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Sub-system mechanical design for an eLISA optical bench

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Abstract. We present the design and development status of the opto-mechanical sub-systems that will be used in an experimental demonstration of imaging systems for eLISA. An optical bench test bed design incorporates a Zerodur® baseplate with lenses, photodetectors, and other opto-mechanics that must be both adjustable - with an accuracy of a few micrometers - and stable over a 0 to 40°C temperature range. The alignment of a multi-lens imaging system and the characterisation of the system in multiple degrees of freedom is particularly challenging. We describe the mechanical design of the precision mechanisms, including thermally stable flexure-based optical mounts and complex multi-lens, multi-axis adjuster mechanisms, and update on the integration of the mechanisms on the optical bench.

1. Introduction

eLISA optical metrology involves interfering static optical beams with optical beams that are changing direction over time. This can lead to an unwanted coupling of beam movement to apparent longitudinal signal, so called tilt-to-piston coupling. This coupling is one of the largest sources of error in the metrology error budget for eLISA. The method proposed for minimising the effect of tilt-to-piston coupling in the eLISA baseline design is the use of imaging systems placed directly in front of the detectors.

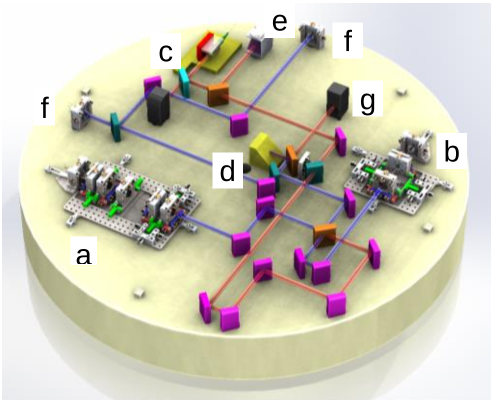

Figure 1. CAD representation of the Ø580 mm ‘minimal’ optical bench (OB) test bed with both classical (a) and non-classical optical imaging system (b) opto-mechanics integrated.

Amongst the various mirrors and beamsplitters on the OB, several other optical and opto-mechanical assemblies that make up the interferometer can be seen: fibre injector optical sub-assembly (c), out-of-plane telescope mirror (d), power monitor and alignment photodiodes (e, f), beam dumps (g).

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To experimentally verify the performance of different optical imaging systems in a representative way a test bed has been designed and is under construction. On the test bed, the performance of the imaging systems will be tested by measuring the tilt-to-piston coupling coefficients and by investigating the alignment sensitivity of the overall imaging systems and of its sub-units. Two candidate optical designs have been developed, both of which are to be tested as part of the study. To enable the two phases of testing and investigation, precision opto-mechanical mounts for these two candidate optical designs are required. These adjustable multi-lens mechanisms must be designed to interface with the polished Ø580 x 80 mm thick Zerodur® optical bench (OB) test bed yet they must be fully removable such that the candidate designs may be interchanged.

This paper reviews the design of the opto-mechanical mechanisms and their use on the OB test bed, a representation of which can be seen in Figure 1.

2. Imaging system optical design

The motivations behind the two optical design approaches are described in [1] although the exact optical designs have been altered in line with a re-scoping of the original study. The primary performance requirement for the imaging system is to reduce the tilt-to-piston coupling to less than 25µm/rad over the entire field of view. One of the designs to be tested is a four lens optical design based upon a classical pupil relay system. This design can be seen in Figure 2. All four lenses are custom manufactured from fused silica.

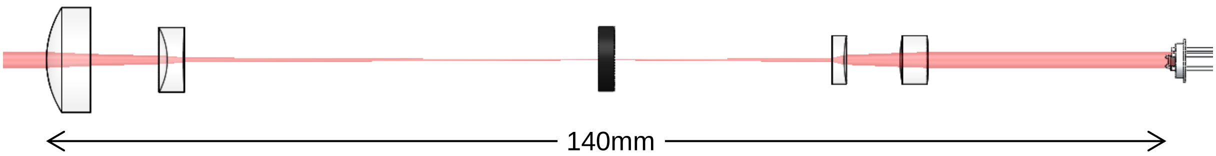

Figure 2. Four lens classical optics approach. The component in the centre of the schematic is a field stop. The component at the right hand side is a quadrant photodetector (QPD).

For the second optical design, the approach was to use Gaussian beam properties as opposed to classical ray tracing methods and to incorporate commercially available fused silica optics. This more compact design, shown in Figure 3, will also be tested as part of the investigations.

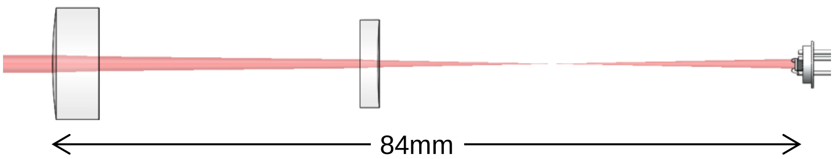

Figure 3. Two lens non-classical optics approach. The component at the right hand side is a QPD.

3. Mechanical design requirements

In each imaging system the lenses must be aligned to one another to accurately form an image on the photodetector. To do so, each lens must be able to be manipulated in five degrees of freedom (5DoF). It must also be possible to align the imaging systems, as a whole, to the photo detector on the OB. The assembled unit must then remain static and be thermally stable throughout the interferometric imaging performance testing. The alignment specifications can be seen in Table 1.

Table 1. Typical alignment adjustment specifications for each lens or lens pair.

	Specification		Tolerance
Alignment specifications	De-centre	X, Y	+/- 20 µm
	Distance tolerance to next lens	Z	+/- 50 µm
	Lens centring		+/- 3’ (or ~1 mrad)
	Lens tilt	pitch/yaw	+/- 3’ (or ~1 mrad)

Thereafter, for the characterisation activity, the mounting hardware for each system must include a wider range of adjustment to investigate the effect of systematic offsets on individual mounts, lens pairs and the whole imaging system. Table 2 summarises these characterisation requirements and the resolution required by the adjustment mechanisms.

Table 2. Typical alignment characterisation specifications for each lens or lens pair.

	Specification		Tolerance
Adjustment specifications for imaging system characterisation	De-centre	X, Y	+/- 60 µm
	Distance tolerance to next lens	Z	+/- 200 µm
	Lens tilt	pitch/yaw	+/- 10’ (or ~3 mrad)
Resolution of adjustment	Linear	X, Y, Z	micrometer
	Angular	pitch/yaw	<arc-minute (~100s of µrad)

4. Mechanical design detail

Both imaging system mechanical designs are made up of three equivalent modules: the super-baseplate, carrying all lens mounts; the lens pair assemblies and the QPD mount. The larger and more-complex, four-lens design, shown in Figure 4, has two of the lens pair assemblies and an additional field stop mount.

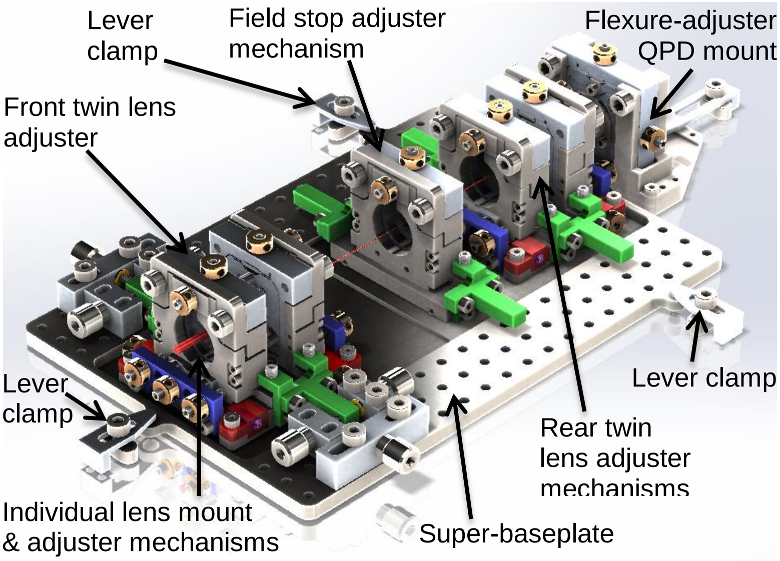

Figure 4. Four lens imaging system design. The super-baseplate is 151 x 112 mm. The red beam represents the laser light.

Techniques of ultra-precision mechanism design [2] are widely adopted throughout the imaging system design including kinematic mounting techniques for stable positioning and flexures for fine adjustment and positional control. Ultra-fine threaded screws with a thread pitch of 0.25 mm are used to provide precision adjustment of the lenses and QPD, and when employed in combination with flexures they provide the required levels of precision adjustment and clamping. The imaging system assembly and its sub-assemblies are made stable by the use of kinematic mounts: three hemispherical features on the underside of the assemblies bear against a flat surface in the interfacing part.

4.1. The super-baseplate

The super-baseplate is a precision machined titanium plate kinematically mounted to the Zerodur® baseplate by way of three underside-mounted ball-bearings. Three lever-arm clamps that attach to one of three custom titanium nuts epoxied to the Zerodur® provide the clamping. At either side of the lens mounts on the super-baseplate there are M3 mounting holes to allow the flexible attachment and removal of lateral and transverse adjusters for the twin lens and field stop assemblies.

4.2. Lens pair assembly

The lens pair assembly, see Figure 5, consists of two individual lens holders and their 5DoF adjuster mechanisms. These assemblies are attached to a titanium baseplate which is in turn mounted to the super-baseplate via three hemispherical points on the underside. The symmetrically designed lens pair assembly is locked in place on the super-baseplate at a single point through the centre of the assembly.

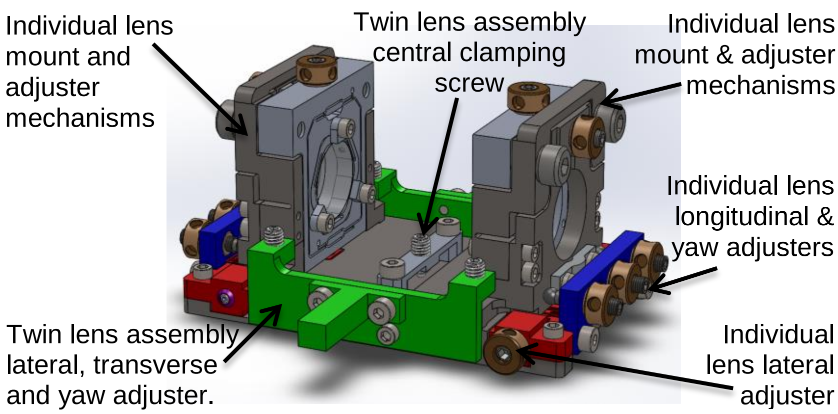

Figure 5. Isometric view of a lens pair assembly from the non-classical imaging system design.

4.3. Individual Lens Holders

The individual lens holders are constructed from an aluminium and titanium architecture. Lenses with diameters ranging from 6mm to 13mm are held in a tailored aluminium mounts that attach to a monolithic aluminium flexure mechanism which, as can be seen in Figure 6, are then mounted to a titanium frame. Thermal stability of the lens holder, and also of the overall assembly comes through careful design of the aluminium mount and the titanium frame such that they expand in opposite directions from one another results in a stable lens centre.

4.3.1. Vertical and pitch adjustment

The aluminium flexure mechanism in combination with an ultra-fine threaded screws allow for vertical adjustment of the lens in the mount. For pitch adjustment of the lens another precision adjustment screw, bearing against the aluminium lens mount but affixed to the titanium frame, utilizes a flexure hinge in the titanium frame to provide a pitch mechanism in the mount. These mechanisms can be seen in Figure 6 and Figure 7.

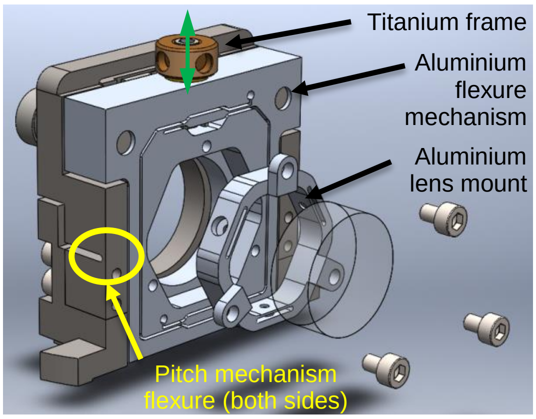

Figure 6. Exploded view of individual lens holder.

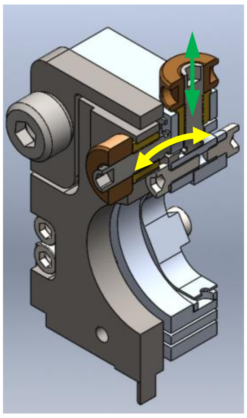

Figure 7. Cross-section view of individual lens holder showing vertical and pitch mechanism.

4.3.2. Lateral adjustment
The individual lens holder may be adjusted laterally using a titanium flexure mechanism, Figure 8 and Figure 9, that sits beneath each lens holder and is driven by fine pitch screws. The frame of the lens holder interfaces with this lateral adjuster through a 2mm pin at the base of the mount.

4.3.3. Longitudinal and yaw adjustment
Longitudinal and yaw adjustment is made using three fine pitch screws with customised screw tips as shown in Figure 10. The central screw performs the longitudinal movement but, thanks to its bevelled end, can permit rotation via the two side pusher screws.

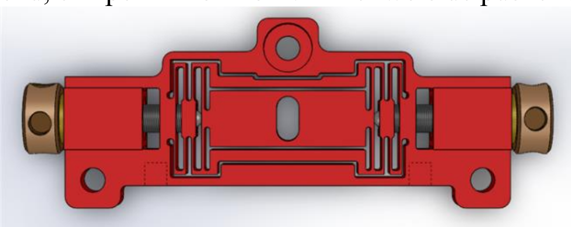

Figure 8. Top view of individual lens holder lateral adjustment mechanism with adjuster screws and locking screws attached.

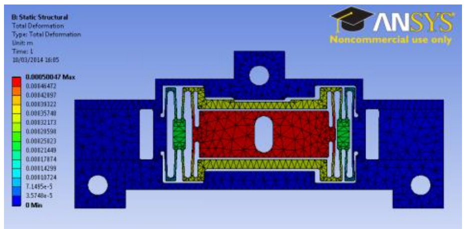

Figure 9. The individual lens holder lateral adjustment mechanism in its deformed state using ANSYS Finite Element Modeller.

4.4. QPD mount
The QPD mount, Figure 11, differs from to the aforementioned individual lens mount design in that the aluminium flexure mechanism is mounted in a rigid titanium frame with no pitch adjustment. Further, in addition to a vertical flexure mechanism, the QPD mount also incorporates a lateral flexure mechanism within the aluminium part. The QPD itself is glued to a MACOR interface collar, for electrical and thermal isolation, and this is attached to the rear of the aluminium flexure mechanism. The base of the QPD mount is titanium which, like the super-baseplates, sits on three hemispherical points and is lever-clamped to the Zerodur® OB.

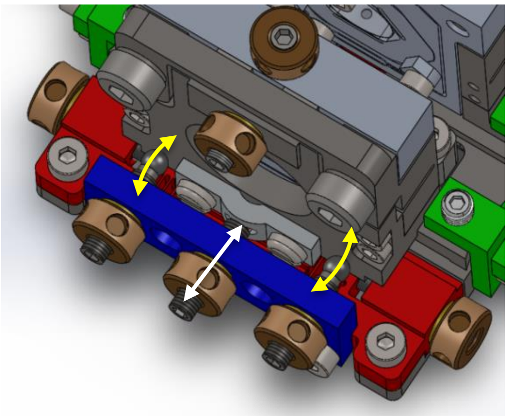

Figure 10. Longitudinal and yaw adjustment mechanisms of the individual lens holder.

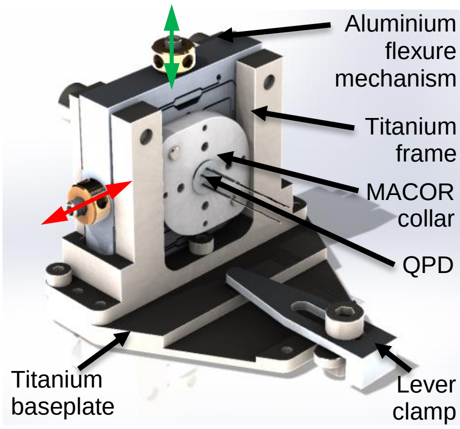

Figure 11. Rear isometric view of the QPD mount.

5. Conclusions
The design of high precision opto-mechanics to be used in the investigations of imaging systems and photodetectors for eLISA are detailed in this paper. By using an array of fine adjustment mechanisms incorporating monolithic flexures, ultra-fine precision screws and kinematic mounting techniques, the required alignment, adjustment precision, and interchangeability has been achieved in the design. These imaging system designs are currently under manufacture and shall be integrated on to an optical bench test bed for investigation. Rather than the previously planned elegant breadboard, the re-scoped study will see the construction of a ‘minimal’ optical bench with features necessary to the testing the

imaging systems as a science interferometer. As part of the same re-scoped study, a telescope simulator is being developed that will generate a representative Rx beam and local oscillator beam, and include a reference interferometer to combine these beams for use on the OB.

References

[1] d'Arcio et al 2012 An Elegant Breadboard of the Optical Bench for eLISA/NGO *ICSO 2012* http://www.icsoproceedings.org/
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Acknowledgments

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