Title advances in optical fabrication for astronomy

David D. Walker,1,2 Guoyu Yu,1 Hongyu Li,1,3 Brian W. Myer,4 Anthony T. Beaucamp,5 Yoshiharu Namba6 and Lunzhe Wu7

1National Facility for Ultra Precision Surfaces, University of Huddersfield, OptiIC Centre, Ffordd William Morgan, St Asaph, LL17 0JD, UK
2Zeeko Ltd, OptiIC Centre, Ffordd William Morgan, St Asaph, LL17 0JD, UK
3Research Center for Space Optical Engineering, Harbin Institute of Technology, Harbin, 150001, China
4Optimax Systems, Inc., 6367 Dean Parkway, Ontario, NY 14519, USA
5Dept. of Micro-Engineering, Kyoto University, Nishikyoku, Kyoto, Japan
6Dept. of Mechanical Engineering, Chubu University, 1200 Matsumotocho, Kasugai, Aichi, Japan
7Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, 390# Qinghe Road, Jiading District, Shanghai City, 201800, China

ABSTRACT

The fabrication of precision optical surfaces has undergone a revolution in recent years. The first purpose of this paper is to present case studies of novel optical designs not previously published, that utilize complex, or ‘freeform’, surfaces. These designs are described both for their own merits, and as pointers towards the types of adventurous designs for ground or space-based astronomy that might now be envisaged. The potential benefits are enhanced optical performance in more compact, lower mass, and rugged packages. Such designs would, until recently, have been impossible to fabricate, and so we also describe some of the recent technical advances that have materially changed this position.

Key words: instrumentation: spectrographs – space vehicles: instruments – telescopes.

1 INTRODUCTION

Regular (unstructured) optical surfaces are needed to collect, direct and focus light, whilst minimizing effects that degrade detected signal-to-noise ratio, e.g. optical aberrations, absorption, vignetting, diffraction and scattering and (in the infrared) thermal emissivity. In this paper, we describe new developments that impact future capability for astronomical observations using complex optics. We focus on work in the UK in computer numerically controlled (CNC) polishing and allied processes, aided by collaborators from Japan and China. This work includes mathematical descriptions, manufacture and analysis of ‘freeform’ optics; a true freeform having no axis of symmetry on or off the part. We illustrate the practical potential through case studies contributed by co-authors who are users of the technology. These show how freeform capability has ‘set optical designers free’ to pursue avenues previously considered impractical. This has a potentially revolutionary impact on future ground and space-based telescopes and their instrumentation, from X-ray to infrared and beyond. As an extreme case of surfaces demanding high spatial frequency content, we summarize our work on edge control, but considering power spectral density (PSD), rather than peak-to-value edge misfigure as previously reported.

For clarity, we distinguish ‘shape’ (square or circular etc.), ‘form’ (overall 3D surface topography), ‘mid-spatial frequencies’ (ripples superimposed on form), and ‘texture’ (local surface roughness).

1.1 The basis of modern optical fabrication

A spherical surface in reflection or transmission cannot bring parallel rays to a diffraction-limited point, leading to various manufacturing approaches for more complex geometries. For the infrared, single-point diamond turning of suitable materials can directly produce parabolic surfaces, and off-axis and freeforms by servoing tool in-feed synchronously with part rotation. For more critical parts, post-polishing (Beaucamp et al. 2008) may be required to remove the repetitive tool signatures.

Brittle materials such as glasses and ceramics, may be CNC ground to final dimensions, including complex forms. Grinding is mediated by precise positioning (with respect to the part) of a grinding wheel containing many diamonds. High contact forces and vibration modes then give rise to surface and sub-surface damage. Cranfield University’s highly stiff BoxTM (Tonnellier et al. 2006, 2007; Comley et al. 2011) exemplifies a state-of-the-art machine.

Following CNC grinding, the part may be CNC pre-polished to remove the damage, whilst preserving the ground form. Polishing is
effectively a rubbing process, mediated by surface speed, pressure and time; approximating to Preston’s law (Preston 1927). Corrective polishing based on metrology data is then used iteratively to refine the form to specification. A final finishing pass may be required to clean up surface texture and mid-spatial frequencies, which degrade imaging and stray light.

1.2 Processing aspheric and freeform surfaces

Given a CNC ground part, a spherical surface is the simplest to process, because a rigid polishing tool pressed into intimate contact at one location, can maintain contact anywhere else. With aspheres and freeforms, this is not the case, tool misfit creating surface artefacts. Misfit is most severe for full size tools (Fig. 1), but still evident with small tool (sub-aperture) polishing. Several approaches have been developed to tackle this. The University of Arizona sub-aperture stressed lap (West et al. 1994) is deformed actively to match the part’s local surface topography. Conversely, in the University of California stressed mirror polishing (Lubliner & Nelson 1980), a thin mirror is actively deformed to the inverse target asphere, polished spherical, and then relaxed. Such techniques require customized tooling or fixtures for each new mirror design. Magnetorheological finishing [MRF, developed by University of Rochester and commercialized by QED (Harris 2011)] uses a magnetic polishing slurry which is stiffened by a magnetic field at its interface with the part, providing a local spot of action with no physical tool. MRF is a finishing process, in that its purpose is to correct parts which are near net form. In ion figuring (Zeuner & Kiontke 2012), material is ablated by bombardment with a Gaussian ion beam scanned over the surface in vacuum. It is a very fine corrective process which does not polish a rough surface.

Given this process landscape, there was clear demand for a fully industrialized and ‘universal’ solution that could rapidly polish ground surfaces and correct form on diverse materials (ductile and brittle) and generalized geometries. This was the genesis of the Precessions™ process and machines.

1.3 The Precessions™ process

The Precessions™ process was spun out of research at University College London, and has been developed and productionized in a range of machines from 30 mm to 1.6 m capacity by Zeeko Ltd. These machines, supported by comprehensive software for metrology analysis and tool path generation etc., are in regular use in numerous commercial optics shops around the world. The core technology uses an inflated spherical membrane (or elastomeric) ‘bonnet’, covered with polishing cloth, in the presence of a polishing slurry. The bonnet is pressed against the part to create a local region of removal (Fig. 2). By spinning the bonnet about its axis, and precessing this axis around the local normal to the part (Fig. 3), a close approximation to a Gaussian removal profile can be achieved (Walker et al. 2003a,b, 2006, 2007, 2012a). This profile – the ‘influence function’ (IF) – is analogous to that of a single actuator distorting an adaptive mirror.

The bonnet is tracked over the part’s surface along a pre-determined tool path (spiral, raster, or pseudo-random (Dunn & Walker 2008; Takizawa & Beaucamp 2017), using a dedicated CNC machine tool. At constant speed, the tool removes a uniform ‘skin’, providing pre-polishing (with complications at the edge; see below). In corrective polishing, the surface form is measured, the dwell time map to correct form computed, and interpreted as variable traverse speeds over the surface. This is analogous to computing actuator settings for an adaptive mirror, given wavefront sensor data. Up to 80 per cent convergence (20 per cent error) can be achieved under optimal conditions. Convergence is limited in practice by a host of factors, including metrology errors, polishing pad wear, and variability of the slurry condition and flow dynamics at the tool part interface.

Machines operating the Precessions™ process can also be configured for fluid jet polishing (FJP). In this mode, the bonnet is replaced by a rotating, angled orifice, which discharges a pressurized jet of polishing slurry, which may be further energized ultrasonically. This jet can be precessed around its point of contact with...
the workpiece surface, giving a near-Gaussian influence function, and removing material through the kinetic energy of the impacting abrasive particles. This uses the same machine kinematics and software as bonnet polishing. Applications have included optical moulds from visible to X-ray (Beaucamp et al. 2011), and removing diamond turning signatures (Beaucamp et al. 2008).

To avoid confusion, ‘precession’ describes the motion of the axis of the tool, and Precessions™ refers to the proprietary process, machines, and software.

1.4 Dynamic range with the Precessions™ process

The ultimate objective of a process chain is to convert input quality into specified output quality, with minimum time, cost, and risk. Process dynamic range plays a key role in achieving this.

Abrasives used with bonnet processing may be mobile in a liquid carrier, or bound to a layer attached to the surface of the bonnet. For optics and optical moulds made from relatively soft materials such as glass or electroless nickel, one of a wide range of standard pads is pre-moulded spherical and cemented to the bonnet. For glasses, a re-circulated aqueous slurry of CeO2 abrasive is the normal choice, and can be diluted to give arbitrarily low removal rates. For metals, un-recirculated Al2O3 or diamond particles (Beaucamp & Namba 2013; Li et al. 2013a) may be used.

For fast removal, a variety of ‘grolishing’ methods intermediate between grinding and polishing (Yu Walker & Li 2012; Walker et al. 2007), have been developed using coarser abrasive slurries, or diamonds bound in a solid matrix pre-moulded for cementing to the spherical bonnet. Particularly for harder materials, e.g. sapphire, silicon carbide, or moulding alloys, the Shape Adaptive Grinding (SAG) process is highly advantageous, where ‘superabrasives’ are embedded in resin or nickel pellets directly electroplated onto the bonnet’s surface (Beaucamp et al. 2014).

Given the above, we discriminate three types of ‘process dynamic range’:

(1) The range of removal depths and volumetric removal rates which a machine can deliver, given appropriate selection of abrasives and tooling for particular materials and input qualities.

(2) The ranges achievable in a single polishing run, as required to correct measured form errors.

(3) The range of surface forms compatible with the machine, process, and tooling.

As regards machine capability, the low removal end is important for very fine form correction based on metrology data (in the tens of nm RMS and below), and ultimate texture (down to fractions of a nm Sa). The high end is needed to accommodate different materials and input qualities. One workpiece may have been machined using a modern CNC grinding machine, directly approximating the target aspheric or freeform surface. The CNC polisher then removes \( \sim 10-20 \) μm of sub-surface damage, improves texture to perhaps 0.2–2 nm Sa, and corrects a few μm or so of RMS form errors. Another workpiece may have been prepared on a classical spherical grinder, leaving the CNC polisher to impose an aspheric or freeform characteristic in its entirety. In accommodating these extremes, practical removal depths span many tens of microns down to nanometres, and tens of mm\(^3\) min\(^{-1}\) down essentially to zero.

In regards to dynamic range in a single run for corrective polishing, removal depth is typically varied by moderating the traverse speed, as above. Note that the faster the traverse speed, the less material is removed, and so minimum removal is governed by the maximum linear speeds the machine can deliver. In practice, this means that zero removal (e.g. at the highest region on the part) is impractical, and corrective polishing acts as a modulation on a removal pedestal. From experience, a 10:1 variation in feed rate (and so removal depth) is the practical limit during a single run.

The range of forms that manufacturers can bonnet polish is not constrained by rotational symmetry, or even by the surface being describable by an equation. However, the surface does need to be a continuous function (e.g. without steps), but of any generalized form (it may even be characterised by a point cloud). The dynamic range of forms extends from plano at one extreme, to freeforms at the other, limited by the ability of the spherical bonnet to fit within the shortest local radius of curvature on the surface. In practice, manufacturers select the appropriate tooling for the specific workpiece, and 10 mm local radius of curvature is a pragmatic lower limit. Below this, and for discontinuous surfaces, fluid jet polishing may be used.

In practice, it is often the available surface metrology, and uncertainty of measurement, that are the limiting factors in corrective processes. For the earlier stages where surfaces are non-specular, contact probe methods will often be adopted due to their large dynamic range. For high-precision specular surfaces, interferometry will typically be used, and fringe density then limits the dynamic range of the test. Aspheric and freeform surfaces usually demand some form of nulling optics. The desired surface error is then derived effectively from the small differences between two sets of large numbers – the surface wavefront and the artificially created reference wavefront. Small set-up errors can then have a disproportionately large effect, as evidenced by the Hubble Space Telescope Failure Report (Allen et al. 1990). In the case of Precessions™ machines, set-up time and errors in interferometric testing can, in certain cases, be mitigated by testing in situ on the polishing machine. A good example was the manufacture of prototype mirror segments for the European Extremely Large Telescope (Walker et al. 2014). The nulling interferometric test was implemented in a 10 m high test tower around and above the machine, so that the segment was not moved between polishing and metrology. This project also provides an excellent example of CNC polishing to a challenging specification (defined by Swat & Spyromilio 2009), as discussed further in Section 5.

The Precessions™ process, and the continuous precessing variant, have been compared against several other ultraprecision grinding and polishing techniques in an excellent review (Beaucamp & Namba 2014). Their concluding summary says, ‘Free flowing abrasive processes yield the finest surfaces (fluid jet polishing, elastic emission machining), while the pad based method (continuously precessed polishing) offers optimal productivity’.

![Figure 4. Example of NURBS surface, with the controls points shown as small spheres.](https://academic.oup.com/mnras/article/485/2/2071/5222666)
captures the impact of Precessions™ processing in manufacturing environments, deploying the diversity of tooling and abrasives available for ‘contact processes, and complemented by non-contact fluid jet capability’.

2 DESCRIPTIONS OF FREEFORM SURFACES, INCLUDING NURBS

Aspheric surfaces are typically described using eq. (1) – a conic section of radius $R$ and constant $k$, and adding some polynomial terms $a_0 \ldots a_n$ along the radial direction, as follows:

$$z (r) = \frac{r^2}{R \left(1 + \sqrt{1 - (1+k)r^2/R^2}\right)} + \sum_{j=0}^{n} a_j r^j. \quad (1)$$

In the off-axis aspheric case, this same equation is applied to a domain spanning a region of the $XY$ plane away from the origin. In such case, the surface described by the equation appears slanted and far away from the centre. Actual components thus require tilting and polishing. In the more general case of freeform optics, such as used in head-up displays (HUD), the polynomial terms are applied to the $X$ and $Y$ directions, and leads to eq. (2):

$$z (r) = \frac{r^2}{R \left(1 + \sqrt{1 - (1+k)r^2/R^2}\right)} + \sum_{i=0}^{m} \sum_{j=0}^{n} a_{i,j} x^i y^j. \quad (2)$$

However, more complex cases exist, such as Fresnel and illumination optics, for which the equation above is not sufficiently detailed to produce the required surface characteristics and with the required fidelity. In such cases, highly detailed piecewise polynomials, Zernike terms, or splines may be required. While the grinding and polishing control software may attempt to implement each of the cases above independently, the complexity of the equations and existence of transformations renders the implementation task both arduous and error prone.

A highly generic method for representing complex surfaces is non-uniform rational B-splines [NURBS (Chrschn 2008)]. Fig. 4 shows an example of a NURBS surface, with its grid of control points represented by small spheres. The control points act as attractants for the surface, and can have their positions and attraction weights adjusted to fit a target shape. We have found that a software implementation based entirely on NURBS surfaces offers several advantages, as follows:

1. Surface fitting algorithms can convert any of the above equations (aspheres, off-axis aspheres, freeform polynomials) into NURBS surfaces (Ma & Kruth 1998).

2. In cases where the coordinate reference frame changes from one machine to the next, NURBS surfaces can be conveniently relocated using $4 \times 4$ transformation matrices.

3. The 2D parametric UV space of NURBS surfaces can be used to generate rectilinear tool paths such as rasters, which are then transformed to the 3D Cartesian XYZ space corresponding to the workpiece shape.

4. Important surface properties such as normal vectors (used to compute tool position and orientation) and principal curvatures (used to compute the change in shape of influence functions with compression of a bonnet tool) can be readily extracted at any point on the NURBS surface.

5. NURBS surfaces can be used with a rolling ball algorithm to analyse and fit workpiece form data from coordinate measurement machines (CMM), to retrieve the residual form error.

6. Most modern commercial CNC controllers are NURBS compatible.

First, B-spline basis functions $N_{i,n}(u)$ are used in the construction of NURBS curves, in which $i$ correspond to a control point index, and $n$ its order. Fig. 5 shows how basis functions of 1st (linear) and 2nd (quadratic) order partially overlap, with the vertical dashed lines denoting the location of knots where the basis function reaches the value 1 (corresponding to the control points $P_i$).

Secondly, weights are applied at each control point, in the form of multipliers to the basis functions. A NURBS curve $C(u)$ eq. (3) consisting of $k$ pairs of control points and weights can thus be expressed as:

$$C (u) = \frac{\sum_{i=1}^{k} N_{i,n} w_i P_i}{\sum_{i=1}^{k} N_{i,n} w_i}. \quad (3)$$

A NURBS surface $S(u, v)$ eq. (4) is the tensor product of two such NURBS curves, each associated with independent parameters $u$ and $v$, giving the final expression:

$$S (u, v) = \frac{\sum_{i=1}^{k} \sum_{j=1}^{q} N_{i,n} N_{j,m} w_{i,j} P_{i,j}}{\sum_{i=1}^{k} \sum_{j=1}^{q} N_{i,n} N_{j,m} w_{i,j}}. \quad (4)$$

where the weights $w_{i,j}$ and control points $P_{i,j}$ and distributed across a 2D grid. For instance, Fig. 6 shows the parameters of the NURBS surface describing the workpiece in Case Study 3.

Partial derivation of $S(u, v)$ in the $u$ and $v$ directions can be used to determine in 3D space the tangent vectors $\vec{t}_{u}$ and $\vec{t}_{v}$ to the

Figure 5. Basis functions used to build NURBS curves.

Figure 6. Parameters of NURBS surface in Case Study 3.

| form: 'B-NURBS' |
| [xyzw] dim: 4 |
| [k] number: [256 256] |
| $P_{i,j} w_{i,j}$ coefs: [4x256x256 double] |
| $N_{i,j}$ knots: [(1x261 double) (1x261 double)] |
| [nn] order: [5 5] |

Downloaded from https://academic.oup.com/mnras/article/485/2/2071/5222666 by guest on 25 October 2021
Optical fabrication for astronomy

Figure 7. Computation method of tangents, normal, and precess vector. (a) Tangent and normal vector, (b) precess direction from tangents, and (c) precess vector from normal.

Figure 8. Illustration of a 6U CubeSat footprint, showing that by design, each monolith has been constrained to occupy no more than 1U volume (100 mm x 100 mm x 100 mm).

3 FREEFORM CASE STUDIES AND THE IMPACT ON ASTRONOMY

Freeform surfaces confer additional degrees of freedom on the optical design, providing enhanced control of optical aberrations at each surface. As a result, optical function and performance can be achieved with reduced mass, size, and complexity, or performance can achieved that would be otherwise impossible. The literature has many examples; a particular one is the Alvarez zoom lens (Alvarez 1967), consisting of two cubicform lenses in close proximity, with zooming by lateral shear rather than axial displacement. This can be designed so that, in the neutral position, the combination has negative, zero, or positive overall power. The approach has historically been limited by technical difficulty of manufacture of the freeform surfaces, but modern methods such as we describe are overcoming these. The lens has potential for diverse applications; ophthalmic, cell phone zoom cameras, and (in astronomy) continuously variable image-scales in remote-sensing cameras, and astronomical imagers, guiders, and spectrographs.

The three case studies below are demonstrations of compact telescopes (or sub-systems) with multiple freeform surfaces in a single substrate block, or made from replicated mirrors. For design purposes, allowable volume was determined by cube units for space launch payloads (Fig. 8). A CubeSat (U-class spacecraft) is a type of miniaturized satellite for space research that is made up of multiples of 100 x 100 x 100 mm cubic units. Such small satellites furnished with compact optical systems can be launched and released in numbers for science experiments, either in dedicated launches, or occupying a role as ‘ballast’ on larger missions (Zurbuchen et al. 2016). In astronomy these could be, for example monitoring transient or time variable phenomena, or proving space worthiness of new detector or instrumentation techniques. Indeed, several opportunities for astronomical CubeSat missions have recently been described (Walker et al. 2018).

Design forms illustrated below have evolved from pentaprisms, Maksutovs, and off-axis imagers, all rolled into one. Potential advantages of a monolithic system include freedom from operational misalignment, e.g. under launch vibrations, and improved thermoelastic behaviour with reduction of jitter and drift. For purposes of manufacturing demonstration, these designs were limited to only two surfaces with power, achieving performance inferior to diffraction limited. We next consider the characteristics these example forms offer.

3.1 Case Study 1: freeform monolithic multisurface telescope – solid design

The optic described in Fig. 9 occupies most of the volume of the 1U cube, and with the right angle formed by surfaces 1 and 4, lends itself naturally to manufacture from a cube of glass. Furthermore, surfaces 1 and 4 form part of a Cartesian datum structure supporting subsequent metrology. At first glance, the bulk of glass appears to have little value optically, however the result is a slight reduction in back focal distance. Once coated, the freeform surfaces are completely protected, embedded in solid glass, and are immune to dust or contamination. The overall convex shape is robust against
deflection and deformation when compared with an assembly of lenses.

Freeform surfaces were defined using \( XY \) polynomials, with departure from best-fitting sphere of approximately 0.15 mm. The virtue of this design is not specifically resolution (rms spot radius is 40 \( \mu \)m), but instead, the relatively wide FOV over which that imaging quality extends (Fig. 10).

Several units were produced, starting with ultrasonic grinding, then fully polished using a robotic CNC polisher, and finally coated with protected aluminium at Optimax. In that stage of research, UA3P measurement, smoothing and finishing (MRF) tools had not yet been brought online which could accommodate this optic. As will be seen later, such tools are critical for production of precision freeform surfaces. Transmitted wavefront error (TWE) was measured in double pass and the Zernike fit is reported in Fig. 11, along with micrographs of the back focus spot. Serially numbered units SN02 and SN03 are compared, where SN03 showed a relatively more pronounced astigmatism.

### 3.2 Case Study 2: freeform monolithic multisurface telescope – open design

Fig. 12 shows a novel design complementary to the ‘solid’ monolith. In this case, a weight reduction of over 50 per cent can be achieved by creating a ‘light weight’, ‘open jaw’ design that joins the two reflective surfaces using minimal material. With the same optical prescriptions, imaging performance is essentially equivalent. Such a design may even lend itself to 3D printing (additive manufacture) of the mirror substrate. Once completed, the exposed surfaces are vulnerable to dust, and this form may be less robust against deflection.

For finishing, generation and polishing proceed using the same equipment as case 1, however tool access is complicated by the reduced clearance between the surfaces. Nevertheless, technical process developments resulted in improved performance relative to stage 1 (Fig. 13). Metrology of these surfaces is certainly more challenging ergonomically compared with that on singlet lenses. CMM measurement is fairly straightforward, but optical measurement of each surface in isolation is complicated by reduced access. This can be approached with a ‘periscope’ optical probe inserted into the ‘jaws’ of the assembly.

An interesting variant for astronomy would be to replicate a diffraction grating onto one of the flat surfaces, providing a slitless imaging spectrograph.

### 3.3 Case Study 3: X-Ray mirror moulding die for Wolter type-1 off-axis parabola

The most practical mirror configuration for focusing X-ray radiation is the Wolter type-1 grazing incidence telescope (Wolter 1952), as in Fig. 14. Since the assembly requires hundreds of off-axis parabolic mirrors, each a millimetre thick, the preferred fabrication methods rely on replication from moulding dies. A process chain for automated fabrication of such dies is shown in Fig. 15. Blocks of fused silica are precision ground to the approximate freeform shape with an accuracy of few dozens of microns. The aspherical shape accuracy is then measured with an ultra-precise coordinate measurement machine. Given adequate fiducialization between measuring and polishing equipment, corrective polishing of the moulding die was possible using the Precessions\textsuperscript{TM} method.

A demonstration optic has been fabricated at Chubu University in Japan: a 200 \( \times \) 200 mm block of fused silica was precision ground to an initial form error of about 40 \( \mu \)m P-V. Precessions\textsuperscript{TM} corrective polishing runs were performed using a slurry of cerium oxide abrasive of nominal size 1.5 \( \mu \)m, bringing form accuracy in the optical axis direction down to < 50 nm P-V, as shown in Fig. 16. Once corrective polishing was completed, the moulding die was finished by a smoothing run with CeO\textsubscript{2} abrasives of nominal size 0.5 \( \mu \)m, achieving a final microroughness around 0.3 nm rms, as measured by atomic force microscopy (AFM), and as shown in Fig. 17.

### 4 ISSUES OF DIMENSIONAL AND FORM METROLOGY

Measurement of freeform surfaces requires new approaches to generalizing geometrical definition of optical specifications. This is not arbitrary, but driven by performance. This raises the question, ‘What reasonably small set of parameters can be used to describe errors typical of freeform manufacturing?’ For rotationally symmetrical optics (spheres and mild aspheres), wedge and centre thickness normally have specified tolerances. In the case of prisms, cylinders, and freeforms, it is possible to incur twist or clocking errors between two surfaces in manufacture. Generally, freeform performance will be determined not only by the ‘best-fitting’ quality of the surfaces, but also their relative positions. The concept of surface position or location becomes key in freeform metrology. Several methods can be used to obtain the positional information for surfaces, such as external fixtures (e.g. optomechanical bench), various technologies for tomography or 3D...
scanning, and contact probing. Fiducials or datum structures can be used to link mechanical features defined in the manufacturing drawings (and CAD files) with individual optical surfaces. The following are examples illustrating the use of fiducials in position measurement.

A meniscus window (concave–convex) with aspheric–toroid (atoroid) prescription was manufactured using the generation methods mentioned earlier, and polished using the Zeeko IRP200 robotic CNC polisher. A flange and two flats were created integral to the part, and used to maintain a reference Cartesian coordinate system as shown in Fig. 18.

By referencing fiducials during surface measurement, relative positions were determined (Fig. 19). During finishing, this allowed the decoupling of individual surface errors from alignment errors, which can confound non-referenced measurements using interferometry or profilometry. Absolute surface data can help system integrators, who wish to model ‘as-built’ performance.

In addition to aiding the manufacturer, properly employed fiducials can be used in assembly and alignment of completed optical components into larger systems. It is prudent to introduce fiducials into the design process at an early stage, using the optical design to inform the required tolerances for both manufacture of the optic and its final integration. Tolerance specifications that encompass both ‘best fit’ as well as rigid body or modal alignment errors can sometimes assist the alignment of challenging designs.

In cases where fiducials may not be physically incorporated into the optical component (or temporarily attached), the use of a jig may be necessary in order to assess the best-fitting location of the measurement data. In Case Study 3, a special measurement jig was produced, as shown in Fig. 20, to create a reference frame attached
Figure 13. Nominal on-axis imaging focus spot for this design (left), measured on-axis focus spot in 500 μm circle (centre) and across the ± 4.3° x ± 1.4° FOV (right).

Figure 14. Principle of Wolter type-1 X-ray telescope.

Figure 15. Manufacture of Wolter type-1 X-ray telescope.

to the physical centre and orientation of the mandrel (by intersecting the lines passing through the centres of 4 silicon nitride precision balls). The centre point was then referenced against this frame using a 5th ball on the opposite side of the mandrel (used to measure the exact width and length, which were then divided by 2). The jig and mandrel were measured with a UA3P CMM at Panasonic in Osaka, as shown in Fig. 15(c).
5 Active Control of Edges

Perhaps the most extreme ‘freeform’, with the highest spatial frequency content, is an edge. In general, boundary condition effects in polishing lead to edge misfigure. However, if the polishing influence function could be progressively contracted as it encroaches the edge zone, this could provide the basis for edge control. The Precessions™ process facilitates this, because the polishing bonnet can be raised as it encroaches the edge zone, progressively narrowing the influence function. Ideally, the spot size would fall to zero when the leading edge of the influence function reaches the precise edge of the part. Unfortunately, this would require infinite dwell time to remove a depth of material at the edge to match the rest of the workpiece. Instead, the process is empirically optimized so that the influence function slightly overlaps the edge of the part, leaving a narrow upstanding edge, which can be removed using a small pitch tool. This method was first developed on hexagonal witness samples, and achieved an average edge misfigure of 110 nm P-Vq (95 per cent) on a 400 mm across corners part (Walker et al. 2012a).

This approach was further developed by the OpTIC Centre in North Wales for polishing 1.4 m across corners, hexagonally shaped, off-axis aspheric, prototype mirror segments for the European Extremely Large Telescope (E-ELT) project, using a 1.6 m Zeeko machine. (Walker et al. 2012b; Gray et al. 2013; Li et al. 2013b; Walker et al. 2017). The specification for any segment (Swat & Spyromilio 2009) can be summarized as follows. The maximum wavefront error (excluding a 10 mm edge zone) was 100 nm RMS. This included errors of matching segment base radii between segments. After removing specified low-order terms to leave mid-spatial frequencies, the allowance was 30 nm RMS. (These numbers are halved for surface errors). Maximum allowable misfigure in the edge zone was 400 nm peak-to-valley wavefront (200 nm surface), and maximum surface texture was 3 nm.

Uniquely amongst large telescope segments, these prototypes were produced entirely in their final hexagonal shape. In practice, this meant that each process step had to operate over the entire surface, to avoid issues in blending separately processed sub-areas together. In this way, the pitch edge finishing step conveniently cleaned up mid-spatial frequencies and texture on the global surface. Nevertheless, a key challenge was to achieve the edge specification.
with low scratch dig (Walker et al. 2014).

Future applications of edge control include image or pupil slicers, secondary or relay mirrors undersized to minimize IR emissivity, and segmented optics. The last is relevant not only for mirrors, but could enable novel geometries, such as ‘christmas tree’ segmented prisms (e.g. for large objective prisms, or cross-dispersion in echelle spectrographs), illustrated schematically in Fig. 21. Such a system might be made by classical techniques, working a large boule of material into a single, long prism, which is finally diamond sown into prism segments. This would method would assure the critical matching of apex angles. An alternative approach would be to manufacture the prism segments individually from small, lower cost boules, with CNC corrective polishing used to match apex angles, and edge control used to achieve sharp edges at the bases of the prism segments. This is analogous to the matching of base radii of curvature, and edge control, on E-ELT prototype segments as above.

There is an equivalent concept for a segmented lens, which could feed a mosaic detector array, delivering modest de-magnification to avoid gaps in focal plane coverage due to the dead space around individual sensors. Segmented solutions more generally can be advantageous through reduction in (i) mass and gravity distortion and (ii) optical path length through the refracting medium – important where material transmission or homogeneity is an issue at the wavelength of operation.

Our previously reported work on form and indeed edge control consistently optimised peak-to-valley edge height misfigure, as this accorded with the specification for the E-ELT prototype mirror segments (Swat & Spyromilio 2009). Recently, we have realised that this disregarded important diagnostic information in the spatial frequency domain (i.e. power spectral density, or PSD) at different stages of manufacture. In order to understand this better, we first created synthetic data representing perfect edges on a finite part, sampled in discrete intervals, and compared the PSD calculated from first principles, with predictions from commonly used commercial software.

Consider \( z(n) \), the discrete surface height data at equally spaced intervals \( \Delta x \) (mm) over a total length \( L = N \Delta x \). For a given \( fm \) the spatial frequency components, \( fm = m/N \Delta x \), where \( -N/2 \leq m \leq N/2 \), or the wavelength \( \lambda_{mn} = 1/fm \). From first principles, PSD was calculated by the FFT periodogram method to reduce the variance of the result, following (Merle & Bennett 1995), giving eq. (5)

\[
\text{PSD} \left( \sigma \right) = \frac{\Delta x}{N} \left[ \sum_{n=0}^{N-1} z(n) \exp \left( -2\pi i n m / N \right) \right] ^2 \tag{5}
\]

Due to the symmetry of the result, the scale of \( fm \) is from \( 1/(N \Delta x) \) to \( 1/(2 \Delta x) \) and the unit of \( fm \) is \( 1/\text{mm} \). Meanwhile, the unit of PSD is \( A^2 \) mm, where \( A \) is the dimension of \( z(n) \). This accords with Parseval’s theorem that the integral of the square of a function is equal to the integral of the square of its Fourier Transform. In interpreting PSD results from commercial software, two issues arise. First, some codes adopt the \( A^2 \) mm unit of PSD, and some \( A^2 \). Secondly, autoplottting may be on logarithmic or linear scales, which can disguise or accentuate specific signatures.

The \( \Delta x \) data discretization profoundly affects measured PSD, which reaches zero at a spatial wavelength of \( 2 \Delta x \), irrespective of higher spatial frequencies on the surface. This is due to the Nyquist limit, as demonstrated in Fig. 22 where PSD plots for a simulated perfect edge are shown with different sampling – analogous to pixel sampling of astronomical spectra. In optical testing using an interferometer, this corresponds to the detector pixels projected onto the surface under test. With stylus profilometry, tip size imposes a Nyquist limit, but with a more complex relationship depending on the fit of the stylus tip to the local surface curvature.

In Fig. 23, process results from two successive corrective polishing runs on a single surface, using variable spot sizes, are each compared with predictions. The predicted removal profiles were obtained through convolution of the fitted empirical influence function (IF) data and dwell times, at each calculation point on the surface. These points were distributed with a uniform spacing of 0.635 mm, equivalent to the projected pixel size in the interferometric test data used by the form correction algorithm. The figure also shows the corresponding predicted and measured PSDs, with good agreement.

Figure 21. Schematic concept of a low-mass segmented prism (left) and equivalent monolithic prism (right).

Figure 22. PSD of simulated perfect edge with different X sampling.
This means that process parameters such as variable spot size and dwell times can be optimized before polishing, not only to optimise residual form error, but also to tune PSD.

6 CONCLUSIONS

Freeform designs, such as demonstrated in this paper, have several potential applications to astronomy. They can enable novel instrument concepts with reduced size and mass, and/or improved performance (image quality, field of view, throughput, stray light, etc.). One candidate would be rapid response to transient phenomena, observed from space using single or multiple CubeSats, where allowable volume is non-negotiable, or available in only 1U multiples.

In addition, the monolithic design of Fig. 9, with its plano input and output faces, lends itself to incorporating a transmission grating cemented, optically coupled, or directly replicated onto the exit face. Such a development would provide an extremely compact slitless imaging spectrometer.

We have drawn attention to the need to interpret power spectral density data allowing for effects of the Nyquist sampling limit. Furthermore, with stylus profilometer data, the Nyquist limit itself may vary with changes in stylus fit over an aspheric or freeform surface. The ability to predict PSD before corrective polishing given process parameters, presents a new way to estimate PSD content and optimize process parameters.

From the perspective of the manufacturer, modern CNC polishing technology, machines, and tooling can process a huge range of generalized forms from simple to freeforms, and including edges. Furthermore, substrates within scope range from soft and ductile substrate materials such as aluminium, through optical glasses, to hard materials such as sapphire, silicon carbide, and tungsten carbide. The factors that limit the extremes of freeform capability with bonnet tooling is the capacity to accommodate the tool curvature within the shortest local radius of curvature on the part, and the ability to measure the freeform surfaces produced. Fluid jet polishing extends polishing capability to more extreme forms, discontinuous surfaces, and otherwise inaccessible features.

It is our hope that this paper will inspire the ground and space-based astronomical instrumentation communities to exploit these new capabilities, through more adventurous – and higher performance – optical designs.

ACKNOWLEDGEMENTS

The UK work reported was supported by a variety of grants and contracts, from the Science and Technologies Funding Council, the Engineering and Physical Sciences Research Council, Innovate-UK, the Royal Society, Centre for Earth Observation Instrumentation, Welsh Government, internal funds from the respective universities, the European Union and the European Southern Observatory. These were reinforced by numerous contributions from Zeeko Ltd. The work in Japan was supported by the Grant in Aid for Scientific Research No. 17K14571 from the Japan Society for the Promotion of Science. The Japanese authors also acknowledge support from Zeeko Ltd, for loaning the IRP200 polishing machine on which some of the demonstration work was conducted.

REFERENCES

Allen L., Angel R., Mangus J. D., Rodney G. A., Shannon R. R., Spoolhof C. P., 1990. The Hubble Space Telescope Optical System Failure Report. NASA Publications, NASA, Washington DC.

Alvarez L. W., 1967, US patent 3305294 A, pub. 1.

Beaucamp A., Freeman R., Matsumoto A., Namba Y., 2011, Burge J. H., Fahnle O. W., Williamson R., Proc. SPIE Conf. Ser. Vol. 8126. Optical Manufacturing and Testing IX. SPIE, Bellingham, p. 81260U.

Beaucamp A., Namba Y., 2013, CIRP Ann., 62, 315.
This paper has been typeset from a TeX/LATEX file prepared by the author.