Development and testing of a high-precision, high-stiffness linear actuator for the focus-center mechanism of the SOFIA secondary mirror

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ABSTRACT

The SOFIA telescope chopping secondary mirror is mounted on a Focus Centering Mechanism (FCM). This system is a novel type of parallel manipulator (hexapod) made of six linear actuators which provide active alignment and focus of the chopper unit with respect to the top ring frame. We describe the development of the compact high-precision linear actuator used for this hexapod mechanism. The paper reports the test results measured on the actuator prototype proving its submicron position accuracy capability as well as its high stiffness and force. The prototype was designed to be largely representative of the flight unit ones currently in the construction phase.

Keywords: Linear actuator, hexapod.

1. INTRODUCTION

The US and German aerospace agencies NASA and DLR are jointly developing the Stratospheric Observatory For Infrared Astronomy (SOFIA), a 2.5-meter telescope carried by a Boeing 747-SP aircraft in a special compartment which can be opened in flight. The telescope is operated above 12.5 km altitude in an open section of the airplane fuselage, at temperatures down to -60°C and a pressure of 120 mbar.

CSEM is in charge as a subcontractor of MAN Technologie of the development and manufacturing of the secondary mirror mechanism (SMM). The SOFIA secondary mirror has a diameter of 350 mm and is supported by a complex mechanism which has two general functions:

- fine positioning of the mirror in order to be able to center and focus the telescope light beam;
- very fast tilting and chopping of the mirror.

The Secondary Mirror Mechanism (SMM) is subdivided into two subsystems named Tilt-Chopping Mechanism (TCM) in charge essentially of fast tip-tilt and chopping actuation, and the Focus-Center Mechanism (FCM) which is responsible in particular for focus and centering alignment and, more generally for all offsets of the mirror positions. The TCM and the FCM are functionally distinct but closely integrated in order to meet the very stringent requirements regarding the overall volume envelope of the SMM.

The SOFIA FCM consists essentially of a Stewart platform hexapod-like mechanism, capable of orienting is mobile base along all six degrees-of- freedom (DoF), although only five DoF’s are actually operated. To gain space for the TCM, the hexapod is divided in two actuator groups, one with three vertical actuating legs, and one with three horizontal legs.

The FCM is designed for low bandwidth positioning, i.e. correction of steady errors in focusing and centering. Therefore it has no particular dynamic positioning capability for fast corrections.

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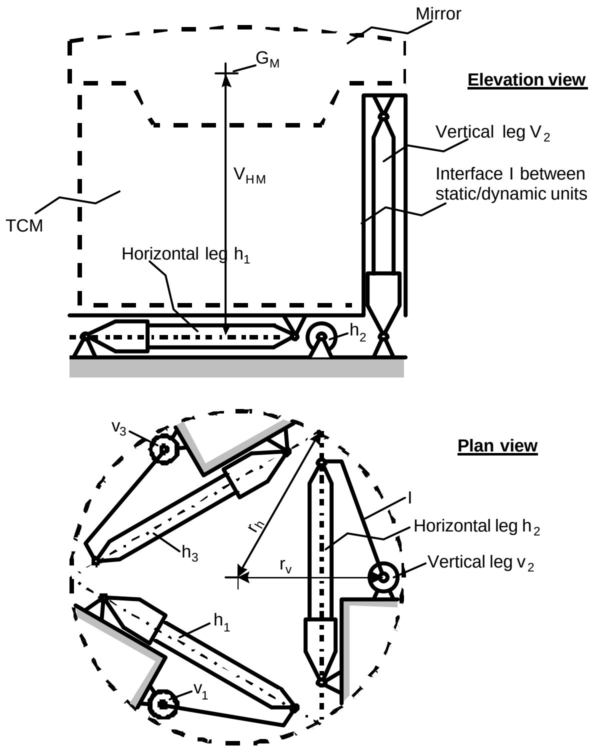

Figure 1 - Principle of the SOFIA FCM hexapod with three vertical and three horizontal legs.

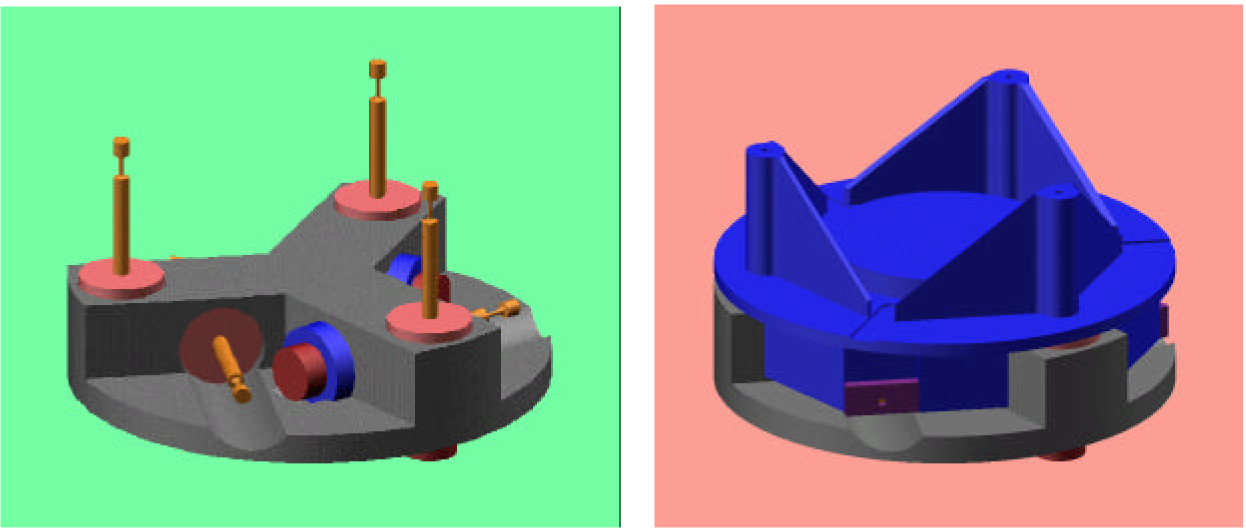

Figure 2 - FCM hexapod design.

2. DESIGN REQUIREMENTS

The design of the actuator for the FCM hexapod is driven by a combination of very stringent requirements:

- High absolute accuracy: < 5 µm
- High resolution: < 0.2 µm
- High stiffness: the hexapod made with these actuators will typically have a first eigenfrequency >200 Hz
- High strength and load capability, with no backdriving
- Small volume in order to be useable within the planned FCM geometry

Technical specifications

Actuator length	125 mm
Actuator diameter	63.5 mm
Stroke length	12 mm
Resolution	< 200 nm
Absolute accuracy	< 5 µm
Repeatability	< 3 µm
Axial stiffness	45 N/µm
Maximum load	> 3000 N
Backdriving (reversibility) load	> 1500 N
Temperature range	-60 C to 70 C

Table 1 – Actuators requirements.

Such requirements prevent using off the shelf actuators and demand the development of a novel solution tailored to the SOFIA FCM specific application.

3. ACTUATOR DESIGN FEATURES

The linear actuator is based on a recycling roller screw that transforms the rotational motion of the nut into a linear motion of the screw. The nut is directly driven by a brush-less motor, that is the motor shaft is machined directly on the nut housing. Such solution allows augmenting both the actuator compactness as well as its rigidity and dynamic response.

The roller screw is preloaded in order to eliminate the axial play. Moreover, the preload allows avoiding the backdriving (reverse motion) of the screw up to a given external load threshold: the higher the preload, the higher the external load that produces reverse motion of the screw.

The overall stiffness of the actuator is mainly affected by two factors: the roller screw own stiffness and the axial rigidity of the bearings holding the rotor into the actuator frame. The roller screw stiffness is also affected also by the amount of preload applied to the nut. In both cases the high stiffness requirement demands selecting a suitable motor to deal with the overall actuator friction caused by the bearings and the roller screw preload. The choice of a brush-less and frame-less motor allows getting high motor torque while keeping the actuator size compact.

The rotation of the motor axis is controlled through a brush-less resolver that is directly coupled to the rotor shaft behind the motor itself. This sensor fulfils the requirement of compactness and robustness demanded by the application.

Finally, the coupling between the actuator screw and the mobile plate of the FCM is achieved by a rod terminated at both ends by flexure joints. The motor torque is reacted by multiple grooves coupling between the sliding piston fixed to the screw and the actuator frame.

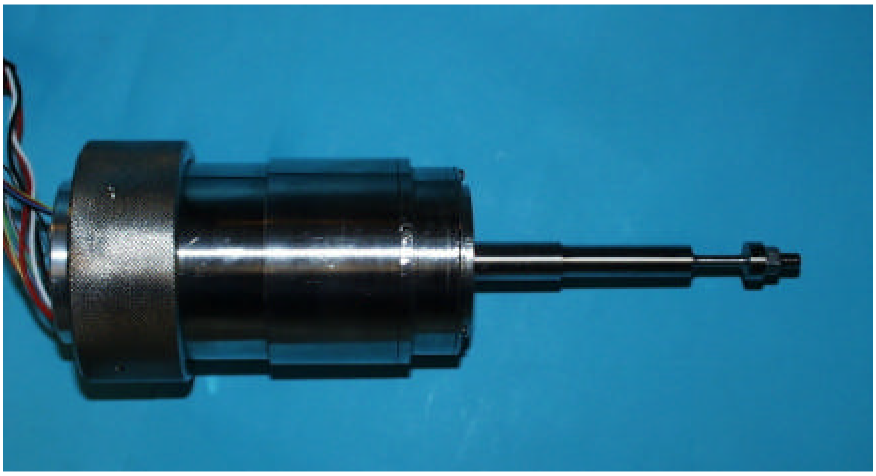

Figure 3 - The actuator prototype.

4. ACTUATOR PROTOTYPE TEST RESULTS

The following sections report on the results of the functional tests performed on the SOFIA FCM actuator prototype. All tests were performed in ambient conditions.

4.1 Stiffness

The actuator stiffness was measured by loading the actuator through a test bench frame. To compute the actuator own stiffness, the bench contribution had to be measured as well. For this reason a dummy actuator having a known stiffness was mounted on the test bench and a tensile load sequence was then applied. The measured stiffness value is 7.98 N/µm, that includes the bench and dummy contributions. From this value, the frame own stiffness can be derived and its value is 8.06 N/µm.

The compression loading of the actuator produced the force-displacement diagram reported in Figure 4. The measured stiffness value is 6.54 N/µm, that removing the bench contribution gives the actuator own stiffness: 34.7 N/µm.

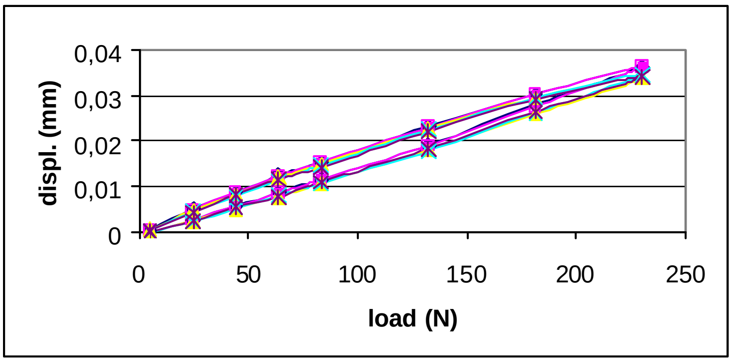

Figure 4 – Actuator compression loading test.

To confirm this results, an eigenfrequency test (Figure 5) with a load mass was performed from which a stiffness value of 32 N/µm is evaluated. Once the contribution of the rod flexures is taken into account, the net actuator stiffness result is about 45 N/µm.

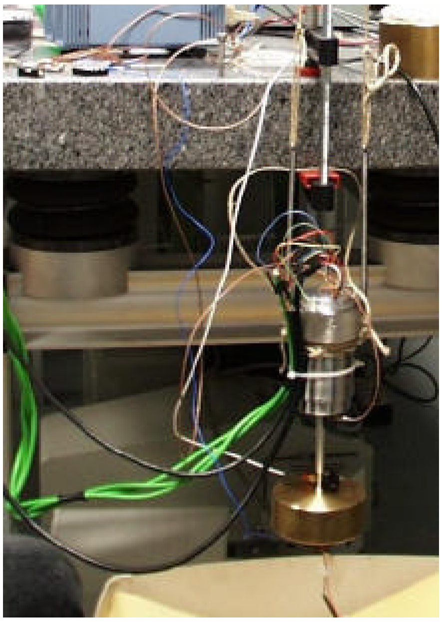

Figure 5 – Actuator eigenfrequency test.

4.2 Backdriving

The test was carried out by applying to the actuator a sequence of increasing compression loads and by monitoring the actuator length. The preload is made by two Belleville springs packed in parallel plus one put in opposition. The compression load was chosen to avoid directly loading the set of nut preload springs.

The nominal height of such uncompressed springs pack is 3.7 mm. The gap in the nut housing where the springs are placed is 3.4 mm. The loading on the nut can be estimated assuming that the tensile actuator stiffness is mainly the springs one. Thus, the order of magnitude of the preload is then 10 N/µm x 300 µm = 3000 N.

According to screw manufacturer such preload is about two times the level needed to avoid backdriving up to 1500 N axial load. No backdriving was measured up to the maximum test bench loading capability of 300 N.

4.3 Accuracy

The accuracy tests were carried out by commanding a number of independent positioning sequences that sweep over the whole screw length. A compression load of 160 N was applied to the actuator.

The system was initialized at its zero position, defined by the piston head aligned with the actuator frame. Then, a sequence of absolute positioning commands was executed, extending the actuator to the full stroke, by steps having 1 mm average length. The actual step length was randomized to avoid settling on the same nut position at every turn. Once the full stroke was reached the inverted sequence was commanded to drive back the actuator to the origin.

A set of five cycles was executed. The result is reported in table 2 and figure 6.

The positioning error is expressed as the difference between the position read by the actuator sensor and the reference one (Heidenhain linear encoder MT101M, 0.1 µm accuracy). The mean value of the error curves represents the screw lead error. The standard deviation over the five measurements is the positioning repeatability and it embeds the effects of all the mechanical and servo uncertainties.

Commanded Position		**Actual Position (mm)**					
(cts)	(mm)	Test #1	Test #2	Test #3	Test #4	Test #5	Average Value
0	0	0	0	0	0	0	0
14508	1,0075	1,0067	1,0056	1,0065	1,0069	1,0068	1,0065
27797	1,9303	1,9296	1,9284	1,929	1,9295	1,9295	1,9292
43285	3,0059	3,0078	3,0061	3,0069	3,0072	3,0069	3,0070
57980	4,0264	4,0259	4,025	4,0257	4,0266	4,0261	4,0259
69918	4,8554	4,8528	4,8538	4,8546	4,855	4,8552	4,8543
88194	6,1246	6,1231	6,1223	6,1228	6,1229	6,123	6,1228
101631	7,0577	7,0562	7,0552	7,0568	7,0555	7,0566	7,0561
115005	7,9865	7,9864	7,9858	7,9864	7,9867	7,9866	7,9864
127771	8,8730	8,8733	8,8727	8,874	8,8741	8,8736	8,8735
143935	9,9955	9,9971	9,9968	9,9973	9,9974	9,9972	9,9972
157298	10,9235	10,9268	10,9259	10,9263	10,927	10,9267	10,9265
172800	12	11,985	11,9848	11,9855	11,985	11,9853	11,9852

Table 2 – Accuracy test results.

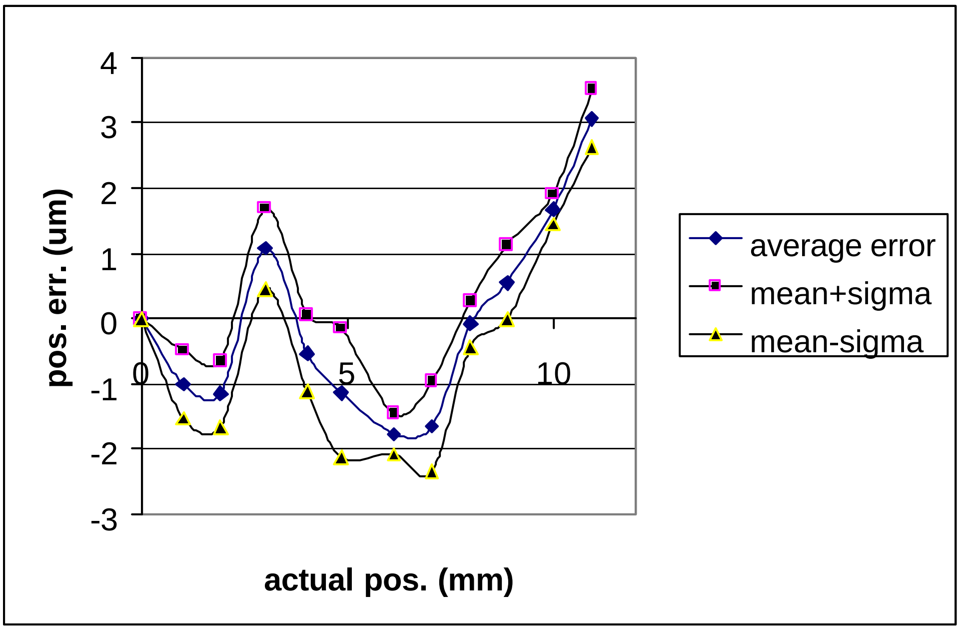

Figure 6 – Positioning repeatability.

4.4 Backlash

The backlash test measures the positioning error that occurs when the motion of the mechanism is inverted.

The test was executed by approaching a reference position with small steps to assure the absence of overshoot in the screw motion. In this position the reference linear encoder was reset. At this point, a further displacement was commanded in the same direction of the previous motion. Then, a second movement with the same amplitude of the previous was commanded from the final position, but in the opposite direction. The final position error represents then the backlash error itself.

This test was repeated three times and the measured backlash errors were: 2.8 μm, 2.5 μm and 2.6 μm respectively.

4.5 Resolution

The goal of the resolution test is to measure the actuator correction capability, that is the minimum controllable step.

For this purpose the actuator was positioned at a given point with a large stroke command. Then from that point, a sequence of decreasing amplitude steps was commanded and the error between commanded and achieved step amplitude was analyzed as function of the step amplitude itself. The same test is executed by extending and also by closing the actuator, always with a compression load applied.

In order to validate the controller design this test was repeated twice. In one case the compression load was 160 N and in the other one was 110 N. The controller setup was kept unchanged in both cases. The test results reported in table 3 were achieved with the preload configuration discussed in the backdriving analysis paragraph.

Comm. step (μm)	**Step error (μm)**					
	test #1	Test #2	test #3	test #4	test #5	Average error
3,5	0,1	0,1	0,1	0,2	0,1	0,2
1,7	0,2	0,2	0,2	0,2	0,2	0,2
0,8	0,1	0,1	0,0	0,1	0,1	0,1
0,4	0,1	0,2	0,1	0,0	0,1	0,1
0,2	0,1	0,0	0,1	0,1	0,0	0,1

Table 3 – Resolution test @ 160 N compression load.

5. FINAL REMARKS

A novel linear actuator for the SOFIA Focus Center Mechanism has been developed and successfully tested. The prototype is largely representative of the flight unit actuators that are now entering the production phase.

ACKNOWLEDGMENTS

The design of these actuators involved, beside the authors, many persons at CSEM and ADS. The personal contribution of Ivar Kjelberg and Laurent Giriens at CSEM and Enzo Anaclerio and Paolo Lazzarini at ADS are particularly acknowledged.

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