Flexure-based Pointing Mechanism with Sub-microradian Resolution for the Laser Interferometer Space Antenna

S. Henein, P. Spanoudakis, P. Schwab, I. Kjelberg, L. Giriens, L. Dassa
Centre Suisse d'Electronique et de Microtechnique (CSEM), Switzerland

simon.henein@csem.ch

Abstract

The Point Ahead Angle Mechanism (PAAM) for ESA's Laser Interferometer Space Antenna (LISA) mission will compensate the out-of-plane point-ahead angle between three satellites flying 5 million kilometres apart. The PAAM consists of a mirror supported by flexures allowing the mirror to rotate with a maximum stroke of ± 412 µrad. The mirror is actuated in 0.14 µrad steps by two redundant linear Piezo LEGS® actuators driving a sine-bar. Since the actuators are self-locking, a special lever performing the role of a linear mechanical differential is used to provide redundancy. The angle is driven in closed loop using two capacitive sensors.

1 Introduction

The objective of the Laser Interferometer Space Antenna (LISA) mission is to detect and observe gravitational waves from massive black holes and galactic binaries. A gravitational wave passing through the Solar System creates a time-varying strain in space that periodically changes the distances between all bodies in the Solar System.

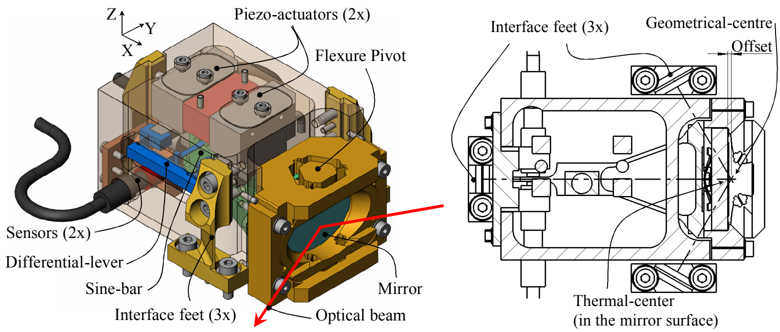


Figure 1. Left: CAD view of the PAAM mechanism. Right: arrangement of the three isostatic feet and corresponding geometrical and thermal centres.

Gravitational waves will be observed by LISA using laser interferometry. The mission is composed of three identical spacecraft located at 5 million kilometres apart flying in an equilateral triangle formation rotating in a heliocentric orbit trailing the earth. Each spacecraft will contain two reference targets, known as "proof masses", each of which acts as the end mirror of a single-arm interferometer. The measurement system has to provide an absolute accuracy in the range of 10 pm/√Hz for a single arm laser link, given an arm length of 5×10^6 km.

The Point Ahead Angle Mechanism (PAAM), Fig. 1, will compensate the out-of-plane point-ahead angle between the three satellites, resulting from residual seasonal changes and the 16 s travel time of the laser light between the spacecrafts.

The mechanism was designed and developed jointly by CSEM (CH) and RUAG Aerospace (CH) and is currently undergoing tests. The objective of the project is to design, develop, test and validate an elegant breadboard (EBB), of the PAAM with a design maturity ready to enter directly into the LISA implementation phase.

2 Performance requirements

Particularly critical is, the parasitic "piston" motion of the mirror (i.e. the translation perpendicular to the mirror surface) that might accompany its rotation, since it is directly seen by the system as a pathlength error.

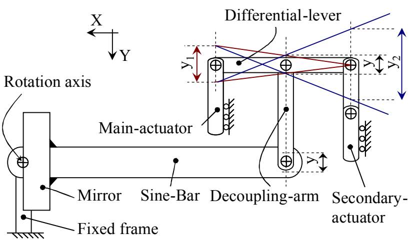
Technically, the critical design requirements for the PAAM are: angular stroke : ± 412 µrad (mechanical angle); Scanning speed : ± 62.5 prad/s; Scanning error at any time should be below ± 4 µrad; Longitudinal pathlength stability $1.4\frac{pm}{\sqrt{Hz}}\sqrt{1+\left(\frac{2.8mHz}{f}\right)^4}$; Maximum pointing jitter below $8\frac{nrad}{\sqrt{Hz}}\sqrt{1+\left(\frac{0.0028}{f}\right)^4}$ in the frequency band between 10^{-4} Hz and 1 Hz (mechanical angle); Total Piston error below 1.5 pm for a 0.14 µrad rotation; Design loads of 736 m/s^2 (75 g); Use of non-magnetic material and components; Stringent cleanliness requirements

3 Mechanism's general description

The general architecture and functionality of the PAAM mechanism (mass 160 g, 73x56x36 mm) is described below.

The optical mirror is supported by a **monolithic flexure pivot** with a motion range of ± 412 µrad. To get a rotation that is devoid of any parasitic shifts [1,2] and that is very stiff in the piston direction (X), two identical concomitant three-blade flexure pivots are used, one on each side of the mirror. The pivot is cut monolithically by high-precision Wire Electrodischarge-machining (EDM) in Aluminium alloy 6061-T651.

The flexure pivot is driven by a **sine-bar** attached to it. The sine-bar is actuated by **two redundant piezoleg-actuators** acting through a **differential-lever** (Fig. 2). Each of the two extremities of the differential-lever is attached to one piezoleg-actuator via a flexure pivot. The mid-point of the differential lever is attached to the sine-bar via a decoupling arm. The idealized planar kinematic structure shown on Fig. 2 is composed of 8 1-Degree-of-Freedom (DOF) joints and 2 closed kinematical loops. Therefore, according to Grübler's kinematical criterion [3] for planar linkages, the structure has 8 - 2·3 = 2 DOF. Each of those DOF is driven by one actuator. The motion range of the secondary actuator is twice that of the main actuator. Thus, if the main actuator fails at any position, the secondary actuator can still drive the sine bar over its full angular range.



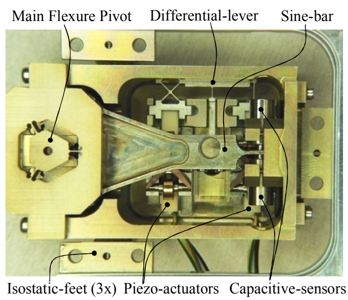


Figure 2: Kinematic chain from mirror to actuator and photograph of the mechanism

The mechanism is attached to the optical bench by three flexible feet that constitute a **kinematic mount** (Fig. 1). The elastic region of the feet is a simple blade. The three feet are oriented so that the three lines that stem perpendicularly from each blade meet in one point, called the **geometrical-centre of the mount**. Due to volume constraints, the feet could not be placed in a symmetrical arrangement with respect to the geometrical-centre as it is usually done with such assemblies. Consequently, the **thermal-centre** of the mechanism does not exactly coincide with the geometrical-centre. It has been determined, through iterative FEM simulations that in order to obtain a thermal shift close to zero within the operative condition temperature stability (1×10^{-5} K/√Hz), the required offset between the geometrical and thermal centres of the mechanism is 1.05 mm.

The three isostatic feet are pin-screwed to titanium (Ti6Al4V) support blocks that are bonded with epoxy to the Zerodur optical bench (no inserts are allowed in the optical bench). The use of titanium as an interface material (instead of aluminium as the rest of the mechanism) allows a significant reduction of the thermo-elastic stresses in the optical bench due to differential thermal expansion. The PAAM mechanism, including its feet is separable from the optical bench. Only the three titanium blocks remain permanently bonded on the bench. The average power dissipation is below 10 mW.

4 Functional and Performance Tests

A comprehensive test campaign has been performed by RUAG (CH) and the Albert Einstein Institute in Hannover (D). The following performances have been successfully verified: pointing range, step-size, actuator maximal speed, orthogonality, stability over 10 hours with PSD evaluation and jitter.

5 Conclusion

A redundantly actuated, high stability tilt mirror concept for the LISA PAAM has been designed, prototyped and tested. The tilt range exceeds the specified ±412 μrad and meets the stringent piston error or pathlength stability requirements well within the power consumption budget.

Extensive simulations and design effort has been utilised to minimise stress levels and optimise the stability of the device to reach the pico-metre level pointing noise performance required. High stability is obtained by relying on precision compliant mechanics machined by EDM and operated with a stiff actuator in quasi-static open-loop stepping mode.

Acknowledgments

L. Scolamiero (ESTEC), L. Rossini (CSEM), Ralf Greger (RUAG Aerospace AG), S. Bottinelli (Mecartex SA).

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