perfectly shielded—digital equipment.
>
> In addition, the devices must not generate interference that would be objectionable to the instruments and data acquisition systems that are used with a telescope.
>
> Ease of Installation/Maintenance/Removal: Maintenance personnel should be able to remove and replace an acutator with common tools in a short time (minutes). This rules out complicated alignment or adjustment procedures. Further, the actuator should require no periodic maintenance, or at most, maintenance that can be done quickly (less than one working shift) and infrequently (less than once a month) for the entire set of acutators.

We have found five general actuator types that may eventually meet the requirements of the CELT project. Listed in no particular order, they are:

Table 2: Candidate Actuator Types

Name	Brief Description
Conventional Lever	Motorized micrometer and flexured lever.
High Resolution Micrometer	Direct motorized micrometer with no external reducing mechanism.
Elastic Lever[1]	High ratio elastic lever reducer and coarse actuator.
Voice Coil	Voice coil actuator with position feedback.
Inchworm	High capacity inchworm using piezoelectric or magnetostrictive materials.

We have found no acutuator that will unequivocally meet all the requiments at the present. The most common difficulty is uncertainty about the lifetime and reliability of the mechanical mechanisms. The particular issues are wear and surface failure of the sliding and rolling elements. These mechanisms generally operate in a regime where existing analytical tools are unreliable, and where relevant experience outside of the Keck telescopes appears to be nil (see Section II). As a practical matter, one must test the actuators to ascertain their reliability.

In the two candidate actuators that that use no sliding or rolling elements—the inchworm and voice coil—the life issue is more tractable in advance. We can say with some confidence that the mechanisms can be designed with the required reliability. Each of these actuators, though, has its own particular issues that must be addressed. For the inchworm, it is the performance of the clamping mechanism; for the voice coil,

[1] The Elastic Lever actuator discussed in this report is based on a concept provided by Alson E. Hatheway. The concept is patented, and the patent is held by Alson E. Hatheway, Inc. (626)795-0514.

the necessary output sensor. While there is little doubt that one can implement a suitable technical solution for each of the questionable areas, some uncertainty still exists regarding the final costs of those solutions.

II. Preliminary Notes on Reliability and the Keck Telescope Actuators
Most of the actuators considered contain some sort of sliding elements (e.g. a screw and its nut) or rolling elements (e.g., ball screws or roller bearings). In a typical situation, one would resort to semi-empirical relations to predict the service life for such elements. The situation with the mirror actuators is, however, not tyipical.

Sliding Elements
In the case of the sliding elements, the usual relationship used to predict the rate of wear[2] is:

$$\frac{dV}{dt} = K \cdot F \cdot v$$

where

$\frac{dV}{dt} =$ Volumetric material removal rate.

$K =$ Empirical constant based on the materials and lubrication involved.

$F =$ Normal force between the wearing surfaces.

$v =$ Relative velocity between the wearing surfaces.

A difficulty arises because this relationship presumes that the particles generated by the abrasion of the surfaces do not contribute substantially to their wear. In other words, it assumes that there is enough motion so that the wear particles have an opportunity to be expelled from the gap between the surfaces and that they generally do not reenter the gap.

In the case of the mirror actuators, this may not be the case for some regimes of operation. One would expect that at times some actuators are more-or-less holding a fixed position. The position would not be truly fixed since the actuators will always be operating to reject disturbances, and they will actually be making small excursions about a nominal position. If the sliding surfaces were a typical micrometer screw and nut, the relative motions would be on the order of 0.1 μm. It is unlikely that this is enough to clear particles from the gap

Rolling Elements
For rolling elements, the usual reliability calculations presume that the limiting factor is surface fatigue of the material. Life predictions are then made based on an empirical fit of test data to a Weibull distribution. For things such as ball bearing in electric motors, the calculations are remarkably good—much better than 10% with regard to statistical life.

In the case of the mirror actuators, these calculations may be misleading. It is likely that so-called "micro-welding" will be and important factor in the life of the rolling surfaces, and this in fact may be the limiting factor. Surface fatigue calculations do not account for this sort of wear.

Micro-welding occurs when two metal surfaces come in intimate contact and the surfaces then stick. When motion resumes, a particle of material is pulled from one surface or the other. This can occur when the lubrication is squeezed from between two stationary (or nearly stationary) surfaces and the oxide layer on the surfaces is breached. This results in a visible blackening of the lubricant as the particles accumulate. In more gross instances, the phenomenon is macroscopic and is called galling or scuffing. It is an easily

[2] This is the same relationship used by opticians in estimating the material removal rate when grinding an element.

observed effect between the untreated surfaces of all common aluminum alloys and many stainless alloys--316 and 17-4PH in particular.

Some Representative Calculations and The Weibull Distribution

It is interesting nevertheless to see what a surface-fatigue life prediction would be. As an example, we do the calculation for a roller screw in an elastic lever mechanism (discussed later in Section III). This is a reasonable worst-case since this type of mechanism subjects the screw to higher loads than other mechanisms.

We select a screw with a catalog load rating of 19 kN (Rolvis RV12x1). This is approximately 10 times the maximum load that the screw will experience. With a few assumptions, one might guess that in a 10 year period the screw will undergo 6,000,000 revolutions. We will be conservative and calculate as if all the revolutions occurred with the screw under the maximum load[3].

If we subject a number of screws to their catalog load rating, the expectation is that 10% of the screws will fail within 10^6 revolutions. This is the so-called L_{10} life. If the load were reduced, the L_{10} life would increases as the inverse cube of the load. In our example, we are using a load of 1.9 kN (one-tenth of the catalog rating), and the L_{10} life in service is 1000 times greater than the catalog life of 10^6 revolutions; i.e., 10^9 revolutions.

At our anticipated rate of use, this corresponds to about 1700 years. In other words, we would expect 10% of the screws to fail within 1700 years of service. Using catalog information (or the Weibull distribution on which the catalog information is based), we can also predict that 1% of the screws will fail within about 330 years of service. These numbers are interesting perhaps, but, they are not what we really what we want to know.

Rather, we want the likelihood of a failure in the year following the tenth year of service. For this we resort to the Weibull distribution itself. The cumulative failure density function is

$$P(t) = 1 - \exp(-ut^{a})$$

For roller screws, the parameter "a" is taken as 1.5, and the parameter "u" is chosen to fit the catalog values for the L_{10} life. "t" is the length time for which we want to know the expected number of failures. The rate of failure at any time is then the derivative of the density function.

$$R(t) = uat^{a-1}\exp(-ut^{a})$$

For our example case, we find that the failure rate after ten years of service is about 10^{-4}. In a collection of 3300 actuators, we would expect about a 1-in-3 chance of a screw failure during year eleven. We can also calculate that at 55 years of service, the annual failure rate would be about 10^{-3}.

Comforting though all this may be, it is also dubious.

The Keck Actuators[4]

Less suspect is the accumulated experience with the Keck actuators. While there appears to be no formal study of any failures and their remedies, there is enough anecdotal evidence that one can consider it data.

Specifically, there are no known failures of the roller screws in the Keck actuators. In evaluating this it is important to know the load on the screw, and is it thought to be in the neighborhood of one-twentieth of the catalog value.

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[3] It is really the nut that will fatigue first. The cycles are spread over a larger area on the screw.

[4] Credit and gratitude are due Bob Minor, Joe Killian, and Kyle Kinoshita for sharing their observations and knowledge of the Keck actuators.

While there have been no failures, there is evidence of at least minor wear. During periodic servicing in which the actuators are disassembled, cleaned, and relubricated, metal particles are found on a lubrication wiper that runs against the screw. Notably, the effect of this wear has not been detected in the telescope performance. It would be interesting to examine the screws and nuts under a microscope to verify the source of the particle and perhaps get some indication of the rate of wear in the mechanism. At present, there are actuators that have been in service for more than three years since their last servicing.

During the servicing, care is taken to insure that the components are clean (ultrasonic cleaning, assembly on a clean-bench). This undoubtedly contributes to the life and performance of the actuators. Also, every day all of the actuators in the telescopes are exercised over their full stroke. This probably has two beneficial effects. First, it allows the lubrication wiper to redistribute the lubricant along the length of the screw, and second, it may wipe any particles from the mechanism.

The lubricant, "Technolube B5200", was specially selected and is an oil containing antimony particles. The antimony proved crucial in reducing the stiction in the screws and this may be because it reduces the micro-welding that one would otherwise expect. This would be consistent with the facts that antimony is used in anti-seize compounds and that micro-welding is though to be a source of stiction.

The control algorithm for the Keck actuators was also designed to minimize the wear on any one position of the screw. It prevents the screw from dithering back and forth over any one position and this may prevent the antimony from being worked out of the interface. It would also minimize the damage done by any metal particles that were generated in the interface.

The most common actuator failure is leakage from the hydraulic reducing mechanism. This is usually detected visually as oil on the outer surface. Apparently, the actuators are still functional, although there is undoubtedly an offset in their position.

III. Description of Candidate Actuators

We are presenting candidates that could possibly meet the requirements as outlined in Section I. The descriptions focus on the aspect of the actuators that are notable—either as exceptional strengths or potential weaknesses. If a particular criterion is not mentioned in a candidate's description, it likely means that the requirement is met in an adequate fashion.

Of the six candidates, only the Voice-Coil Actuator requires a position sensor on the output in order to be useful. The other five would benefit from such a sensor, but they may not strictly require it. It was only very late in the survey[5] that the availability of an output sensor became a certainty, and this has an effect on how one views the candidates. If the survey were done again with this new information, it is likely that there would be a different actuator or two in the list, each with a sensor on the output.

This aspect is discussed further in Section IV, and in Section V we list the actuators that were investigated but are not in the candidate list. Among those devices we note the ones that we would consider candidates if a sensor were placed at the output.

<u>Candidate 1: Conventional Lever</u>
Proposed by: CSEM (Swiss Center for Electro-Mechanics)
Contact: Dr. Lorenzo Zago
Complete proposal materials in Appendix A.
Short description: Motorized micrometer with internal position feedback driving a flexured lever.

Figures 1 and 2 show a conceptual layout of two proposed lever actuators. Both devices consist of an off-the-shelf motorized micrometer (Physik Instrumente M-230.25) as the basic actuator and a flexured lever

[5] One day prior to this writing, to be exact.

mechanism to achieve the desired position resolution. The difference between the two systems is the type of reducing mechanism. Depending on space constraints, one may be more suitable than the other. The micrometer itself consists of a screw and nut driven by a gearhead and DC motor. A control loop is closed around a motor-mounted encoder. This yields a minimum commandable move of 50 nm at the tip of the micrometer.

This design appears capable of meeting the structural and environmental requirements and has the advantage of using relatively common commercial components. The lever arrangement in Figure 2 is notable in that it is particularly compact. It appears that it could be quite stiff, light, and accurate. (See the CSEM proposal materials in Appendix A for a better illustration.) In the detailed design, care would be necessary to insure that fabrication costs are reasonable for either lever option, and that ease of installation and maintenance is adequately addressed.

Nominally, the system is capable of meeting the positioning performance requirement; considerable uncertainty exists however with regard to the inevitable backlash in the micrometer. The micrometer manufacturer does not specify the amount of backlash present, but conversations with the manufacturer's representative indicate that it is likely between 0.5 and 1 μm when the device is new. This translates to about 25 to 50 nm at the output of the lever mechanism.

CSEM proposes to use the controller compensate for any backlash. This can be adequate provided that the backlash does not change by too much between recalibrations. It is certain that backlash will increase as the mechanism wears, but the rate of wear cannot be known without testing. Even then, there will be a certain amount of variability in results from different micrometers and questions about how well the tests represent the telescope operating conditions.

Closely related to backlash is the overall life of the micrometer, which is also unspecified and would have to be determined through testing. Particular concerns are the gears, bearings and motor brushes if a brushless motor is not used.

CSEM notes that it is possible to use other actuators in place of the Physik Instrumente micrometer. Specifically, they mention a variation on an actuator they have developed for another purpose which uses a ball screw. This does not change the basic nature of the system, although it may mitigate to a certain extent the backlash and wear issues.

The informal estimate for the cost of prototypes is $75,000 for the first four units. We are still awaiting the official cost proposal from CSEM. In volume, the devices are estimated to cost between $1500 and $2000 including the electronics.

Note that the CSEM proposal materials list a position resolution of 7 nm. This should be 4 nm. CSEM is aware of the error, and it does not otherwise change their proposal.

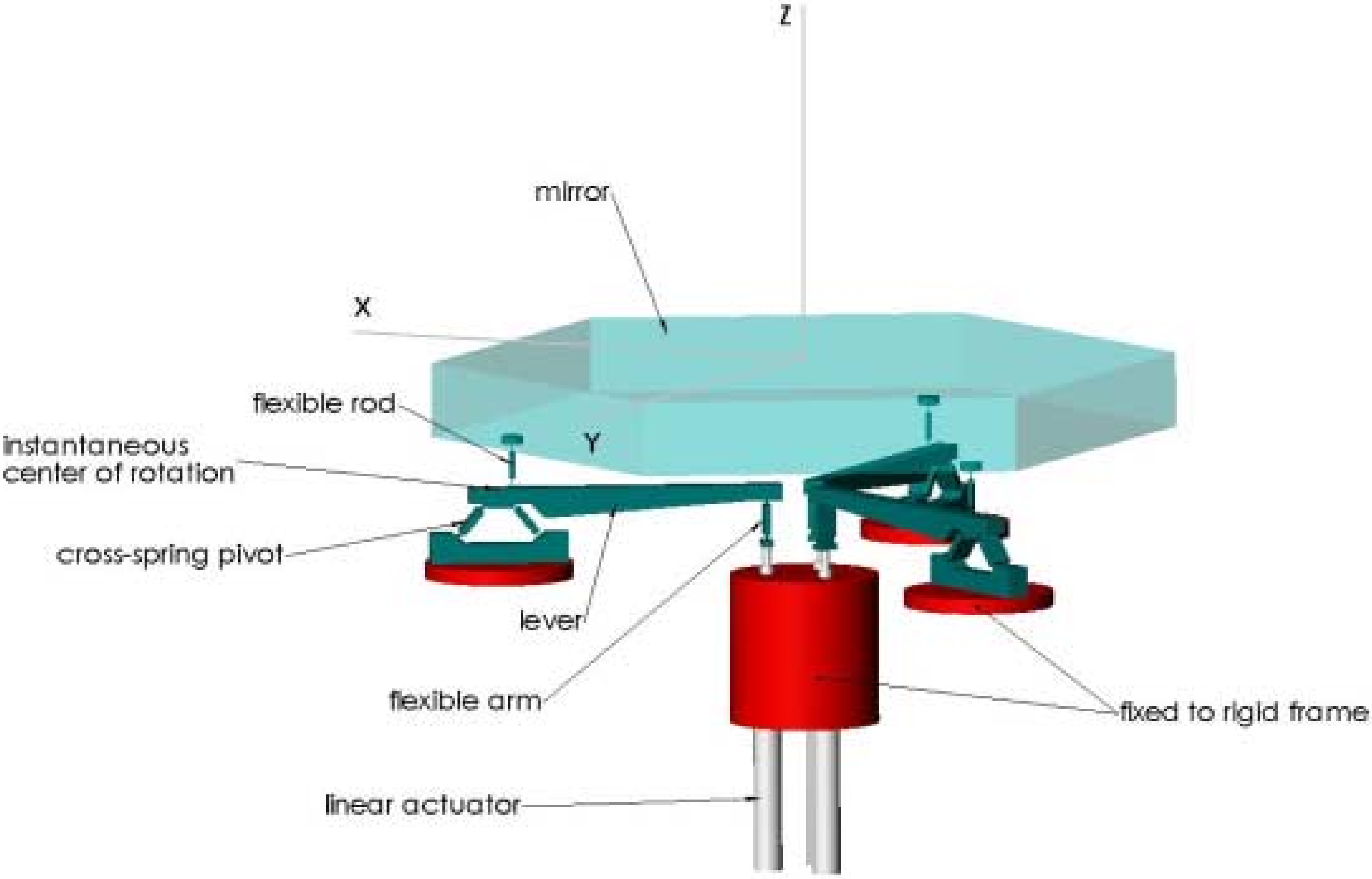

Figure 1: CSEM proposed flexured lever actuator design.

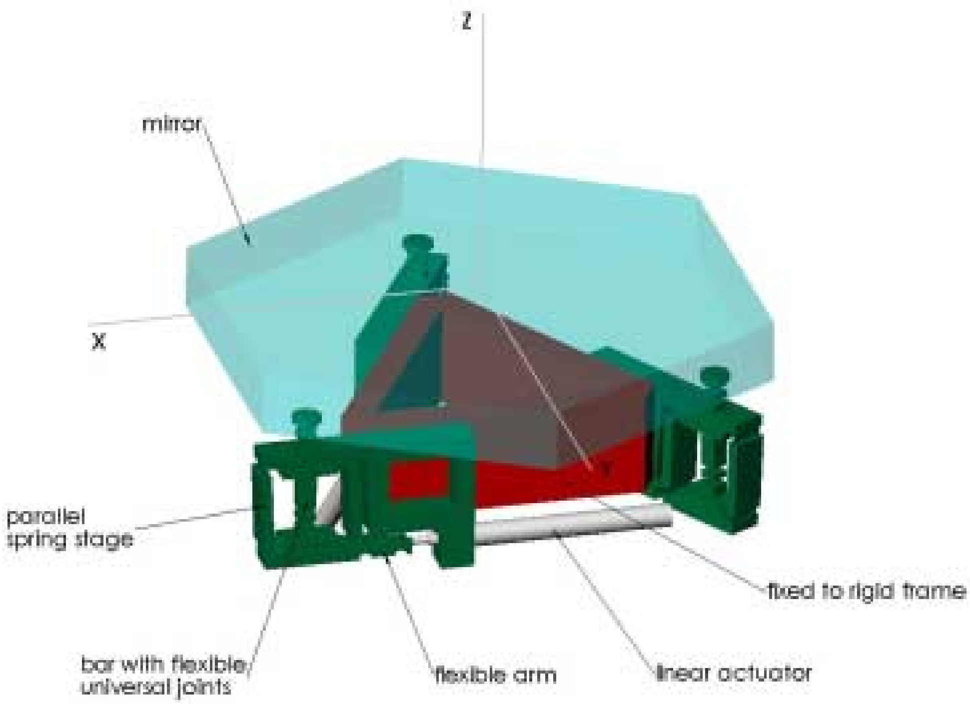

Figure 2: CSEM alternate flexured lever actuator design. This design is more compact than that in Figure 1.

Candidate 2: High Resolution Micrometer
Proposed by: Diamond Motion (formerly TS Products)
Contact: Jim Thomasson
Complete proposal materials in Appendix B.
Short description: Motorized micrometer with high ratio internal gearhead and no external reducer.

Figure 3 shows a schematic design for the actuator proposed by Diamond Products. It consists of a micrometer screw driven by a motor through a high-ratio (>10,000:1) gearhead. This is a variation of an actuator that Diamond Products provided to the Hobby-Eberly Telescope. This actuator's greatest strength is that it is available for less than $2000 in small quantities, drive electronics included. Delivery is 5 weeks after the order is placed.

Some skepticism is justified in evaluating this proposal. Other manufacturers of motorized micrometers specify a motion resolution of 50 nm at best. Diamond Products specifies a resolution of about 2.5 nm, and the president of the company is adamant that this will be the case.

Further, the intent is to have no backlash[6] in the system. While this is strictly impossible due simply to the compliance of the elements in the mechanical system, one cannot easily say that the compliance is unacceptable.

For example, 4 nm represents a rotation of about 40 μrad of a 40-pitch micrometer screw. If the screw is 0.25" in diameter and 0.5" long and made of steel, a torque of about 0.35 in*lb would be required to twist the screw (torsional elastic deformation) the same amount. This torque is of the same order as that required to advance the screw against a 75 lb. mirror load. If it were one-tenth the torque, one would say there's a problem as the screw would "wind-up" excessively.

And still, there are other issues to address including life, reliability, and power dissipation. The latter is presently an issue since Diamond Motion is proposing to use a stepper motor at the input of the gear train. It will require some ingenuity in order to keep the power dissipated in a stepper motor to an acceptable level. Alternatively, a DC motor and encoder could be used, but this would result in an appreciable—but perhaps not unacceptable—increase in cost of the system. The life and reliability issues of the system are almost wholly unaddressed and may be unanswerable except through testing.

Finally, Diamond Products proposes to have the micrometer push against a sapphire pad rather than have a mechanical connection to the micrometer since the tip of the micrometer rotates. This admittedly seems unconventional for the application we are considering, but is often done in lab setups.

Despite all the uncertainties, this device is still a candidate because of the low cost. It is a relatively inexpensive device to investigate further, and an informal estimate of the cost in large quantities is about $750 per unit, electronics included.

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[6] The proposal in Appendix B lists a non-zero backlash geartrain for the prototype actuator. Diamond Products believe a zero backlash unit will be available in several months. This would be important for the prototype actuator.

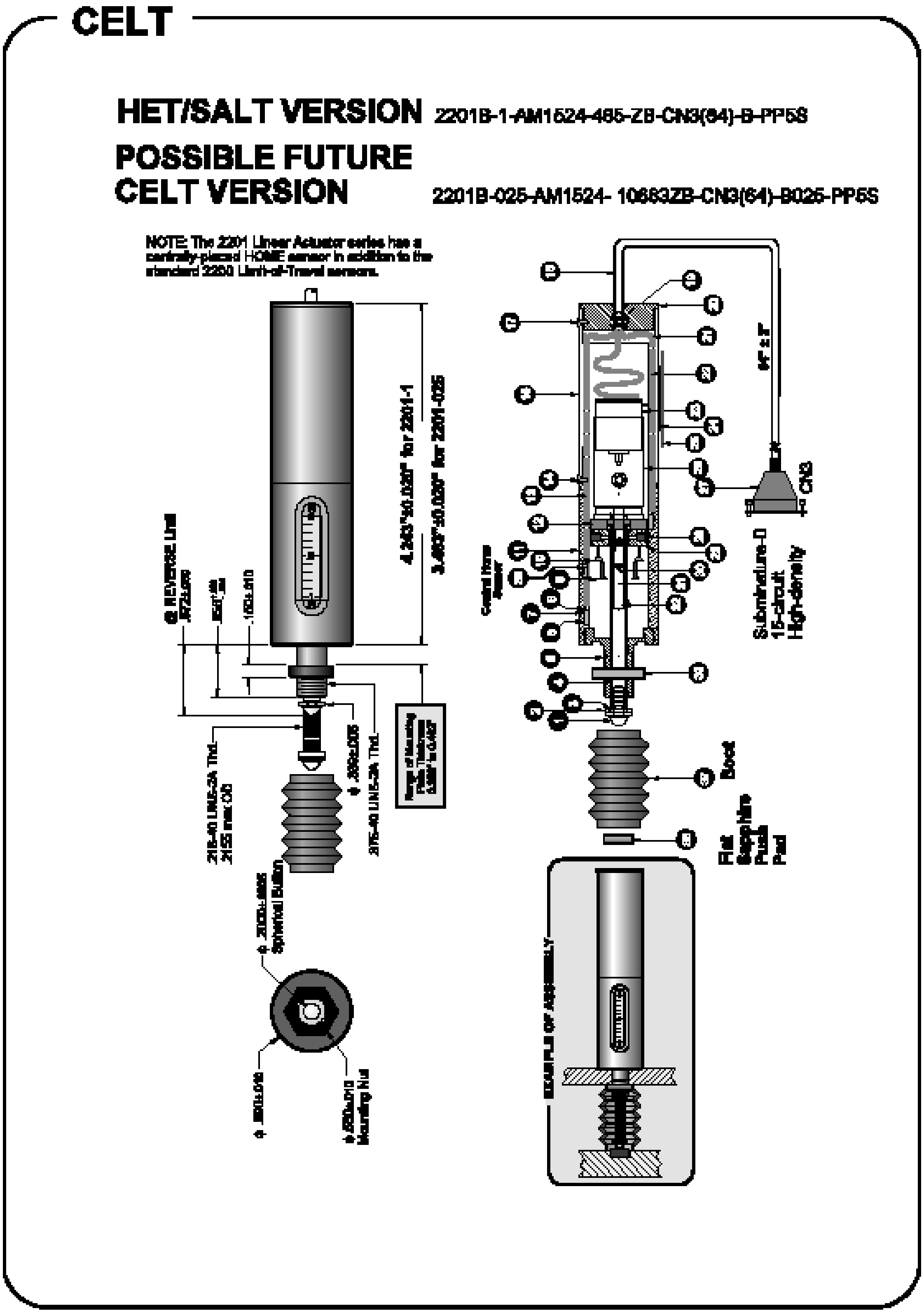

Figure 3: Diamond Products' proposed actuator. It consists primarily of a micrometer screw driven through a high-ratio gear reducer. A better version of this illustration is in Appendix B.

Candidate 3: Elastic Lever
Proposed by: The Pilot Group, after a concept by Alson E. Hatheway
Contact: Alan Schier
Short description: A lever mechanism that relies on the elastic deformation of the lever to achieve the motion reduction. A relatively coarse actuator with position feedback is placed at the input of the lever.

Figure 4 shows a layout drawing of the elastic lever actuator. In this drawing, the motor and gearhead wind up a cable. This draws the ends of the two long rails together. As this is done, the top beam deforms so that the motion the output location has the desired range and resolution relative to the indicated mounting surface.

A position control loop around the motor/cable mechanism means that the mechanism itself need not have particularly good performance. The strength of this concept is that there are no particularly delicate or sensitive components. This includes the position encoder which is normally intended for use in a shop environment (albeit a reasonably clean shop environment). The other mechanical components are generously oversized and could likely be permanently lubricated. The final design would include a cover for the encoder, but the rest of the components could remain exposed.

This design has some of the same uncertainty about wear and reliability as other designs. The uncertainty is mitigated, though, by the encoder at the output of the cable-drive portion of the system. The presence of the encoder means that even with some wear, the actuator/encoder portion of the system could still accurately control the output position.

Since the required stiffness of the output is provided by the elastic structure alone, the stresses present in the system are necessarily larger than in a conventional lever systems. This by itself is not a problem, but it does mean that the structure must have at least one relatively long dimension in order to keep the forces at the actuator manageable. This further means that the mass of this system is larger than otherwise.

A prototype system with electronics and software can be designed and fabricated for $18,800 and delivered within 12 weeks of placing the order. The electronics and software would be suitable for testing the mechanism but would not be representative of a final design.

(Elastic Lever drawing not available on the Web.)

<u>Candidate 4: Voice-Coil Actuator</u>
Proposed by: Blue Line Engineering
Contact: Greg Ames
Complete proposal materials in Appendix C.
Short description: A voice-coil actuator with position feedback around the output.

Figure 5 shows concept drawings of the proposed voice coil actuator. It consists primarily of a large voice coil with two diaphragm flexures to support the armature. An eddy-current sensor is used to measure the position of the armature relative to the housing. The device functions as a position actuator since a control loop is closed around the position sensor.

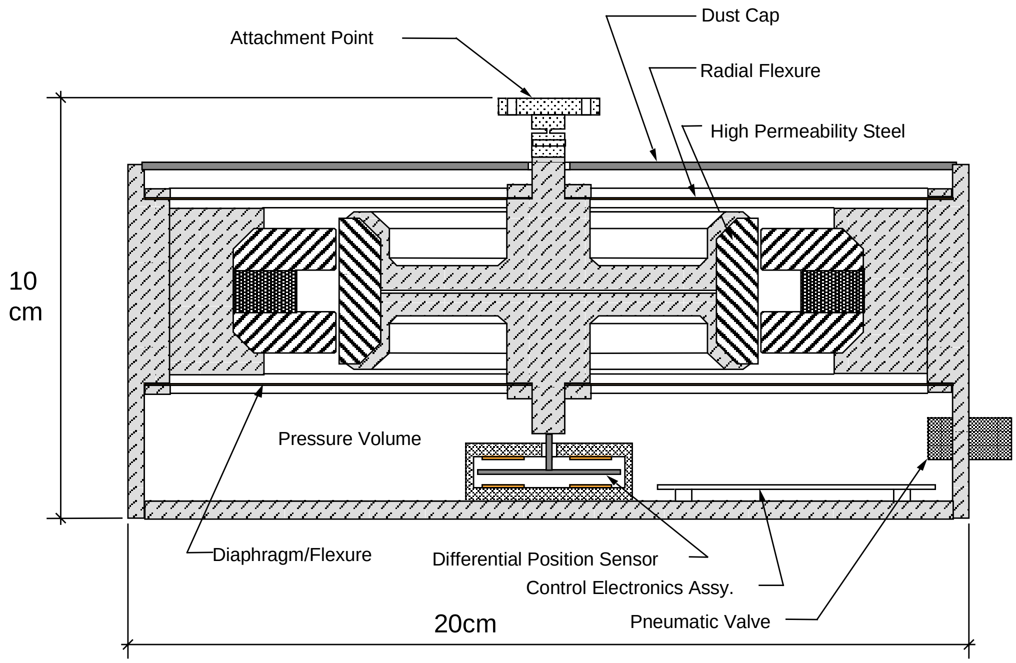

Figure 5: Concept drawings of the proposed Blue Line Engineering voice-coil actuator.

Since voice coils inherently generate force rather than position as their output, and since they require a current to generate the force, they dissipate substantial power when resisting a steady load. To make the power requirements acceptable for CELT, the steady load must be reacted by some other means. The candidate actuator does this by means of air pressure in the lower chamber. A pair of small solenoid valves—one each for the inlet and exhaust—regulates the pressure within the chamber to keep the steady-state current in the voice coil near zero.

A particular feature of this actuator is that there are no rolling or sliding parts and therefore no mechanical parts to wear out. This includes the diaphragm flexures whose fatigue life can be well beyond the expected life of the telescope. A possible exception is the solenoid valves, and even this seems manageable. The valves are rated for 10^9 cycles. At 1 cycle/second, this is more than 30 years.

Another feature of this actuator is that it provides vibration isolation at high frequencies. In this context "high frequencies" means frequencies beyond the bandwidth of the position feedback. With proper design of the coil drive amplifier, it is also possible to provide substantial damping, and the damping may be frequency selective if desired.

The position sensor is a crucial element in this design. There appear to be no off-the-shelf commercial sensors that are capable of the required performance (4 nm resolution, 1.2 mm range, bandwidth > 100 Hz) except for a few prohibitively expensive devices. Blue Line Engineering has submitted test data for a sensor they have built that seems to meet the technical requirements (see Appendix C). It presumably will also meet the cost requirements.

The entire actuator is estimated to weigh less than 5 kg, and power dissipation is estimated to be within the allowed 2 watts. Blue Line Engineering has quoted a $35,000 fixed price for design and fabrication of two prototypes including the electronics with a lead-time of about 5 months. The cost of the device in large quantities is uncertain but should be within the $2000 requirement.

For this design to work acceptably, it will probably be necessary to move the position sensor to another location. Otherwise, changes in air pressure in the lower chamber will likely deform the structure enough to cause an appreciable change in the sensor reading.

<u>Candidate 5: Magnetostrictive Inchworm</u>
Proposed by: Etrema Products
Contact: Rick Zrostlick, Bob Clifford
Complete proposal materials in Appendix D.
Short description: An inchworm actuator and reducing lever using magnetostrictive materials.

Etrema Products proposes an inchworm type actuator using magnetostrictive materials rather than the more usual piezoelectric materials. (See pages 18 and 19 in Appendix D for sketches of the proposed concept). Magnetostrictive materials change shape in response to a magnetic field similar to the way piezoelectric materials change shape in response to an electric field.

Inchworm actuators of any sort have a load capacity that is typically limited by the clamp or brake portion of the device. Etrema overcomes this difficulty by using a lever mechanism that reduces the force the actuator must support. The lever mechanism is only mentioned in the proposal material text; it is not shown in the illustrations.

With inchworms, there will be a position disturbance as the front brake engages and disengages. Etrema proposes to mitigate this problem by sensing the force in two places either side of the front brake. If the force in these two places is equal then the brake is carrying no load, and there will then be no "glitch" as the brake is released. This aspect of the proposal is flawed in that it is not economically feasible to measure the forces to the required accuracy. It may be technically infeasible as well. Fortunately, Etrema also proposes to include an unspecified position sensor in the device. An adequate position sensor (see Blue Line Engineering's proposal in Appendix C) and position control loop could likely attenuate the transients to an acceptable level.

In their proposal, Etrema inadequately estimates the power dissipated by the device as about 1.5 watts. Later calculations on their part indicate that the peak power in the actuator can nevertheless be under 2 watts, and of course the average power would be less. To estimate the power more accurately, a bit of engineering still needs to be done.

Etrema proposes a two-stage design-and-fabricate effort to deliver a prototype with electronics. The effort is scheduled over five months and is offered for a fixed-price of $111,800. Due to the technical errors and misunderstandings, their proposal would require revision before it could be accepted. At least some of the difficulty stems from their unfamiliarity with telescope operation. Etrema has the attractive features of being about the right size and in the right position to take on the task.

<u>Candidate 6: High-Capacity Inchworm</u>
Proposed by: UCLA/Prof. Greg Carman
Contact: Greg Carman
Short description: A piezoelectric inchworm actuator with high-capacity clamp mechanisms.

Figure 6 shows a photograph of a prototype high-capacity inchworm. The device functions like other inchworm devices by first releasing one brake, extending the spine, engaging the first brake, releasing the second brake and contracting the spine. In this way it "crawls" along the supporting member.

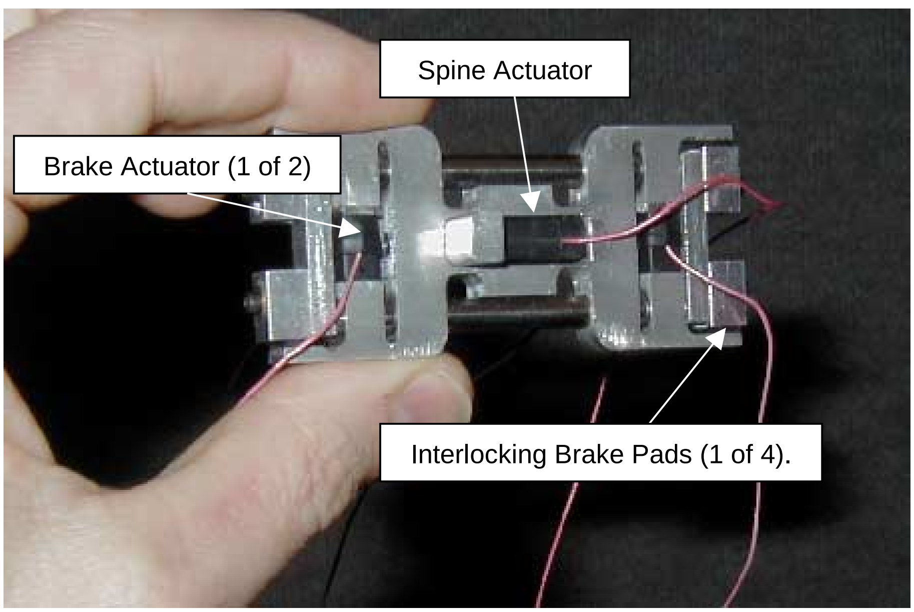

Figure 6: High capacity inchworm.

The high load capacity is achieved by using silicon chips about 6 mm on a side as brake pads. The pads are affixed in pairs at the four corners of the device. Further, the pads have parallel grooves etched in them so that when the grooves on two pads face each other, the grooves in one pad will interlock with the ridges on the other.

The design shown has a capacity of 50 kg., a stroke of 3 mm, a slew rate of about 10 mm/sec, and a groove spacing of 11 μm. It has a demonstrated life of 10^9 full steps. Power dissipation in the device is about as much as the mechanical power being delivered. For CELT this is about one-third of a watt, peak. The power dissipated in the drive electronics is unknown.

As designed, the device is intended to move to positions at 11 μm increments with a constant load. That is, the spine actuator serves only to get the brake pad to the next position where the grooves will properly interlock. In contrast, CELT would require continuous control of the spine actuator while the front brake is disengaged and at any arbitrary position between the locking positions. Additionally, the load will usually be changing as this occurs.

This mode of operation introduces a complication. A changing load combined with the compliance of the device makes it difficult to know when the brake may be engaged. Without knowledge of the load or the position of the brake, there is no way to tell if the brakes are in a position where they will properly nest.

For CELT, it may be possible to adequately predict the load provided disturbances such as the wind are not too large. Alternatively, it would be possible to incorporate a position sensor in the device suitable for indicating groove alignment. This could be a strain gage affixed to the spine. Notably, such a position sensor need not cover the whole stroke of the device, just the stroke of the spine actuator.

This device also has the position transient problem similar to other inchworms and two-stage actuators in general. That is, when it takes a coarse step, there is some "jostling" as the grooves on the brake pads find their nesting locations. The jostling is estimated to be of the order of 0.1 μm, but has not been measured. Clearly, if a position sensor were placed at the output of the device, the position transient could be attenuated with closed-loop control.

The present device exists as a lab test article. It has been developed over five years for about $500,000. Greg Carman estimates that it would cost $50,000 to redesign a device specifically tailored to CELT. He is interested in working with a commercial facility to develop the actuator. It seems reasonable to expect the volume cost to be within the CELT budget.

IV. Some Comments On the Candidates and Other Possibilities

The actuators in the preceding section are candidates because they meet the following criteria:

1). Each of them has a substantial chance of meeting the CELT requirements.

2). With the exception of the high-capacity inchworm, we have found someone who is willing to deliver a prototype on a fixed-price basis.

They are not all of the candidates that one could imagine, and some interesting hybrids and variations are apparent:

1). A magnetostrictive inchworm with Carman's silicon pads.

2). An inchworm with electromagnetic or permanent magnet clamp.

3). A conventional lever with a relatively coarse actuator and 0.1 μm resolution encoder at its input.

4). Any of the actuators with a high-resolution position sensor on the output.

And there are others. Based one manufacturer's assessment (see Differential Ball Screw in Section V) we had early on been steered away from ball and roller screws in this application. The concern was with the micro-welding of the surfaces. Later, the information about the Keck actuators made it clear that this is not wholly intractable if one takes the proper precautions with lubrication and the control algorithm (see Section II). If it were known earlier that micro-welding could be managed, ball and roller screws might be more apparent among the candidates.

In another area, we recognized early in the study that feedback from a sensor at the actuator output could make an unacceptable actuator wholly satisfactory. A bit of analysis confirmed that such a sensor was technically feasible, could be assembled from largely commercial components, and this would likely have an acceptable price. There was, however, no suitable commercial sensor available. As a result, we made the decision to separate the sensor and actuator problems, focus on actuators that did not require a sensor at the output, and give the other actuators a lower precedence.

At the end of the survey, it became apparent that a sensor suitable for use on the output of a CELT actuator was both technically and economically feasible. This was demonstrated by Greg Ames of Blue Line Engineering with a device built in his lab (see Voice Coil Actuator in Section III and the sensor test data in Appendix C). Prior to this, it had only seemed that such a device ought to be feasible. Now it appears to be a certainty.

Had this been known earlier, the candidate list would likely include some other entries. Consider this example: There are motorized micrometers from Physik Instrumente with piezoelectric tips. Without a position sensor, the uncertainty in the micrometer motion vitiates the fine resolution of piezoelectric tip. However, feedback around a position sensor would enable the piezoelectric tip to compensate for the micrometer's imperfections. Further, the micrometer would only need to move infrequently, minimizing wear on the one part of the system that experiences any wear. It is likely that such a coarse-fine two-stage system can be a strong candidate.

In the following section, we summarize the vendors and technologies we investigated, but which did not make it into the candidate list. Some of them become attractive once an output sensor is included, and we identify them as such.

V. Summary of Other Technologies and Vendors Investigated

The following actuators and vendors appeared less able to meet the CELT requirements. Some of these devices become stronger candidates with the availability of a position sensor to place at the output. These devices are marked with a "*".

<u>Ball Aerospace</u>

Contact: Steve Clem, Director of Development for Commercial Products

Ball Aerospace is developing an actuator for the Next Generation Space Telescope (NGST). After one meeting with Ball representatives, it seemed likely they would not be interested in making actuators for price CELT requires. They have not responded to several follow-up inquiries, but neither have they said "no". By the time the actuators are required, their position may change.

<u>Burleigh Piezoelectric Inchworm.</u>

Contact: Galen Powers

The catalog version of the Burleigh piezoelectric inchworm is not suited to CELT since its output force is limited to about 15 N. The limited life of the clamping mechanism would also preclude its use.

Like Ball Aerospace, Burleigh is also developing an actuator for the NGST under a DARPA grant. It is another inchworm and is also unsuitable as its anticipated output force is 5 N. The latest report from this development effort is included in Appendix E.

Burleigh would be willing to undertake a development program for the CELT project provided that it was similar to a DARPA SBIR program: a Phase I paper study for approximately $40-$100k, and a Phase II prototype fabrication effort for between $100k and $400k.

<u>*Differential Screw Micrometer</u>

Vendor: Mitutoyo

We examined a model 110-112 differential screw translator sold by Mitutoyo. This device has a 2.5 mm travel with 50 nm resolution when adjusted by hand. The differential screw mechanism is interesting since it provides a means of motion reduction without the need for a lever. It may be possible to achieve considerably better resolution (a factor of 10?) if the device were operated with a motor/encoder combination, rather than human fingers.

The differential screws were given a low priority because of the concerns with life and reliability of the sliding surfaces. If this could be overcome, they would be worth considering since they are inexpensive relative to mechanisms of similar resolution (e.g. ball screws). The high-resolution micrometer from Diamond Motion (one of the candidates) could be an inexpensive way to investigate the wear of a precision screw. Alternatively, the Mitutoyo device itself could be fitted with a motor and exercised.

Differential Ball Screw

Vendor: Steinmeyer
Contact: Alex Beck

We investigated differential ball screws in some depth before setting them aside. The turning point was the manufacturer's increasing concerns about micro-welding resulting from the sort of service the device is expected to see. This was before we had received the information regarding the Keck actuators (see Section II). While micro-welding is certainly a concern, the experience with the Keck actuators seems to indicate that it is in fact a manageable issue.

There are nevertheless other issues to contend with. One is the position noise in a differential screw. While the theoretical mechanical advantage may be quite good (perhaps 50 μm per turn), there will now be position noise from two nuts instead of one. Since the best commercial balls (grade 10) are spherical only to within 200 nm, the noise from the nuts may be the limiting factor.

Another concern is cost. A rough estimate of the cost from Steinmeyer was between $800 and $1200.

Direct Piezoelectric or Magnetostrictive Actuators

Vendors:
Piezoelectric: Various
Magnetostrictive: Etrema

Based on the required stiffness and travel, one can calculate the minimum amount of piezoelectric (PZT) or magnetostrictive (Terfenol) material needed to make a single stage. In both cases, the length of the active material must be about a meter. The length of the actuator could be shortened if segments of the material could be nested in one another, for example in concentric cylinders, but other issues still remain.

For PZT piezoelectric materials, electric fields approaching 1 kV/mm are required to make efficient use of the material. Practically, this means that the actuator must be assembled from many thin slices to keep the supply voltage reasonable. This actuator would have an order of magnitude more connections and layers than any commercial piezoelectric device. We have not been able to assess the difficulty of this problem as apparently no one has done this before.

For Terfenol magnetostrictive materials, the problem is cost. The price of the active element alone would be more than $3000.

IDC Motion Control

Contact: Paul Borloz

IDC manufactured the actuators for the Green Bank Telescope, and they were initially interested in the CELT work. They became less interested when an important difference between the GBT and CELT sank in. Namely, GBT required a resolution of about 20 μm vs. 4 nm for CELT.

Shortly thereafter they issued a formal "no-bid" letter which we have on file.

<u>JPL Optical Delay Line Actuator</u>

Contact: Boris Lurie

The Jet Propulsion Laboratory has built an actuator for the optical delay line in a space interferometer. It is a two-stage device with a piezoelectric stack mounted on a voice coil. It has a travel of 10 mm with a resolution of 5 nm.

This device was ruled out because of the complexity. We can apparently do the job with the voice coil alone. See Voice-Coil Actuator in Section III.

<u>*New Focus Pico Motor</u>

Vendor: New Focus

The New Focus Pico Motor is essentially an 80-pitch screw with a piezoelectrically driven nut. It is capable of better than 30 nm resolution with an output force of about 25 N. Only the length of the screw limits its travel, and that can easily be 50 mm. 100 mm would not be unreasonable. The device has been tested to 3.6e9 steps and costs about $800 per device in small quantities, electronics included.

The Pico Motor was set aside because the actual travel per step is a function of the output load. It is only specified to be *less* than 30 nm. Of course with an output sensor, this would not be a problem. The device would be placed at the input of a, say, 15:1 lever system with a control loop closed around the sensor at the output. Also to meet the slew rate requirements, and additional motor would be required to provide fast motion of the screw.

A further possible concern is the electrical noise generated by the pulses used to drive the piezoelectric nut.

<u>*Motorized Micrometers</u>

Vendors: Various

There are a variety of vendors that sell motorized micrometers that have similar specifications: Newport, Oriel, Melles Griot, Physik Instrumente, and others. They all can supply devices with resolutions better than 100 nm and load capacities suitable for use at the input of a reducing mechanism. The costs range from about $700 to $900 in small quantities. The (relatively simple) drive electronics are not included in that cost. Diamond Motion would supply a comparable device for about $600.

<u>Rollvis (roller screws)</u>

Contact: Jean-Paul Ducimetiere, President
Jose Duran, Technical Manager

Rolvis manufactures planetary and recirculating roller screws. They seem to have the reputation of having lower costs than SKF and the same or better quality. The roller screws in the actuators that CSEM builds are made by Rolvis.

A rough estimate of the cost of a suitable 1 mm pitch screw from Rolvis is $1200. While the cost does not strictly rule out its use, it certainly puts tight constraints on the cost of the necessary motor, encoder, reducing mechanism, and drive electronics.

SKF, Exlar, Moog (roller screws)

Judging by their web sites, these three vendors all sell roller screws. Neither phone calls nor e-mails were returned from any of them. If a roller screw is to be used in the actuator, it would be important to have more than one possible vendor. In this case, a new effort should be made to interest these vendors. To date, Rollvis (see above) is the only roller screw supplier that has responded.

Steinmeyer (ball screws)

Contact: Alex Beck

Steinmeyer manufactures ground ball screws, and Alex Beck is a knowledgeable sales engineer. See “Differential Ball Screws” above.

*Steward Observatory Impulse Screw

Brian Cuerden and Roger Angel of the Steward Observatory have built a prototype actuator that is a screw whose nut is driven by an impacting mass. When the mass strikes the nut, the inertia of the screw prevents it from accelerating as fast as the nut, the nut turns relative to the screw, and the screw advances. A short paper describing the device is included in Appendix F.

This device has drawbacks similar to that of the New Focus Pico Motor: the travel per step is dependent on the load, and some modification would be necessary for it to meet the slew rate requirements.

The device has an additional drawback in that support from Steward Observatory may be difficult to obtain.

Thermal Actuators

We briefly investigated using paraffin wax or the metal alloy Nitinol as the active element in an actuator. Both these materials undergo a phase change at reasonable temperatures. In doing so, Nitinol changes shape and can deliver modest mechanical energy. When paraffin melts, its volume increases by about 15%. Both of these phenomena have been used in commercial actuators[7].

The drawback is that they are slow. While it may be possible to heat the materials quickly (e.g. with electric current of microwaves), there appears to be no fast way to draw the heat out. This would result in an actuator with an unacceptably low control bandwidth.

*Various Two-Stage Actuators

A two-stage position actuator would have a fine positioning portion capable of the required resolution and a coarse positioning section that kept the fine stage within its operating range. This might take the form of a piezoelectric or magnetostrictive fine actuator on the end of a ball screw or even just a fine-pitch plain screw.

[7] The radiator thermostats in most cars is actuated by a paraffin slug.

All two-stage devices were initially ruled out because of the need for a sensor on the output. With the availability of a sensor these devices are much more attractive.

They have the following advantages:

1). Manageable life and wear. If the coarse stage is a screw, it moves relatively infrequently in relatively large steps. The fine stage can be something for which wear is not an issue (e.g., piezoelectrics).

2). Low cost. The fine stage can be short stroke and presumably have a lower cost than a precision device with a longer stroke. The coarse, long-stroke device can be a comparatively crude screw.