Summary – Design of a High Resolution Hexapod Positioning Mechanism

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Large, active optics systems for space are pushing the limits of positioning mechanisms for lenses and mirrors, requiring higher resolution motion, more accurate positioning, and increased position stability, often in multiple degrees of freedom. One example of this type of system is a telescope designed for one of the Next Generation Space Telescope's wave-front sensing and control testbeds. The stringent requirements of this testbed required a mechanism capable of positioning one-foot wide hexagonal mirrors in six degrees of freedom, with a resolution and stability on the order of nanometers and tenths of arc-seconds, over a range of millimeters and degrees. The result was a hexapod mechanism utilizing PZT-inchworm actuators, designed to be stiff and resistant to thermal expansion, and requiring sophisticated control software. Designing and developing this mechanism brought to light a number of issues and challenges that may be relevant to future active optics mechanisms. This paper will summarize the mechanism design effort and the important lessons learned from it.

The paper will begin by summarizing the key requirements imposed on the mechanism by the Developmental Comparative Active Telescope Testbed (DCATT). This testbed incorporated an f/15 Cassegrain telescope with a 40-inch-diameter, segmented, active primary mirror and an active secondary mirror. The actuation mechanisms for the primary mirror segments were required to position the segments accurately enough to produce diffraction-limited system performance. DCATT's experimental plan also called for the mechanisms to be used for introducing large mirror misalignments in up to 6 degrees of freedom. This created competing requirements of high resolution and large range. In addition, the mechanisms were required to hold their positions with minimal jitter and drift for periods of an hour or more. These requirements are important to understanding the technical challenges encountered during the design.

Next, the paper will present the mechanism design and the technical motivations behind important design features. The mechanism is a hexapod based on the Stewart platform concept, with each leg containing a PZT inchworm actuator. Initially made of aluminum, the final design incorporates composites and invar to reduce the effects of thermal expansion. The hexapods are controlled by software that converts desired mirror motions given in the telescope's reference frame into individual actuator commands. Internal encoders in the actuators provide rough position feedback. More accurate position feedback must be provided externally, in this case by the wave-front testbed itself.

The remainder of the paper will discuss technical challenges that arose during the mechanism development and the lessons learned from them. This includes characterization and control issues with the actuators, difficulties with short and long-term position stability, and testing and calibration problems.

These lessons are supported by component level tests and tests performed with the hexapod mechanism prototype.

At this time, the hexapod development has been carried through prototype testing and final fabrication. For reasons unrelated to the hexapod development, the DCATT project was cancelled before final assembly and qualification could be performed. Some limited design validation is still planned, but it is unclear when this will be completed.
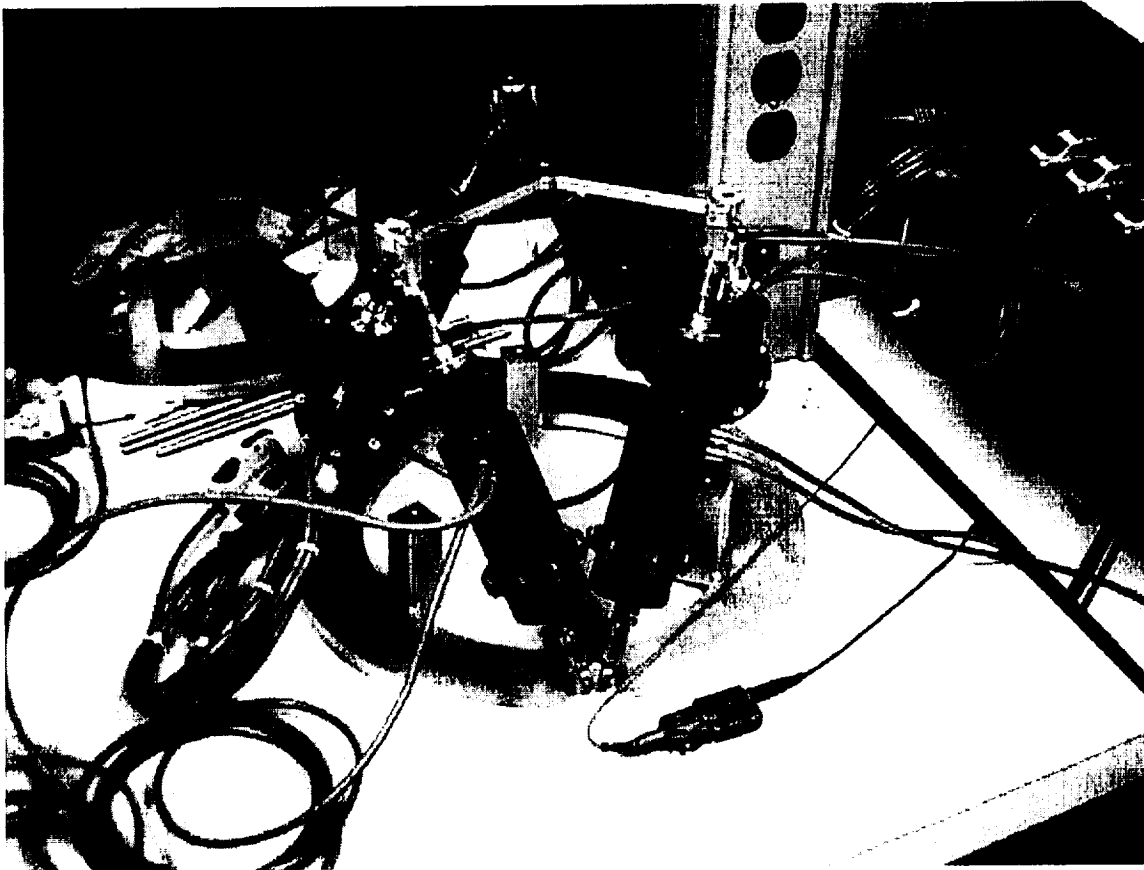

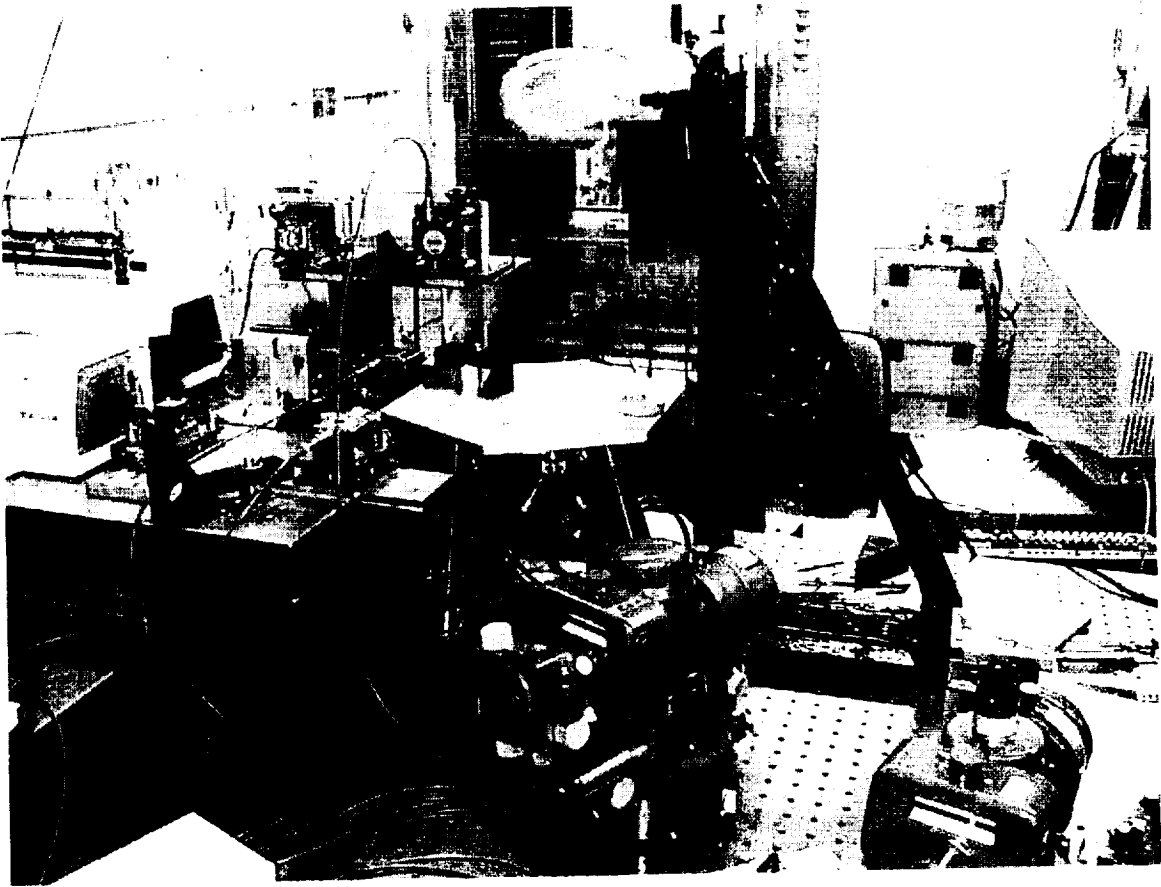Figure 1: Hexapod Mechanism Prototype

Figure 2: Hexapod Prototype in 6 Degree of Freedom Test Setup

Design of a High Precision Hexapod Positioning Mechanism

Jamie Britt[*]

Abstract

This paper describes the development of a high resolution, six-degree of freedom positioning mechanism. This mechanism, based on the Stewart platform concept, was designed for use with the Developmental Comparative Active Optics Telescope Testbed (DCATT), a ground-based technology testbed for the Next Generation Space Telescope (NGST). The mechanism provides active control to the DCATT telescope's segmented primary mirror. Emphasis is on design decisions and technical challenges. Significant issues include undesirable motion properties of PZT-inchworm actuators, testing difficulties, dimensional stability and use of advanced composite materials. Supporting test data from prototype mechanisms is presented.

Introduction

Large, active-optics systems for space are pushing the limits of positioning mechanism design. Active optics mechanisms require increased motion resolution and position stability, often in multiple degrees of freedom. The DCATT telescope is a ground-based example of this type of system. Figure 1 shows a model of the DCATT testbed. The vertical structure is DCATT's Cassegrain telescope, standing 15 feet tall. Figure 2 shows DCATT's one-meter-diameter primary mirror, which consists of seven hexagonal, aluminum segments. As part of the testbed's experimental plan, these segments must be actuated in six degrees-of-freedom (6-DoF) with nanometer and arc-second resolution over a range of millimeters and degrees. Once in position, the mechanisms must hold position for one or more hours.
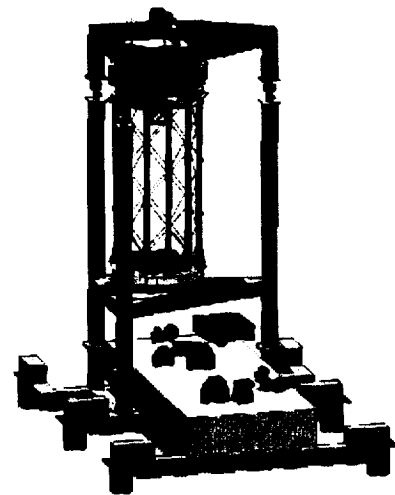

Figure 1. DCATT Testbed

The result is the DCATT hexapod positioning mechanism. Based on the Stewart platform concept, the DCATT hexapod provides 6-DoF motion using a truss-like arrangement of linear actuators. This arrangement is both compact and rigid. Commercially available, piezo-electric, PZT-inchworm actuators provide the hexapod's high-resolution motion. Materials with low and negative coefficients of thermal expansion (CTE) are used in the legs to provide maximum dimensional stability.
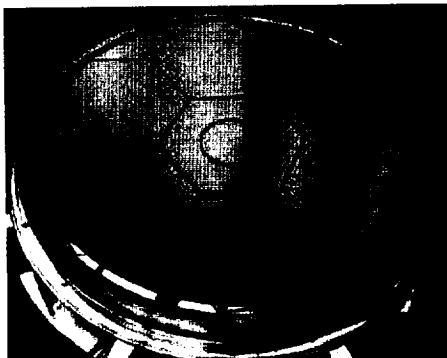
Figure 2. DCATT Primary Mirror (shown in polishing fixture)

A number of obstacles had to be overcome during development of the mechanism. The first challenge involved motion tests of the selected actuators, which revealed undesirable motion properties. Developing a high-resolution, 6-DoF motion test was the next challenge. This test brought to light problems with the dimensional stability of both the mechanism and the test setup. These were addressed with new designs incorporating low-CTE metals and negative-CTE composites. All of these issues, along with their solutions will be presented in this paper.

Prior to integration and testing of the final hexapod design, the DCATT project was cancelled due to a shift in focus of the NGST project. Thus, final performance testing of the hexapods was never performed.

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DCATT Hexapod Requirements

General Requirements

The DCATT testbed was created to test optical wavefront control for NGST. The goal was to use these methods to achieve diffraction-limited performance in the DCATT telescope. This required active control of the telescope's segmented primary mirror. The DCATT hexapod was designed to perform this task.

The segments were constructed from machined aluminum with mirror surfaces of polished-nickel. Each outer segment weighed 2.3 kg (5 lb). The center segment weighed 1.4 kg (3 lb). All seven segments had to be actuated in 6-DoF from beneath the mirror. Thus, each mechanism had to support and actuate the weight of a segment. In addition, light passing through center segment's hole could not be obstructed.

Actuation Range and Resolution

Table 1 gives the range and resolution requirements for the DCATT hexapod in three critical degrees of freedom. Tip and tilt are rotations perpendicular to the optical axis of the mirror. Piston is linear motion parallel to the optical axis of the mirror. Although the other degrees of freedom where required, they did not have specific resolution or range requirements attached to them. They simply had to be of the same order of magnitude as the critical three.

Table 1. Actuation Requirements: Resolution and Range

Tip/tilt resolution	+/- 0.01 arc-sec
Tip/tilt range	+/- 0.5°
Piston resolution	+/- .1 µm
Piston range	+/- 0.05 mm

The DCATT hexapod's resolution requirement is driven by the need to align the segments of the primary mirror. The range requirement is driven by the need to misalign the segments by optically large values at the start of an experiment.

Position Stability

A minimum requirement for jitter motion was not given at the start of the design process. Jitter stability was implied by a 100-Hz minimum-stiffness goal for the hexapod's first mode of vibration.

Long-term stability was implied by a requirement that the telescope be "self-compensating" for dimensional changes caused by thermal expansion. This mandated that the structure have the same CTE as the mirrors. Since the mirrors were made of aluminum, the structure and hexapods were to be aluminum as well.

DCATT Hexapod Concept

Figure 3 shows a computer model for the aluminum DCATT hexapod. Each leg contains an IW-700 PZT Inchworm linear actuator manufactured by Burleigh Instruments[1]. All parts are aluminum except for the actuators and three flexures in each leg. Figure 4 shows an exploded view of a leg assembly. The flexures provide the same degrees of freedom as ball-and-socket joints in an ideal Stewart platform, but without the frictional problems of real ball-and-socket or universal joints.
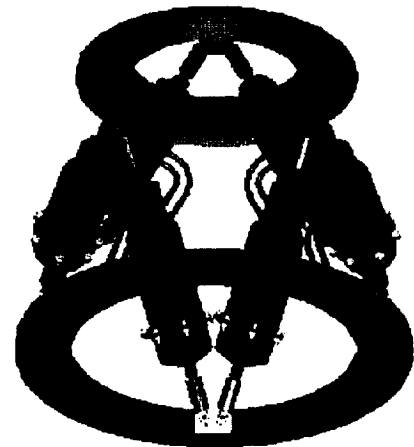

Figure 3. Hexapod Model

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[1] Burleigh Instruments, Inc., Burleigh Park, Fishers, New York, 14453-0755
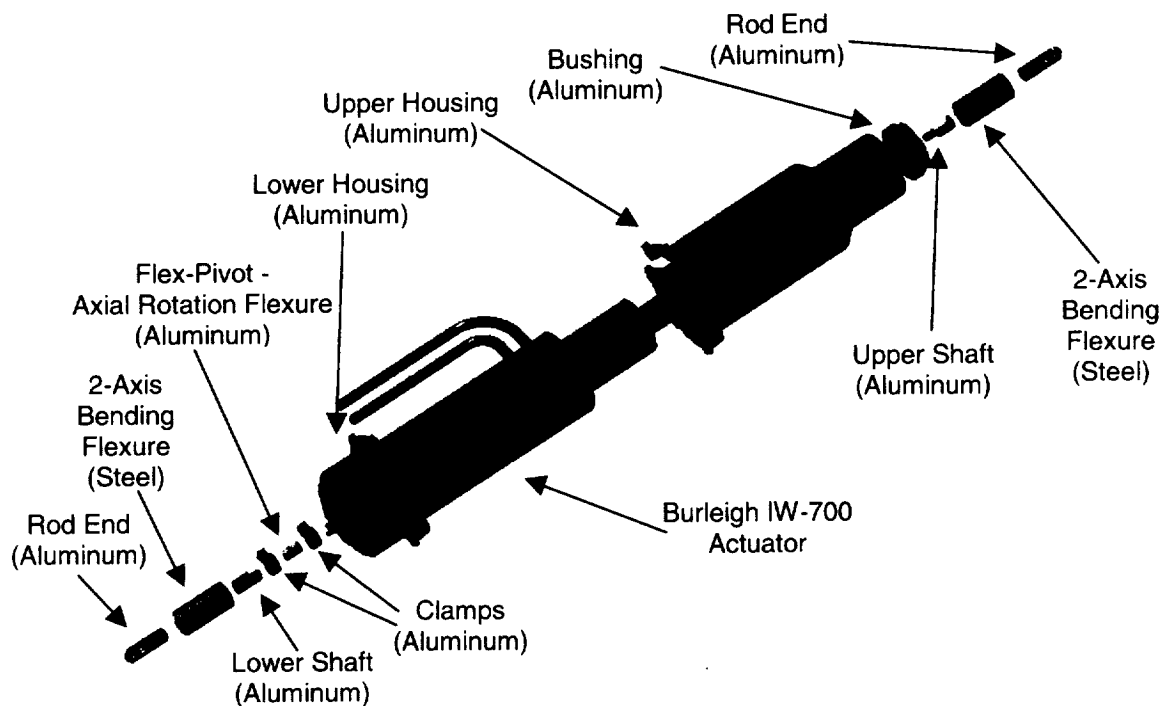
Figure 4. Exploded View of Hexapod Leg

Table 2 shows the stated performance of the IW-700 actuators. Table 3 shows the predicted performance of the hexapod compared to the requirements. These predictions were calculated using the IW-700 performance numbers and a kinematics model based on the geometry of the hexapod.

Table 2. IW-700 Performance

Minimum Step Size:	4 nm
Actuation Range:	6 mm

Table 3. Predicted Hexapod Performance

Motion	Requirement	Predicted Performance
Tip/Tilt Resolution	+/-0.01 arc-sec	+/-~0.002 arc-sec
Tip/Tilt Range*	+/- 0.5 deg	+/- 1.0 deg w/+/-1.0 mm piston
		+/- 1.7 deg w/+/-0.5 mm piston
		+/- 2.0 deg maximum range
Piston Resolution	+/- 0.1 μm	+/- ~0.005 μm
Piston Range*	+/- 0.05 mm	+/- 0.5 mm w/+/-1.7 deg range
		+/- 1.0 mm w/+/-1.0 deg range
		+/- 3.4 mm maximum range

*NOTE: Maximum ranges for all degrees of freedom are coupled. Sample extremes within the motion envelope are given.

PZT-Inchworm Actuator Motion Issues

For a good portion of the design process, the assumption was made that the IW-700 actuators would move with the resolution stated in Table 2 over their entire range of motion. This would allow the actuators to be operated in an essentially open-loop fashion. Control software would determine how far each actuator had to move to position the mirror segment and then command a certain number of

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actuator steps to achieve that motion. Characterization of the actuator motion was not done until later in the program. This was a mistake, as characterization turned up a significant design issue.

The IW-700 inchworm consists of a moving shaft, two PZT clamps, and a third PZT element that changes the distance between the two clamps. Figure 5 shows how these elements work together to move the shaft. First, PZT Element 1 clamps the shaft while PZT Element 2 extends. This causes the shaft to move to the left. The distance moved is determined by the voltage applied to Element 2. A 1 V increment causes a single step of 2-4nm. After 665 steps, Element 2 becomes fully extended. Then Element 3 clamps the shaft followed by the release of Element 1. In this configuration, the shaft will continue to move to the left as Element 2 contracts. This process is repeated to move the shaft through the actuator's entire range of motion.
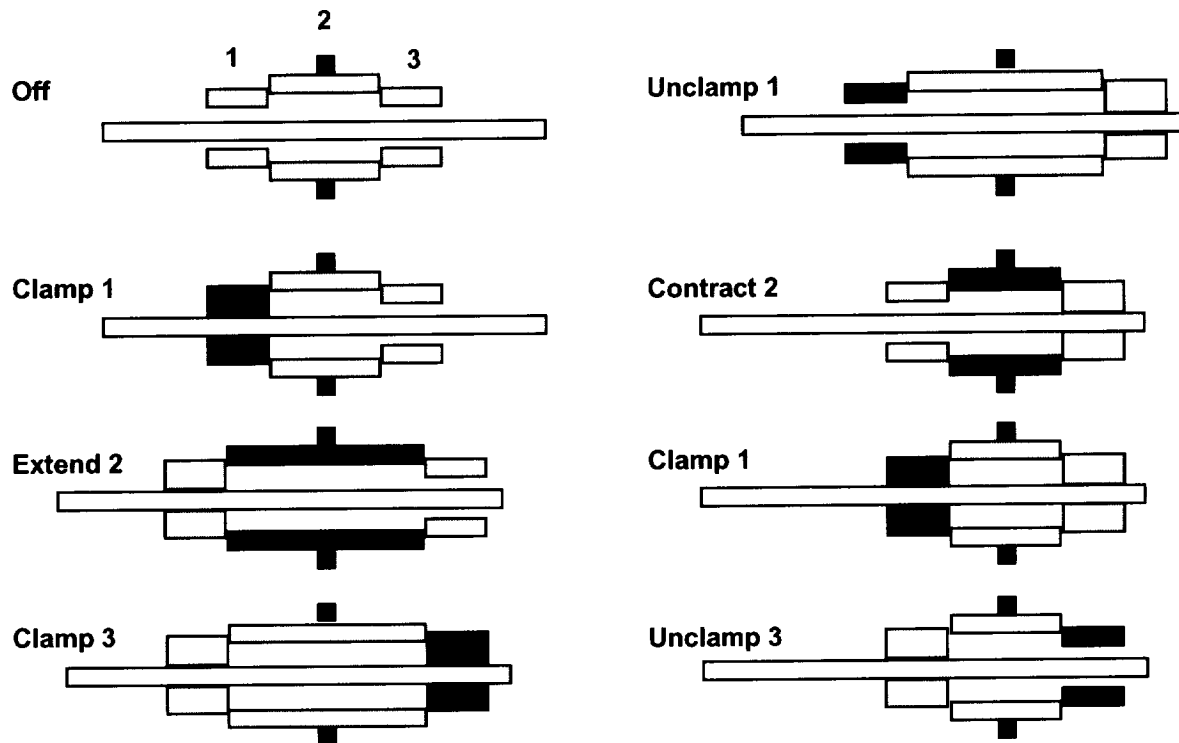

Figure 5. Inchworm Actuator Motion

Characterization tests of the actuators revealed that a motion discontinuity occurs when the clamps exchange. Imperfections in the way the clamps grip the shaft cause the shaft to move forward or backward by an uncontrolled amount. Tests showed this discontinuity to be as large as 215 nm. Since thousands of clamp changes occur throughout the actuator's range, this prevents the actuator from being accurately commanded in an open-loop fashion. Furthermore, it was feared that the actuator could have "dead-zones", positions within the length of a discontinuity that the actuator could never reach.

Figure 6 shows a graph of commanded actuator position plotted against measured position determined using a Zygo laser-ranging interferometer. The actuator has been run back and forth repeatedly through the same clamping cycle. That is, the actuator was run through 1330 steps, causing element 2 to go through full expansion and contraction, and causing both clamps to open and close on the shaft. Then the actuator was run backwards to its starting position, and the process was repeated.

The discontinuities can be clearly seen every 665 steps. It is important to note that discontinuities occur in both the forward and reverse directions, but with different magnitudes. Discussions with the manufacturer suggest that the magnitudes vary depending on the actuator's loading condition. This result suggested that by moving back and forth across a discontinuity, the actuator could achieve any position within its
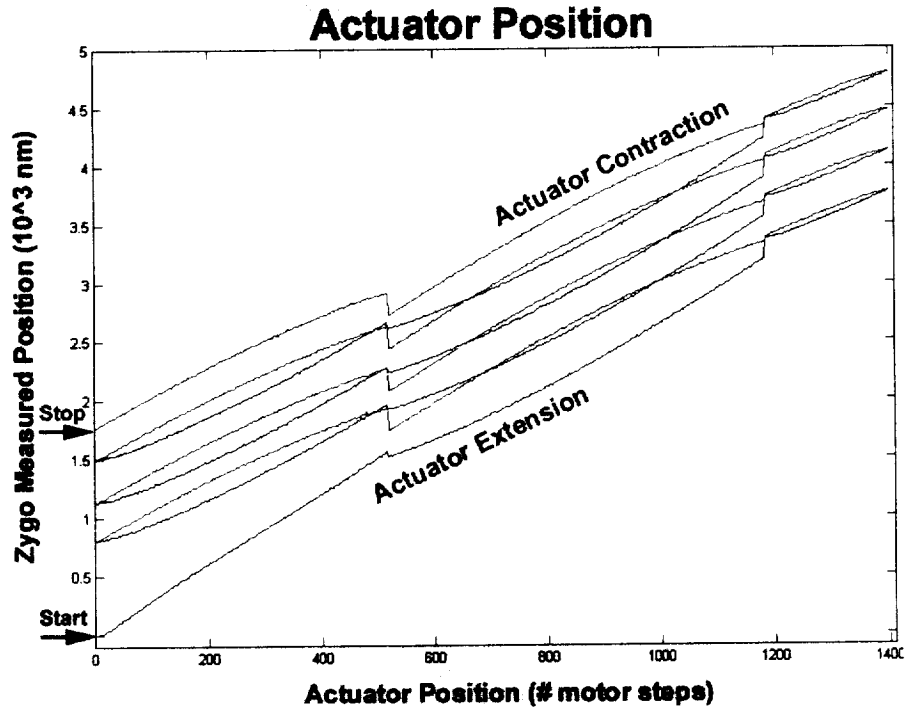
Actuator Position

Figure 6. Actuator Motion Discontinuities

range. Thus, the discontinuities do not cause any "dead-zones". In order to operate the actuator in this fashion, however, high-resolution position feedback must be provided to the control system. The DCATT controls team made efforts to address this problem, but that work is beyond the scope of this paper.

Anyone considering the use of high-resolution inchworm actuators should be aware of these potential discontinuities, and design their system accordingly. Discuss this issue with vendors before selecting actuators for a design. Early actuator characterization is also strongly recommended.

6-DoF Motion Testing

The 6-DoF Test Facility

In the hexapod mechanism, all six actuators move in combination to achieve motion along one degree of freedom. The required motion from each actuator is calculated using the hexapod kinematics model. Deviations from the geometry used in that model, including machining and assembly errors, will introduce errors into that calculation. Early in the design it became clear that characterizing and calibrating the motion of each assembled hexapod would be critical. In order to accomplish this, a test was required that could measure the hexapod's motion in all six degrees of freedom simultaneously. Devising this test with the required resolution was not trivial.

Laser-ranging interferometers were selected to make most of the measurements. By reflecting off a mirrored cube attached to a hexapod, three beams could be used to measure linear motion of the hexapod. Parallel beams hitting the same cube face could be used to measure rotation over a small range. As long as rotations remained small, all the interferometers could make measurements simultaneously. An autocollimator reflecting off another mirror provided 2-axis rotational measurements with greater range than the interferometers but less resolution.

Figure 7 shows a prototype hexapod that was used to help develop the 6-DoF testing facility. Figure 8 shows the prototype in the facility. A flat "dummy segment" has been bolted to the prototype to provide a mounting surface for the mirrors. In this picture, two lasers have been split to feed three interferometers.
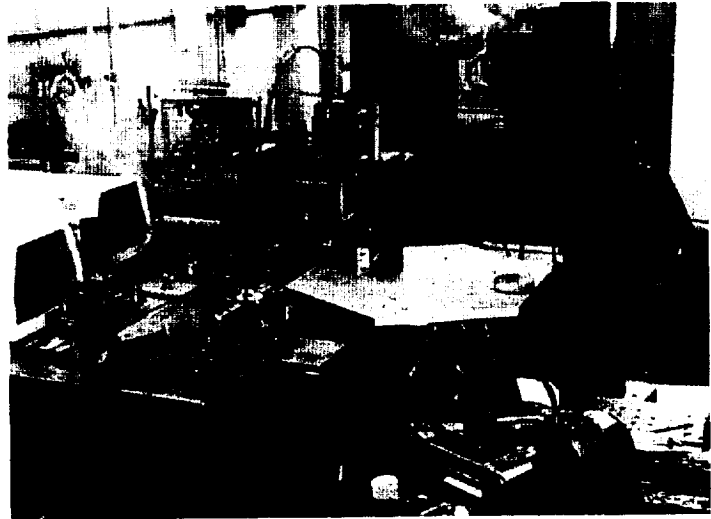
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Figure 6. Prototype Hexapod

Figure 6. 6-DoF Testing Facility

These interferometers are measuring the three linear degrees of freedom as well as rotation about the piston axis. An autocollimator is being used to measure tip and tilt rotation.

6-DoF Testing Results

The 6-DoF facility was never used to fully characterize a hexapod. During testing with the prototype, the design team discovered significant dimensional stability problems. Part of this instability was thermal expansion in the hexapod, which is discussed in the following section. The rest of the problem was attributed to thermal expansion of the test setup. It became clear that dimensional stability of the test setup was imperative for measuring the high-resolution motion that was desired from the hexapod. Machined aluminum parts traditionally used to mount optical elements were unacceptable for this test. Plans were made to replace the aluminum parts in the test setup with low-CTE metals such as Invar or Super Invar. This effort was not completed before the project was cancelled.

Although 6-DoF tests were performed on the prototype hexapod, that data will not be presented here. In addition to dimensional stability errors, these tests occurred before the inchworm motion discontinuities were discovered and addressed. With multiple sources of error in the measurements, the data from these tests is considered highly unreliable.

Despite errors in the data, the 6-DoF testing effort is considered a partial success. The facility was sensitive enough to detect both dimensional stability problems and systematic errors that resulted from inchworm discontinuities. It is believed that DCATT's 6-DoF testing facility is a good model for similar testing endeavors. As will be described in the following section, designers of similar facilities should carefully examine the dimensional stability of their potential test setup. When attempting to measure movement on the scale of nanometers, thermal expansion of the test setup can be as large or larger than the motions that are being measured.

Dimensional Stability and New Requirements

Discovery of the Dimensional Stability Problem

In keeping with the early goal of a self-compensating telescope, the dimensional instability of aluminum was at first seen as a bonus. As the temperature changed, it was desirable to have the telescope structure expand or contract at the same rate that the mirror's figure was changing. Experiments with the prototype hexapod in the 6-DoF testing facility brought to light serious flaws with this thinking. Initial discussions of thermal expansion assumed that the structure would expand or contract as a unit. Testing,

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however, showed how the hexapods could behave as individual structures growing at different rates. Worse still, individual hexapod legs might grow at different rates, causing the mechanism's position to drift in all 6 degrees of freedom.

Prototype tests showed that the hexapod's position was drifting. In an attempt to isolate this motion, tests were run with the hexapod in a static position. The test facility monitored changes in the hexapod's position over time. Figure 8 is an example of this data taken by the autocollimator. As can be seen, the measurement drifts in tilt by about 1 arc-second and then back during the course of the test. The bottom axis of Figure 9 is given in the number of measurements taken. The total time of the test is about 1 hour.
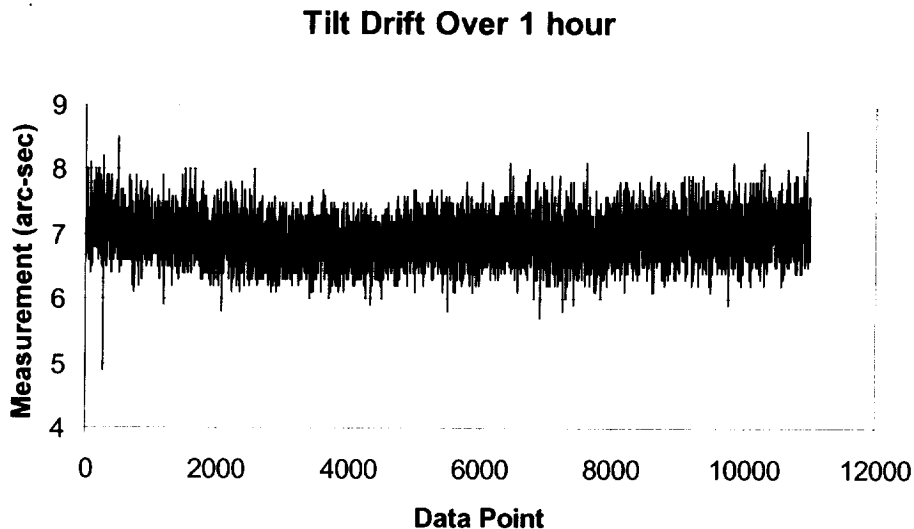

Figure 7. Position Drift in Prototype Hexapod

After ensuring that there was no data drift caused by the measuring tools, it was hypothesized that this drift was the result of thermal expansion within the hexapod and/or the test setup. The next step was to analyze the hexapod's dimensional stability in more detail.

Hexapod Dimensional Stability Analysis

A simple thermal-expansion model was created to analyze the dimensional stability of the hexapod. The analysis focused only on the hexapod legs, not the base or mounting platform. This was done for several reasons. First, the legs comprise most of the height of the hexapod, so their contribution to growth is much larger than either the base or the platform. The parts in the legs are also much less massive than the base or platform, so they are likely to change temperature more rapidly. Lastly, the actuators themselves are a source of heat, and fluctuations in that heat will effect the legs much more than the base or platform. Since all legs are identical, only one hexapod leg was modeled.

In the model, each part was represented by an effective length (L), a coefficient of thermal expansion (α), and a temperature differential (ΔT). Only parts that added to the growth of the leg were included in the model, and L represents only the portion of that part which contributes to leg growth when it expands. The value ΔT represents a static, bulk temperature increase in the leg. The growth (ΔL) of each part was calculated by multiplying these three characteristics together:

$\Delta L = L * \alpha * \Delta T$

The total growth of the leg was calculated by adding the growths of all the parts. Thermal expansion coefficients were based on part material, with the exception of the actuator itself. For the actuator, the

Characterizing the Thermal Environment

With the thermal model in hand, the next step was to determine the actual temperature variation that was likely to exist between hexapod legs. Thermocouples were attached to each leg of a prototype hexapod, and that hexapod was placed on the DCATT testbed. Additional thermocouples were placed on the hexapod's base, on a dummy mass that represented a neighboring segment, and on the telescope baseplate. After the legs came to equilibrium in the environment, the actuators were turned on and temperature data was taken for a period of 24 hours. This data included a one to two hour period during which the legs rose to a new equilibrium temperature due to actuator heating. The remainder of the data showed how the temperature of the legs varied with time.

Figure 10 is a graph of the raw data from this test. Note that leg #2 appears to be significantly colder than the other hexapod legs. Examination of the test setup revealed that leg #2's thermocouple had become partially unattached during the experiment. For this reason, leg #2's data was not included in the analysis.
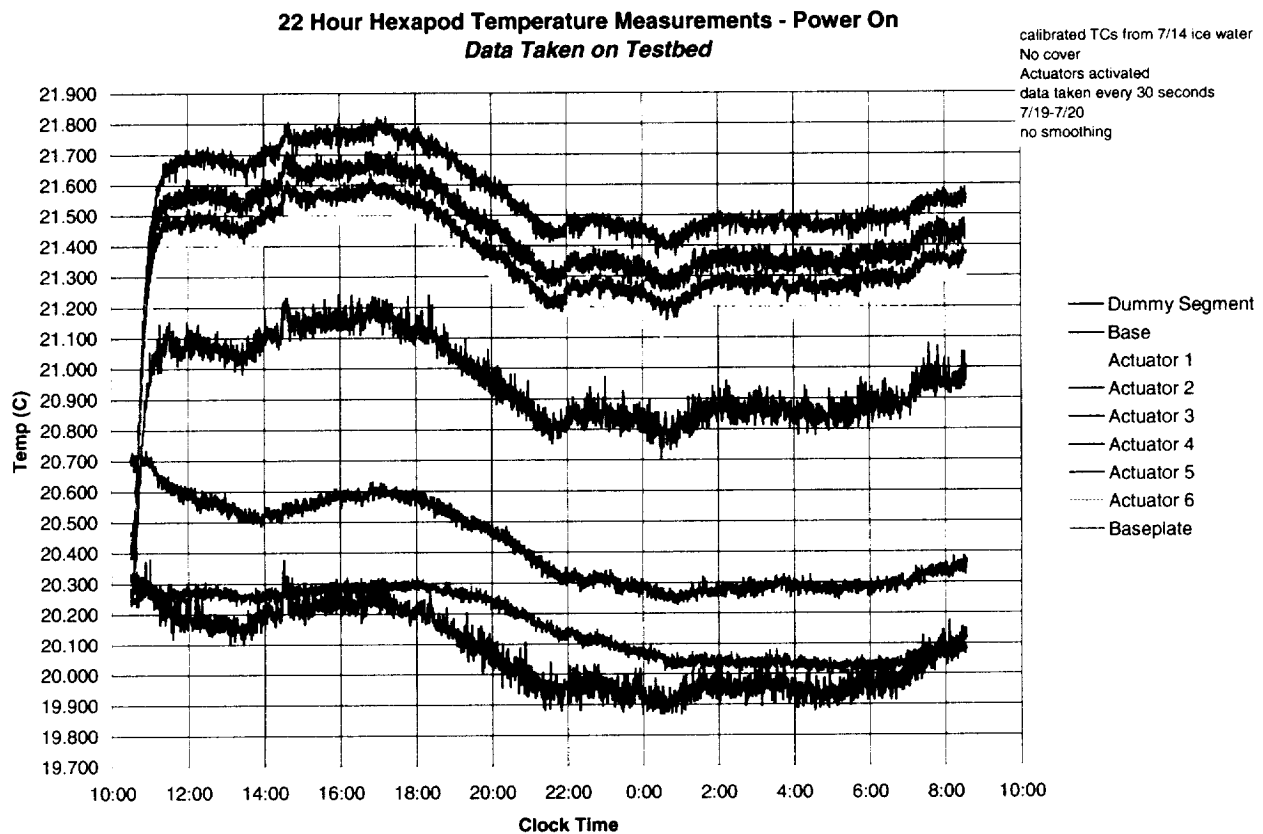
Figure 7. Hexapod Temperature Measurements

Analyzing the Hexapod in the DCATT Thermal Environment

Because the dimensional stability requirements are effected by relative leg growth, it is necessary to compare the temperatures of one leg with another. Figure 11 shows three curves derived by subtracting one leg's test results from another, after those results were smoothed with a running average. Ideally, it would be desirable for these curves to be constant at zero. This would produce no segment drift. If the curves were constant but non-zero, the segments would move in piston, but would have no relative drift or significant tip/tilt drift. This would still meet the long-term stability requirements. As can be seen in Figure 11, however, the difference curves are not constant. Therefore, undesirable drift will occur. The

worst variation in the test occurs in the difference between leg#5 and leg#4. This curve was used for the rest of the analysis, and was referred to as the 5-4 curve.

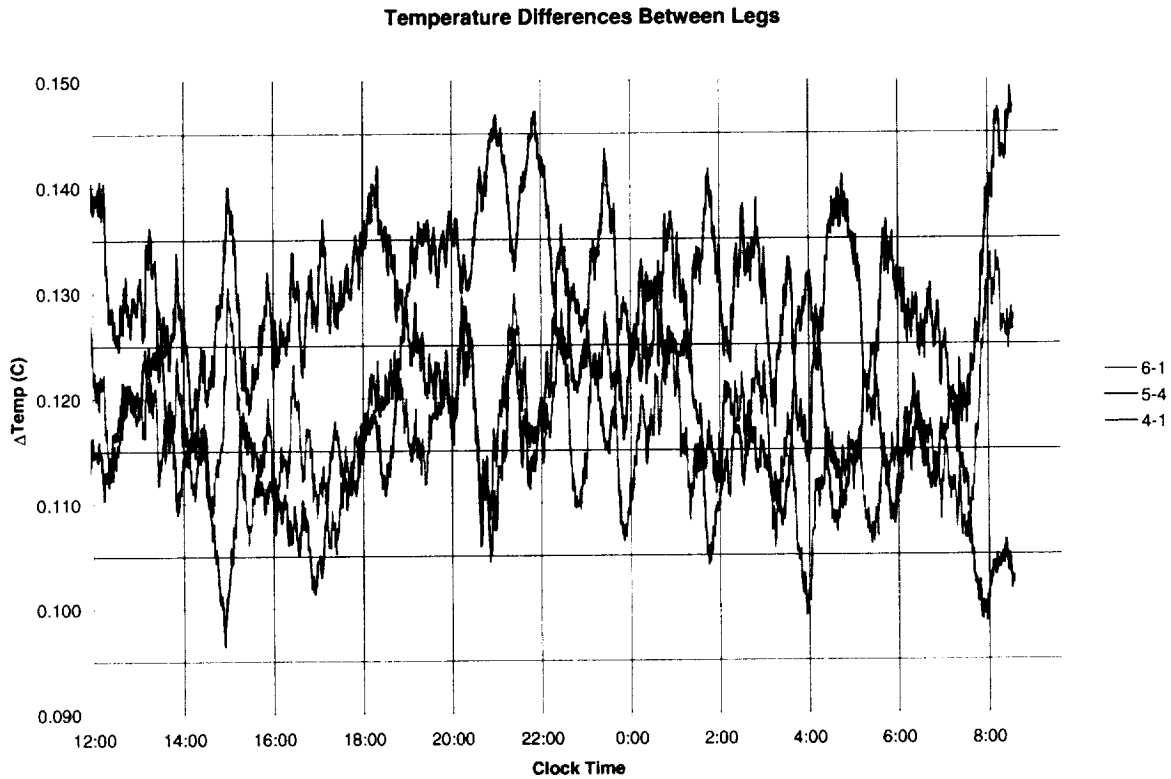**Temperature Differences Between Legs**

Figure 7. Temperature Difference Curves for Selected Pairs of Hexapod Legs

To examine the hexapod's response, the 5-4 curve was treated as a leg temperature vs. time curve and variations in it were considered to be ΔT values which could be input into the hexapod-leg thermal model. The largest variations in the curve for 1, 2, 3, 4, and 8-hour intervals were determined. These values are given in Table 5. Recall that the requirements will be exceeded if the differential change in temperature between hexapod legs is larger than 0.002 deg C. Table 5 shows that the requirement will be exceeded during any of the time intervals considered.

Table 5. Maximum Variation in 5-4 Curve for Selected Time Intervals

Time Interval	Time Range for Largest ΔT	ΔT (deg C)
1 hr.	18:30 – 19:30	0.026
2 hr.	21:52 – 23:52	0.032
3 hr.	16:55 – 19:55	0.035
4 hr.	21:52 – 01:52	0.043
8+ hr.	14:00 – 22:00	0.05

Table 6 shows how the thermal growth model responds to the ΔT values in Table 5. Again, the requirements are exceeded in all of the time intervals by at least an order of magnitude. Controlling the temperature of the hexapod legs to 0.002 deg C was considered unreasonable, so it was decided that the aluminum hexapod design would not meet the new requirements.

Table 6. Predicted Drift of Hexapod in DCATT Environment

Time Interval	ΔT (deg C)	Piston Error (nm)	Tip/Tilt Error (arc-sec)
1 hr.	0.026	130	0.214
2 hr.	0.032	160	0.263
3 hr.	0.035	175	0.288
4 hr.	0.043	215	0.353
8+ hr.	0.05	250	0.411
Requirements:		10	0.025

Dimensionally Stable Design for a Hexapod Leg

Proposed Design

The goal of the new design was to maximize the dimensional stability of the hexapods legs by using materials with low or negative CTEs. The first iteration used only low-CTE metals: Invar and Super Invar. The final design incorporated graphite-epoxy composites with a negative CTE along the axis of the leg. Figure 12 shows the final leg design.

Rod End
(Invar)

Bushing
(Unchanged)

Flex-Couple
(Invar)

Housing
(Formerly Upper and Lower Housings)
(Graphite-Epoxy composite tube
bonded to Super Invar end-fittings)

Upper Shaft
(Super Invar)

Flex-Pivot
(Unchanged)

Upper End-Cap
(New Part)
(Super Invar)

Actuator
(Unchanged)

Flex-Couple
(Invar)

Lower End-Cap
(New Part)
(Super Invar)

Clamps
(Unchanged)
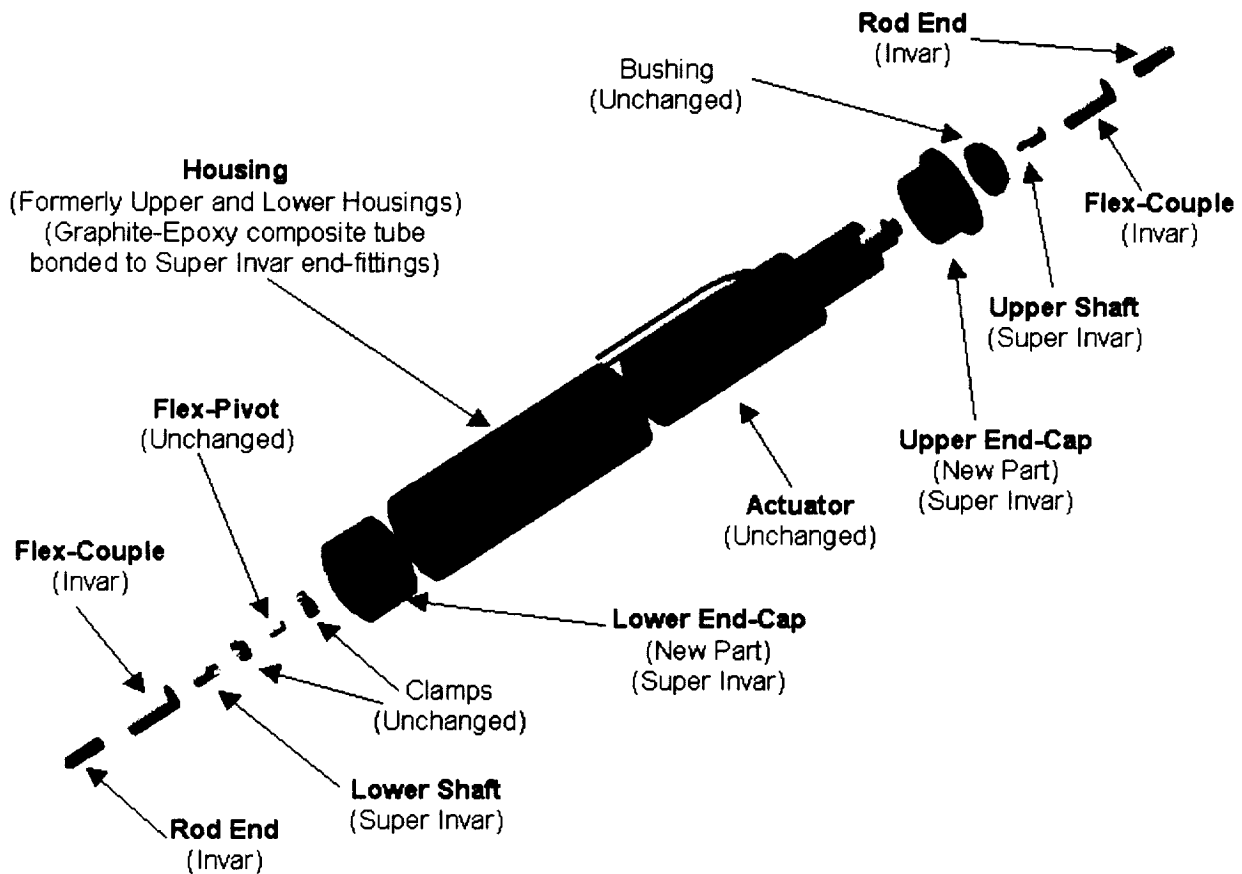
Rod End
(Invar)

Lower Shaft
(Super Invar)

Figure 7. Dimensionally Stable Hexapod Leg

Composite Design Effort

The design of the composite tube required its own effort, with assistance from a materials engineer specializing in composites. Analysis suggested that with the proposed leg concept, a composite tube could be designed that would provide the leg assembly with a near-zero CTE in the axial direction. The goal for the tube was to have a CTE in the axial direction of –4.4E-6 per deg C. Specific analysis was also required to estimate the effective CTE of the overlap between the tube and the Super Invar end-fittings that were bonded to it.

The composite material designed uses 9 layers of Amoco's T50 graphite fiber with Cytec Fiberite's 954-2A cyanate ester resin. A layup of 30/30/-30/-30/0/-30/-30/30/30 was predicted to provided the desired CTE of –4.4E-6 per deg C. This layup takes advantage of the large Poisson's ratio of the material to amplify the negative thermal expansion of the tube. As the temperature increases, the tube expands in the hoop direction, and this causes the tube to shrink in the axial direction. This is in addition to the shrinking caused by the negative CTE of the composite fibers themselves. This layup design has reduced strength and stiffness compared to other layup options. In this application, however, the strength and stiffness properties were determined to be adequate. This was an acceptable trade-off.

Since the hexapod would be in a terrestrial environment, dimensional changes caused by moisture absorption in the composite were a concern. The composite selected had a large coefficient of moisture expansion (CME). This effect had to be minimized, or the new hexapod would be just as dimensionally unstable as the old one. This problem was solved by applying a moisture barrier. Parylene-C, a polymer commonly used for conformal coating electronics, was selected. This vapor-deposited coating is easy and inexpensive to apply and has a very low rate of moisture transmission. The coating itself is thin and compliant, so it was not expected to change the thermal expansion properties of part.

Final Design

Table 7 shows the predicted expansion of the dimensionally stable hexapod design with a 1 deg C ΔT applied. Table 8 shows how the model behaves when the temperature variations from Table 5 are applied. The analysis predicted this design would meet the requirements with significant margin. A 1.53 deg C temperature change between legs is necessary to cause this model to exceed the drift requirements.

Table 7. Expansion of Dimensionally Stable Hexapod Design

Part	Number Per Leg	Length (mm)	Material	α at 20 C (/C)	Δ T (deg C)	Growth (nm)	Total Growth (nm)
Rod end	2	12.065	Invar	1.25E-06	1	15.08	30.16
Flex couple	2	6.0198	Invar	1.25E-06	1	7.52	15.05
Upper shaft	1	9.144	Super Invar	3.00E-07	1	2.74	2.74
Upper cap	1	6.48	Super Invar	3.00E-07	1	1.94	1.94
Upper bond	1	15.875	Invar-to-Comp. Joint	-1.60E-06	1	-25.35	-25.35
Housing	1	70.74	Graphite-Epoxy	-3.83E-06	1	-270.93	-270.93
Actuator*	1	*NA*	Steel and Al	*2.38E-07*	*1*	*238.37*	*238.37*
Lower Cap	1	28.94	Super Invar	3.00E-07	1	8.68	8.68
Lower bond	1	15.875	Invar-to-Comp. Joint	-1.60E-06	1	-25.35	-25.35
Flex pivot	1	7.62	420 Stainless Steel	9.90E-06	1	75.44	75.44
Lower shaft	1	11.938	Super Invar	3.00E-07	1	3.58	3.58
							54.33

Hexapod Height change if all actuators grow: **62.48 nm**

Hexapod tilt if 2 actuators grow: **0.10258 arc-sec**

Table 8. Predicted Response of New Hexapod Design to Measured Temperature Environment

Time Interval	ΔT (deg C)	Piston Error (nm)	Tip/Tilt Error (arc-sec)
1 hr.	0.026	0.17	0.00028
2 hr.	0.032	0.22	0.00034
3 hr.	0.035	0.23	0.00038
4 hr.	0.043	0.28	0.00046
8+ hr.	0.05	0.33	0.00054
Requirements:		10	0.025

Invar Considerations

Before incorporating Invar or Super Invar into a mechanism, the design team did considerable research to fully understand these complex metals. Invar's CTE varies non-linearly with temperature, so the operating thermal environment must be well understood. Achieving the listed properties for Invar requires specific heat treatment, and machining Invar after the heat treatment will alter these properties. Therefore, heat treatment is required again for finished parts. Lastly, Invar is subject to dimensional creep over long periods. Consider all these properties carefully before deciding to use Invar or Super Invar. The primary source of Invar information used by the DCATT team was "The Invar Effect"[2].

Final Status of DCATT Hexapods

Fabrication and Assembly Status

The DCATT project was cancelled shortly after the dimensional stability design effort. Limited funds were made available to fabricate parts for one hexapod in the interest of verifying design elements that might be useful to future projects. At this time, all parts have been fabricated, but the hexapod itself has not been assembled. Thermal expansion tests have been performed on some of the components to verify design predictions of their CTE. At this time, final assembly and testing of a hexapod is not being pursued due to funding and manpower limitations. It is possible, however, that renewed interest in the future may revive this development effort.

Component-Level CTE Testing

CTE tests have been performed on several of the composite tubes. The results show an average CTE of –3.83E-6 per deg C over a temperature range of 7-31 deg C. This is within 13% of the design value. One measurement was made on each of two sub-assemblies consisting of composite tubes bonded to their Super Invar end-fittings. Both CTE measurements were -1.9e-6 per deg C. More measurements on the sub-assemblies were not possible on the restricted budget, so the sub-assembly CTEs carry less confidence than the tube CTEs.

Dimensional Stability Predictions with Measured CTEs

If the measured CTEs are included in the hexapod thermal models, the design performance degrades by nearly a factor of 10. This still meets the drift requirements, however. Worst case 8-hour drifts are 6 nm in piston and .01 arc-seconds in tip/tilt. Drift requirements are exceeded by a 0.09 deg C differential temperature change. Table 9 further details these results.

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[2] "The Invar Effect: A Centennial Symposium." International Symposium on the Invar Effect (1996: Cincinnati, Ohio). ed. Jerry Wittenauer. Warrendale, PA: Minerals, Metals & Materials Society, 1996

Table 9. Hexapod Drift Predictions with Measured CTEs

Model Description	Predicted 8-Hour Drift		ΔT to Exceed Req. (deg C)
	Piston (nm)	Tip/Tilt (deg C)	
Analytical model with no measured CTEs	0.33	.00054	1.53
Model with measured CTE of composite tubes	3.1	.0051	0.17
Model with measured CTE of tube sub-assemblies (low confidence in measurement)	5.9	.0096	0.09

Conclusions

The DCATT hexapod is a response to the need for a high-resolution, 6-DoF positioning mechanism for use in a large, active-optics system. Although the final design has not been assembled or tested, the development brought to light several challenging obstacles which were analyzed and overcome. With active optics being proposed for increasing numbers space flight missions, the experiences of the hexapod design team may prove relevant to many future aerospace mechanisms.

The most important lessons learned from the hexapod design effort are as follows:

- High-resolution inchworm actuators may have unacceptable motion discontinuities caused by the clamping and unclamping of the inchworm mechanism.
- High-resolution, 6-DoF motion tests require significant design effort. Analyze dimensional stability in the test setup.
- Relative dimensional stability may be more restrictive than absolute dimensional stability in active-optics systems.
- Large negative CTEs can be achieved with graphite epoxy. Tube structures can amplify this by taking advantage of the Poisson's ratio of the material.
- Composites with a large, negative CTE may have reduced strength and a large CME.
- If a composite's CME poses a problem, Parylene-C can be a simple, cost-effective moisture barrier.