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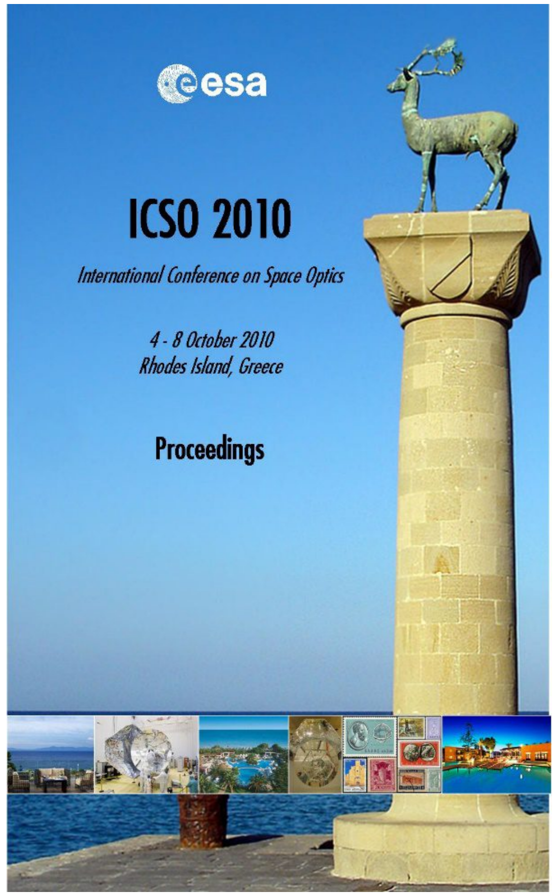

Active x-ray optics for high resolution space telescopes

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ACTIVE X-RAY OPTICS FOR HIGH RESOLUTION SPACE TELESCOPES

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INTRODUCTION

The Smart X-ray Optics (SXO) Basic Technology project started in April 2006 and will end in October 2010. The aim is to develop new technologies in the field of X-ray focusing, in particular the application of active and adaptive optics. While very major advances have been made in active/adaptive astronomical optics for visible light, little was previously achieved for X-ray optics where the technological challenges differ because of the much shorter wavelengths involved.

The field of X-ray astronomy has been characterized by the development and launch of ever larger observatories with the culmination in the European Space Agency's XMM-Newton and NASA's Chandra missions which are currently operational. XMM-Newton uses a multi-nested structure to provide modest angular resolution (~10 arcsec) but large effective area, while Chandra sacrifices effective area to achieve the optical stability necessary to provide sub-arc second resolution. Currently the European Space Agency (ESA) is engaged in studies of the next generation of X-ray space observatories, with the aim of producing telescopes with increased sensitivity and resolution. To achieve these aims several telescopes have been proposed, for example ESA and NASA's combined International X-ray Observatory (IXO), aimed at spectroscopy, and NASA's Generation-X. In the field of X-ray astronomy sub 0.2 arcsecond resolution with high efficiency would be very exciting. Such resolution is unlikely to be achieved by anything other than an active system. The benefits of a such a high resolution would be important for a range of astrophysics subjects, for example the potential angular resolution offered by active X-ray optics could provide unprecedented structural imaging detail of the Solar Wind bow-shock interaction of comets, planets and similar objects and auroral phenomena throughout the Solar system using an observing platform in low Earth orbit.

A major aim of the SXO project was to investigate the production of thin actively controlled grazing incident optics for the next generation of X-ray space telescopes. Currently telescope systems are limited in the resolution and sensitivity by the optical quality of the thin shell optics used. As part of its research programme an actively controlled prototype X-ray thin shell telescope optic of dimensions 30x10cm has been developed to bench test the technology. The design is based on thin nickel shells bonded to shaped piezo-electric unimorph actuators made from lead zirconate titanate (PZT).

DESIGN AND MODELLING

The prototype optic was designed such that it could be tested at the 28m X-ray Tunnel Test Facility (TTF) at the University of Leicester. The optic is an elliptical segment and the ellipse size and shape is designed to fit the testing facility and provides a simple point-to-point focusing of the X-ray beam, relying on only a single reflection unlike the dual reflection from the traditional Wolter I configuration. In order to make the prototype easier to manufacture, the axis of the ellipse was tilted from the axis of the TTF. This allowed the semi-minor axis of the ellipse to be larger and therefore closer to a cone in form. The control of the actuators is via a 32 channel output voltage drive connected in series to a high voltage amplifier, this arrangement allows a voltage range between 0 − 200V. Computer control of the system is via a programme written in LABVIEW. Table 1, shows the prototype specifications

Table 1. Elliptical design specifications

Elliptical Prototype Design	
Ellipse Semi major axis	14145 mm
Ellipse Semi minor axis	228 mm
Position of the front of the optic (from the centre)	9442.5 mm
Position of the rear of the optic	9742.5 mm
Position of the rear from the detector	4402.5 mm
Radius at the front of the optic	169.761 mm
Radius at the rear of the optic	165.298 mm
Circumference at the front	1066.64 mm
Circumference at the rear	1038.598 mm
Grazing angle	1.163deg
Angle at the front	33.751deg
Angle at the rear	34.662deg
Sagital distance from a cone	0.0325 mm

Extensive finite element modeling (FEA) of the active optic was undertaken to optimize the design parameters. In a particular the actuator size, thickness and influence function (see Fig.1) was studied along with the effect of using different nickel shell thicknesses.

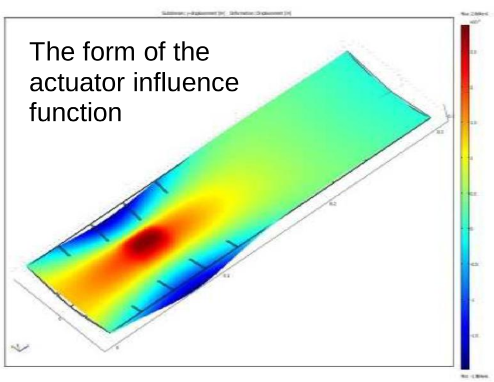

Fig. 1. FEA model of actuator influence function

Fig. 2. Optic support structure

In the initial prototype it was decided to use 30 actuators in a 10 by 3 arrangement, on later prototypes this was changed to 24 actuators in an 8 by 3 arrangement.

The active mirror needs to be accurately aligned in the test beam facility. It also needs to be supported in a relatively unconstrained way and minimising gravitational distortion. To fulfil these requirements a support structure was designed and built by MSSL to hold the prototype (Fig.2). The support structure consists of two individual components. The first component is connected directly onto a flange on the x-ray beam tube, this component incorporates tip-tilt and yaw movement so that the optic can be positioned accurately in the beam line. The second component, the optic cradle, is an aluminium framework that has pliable strips attached that support the optic along the lengths of its sides. In initially testing the optic was supported by strips of polymide foam material down each side of the optic. This foam is vacuum compatible and space qualified. This arrangement was found to under constrain the position of the optic and in later tests the polymide foam was replaced by a strip of Viton synthetic rubber.

SHELL PRODUCTION.

The material chosen for the optic substrate was nickel. Nickel has an established history of use for X-ray mirror shells, for example in the XMM-Newton space observatory. The shells were produced in-house at UCL using an electroplating technique. A kanigen coated aluminium mandrel (see Fig. 3) was produced which was ground and polished to the required elliptical section form with a final surface roughness of 1.3nm RA. Gold was vacuum deposited upon the kanigen surface to provide a passivation layer for the nickel deposition and a reflective layer for the X-rays. Wasters were included as a sacrificial electrode to improve the uniformity of current density upon the mandrel to achieve an even coating. Polyester insulating tape used to mask off the undesired regions and thin polypropylene insulator is used to isolate the electroformed optic from the excess over plated regions.

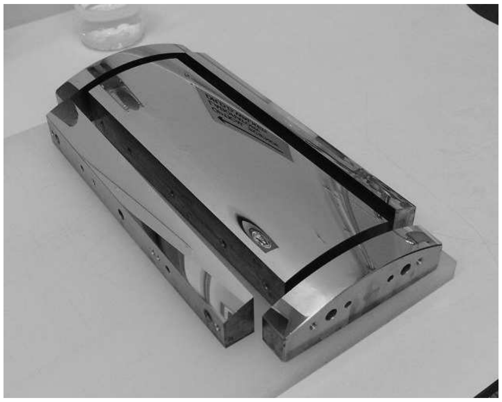

Fig. 3. Coated mandrel

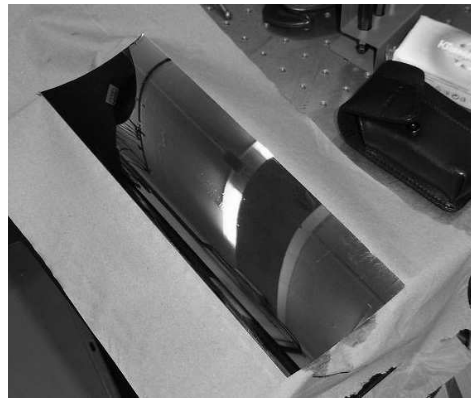

Fig. 4. Nickel shell

Using the mandrel a series of nickel shells (see Fig 4.) were produced with thicknesses of between 0.4-0.8mm. It was found that the surface roughness of the shells were slightly higher than that of the mandrel with a surface roughness of ~1.7nm RA.

The use of nickel as the substrate in this project does not mean that other substrate materials would not be suitable, and the project is currently also investigating the possible use of thin slumped glass shells.

PIEZO-ACTUATOR PRODUCTION

Piezoelectric actuators have to date been employed in X-ray adaptive optics, and used in synchrotrons and other commercial applications. In order for the piezoelectric devices to have any useful effect, they need to be able to change the gradient of the mirror surface by □1” equivalent to a surface height shift of □1µm over the mirror length of 300mm.

Thin curved PZT actuators have been developed by the project with controlled surface finish, thickness and curvature using a viscous plastic process (VPP) technique. In order to match the curvature of the mirror shell in the large optic applications and reduce the bonding stress and possible mirror distortion, a curving technique was developed to shape PZT membranes into an appropriate curvature [1][2]. Fig. 5 shows a piece of ZrO_2 former whose top surface has the required curvature, with two pieces of PZT membranes on top after sintering process. Fig. 6 shows a single PZT membrane seen side on showing the curvature.

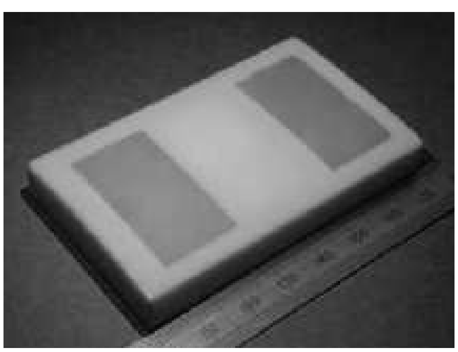

Fig. 5. PZT actuators on former

Fig. 6. Side view of single PZT actuator

OPTIC ASSEMBLY

A key part of the production of the active mirror is the bonding of the piezo-actuators to the optic. An even bond layer is required to maintain performance uniformity and a very small gap of less than 100µm between each actuator to avoid the problem of ‘kinking’ between actuators. Each actuator was laser cut at MSSL to achieve the desired shape. An even glue layer was maintained by a blading process (see Fig. 7) and by the inclusion of 80µm ceramic spheres in the glue. Fig. 8 shows a cross section of a test piece showing the glue layer, note the spacer spheres in the glue layer. Each piezo-actuator was then placed on the optic with a vacuum pencil (Fig. 9). Further details of this process are given in [3].

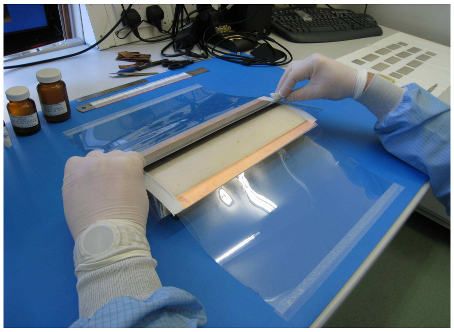

Fig. 7. Glue layer being applied to back of optic

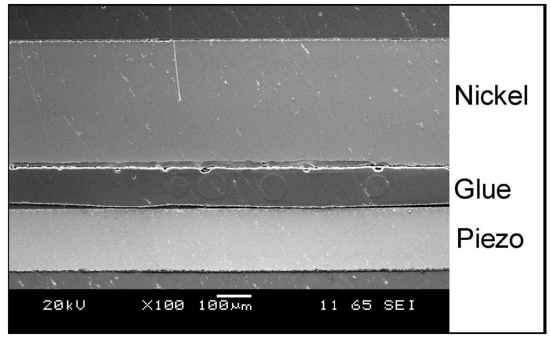

Fig. 8. Cross section of test piece showing glue layer

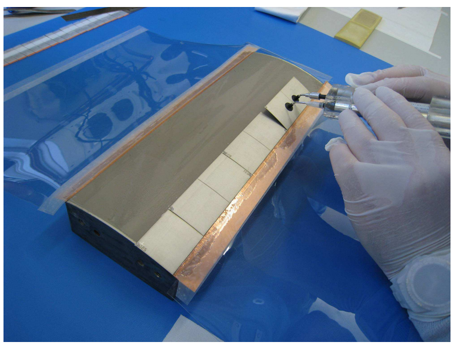

Fig. 9. Placement of actuators on optic

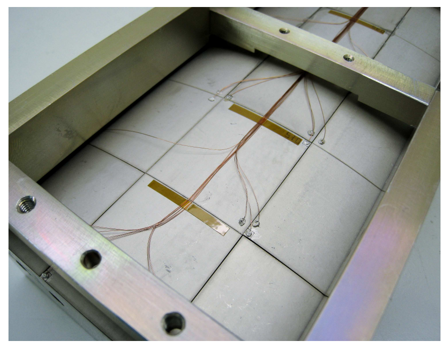

Fig. 10. Close up of back of optic showing wiring

A completed prototype optic on the alignment mount is show in Fig. 11

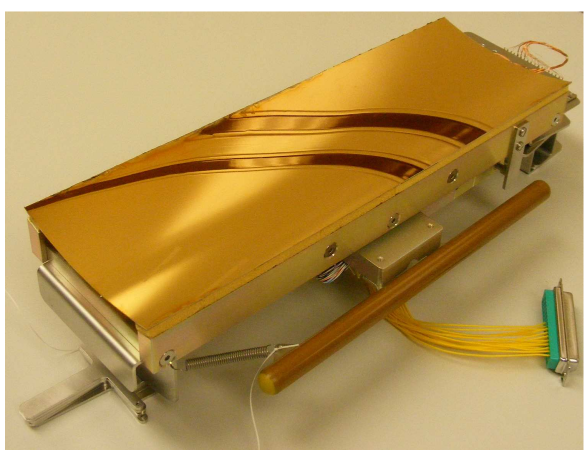

Fig 11. Prototype optics on its alignment mount.

OPTIC TESTING

Initial testing of a prototype optic was performed at the Leicester beam-line facility in November 2008. The results of these test are fully reported in [4][5]. Though the results show some image improvement with actuation, the tests also showed some problems with the design and mounting of the optic. There was found to be a problem with the motors on the mounting of the optic which prevented alignment of the optic in pitch and yaw and restricted the achievable focus to a Half Energy Width (HEW) of 7.36’ and a Full Width Half Maximum (FWHM) of 2.27’. It was also discovered that the gaps between the piezo-actuators were too large and resulted in 'kinks' developing at actuator boundaries. This led to changes in the mounting actuators and also to the assembly methods for the piezo-actuators to reduce the inter-actuator gap.

Measurements on the optic were also carried out at Daresbury Laboratory using a long trace profiler (LTP). The individual influence functions of the central actuators were measured and confirmed the predictions of the FEA analysis in showing movement ~$1x10^{-5}$m

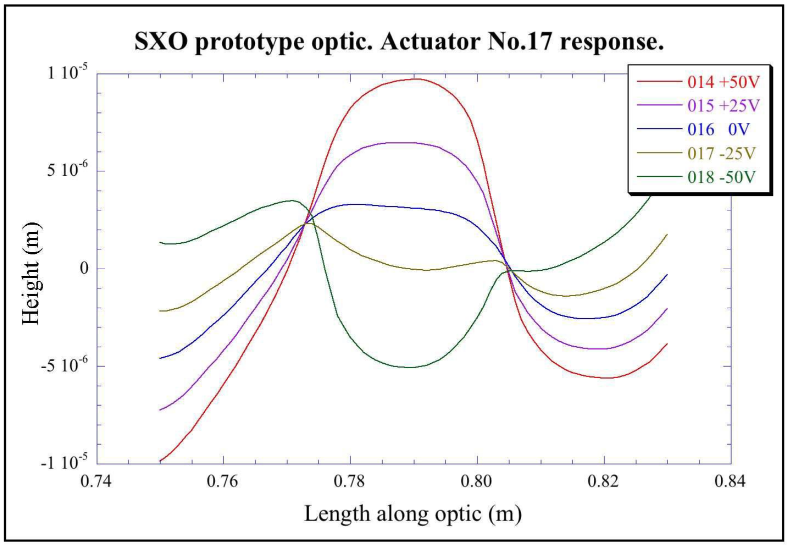

Fig. 11. Long trace profiler measurement of a single actuator at various voltages

A further test run, reported in detail in [6], at the Leicester beam-line was made in July 2010, however there were extensive problems with the beam-line facility itself and though confirmation of the improvements in the mounting system and alignment of the optic were made, only limited testing of the actuation of the optic was achieved. A direct interferometric metrology method of measuring the surface of the optic using a 30cm ZnSe cylindrical lens is at present under construction at UCL (see Fig. 12) and it is hoped to test the optic more fully at the end of August 2010.

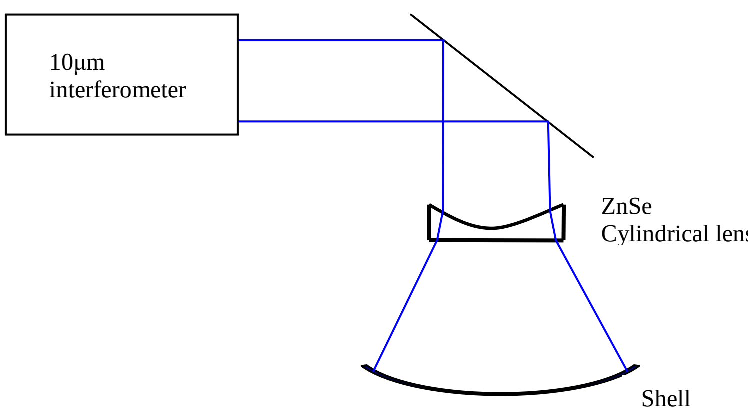

Fig. 12. Inteferometric test setup

FURTHER WORK

To demonstrate that the technology developed could be applied to space systems the next stage of the project would seek to raise the technology readiness level (TRL) to a value that will allow its inclusion in a future space science mission. This would involve addressing the range of implementation issues associated with a full scale system. The ultimate aim would be to achieve sub-arcsecond resolution with a throughput similar to that obtained by the XMM Newton telescope.

There are four main technology areas that need to be further addressed to reach the stage where a viable instrument design could be envisaged:

- Optic production optimisation
- Piezo electric actuator qualification and characterisation for flight;
- Bonding layer qualification and characterisation for flight;
- Mounting of nested X-ray active shells.

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